Solutions Manual to Accompany

MATERIALS AND PROCESS IN MANUFACTURING

Ninth Edition

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Contents

Preface

This version of the textbook contains significant new content and, so then, does the Solution Manual. These notes are provided to explain some aspects of the new content.

The authors of the textbook prepared the new content for the book, including all new questions and problems. I prepared only the answers to the new questions and solutions for the new problems.

Many of the questions are broad, open-ended and raise real, practical concerns. The answers that I have prepared are intended to directly address the important concepts raised and provide some of the thought process leading to the answers. Where example applications of the concepts are provided these are intended to be starting points for consideration and discussion, not final, definite or unique answers.

Some internet web sites are suggested as example sites containing useful information. These are only suggestions as typical starting points for more in-depth investigation of the questions raised. I am always hesitant to refer to internet web sites since often the updating of them, and sometimes their continued existence, is problematic. Perhaps the best way to view the inclusion of a web site in the Solution Manual is as an indication of questions that are more open-ended and may require more material than is in the text for preparing answers.

For the new quantitative problems and some of the problems from previous editions of the text I have used spreadsheets to produce solutions. The intent is to provide the opportunity for users of the text to customize these problems. Problem variables and variable values can be changes with little effort. The difficulty is that to provide this capability specific software must be used since writing code that can be used on most computers is not warranted. Microsoft Excel 97 was used. In any case, the solutions are also provided in fixed form.

Some question answers were put in the form of tables so that it is possible to slightly manipulate the questions. For example, various table cells can be cleared and fill-in-the-blank questions formulated. Microsoft Word 97 was used for the Solution Manual text.

Barney E. Klamecki
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CHAPTER 1
Introduction to Materials and Processes in Manufacturing

Review Questions

1. The availability and cost of manufactured products are an important part of our cost of living and the real wealth of the nation. Thus, reducing the cost of producer and consumer goods improves the productivity while holding down inflation, thereby improving the general standard of living.

2. This is true if you consider that everyone who used the output from a process, including all the intermediate steps, is a customer. The operator of the next process is the user and customer of the proceeding process. In fact, some companies identify two customers, the external customer who buys the finished product and the internal customer, who builds the product one - i.e., the people who work in the manufacturing system. See Chapter 43

3. Job shop - an injection mold manufacturing shop, the shop at a large university that produces research equipment and apparatus. Job shops are capable of producing products with great variety, typically employing highly skilled workers.
Flow shop – automobile assembly. Flow shops are usually laid out so that specific products pass through a series of operations with no backflow. The product range is limited, production volume is large and labor skill is lower than in job shops.
Project shop – diesel-electric locomotive production facility. The end product is very large and so many machines, tools and people come to the product to produce it at a relatively fixed location.

4. In the context of manufacturing, a manufacturing system is a collection of men, machine tools, and material-moving systems, collected together to accomplish specific manufacturing or fabrication sequences, resulting in components or end products. The manufacturing system is backed up by and supported by the production system, which includes functions like control of quality, inventory, production, and manpower, as well as scheduling, planning and the like. Within the manufacturing system, there will be machine tools, which can perform jobs or

5. No. The cutting tool is the implement that does the cutting. It contains the cutting edge and is used in the machine tool. The machine tool drives the cutting tool through the work material.

6. The basic manufacturing processes are: casting or molding, forming, (heat) treating, metal removal, finishing, assembling, and inspection.

7. By casting, the desired shaped in final or near-final form, could be obtained. This greatly reduces the necessity for machining the hard-to-machine metal. Less machining

is needed when the raw material shape is close to the finished part size and shape (called near net shape casting).

8. The foam is melted and vaporized and so moves into the atmosphere around the process.

9. The cavity in the die that the work material is deformed into when the die is pressed into the workpiece. Material on the workpiece moving into the cavity, “concave,” of the die results in the raised, “convex,” part of the medal surface.

10. Trains stop at the station to load and unload people and materials. In an assembly line, products stop at the job station to take on materials or have operations performed on them.

11. False. Storage is very expensive because time costs the company money. It is expensive to keep track of stored materials, to put them into storage, to get them back from storage, to damage them as a result of excessive handling, and so on. More importantly, storage usually adds no value - very few items appreciate on the shelf.

12. For the simple, conventional paper clip, wire is cut to length and then formed in three bending operations.

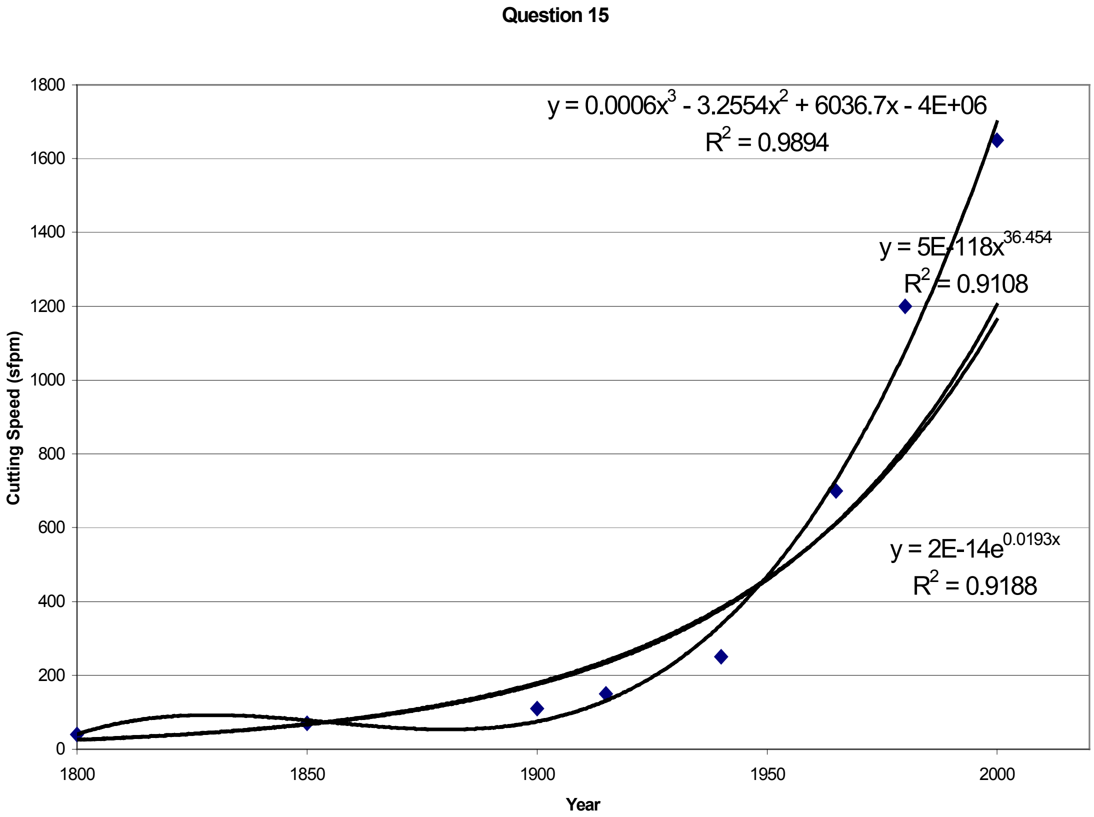
13. The university is an example of a service job shop and shows that value can be added by service processes and operations --the student enters engineering worth the minimum wage and graduates worth $15 to $20/hour. In the university job shop, the professors are the machine tool operators, the students are the workpieces, courses are the processes, tests are the inspections, books are the tooling, and department heads are the foremen.

14. Inefficient is a relative term here. If we can eliminate machining, we can save the time and the money. Machining processes are generally those which give the part its final size, shape, and surface finish and add value to the part. Because they do not produce the shape and size in bulk, but rather by localized action they may not be as efficient as forming and casting processes.

15. For the following set of data estimated from Figure 1-1

Year	**Speed**
1800	40
1850	70
1900	110
1915	150
1940	250
1965	700
1980	1200
2000	1650

fitting the data, shown as diamonds, to polynomial, power and exponential forms gives



The coefficients in the equations have little meaning since equations are a fit of cutting speed to years. The form of the equations shows a rapid rise, and an "exponential growth" conveys this idea.

16. The cost to manufacture a typical manufactured product is 20% - 30% of the selling price. For the mass produced product at the lower end of this range the manufacturing cost is \$0.20. These 20 cents includes material and processing costs. Processing includes assembly in addition to producing the components. Since the blade cost involves forming the edge in a material it is probably the highest cost part of the razor.

So, with 20 cents to cover materials, processing and assembly, and the blade the most expensive individual part an estimate of 2-3 cents is reasonable for the production of the high precision (in terms of edge) blade.

The same kind of reasoning can be used with manufacturing cost being 40% of selling cost as suggested in Problems 1 and 2.

17. Packaging is used to protest the product from the environment, to protect the product during shipping and to hold fixed numbers of products for sale.

18. Assembly of a binder type paper clip involves putting the formed wire handles in to the spring steel binder part of the clip. Assembly of bicycle wheels involves putting spokes into the wheel and hub.

If the ingredients of the club sandwich are all in their finished state then they can be assembled. If processing is necessary as in slicing meats and tomatoes and toasting bread, then the entire process is more than just assembly.

House building is usually considered construction as large parts of the effort involve manufacture of elements of the house – before they are assembled. For example, foundations are poured and let solidify before the sills for the walls are assembled to them. Houses that are simple in design and composed of large elements that are manufactured in factories can be viewed as assembly on-site. For example, assembly of entire wall sections and trusses to support roofs.

19. The physical elements of a manufacturing system are the machines, tools and inspection equipment used to produce the product. They are characterized by having measurable parameters. For example machine tools are characterized by the size of the workpiece that can be processed, in addition to a large number of other characteristics. Tools are described by their shape. Measuring and inspection instruments have measurement resolution limits. Measurable parameters extend past machine specifications to higher level (involving more than one aspect of part production) descriptions of the process such as production rates. The manufacturing system is more than the physical elements. Support and control systems, along with the physical elements, are combined in the manufacturing system.

20. The manufacturing engineer is responsible for selecting or designing and overseeing operation of the manufacturing processes. In the sense of immediate contact with processes the manufacturing engineer is often the center of "making the product." However, the decisions made by part and product designers and materials engineers have large influences on the kind of processes that can be used to make the part. How the part can be made is constrained by part design and materials used. So, all individuals who make decisions that determine manufacturing process choice should be involved in figuring out how to make the part.

21. Three general kinds of information are missing from Figure 1-6 that are contained in Figure 1-8.
1. The number and activities of the workers,
2. The measurable parameters that can be used to evaluate the operation,
3. The general view that the system in Figure 1-8 is designed for a certain product and so is more specific in design and operation than the manufacturing job shop shown in Figure 1-6.

22. This is really a discussion question to get the students to be aware of all the things involved in characterizing a process technology. The extrusion process results when the pressure applied to a material exceeds its flow strength. Sufficient energy must be applied to overcome friction, so lubrication is very important. The tooling is generally very expensive. A single die may cost $5000 and setup time can be long. The process usually produces 10 to 25 surface feet per minute of material. The critical process parameters are temperature and pressure, the material being extruded, lubrication, and extrusion rate. Some metals cannot be extruded very well. The process is constrained by

the power available and the size of the billets --i.e. the standard process is not continuous. The process operates reliably but users should always be aware of the high pressures involved in upsetting the materials. Operator skills are not critical and the process is semiautomatic. The process can do a wide variety of parts, depending only on the die design. It is hard to do hollow extrusions. Extrusion as a process is typically good to a tolerance of about 0.001 or 0.002 inches.

23. The emphasis of the question is on assembly and so can be answered relatively simply since assembly means interconnecting finished products or subassemblies. That is, automobile assembly is a series of steps in which the chassis/frame is populated with an engine, drive train, wheels/tires, seats, body panels, windows, etc. This is in contrast to manufacturing of parts such as engine blocks, crankshafts, pistons, camshafts, etc. that are then assembled into an engine, that is then used in assembling the automobile.

24. Production planning is deciding what should be done and how it should be done, what machines should be used, in what sequences, to make a part, and how these machines should be tooled, set-up, and operated. Scheduling is deciding when the production should take place, and therefore, when parts and products should be completed and ready for sale. Without these kinds of critical functions in the production system, the manufacturing system would grind to an inefficient halt.

25. How would a bumper have to be redesigned to provide the equivalent strength? What other components would have to be redesigned? What additional or different processing equipment, including finishing equipment, would be needed? Would the aluminum bumper satisfy the safety requirements (5 mph crash test) needed by the car? What are the costs savings produced by this change?

26. It is almost impossible to fabricate a low-cost item that is poorly designed and do it in an economical way. It must be designed so that it is easy to produce if it is going to be inexpensive (i.e. it has producibility). Thus, this statement is true.

27. Operations like load and unload parts from the machine, change the machine over from one part design to another (this is called set up), and change the tooling in the machine all add no value.

28. The rolls produce many feet of sheet metal that end up in many cars, so the fixed costs (like the rolls) are spread out over many sheets (feet) of metal. Thus the cost of sheet metal per car may be 50 to 100 dollars before the metal is formed into fenders and door panels.

29. Insurance, health, entertainment, sporting events, transportation, lodging, banking, communications, education, etc. are examples of service industries -- anything bought or sold in trade that cannot be dropped on your foot. Service industries worry about productivity, quality, and economic output just as much as manufacturing industries.

30. Disassembling it adds costs and value - you want the cuts of meat, not the whole animal. You are adding value to the cow when you are raising it and feeding it, so it becomes more valuable in the market. You add cost, not value when you ship the cow to the market.

31. At different levels of specification detail, hot isostatic pressing is
- a unit manufacturing process,
- a hot working process,
- a material consolidation process,
- a powder material processing technique.

32. The selling price is determined by the marketplace and what the customer will pay. The best way to improve profit is to reduce manufacturing costs per unit. This can be difficult to do when the price keeps going up.

33. The manufacturing cost for an assembled product, e.g., a car, is made up of materials (raw materials, cutting tools, purchased parts and components and their storage and handling), direct labor, indirect labor (people who work in the manufacturing system but don't work directly on the product – the car), and energy and depreciation (machines and tooling).

34. A start point for answering the question is to consider the shape of different regions of the product, Figure 1-10, and the shapes that are produced by the machining processes, Figure 1-14.
Starting with a rough cylindrical workpiece that may have been produced in a drawing or rolling operation, an overview of the machining processes starting at the top of Figure 1-14 is,
- lathe turning to produce a cylindrical workpiece,
- center drilling of end,
- a facing operation on the end of the workpiece,
- lathe turning to produce diameters and flats,
- milling to produce slot and flats,
- drilling (and perhaps reaming) of holes.

35. Product lifecycle is composed of startup, rapid growth, maturation, commodity or decline.

36. Figure 1-15 shows lifecycle phases for an existing product and includes manufacturing cost and sales volume. Before the product exists design and development costs accrue and are not shown. With product in existence use, repair and disposal costs arise.

37. To use the concepts presented in Figure 1-17 the type of components and required production rates have to be specified.
Say, two 8-hour shifts and 250 working days per year, then

Production rate of 16,000 parts/year = (16,000 parts/year)(year/250 days)(day/16 hours) = 4 parts/hour.
The lower part of Figure 1-17 shows that for part variety of 10 and 4 parts per hour production rate there is significant overlap of the system possibilities of 1) flexible manufacturing system, 2)manned and 3) unmanned cells, 4) CNC equipped job shop.

Problems

1. Solution is provided in text and is/should be
% Direct labor = [(labor cost) / (manufacturing cost)] 100%
labor cost = (20 hours)(\$30/hour) = \$600
manufacturing cost = assumed 40% of selling price = (0.40)(\$16,000) = \$6,400
% Direct labor = (600 / 6400) 100% = 9.4%

Production rate = (150,000 vehicles/year)(year/300 days)(day/8 hours) = 62 trucks/hour

2. Redesign of stapler:

The redesign of an existing product can involve
- redesigning individual parts to perform better,
- eliminating parts,
-- by combining existing parts into a new part
-- by replacing part function such as replacing fasteners with snap fits
- changing material

One way to formulate a problem solution is to use a table to summarize the potential for redesign.

		Possible Design Change			
Part	Function	Combine	Eliminate	Material	New design
1					
2					
3					
…					

Case Study:

None

CHAPTER 2
Properties of Materials

Review Questions

1. Metallic materials typically possess the properties of luster, high thermal conductivity, high electrical conductivity, and ductility.

2. There are several classes of nonmetallic materials and more or less specifically defined examples can be given in these classes. For example,
Polymers or plastics – polyethylene, polypropylene, epoxy.
Ceramics – aluminum oxide, silicon nitride.
Amorphous materials – glass, borosilicate glass
Organic materials – wood, oak wood
Inorganic materials – stone, granite

3. Some common physical properties of metals include:
density or weight, melting point, optical properties (such as transparency, opaqueness or color), thermal properties (such as specific heat, coefficient of thermal expansion and thermal conductivity), electrical conductivity and magnetic properties .

4. The results of standard tests apply only to the specific test conditions that were employed. Since actual service conditions rarely duplicate the conditions of laboratory testing, caution should be employed.

5. The standard units for reporting stress in the English system is pounds per square inch (psi) , and in the metric system, it is megapascals (MPa). Being the ratio of one length to another length, strain is a dimensionless number. However, it is usually reported in terms of millimeter per meter, inch per inch, or strict percentage.

6. Modulus of elasticity is a material property that describes the elastic behavior of a material. It is useful for describing the elastic response of a material and quantities related to elastic behavior. Examples are the deflection of a material subjected to loading that does not cause plastic deformation and the resilience of a material.

Resilience is the energy absorbed by a material in the elastic range. For uniaxial tension it is the area under the elastic part of the stress-strain curve and so is $(1/2)\ \sigma_Y\ \varepsilon_Y$, with σ_Y and ε_Y being the yield stress and strain at yield. Using $\sigma_Y = E\ \varepsilon_Y$ shows that resilience depends on E.

7. The elastic-to-plastic transition can be designated in a variety of ways. If the transition is a distinct one, it is known as <u>yield point</u>, with the highest stress preceding the plastic strain being called the <u>upper yield point</u>, and the lower, "runout" value is the <u>lower yield point</u>. If the transition is not distinct, it is DEFINED through the concept of <u>offset yield</u>

strength, the value of the stress associated with a specified, but tolerable, amount of plastic strain.

8. The percent elongation at fracture in a tensile test can be used as a measure of ductility. Also, the percent reduction of cross sectional area can be used. These two quantities are not directly related to each other since the cross section area changes in an unknown way in the necked region of tensile specimens loaded to fracture.

9. In many cases, material "failure" is defined as the onset of localized deformation or necking. Since additional plastic deformation after necking would occur after "failure", it would be more appropriate to measure and report the uniform elongation (or the percent elongation prior to necking) .

10. Brittleness should not be equated with a lack of strength. Brittleness is simply the absence of significant plasticity. Many brittle materials, such as glass and ceramics can be used to impart significant strength to reinforced composites.

11. Toughness is defined as the work per unit volume required to fracture a material, and can be used as one measure of a material's ability to absorb energy or impacts without cracking or breaking. Plastic deformation occurs during the measurement of toughness, whereas resilience requires the material to remain elastic.

12. True stress considers the load as being supported by the actual area of the specimen and is a true indication of the internal pressures. Engineering stress is simply a normalizing of the load, dividing it by the original cross-sectional area of the specimen, i.e. dividing it by a constant. While easy to obtain, the engineering stress has little, if any, physical significance when the actual area is different from the original.

The true, natural, or logarithmic strain is calculated by taking the natural logarithm of the current length divided by the original length, which is the sum of all of the incremental changes in length divided by the instantaneous length. It has the attractive property of being additive, i.e. the sum of the incremental strains is equal to the total strain from start to finish. Engineering strain, on the other hand, simply divides the elongation by a constant, the original length. While mathematically simple, the resultant value is not additive and has meaning only in reference to the original shape.

13. Strain hardening or work hardening is the term used to describe the phenomenon that most metals actually become stronger and harder when plastically deformed. In deformation processes, this means that further deformation will generally require greater forces than those required for the initial deformation. Moreover, the product will emerge stronger than the starting material. Prom a manufacturing perspective, this means that the material is becoming stronger as it is being converted into a more useful shape -- a double benefit. One method of measuring and reporting this behavior is through the strain hardening exponent, n, which is obtained by fitting the true stress-true strain data to the equation form:

$$\sigma = K\,\varepsilon^{n}$$

14. The hardness of materials has often been associated with the resistance to permanent indentation under the conditions of static or dynamic loading. Other phenomena related to hardness include the resistance to scratching, energy absorption under impact loading, wear resistance, and resistance to cutting or drilling .

15. Brinell Harness Test
(If test surface is rough, it must be made smooth usually by abrasive finishing. This is done in a series of progressively less severe steps to minimize changes in surface properties.)
Select indenter diameter to be used - larger ball for softer materials,
Select load to be applied – larger load for harder materials,
Apply load and hold for specified time,
Remove load,
Measure indentation diameter,
Calculate hardness as load over indentation surface area, or use compiled tabular measured diameter-Brinell Hardness Number data.

16. The test conditions along with the measured Rockwell Hardness Number should be reported. This is usually done by using a specific, standard, Rockwell hardness designation such as R_C60. The Rockwell Harness Number is given, 60 in this case, and the testing conditions are indicated by the "C." The testing condition include the type of indenter, the major and minor loads and the type of test (standard or superficial with the superficial hardness tests usually indicated by "T").

17. The various microhardness tests have been developed for applications where it is necessary to determine the hardness of a very small area of material or the hardness of thin material where one wishes to avoid any interaction with the opposing surface and support material.

18.There are a wide variety of hardness tests and they often evaluate different phenomenon: i.e. resistance to permanent or plastic deformation, scratch or wear resistance, rebound energy, and elastic deformation. All results are termed "hardness", but little correlation is expected.

19.There is often a direct correlation between penetration hardness and tensile strength. For plain carbon and low-alloy steels, the tensile strength in pounds per square inch can be estimated by multiplying the Brinell hardness number by 500. For other materials, the relationship may be different.

20.The compression test is more difficult to conduct than the standard tensile test. Test specimens must have larger cross-sectional areas to resist buckling. As deformation proceeds, the cross section of the specimen increases, producing a substantial increase in the required load. Frictional effects between the testing machine surfaces and the end surfaces of the specimen will tend to alter the results if not properly considered.

21. Dynamic loads change over time such as in impact and cyclic loading. Cyclic loading can be reversed type loading as in tension-compression or only changing magnitude as in tension-tension. Dynamic loading usually refers to relatively short term changes in load.

22. The two most common bending impact tests are the Charpy test and the Izod test. The Charpy test loads the specimen (usually notched) in three-point bending. The Izod test loads the specimen in a cantilever fashion.

23. Designers should use extreme caution when applying impact test data for design purposes because the test results apply only to standard specimens containing a standard notch loaded under one condition of impact rate. Modifications in specimen size, the size and shape of the notch, and speed of the impact can produce significant changes in the results.

24. Endurance limit / tensile strength ratios are given in Table 2-3. The table if data show that this ratio varies with material and so no universal relationship between endurance limit and tensile strength exists. A very rough estimate is that endurance limit is about one-half the tensile strength.

25. Fatigue strength is the stress that a fatigue specimen was capable of withstanding for a specified number of load cycles, and therefore refers to any point on a standard S-N plot. Endurance limit or endurance strength, on the other hand, is the limiting stress level below which the material will not fail regardless of the number of cycles of loading.

26. Several factors can drastically alter the fatigue properties of a material. One dominant factor is the presence of stress raisers, such as small surface cracks, machining marks, or gouges. Other factors include the temperature of testing, variation in the testing environment (such as humidity or corrosive atmosphere), residual stresses, and variations in the applied load during the service history.

27. For steels, the endurance limit can be approximated as 0.5 times the ultimate tensile strength as determined by a standard tensile test.

28. Initiation of a fatigue crack involves the development of high stress in a very small, local region of the material. So, any part/loading situations that give rise to high local stresses will tend to cause fatigue crack initiation and these extend all the way from microscopic inherent characteristics of the material to macroscopic part characteristics. Examples are,
- dislocation pileups in the material microstructure,
- part design features such as sharp corners and notches in keyways that cause stress concentrations,
- irregularities (surface roughness) due to manufacturing such as the “peaks-and-valleys” produced on ground surfaces.

29. Fatigue striations are the regular deformation patterns produced on fatigue surfaces as fracture progresses across the surface after a fatigue crack initiation. In fatigue, stress is

varying and the fatigue crack grows progressively or in stages when stress in high. This gives rise to the regions of crack growth called striations.

30. Engineered products frequently operate over a range of temperatures and often have to endure temperature extremes. The materials that are used in these products must exhibit the desired mechanical and physical properties over this range of temperatures. Thus, it is imperative that the designers consider both the short-range and long-range effects of temperature on the materials. This is particularly important when one realizes that the bulk of tabulated material data refers to properties and characteristics at room temperature.

31. Steels and other body-centered crystal structure metals exhibit a ductile-to-brittle transition upon cooling. If this transition occurs at temperatures above those of service, the material will be used in a brittle condition, and sudden, unexpected fractures can occur under conditions that the material would be expected to endure.

32. Material behavior under long-time exposure to elevated temperature is generally evaluated through creep testing, wherein a tensile specimen is subjected to fixed load at elevated temperature. Single tests provide data relating to the rate of elongation and the time to rupture under the specific conditions of testing. A composite of various tests can be used to evaluate the creep rate or rupture life under a variety of load and temperature conditions .

33. The stress-rupture diagram is developed by running a number of creep tests at different temperatures and different stress levels and showing all the data on a single plot. The results show changes in material behavior with changing temperature at various stress levels.

34. Terms such as machinabilty, formability and weldability convey only the general though of how easy it is to process a material and may be useful for very general qualitative comparison of materials. For example, one material may be more formable that another if it is more ductile.

The difficulty in using this general concept arises when quantitative or engineering measures are desired. Ease or difficulty of processing depends not only on material properties but also on the deformation conditions imposed in processing and on material properties at the processing conditions. For example, the performance of a manufacturing process depends on the friction acting, any lubricants and coolants used, the constraints imposed on the deformation such as by die shape in forging, etc. Further, material properties change with temperature and rate of deformation. In addition to heating materials to change there temperature before processing temperature changes during the process due to cooling and heating due to deformation. Materials are often processed in high speed operations in which strain rates are very high.

Comparing material behaviors in processing is very difficult, and dubious, since the behavior depends so critically on the processing conditions.

35. The basic premise of the fracture mechanics approach to testing and design is that all materials contain flaws or defects of some given size. Fracture mechanics then attempts to distinguish between the conditions where these defects will remain dormant and those conditions for which the defects might grow and propagate to failure.

36. The three principal quantities that fracture mechanics tries to relate are: (1) the size of the largest or most critical flaw, (2) the applied stress, and (3) the fracture toughness of the material (a material property).

37. Fracture toughness is resistance to crack growth, *K*. Crack growth rate is shown as it depends on K in Figure 2-36. Units of *K* are $(N/m^2)\ m^{1/2}$ or $(lb/in^2)\ in^{1/2}$.

Toughness or modulus of toughness is work per unit volume up to fracture and units are energy/volume = $ftlb/ft^3$ and $Joule/m^3$.

When evaluated using a tensile test the area under the tensile test curve up to fracture has units of (stress)(strain) and so $(lb/in^2)(in/in) = inlb/in^3$ and $(N/m^3)(m/m) = Nm/m^3$.

38. The three primary thermal properties of a material are:
(1) heat capacity or specific heat - a measure of the amount of energy that must be imparted or extracted to produce a one degree change in temperature; (2) thermal conductivity - a measure of the rate at which heat can be transported or conducted through a material; and (3) thermal expansion - a measure of the degree of expansion or contraction that will occur upon heating or cooling of the material.

39. Since density is directly related to weight any engineering application in which weight is important will be one in which density is an important material property. An example of light weight, low density, being important is an airplane. An example of heavy weigh, high density, being important is a boat anchor.

Often the minimum weight structure needed to support a loading is desired and strength-to-weight ratio is relevant. In this case the strength/density ratio of materials is important.

Problems

1. Products in which performance does not depend on resistance to mechanical loading are probably examples where performance does depend on physical properties.
a. An example is electrical wire. The intent is to conduct electricity, not to withstand appreciable loads. Another example is a camera lens.
b. Electrical conductivity and optical properties determine the major part of the performance of wires and lenses.
c. For wires the material should be ductile so it can be routed and should be a low strain hardening material so working it in installation will not cause large loads and fracture.

2. a. Bookshelves are subjected to static loading over long time.

b. In addition to static strength, bookshelf materials should be stiff and should not creep, i.e., deform over long time at relatively low stress.
c. Material secondary characteristics might include light weight (low density), easy to work and easy to finish in various ways.

3. a) A common component that is subjected to dynamic mechanical loading is a power transmission shaft.
b. The material should have a high fatigue strength (large number of cycles to failure under the expected loading situation).
c. A desirable secondary characteristics is being easy to work so as not to produce a rough surface containing sites of fatigue failure initiation.

4. a) Steels exhibit ductile-to-brittle transition with the transition temperature/temperature range dependent on carbon content and alloying additions.

b) The two steels behaviors shown in Figure 2-32 show ductile-to-brittle transition temperatures in the range of about -30^{o}C (-22^{o}F) to -5^{o}C (23^{o}F).

c) The melting temperature of nitrogen is -210^{o}C, 63 K, -346^{o}F
The boiling point of liquid nitrogen is -196^{o}C, 77 K, -321^{o}F.

For discussion of ductile-to-brittle transition using the data for steel presented in Section2.4, liquid nitrogen is well below the ductile-to-brittle transition for steel and so steels are not a reasonable choice for a liquid nitrogen container.

Typical transport and short time storage containers for liquid nitrogen are composed of Dewar flasks usually made of annealed borosilicate glass held in an aluminum, stainless steel, plastic or steel casing. The Dewar may be surrounded by netting to contain the glass in case of breakage. Since the liquid nitrogen does not come into contact with the casing steel casings are used.

In the event of Dewar fracture the liquid nitrogen is not contained on the surface so boiling and the formation of gas at the liquid nitrogen-casing interface probably means that a steel casing would not be subjected to stress and temperature conditions to make ductile-to-brittle transition considerations important.

Stainless steel Dewars are available.

d) There are differences in work material deformation in rolling between the longitudinal and transverse directions with respect to the rolling direction. A different deformation pattern, rolling texture, results and this leads to different microstructure and properties in different directions.

The difference in absorbed energy with rolling direction shown in Figure 2P-1 indicates that the rolling texture has an effect on energy absorbed, i.e., one of the properties affected by rolling texture is toughness.

If impact properties have been improved in steel making the causes must be in the areas of
- development of alloys that are less temperature dependent, i.e., pushing the dashed line in Figure 2-32 further to the left,
- improvement in uniformity of the microstructure so subsequent processing has less effect in changing microstructure uniformity.

The general explanation is that material properties and deformation behavior are determined by composition, structure and surrounding conditions. For fixed deformation conditions, improvement in deformation behavior is the result of improvements in structure, probably due to changing steel composition.

5. The materials are to be distinguished based on the tests described in Chapter 2, the use of readily available household items and the ability to machine the materials. The use of household items and a machine shop indicates that mechanical and physical properties listed in Chapter 2 may be qualitatively measured (comparisons rather that quantitative measurements) in addition to the tests described in Chapter 2.

One way to organize a material separation plan is to consider the applicability to material separation of each test described. The tests may be obviously useful for identifying distinguishable properties, perhaps useful or not useful depending on if the measured quantity is sufficiently different for the two materials. The materials used in this problem are described in detail further on in the text as listed in the table.

Test	1020 vs 1040 Chapter 6	430SS vs 316SS Chapter 6	6061-T6 vs AZ91 Chapter 7	Polyethylene vs Polypropylene Chapter 8
Tensile - strengths - strain hardening	No	Probably based on hardening	Probably – based on strength and hardening	Possibly – based on ductility
Compression	No	Possibly	Probably	No
Hardness	No	Possibly	Yes	No
Impact	No	Possibly	Yes	No
Fatigue	No	No	Yes	No
Toughness	No	Possibly	Yes	No

The general conclusions are
- for materials of the same general type, e.g., steels, thermoplastics, similar strengths and deformation behaviors make drawing distinctions between material difficult,
- the more different the type of material the easier it may be to distinguish between them, e.g., aluminum and magnesium are both metals but sufficiently different to make mechanical testing viable for identifying differences in properties and behavior,

- while strength properties such as yield strength may be difficult to use the changes in material behavior with continuing deformation such as strain hardening and ductility may be useful.

Distinguishing between materials based on the characteristics and properties mentioned in Chapter 2 and using readily available items can be discussed by considering the properties mentioned.

	1020 vs 1040	430SS vs 316SS	6061-T6 vs AZ91	Polyethylene vs Polypropylene
Metallic/Nonmetallic	No	No	No	No
Temperature effects	No	No	No	No
Machinability	No	Yes – effort needed to cut	Yes – effort needed to cut	No
Formability	No	Yes – amount of bending before fracture	Yes – minimum bend radius before fracture	No
Weldability	No	Yes – weld and break	Yes – weld and break	No
Heat capacity	No	No	No	No
Specific heat	No	No	Perhaps	No
Thermal conductivity	No	No	Perhaps – hold end of bars while heating other end	No
Thermal expansion – difficult to test with ordinary items	No	No	No	No
Electrical conductivity	No	No	No	No
Magnetic response	No	Yes – use a magnet	No	No
Weight – accurate electronic scales are available	No	No	Yes	Perhaps
Density	No	No	Yes	Perhaps
Melting point – only relatively small increases in temperature available	No	No	No	Yes
Boling point	No	No	No	No
Optical properties	No	No	No	No

The same general conclusion can be reached – when materials are of similar type distinguishing between them is difficult. However there are particular differences in properties that are qualitatively different and make for easy material identification, e.g., magnetic response of different classes of stainless steels. Differences in deformation behavior can lead to identifiable differences in material use and processing, such as differences in ductility leading to differences in formability.

Case Study:

Overhead Conveyor for Meat Processing

a. There are two reasonable causes of failure worth investigating, given that the hooks have sufficient load carrying capacity to support 300 pounds under typical conditions. The candidate failure inducing mechanisms might stress-corrosion cracking and/or brittle behavior at the freezer temperature.

b. First a simple experiment or analytical stress analysis to determine expected load capacity. With assurance that the hooks are capable of holding the anticipated load, the problem is use of a material that is adversely affected by the in-use environment. A recommended solution is to use stainless steel for the material. It is corrosion resistant and does not behave in a brittle manner at the use temperature. It seems that in a meat packing plant stainless steel would be the first choice for health, cleanliness and mechanical reasons.

c. Underlying materials engineering is the close relationship between structure and mechanical behavior. So, at the level of determining mechanical properties, all microstructural characteristics are important. With respect to the behavior in the use situation described and possible accelerated failure mechanisms, grain boundaries are important in stress corrosion since they are active chemical-mechanical process initiation sites.

CHAPTER 3
Nature of Metals and Alloys

Review Questions

1. Material structure determines material properties. So if material structure can be designed and produced, desirable properties can be obtained. For example, the strength of steel can be controlled by changing not only composition but also by producing useful microstructures in heat treating processes.

2. Microstructure is the structure in a polycrystalline material that is determined by the size, shape and arrangement of the grains making up the material. This is in contrast to the atomic level structure of the material.

3. An ion is an atom that has a different number of electrons than the number of electrons needed for stability. That is, a different number of electrons and protons.

Negative ions have more electrons than protons and so have a net negative charge. Positive ions have missing electrons and so contain more neutrons than electrons and so have a net positive charge.

4. Valence electrons play a large part in an atoms interactions with other atoms and in atomic level processes. The determine the kind of interatomic bonding, chemical properties, electrical properties and optical properties.

5. The three types of primary bonds are
i. ionic bond,
ii. covalent bond,
iii. metallic bond

Ionic bonds form due to the attraction between ions and so atoms that can lose or gain electrons can be bonded. In contrast atoms that assume a lower energy state by sharing electrons form covalent bonds. Metallic bonds form between atoms that readily give up electrons to a shared electron gas. Position in the table of elements is a starting place for predicting what kind of boning will occur between atoms.

6. Ionic bonds are strong primary bonds between ions. The result is that ionically bonded material are hard, brittle, have high melting point and low electrical conductivity. They are strong but not as strong as typical covalently boned materials.

7. Covalent bonds are strong and so materials are strong, hard and brittle. Depending on the number of electrons participating in the bond, covalently bonded materials show wide ranges of electrical, chemical and optical properties.

8. In metallically bonded materials there is a mobile electron cloud that produces bonding. Properties that depend on electron mobility are extreme compared to other types of materials. For example, metals have high electrical and thermal conductivities. Electron-photon interactions account for the opacity of metals.

9. Asymmetric molecules that have nonsymmetrical charge distribution form van der Waal bonds. The bonding is due to the attraction between the differently charged regions of the molecules.

10. The atomic radius is the distance between centers of atoms in a grouping of atoms, i.e., it is not defined and measured for single atoms. The distance between a particular pair of atoms is determined by the balance of attractive and repulsive forces between atoms and between the particular atoms and all their surrounding atomic neighbors. In different crystal structures the ordering of atoms is different, so interatomic force interactions are different, the compliant response of individual atoms to their surroundings is different and hence the distance between atom centers, atomic radius, is different.

11. Crystalline materials have a regular, repeating structure, a repeating elementary arrangement of atoms. Amorphous material does have a repeating, predicable arrangement of the atoms or molecules that make up the material.

12. The metallic bonding of the atoms making up a metal results in a material that is strong, ductile, has high density, high electrical and thermal conductivities and optical luster.

13. Allotropic materials are those that can exist in two or more atomic lattice structures depending on temperature and pressure conditions.

14. Compared to the simple cubic structure, the closer packing arrangement of atoms in face center cubic and body center crystal structure results in a higher packing density of atoms and so more effective electron sharing.

In contract to the existence of particular metallic structures, a more general definition of engineering metals is metals that are used in engineering applications. Simple cubic structure materials are, would be, brittle and so difficult to mechanically work into useful shapes.

15. The common metal crystal structures are body-centered cubic, face-centered cubic and hexagonal close-packed.

16. Efficiency is the amount of space in the lattice that is occupied by the atoms modeled as solid spheres.

Lattice Structure	**Packing Efficiency (%)**
Simple cubic	52

Body-centered cubic	68
Face-centered cubic	74
Hexagonal close-packed	74

17. When close-packed planes form in the face-centered cubic arrangement there are many possible direction of atomic plane motion resulting in higher ductility than for the hexagonal close-packed arrangement with its smaller number of easy deformation directions. Deformation or slip systems are determined by the possible planes on which deformation can occur easily and the possible directions of slip. Face-centered cubic arrangements have more active slip systems than hexagonal close-packed arrangements.

18. A grain boundary is the relatively disordered region between crystals or grains in which atomic arrangement is relatively well defined and well ordered.

19. The American Society for Testing and Materials grain size number is commonly used to specify grain size. It is defined as n in the relationship

$$N = 2^{n-1}$$

in which N is the number of grains per square inch visible at 100x magnification. Standards are specified for specimen preparation and measurement procedures.

20. Metallic crystals respond to low applied loads by simply stretching or compressing the distance between atoms. All atoms retain their basic positions, with the load serving only to disrupt the force balance of the atomic bonds in such a way as to produce elastic deformations.

21. Plastic deformation is a permanent shift of atoms resulting in a permanent change in size or shape.

22. A slip system for the plastic deformation of a metal is the specific combination of a preferred plane and a preferred direction within that plane. In general, the preferred planes are those with the highest atomic density and greatest parallel separation - the close-packed planes. The preferred directions are the close-packed directions.

23. The dominant mechanical property of the bcc crystal structure metals is high strength. The fcc metals have high ductility. The hcp metals tend to be brittle.

24. A dislocation is a line-type defect within a crystalline solid. Edge dislocations are the terminal edges of extra half-planes of atoms, and screw dislocations are the ends of partial "tears" through the crystal. Since the movement of dislocations provides the plasticity of a material, the force required to move dislocations determines the resistance to plastic deformation, or the strength of the material.

25. Other crystal imperfections can provide effective barriers to dislocation movement and be used to strengthen the metal. These include: point-type defects (such as vacancies, interstitials, or substitutional atoms), additional line-type dislocations, and surface-type

defects (such as grain boundaries) .

26. The three major types of point defects in crystalline materials are: vacancies (missing atoms), interstitials (extra atoms forced between regular atom sites), and substitutional atoms (atoms of a different variety occupying lattice sites).

27. The strain hardening of a metal is the result of the multiplication of the number of dislocations and the interaction between the various dislocations to pin or block the movements of one another.

28. Since dislocations cannot cross grain boundaries (a discontinuity to crystal structure), these boundaries serve to impede dislocation movement and make the material stronger. A material with a finer grain structure (more grain boundaries) will, therefore, tend to be stronger than one with larger grains.

29. An anisotropic property is a property that has different values in different directions.

Possible causes of anisotropy are;
- material creation as in the growth of trees and the casting of metals in which small scale structures (wood fibers, dendritic metallic microstructure) have anisotropic structures and combine in an oriented way to produce large scale anisotropic structure (grain in wood, large grains near the surface of castings),
- material processing in which symmetric microstructures are deformed into structures with distinctive shapes. For example, rolling of a metal that has ideally spherical grains produces elongated grains along the rolling direction. The resulting product has anisotropic mechanical properties, such as different strength and ductility along the rolling direction and perpendicular to the rolling direction..

30. Brittle fractures occur without the prior warning of plastic deformation and propagate rapidly through the metal with little energy absorption. Ductile fractures generally occur after the available plastic deformation has been exceeded.

31. Plastic deformation increases the internal energy of a material through both the creation of numerous additional dislocations and the increased surface area of the distorted grain boundaries. Given the opportunity, the metal will seek to reduce its energy through the creation of a new crystal structure, i.e. recrystallize.

32. Recrystallization is often used to restore ductility to a metal and enable further deformation to be performed. Without recrystallization, further deformation would result in fracture.
NOTE: If the deformation is performed at temperatures above the recrystallization temperature, deformation and recrystallization can take place simultaneously and large deformations are possible .

33. The major distinguishing factor between hot and cold working is whether the deformation is produced at a temperature that is above or below the recrystallization

temperature of the metal. In cold working, no recrystallization occurs and the metal retains its strain hardened condition. When hot working is performed, recrystallization produces a new grain structure and no strain hardening is possible.

34. When an alloy addition is made to a base metal, several possibilities can occur. The two materials can be insoluble and refuse to combine or interact. If there is solubility, the alloy can dissolve in the base metal to produce a solid solution of either the substitutional or interstitial variety. A final possibility is that the two can react to produce an intermetallic compound - a combination with definite atomic proportions and definite geometric relationships.

35. Intermetallic compounds tend to be hard, brittle, high-strength materials .

36. The charge carriers in metals are the valence electrons. The general concept becomes slightly cloudy since in metals the electron sea or electron cloud is composed of electrons that are in essence shared by all the atoms. In a sense the valence electrons belong to all the atoms and are not valence electrons in the sense of the valence electron of an atom.

37. Electrical resistance in a metal depends largely on two factors - the number of lattice imperfections and the temperature . Vacancies, interstitials, substitutional atoms, dislocations, and grain boundaries all act as disruptions to the regularity of a crystalline lattice. Thermal energy causes the atoms to vibrate about their equilibrium positions and interferes with electron transport.

38. Intrinsic semiconductors are ones that occur naturally. Extrinsic semiconductors have chemistries that have been modified by "doping" to enhance or alter their conductivity.

Problems:

None

Case Study:

Window Frame Materials and Design

Wood (such as kiln-dried Ponderosa pine) is easily shaped, can be painted or finished in a wide spectrum of finishes, and has low thermal conductivity (keeping the winter cold and summer heat out). Unfortunately, the material has a definite grain structure, which may lead to cracking or splintering. The material requires special impregnation and coating to improve its ability to resist degradation. Wood requires regular surface maintenance (such as painting or sealing) to minimize moisture absorption and rot. While its dimensions are relatively insensitive to changes in temperature, they can change significantly with changes in humidity or moisture content, leading to possible warping or twisting. The shrinking, swelling and cracking tendencies make it extremely difficult to provide a durable surface protection. Finally, wood is a combustible material.

Aluminum can be extruded into the complex channels used for window frames, is durable, non-corrosive, and can be color anodized or finished into a variety of surfaces. The properties are consistent and predictable and do not change over time, or with variations in temperature (over the range where windows would operate). The material does not absorb moisture, swell, shrink, split, crack or rust. Maintenance is extremely low, but the material has a high thermal conductivity. If the same piece is exposed to a cold exterior and warm, moist interior (as in winter weather), the material will try to achieve thermal uniformity. The inside surfaces will "sweat" with condensation, and thermal efficiency of the window will be poor. Compared with alternatives, however, aluminum is stronger and more rigid (23 times stiffer than vinyl) . From a safety perspective, aluminum is noncombustible and does not emit any toxic fumes when heated to high temperature.

Vinyl windows offer a range of color, and the color is integral to the material. There is no need for any surface finishing and the appearance requires no periodic maintenance. In addition, the thermal conductivity is low, giving the window good thermal efficiency. Unfortunately, polymers have poor dimensional stability, generally shrinking over time, and often deteriorate with prolonged exposure to ultraviolet light (becoming brittle) . Since windows will see prolonged exposure to sunlight, the long term durability and stability may come into question. The thermal expansion of vinyl is considerably greater than either aluminum or wood, and the resulting dimensional changes may cause distortion of the windows. In addition, the properties of vinyl will vary over the temperature range that the product will see. When heated, vinyl loses strength, and when cold, it becomes more brittle and less impact resistant. The material is combustible and may emit toxic fumes when exposed to high temperatures.

It would appear that aluminum is a superior structural material, whose primary detriment is its high thermal conductivity. If a design could be developed to insert some form of conductivity barrier between the outside and inside surfaces, the resulting window would offer the best of all worlds. Several companies currently offer such a design, linking the inside and outside extrusions with a high-strength polymeric link. Being totally internal, this polymer is not subject to sunlight deterioration, and does not significantly impair the structural performance of the window.

CHAPTER 4
Equilibrium Phase Diagrams and the Iron-Carbon System

Review Questions

1. A phase is a portion of a substance possessing a well-defined structure, uniform composition, and distinct boundaries or interfaces.

2. In a glass of soda with ice, the soda is continuous and the ice is discontinuous. Helium in a balloon is a gaseous phase, and coffee with cream is a single-phase solution.

3. An equilibrium phase diagram is a graphical mapping of the natural tendencies of a material system (assuming that equilibrium has been attained) as a function of such variables as pressure, temperature, and composition.

4. The three primary variables considered in equilibrium phase diagrams are: temperature, pressure and composition.

5. A pressure-temperature phase diagram is not that useful for many engineering applications because most processes are conducted at atmospheric pressure. Most variations occur in temperature and composition.

6. A cooling curve is a temperature versus time plot of the cooling history when a fixed-composition material is heated and subsequently cooled by removing heat at a uniformly slow rate.

7. Transitions in a material's structure are indicated by characteristic points on the cooling curve. These characteristic points may take the form of an isothermal hold, abrupt change in slope, or localized aberration to the continuity of the curve.

8. Solubility limits denote the conditions at which a solution becomes completely saturated, i.e. any additional solute must go into a second phase. Solubility limits are generally determined through use of inspection techniques such as X-ray analysis (detects where a new crystal structure or lattice spacing appears) or microscopy (detects the presence of the second phase), that can be used to identify the composition where the transition from one to two-phase occurs.

9. In general, as the temperature of a system is increased, the maximum amount of a substance that can be held in solution also increases.

10. Complete solubility implies complete solubility in both liquid and solid states. The two types of atoms have to be able to exist in the same crystalline structure. Atom "size" and valence electron structure have to be similar.

Partial solubility results when there is a saturation limit for one type of material in another and this saturation limit depends on temperature. So, as temperature is lowered and solubility decreases a two phase material forms from the initially one phase material.

Insolubility means that the materials are so different in nature (atomic size, valence electron structure, etc.) that they are totally insoluble in each other.

11. Upon crossing the liquidus line during cooling, the first solid begins to form in the material. Upon crossing the solidus line, solidification is complete, i.e. there is no longer any liquid present. Upon crossing a solvus line, a single phase material begins to precipitate a second phase, since the solubility limit is now being exceeded.

12. The three pieces of information that can be obtained from each point in an equilibrium phase diagram are: the phases present, the composition (or chemistry) of each phase, and the amount of each phase present.

13. A tie-line is an isothermal line drawn through any point in the two phase region of a phase diagram, terminating at the boundaries of the single phase regions on either side. It is used in the two-phase regions of an equilibrium phase diagram.

14. The end points of the tie-line correspond to the compositions of the two phases present.

15. The relative amounts of the component phases in a two-phase mixture can be computed through use of the lever law. The tie-line is separated into two segments by dividing it at the chemistry of the alloy in question. The fraction of the total length of the tie-line that lies opposite to a given phase corresponds to the fractional amount of that particular phase.

16. Cored structures refer to materials that have microscopic level variations in chemical composition.

Cored structures form because as the metal solidifies through the freezing range the chemical composition constantly changes. If cooling rate is rapid, material diffusion rate is too slow to produce uniform chemistry. Different regions of the solid material have different chemical characteristics determined by the temperature at which the regions solidified.

17. Three-phase reactions appear as horizontal lines in binary (two-component) phase diagrams. These lines have a distinctive V intersecting from above, or an inverted~ V intersecting from below. The intersection of the V and the horizontal line denotes the three-phase reaction, which is usually written in the form of cooling, i.e. the phases present above the line going to those present below.

18. A eutectic reaction has the general form of Liquid ---> Solid 1 + Solid 2. In essence, a liquid solidifies to form two distinctly different solids of differing chemistries.

19. Eutectic alloys are attractive for casting and as filler metals in soldering and brazing because they generally have the lowest melting point of all alloys in a given system and solidify into a relatively high-strength structure.

20. A stoichiometric intermetallic compound is a single-phase solid that forms when two elements react to form a compound of fixed atomic ratio. The compound cannot tolerate any deviation from that fixed ratio, so it appears as a single vertical line in a phase diagram, breaking the diagram into recognizable sub areas . Non-stoichiometric intermetallic compounds are single phases that appear in the central regions of a phase diagram, that can tolerate chemical variations, and thus have an observed width. They appear as a region and not a line.

21. In general, intermetallic compounds tend to be hard, brittle materials .

22. If an intermetallic compound can be uniformly distributed throughout a structure in the form of small particles in a ductile matrix, the effect can be considerable strengthening of the material. If the intermetallic should become the continuous phase (as in a grain boundary coating) or be present in large quantities, the material will be characteristically brittle.

23. The four single phases in the iron-carbon equilibrium phase diagram are: ferrite (alpha), which is the room-temperature body-centered cubic structure; austenite (gamma), the elevated temperature face-centered cubic phase; delta-ferrite (delta), the high-temperature body-centered cubic phase; and cementite (Fe_3C), the iron-carbon intermetallic compound that occurs at 6.67 wt. percent carbon.

24. The point of maximum carbon solubility in iron, 2.11 weight percent, forms an arbitrary division between steels and cast irons. Cast irons contain greater than 2.11% carbon and experience a eutectic reaction upon cooling.

25. Some of the key characteristics of austenite are its high formability (characteristic of the fcc crystal structure) and its high solubility of carbon (a good starting point for heat treatment) .

26. The most important three-phase reaction in the iron-carbon diagram when considering steels is certainly the eutectoid reaction. Under equilibrium conditions, austenite of 0.77 weight percent carbon and the fcc crystal structure transforms into ferrite of the bcc crystal structure, capable of holding only 0.02% carbon and cementite or iron carbide with 6.67% carbon. In essence, iron changes crystal structure and the rejected carbon goes to form the iron carbide intermetallic.

27. The fcc crystal structure of austenite is capable of dissolving as much as 2.11% carbon at elevated temperature. In contrast, the bcc crystal structure of ferrite can hold only 0.02% carbon at its maximum solubility and 0.007% at room temperature .

28. Pearlite is the name given to the structure formed when austenite undergoes the eutectoid reaction under equilibrium (or near-equilibrium) conditions. It is a lamellar structure composed of alternating plates of ferrite and cementite, but has its own characteristic set of properties, since it always forms from the same chemistry at the same temperature.

29. Steels having less than the eutectoid amount of carbon (less than 0.77% carbon) are called hypoeutectoid steels. Their structure consists of regions of ferrite that formed before the eutectoid reaction (primary or proeutectoid ferrite) and pearlite that formed as the remaining austenite underwent the eutectoid transformation. Steels with greater than 0.77% carbon are called hypereutectoid steels and have structures consisting of primary cementite and pearlite.

30. The general composition of cast irons is 2.0 to 4.0% carbon, 0.5 to 3.0% silicon, less than 1.0% manganese, and less than 0.2% sulfur. In addition, nickel, copper, chromium and molybdenum may be added as alloys. Silicon is the major new addition. It partially substitutes for carbon, and promotes the formation of graphite as the high-carbon phase.

31. Silicon content of cast iron is 0.5% to 3.0%. Silicon partially substitutes for carbon and promotes the formation of graphite as the high-carbon phase.

32. Cast irons often contain graphite as the high-carbon phase instead of the cementite (or iron carbide) commonly found in steels. Graphite formation is promoted by slow cooling, high carbon and silicon contents, heavy section sizes, inoculation practices, and alloy additions of Ni and Cu. Cementite is favored by fast cooling, low carbon and silicon levels, thin sections, and alloy additions of Mn, Cr, and Mo.

33. The microstructure of gray cast iron consists of three-dimensional graphite flakes dispersed in a matrix of ferrite, pearlite, or other iron-based structure.

34. Since the graphite flakes in gray cast iron have no appreciable strength, efforts to increase the strength of this material must focus on improving the strength of the iron-based matrix structure.

35. Gray cast irons possess excellent compressive strengths, excellent machinability, good wear resistance, and outstanding vibration damping characteristics. In addition, the silicon provides good corrosion resistance and the high fluidity desired for castings. Low cost is an additional asset.

36. Gray cast iron contains graphite flakes and so exhibits low ductility. The graphite component produces stress concentrations, crack initiation sites and the resulting brittleness.

37. White cast iron is very hard, but very brittle. It finds application where extreme wear resistance is required.

38. Malleable iron is essentially heat-treated white cast iron where a long time thermal treatment changes the carbon-rich phase from cementite to irregular graphite spheroids. The more favorable graphite shape removes the internal notches of gray cast iron and imparts the increased ductility and fracture resistance .

39. The graphite is in the form of smooth, approximately spherical particles.

The graphite shape formation is controlled by material additions to the cast iron and cooling rate. In contrast to controlling graphite particle shape by complicated heat treatment as in the malleable cast irons.

Since the graphite flakes do not act as strong fracture initiation sites due to their shape, material ductility increases.

40. Increased cost of ductile cast iron compared to gray cast iron is due to
- increased cost of material additions needed to form spherical graphite,
- more sophisticated furnaces and control systems to assure the formation of desired graphite structure.

41. Compacted graphite cast iron is characterized by a graphite structure intermediate to the flake graphite of gray cast iron and the nodular graphite of ductile iron. It forms directly upon solidification, and possesses some of the desirable properties and characteristics of each.

Problems:

1.Since the topic is producing and processing engineering materials, the phase diagram will be a temperature-composition diagram and the temperature range is over the solid and liquid material state range.

i. The two components selected can be completely soluble in each other in both liquid and solid states. The general form of the equilibrium diagram is shown in Figure 4-6.

ii. The two components can be completely insoluble in each other in liquid and solid phases and the general form of the equilibrium or phase diagram is shown in Figure 4-7.

iii. For materials that are partially soluble the general equilibrium diagram is shown in Figure 4-8 and is extended to include a three phase reaction for some materials. The diagram then contains a V-shaped line meeting another line such as at composition of 61.9% tin and temperature of 183^{o} C in Figure 4-5. General cases are shown in Figure 4-9. The cusp/inflection of the liquidus line indicates a very particular, well defined state and solidification process.

The identification is then
a. Single phase

i For completely soluble materials there will be a liquid solution for temperature-composition states above the liquidus line. A solid solution exists at states below the solidus line.
ii. For insoluble materials there will be no single phase regions on the diagram.
ii For the point of contact between the V-shaped line with the solidus line single phase material exists above and below the contact point and two phase material to the left and right of the point.

b. Three phase reaction
i. Reactions between two completely soluble materials will not result in a three phase state.
ii. The is no interaction between insoluble materials and so two such materials will not form three phases.
iii. Three phase reactions occur for partially soluble materials at the point of contact between the V-shape line and the solidus line. The liquid phase meets two-phase regions at this point.

c. Intermetallic compound
i. Completely soluble material form solutions not compounds.
ii. Ideal completely insoluble materials do not interact and so will not form compounds.
iii. Stoichiometric intermetallic compounds exist in a fixed atomic ration and so are represented by vertical lines on equilibrium diagrams, Figure 4-9. Nonstoichiometric intermetallic compounds are shown as regions of compositions. These regions are usually narrow.

2. A way to approach looking for applications of particular material is to identify material characteristics that point to particular kinds of use and so to look for products in that use area.

a. Gray cast iron has low alloy content and is easily produced resulting in a low cost material and the possibility of casting complex shapes. The microstructure is composed of dispersed graphite flakes in a metal matrix. This leads to brittleness, ease of machining, high damping capacity and low tensile strength but high compressive strength.

Application in situations with large size, compressive loading and required damping are indicated, e.g., machine tool structures.

b. White cast iron behavior is determined to a large extent by the high iron carbide content. White cast iron is hard and brittle.

Applications in which minimal wear rate is required and the loading is compressive are typical, e.g., machine tool ways.

c. Malleable cast iron has higher ductility than gray or white cast irons because the form of the graphite is nodular, not flake-like. To produce this microstructure high cooling rates are required.

The ductility of malleable cast iron means higher tensile strength, greater impact strength and easier further processing (e.g., machining) than for the more brittle cast irons. The required fast cooling rate implies the production of relatively small castings to assure fast cooling and acceptable temperature gradients.

Applications are small parts that require significant further processing and are used in relatively high tensile stress situations, e.g., rigging components such as pulley supports.

d. Ductile cast iron has the same type of graphite shape as malleable cast iron, but the microstructure is formed by alloying additions rather than the involved heat treatment needed to produce malleable cast iron. The desirable mechanical properties and ease of processing of malleable cast iron are also characteristic of ductile cast iron. The need to carefully control alloying and production of ductile cast iron leads to a higher cost material than malleable cast iron.

Applications are then similar to those for malleable cast iron in which higher cost can be justified, e.g., jigs and fixtures.

e. Compacted graphite cast iron has graphite microstructure between those of gray cast iron and ductile cast iron. The newly developed, easier to control production process makes for a less costly material that still possesses reasonable strength, ductility and machinability. Compacted graphite cast iron has higher thermal conductivity than ductile cast iron.

Applications are in newer applications in which the increased mechanical properties of ductile cast iron are desirable along with high thermal conductivity. Cast iron internal combustion engine components are starting to be the major uses of compacted graphite cast iron

Case Study:

The Blacksmith Anvils

1. The anvil will be subjected to the shock of direct and indirect hammer blows during the forging of metals. The surfaces must be resistant to wear, deformation and chipping, and good energy absorption or damping characteristics would be an added plus, acting to reduce noise and vibration. The anvil must have sufficient mass to absorb the blows, and not tip or move when the blows are offset from the base. The material must resist damage when red-hot metal is placed in contact with its surfaces for brief to moderate periods of time. Since heat retention in the workpiece is desirable, heat transfer to and through the anvil should be minimized. Corrosion resistance to a normal shop atmosphere would also be desirable. While the dimensional requirements can be somewhat lenient, the working surface should be flat and reasonably smooth.

2. Features influencing the method of fabrication include the cited yield strength, elongation and hardness, and somewhat limited production quantity. In addition, the somewhat massive size (both weight and thickness) can be quite restrictive. The width is probably about 4-inches or greater. Other than a single mirror plane, there is no

significant symmetry or uniformity of cross section. Handling should be minimized because of the size and weight.

Because of the size (both length and thickness), complexity of shape, and limited production quantity, some form of expendable-mold casting appears to be the most attractive process. Forging would be another alternative, but the size and quantity could be quite limiting.

3. Because of the need for impact resistance, cast irons would most likely come from either the malleable or ductile families, but the section thickness may present problems for the production of malleable. Cast steels would also be quite attractive, but the higher melting temperatures, lower fluidity, and high shrinkage could present problems. Alloyed material may be necessary for the desired heat treatment response.

4. Production alternatives include casting the entire piece from a single material, or casting the base of one material (including the horn) and welding or otherwise attaching a plate of stronger material to the top. Because of the desire to replicate the 1870's design, a single material is probably preferred .

While any of the materials discussed in section 3 would be workable alternatives, ductile cast iron might be the most attractive. It would most likely be cast in some form of sand mold, possibly one with higher strength than green sand. After casting, heat treatment would likely be necessary to establish the desired properties. A normalizing or annealing treatment would produce the desired properties with a very stable structure. The working surfaces and mounting base would be subjected to some form of surface grinding. If needed, a deep surface hardening treatment, such as flame hardening, could be used on the critical surfaces to increase the hardness.

CHAPTER 5
Heat Treatment

Review Questions

1. Heat treatment is the controlled heating and cooling of metals for the purpose of altering their properties. Its importance as a manufacturing process stems from the extent to which properties can be altered.

2. Heat treatment changes material structure at the microscopic level and so can change both physical and mechanical properties.

3. While the term "heat treatment" applies only to processes where the heating and cooling are done for the specific purpose of altering properties, heating and cooling often occur as incidental phases of other manufacturing processes, such as hot forming and welding. Material properties will be altered as the material responds in the same way it would if an intentional heat treatment had been performed. Properties can be significantly altered by the heating and cooling.

4. Processing heat treatments are slow cool, rather long time, treatments designed to prepare a material for fabrication. Some possible goals of these treatments are: improve machining characteristics, reduce forming forces, or restore ductility for further fabrication .

5. Since most processing heat treatments involve rather slow cooling or extended time at elevated temperature, the conditions tend to approximate equilibrium, and equilibrium phase diagrams can be used as a tool to understand and determine process details .

6. The A_1, A_3 and A_{cm} lines are used to describe transitions on iron carbon phase diagrams. The A_1 line designates the eutectoid line. A_3 designates the boundary between austenite and ferrite+austenite regions. A_{cm} separates the austenite and austenite+cementite regions.

7. Annealing operations may be performed for a number of reasons, among them: to reduce strength or hardness, remove residual stresses, improve toughness, restore ductility, refine grain size, reduce segregation, or alter the electrical or magnetic properties of a material.

8. Full anneals can produce extremely soft and ductile structures, but they are time consuming and require considerable energy to maintain the elevated temperatures required during the soaking and furnace cooling. In addition, the furnace temperature is changed during the treatment, so the furnace must be reheated to start another cycle.

9 . If hypereutectoid steels were slow cooled from the all-austenite region, they would spend considerable time in the austenite plus cementite condition, and the hard, brittle cementite that forms would tend to produce a continuous network along the grain boundaries. A small amount of cementite in a continuous network can make the entire material brittle.

10. The major difference of normalizing compared to full annealing is the use of an air cool in place of the long time, controlled furnace cool. This reduces processing time, furnace time, and fuel and energy use. However, the furnace cool of a full anneal imposes identical cooling conditions at all locations within the metal and produces identical properties. With normalizing, the cooling will be different at various locations. Properties will vary between surface and interior, and different thickness regions will have different properties.

11. Process heat treatments that do not require the reaustenitization of the steel include: the process anneal, designed to promote recrystallization and restore ductility; the stress-relief anneal, designed to remove residual stresses; and spheroidization, a process to produce a structure that enhances the machinability or formability of high-carbon steels.

12. Process anneals are performed on low-carbon steels with carbon contents below 0.25% carbon. Spheroidization is employed on high-carbon steels with carbon contents greater than 0.6%C.

13. The recrystallization process and its kinetics is a function of the particular metal, the degree of prior straining, and the time provided for completion. In general, the more a metal has been strained the more energy has been stored, and the lower the recrystallization temperature or the shorter the time.

14. The six major mechanisms available to increase the strength of a metal are: solid solution strengthening, strain hardening, grain size refinement, precipitation hardening, dispersion hardening, and phase transformation hardening. All techniques are not applicable to every metal.

15. The most effective strengthening mechanism for the nonferrous metals is precipitation hardening.

16. Precipitation hardening begins with a solution treatment to create an elevated-temperature single-phase solid solution, followed by a rapid quench to produce a supersaturated solid solution, and then a controlled reheat to age the material (cause the material to move toward the formation of the stable two-phase structure).

17. Precipitation hardening metals are either naturally aging (ages at room temperature) or artificially aging (requires elevated temperature to produce aging). Considerable flexibility and control is offered by artificial aging, since the properties can be altered and controlled by controlling the time and temperature of elevated temperature aging. Dropping the temperature terminates diffusion and retains the structure and properties

present at that time. NOTE: Subsequent heating, however, will continue the aging process.

18. In a coherent precipitate, the crystallographic planes of the parent structure are continuous through the precipitate cluster, and the solute aggregate tends to distort the lattice to a substantial surrounding region. In contrast, second-phase particles have their own crystal structure and distinct interphase boundaries .

19. Overaging is the decrease in hardness and strength of precipitation or age hardened materials. Overaging occurs when the solute atoms form large enough clusters that coherency of the solute atom clustering is lost. The large effects of coherent clusters on hindering dislocation motion are lost. The large noncoherent clusters than act as a dispersion hardening mechanism.

20. In constructing the IT or T-T-T diagram, thin specimens of a metal are heated to form uniform, single-phase austenite, and are then instantly quenched to a temperature where austenite is not the stable phase. The samples are then held at this constant temperature for variable periods of time and the kinetics of the structure change are determined. Such instantaneous changes in temperature followed by isothermal holds are quite unrealistic for manufactured items, which usually undergo some form of continuous cooling as heat is extracted from surfaces and fed to the surfaces from the hot interior.

21. For steels below the A_1 temperature, the stable phases predicted by the equilibrium phase diagram are ferrite and cementite .

22.According to the T-T-T diagram, some of the non-equilibrium structures that may be present in heat-treated steels are:
bainite, martensite, tempered martensite, and retained austenite.

23. Martensite forms from austenite by an instantaneous change in crystal structure with no diffusion. The fcc austenite transforms to the body-centered structure which is distorted into a tetragonal shape to accommodate the additional carbon. The degree of distortion is proportional to the amount of trapped carbon .

24. The major factor determining the strength and hardness of steel in the martensitic structure is the amount of carbon present in the steel.

25. Retained austenite is austenite which remains in a metastable state at temperatures where the equilibrium phase diagram predicts that it should no longer exist. It can be responsible for low strength or hardness, dimensional instability or cracking, or brittleness (by transforming to untempered martensite at some later time) .

26. As formed, martensite lacks sufficient toughness and ductility to be useful as an engineering material. Tempering is the controlled decomposition of the single-phase supersaturated solid solution toward the formation of the stable ferrite and cementite structure. Ductility and toughness improve at the expense of strength and hardness.

27. Both heat treatments begin by replacing the original structure with an elevated-temperature, single-phase solid solution (redissolving any second phases) . A quench then produces a supersaturated solid solution. A more moderate reheating then permits diffusion to move the material toward formation of the stable two-phase configuration. When age hardening, the quenched material is weaker and more ductile, and aging increases the strength at the expense of ductility. With the quench-and-temper process, the quenched structure is strong, but lacks ductility. Tempering increases ductility at the expense of strength.

28. The C-C-T diagram, continuous-cooling-transformation diagram, shows the phase and composition of steels on cooling as functions of temperature and time.

The C-C-T diagram is more useful than the T-T-T diagram since it describes more realistic heat treatment conditions. The T-T-T diagram assumes instantaneous cooling and complete isothermal transformations that are not the actual situations.

29. In the Jominy end-quench hardenability test, a standard steel specimen is subjected to a standardized quench. Since the thermal conductivity of steel is essentially constant for the range of carbon and low-alloy steels, the cooling rate varies with the distance from the quenched end - from rapid quench to an approximate air-cool.

30. The quench in the Jominy test is standardized by specifying the quench medium (water), quenchant temperature (75 F), internal nozzle diameter (1/2 inch), water pressure, and the gap between the nozzle and the specimen.

31. The concept of "equivalent cooling rates" is based on the assumption that identical results will be obtained if a material undergoes identical cooling history. If the cooling rate is known for a given location within a part, the properties at that location can be predicted as those at the equivalent cooling rate location of a Jominy test bar (well-documented in many reference texts) .

32. Hardenability is a measure of the depth to which full hardness can be obtained when heat-treating a steel. It is primarily dependent upon the types and amounts of alloy elements in the steel.

33. The depth of hardening can be increased by increasing either the severity of the quench or the hardenability of the steel. Quench changes may be limited by cracking or warping problems, however. Hardenability is increased by increasing the amount of alloy additions.

34. The three stages of liquid quenching are: the vapor-jacket stage, the second stage in which the quenchant extracts heat by boiling, and the third stage where the mechanism of heat transfer is limited to conduction and convection.

35. As a quench medium, water offers a high heat of vaporization, and second-stage cooling down to 212^0F. It is cheap, readily available, easily stored, nontoxic, nonflammable, smokeless, and easy to filter and pump. On the negative side, the bubbles tend to cling, it is an oxidizing medium, and is corrosive. In addition, the rapid rates of cooling often induce distortion and cracking.

36. Oil quenches are generally less likely to produce quench cracks than water or brine for several reasons. The rate of heat extraction into boiling oil is slower than in boiling water. The major difference, however, is due to the fact that the boiling points of oils are sufficiently high that the transition to the third-stage of quenching occurs before the martensite start temperature. Slower cooling through the martensite transformation leads to a milder temperature gradient and a reduced likelihood of cracking.

37. Polymer or synthetic quenches cool more rapidly than oils but slower than water or brine. They can be tailored by varying the concentrations of the quench components to provide extremely uniform and reproducible results. They are less corrosive than water or brine, are cheaper and less of a fire hazard compared to oils, and tend to minimize distortion.

38. Some undesirable design features in parts that are to be heat treated include: nonuniform sections or thicknesses, sharp interior corners, and sharp exterior corners.

39. When steel is quenched, the elevated temperature face-centered cubic structure changes to the body-centered configuration, and expands When aluminum is quenched, it cools and thermally contracts. In most cases, the residual stresses formed by cooling tend to be opposite for the two materials.

40. Residual stresses can be undesirable because, in service, they add algebraically to the stresses applied to the part. Loads well within the design limit may couple with unfavorable residual stresses to produce failure. By themselves, residual stresses may produce unwanted distortion or cracking.

41. Quench cracking is due to temperature gradients. Differences in temperature between different regions produce stresses and possibly different phases. The mechanical and structural mismatches are large enough to cause fracture.

42. Two methods of producing strong structures while minimizing residual stresses and the likelihood of cracking are austempering and martempering. A rapid cool is used to reduce the temperature of the material to just above the martensite start. The temperature is then allowed to become uniform prior to either further cooling to martensite (martemper) or isothermal transformation to bainite (austemper) .

43. In thermomechanical processing, mechanical deformation and heat treatment are intimately combined into a single process.

44. Selective heating techniques for surface hardening include:

flame hardening, induction hardening, laser beam hardening, electron beam hardening, and lead-pot or salt bath immersion.

45. Laser beam surface hardening operates at high speeds, produces little distortion, induces compressive residual stresses on the surface, and can be used to harden selected surface areas while leaving the remaining surfaces unaffected. Computer control and automation can be readily used and conventional mirrors and optics can be used to shape and manipulate the beam.

46. Carburizing is the elevated temperature surface treatment in which carbon is caused to diffuse into steel. The carbon may be in a solid, liquid or gaseous environment around the part being treated.

The intent of carburizing is to alter material composition and structure in selected regions of the part. In order to control the distribution of carbon in the part further heat treatment after the initial diffusion process may be required. Rapid cooling is used to fix the carbon in the high temperature state. Slow cooling is used to produce further, controlled diffusion of the carbon into the part.

47. Compared to conventional nitriding or carburizing, ionitriding offers shorter cycle times, reduced consumption of gases, significantly reduced energy costs, reduced space requirements and the possibility of total automation. Product quality is improved and the process is applicable to a wider range of materials.

48. Batch furnaces may be preferred to continuous furnaces when the productions runs are small and the details of the thermal processing vary from lot to lot. Continuous furnaces are best for large production runs of the same or similar parts that undergo the same thermal process.

49. Artificial atmospheres are often used during heat treatment operations to suppress undesirable reactions such as scale formation or tarnishing, prevent decarburization, or supply carbon or nitrogen for surface modification.

50. In a fluidized-bed furnace, a bed of dry, inert particles is heated and fluidized by a stream of flowing gas. Parts introduced into the fluidized media become engulfed and are heated by radiant heating. Temperature and atmosphere can be altered quickly, heat transfer rate and thermal efficiency are high, and fuel consumption is low. Due to high flexibility, one furnace can be used for multiple applications.

51. While heat treatment consumes large amounts of energy, its use may actually be an energy conservation measure because it enables the manufacture of a higher-quality, more durable, product. In addition, higher strengths may permit the use of less material to produce a comparable product.

Problems:

1. While this is essentially a library-research project, it is hoped that the student will note such features as the following:
Flame and induction hardening are performed on materials that have the capability of possessing both the desired substrate properties and the desired surface properties. Carburizing alters the surface chemistry and achieves the desired hardness through subsequent heat treatment. This treatment can take the form of a direct quench from the carburizing treatment, a quench from a reheat to a lower temperature, 'or dual surface and substrate treatments. Nitriding also modifies the surface chemistry, but the nitrided layer cannot sustain subsequent heat treatment. Therefore, the substrate is fully heat-treated prior to nitriding, and the hard surface is formed after the heat treatment .The additional information can be found in numerous references, such as Metals Handbook, or the references cited under the "Heat Treatment" and "Surfaces and Finishes" sections of the Selected References for Additional Study.

2. At the time of preparation a internet search for “boriding” gave the following sites in the first 15 sites listed and the information gleaned from them is presented in the table below.
www.thomasregister.com/olc/metlab/bori.htm
www. concentric.net/~ctkang/boride.shtml
www.staff.ncl.ac.uk/s.j.bull/SENotes.html
www.mrs.org/publications/jmr/jmra/1989/novdec

	Boriding / Boronizing	
1	Process description	parts are packed in a boron containing material and heated in a furnace in - vaporized boron reacts with the work material forming hard boron compounds
2	Materials	typically steels, but many alloying additions react with boron
3	Equipment	only a controlled atmosphere furnace
4	Processing conditions	boron gas atmosphere, up to 980^{o}C, 1800^{o}F, hours
5	Hardened depth	10 - 100 μm, 0.0003 - 0.003 in
6	Hardness	1600 – 4000 HV depending on boron compound formed
7	Further processing	may be followed by tempering
8	Distortion/Stress	as with any surface layer production or modification process mismatches in microstructure or deformation state result in stress gradients and distortion
9	Selective area hardening	conceivable to shield areas of part with only small diffusion of boron under shield parallel to surface

3. While the basic information on these processes has been summarized in the text, this problem encourages the students to dig deeper in a library-research mode. One will learn, for example, that there are actually several means of spheroidizing a high-carbon steel. These are different processes with the same objective and utilize the same name. It is important that users understand the entire process, and all of the intricacies, such as the different effects of full anneal and normalizing on subsequent machining (as discussed in the text) .
Useful references again are Metals Handbook and those listed in the "Heat Treatment" section of the Selected References for Additional Study.

4.The effectiveness of quenching usually means the length of time needed to bring the workpiece temperature to a desired temperature. The shorter this time the more effective the quench. In the typical quenchant vaporization – quenchant boiling – conduction heat transfer processes that occur when the work is immersed in the quenchant. The initial vaporization process has the lowest rate of heat transfer out of the workpiece. If the vaporization phase can be minimized the effectiveness of quenching will be increased. With use of a hot oil the quenchant is brought to the boiling stage of quenching faster than with a cold oil and so quenching is more effective.

Case Study:

A Flying Chip from a Sledgehammer

The hammerhead chipped because of the formation of untempered martensite. Untempered martensite of 0.6% carbon would have a hardness of about Rockwell C 65 and would be extremely hard and brittle, quite likely to crack upon impact.

The procedure used to grind off the mushroom would likely involve removing the handle to permit hand grinding of the head. This would then be periodically dipped into a container of water when it gets too hot to hold. Considering the size and mass of a 15-pound sledge hammer head, and the thermal conductivity of steel, it is quite possible that the temperatures in the grinding region could be sufficient to reaustenitize ($>1333^0$F) the metal before the operator would feel uncomfortably high temperatures in the gripped region (especially if he were wearing some type of protective leather-palmed glove) . Upon water quench, the austenite would transform to untempered martensite. Subsequent grinding might bring about some degree of tempering, but this is not assured and all of the untempered martensite may not be affected.

Possible solutions to the problem include: (1) alteration of the grinding procedure to prevent the generation of such excessive temperatures, or (2) a required furnace retempering of the entire head prior to reassembly and reuse, and (3) mandatory use of safety goggles when using the sledge hammers.

CHAPTER 6
Ferrous Metals and Alloys

Review Questions

1. Many of the properties and characteristics of engineering materials depend not only on the material itself, but also on the manner of production and the details of processing. Aspects of prior processing can significantly influence both further processing and the final properties of the product.

2. A ferrous material is one that is based on the element iron (i.e. iron is the major chemical constituent of the material).

3. When iron ore is reduced to metallic iron, other elements are usually present in the product. All of the phosphorus and most of the manganese in the ore will also reduce and will enter the iron. The oxides of silicon and sulfur will be partially reduced and these elements will also become part of the metal.

4. Pig iron is a high-carbon, high-silicon material with a chemistry in the range of 3.0 to 4.5% carbon, 1.0 to 3.0% silicon, 0.15 to 2.5% manganese, 0.05 to 0.1% sulfur, and 0.1 to 2.0% phosphorus. In the conversion into steel, the pig iron is subjected to an oxidation process that substantially decreases the amount of carbon, silicon, manganese, phosphorus, and sulfur.

5. Ladle metallurgy refers to a variety of processes designed to provide final purification and fine tune both the chemistry and temperature of the melt. Alloy additions can be made, carbon can be further reduced, dissolved gases can be reduced or removed, and steps can be taken to control subsequent grain size, limit inclusion content, reduce sulfur, and control the shape of any included sulfides. Stirring, degassing, reheating, and various injection procedures can be performed to increase the cleanliness of the steel and provide tighter control of the chemistry and properties.

6. By extracting molten steel from the bottom of a ladle, slag and floating matter are not transferred to the solidified product .

7. Solidification shrinkage is the term applied to the often substantial change in dimensions that occurs when a liquid changes to solid. The more efficient arrangement of atoms results in an increase in density and a decrease in volume.

8. Continuous casting virtually eliminates the problems of piping and mold spatter. In addition, it eliminates the pouring into molds, stripping the molds from the solidified metal, and the handling and reheating of the ingots prior to rolling. Cost, energy and

scrap are all significantly reduced. The products have improved surfaces, more uniform chemical composition, and fewer oxide inclusions.

9. Dissolved oxygen in molten steel can be removed by adding aluminum, ferromanganese or ferrosilicon to the molten steel. In this deoxidation process the added materials react with the dissolved oxygen to form solid metallic oxides.

10. Gases can be removed from molten steel by vacuum degassing, vacuum arc remelting, vacuum induction melting and electroslag remelting.

11. Electroslag remelting can be used to produce extremely clean, gas-free metal. The nonmetallic impurities are collected in the flux blanket, leaving beneath a newly solidified structure with improved quality.

12. A plain carbon steel is an alloy of iron and carbon, containing manganese, phosphorus, sulfur, and silicon in normal, but small, quantities.

13. A low-carbon steel is one that has less than 0.20% carbon.

Medium-carbon steel contains 0.20% to 0.50% carbon.

High-carbon steels contain more than 0.50% carbon.

14. Medium-carbon steels are used in high volumes because they offer the best overall balance of engineering properties. The high fatigue and toughness properties of the low carbon steels are effectively compromised with the strength and hardness of the higher carbon contents.

15. Plain-carbon steels are the lowest-cost steel material. Because of the low cost, they should be given first consideration for many applications.

16. The most common alloy elements added to steel include:
chromium, nickel, molybdenum, vanadium, tungsten, cobalt, boron, and copper, as well as manganese, phosphorus, sulfur, and silicon in amounts greater than normally present.

17. Alloy elements are added to steel for a variety of reasons, among them: to improve the strength and hardenability, or to produce special properties, such as corrosion resistance or stability at high or low temperatures.

18. Alloy elements that are particularly effective in increasing the hardenability of steel in order of decreasing effectiveness are: manganese, molybdenum, chromium, silicon, and nickel. Vanadium and boron are also used in small, but effective quantities .

19. Chromium, vanadium, molybdenum, and tungsten can all be used to impart strength and wear resistance through the formation of stable second-phase carbides.

20. The last two digits in the AISI-SAE designation system for steel indicates the approximate carbon content of the steel in hundredths of weight percent. This is useful information since many engineering properties are directly tied to the carbon content.

21. Letters are added between the second and third digits in the steel designation and at end of the numerical designation.

The letter in the center of the numerical designation indicates an addition to the base metal or the process used to produce the steel. Examples are B and L indicating addition of boron or lead and E signifying steel produced in an electric furnace.

The letter added at the end of the numerical designation indicates the hardenability of the steel.

22. In selecting a steel, it is important to keep use and fabrication in mind. For example, a product that is to be assembled by welding would benefit from a lower carbon content as such would reduce the likelihood of cracking. Additional strength, if desired, would be better obtained through selection of additional alloy elements rather than an increase in the carbon content of the steel.

23. There is a fundamental difference in the way strength is obtained in the HSLA and constructional alloy steels. The high strength/low alloy (HSLA) types rely largely on the chemical composition to develop the desired mechanical properties in the as-rolled or normalized condition. In contrast, the constructional alloys generally develop the desired properties through the use of nonequilibrium heat treatment.

24. Microalloyed steels are steels that contain small amounts of alloying elements like niobium, vanadium, titanium, zirconium, boron, rare earth elements, or combinations thereof and are used as substitutes for heat-treated steels. Attractive strength and hardness is obtained without interfering with the material processing (weldability, machinability and formability) .

25. Microalloyed steels require less cold work to attain a desired level of strength, so the remaining ductility can be greater than with alternative materials. Hot formed products can often be used in the air cooled condition to provide properties comparable to quenched-and-tempered alloys . Machinability, fatigue life, and wear resistance can be superior to alternative materials. Energy savings can be substantial, straightening or stress relieving after heat treatment can be eliminated, and quench cracking is not a problem. Weight can often be reduced in parts, since the strength is increased.

26. Dual phase steels contain ferrite and high-carbon martensite.

27. Dual phase steels are more formable (ductile) than high strength low alloy steels. They are attractive than HSLA steels for making products that require a large amount of deformation in their production, e.g., parts with small radius bends.

28. Free machining steels are basically carbon steels that have been modified by an alloy addition to enhance machinability. Sulfur, lead,. bismuth, selenium, tellurium, and phosphorus have all been added to enhance machinability.

29.When free-machining steels are selected, the ductility and impact properties are somewhat lower than with the unmodified steels

30. Bake-hardenable steels are aging resistant during normal storage, but begin to age during forming, and continue to age while exposed to heat during the paint baking operation. Since strengthening occurs after forming, the forming characteristics are good, coupled with improved product properties.

31. Precoated steel sheets can often be used to offset the high cost of finishing products on a piece-by-piece basis -- a costly and time-consuming approach. Caution must be exercised to protect the coating during fabrication, but this is usually far less than the cost for finishing the individual pieces.

32. The amorphous metals have attracted considerable attention for use in magnetic applications. Since the material has no grains or grain boundaries, the magnetic domains can move freely in response to magnetic fields, the properties are the same in all directions, and corrosion resistance is improved. The high magnetic strength and low hysteresis losses offer the possibility of smaller, lighter weight magnets.

33. Maraging steels are used when super-high strength is the dominant requirement, and acceptable toughness is also needed. Yield strengths are often in excess of 250 ksi with elongations in excess of 11%.

34. The elevated temperature limit for plain-carbon steels is about 250^{o} or 500^{o}F

35. Recycling of a material is easier if the material can be easily collected and reprocessed with no major complications.

Steel is widely used so it available for recycling. Steel is magnetic so it can be separated easily from other materials.

Except for high quality, special application steels requiring tight composition controls, steel is easily reprocessed from scrap steel.

36. The corrosion resistance of stainless steels is the result of a strongly adherent chromium oxide that forms on the surface when the amount of chromium dissolved in the metal exceeds 12%.

37. The ferritic stainless steels are the cheapest of the various families. If their properties are adequate, they should be given first consideration when a stainless steel is required.

38. Martensitic stainless steels frequently contain significant amounts of carbon since

they are used in the quenched and tempered structure. The carbon is dissolved in the austenite at elevated temperature and then trapped into the body-centered structure by quenching. Different amounts of carbon provide different levels of strength, as in the plain-carbon and alloy steels .

39. Stainless steels are stainless when there is at least 12% chromium in atomic form that can react with oxygen at the surface. When martensitic stainless steels are slow cooled or annealed the chromium in the steel reacts with other elements and so is not available to react with oxygen at the part surface. The steel is then not stainless since the protective surface reaction layer is not present. The annealed material is subject to red rust corrosion.

Martensitic stainless steels can be made stainless by a quench and temper process. In this type of process reaction between chromium and other alloying additions are limited.

40. Austenitic stainless steels are nonmagnetic and offer superior corrosion resistance to a host of media. Formability is outstanding, and they respond well to strengthening by cold work.

41. Duplex stainless steels have a chemistry and processing designed to produce a microstructure that is a combination of ferrite and austenite, and properties that are often superior to either the straight ferritic or austenitic varieties.

42. Sensitization of a stainless steel is the loss of corrosion resistance that occurs when the local concentration of chromium drops below 12%. This is usually caused by the formation of chromium carbides along grain boundaries. Methods of prevention include: keep the carbon content low, tie up the carbon with an alternative element, and rapidly cool the material through the carbide-forming temperature range.

43. Tool steels are metals designed to provide wear resistance and toughness combined with high strength. They are basically high-carbon steels where the alloy chemistry provides the desired balance of toughness and wear resistance.

44. While the AISI-SAE designation system for plain-carbon and alloy steels is based on material chemistry, the AISI-SAE system for tool steels identifies materials by a letter indicating the primary feature, such as quenching medium, primary application, special characteristic, or specific industry, followed by a number that simply designates the specific member within the family .

45. Air-hardenable tool steels can be hardened by less severe quenches, permitting tighter tolerances through heat treatment and reduced tendency to crack or warp. Applications involving large amounts of costly or precision machining are particularly attractive .

46. Hot-work tool steels generally use additions of the carbide-forming alloys, such as chromium, tungsten, and molybdenum .

47. If alloy cast irons are to be heat treated, the alloy elements are often selected to improve hardenability. If the cast iron is not to undergo heat treatment, the alloy elements are often selected to alter the properties through affecting the formation of graphite or cementite, modifying the morphology of the carbon-rich phase, or simply strengthening the matrix material. Other reasons for an alloy addition might include improving the wear resistance or providing some degree of enhanced corrosion resistance.

Problems:

No problems

Case Study:

Interior Tub of a Top-Loading Washing Machine

1. The present product is currently performing in an adequate manner and has established itself as somewhat of an industry standard. The material is relatively inexpensive, and readily available, but the necessary surface treatment requires considerable energy and handling with the coating, drying and firing, often of multiple layers. The deep drawing of the material will most likely require intermediate anneals, which will further increase manufacturing cost. While both of the above areas include significant possibilities for problems and involve additional cost, it is likely that the coating process would be the most problematic and most costly.

2. The conversion to stainless steel would enhance customer attractiveness, but also eliminate the need for a coating operation. Unfortunately, the stainless is a more costly material, would require more force to deform, and, depending on the particular type, may have poorer formability. Because of the higher forming forces, equipment and tooling would have to be stronger and would therefore be more costly.

3. Because of the superior formability, some form of austenitic stainless steel would be preferred. This part requires conversion from flat sheet to a deep drawn shape, a procedure that will likely require multiple stages of forming. In addition, the austenitic stainlesses offer superior corrosion resistance, and the product will come into contact with a wide spectrum of water qualities, laundry products, and additives, such as chlorine bleach. There is no need for the high strength of the heat-treated martensitic grades, and the less expensive ferritic alloys lack the superior formability of the face-centered cubic structured austenitic material. Because of the spectrum of possibilities, no attempt is made to select a specific alloy.

4. The austenitic stainless steels strengthen considerably when cold worked, and this can be a useful means of achieving the desired strength. However, it is doubtful that the additional strength of cold working is necessary, and the residual stresses imparted by the

deformation may be detrimental in the form of stress-corrosion problems during service .

If the strengthening of cold work is deemed desirable, the effects of the residual stresses could be reduced by taking the material through the recovery stage of the recrystallization process. This reduces the residual stresses while retaining the mechanical properties set by the cold working.

If intermediate anneals are required during the deformation sequence, the effects of prior cold work will not be carried to the finished product. In addition, one consequence of partial cold rolling of the starting material will be to reduce the; ductility of a material being used for an application that requires extensive deformation. It is unlikely, therefore, that the use of prior cold rolling would be appropriate or desirable for this product.

5. It is possible that a surface passivation treatment would be beneficial for this product, but the inherent properties of the stainless should be adequate.

CHAPTER 7
Nonferrous Metals and Alloys

Review Questions

1. Nonferrous metals often possess certain properties not usually associated with ferrous metals, among them being: corrosion resistance, ease of fabrication, high electrical and thermal conductivity, light weight, strength at elevated temperatures and color.

2. The nonferrous alloys are generally inferior to steel in terms of strength and elastic modulus, and possibly weldability.

3. Alloys with low melting points are often easy to cast, using sand molds, permanent molds, or dies.

4. The wide use of copper and copper alloys is largely due to the high electrical and thermal conductivity, high ductility, and corrosion resistance .

5. The relatively low strength and high ductility make copper quite attractive far forming operations. By cold-working, the tensile strength can be raised from about 30,000 psi to over 65,000 psi., with a concurrent drop in elongation from 60% to about 5%. The low recrystallization temperature is attractive when additional cold working is desired.

6. A primary limitation of capper is its high density --heavier than iron. Strength-to-weight comparisons place it below most engineering metals. In addition, some significant problems can occur when the metal is used at elevated temperature.

7. Commercially pure copper is classified as
- electrolytic tough pitch, ETP, copper if it contains 0.02% - 0.05% oxygen,
- oxygen-free high-conductivity, OFHC, copper if it contains much less than 0.02% oxygen.

These two types of copper differ primarily in oxygen content. This difference implies difference in conductivity and differences in production to control oxygen content.

8. The copper-zinc alpha brasses are quite ductile and formable, achieve good strength through cold working and have good corrosion resistance and high electrical and thermal conductivities. Both strength and ductility increase with zinc content up to about 36% zinc. In addition, variations in chemistry can be used to produce changes in color and various platings are easy to apply.

9. Brasses are susceptible to stress corrosion cracking. Stress corrosion requires a hostile environment and stress. The stress acting is a combination of stress due to loading in

service and residual stresses created during processing. To reduce the net stress acting in service, residual stress can be removed or reduced by a stress relief process.

10. The term "bronze" can be particularly confusing. While the term frequently refers to copper-tin alloys, it can be used to describe any copper alloy where the major alloy addition is neither zinc nor nickel.

11. The copper-nickel alloys are particularly well known far their high thermal conductivity and high-temperature strength, coupled with good corrosion resistance.

12. Copper-beryllium alloys can be age hardened to produce the highest strengths of the copper-based metals. In addition to having strengths similar to steel, the alloys are nonsparking, nonmagnetic, and have high electrical and thermal conductivity. Its use has been drastically limited, however, by concerns over the toxicity of the beryllium.

13. Aluminum and its alloys have achieved popularity due to their light weight, high electrical and thermal conductivity, good corrosion resistance, and workability.

14. A given volume of aluminum is about one-third the weight of the same volume of steel. The specific gravity of aluminum is about 2.7 while for steel specific gravity is about 7.9.

In manufacturing operations both cost per unit weight and cost per unit volume are useful quantities. The cost of many metal raw materials and structural shapes that will be converted into finished parts are quoted as cost per weight.

The cost of the finished part includes manufacturing costs and material costs. If the volume of a particular part will be the same whether it is made of aluminum or steel, the relevant material cost for the part is cost per unit volume of material.

15. The electrical conductivity of pure aluminum is approximately 62% that of copper for the same size wire and 200% that of copper on an equal weight basis.

16. Aluminum alloys are inferior to steel in the area of elastic modulus. In addition, the wear, creep, and fatigue properties are generally rather poor.

17. The observed corrosion resistance of aluminum alloys is again the result of a tight, adherent oxide coating, similar to that found in stainless steels.

18. Wrought means “worked” and the wrought aluminum alloys are designed to have properties that are desirable for making worked or formed parts. Mechanical properties that are desirable for making formed parts include low yield strength, high ductility, high toughness, high strain hardening rate if high strength is desired in the finished part.

Cast or casting alloys are designed to have properties desirable for making cast parts. For example, casting alloys have low melting temperature, high fluidity when molten and desirable as-solidified structures and properties.

19. While the four digit number of an aluminum alloy only designates chemistry, the temper designation or suffix denotes the condition or nature of the prior processing history of the material. This can be used to provide a good indication of the structure and properties of the alloy.

20. The high-strength, aircraft-quality" aluminum alloys generally receive their strengthening through an age hardening treatment.

21. Alcad is a composite with a thin layer of corrosion resistant aluminum bonded to a higher strength corer material. The result is a corrosion resistant and high strength material.

22. The aluminum alloys used for permanent mold casting must be designed to have lower coefficients of thermal expansion because the molds offer restraint to the dimensional changes that occur upon cooling. Die casting alloys require high degrees of fluidity and "castability" because they are often cast into thin sections. In addition, many are designed to have rather high as-cast strength under rapid cooling conditions.

23. The aluminum-lithium alloys offer higher strength, greater stiffness and lighter weight than most of the commercial aluminum alloys, coupled with the relative ease of fabrication of aluminum alloys.

24. Magnesium and magnesium alloys can be characterized by poor wear, creep, fatigue, and corrosion resistance properties. The modulus of elasticity is low and the alloys possess limited ductility .

25. The use of magnesium is generally restricted to applications where light weight is very important. Magnesium alloys are best suited for applications where lightness is the primary consideration and strength is a secondary requirement.

26. Classification of metals typically involves specifying the composition (alloying), heat treatment and sometime other characteristics such as addition of base metals and method of production (Question 21 in Chapter 6).

Magnesium alloys classification uses
- one or two prefix letters to specify the two largest alloying additions,
-, two or three numerals that specify the percentages of the two main alloying metals,
- sometimes a suffix letter to denote a base alloy variation,
- sometimes a suffix letter to designate material temper.

27. The forming behavior of magnesium alloys is poor at room temperature, but most conventional processes can be performed when the material is heated to between 450 and 7000P.

28. Magnesium is flammable or explosive when it is in a finely-divided form, such as powder or chips. A critical feature here is the ratio of surface area to volume. In addition, magnesium is flammable when heated above 800^{o}F in the presence of oxygen.

29. The primary application of pure zinc is the galvanizing of iron and steel. The principal use of the zinc-based alloys is in die-casting operations. They are low in cost, have low melting points, do not affect steel dies adversely, and can possess good strength and dimensional stability.

30. Zinc-aluminum casting alloys are designed to have higher strength, hardness and wear resistance and lower melting and casting costs than zinc casting alloys.

31. Titanium and its alloys are strong, lightweight, corrosion resistant, and offer strengths similar to steel at temperatures up to 9000F.

32. The attractive mechanical properties of titanium and titanium alloys are generally retained at temperatures up to 900^{0}F.

33. The nickel-based Monel alloys probably offer better corrosion resistance to more media than any other commercial alloy.

34. Nickel, iron and nickel, or cobalt forms the base metal for the superalloys.

35. when the operating temperature exceeds the limits of the superalloys, exotic materials must be employed, such as TD-nickel or the refractory metals.

36. The refractory metals consist of: niobium, molybdenum, tantalum, rhenium and tungsten.

37. While the eutectic lead-tin alloy offers the lowest melting temperature of the lead-tin solders, the high cost of tin has prompted many users to specify solders with a lower-than-optimum tin content.

38. Beryllium has low density (less than aluminum) and high stiffness (greater than steel) and so parts with high stiffness-to-weight ratio can be design and produced.

39. Graphite possesses the unique property of actually increasing in strength as the temperature is increased. This makes the material attractive for elevated temperature applications, such as electrodes in furnaces.

Problems:

No problems

Case Study:

Nonsparking Wrench

Many safety tools have been made from the copper-2% beryllium alloy, since its age-hardened properties approach and often exceed those of many heat-treated alloy steels. This is fine for small tools where the cost of the material and the weight of the copper alloy (greater than that of steel) are not objectionable. However, with the proposed pipe wrench, both cost and weight may pose serious problems to the acceptance of the tool.

The copper-2% beryllium alloy will likely have to be used in the actual jaws of the wrench, as it is one of the few nonferrous materials that can provide the necessary strength, wear resistance, and fracture resistance for this use. However, the handle, adjuster ring, and moving L-shaped upper jaw will likely have lower mechanical property requirements that could be met by some of the other age-hardenable, higher-strength nonferrous materials. Aluminum alloys, such as 6061, 2014, 2024, 7075, 7079 and others could be forged and heat-treated to produce the handle and jaw components, and copper-beryllium inserts can be installed in the jaws. Alternately, an age-hardenable aluminum casting alloy could be selected and these components could be fabricated by sand, permanent mold, or even die casting. One problem with the use of the aluminum alloy with a copper insert would be the presence of a galvanic corrosion cell (dissimilar metals), which could be aggravated by some of the environments in which tools are typically stored. Since replaceable inserts would be desirable, and the method of assembly would likely involve a removable fastener, electrical contact between the components would be virtually assured. The possible severity of this problem would have to be monitored.

Alternative solutions would not be as attractive. Manufacture of the handle from a less expensive copper-base alloy would reduce cost and significantly reduce the galvanic corrosion problems, but the weight of such a wrench may be objectionable. Smaller wrenches in the series might be made in this manner. Magnesium alloys offer light weight, but lack the necessary strength and rigidity. Titanium alloys are difficult to fabricate (too reactive to easily cast and generally require isothermal forging) . Nickel-base alloys would offer no cost advantage to the copper-beryllium.

Unless the galvanic corrosion problems become excessive in the jaws, the most attractive solution would appear to be a to use copper-beryllium inserts in cast or forged aluminum components. All parts would probably require strengthening through age hardening treatments.

CHAPTER 8
Nonmetallic Materials: Plastics, Elastomers, Ceramics, and Composites

Review Questions

1. Some of the naturally occurring nonmetallic engineering materials are: wood, stone, clay, and leather.

2. The term "nonmetallic engineering material" now includes plastics, elastomers, ceramics and composites.

3 . The term "plastics" refers to engineered organic materials, composed of hydrogen, oxygen, carbon and nitrogen, in the form of large molecules that are built up by joining smaller molecules. They are natural or synthetic resins, or their compounds, that can be molded, extruded, cast, or used as thin films or coatings.

4. Considering a macroscopic piece of plastic/polymer there are two types of bonds within it. Within the molecules themselves the bonding is covalent. This is the primary bonding in the material.

Between the molecules much weaker van der Waals bonds act.

5. A saturated molecule is one to which no additional atoms can be added. If the molecule is a pure hydrocarbon, it contains the maximum number of hydrogen atoms. An unsaturated hydrocarbon does not contain the maximum number of hydrogen atoms.

6. An isomer is one structural form of a given kind and number of atoms that can form in different ways. That is, isomers are different structural arrangements of a given number and kind of atoms and an isomer is one instance of the possible isomers.

7. Polymerization can take place by either addition or condensation. In addition, a number of small molecules unite to form a large molecule with repeated units. Condensation polymerization results in the formation of a polymer and a small by-product molecule .

8. The repeated molecular unit in a polymer molecule is a mer. The degree of polymerization is the average numbers of these units (mers) in the polymer molecule.

9. The terms thermoplastic and thermosetting refer to a material's response to elevated temperature. Thermoplastic materials soften with increasing temperature and become harder or stronger when cooled. The cycle can be repeated as often as desired and no chemical change is involved. In the thermosetting materials, elevated temperatures tend to promote an irreversible condensation reaction. Once set, additional heatings do not

produce softening. Instead, the materials maintain their mechanical properties up to the temperature at which they char or burn .

10. Crystallization of a polymer means that the polymeric molecules align into a repeating, orderly structure. Crystallization occurs in only individual regions of the polymer, not over the entire, macroscopic piece of material.

11. The strength of the thermoplastic materials can be altered by mechanisms that restrict or alter the intermolecular slippage. These mechanisms include: longer chains, polymers with large side groupings, branched polymers, cross-linking, and crystallization.

12. The deformation of thermosetting material requires the simultaneous breaking of numerous primary bonds. Therefore, these materials are strong, but brittle.

13. .Upon subsequent heating, the thermosetting polymers maintain their mechanical properties up to the temperature at which they char or burn.

14. While thermoplastic materials are easily molded, the temperature of the mold must be cycled to permit the molded product to cool and strengthen prior to ejection. In contrast, the mold used to process thermosetting polymers can operate at a fixed temperature, but the molding time is often longer because of the need to complete the curing or "setting" of the resins.

15. Attractive engineering properties of plastics include:
light weight, corrosion resistance, electrical resistance, low thermal conductivity, the variety of optical characteristics, formability, surface finish, low cost, and low energy content.

16. The inferior properties of plastics generally relate to mechanical strength. Yield strength, impact strength, dimensional stability, property retention at elevated temperature, sensitivity to humidity, and degradation under certain forms of radiation are all limiting or undesirable properties.

17. Environmental conditions that may adversely affect the performance of plastics include: elevated temperature, humidity, and ultraviolet and particulate radiation.

18. Additive agents are frequently added to plastics to improve their properties, reduce their cost, improve their moldability, and impart color.

19. Filler materials are added to molded plastic to: improve strength, stiffness, or toughness; reduce shrinkage; reduce weight; or provide cost-saving bulk.

20. Common filler materials for plastics are wood flour, cloth fibers and particles, glass fibers, mica and inorganic materials such as talc and clay. They are intended primarily to improve mechanical properties of the polymeric material and in some cases to reduce cost by including a low cost volume fraction in the higher cost plastic.

21. Stabilizers or antioxidants are added to plastics to reduce long term degradation of the polymer due to factors such as heat and radiation.

22. Oriented plastics are intended to have increased strength in a particular direction.

23. The "true engineering plastics" offer improved thermal properties, first-rate impact and stress resistance, high rigidity, superior electrical characteristics, excellent processing properties, and little dimensional change with temperature or humidity. They offer a balanced set of engineering properties.

24. Plastics have replaced glass in containers and flat glass. PVC competes with copper and brass in pipe and plumbing fittings. Plastics have replaced ceramics in sewer pipe and lavatory facilities. New automotive uses include engine components and fuel tanks and fittings.

25. With the amount of a particular type of plastic that is recycled being an indicator of ease of recycling, polyethylene terephthalate (PET) and high density polyethylene are the easiest to recycle.

26. Mixed plastics contain multiple types of resins, fillers and colors, and may mix thermoplastics and thermosets. Most, however, have the same physical properties, making separation extremely difficult.

27. Elastomers are a class of linear polymers that display an exceptionally large amount of elastic deformation when a force is applied, frequently stretching to several times their original length. In these materials, the long polymer chain is in the form of a coil, which elastically uncoils and recoils in response to loads.

28. By cross-linking the molecules, it is possible to prevent viscous deformation, while retaining the large elastic response. The elasticity or rigidity of the product can be determined by controlling the number of cross-links. Small amounts of cross-linking produces soft, flexible material. Additional cross-linking makes the material harder, stiffer, and more brittle. Thus the properties of an elastomer can be tailored through control of the amount of cross-linking.

29. Natural rubber is an organic material and so its strength is very sensitive to temperature and its structure is degraded by solvents such as petroleum based oil, gasoline and naphtha and radiation energy.

30. The outstanding physical properties of ceramics include their ability to: withstand high temperatures, provide a variety of electrical properties, and resist wear.

31. The crystal structures of ceramic materials are frequently more complex than those for metals because atoms that differ greatly in size must be accommodated within the same structure and interstitial sites become extremely important. In addition, charge

neutrality must be maintained throughout the structure of ionic materials. Covalent materials can only have a limited number of nearest neighbors - forcing inefficient packing and low density.

32. Amorphous or noncrystalline ceramics are often called glasses, and said to be in a glassy state or have a glass structure.

33. The refractory ceramics are materials that are designed to provide acceptable mechanical and chemical properties while at high temperatures .

34. The dominant property of the ceramic abrasives is their high hardness.

35. Glass products are formed by heating the feed stock or initial workpiece and then mechanically shaping it at the elevated temperature. Examples of forming techniques are mechanical forming using paddles and blowing of hollow shapes.

Machinable ceramics have been developed but these are typically called ceramics, not glasses.

36. Cermets are combinations of metals and ceramics that are bonded together in the same manner in which powder metallurgy parts are produced. They combine the high refractory characteristics of ceramics and the toughness and thermal shock resistance of metals.

37. Ceramic materials generally do not exhibit their potentially high tensile strength because small pores or flaws act as stress concentrators and their effect cannot be reduced by plastic flow.

38. The mechanical properties of ceramics generally show a wider statistical spread than the properties of metals since the size, number, shape and location of the flaws is likely to differ from part to part, inducing failure at very different applied loads.

39. Even if all of the flaws or defects could be eliminated from the structural ceramics, the materials would still fail by brittle fracture with little, if any, prior warning. Thermal shock may be a problem, cost would be high, joining to other materials is difficult, and machining limitations favor net-shape processing .

40. The structural ceramic materials include: silicon nitride, silicon carbide, partially stabilized zirconia, transformation-toughened zirconia, alumina, sialons, boron carbide, boron nitride, titanium diboride, and ceramic composites.

41. Sialon is stronger than steel, extremely hard, and light as aluminum. It has good resistance to corrosion, wear and thermal shock, is an electrical insulator, and retains good tensile and compression strength up to 2550°F. In addition, its thermal expansion is quite low compared to steel or polymers. When overloaded, however, it will fail by brittle fracture.

42. Some of the ceramic materials currently being used as cutting tools include: silicon carbide, cobalt-bonded tungsten carbide, silicon nitride, cubic boron nitride, and polycrystalline diamond. The ceramic cutting tools offer low wear rates, low friction, high rates of cutting, and long tool life.

43. A composite material is a heterogeneous solid consisting of two or more components that are mechanically or metallurgically bonded together. Each of the components retains its identity, structure and properties, yet by combining the components, unique properties are imparted to the composite.

44. The properties of composite materials generally depend upon: the properties of the individual materials; the relative amounts of the components; the size, shape and distribution of the discontinuous components; the degree of bonding between the components; and the orientation of the various components.

45. The three principal geometries of composite materials are: laminar or layer-type, particulate, and fiber-reinforced.

46. A bimetallic strip consists of two metals with different coefficients of thermal expansion bonded together as a laminate. Changes in temperature produce a change in shape.

47. The attractive aspect of the strengthening that is induced in the dispersion-strengthened particulate composites is the stability and retention that is observed at elevated temperatures. The particles are selected to be insoluble in the matrix material, their effect persists to temperatures much higher than for the naturally-occurring two-phase materials.

48. Due to their unique geometry, the properties of particulate composites are usually isotropic. This is usually not true for the laminar, whose properties differ perpendicular and within the plane of the laminate. Fiber-reinforced composites, may or may not be isotropic depending on the length and randomness of the orientation of the fibers.

49. In a fiber-reinforced composite, the matrix supports and transmits loads to the fibers, and provides the ductility and toughness. The fibers, on the other hand, provide strength by carrying most of the load.

50. Common fibers used in fiber reinforced composites are nylon, rayon, Kevlar, glass and graphite. Since the matrix protects the fibers from fracture initiation and growth conditions in use, brittle materials can be used as the strength producing components of composites.

51. In a fiber-reinforced composite, the fibers can be in a variety of orientations: short, random fibers; unidirectional fibers; woven fabric layers; and complex 3-dimensional weaves.

52. Tbe properties of fiber-reinforced composites depend strongly upon: the properties of the fiber material, the volume fraction of fibers, the aspect ratio of the fibers, the orientation of the fibers, the degree of bonding between the fiber and the matrix, and the properties of the matrix.

53. Compared to metals, the metal-matrix composites offer higher stiffness and strength and a lower coefficient of thermal expansion. Compared to the organic matrix materials, they offer higher heat resistance as well as improved electrical and thermal conductivity .

54. In a ceramic matrix composite, the fibers add directional strength, increase fracture toughness, and improve thermal shock resistance.

55. Current limitations to the extensive use of composite materials in engineering applications include: the high cost of the material, the intensity of labor required for fabrication, and the lack of trained designers, established design guidelines, information about fabrication costs, and methods of quality control and inspection. In addition, it is often difficult to predict interfacial bond strength, strength of the composite, response to impacts and probable modes of failure. There is concern about heat resistance, sensitivity to various environments, and instability of properties. Repair, maintenance, and assembly are difficult or require special procedures.

56. Composites are quite attractive for aerospace applications because they offer high strength, light weight, high stiffness, and good fatigue resistance.

Problems:

1. a). Some of the desirable features for a submarine material are high strength (to withstand water pressure), fracture resistance (to withstand possible impacts), corrosion resistance (to both fresh and salt water), and the ability to be fabricated into a leak-tight assembly (possibly using techniques like welding) . Possible materials would include high-strength steels, titanium alloys, and possibly nickel-based alloys.

b) For aerospace applications, concerns focus on areas such as: light weight, strength-to-weight ratio, fatigue resistance, and ease of fabrication and ability to fabricate in small production quantities .

c) Engineers are constantly pushing the limits of engineering materials. Some current targets that are presently unattainable include: (1) reuseable rocket engines that, can withstand temperatures in excess of 4000^0F, stresses and severe vibrations, and (2) light weight wing skin materials for hypersonic aircraft that will withstand temperatures in excess of 1800^0F, and be resistant to fracture, fatigue and corrosion.

Since these applications both require elevated-temperature properties, they will likely be addressed through ceramic materials, the family of intermetallic compounds, or even the high-temperature metals (although these are sufficiently heavy as to be inappropriate for the airplane use) . Any use of polymers would be highly unlikely at the specified temperatures.

2. This is an open-ended problem, but numerous examples can be considered, such as: (1) window frames (wood, metal, vinyl); (2) lavatory basins (metal, cast polymer, ceramic whiteware); and (3) window cranks for autos or mobile homes (die cast plastic or die-cast zinc) .

3. Coated cutting tool preparation is described in Section 22.2.

The performance of the coating is in machining, in contrast to performance in mechanical and chemical tests related to expected performance in machining, e.g., hardness, hot hardness (e.g., Figure 22-3, Table 22-1), corrosion. Using the information available in Chapter 22 enables a comparison of performance in terms of tool wear/tool life in machining.

	Deposition conditions	Performance
TiC	chemical vapor deposition 1000°C 1800°F initial heating in inert atmosphere	cutting speed – up to 1200 sfpm, Fig 22-1 n = 0.33, page 537
TiN	chemical vapor deposition preferred – as above - or physical vapor deposition (reactive sputtering, reactive ion plating, arc evaporation) 200-485°C, 400-900°F in vacuum	cutting speed – up to 1200 sfpm, Fig 22-1 n = 0.35, page 537
Al_2O_3	alumina compacts made by compaction and sintering 267 – 286 MPa, ~40,000psi ~ 1000°C, 1800°F alumina coatings	cutting speed – up to 1200 sfpm, Fig 22-1 n = 0.40

Maximum useful cutting speeds are about the same for all materials. Based on the value of n which is the exponent in the Taylor Tool Life equation aluminum oxide cutters will have the longest tool life followed by titanium nitride and then titanium carbide.

Mechanical properties will enter in determining tool performance in specific machining operations. For example, the brittle aluminum oxide tool is expected to perform poorly in interrupted cutting such as milling due to varying cutting forces and temperature cycling.

4. Ceramics are hard, strong, brittle materials. Oxides are chemically stable. These materials have low thermal conductivity. Ceramic parts are made in high temperature compaction followed by sintering and finishing processes, Section 8.4. Residual voids in the part, coupled with the inherently brittle ceramic materials, usually results in brittle materials.

a. With respect to part manufacture these material characteristics have important implications. Compaction of a ceramic part before sintering requires application of high pressure. This implies difficulties for production of large parts since this implies the need for high pressure, high load, high stiffness machinery. Compaction requires high strength dies and formed parts have to be removed from the die so complex shaped parts may not be feasible to manufacture. Mechanical manufacturing processes such as forming and machining produce a part by controlled deformation of the work material. The brittleness of typical ceramics means that they will fracture during production processes except in processes in which very little deformation is needed to produce the part. In many finishing operations such as machining brittle materials fracture leaving rough surfaces subject to fracture initiation at the sharp nonuniformites in the surface. (There is recent development of ductile regime machining/grinding in which small depths of cut are used and ductile workpiece deformation is produced.) The low thermal conductivity of ceramics means that extreme temperature gradients can arise in high speed deformation processes. Relatively low processing speeds may be required, e.g., low grinding speed, low depth of cut. Further, the low thermal conductivity of ceramic parts will present problems when these parts mate with metallic or other material parts with high thermal conductivity. The chemical stability of ceramics implies that joining processes will be difficult.

These kind of arguments lead to the conclusion that the primary limitations to the production of a ceramic engine are that only relatively small, simple shape parts that require little finishing can be easily produced, Figure 8-7. Small ceramic parts are finding their way into traditional internal combustion engines, e.g., valve guides, turbocharger impellers.

b. To make the small, simple shape parts most of the technical ceramics materials (in contrast to the fine ceramics and glasses) can be used, given that the part will be made. That is, if a ceramic part can be realistically produced in the face of limitations such as those described above, most common ceramics that can be sintered can be used.

c. As discussed in part a above, part design and production processes in which little deformation is needed to produce relatively small, simple shape parts are expected to be successful when manufacturing ceramic parts. This implies net final shape compaction and sintering followed by finishing processes that remove only small amounts of material. The hardness of ceramics also indicates small material removal finishing operations using hard tools, e.g., grinding, lapping polishing.

d. For the manufacture of ceramic parts

- with respect to material properties materials that exhibit as much plastic deformation as possible are desirable. This will lead to being able to process the materials in conventional processes that typically impose significant deformation on the workpiece.
- with respect to processes, processes that do not impose large scale deformation will be useful since they will avoid the fracture associated with deforming brittle materials.

Case Study:

Two-Wheel Dolly Handles

There is considerable variability to this problem, but concerns should address the durability, impact resistance when dropped on the handles, and the ability to withstand high localized stresses (such as at the bolt holes) without cracking or fracture. Since the product may be used on outdoor loading docks in mid-winter, critical properties must be present at low temperatures -- a possible problem for polymeric materials.

A number of alternatives are possible, including such techniques as the injection molding of polymeric material containing chopped fibers, and others. Since the design was made for casting, one might expect incorporation of pattern-removal draft, and a preference for uniform thickness or section size.

CHAPTER 9
Material Selection

Review Questions

1. Exceeding product requirements will usually involve using different materials and possibly different manufacturing processes to produce the product. Changes (higher quality materials and operations to work them) in materials and processes may result in higher costs. Using different materials and processes may also require the acquisition of new knowledge, understanding and experience – the development of new knowledge bases for materials and processes.

2. In a manufacturing environment, the selection and use of engineering materials should be a matter of constant reevaluation. New materials are continually being developed. Others may no longer be available. Prices are subject to change and fluctuation. Concerns regarding environmental pollution, recycling, and worker health and safety impose new constraints. The desire for weight reduction, energy savings, or improved corrosion resistance may require a material change. Increased competition, the demand for improved quality and serviceability, and negative customer feedback may all prompt review and evaluation. Finally, the climate of product liability demands constant concern for engineering materials.

3. Recent shifts in the materials used in automobiles show increased use of lighter weight materials and high-strength steels, as well as plastics and composites. Early automobiles made extensive use of wood, and some early fenders were made of leather .

4. The development, substitution and use of materials in aerospace applications are generally driven by the need for improved strength-to-weight ratio and high temperature resistance. Some of the newer materials used for improved strength with light weight are high strength, light weight metal alloys such as aluminum-lithium alloys, metal-matrix composites, polymer-matrix composites, carbon fiber composites. The refractory superalloys and newer titanium alloys are being used where maintaining strength at high service temperatures in important.

5. There is a distinct interdependence between engineering materials and the processes used to produce the desired shape and properties. A change in materials will often require a change in manufacturing processes; and improvements in processes may lead to a reevaluation of materials.

6. At a very high level of description, engineering design is specifying what material to use and how to distribute it in space to provide a specified function(s). Design should also include manufacturing considerations – how to produce the part or product.

In more detail, design is detailed specification of

- what to produce based on quantitative performance measures,
- the required material and geometric properties,
- the material(s) to use,
- and the related issues of manufacturing process selection.

Design is often specific to a part of the overall product production activity, e.g., part design, process design, manufacturing system design. All of these kinds of activities are related and should be integrated in the product production enterprise.

7. The three usual phases of product design are: conceptual design, functional design and production design. Consideration of material is of almost no concern in the first phase; is of importance in the second phase in that suitable materials must be available and selected; and in the third phase, the exact materials to be used must be related to the production processes and to the tolerances required and the cost.

8. If one does not require that prototype products be manufactured from the same materials that will be used in production and by the same manufacturing techniques, it is possible to produce a perfectly functioning prototype that cannot be manufactured economically in the desired volume or one that is substantially different from what the production units will be like. By using the same material and process, the prototype will provide a true assessment of the performance and manufacturability of the product.

9. New materials should be evaluated very carefully to assure that all of their characteristics are well established. Numerous product failures have resulted from new materials being substituted before their long-term properties were fully known. when changing a process, it is important that the effect of the process on the properties of the material be known and acceptable .

10. The "case-history" approach has several pitfalls. First, minor variations in service requirements may well require different materials or different manufacturing operations. In addition, this approach precludes the use of new technology, new materials, and other manufacturing advances that may have occurred since the formulation of the previous solution.

11. The most frequent problem that arises when seeking to improve an existing product is to lose sight of one of the original design requirements and recommend a change that in some way compromises the total performance of the product.

12. A thorough job of defining needs is the first step in any materials selection, and all factors and possible service conditions should be considered. Many failures and product liability claims have resulted from simple engineering oversights or failure to consider all types of reasonable product use.

13. Dimensioned sketches show the desired end result shape. Since the shape is explicitly specified and the means of producing it are not specified, the specified shape has numerous implications. These implications extend from possible redesign of the part by

making it a combination of simpler shapes to the part shape determining possible manufacturing processes, e.g., prismatic and cylindrical parts will be made using different types of processes, perhaps milling and lathe turning.

Dimensioned sketches probably specify shape, dimensions and perhaps tolerances. Part performance determining characteristics such as required surface finish (surface shape) may not be specified. Surface finish requirements will determine the kind of processes that can produce the required surface and the possible need for more than one process as in turning and then grinding a shaft.

Overall shape also may be inadequate for specifying part characteristics for parts used in assemblies. When parts have to mate with other parts dimensional and geometric (shape) characteristics are important. The natural variations in them when large numbers of parts are being made become important. Part accuracy and precision and the allowable variations in them during manufacture are probably not shown on a dimensioned sketch.

14. Material properties change with temperature and so specifying the required mechanical properties for a design/part/product has to include changes in properties that result from
- the temperature in use,
- variations in temperature as thermal cycling can cause stress cycling if the part is constrained.

Also, the rates of many chemical, physical and mechanical processes vary with temperature. For example, the effective strength of a part changes with corrosion and corrosion rate varies with temperature.

15. The compatibility of a product to its service environment is absolutely necessary for its success. Some considerations should include: highest, lowest, and normal operating temperatures, and the nature of any temperature changes; possible corrosive environments; desired lifetime; and the anticipated level of maintenance or service.

16. In design many manufacturing concerns arise and should be considered as part of the design process, for example,
- part production quantity and required production rate as this affects the type of machine tools that can be used,
- part quality since different manufacturing processes have different capabilities,
- part test and inspection requirements as these are included in most manufacturing operations,
- part mating requirement for assembly,
- part disassembly requirements related to repair, disposal, recycling,
- part section changes since they affect part handling in sequences of processes and in assembly,
- use of standard sizes for part features since this may enable use of standard size tooling,
- material selection criteria that include ease of manufacture, e.g. use of easy to machine, machinable, or easy to form, formable, materials.

17. Although there is a tendency to want to jump to "the answer", it is important that all factors be listed and all service conditions and uses be considered. Many failures and product liability claims have resulted from simple engineering oversights or the designer not anticipating reasonable use for a product or conditions outside of the specific function for which he designed it.

18. All factors have to be considered since each and every one can have an effect on performance and so on the quality of the product. In addition, interactions between design factors, between service conditions and between all design factors and in-use conditions should be considered, e.g., the interactions of stress due to static and dynamic loading and environment of sea-based structures since stress corrosion cracking is an important issue.

19. "Absolute" requirements are those for which no compromise or substitution can be permitted. "Relative" requirements are those which can be compromised to some extent.

20. Handbook-type data is obtained through the use of standardized materials characterization tests. The conditions of these tests may not match with those of the proposed application. Significant variation in factors such as temperature, rates of loading, and surface finish can lead to major changes in material performance. In addition, the handbook values often represent an average, and the actual material properties will vary on either side of that value.

21. While cost is indeed an important consideration, it may be desirable to first demonstrate that the material or materials meet all of the necessary requirements. If more than one candidate emerges, then cost becomes a factor. If only one is satisfactory, then one must determine if its cost is acceptable.

22. Barbell weights should be evaluated on a cost per pound basis. Parts with fixed size, like door knobs should be evaluated on a cost per cubic inch basis. There are numerous other examples.

23. Product failures can provide valuable information. By identifying the cause of the failure, the engineer can determine the necessary changes that would be required to prevent future occurrences. Failures of similar parts in similar applications can provide additional information.

24. In selecting a material, one should consider the possible fabrication processes and the suitability of the various candidate materials to each process. All processes are not compatible with all materials. The goal is to arrive at the best combination of material and manufacturing process for the particular product .

25. In general, decisions about a material or process to be used influence the other. Processing options for materials depend on the material selected. In an extreme case, the specification of a material may result in not being able to process it with available equipment. For example, if a highly temperature resistant material has to be used for a part there is no choice but to obtain the machines and tooling capable of processing the

material or finding a source for part manufacture. The only way rational manufacturing planning can be done is if this is realized at the part design stage.

Conversely, if available manufacturing machines have to be used, only materials that can be processed are feasible options.

Further, if the processes to be used changes material characteristics the extent of the effects on different materials has to be considered in material selection. For example, a residually stressed surface layer is produced in machining. Some metals are more strain hardening than others and so the level of residual stress produced will be different.

Since part or product cost depends on both material and processing costs, specification of a material determines part of the manufacturing cost.

26. Since a wide range of knowledge is needed in all aspects of
- material properties and behavior,
- the capabilities of manufacturing processes,
- and the effects of processing on material structure, properties and performance,

multiple individuals will probably be involved in material and process selection.

27. Material substitution problem example:
The replacement steel automobile body panels with new high strength, low alloy steel resulted in thinner, lighter body panels of essentially the same strength. However, the less corrosion resistant, thinner HSLA steel panels rusted through more quickly.
Initial replacement of cast iron engine blocks with aluminum block resulted in lighter engines but with less damping. Vibration became a problem, subsequently solved.

28. Product liability cases have resulted from a number of reasons, most commonly: failure to know and use the latest information about the material used, failure to foresee and take into account reasonable uses for the product, use of materials about which insufficient data is known, inadequate quality control, and material selection made by unqualified people.

Problems:

1. Based on the chart below, material Y has the highest rating number. However, because it does not have satisfactory weldability and this is an "absolute" requirement, it should not be selected. Material Z should be used.

Material Characteristic
1. Corrosion
2. Weldability
3. Brazability
4. Strength
5. Toughness

6. Stiffness
7. Stability
8. Fatigue
9.As-welded Strength
10. Tensile Strength
11. Cost
R = Material Rating Number

	Go – No Go			**Relative Rating Number**								**R**
	1	2	3	4	5	6	7	8	9	10	11	
X		S				3x1	3x4	2x5		3x4		**37**
Y		U				3x1	5x4	3x5		5x4		**58**
Z		S				3x1	3x4	5x5		2x4		**48**

2. The problem specifies performance and durability as factors to be considered. Chalk trays have few performance requirements and so the Rating Chart is simple. Durability is also not a complex issue. The manufacture of the tray is considered in the next part of the discussion.

With the simple performance and durability concerns it is reasonable to simplify the Rating Chart by making all requirements Go – No Go except for cost. Or, to use weighting factors for all with the probable result that cost will be the overriding factor and then the Rating Chart can be redone as No – No Go except for cost. This Go – No Go versus weighting is somewhat analogous to the distinction of Variable and Attribute testing discussed in Chapter 10.

Material	Go – No Go Screening				Weight	Rating
	Cross section shape	Paintable Finishing	Ease of Cleaning	Can be cut to length, joined	Cost 1 = low 5 = high	
Wood	S	S	S	S	2	
Aluminum	S	*	S	S	2** 4**	
Plastic	S	S	S	S	1	

S = Satisfactory, U = Unsatisfactory,
* limited range of anodized colors and this is reflected in cost
** cost for metallic finish
*** cost for anodized colors

With only the cost criterion distinguishing the choices available funds and subjective appearance and look-and-fell will determine choice.

The “continuous cross section” in the problem statement indicates the same cross section along the tray length. Two issues arise; the cross section shapes that need to be produced and the desirability (production rate and manufacturing cost) of producing parts in a continuous manner.

Wooden trays can be made by machining long pieces of work material in a shaping operation. Cutters can be ground to the desired shape, mounted on the shaper arbor and the long workpieces fed past the cutter. A series of cutting heads or machines will probably be required to sequentially change the initial, perhaps rectangular, cross section to the final cross section shape. Molders are similar machines used to produce wooden moldings. Cutting speeds (speed of the cutting edge through the work material) for wood are high as is the feed speed, the rate at which the workpiece moves past the cutter.

The machining process produces a finished surface that in sophisticated, well run operations may be smooth enough to paint of finish with some other coating. If the surface is not sufficiently smooth subsequent abrasive finishing may be required. In addition to the finished surface shavings or chips are produced. This is a low value by-product even if it is used in other reconstitutes wood products such as flake board. And, the chips may have to be further processed for some products such as oriented strand board.

In contrast to wood that cannot be easily formed, aluminum ductility enables it to be formed in extrusion and rolling processes (Chapter 18), perhaps at elevated temperature. Both processes are continuous in the sense that long sections of product can be formed from standard size and shape feedstock. Since complex, hollow shapes can be extruded, extrusion is a logical choice for chalk tray production. Long sections can be cut to length. Joining sections such as at a corner is not a problem since the tray is not a load bearing structure and so load transference is not needed. Smooth corner joints with the sections simply butted up against each other is a adequate.

Long shaped sheet metal parts can be continuously produced in roll forming, Chapter 19. Depending on the cross section shape required and the tray section thickness roll forming may be feasible. Qualitatively, thick sheet deformed to a tight bend radius will fracture on the outside of the bend and wrinkle on the inside surface of the bend. Steel rain gutters are roll formed (usually on-site) since the initial sheet workpiece is thin.

High forces are needed to extrude aluminum through a complex geometry die and so strong, stiff machines and tooling is required. If plastic trays will suffice they can be produced from potential less expensive plastic in a less complicated plastic extrusion machine, Chapter 20. Plastic rain gutters are extruded.

3. This is considered in the Case Study in Chapter 3

4. The explanation given for the better performance of newer turbine blades is in terms of typical polycrystalline cast material versus single crystal turbine blades. So, the materials used must have adequate high-temperature, high-stress properties and behavior. The material-manufacturing process pair must be capable of producing large single crystal products.

At the time of preparation of this solutions manual
a search for jet & engine & turbine & blade & casting produced

www.cmse.ed.ac.uk/AdvMat45/SuperEng.pdf that presents overviews of
- the pressure, temperature operating environment in jet engines,
- the failure modes of engine components,
- jet engine design,
- material strengths as a function of temperature

leading to the development of Ni-based superalloys up to the current alloys and their characteristics. Explanation of mechanical behavior in terms of composition and microstructure are presented.

Microstructures are shown – equiaxed crystal structure, directionally solidifies, single crystal. The advantages and use of coatings is covered.

The production of single crystal blades by using a "spiral selector" that allows the nucleation and growth if only one crystal is illustrated.

www.msm.cam.ac.uk/phase-trans/2001/slides.IB/photo.html provides an explanation of creep behavior in terms of the grain boundaries in a metal part and shows photographs of turbine blades with the same composition but produced by
- casting,
- directional solidification,
- directionally solidified using a spiral mold section that allows production of a single crystal blade.

The general conclusions that can be drawn are that
- the inherent strength of material is determined by their composition and structure,
- high strength materials have been designed and developed using fundamental engineering science knowledge about composition and composition-structure relations,
- in product design the in-use conditions have to be considered when specifying required strength of materials,
- in-use conditions may lead to various failure mechanisms,

--- in jet engines, high temperature results in lowering material strength and also creep and corrosion arising as important types of failure.

More specifically,
- loading applied at elevated temperatures makes material strength and deformation behavior more dependent on grain boundary behavior (strength decreases, creep and corrosion),
- one way to increase material high temperature performance is to produce alloys and microstructures that limit grain boundary effects such as diffusion along grain boundaries and grain boundary sliding,
- another way to limit grain boundary effects is to control the size of grains and the orientation of the boundaries - directional solidification,

- another possibility is to eliminate grain boundaries, - single crystals.

In order to produce desired product behavior by using engineered materials (composition and structure), special, new manufacturing processes may have to be developed. In the case of single crystal jet engine turbine blades a process was developed in which
- the fundamental concept is to make only one crystal available for growth,
- and to set crystal growth conditions so that growth of one crystal occurs without the nucleation of other crystals.

One example of a process to do this is shown.

An example of Nondestructive Evaluation (X-ray) is shown at
www.sv.vt.edu/xray_ct.html

Case Study:

Material Selection

This is an open-ended and extremely variable problem that is designed to get the student to question why parts are made from a particular material and how they could be fabricated to their final shape. In addition, they are asked to consider the need for property modification via heat treatment and/or surface treatment, and should begin to recognize the need to properly integrate these operations in the manufacturing sequence. The specific answers received will depend not only upon the specific product or products chosen but also upon the background and perception of the student.

CHAPTER 10
Measurement and Inspection

Review Questions

1.In order for parts to be interchangeable, they must be manufactured to the same standards of measurement. Simply put, everybody's definition of an inch or a centimeter must be the same identical measurement. In addition, certain sizes and shapes (like threads on a shaft or teeth on a thread) are standardized. Thus, all spark plugs for automobile engines have a standard diameter size and thread shape to fit into everyone's sockets. Standardization is fundamental to interchangeability and interchangeability is fundamental to repetitive part manufacture and mass production.

2. The least expensive time to make a change in the design is before the part is being made. Putting the manufacturing engineering requirements into the design phase helps insure that the part can be economically fabricated.

3. Attributes inspection trys to determine if the part is good or bad. Variables inspection requires a measurement be made to determine how good or how bad and thus, more information about part quality is obtained. If your car has an oil pressure gage, you always know what the oil pressure is (variables), but if it only has a warning light, you only know whether the pressure is good (no light) or bad (light comes on).

4. Warning lights (usually red) readily alert the driver to a bad situation, whereas the driver may completely ignore a low gage reading. The driver may not even know what a bad reading is or that a dangerous condition exists, or worse, what the gage is actually informing him or her about. Most cars today have both kinds of inspection devices to keep the driver informed. Sometimes the decision to change is based on economics as attributes gages are usually less expensive than variables types.

5. The four basic measures are: length, time, mass, and temperature .

6. Referring to Figure 10-1, the Pascal is a measure of pressure in SI units. Pressure is the force per unit area and its dimensions are newtons per square meter (N/ m^2) in SI units or psi in English units. This unit is named after Blaise Pascal (1623-1662), a French mathematician and scientist who developed the following principal - a pressure applied in any portion of the surface of a confined fluid is transmitted undiminished to all points within the fluid - Pascal's principal.

7. The grades of gage blocks are laboratory, precision, and working - in decreasing level of accuracy. The blocks come in sets so that they can be "wrung" together into any length needed from 0.1001 to over 25 inches in increments of 0.0001 inch.

8. The surface tension of an ultrathin film of oil between the very smooth, flat, block faces keeps the blocks locked together. Because they are so smooth and in such intimate contact, they can actually weld together via diffusion if left in contact for prolonged periods of time.

9. The allowance determines the desired basic fit between mating parts. Tolerance takes into account deviations from a desired dimension and fit, and are necessary in order to make manufacturing practicable and economical .

10. (a) Sliding fit would be too loose and wring fit, too tight - therefore, snug fit, hand assembled. (b) Obviously, a sliding fit as the speed is very low. (c) Free fit with liberal allowance as speeds are high and so are pressures.

11.

Hole Basis	Shaft Basis	Fit Description	Example
H11/c11	C11/h11	Loose-running	door hinges
H9/d9	D9/h9	Free-running	pulley held on shaft by set screw
H8/f7	F8/h7	Close-running	keyed gear on shaft
H7/g6	G7/h6	Sliding	folding knife pivot
H7/h6	H7/h6	Locational-clearance	flat electrical cable connectors
H7/k6	K7/h6	Locational-transition	tapered shank drill – lathe tailstock
H7/n6	N7/h6	Locational-transition	locating pins between cylinder and crankcase on single cylinder engines
H7/p6	P7/h6	Locational-interference	ball bearing inner race on shaft
H7/s6	S7/h6	Medium-drive	cast iron drive gear on shaft
H7/u6	U7/h6	Force	steel drive gear on shaft

12. A shrink fit is permanent, but can be disassembled by proper heating and/or cooling of the members. The word shrink implies that one element is heated (to expand it) and the other is cooled (to shrink it). Then the elements are joined to form a shrink fit. A weld is absolutely permanent -- cannot be disassembled without ruining the parts.

13. To determine the aim of a process, one needs measures of accuracy. To determine

the variability in a process, one needs measures of precision. Accuracy is measured by distribution means and precision is measured by variances or standard deviations (square roots of variances) . A process capability study is usually performed by taking samples of the output from the process and measuring them for the desired characteristic.

14. Interferometry is an example of an optical inspection.

15. The factors should include the rule-of-ten, linearity, repeat accuracy, stability, resolution and magnification, the type of device, the kind of information desired (attributes or variables), the size of the items to be measured, the rate at which they must be measured, and the economics of buying, installing, and using the device.

16. Determining repeat accuracy is easy. Just step on the scale and step of f numerous times and take readings. Determining linearity requires that you have a set of standard weights which you can load on and off -- say 10, 50, 90, 130 etc. pounds -- and plot linear loads versus readings. Generally, scales and other measuring devices are nonlinear at the ends of the scale and linear in the central area.

17. Variable with student. The experiment should show that magnification amplifies the measurement while resolution refers to the limit of detection.

18. Magnification of the output of a measuring device beyond the limits of its resolving capability is of no value. Magnification of a photographic negative beyond the size of the silver halide grains results in grainy photographs. Every measuring device has a limit to its resolving capability. All the magnification in the world will not change that limit.

19. Parallax is the apparent change in the position of an object when it is viewed from a different direction, i.e. the position from which the object is viewed has an effect on the apparent position of the object. Tennis linesmen want to maintain their position so that the apparent position of the ball does not change due to the linesman moving his/her position. The linesman looks right down the line and tries not to move his/her head. A spectator with a different viewing angle than the line judge will see an apparently different ball position.

20. The measuring instrument should be an order of magnitude (10 times) more precise than the object being measured. This rule actually refers to the gage capability. Gage capability is determined by gage R&R studies. See <u>Statistical Quality Design and Control</u> by Devor, et al.

21. The 25 divisions of the moveable vernier plate are equal in length to the 24 divisions on the main scale. Thus each division on the vernier equals 1/25 of .6 or .024 inches. Each division on the main scale is equal to 1/24 of an inch or .6 or 0.025 inches. Thus each division on the vernier is 0.025 - 0.024 = 0.001 inches less than each division on the main scale.

22. The micrometer is sensitive to the closing pressure and the lack of pressure control. Errors in analogue devices are also made by misreading the barrel by a factor of 0.025.

23. They are both about the same order of magnitude in terms of their precision and repeatability, but the micrometer has a limited size range and, thus, must be purchased in sets (quite expensive), whereas a vernier can measure a wide range of sizes with one device. The micrometer is more rugged and better suited for the industrial setting (shop floor). It is also less sensitive to dirt and it is easier to teach someone how to read it.

24. The device tends to lift itself off the surface if too much torque is applied.

25. The equation for thermal expansion is
$\Delta l = \alpha\, \Delta T$
where Δl is the change in length for a given change in temperature ΔT and α is the coefficient of thermal expansion ($11 \times 10^{-6}/^{0}C$)
and 1 is the length of the bar (2 feet). 20 $^{0}F = 6.67^{0}C$ and 2 ft = 24 inches.
Therefore:

$$\Delta l = 11 \times 10^{-6} \times 24 \times 6.67 = 0.017768 \text{ in.}$$

which is well within the measuring capability of a supermicrometer. However, don't forget that the supermicrometer will also expand (or contract) with this temperature change, so if you tried this experiment, you would not get this reading unless only the steel bar expanded, not the supermicrometer itself. You can detect a change in length of a bar with a supermicrometer simply due to heating with your hands.

26. Optical means are used so that nothing touches and thus distorts a delicate part.

27. Parts can be measured directly using the micrometer dials or compared with a profile or template drawn directly on the screen. The images on the screen can also be directly measured by a ruler and these dimensions then divided by the magnification being used -- usually 10 to 20X. The projector magnification should be checked, however, when this technique is used by projecting a known standard onto the screen.

28. Because of the large distance and the accuracy and precision needed, a laser interferometer would probably be most suitable.

29. The laser scanner is more precise and likely to be faster with less image processing.

30. The CMM is a mechanical device with precise X - Y - Z movements for precision 3D measurements. Usually a probe is used to touch the surfaces of parts being measured and the dimensions are read on digital displays and computer terminals.

31. The principle of the sine (definition of sine) is that the sine of an angle in a right triangle is the ratio of the length of the side of the triangle opposite the angle to the length of the triangle hypotenuse.

32. The not-go member is usually made shorter than the go member because it undergoes less wear.

33. In using a dial gage, one must be sure that the axis of the spindle is parallel with the dimension being measured. Dial indicators also suffer from friction in the gears, so multiple readings are highly recommended.

34. The gage is designed so that if it errors, it will reject a good part rather than accept a bad part. The gage has a tolerance added for manufacturing and a tolerance added for wear.

35. The go ring should slip over the shaft. If it does not, the shaft is too large. The not-go ring should not slip over the shaft. If it does, the shaft is too small.

36. Air gages will detect both linear size deviation and out-of-round conditions of holes. They are fast and there is virtually no wear on the gage or part.

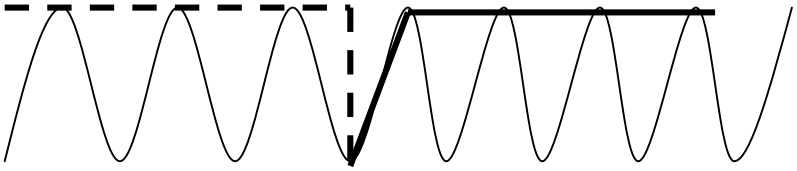
37. Monochromatic light waves will interfere with each other (producing light and dark bands) if they get out of phase. Thus, a dark band indicates that the two beams have cancelled each other out. Light from a single source can be shifted out of phase by having it travel different distances.

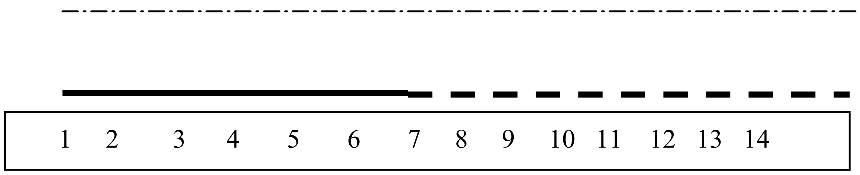
38. An optical flat is made from glass or quartz, is transparent, and the two faces are flat and parallel to a high degree of accuracy. A toolmaker's flat is made of steel, with the two faces very flat, but they do not have to be exactly parallel .

39. The microinch roughness, either arithmetic average roughness or root mean square roughness, is a single number that describes an extended line. So, different profile patterns can have the same average height value just as different populations of measurements can have the same average value.

For example, consider the three surface profiles shown (wavy, dashed line, solid line) which each have the same maximum height of roughness = 1 unit, the same number of height measurements = 14 and the height measurements made at the maximum height points of the wavy profile and labeled 1-14.

The reference line for calculation of R_a is at the mid-height of the profiles = ½ and so the 14 height measurements are all = ½.





The R_a value for all the profiles is $R_a = (14)(1/2) / 14 = ½$

40. Because identical roughness values can be very different in appearance, surface-finish blocks enable a designer to better relate a desired surface, obtained by a specific process, to the measured value that must be specified.

41. The spherical radius of the tip of a diamond stylus limits the resolution. Suppose you have a smooth plate with small holes on it. In your hand you have a needle and are trying to locate the holes. Let's assume the holes are square, round, and triangular in shape. The needle will allow you to detect the location of the holes, but not identify their shape when the holes are about the same size as the tip of the needle or smaller. Thus, there is a big difference between being able to detect the presence of a flaw and being able to resolve its geometry .

42. As the surface finish improves (surface gets smoother and AA or rms values get smaller), the tolerance generally improves
--gets smaller. Improving the surface finish and tolerance usually means identifying better, more precise processes, so the cost goes up accordingly. The exception is finishing processes which are used to improve the surface finish without strong regard to the tolerance.

43. Devices that use light scattering correlated to surface roughness lose their validity when surface roughness gets much above 40 - 50 mm. AA.

Problems:

1. Reading 1.436 in.

Inches are numbered in sequence over the full range of the bar. Every fourth graduation between the inch lines is numbered and equals one-tenth of an inch or 0.100". Each bar graduation is one twenty-fifth of an inch or 0.025".

The vernier plate is graduated in 25 parts, each representing 0.001". Every fifth line is numbered - 5, 10, 15, 20, 25 - for easy counting.

To read the gage, first count how many inches, tenths (0.100") and twenty-fifths (0.025") lie between the zero line on the bar and the zero line on the vernier plate and add them.

Then count the number of graduations on the vernier plate from its zero line to the line that coincides with a line on the bar.

Multiply the number of vernier plate graduations you counted times 0.001" and add this figure to the number of inches, tenths and twenty-fifths you counted on the bar. This is your total reading. The vernier plate zero line is the one inch (1.000") plus four tenths (0.400") plus one twenty-fifth (0.025") beyond the zero line on the bar, or 1.425". The 11th graduation on the vernier plate coincides with a line on the bar (as indicated by stars). 11 x .001" (.011") is therefore added to the 1.425 bar reading, and the total reading is 1.436".

2. Reading 41.68 mm

Each bar graduation is 0.5 mm. Every twentieth graduation is numbered in sequence - 10 mm, 20 mm, 30 mm, 40 mm, etc. - over the full range of the bar. This provides for direct reading in millimeters .

The vernier plate is graduated in 25 parts, each representing
0.02 mm. Every fifth line is numbered in sequence -0.10 mm,
0.20 mm, 0.30 mm, 0.40 mm, 0.50 mm - providing for direct reading
in hundredths of a millimeter.

To read the gage, first count how many mm lie between the zero line on the bar and the zero line on the vernier plate.

Then find the graduation on the vernier plate that coincides with a line on the bar and note its value in hundredths of a mm.

Add the vernier plate reading in hundredths of a mm to the number of mm you counted on the bar. This is your total reading. The vernier plate zero line is 41.5 mm beyond the zero line on the bar, and the 0.18 mm graduation on the vernier plate coincides with a line on the bar (as indicated by stars.) 0.18 is therefore added to the 41.5 mm bar reading, and the total reading is 41.68 mm.

3.

41.68 mm = 1.6409 inches
1.6409 - 1.436 = 0.2049 inches

4. Same as in 8th edition

$\sin \theta = 3.250 / 5.000 = 0.65$
$\theta = 40.54$ degrees

5. The error due to the gage blocks will be covered up by the dial indicator error

+0.000,008 or -0.000,004 for gage blocks versus
+0.001 or -0.001 for dial indicator

The error will be 3.249 to 3.251 due to leveling of the part with the dial gage.
= 40.53 to 40.55
Error ~.02 degrees, due to dial indicator not the gage blocks.

6. A 0.359 B 0.242 C 0.376

7. A 0.2991 B 0.3001

8. Metric vernier micrometers are used like those graduated in hundredths of a millimeter (0.01 mm), except that an additional reading in two-hundredths of a millimeter (0.002 mm) is obtained from a vernier scale on the sleeve.

The vernier consists of five divisions each of which equals one fifth of a thimble division - 1/5 of 0.01 mm or 0.002 mm.

To read the micrometer, obtain a reading to 0.01 mm. Then see which line on the vernier coincides with a line on the thimble. If it is the line marked 2, add 0.002 mm; if it is the line marked 4, add 0.004 mm, etc.

The left side micrometer reads 5.500 mm

The 5 mm sleeve graduation is visible 5.000 mm

The 0.5mm line on the sleeve is visible.	0.500 mm
Line 0 on the thimble coincides with the reading line on the sleeve	0.000 mm
The 0 line on the vernier coincide with lines on the thimble.........	<u>0.000 mm</u>
The micrometer reading is	5.500 mm

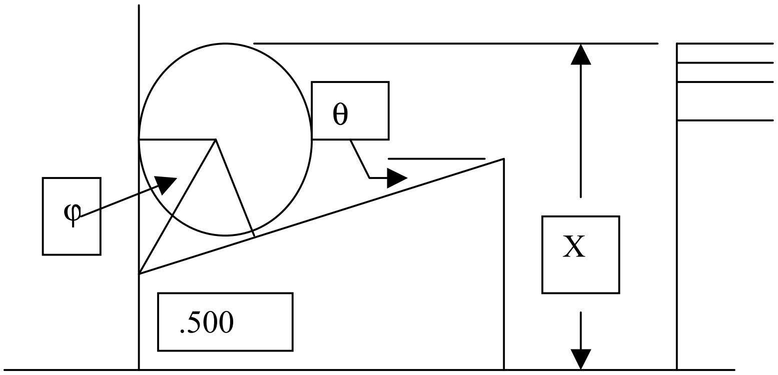
The right side micrometer reads 5.508 mm

The 5 mm sleeve graduation is visible 5.000 mm The 0.5mm lines on the sleeve is visible. . . . . 0.500 mm
Line 0 on the thimble lies below the reading line on the sleeve, indicating that a vernier reading must be added.

Line 8 on the vernier coincides with a line on the thimble............ <u>0.008 mm</u>.
The micrometer reading is.......... 5.508 mm

9. Height difference = 5 x 0.000,001,6 x 2 = 0.000,116 inches.

10. The probe is used to find the stack of gage blocks that exactly matches the height of the ball sitting on the part.



The angle θ is 17.354 degrees, from

$\tan\theta = (1.125 - 0.800) / 2.000 = 0.3125$

X = height of gage blocks = $0.500 + d + r$

$X = 0.500 + .5 \cot\varphi + 0.500$

$\cot\varphi = X - 0.500 - 0.500 / 0.500$

$90^o = 2\varphi + \theta$

$\varphi = (90^o - \theta) / 2 = 36.3^o$

$X = 1.68$

11. The lower vernier reading is the inch scale and

0 on vernier is less than 1 on beam and past the 4 on beam => .4 inch
0 on vernier is 3 divisions past 4 on beam => (3/4)(.100 in) = 0.075 inch
vernier and beam graduations are given as lining up at 14 on vernier =>0.014 inch
Reading = .400 + .075 + .014 = 0.489 inch

For the top, metric, scale

0 on vernier indicates 12 mm
vernier and beam graduations are said to line up at 0.38 mm (0.41-0.42 may look better) => 0.38 mm
Reading = 12 + .38 = 12.38 mm

Case Study:

Machining Accuracy Over the Last Century

1. There are fundamentally different machining processes. For example large chip producing machining processes such as milling, grinding and lapping are all considered machining processes.

To estimate a limit in machining precision there are at least two approaches that can be followed. One is to extrapolate the data shown in the chart. Extrapolation is always dangerous and the issue is how far to extrapolate data.

Considering the “Precision machining” line on the chart the 1990 precision is about 0.3 μm = 12 μin. If this line is extended for 20 years a precision of about 0.07 is forecast. With the long extrapolation this value may be a reasonable limit.

2. Nanoprocessing is working with material either to produce nanometer scale features or working with material bodies that are nanometer size. Current computer hard disk substrates (before the magnetic and protective layers are applied) have surface roughness at the few nanometer level.

3. Industrial precision depends on the industry. Computer chip and disk drive industries routinely work at nanometer and less precision.

4. Without knowing the measurements made, a reasonable guess is that the vertical axis should be label “precision.”

5. Most of the processing of materials at the nanometer level is concerned with producing nanometer level individual particles. These are formed in processes ranging from chemical synthesis to combustion.

CHAPTER 11
Nondestructive Inspection and Testing

Review Questions

1. Destructive testing has to be done on a statistical basis for two general reasons.
i. Since testing involves making the part tested not useful, not all parts can be tested. (In reality, unless absolutely necessary testing of all parts is undesirable even if the testing is not destructive.) So, in order to obtain information about the entire population of parts from a subset of tested, and no longer useful, parts statistical techniques are needed.
ii. Often the behavior of interest in part testing is due to characteristics specific to a particular part, e.g., a flaw that exceeds a certain size and so serves as a fatigue failure initiation site. In such cases and even with nondestructive testing a number of tests are again required to obtain information about a large number of parts from a tested sample of parts.

2. In a proof test, a product is subjected to loads of a determined magnitude, generally equal to or greater than the designed capacity. If the part remains intact, then there is reason to believe that it will perform adequately in the absence of abuse or loads in excess of its rated level.

3. Hardness tests can be used to provide reasonable assurance that the proper material and heat treatment were employed in a given part. The tests can be performed quickly, possibly on every product, and the associated mark can easily be concealed or removed .

4. Nondestructive testing is the examination of a product in a manner that will not render it useless for future service. The testing can be performed directly on production items or even parts in service. The entire production lot can be inspected, different tests can be applied to the same item, and the same test can be repeated on the same specimen if desired. Little or no specimen preparation is required and the equipment is often portable.

5. Some possible objectives of nondestructive testing include: the detection of internal or surface flaws, the measurement of dimensions, the determination of a material's structure or chemistry, or the evaluation of a material's mechanical or physical properties.

6. When selecting a nondestructive testing method, one should consider the advantages and limitations of the various techniques. Some can be performed on only certain types of materials. Each is limited in the type, size, and orientation of the flaws that it can detect. Various degrees of accessibility may be required and there may be geometric restrictions as to part size or complexity. Availability of equipment, the cost of operation, the need for a skilled operator, and the availability of a permanent record are other considerations.

7. By ensuring product reliability and customer satisfaction, nondestructive testing can actually be an asset, expanding sales and profitability. In addition, it can be used to assist product development and process control, further reducing costs.

8. Visual inspection should be a primary means of inspection because,
- it is very discerning, especially with training and experience,
- the brain is a powerful tool for interpreting images,
- aids for optical inspection are readily available, e.g., magnifying instruments and cameras,
- quantitative image analysis techniques and tools are available,
- surfaces are often important regions in determining quality and performance of manufactured parts.

9. Visual inspections are limited to the accessible surfaces of a product, so no information is provided relating to the interior structure or soundness.

10. Liquid penetrant testing can be used to detect any type of open surface defect in metals and other nonporous materials. Cracks, laps, seams, lack of bonding, pinholes, gouges, and tool marks can all be detected.

11. Materials must be ferromagnetic in order to be examined by the magnetic particle technique. Nonferrous metals, ceramics and polymers cannot be inspected .

12. The relative orientation of a flaw and magnetic field is quite important in determining whether the flaw will be detected, since the flaw must produce a significant disturbance to the magnetic field. If a steel bar is placed inside an energized coil, a magnetic field is produced that aligns with the axis of the bar. Defects perpendicular to this axis can be easily revealed, but a flaw parallel to the axis could go relatively unnoticed. By passing a current through the bar, a circumferential magnetic field is produced that will detect axial flaws, but not those in a radial orientation.

13. Testing where one listens for the characteristic "ring" to a product, is limited to the detection of large defects because the wavelength of audible sound is rather large compared to the size of most defects.

14. The coupling medium in ultrasonic inspection is used to improve the transmission of energy, ultrasonic vibrations, into and out of the test piece. The coupling medium couples the transducer and test piece and test piece and received with respect to the incident and transmitted or reflected ultrasonic signals.

15. Three types of ultrasonic inspections are: (1) pulse-echo, where inspection is made from one side or surface; (2) through-transmission, where the sending and receiving transducers are on opposite sides of the piece, and (3) resonance testing, where thickness can be determined from a single side.

16. X-rays, gamma rays and neutron beams can all be used to provide radiographic

inspection of manufactured products .

17. A penetrameter is a standard test piece that provided a reference for the image densities on a radiograph. Penetrameters are made of the same or similar material as the specimen and contain structural features of known dimensions. The image of the penetrameter then permits direct comparison with the features in the image of the product.

18. The limitations of radiographic inspection techniques have to do with incident radiation being scattered by part characteristics other than those of interest and with high cost.

With regard to part characteristics, incident radiation is scattered in all directions due to the material itself and so contrast between characteristics of interest and the overall material background is lost. This may require image enhancement to make the images useful.

19. Since the materials examined by eddy-current inspection must be good electrical conductors, it is unlikely that the technique would be useful to examine ceramic or polymeric materials.

20. Eddy current testing uses the change in magnetic permeability and electrical conductivity as the basis for producing a measurable output and so any part characteristic that depends on these quantities can be identified. Eddy current testing can be used to detect surface and near surface flaws, differences in metal chemical composition and heat treatment , hardness, case hardness depth and residual stress. Other testing techniques can be used to measure these characteristics individually, eddy current testing can be used to measure all of them.

21. Acoustic emission is not a means of detecting an existing, but static defect in a product, but a means of detecting a dynamic change, such as the formation or growth of a crack or defect or the onset of plastic deformation. The sound waves emitted during this dynamic event are detected and interpreted.

22. By using multiple sensors and timing techniques similar to those used to locate earthquakes, acoustic emission can be used to physically locate the flaw or defect emitting the sound.

23. Various thermal methods can be used to reveal the presence of defects. Parts can be heated and means used to detect abnormal temperature distributions, indicative of faults or flaws. The presence of "hot spots" on an operating component can be an indication of defects. Thermal anomalies can also provide an indication of poor bonding in composite materials.

24. Evaluations of resistivity from one sample to another can be used for alloy identification, flaw detection, or the assurance of proper processing - such as heat

treatment, the amount of cold work, weld integrity, or the depth of case hardening .

25. Computed tomography provided a cross-sectional view of the object along the axis of inspection. By multiple scanning, full 3-dimensional representations of the interior of a product can be generated .

26. Since surface regions of materials often serve as initiation sites for failure, e.g., the high stress, irregular surface profile regions of machined shafts, surface region characterization is important. Chemical composition of surface layers can be important in determining part performance since it affects part structure and properties.

Some surface region chemical composition characterization techniques are Auger electron spectroscopy (AES), energy-dispersive X-ray analysis (EDX), electron spectroscopy for chemical analysis (ESCA), and secondary-ion mass spectroscoopy (SIMS).

27. The basis of inspection was once the rejection of any product shown to contain a flaw or defect. With the rapid advances in inspection capability, it is now possible to detect "defects" in almost every product, including those that perform adequately. The basis of discrimination should be the separation of products with critical flaws that could lead to failure, from products where the flaws will remain dormant throughout the lifetime of the product, i.e. allowable flaws.

Problems:

1. X-ray radiography is a poor means of detecting cracks in a product, for the crack or void size must be sufficiently large as to produce a difference in transmitted intensity. Only if the orientation of a crack were parallel to the X-ray beam would there likely be sufficient differences to detect the flaw. Otherwise, the X-ray would indicate a given and constant thickness of material and reveal none of the existing cracks.

Crack detection would be better performed by ultrasonic inspection, penetrant testing, and magnetic particle inspection. These have limitations as to the location, depth and orientation, but are generally superior for detecting cracks than X-ray radiography .

For a permanent record, the electronic signals received at the transducers in ultrasonic inspection, and displayed on some form of screen, can also be recorded on magnetic tape or some other form of storage medium. The surfaces of parts examined by penetrant inspection or magnetic particle techniques can be photographed or recorded on some form of video recorder.

2. A major limitation to each of the following is:

- Visual inspection: Depends upon the skill of an inspector and is limited to surface flaws.

- Liquid penetrant inspection: Can only detect flaws that are open to the surface.
- Magnetic particle inspection: Orientation of the flaw and field affects sensitivity, limited to ferromagnetic materials, detects only surface and near-surface flaws.
- Ultrasonic inspection: Difficult to use with complex shape parts, trained technicians are required, and the area of inspection is small.
- Radiography: Costly, must observe radiation precautions, defects must be larger than a minimum size, must generally process film to get results.
- Eddy current testing: Reference standards are needed for comparison and trained operators are required, materials must be conductive, depth is limited.
- Acoustic emission monitoring: Only growing flaws can be detected, experience is required, and there is no indication of the size or shape of the defect.

3. Consideration of various inspection techniques means will they work, in contract to selecting the best measurement scheme.

Techniques for detection of surface flaw and internal flaws can be separated based on the penetration of the probe into the material. This will depend on the king of probe used and the transparency of the material to it.

a. The most obvious properties of ceramics that will affect choice of measurement technique are low electrical conductivity and absence of ferromagnetism. Some ceramics are transparent to light but overall most structural ceramics are not optically transparent.

b. Polymers are also poor electrical conductors, nonmagnetic and have low density. Different polymers are transparent and opaque.

c. Fiber composite regions that might be of interest are the fibers, the matrix and the fiber-matrix interface. The usefulness of the means of inspection will depend on the region of interest.

The general purpose nondestructive inspection methods (e.g., not leak testing) described in the chapter can be screened using the general Go – No Go concept used in Chapter 9 for materials screening.

Surface Flaws				
	Ceramics	Polymers	Composites polymer matrix	Composites metal matrix
Visual	yes	yes	yes	yes
Liquid Penetrant	yes	yes	yes	yes
Magnetic Particle	no	no	no	probably

Ultrasonic*	yes	yes	yes	yes
Radiography	no	no	no	no
Eddy Current	no	no	no	yes
Acoustic Emission	no – AE are produced by deformation processes and while ongoing deformation depends on existing flaw state to some extent, use of AE seems not feasible			
Thermal Methods	yes – but relatively low high heat capacity and low thermal conductivity of polymers makes thermal methods less useful			
Strain Sensing	yes	yes	yes	yes
Electrical Resistivity	no	no for typical polymers, with conductive polymers a very special case		yes
Surface Topography	yes	yes	yes	yes

* using surface waves,

Subsurface Flaws				
	Ceramics	Polymers	Composites polymer matrix	Composites metal matrix
Visual	no except for transparent materials			
Liquid Penetrant	yes for near surface flaws			
Magnetic Particle	near surface	no	no	near surface
Ultrasonic*	yes			
Radiography	yes, effectiveness depends on material density			
Eddy Current	no	no	no	near surface
Acoustic Emission	no – AE are produced by deformation processes and while ongoing deformation depends on existing flaw state to some extent, use of AE seems not feasible			
Thermal Methods	near surface			
Strain Sensing	no unless accurate mechanical models available for relating measured surface strains to internal stress fields that depend on flaws			
Electrical Resistivity	no	no	no	near surface
Surface Topography	no			

* through transmitted mode

4. High density powder metallurgy parts can be treated as conventional parts from the viewpoint of both inspection and secondary processing. As the density decreases (i.e. the volume fraction of voids increases), the material is less capable of transmitting sound, current, and magnetic field -- the essence of the various probing techniques. Moreover, the voids are actually "defects" and are often detected. when the numbers become great,

the signals become quite garbled, and the presence of additional, more-significant, defects may be difficult, or impossible.

5.Quality control is covered in Chapter 12, Total Quality Control in Section 12.4. The question posed in the problem can be addresses in general terms without recourse to the details provided in Chapter 12.

The facile answer is - just as 100% inspection has an error rate so too do the processes used in total quality control and so it is not clear which is superior. The more complete answer is that if the combination of processes in total quality control systems reduces the defect rate to a lower level than in 100% inspection a superior system exists. In essence, the whole (total quality control) performing better than the sum of its parts, or perhaps better than any particular part (inspection).

A more detailed, quantitative answer can be developed using the concepts presented in Chapter 12 and actual inspection and quality control system data.

6. When both sides of the part are accessible easy-to-use, accurate, inexpensive mechanical measuring instruments can be used – rules, rules and calipers, vernier and micrometer calipers and even dial indicators, depth gages and height gages can be used. Large enough flat surface areas have to be accessible.

Optical instruments such as microscopes, optical comparators and vision systems can be used if edge-on views are practical.

Even though designed for more complicated measuring tasks, coordinate measuring machines can be used to measure part thickness if the two sides are accessible.

In general, when both sides of the part are accessible to mechanical or optical instruments and the part shape is compatible with the size of the probe (the micrometer anvil size for example) many, simple measurement techniques are available.

When only one side of the part is accessible suitable thickness measurement instruments are more limited. The pulse-echo technique described in the problem is a possibility as is the resonance testing method described on page 238.

The theoretical “ability to measure from only one side” is usually not the actual case. The part will probably be resting on a surface and so thickness measurements using various physical phenomena can be envisioned, although they may be impractical due to cost, safety or other concerns. Electrical resistance between the support surface and a electrode on the accessible part surface can be used to measure thickness. A heat source applied to the part surface and temperature measurements at the part surface and support surface along with thermal conductivity data could be used to measure thickness. Similarly, measuring the heat flux needed to maintain a constant temperature difference could be used to deduce thickness.

7. The expression given in Problem 7 can be used

$$t = 2d / V$$

$$d = 2\ (\ 0.003\ \text{m}\ )\ /\ 5000\ \text{m/s} = 1.2\ \mu\text{s}$$

8. Wavelength $=\lambda = V / f$

For parts a. Ultrasonic waves, and c. Acoustic emissions, the relevant velocity of propagation is the speed of sound in the material.

For part b. X-rays, the frequency and speed of the X-ray through the material are needed.

The propagation speed of electromagnetic radiation through free space is 3E8 m/s. Typical X-ray frequencies are $10^{17} - 10^{20}$ Hz as given in most references, e.g., an encyclopedia.

Using f = 10^{17} Hz gives $\lambda =$ 3E8 m/s / 1E17 /s = 3E-9 m = 3 nm as a first approximation for X-rays traveling through a material or electromagnetic field that does not appreciably change the propagation speed, i.e., materials that are transparent to X-rays..

The speed of sound in steel is about 5000 m/s and using this value since it is given in Problem 7 and ZZZ for the speed of X-rays through steel

a. $\lambda =$ 5000 m/s / 500000 /s = 0.01 m

b. $\lambda =$ 3 nm

c. $\lambda =$ 5000 m/s / 10^6 /s = 0.005 m

Case Study:

Portable Failure Analysis Kit

1). The primary purpose of the requested kit is to collect information and specimens for examination back at the laboratory. It would be inappropriate for the investigator to try to perform laboratory-type examination in the field, especially if these could be better or more accurately performed in the lab. NOTE:
On rare occasions, the mere size of the piece in question (such as a bridge) or the desire for immediate results renders such testing desirable, but such is not usually the case. Therefore, a proposed kit would contain:

a) .Equipment for gathering information, such as the observations and opinions of operating personnel, supervisors, observers, etc. This would include: a notebook, pens and pencils, and a small portable tape recorder (with tapes) .

b). Photographic equipment to record the failure site, the locational relationship of failed components, the stages and sequence of disassembly, and/or the location and orientation of samples removed from the failure or the failure site. A Polaroid camera with color film would assure the access of acceptable photos. A close-up lens and flash attachment would be desirable, as would an ample supply of film (a type that provides a negative would be preferred) and spare batteries for the camera. A ruler or other well known object can be included in photos to reveal the relative size of components.

c) . A variety of hand-operated tools to assist in the removal of components and the collection of laboratory specimens. This might include: A hacksaw and blades, hammer, pliers, screwdrivers, knife, wrenches (socket and straight), clamps, chisels, scissors, tweezers .

d). Examination aids, such as: a flashlight with spare batteries, magnifying glass or jeweler's eyepiece (lOX), low-power binocular microscope, small handheld and dental mirror.

e) . Measuring devices, such as a ruler, measuring tape, micrometer, and vernier.

f) . Marking devices to label specimens and denote in photos the locations of cuts or the orientation of the pieces: magic markers, chalk, grease pencils, and pens.

g). Equipment to perform several basic tests:

- A portable dye penetrant testing kit to reveal the presence of cracks.
- A set of triangular metal files can be tempered in the laboratory to various hardnesses to provide an inexpensive means of getting "ballpark" hardness in the field.

h) . A portable drill with attachments can be used to obtain borings, wire brush surfaces, grind surfaces, produce a crude spark test, etc.

i). Equipment for identifying, preserving, and transporting specimens back to the laboratory: envelopes, labels, plastic bottles, zip-lock bags, cellophane tape and masking tape (can be used to remove and preserve corrosion products for X-ray analysis, as well as more normal uses) .

j). Cleaning agents, chemical reagents (solvents, etchants, macroetches, etc.), abrasives (sand paper, toothpaste, etc.), cloths and rags, toothbrush, other small brushes.

k) . Wax or clear nail-polish to coat and preserve critical fracture surfaces .

1). A small magnet - to check materials and discern various types of stainless steels.

m). Gloves and safety glasses.

n) .Environmental evaluation devices: thermometer, hygrometer (humidity), litmus paper (possibly graded by pH).

0).A small vise.

p). A small propane torch - to heat or loosen components. (NOTE:
be sure exposure to heat will not alter or obliterate evidence.)

q) .A cold-mount kit to permanently mount small or fragile specimens .

r) Selected reference manuals on engineering materials and their properties

2). With additional funds, one might want to consider:

a). An additional camera, such as a high-quality 35-mm with a variety of special lenses (telephoto, close-up, wide angle), and upgrade facilities for the previous Polaroid camera, which would be retained to assure the acquisition of acceptable photos.

b) A calibrated portable hardness tester, such as a portable Brinell tester.

c) An improved microscope with special eyepieces to measure case depth, thickness of plating layers, etc.

d). Portable metal identification kit (to identify specific metals and alloys).

CHAPTER 12
Process Capability and Quality Control

Review Questions

1. A PC study examines the output from a process in order to determine the capability of the process in terms of its accuracy (its aiming ability or its ability to hit the desired nominal value) and its precision (the ability of the process to repeat the variability in the process). Accuracy refers to the centering of the process and variability refers to the scattering of the values about the center value. Accuracy is measured by the mean of the values and variability is measured by the standard deviation of the values about the mean -- also called the spread of the distribution.

2. Every process has some inherent variability. The causes of this variability may be known (assignable) but not removable (you know what is causing the variation but it is not feasible or too costly to remove it) or unassignable (i.e., inherent in the process and thus not removable). The latter is its nature.

3. It would look like Figure 12-la with occasional holes scattered to the right of center at various distances from the center -- a random pattern because the wind is gusting, not steady. In real processes, intermittent changes of this sort are extremely difficult to isolate and identify and therefore remove from the process as an assignable cause. This is an example of an assignable cause that would be difficult to remove -- how do you make the wind stop gusting without great cost (i.e. enclose the shooting range) .

4. A good way to get students to review the steps in a P.C. study is to have them try to do one themselves. The example of shooting a gun given in the text can be "simulated" by having the students work with file cards for targets and darts for the bullets. Give each student in your class a different distance to stand from the cards (mounted on a dart board) when the class data is examined as a whole, you will observe the increase in process variability with distance from the target. Depending on the dart throwing ability of the students, there will also be a loss of accuracy.

5. Two "identical" machine tools doing exactly the same process will have different amounts of process variability. The individual machines will have different variability when the work material is changed, the operator is changed, the specific process on the machine is changed, etc. Thus, it is necessary to gather data on the specific machine tool during the process itself .

6. Taguchi experiments can be used to determine the process capability of a process. Taguchi methods used truncated (simplified) experimental designs in which all the causes of variability are explored. They permit the variability to be reduced by selecting the proper combination of input variables to reduce the noise (i.e., the variability) in the output.

7. In typical experimental approach, one variable at a time is examined and all other variables are kept constant. In the Taguchi or experimental design approach, all significant variables are mixed and varied in the same experiment. The latter approach permits one to find the important interactions between dependent variables as well as to evaluate the significance of each variable.

8. The Taguchi approach results in much better understanding and control of the process, particularly the interactions between variables. More importantly, the results point the direction to run complex processes with the minimum variability and explain why some processes go out of control when some parameter is reset.

9. Without doing the actual experiment, one can only guess as to which variables dominate a process. For baking a cake, the oven temperature and the ingredients (like type of flour) would be dominant along with the pressure (altitude) . The cook may be important here also.

For mowing the lawn, the blade sharpness, blade height versus grass height, blade speed, and blade geometry would probably all be important.

For washing dishes, the water pressure, the water temperature, the right kind of soap, and perhaps the dish spacing would be most important. Here the operator would not be as important as the design of the machine. The water softness may also be important. The loading of the machine is setup.

10. Let us assume that you want to drill a 1 cm hole. The drill selected is usually 1 cm in diameter. Undersized holes are not possible until the drill body has worn down, so most of the holes will be oversize. Reground drills often have unequal lip length or rake angles causing the drill forces to be unbalanced, resulting in oversized holes. Assuming you are drilling many holes with many drills, the majority will be oversized, developing a skewed distribution of hole sizes. Do not confuse hole size with hole location. The chisel end of the drill causes problems in obtaining repeated location -- drill "walks" on the surface. Hole location distributions are not necessarily skewed.

11. Examples of items that may receive

a. 100% inspection:
At a general level all automobile engines are tested as the vehicle is driven away from the assembly plant. Critical parts in high value added products used in high potential loss situations are all tested, e.g., large turbine blades in jet aircraft engines.

b. No final inspection:
There are very few manufactured items that do not receive some sort of final inspection. Processes that run very reliably and consistently over long time are candidates for little inspection of the final products. The N = 2 inspection scheme entails inspection of the first and last items and if they pass inspection all items in-between are assumed to be good.

Some items are not inspected immediately after manufacture but the end user is assumed to be the final inspector. If the item does not work for the purchaser it can be returned, e.g., light bulbs.
Examples of no-inspection products are mature products produced in large batches by experienced manufacturers, e.g., nails where often mis-manufactured nails are found in boxes of nails. Manufacturing machines and tools are maintained to produce good parts but individual parts are probably tested only on startup of the operation.

c. Sampling final inspection:
This kind of sampling is usual for almost all but the simplest manufactured parts. Examples are automobile crankshafts and gasoline.

12. If the test is destructive (bullets or flash bulbs), if the test is expensive compared to the cost of the item (newspapers), if the item is made in great volumes by reliable or continuous processes (sheets of paper), if the test takes a long time (lifetime test for electronics), then the output is often sampled. Sampling is thus a more economical means to check the quality, but there is always the trade off that, when you sample, you will make errors in judgement about the whole. See questions

13. When prediction (sample suggestion) is the same as reality there is no error. Type I error, alpha error is when prediction is that change occurred when in reality there was no change. Type II, beta error when prediction is that there was no change when in actuality the process did change.

		In reality, the process	
		Changed	Not changed
Sample suggested that the process	Changed	No error Process bad	Type I error
	Not changed	Type II	No error Process good

14.You always have some probability of error when you sample (look at a selected few) and then make a decision about all. Both types of errors can be detrimental, even devastating. Sampling inspection systems which miss defects that result in automotive recalls are very expensive and hurt the product's reputation with consumers. Suppose you have a herd of cows. The vet finds a sick cow (sample of one) and condemns all the rest (which are not sick). or he looks at one cow, finds it well, but the rest have hoof and mouth disease but are not condemned. Either situation is very bad.

15. It is usually the beta error which leads to legal action since the beta error results in a defective product which was thought ~o be good, according to the sample. Many sampling systems are designed to protect those who do the inspection against making type I or alpha errors (saying something is bad when it is good) because alpha errors are embarrassing --stopping the line only to find nothing is wrong. The same is true in general for beta errors -- the system gets blamed for missing the problem, but since the

engineer took no action, no blame is directly assigned. However, beta errors can be many times more costly in the long run than alpha errors.

16. Assume that some characteristic of many items is being measured and the distribution of the population of measurements is a normal distribution.

The distribution of all the measurements, i.e., measurements of the parent population, has a standard deviation σ'.
For a number, *k*, of samples of size *n* taken from the parent population, some statistics of the individual samples are
- the mean of each sample, $\overline{X}$
- the range of each sample, R
- the average of the *k* sample standard deviations, $\overline{\sigma}$

A distribution of the sample statistics can be formed and some statistics of sample distributions are
- the standard deviation of the distribution of sample averages, $\sigma_{\overline{X}}$
- the standard deviation of the distribution of sample ranges, σ_R
- the standard deviation of the distribution of sample standard deviations, σ_σ

So,
a. σ' is the standard deviation of the population while $\sigma_{\overline{X}}$ is the standard deviation of the distribution of sample average values
b. σ' is the standard deviation of the population while $\overline{\sigma}$ is the average standard deviation for the *k* samples of size *n* taken from the population
c. $\sigma_{\overline{X}}$, σ_R and σ_σ are the standard deviations of three distribution;
- the standard deviation of the distribution of the *k* sample averages,
- the standard deviation of the distribution of the *k* sample ranges,
- and the standard deviation of the distribution of the *k* sample standard deviations, respectively.

16. You have a process which is producing many items and you are measuring some characteristic on each item. All the measurements of all the items create a parent population of measurements of individual items. Assuming the distribution of all the items is normal, it has some standard deviation, called ~. when you take samples from the parent population of size n, you can create distributions of sample statistics. The means of each sample are called ~ and the range of each sample is called R. Thus ~ and ~R are the standard deviations of the distributions of the sample means and sample ranges, respectively. These distributions tend to be normal, regardless of the shape of the parent population (Shewhart's Law of Sample Statistics) .

17. This is the process capability index. A value of 0.8 would mean that the process spread (i.e. the variability as measured by the standard deviation) exceeds the tolerance spread (USL - LSL) . A value of 1.0 means that these two measures are equal. A value of

1.33 means that the tolerance spread exceeds the natural spread of the process so that all parts being made are within the specification, provided the process is centered.

18. The bias factor determines how far the mean of the process lies from the intended mean or the minimal. (How good is the aim of the process?)

19. When the natural variability of the process (6 sigma prime) exceeds the specified total tolerance, you will have a condition which assures that out-of-tolerance products will be made (defectives, scrap, rework, etc.). Has the proper choice of process been made? Can the tolerances be relaxed? Can the process be improved to decrease its variability? (Are there assignable causes of variation which can be eliminated/) Is this a situation where we will have to live with a certain percentage of defective products? Can we automatically sort out the defects? Will a combination of the above kinds of solutions solve the problem?

20. This factor includes a measure of the process's ability to center itself or to be centered or well-aimed.

21. Yes, because sample statistics will be normally distributed about their mean.

22. When a reason for the cause of the variability can be found, one has an assignable cause. A chance cause is inherent to the process and cannot usually be removed, though its effect can be minimized.

23. It is easier to compute (by hand) and easier to understand, but gives less information about the sample.

24. The SD of the distribution of sample means, $\sigma_{\overline{X}}$, is equal to the SD of the parent distribution, σ', divided by the square root of n, the sample size.

$$\sigma_{\overline{X}} = \sigma' / \sqrt{n}$$

25. Customer demands drive much of product development and so customer demands for high quality automobiles is a cause for marked quality improvement.

At the technical or manufacturing level the improvement in automobile quality is in large part due to improved process control, both
- the control of individual or unit processes such as increased accuracy and improved repeatability machine tools,
- at the system control level based on statistical quality control techniques and Taguchi methods resulting in improved parts and products.

Problems:

1. For demonstration of the question, golf balls have been selected. The characteristic to be measured is the diameter. A golf ball is made from hard rubber with a liquid core. It has a dimpled surface to improve flight accuracy and distance. Its diameter is specified as 1.68 inches minimum by the Professional Golf Association. Measurements were made with a 1 to 2 inch micrometer .

Golf balls are made by a process with a natural total tolerance of 6~' approximately equal to 0.01 inches with an average size of 1.68 inch.

The data given for the golf balls (See chart provided) was for good used golf balls found on the golf course near one of the author's home. They were separated by Titleist (TI), Pro Staff (PS), Top Flight (TF), Pinnacle (P1), and Dunlop (DU). Judging from the sample, the Top Flight ball is either the most popular or is played by the poorest golfers, as about half of the balls found were Top Flights. Obviously, this is a mixed sample and all of the balls were not made by the same machine. However, all manufacturers use the same basic process.

You can add to the complexity of the process capability study by using coins and having the student separate the coins by year. Assuming all the coins have been in circulation, if one measures weight or thickness at a given point, one should find a wear factor related to the age of the coin. Thus, the mean should show a trend -- coins get thinner and lighter with use. But what about the standard deviation?

2. This question uses basically the same mathematics as the last. M&Ms come in different colors as candy-coated chocolate. The student must decide what to do with samples from a bag having mixed colors. Ignoring the different colors means that he (or she) assumes that there is no difference in the process, when in fact there must be different processes being used to make the different colors (or different production lines) . It is a bit tricky to measure the thickness or diameter of M&Ms and easier to measure their weight if the student has access to a scale of sufficient precision. The difference between this experiment and the former one is that in the former one, there were only 48 items. Here, there are many items and they are being sampled. Doing the experiment for weight allows the student to see how the sample estimate of X' can be used to obtain the estimate of the true value, which was obtained by weighing all and dividing by the total number. Questions like "Does thickness have a greater variability than diameter?" can be addressed by letting some students measure thickness and some diameter and comparing their results .

Sample No.	Measurements of Diameter	Xbar	R
1 T1	1.683 1.675 1.682 1.680	1.6800	0.007

2 PS	1.681 1.678 1.681 1.682	1.6805	0.003
3 TF	1.676 1.682 1.682 1.679	1.6798	0.006
4 TF	1.677 1.680 1.680 1.679	1.679	0.003
5 TF	1.677 1.679 1.679 1.678	1.677	0.004
6 PI	1.679 1.681 1.682 1.678	1.6800	0.004
7 TI	1.678 1.675 1.678 1.677	1.6770	0.003
8 TF	1.681 1.680 1.680 1.681	1.6803	0.001
9 DU	1.676 1.679 1.680 1.680	1.6800	0.004
10 PS	1.677 1.680 1.677 1.677	1.6775	0.003
11 TF	1.678 1.677 1.679 1.677	1.6778	0.002
12 TF	1.675 1.677 1.678 1.676	1.6767	0.004

$\sum \overline{X} =$ 20.1456

$\sum R =$ 0.044

$\overline{\overline{X}} =$ 1.6788

$\overline{R} = \sum R / 12 =$ 0.044 / 12 = 0.00366

Estimate of $\overline{X} = \overline{\overline{X}} =$ 1.6788

Estimate of $\sigma' = \overline{R} / d_2 =$ 0.00366 / 2.059 = 0.0017775

3. Process Capability

(12-1) $C_p = \dfrac{Tolerance\,spread}{6\sigma'}$

for σ' = 0.0021

C_p = { (1.006 – 0.996) } / { 6 (.0021) } = 0.79

(12-2) $$D = \frac{Estimated\ process\,mean - No\min al}{\frac{1}{2}(Tolerance\,spread)}$$

$$D = \frac{\overline{X}' - No\min al}{\frac{1}{2}(USL - LSL)}$$ = 0.00085 / 0.005 = 0.17

(12-4) $$C_{pk} = \frac{Min\left\{\left|USL - \overline{X}'\right|, \left|LSL - \overline{X}'\right|\right\}}{3\sigma'}$$

$\left|USL - \overline{X}'\right|$ = 1.006 – 1.002 = 0.18

$\left|LSL - \overline{X}'\right|$ = 1.002 – 0.996 = 0.22

C_{pk} = 0.004 / 0.0063 = 0.63

4. Process Capability

(12-1) $$C_p = \frac{Tolerance\,spread}{6\sigma'}$$ = { (0.502 – 0.498) } / { 6 (0.00067) }

= 0.99

(12-2) $$D = \frac{Estimated\ process\,mean - No\min al}{\frac{1}{2}(Tolerance\,spread)}$$

$$D = \frac{\overline{X}' - No\min al}{\frac{1}{2}(USL - LSL)}$$ = (0.500246 – 0..500000) / 0.002 = 0.123

(12-4) $$C_{pk} = \frac{Min\left\{\left|USL - \overline{X}'\right|, \left|LSL - \overline{X}'\right|\right\}}{3\sigma'}$$

$\left|USL - \overline{X}'\right|$ = 0.502 – 0.500246 = 0.001754

$\left|LSL - \overline{X}'\right|$ = 0.500246 – 0.498 = 0.002246

C_{pk} = 0.001754 / { 3 (0.00067) } = 0.87

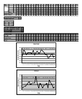
5. The number of measurements per sample is 4 compared to 5 in the 8th edition
The formulas used in the solution are presented in Figure 12-13.
The solution is created in Microsoft Excel 97 and data values can be changed.

It is incorrect to determine the process standard deviation for setting control limits using all the data. The standard deviation from all the data will be affected by the variation between the sample means. The standard deviation for setting control limits must be computed from within-sample variations so excluding between-sample variations.

Further, if the R chart shows that the process is not in control the Xbar chart should not be used – until process control, indicated using the R chart, has been attained.

The net result is that the R chart should be formulated first, but the problem asks for Xbar chart and R chart in that order and this is how the following is presented.

The results using the data in the text give a run of data near the end of the Xbar Chart indicating non-random variation.



6. For the Parent Population, as discussed in Section 12.3

   the parent population mean is estimated by $\overline{X}'$ and so is 0.72 calculated above in Problem 5

   the parent population standard deviation is $\sigma' = \overline{R}/d_2$ and for n = 4,

d_2 = 2.06 (Figure 12-13) and

σ' = 0.078

Process Capability

(12-1) $C_p = \dfrac{Tolerance\,spread}{6\sigma'}$ = { (0.9 – 0.5) } / { 6 (.078) } = 0.855

   which is much smaller than the 1.33 value suggested as the minimum value for good process capability.

(12-2) $$D = \frac{Estimated\ process\,mean - Nominal}{\tfrac{1}{2}(Tolerance\,spread)}$$

$D = \dfrac{\overline{X}' - Nominal}{\tfrac{1}{2}(USL - LSL)}$ = { (0.72 – 0.70) } / { ½ (0.9 - .05) } = 0.1

(12-4) $$C_{pk} = \frac{Min\left\{\left|USL - \overline{X}'\right|, \left|LSL - \overline{X}'\right|\right\}}{3\sigma'}$$

$\left|USL - \overline{X}'\right|$ = 0.9 – 0.72 = 0.18

$\left|LSL - \overline{X}'\right|$ = 0.72 - .5 = 0.22

C_{pk} = 0.18 / { 3 (0.078) } = 0.77

7.

	Problem 12.2	Problem 12.6	% difference
Cp	0.99	0.855	(.86-.99)/.99 => - 13%
D	0.123	0.1	(.10-.12)/.12 => - 17%
Cpk	0.87	0.77	(.77-.87)/.87 => - 11%

The lower values for the data in Figure 12-A (Problem 6) indicate a process producing data with a wider distribution – a less “capable process.

8. Will need the nominal hole diameter, and with equal bilateral limits the nominal diameter is (6.70 mm + 6.00 mm) / 2 = 6.35 mm

a. Process Capability

(12-1) $$C_p = \frac{Tolerance\,spread}{6\sigma'}$$

Tolerance spread = 6.70 mm – 6.00 mm = 0.70 mm

$$\sigma' = \overline{R}\big/ d_2$$

$\overline{R}$ = 0.274 mm

and for n = 5 , (Figure 12-13)

d_2 = 2.33

σ' = 0.274 / 2.33 = 0.118 mm

C_p = 0.70 mm / { 6 (0.118 mm } = 0.989

(12-2) $$D = \frac{Estimated\ process\,mean - No\min al}{\frac{1}{2}(Tolerance\,spread)}$$

$$D = \frac{\overline{X}' - No\min al}{\frac{1}{2}(USL - LSL)} =$$

the parent population mean is estimated by $\overline{X}'$

$\overline{X}'$ = 6.299

$USL - LSL$ = 6.70 mm – 6.00 mm = 0.70 mm

Nominal hole diameter = 6.35 mm

D = (6.3 mm – 6.35 mm) / { ½ (0.70 mm) } = - 0.143

(12-4) $$C_{pk} = \frac{Min\left\{\left|USL - \overline{X}'\right|, \left|LSL - \overline{X}'\right|\right\}}{3\sigma'}$$

$\left|USL - \overline{X}'\right|$ = 6.70 mm – 6.3 mm = 0.4 mm

$\left|LSL - \overline{X}'\right|$ = 6.3 mm – 6 mm = 0.3 mm

C_{pk} = 0.3 mm / { 3 (0.118 mm) } = 0.847

b. σ control chart, Figure 12-13 contains relevant information, especially

$$\sigma = \sqrt{\frac{\sum_{i}^{n}\left(X_i - \overline{X}\right)^2}{n-1}}$$

Note: the calculated values, Total, Mean and Range, are incorrect for Lot No. 3

Without further information the control limits are set to 3*(standard deviation of the sample standard deviations). Also, some supplementary content is added to this solution. Specifically, control limits are also set using arguments similar to those in Section 12.3 that result in the A_2, D_3 and D_4 coefficients. Standard texts, e.g., Quality Control and Industrial Statistics, A. J. Duncan, Irwin, present control limits for standard deviation charts as

LCL = B_3 * (average value of sample standard deviations)
UCL = B_4 * (average value of sample standard deviations)

Finally, if the Lower Control Limit is less than zero representing reality calls for setting it to zero.

n	B_3	B_4
3	0	2.568
4	0	2.266
5	0	2.089

Process Capability – using Sigma Chart

$$\sigma' = \overline{\sigma} = 0.109 \text{ mm}$$

$$\overline{X}' = 6.30 \text{ mm}$$

$$\text{(12-1)} \quad C_p = \frac{Tolerance\,spread}{6\sigma'}$$

for $\sigma' = 0.0021$

$$C_p = \{ (6.70 - 6.00) \text{ mm}\} / \{ 6 (0.109 \text{ mm}) \} = 1.070$$

$$\text{(12-4)} \qquad C_{pk} = \frac{Min\left\{\left|USL - \overline{X}'\right|, \left|LSL - \overline{X}'\right|\right\}}{3\sigma'}$$

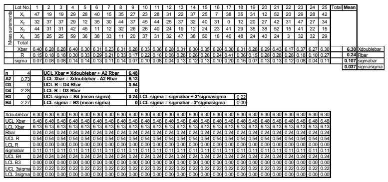
$$\left|USL - \overline{X}'\right| = (6.70 - 6.30) \text{ mm} = 0.40 \text{ mm}$$

$$\left|LSL - \overline{X}'\right| = (6.30 - 6.00) = 0.30 \text{ mm}$$

$$C_{pk} = 0.30 / \{ (3) (0.109) \} = 0.917$$

c. The charts below were developed using
i. not including the X5 measurements, so *n* = 4
ii. not including X3 and X5 measurements, *n* = 3

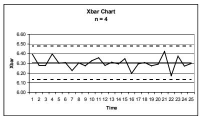
i.

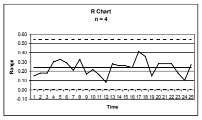


	Lot No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	Total	Mean	
Measurements	X_1	47	19	19	29	28	40	15	35	27	23	28	31	22	37	25	7	38	35	31	12	52	20	29	28	42			
	X_2	32	37	37	29	12	35	30	44	37	45	44	25	37	32	40	31	0	12	20	27	42	31	47	27	34			
	X_3	44	31	31	42	45	11	12	32	26	26	40	24	19	12	24	23	41	29	35	38	52	15	41	22	15			
	X_4	35	25	25	59	36	38	33	11	20	37	31	32	47	38	50	18	40	48	24	40	24	3	32	32	29			
	Total																												
	Xbar	6.40	6.28	6.28	6.40	6.30	6.31	6.23	6.31	6.28	6.33	6.36	6.28	6.31	6.30	6.35	6.20	6.30	6.31	6.28	6.29	6.43	6.17	6.37	6.27	6.30		**6.30**	Xdoublebar
	R	0.15	0.18	0.18	0.30	0.33	0.29	0.21	0.33	0.17	0.22	0.16	0.08	0.28	0.26	0.26	0.24	0.41	0.36	0.15	0.28	0.28	0.28	0.18	0.10	0.27		**0.24**	Rbar
	sigma	0.07	0.08	0.08	0.14	0.14	0.13	0.11	0.14	0.07	0.10	0.08	0.04	0.13	0.12	0.13	0.10	0.20	0.15	0.07	0.13	0.13	0.12	0.08	0.04	0.11		**0.107**	sigmabar
																												0.037	sigmasigma

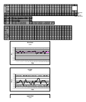
n	4		**UCL Xbar = Xdoublebar + A2 Rbar**	**6.48**		
A2	0.73		**LCL Xbar = Xdoublebar - A2 Rbar**	**6.13**		
D3	0		**UCL R = D4 Rbar**	**0.54**		
D4	2.28		**LCL R = D3 Rbar**	**0**		
B3	0		**UCL sigma = B4 (mean sigma)**	**0.24**	**LCL sigma = sigmabar + 3*sigmasigma**	0.22
B4	2.27		**LCL sigma = B3 (mean sigma)**	**0**	**LCL sigma = sigmabar - 3*sigmasigma**	0.00

Xdoublebar	6.30	6.30	6.30	6.30	6.30	6.30	6.30	6.30	6.30	6.30	6.30	6.30	6.30	6.30	6.30	6.30	6.30	6.30	6.30	6.30	6.30	6.30	6.30	6.30	6.30
UCL Xbar	6.48	6.48	6.48	6.48	6.48	6.48	6.48	6.48	6.48	6.48	6.48	6.48	6.48	6.48	6.48	6.48	6.48	6.48	6.48	6.48	6.48	6.48	6.48	6.48	6.48
LCL Xbar	6.13	6.13	6.13	6.13	6.13	6.13	6.13	6.13	6.13	6.13	6.13	6.13	6.13	6.13	6.13	6.13	6.13	6.13	6.13	6.13	6.13	6.13	6.13	6.13	6.13
Rbar	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24
UCL R	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54
LCL R	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
sigmabar	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11
UCL B4	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24
LCL B3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
UCL 3sigma	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22
LCL 3sigma	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00





ii.



The Xbar and sigma charts give the following values for $\overline{X}'$ (estimated from the grand average) and σ'. The calculations of the process capability measures are shown below.

n	$\overline{X}'$	σ'	C_p	D	C_{pk}
5	6.30*	0.109	1.070	-0.143	0.917
4	6.30	0.107	1.090	-0.143	0.935
3	6.31	0.106	1.101	-0.114	0.975

* corrected value, different from value given in problem statement

(12-1) $$C_p = \frac{Tolerance\,spread}{6\sigma'}$$

= { (6.7 – 6.0) } / { 6 (0.109) } = 1.070 for n = 5
= { (6.7 – 6.0) } / { 6 (0.107) } = 1.090 for n = 4
= { (6.7 – 6.0) } / { 6 (0.106) } = 1.101 for n = 3

(12-2) $$D = \frac{\overline{X}' - No\min al}{\frac{1}{2}(USL - LSL)}$$

= { 6.30 – 6.35 } / { ½ (6.70 – 6.00) } = -0.143 for n = 5
= { 6.30 – 6.35 } / { ½ (6.70 – 6.00) } = -0.143 for n = 4
= { 6.31 – 6.35 } / { ½ (6.70 – 6.00) } = -0.114 for n = 3

(12-4) $$C_{pk} = \frac{Min\left\{\left|USL - \overline{X}'\right|, \left|LSL - \overline{X}'\right|\right\}}{3\sigma'}$$

$$\left|USL - \overline{X}'\right|$$

= 6.70 – 6.30 = 0.40 for n= 5
= 6.70 – 6.30 = 0.40 for n = 4
= 6.70 – 6.31 = 0.39 for n = 3

$$\left|LSL - \overline{X}'\right|$$

= 6.30 – 6.00 = 0.30 for n = 5
= 6.30 – 6.00 = 0.30 for n= 4
= 6.31 – 6.00 = 0.31 for n = 3

C_{pk} = 0.30 / { 3 (0.109) } = 0.917 for n = 5

C_{pk} = 0.30 / { 3 (0.107) } = 0.935 for n = 5

C_{pk} = 0.31 / { 3 (0.106) } = 0.975 for n = 5

Case Study:

Boring QC Chart Blunders

1. This is an Xbar chart showing the average values of the 19 samples of 4 parts.

2. With control limits of about 3 σ = UCL – Mean = 0.00038 – 0.00017
σ = 0.00006 in

3. The center line is the average of the sample means, not the mean of the population from which the samples were drawn.

4. Cp = (USL – LSL) / 6 σ' = {2 (0.0005) } / { 6 (0.00006) = 2.78
Cpk = MIN { | USL – Xbar' | , | LSL – Xbar' | } / 3 σ' = 0.00033 / 0.00018 = 1.83

5. The specification limits are not measured quantities and so do not belong on the chart.

CHAPTER 13
Fundamentals of Casting

Review Questions

1. Materials processing is the science and technology by which a material is converted into a useful shape with a structure and properties that are optimized for the intended service environment. More loosely, processing is "all that is done to convert stuff into things".

2. The four basic families of shape production processes are:
(1) Casting, (2) Material removal, (3) Deformation processes, and (4) Consolidation processes. Casting processes can produce extremely complex shapes, but may have defects related to shrinkage and porosity. Material removal processes can have outstanding precision, but generate scrap as the material is cut away. Deformation processes can offer high rates of production, but require powerful equipment and dedicated tools or dies. Consolidation processes can produce large or complex shapes, but the joints may possess properties that are different from the base material.

3. Cast parts can range in size from a fraction of an inch and a fraction of an ounce to over 30 feet and many tons. Moreover, casting can incorporate complex shapes, hollow sections or internal cavities, and irregular curved surfaces.

4. In the single-use molding processes, a new mold must be made for each casting. In contrast, multiple-use molds can be used for repeated castings and are generally made of metal or graphite. They are quite costly and their use is generally restricted to large production runs where their cost can be distributed over a large number of castings. For small quantities, the single-use molds would be preferred.

5 . when the molten metal is introduced into the mold, all of the air and gases in the mold prior to pouring and those generated by the action of the hot metal on the mold must be able to escape the mold cavity. This will enable the molten metal to completely fill the mold cavity and produce a fully dense casting that is free from defects.

6. If the mold provides too much restraint to the solidifying and cooling casting, the casting will crack as it tries to contract while its strength is low.

7. A casting pattern is an approximate duplicate of the final casting around which the mold material will be packed to form the mold cavity. A flask is the box that contains the molding aggregate. A core is a sand shape that is inserted into the mold to produce internal features in a casting, such as holes or passages. A mold cavity is the void into which the molten metal is poured and solidified to produce the desired casting. A riser is an extra void created in the mold that will be filled with the

8. The gating system of a mold is made up of a pouring cup, sprue, runners and gates. Its purpose is to deliver the molten metal from the outside of the mold to the mold cavity.

9. A parting line or parting surface is the interface which separates the cope and drag halves of the mold, flask, pattern, or core.

10. Draft is the taper on a pattern and so there will be taper on the casting. Draft permits the pattern to be withdrawn from the mold while minimizing damage to the mold (and the casting to be removed more easily from permanent molds).

11. The two steps of solidification are nucleation and growth. During nucleation, a stable solid particle forms from the molten metal and forms the beginning of a crystal or grain in the finished casting. During the growth stage, the heat of fusion is continually extracted from the liquid material and the nucleated solid increases in size.

12. At the equilibrium melting temperature, the bulk energies of the liquid and solid states are equivalent. However, for a solid particle to form in the liquid, additional energy must be provided to create the new surfaces or interfaces. Thus, for solid formation to occur generally requires that the temperature drop to several degrees below the melting temperature. Here the change in state from liquid to solid releases sufficient energy that the net result (with the additional energy required to create interfaces) is a movement to a lower energy state.

13. Since each nucleation event produces a grain or crystal in a casting, and fine grain materials possess improved strength and mechanical properties, attempts to promote nucleation would be rewarded by the production of superior castings. This practice of promoting nucleation is known as inoculation or grain refining.

14. In most casting operations, heterogeneous nucleation occurs at existing surfaces, such as mold or container walls, or solid impurity particles within the molten liquid.

15. Directional solidification, in which the solidification interface sweeps continuously through the material, can be used to assure the production of a sound casting. The molten material on the liquid side of the interface flows into the mold to continuously compensate for the shrinkage that occurs as the material changes from liquid to solid.

16. The cooling curve for a pure metal contains information that will reveal the pouring temperature, superheat (the difference between the pouring temperature and the freezing temperature of the metal), the cooling rate, the freezing temperature (thermal arrest), and the solidification times (both total and local).

17. Superheat is the difference between the temperature of the molten material when it is poured into the mold and the material freezing temperature. Superheat is related to the time between poring and solidification and so is a factor in the time available for complete mold filling.

18. The term, freezing range, refers to the difference between the liquidus and solidus temperatures, i.e. the temperature range through which the material transforms from all liquid to all solid.

19. The amount of heat that must be removed from a casting to cause it to solidify is directly proportional to the amount of metal or the volume of the casting. conversely, the ability to remove heat from a casting is directly related to the amount of exposed surface area through which the heat can be extracted. The total solidification time, therefore can be expressed as proportional to the volume divided by the area to some exponential power - Chvorinov's Rule.

20.The mold constant, B, in Chvorinov's Rule depends upon the metal being cast, the mold material, mold thickness, and the amount of superheat.

21. Since cooling rate influences the structure of the casting it has large effects on casting properties. Usually the faster the cooling rate the finer and more uniform the casting microstructure and the stronger the part.

22. The chill zone of a casting is a narrow band of randomly oriented crystals that forms on the surface of a casting. Rapid nucleation begins here due to the presence of the mold walls and the relatively rapid surface cooling.

23.The columnar region is clearly the lease desirable. Because of the selective growth process, these crystals are long, thin columns with aligned, parallel, crystal structure. Reflecting this preferred orientation, the properties will be quite anisotropic (varying with different direction) .

24. The equiaxed zone has a structure characterized by a larger number of grains per volume, smaller grains, more spherical grains, randomly oriented grains and so more isotropic properties than the other regions of the casting, the chill zone and the columnar zone. To promote the formation of a larger equiaxed zone more nucleation sites are needed and this situation is promoted by lower pouring temperature, alloy additions and the use of innoculants.

25. Dross or slag is the term given to the metal oxides which can be carried with the molten metal during pouring and filling of the mold. Special precautions during melting, pouring and process design can prevent the dross from becoming part of the finished casting. Fluxes can be used to protect the molten metal during melting or vacuum or protective atmospheres can be employed. Dross can be skimmed from the ladles prior to pouring or the metal can be extracted from the bottom of the molten pool. Finally, gating systems can be designed to trap the dross before it enters the mold cavity.

26. Gas porosity can be eliminated by preventing the gas from initially dissolving in the molten metal, using such techniques as vacuum melting, controlled atmospheres, flux blankets, low superheats, and careful handling and pouring. In addition, dissolved gases can be removed by vacuum degassing, gas flushing, or reaction to produce a removable

product compound.

27. Fluidity is the ability of a molten metal to flow and fill the mold - a measure of its runniness. While there is no single method for its measurement, various ^{33}standard molds'^{3} can be used where the results are sensitive to metal flow. One approach is to use a long thin spiral that progresses outward from a central pouring sprue. The length of the casting is a direct indication of fluidity.

28. Misruns are defects in the casting due to the molten material beginning to freeze before the mold is completely filled. Misruns are due to large differences in temperature in the molten material in the mold and so are due to poor mold design leading to regions of unusually low temperature and to too low a pouring temperature, i.e., insufficient superheat. The resulting defects are regions of greatly different properties and structures over the casting since molten metal is freezing at different conditions and is solidifying around already solidified material.

29. As molten material temperature and mold temperature increase
- the melt fluidity increases allowing the material possibly to flow into small spaces between sand grains and on solidification sand grains are in the casting,
- chemical activity rate increases and melt-mold reactions are accelerated leading to reactions which may alter casting material structure and properties.

30. The rate of metal flow through the gating system is important, as is the rate of cooling as it flows. Slow filling and high heat loss can result in misruns and cold shuts. Rapid rates of filling can result in erosion of the gating system and mold cavity and produce entrapped mold material in the final casting .

31. Turbulence of the molten metal in the gating system and mold cavity could promote excessive solution of gases, enhance oxidation of the metal, and accelerate mold erosion.

32. The choke is the smallest cross section region of the sprue-runner system. The choke controls the rate of flow into the mold and also the location of the slowest flow. So, the closer the choke to the sprue entrance the slower the flow through the entire runner system and the smoother the flow and the greater the mold filling time. If the choke is in the runner near the mold cavity, flow rate through the sprue-runner system is faster and more turbulent.

33. Gating systems can be designed to trap dross and mold material before they enter the mold cavity. Since the lower-density materials will rise to the top of the molten metal, long, flat runners with gates that exit from the lower portion of the runner are effective. Since the first metal to enter the mold is most likely to contain the dross, runner extensions and wells can be used to catch this material and prevent it from entering the mold. Screens or ceramic filters can also be used.

34. Turbulent-sensitive materials, such as aluminum and magnesium, and alloys with low melting points generally employ gating systems that concentrate on eliminating

turbulence and trapping dross. Turbulent-insensitive alloys, such as steel, cast iron, and most copper alloys, and alloys with high melting points, generally use short, open gating systems that provide for quick filling of the mold cavity.

35. The three stages of contraction or shrinkage as a liquid is converted into a finished casting are: shrinkage of the liquid, solidification shrinkage as the liquid turns to solid, and solid metal contraction as the solidified material cools to room temperature .

36. Alloys with large freezing ranges have a wide range of temperatures over which the material is in a mushy state. As the cooler regions complete their solidification, it is almost impossible for additional liquid to feed into the shrinkage voids. The resultant structure tends to have small, but numerous shrinkage voids dispersed throughout.

37.A primary concern regarding the contraction of a hot casting after it has solidified is the change in dimensions. In addition, if the product is constrained in a rigid mold, tensile stresses can be induced that may cause cracking. It is best to eject the castings as soon as solidification is complete.

38. By having directional solidification sweeping from the extremities of the mold to the riser, the riser can continuously feed molten metal and will compensate for the shrinkage of the entire mold cavity.

39. Based on Chvorinov's Rule, a good shape for a riser would be one with a small area per unit volume. The ideal shape would be a sphere, but this is rather impractical to the patternmaker and molder. Therefore, the best practical shape for a casting riser would probably be a cylinder with height approximately equal to the diameter.

40. A top riser is one that sits on top of a casting. A side riser is located adjacent to the mold cavity, displaced along the parting line. Open risers are exposed to the atmosphere. Blind risers are contained entirely within the mold. Live risers receive the last hot metal that enters the mold. Dead risers receive metal that has already flowed through the mold cavity.

41. When using Chvorinov's Rule to calculate the size of a riser, one makes several assumptions. Since both the riser and the mold cavity set in the same mold and receive the same metal, the mold constant, B, is assumed to be the same for both regions. The equations in the text assume N=2 and a safe difference in solidification time to be 25%.

42. Chills are used to speed solidification of the casting. Both internal and external chills absorb heat and so not only decrease solidification time but, in extreme cases, can also effect casting microstructure and properties by causing directional solidification.

An insulating sleeve is a low heat flow material placed around the riser to maintain the material in the riser in a molten state and so decrease the needed riser size.

Exothermic materials are added to the mold around the sides and top of the riser. The heat produced by the exothermic reaction maintains the material in the riser in the molten state and so enables the use of smaller risers.

Riser size is important since material that solidifies in the riser is excess material in the sense that it is not used in producing parts.

43. Casting patterns generally incorporate several types of modifications or allowances. These include shrinkage allowances to compensate for thermal contraction, draft to permit pattern removal, machining allowances, distortion allowance, and compensation for thermal changes in mold dimensions.

44. A shrink rule is a simple measuring device that is larger than a standard rule by the desired shrink allowance. The measurements on the shrink rule are the final dimensions of the part after thermal shrinkage has occurred.

45. Draft (see Question 10) is used on casting patterns to enable the pattern to be withdrawn from the mold without the sand particles being broken away from the mold surface.

46. Pattern allowances increase the size of the pattern, and thus the size and weight of a casting and possibly the amount of material that must subsequently be removed by machining to form a finished product. Therefore, efforts are generally made to reduce the various allowances.

47. At a very high level of description the casting process involves fluid flow filling a mold, heat flow causing solidification and the effects of mold cavity design on these processes. So any interaction between parting plane location and part shape, fluid flow and heat transfer affects the casting process. The location of the parting plane with respect to the mold cavity will influence process design, e.g.,
- number of cores,
- method of core support,
- sprue and gate system configuration,
- the relative volume of the part compared to the sprue-runner-riser volume,

and also the quality of the final part since
- part accuracy and part characteristics such as porosity depend on the solidification process which depends on overall mold design including parting plane location.

48. In general, at changes in shape of solid material bodies stress concentrations or stress raisers occur. This happens in castings and parts made by other processes.

During the production of cast parts casting defects can arise where sections meet. The effective section thickness at the intersection of casting sections is larger than the thickness of the intersecting sections. The increased section thickness region cools and solidifies more slowly than the thinner sections on either side of it. The difference in cooling rates between the relatively thicker intersection region and the thinner surrounding sections can cause problems. Differences in cooling rate and shrinkage cause residual stress and local shrinkage cavities as the adjacent regions adapt to each others temperature and amount of shrinkage. Also, the locally thicker, larger volume region will remain at a higher temperature during solidification this can result in porosity.

Problems:

1. Plate dimension: 2” x 4” x 6”; H/D = 1.5; n =2

$t_{riser} = 1.25\ t_{casting}$

$(V/A)^2_{riser} = 1.25\ (V/A)^2_{casting}$

$(V/A)_{riser} = 1.15\ (V/A)_{casting}$

$\{ (\pi/4) D^2 H \} / \{ 2(\pi D^2/4) + \pi DH \} =$

$\{ (1.15)(2 \times 4 \times 6) \} / \{2(2\times4) + 2(2\times6) + 2(4\times6) \}$

with H = 1.5 D

$\{ n\ \pi\ D^3 / 8) / 2\ \pi\ D^2 = 1.15 (0.545)$

$3 D / 16 = 0.627$

D = 3.34 in, H = 5.02 in, Vriser = 43.98 in3

Yield = Vol casting / (Volcasting / Vriser) = 48 / (48 + 43.98) = 52%

2. If the riser sits on top of the casting, heat is not lost from either the casting or the riser at their junction. This interface area should be subtracted from both the area of the casting and the area of the riser in Chvorinov's Rule:

$\{ (\pi\ D^2 H) / 4 \} / \{ 2(\pi D^2/4) + \pi DH - \pi D^2/4 \} = \{ 1.15 (48) \} / \{ 88 - \pi D^2/4 \}$

$(3D / 14)(88 - \pi D^2/4) = 55.2$

$0.168D^3 - 18.86D^2 + 55.2 = 0$

D = 3.25 in, H = 4.875 in and $V_{riser} = 40.44\ in^3$

Yield = 48 / (48 + 40.44) = 54%

3. For the 3" x 5" x 10" solid

$t_5 = B\ (V/A)^2$

$11.5= B(3 \times 5 \times 10)^2 / \{ 2 (3\times5) + 2 (3\times10) + 2 (5\times10)]^2$

$11.5 = B (150)^2 / (30 + 60 + 100)^2 = B (150 / 190)^2 = B (0.789)^2 = 0.623 B$

B = 11.5 / 0.623 = 18.46

For a casting of 0.5" x 8" x 8" cast under the same conditions:

$t_s = 18.46 \text{ x } (.5\text{x}8\text{x}8)^2 \ / \ [2\ (.5\text{x}8) + 2(.5\text{x}8) + 2(8\text{x}8)]^2$

$= 18.46 \text{ x } (32)2 \ / \ [\ 8 + 8 + 128]^2$

$= 0.91$ min

Case Study:

The Cast Oil-Field Fitting

1. The binder for the no-bake sand is a polymerizable alkyd-oil/urethane material. Gases can be evolved from the binder when it is heated and the polymer material begins to depolymerize. In fact, there are two possibilities for gas problems with this material. If the binder had been completely polymerized during the manufacture of the core, the high temperature of the cast iron could break down the binder into small fragments having low molecular weight and low boiling point, thus producing the bubbles. In addition, this particular type of binder has a long curing time --12 to 24 hours are required for the polymerization to complete at room temperature. If the core or the mold were not completely cured, there would already be low molecular weight, low boiling point, constituents present that could form gases as soon as the liquid iron entered the mold cavity.

The gases are located near a surface, just beneath the core. It appears that the gas bubbles formed, started to float, and were trapped by the core.

Vents could be added to the core and/or mold to give the gases an easier path to escape through the sand, rather than becoming trapped in the liquid metal. In addition, we want to make sure that the binder is completely cured prior to pouring. A coarser grained sand with a narrow distribution of sand grain sizes will provide higher permeability and permit easier gas removal. Finally, a switch to a different type of binder could reduce the amount of gas produced from that of the oil/urethane.

2. Penetration occurred by liquid metal flowing between the sand grains of the core. It appears that the core was not properly compacted, with relatively large voids between the sand grains. The core may have also had very large sand grains with a very narrow distribution of sizes (although this is contrary to the conclusion of question 1. The core also gets hotter than the mold, since the core is completely surrounded by liquid metal. In addition, the region showing the penetration is adjacent to the gate where it will have received the molten metal first and would have been hotter longer than the remainder of the mold. The long exposure to high heat may have led to the breakdown of the binder and helped the liquid metal penetrate the sand. Finally, the defect was only noted near the bottom of the casting because of the higher metallostatic pressure head (the pressure of the column of molten metal) helping to force the metal between the sand grains.

3. The enlargement could have occurred because the mold was weak and the high

metallostatic pressure crushed the sand, thus enlarging the mold cavity. Better compaction during mold making would produce denser, and stronger, sand. Using a larger amount of binder might also help, but gas problems would tend to become more severe. Another possible cause would be erosion, because the enlargement occurred next to the gate where all of the liquid metal entered the mold cavity. The sand near the gate becomes the hottest, and the binder may have decomposed prematurely. The use of several gates, rather than just one, might help reduce the problem.

4. Penetration over all of the surfaces is likely due to the sand being too coarse and a narrow distribution of sand grains, or perhaps due to a high pouring temperature. Reducing the pouring temperature would be helpful. Another possible cure would be to use finer sands, perhaps with the addition of silica flour to the aggregate -- although lower permeability and metal-mold defects, such as burn-on might become problems.

5. Both the molds and the cores could be reclaimed. The binders are organic, and, with luck, most of the organic material will have broken down during the casting and cooling process. If the organic breakdown is not sufficient, some form of reclamation process can be used. A mechanical reclamation system would perhaps fire the sand grains at a hard metal plate, where the impact would break the brittle polymer binder of f of the sand grain surface. A thermal reclamation system, in which the sand is heated to a high temperature (usually above 1000^0F), will burn off any residual binder. The processed sand is then carefully screened to assure the proper size and distribution of sizes prior to rebonding and reuse.

CHAPTER 14
Expendable-Mold Casting Processes

Review Questions

1. There is a variety of casting processes. Many casting process characteristics are similar but each has distinct characteristics that determine process requirements and cast part properties. Some of the factors that influence choice of casting process are
- quality of cast surface required,
- desired part dimensional precision,
- part production rate,
- the complexity of the process and process tooling that are required to produce a particular part,
- cost of mold or die,
- material characteristics as they determine feasible casting processes.

2. Using molds and patterns as process classification factors results in three general categories of casting processes
i. Single-use molds with multiple-use patterns
ii. Single-use molds with single-use patterns
 - these two types of processes are often called expendible mold casting processes
iii Multiple-use molds

3. Frequently cast metals are iron, steel, aluminum, brass, bronze. magnesium, zinc alloys and nickel-based superalloys. The large range of properties and melting temperatures indicates that almost all metals can be cast, given enough process development resources. However, there are "easy-to-cast" materials and these are typically used. Materials may be inherently "castable" or alloys specially formulated to produce acceptable parts in easily designed and controlled casting processes.

4. The most common casting process is sand casting. Green sand casting is used to produce about 90% of the casting produced in the United States. Its wide use indicates that it is probably the most versatile.

5. A casting pattern is a duplicate of the part to be made, modified in accordance with the requirements of the casting process, metal being cast, and particular molding technique that is being used.

6. The material used for construction of a casting pattern is determined primarily by the number of castings to be produced, but is also influenced by the size and shape of the casting, the desired dimensional precision, and the molding process. Wood patterns are easy to make and are used when quantities are small. Unfortunately, wood is not very dimensionally stable due to warping and swelling with changes in the humidity. Metal patterns are more expensive, but are more stable and more durable. Hard plastics, such as

urethane, have been used, and expanded polystyrene is used for single-use patterns. Expanded polystyrene and wax can be used for single-use patterns.

7. The simplest type of pattern is the one-piece or solid pattern. Since it is the simplest it is usually the least expensive.

8. In casting a pattern is used to form the mold cavity. In making a two part mold the mold material is formed around the pattern and then the pattern is removed leaving the mold cavity. One way to form the pattern, and the form it the mold cavity, is to use a two part, or split, pattern. The two parts of the pattern are fixed to the match plate, the mold formed around the pattern-match plate, the mold halves separated and the pattern-match plate removed.

So, the match plate is a plate to which parts of the pattern are attached. It aids molding in providing a simple structure to help form the pattern and mold cavity. In a general sense the match plate is a fixture for creating the pattern.

9. With a cope-and-drag pattern, the cope and drag halves of the split pattern are mounted onto separate match-plates, thereby permitting larger molds to be handled easier or two separate machines to be simultaneously producing the two portions of the mold.

10. A loose-piece pattern is frequently used when the object to be cast has protruding sections or geometric features such that a more traditional pattern could not be removed from the molding sand.

11. The four requirements of a molding sand are: refractoriness, cohesiveness, permeability, and collapsibility. Refractoriness is provided by the basic nature of the sand. Cohesiveness is provided by coating the sand grains with clays that become cohesive when moistened. Permeability is a function of the size of the sand particles, the amount and type of clay or other bonding agent, the moisture content, and the compacting pressure. Collapsibility is sometimes promoted by adding cereals or other organic materials that burn out when exposed to the hot metal to reduce the volume of the solid bulk and decrease the strength of the restraining sand.

12. The four requirements of a molding sand are not consistent with one another, so good molding sand is always a compromise between the various factors. The size of the sand particles, the amount of bonding agent, the moisture content, and the organic matter are all selected to attain an acceptable compromise. For example, increasing the amount of clay will enhance cohesiveness, but decrease permeability.

13. A muller is a mixing-type device designed to uniformly coat the grains of sand with the additive agents. The discharge frequently contains some form of aerator which prevents the sand from packing too hard during handling.

14. Standard tests have been developed to maintain consistent sand quality by evaluating: grain size, moisture content, clay content, compactibility, and mold hardness,

permeability and strength.

15. A "standard rammed specimen" is a 2" in diameter, 2" long sand specimen that is produced by means of a standard and reproducible form of compaction. A sufficient amount of sand is placed in a 2-inch diameter steel tube so that after a 14-pound weight is dropped three times from a height of 2-inches, the final height of the sand specimen is within 1/32 of an inch of 2 inches .

16. Permeability is a measure of how easily gases can pass through the narrow voids between the sand grains. A casting mold material must possess permeability to permit the escape of air that was in the mold before pouring, plus gases generated from the molding material itself when materials in the molding sand burn, volatilize, or deteriorate when in contact with the hot metal.

17. Water interacts with the surface of clays so that interparticle bonding sites are activated. Too little moisture and bonding sites are limited resulting in low compressive strength. Too much moisture and although all surfaces are covered and bonding sites maximized, the water acts as a lubricant between grains decreasing the strength from the maximum value at the optimum moisture content.

18. The basic size and geometry of the sand grains can be very influential in determining the properties of the molding material. Round sand grains give good permeability and minimize the amount of clay required. Angular sands give better green strength because of the mechanical interlocking of the grains. Large-grain sands provide good permeability and better resistance to high-temperature melting and expansion. Fine-grain sands provide good surface finish on the finished casting. Uniform size sands give good permeability, while a wide size distribution provides a better surface finish.

19. When hot metal is poured into a silica sand mold, the silica sand heats up, undergoes one or more phase transformations, and has a large expansion in volume. Since only the surface sand heats up and expands, while the remainder stays cool, the mold experiences nonuniform expansion, and the hot surface may buckle or fold (sand expansion defects).

20. Since sand expansion defects are caused by nonuniform sand expansion and phase transformations across the mold, steps that minimize temperature gradients, sand expansion and phase transformations will minimize sand expansion defects. Ways to minimize the effects of expansion and phase transformations include
- using sand particles with shapes that relieve expansion stresses by allowing easier particle motion,
- material such as excess clay and cellulose can be added to absorb expansion,
- use of different mold materials that do not undergo phase transitions and/or have lower expansion on heating.

21. Penetration of the hot metal between the sand grains can be produced by high pouring temperatures (excess fluidity), high metal pressure (possibly due to excess cope height or pouring from too high an elevation above the mold), or the use of coarse, uniform sand

particles.

22. Hot tears are cracks that form in castings during solidification. As the molten metal cools and solidifies it shrinks. If the mold exerts sufficient constraint on the solid, but still hot. weak and shrinking metal, stresses may be large enough to from cracks.

Hot tearing can be decreased by designing casting processes so that the stress that arise are minimized, e.g., by assuring collapsibility of the sand mold during part solidification.

23. If sand is placed on top of a pattern and the assembly is then lifted and dropped several times (jolting), the sand is packed firmly around the pattern, with density diminishing as one moves further from the pattern. When squeezing is used, the maximum density is adjacent to the squeeze head. Density then diminishes as the distance from the squeeze head increases. The jolt-squeeze combination combines these two results to produce a more uniform distribution of sand density.

24. After the mold is produced in the flask it is removed from the flask and may be vulnerable to damage. A metal band, called a slip jacket, can be placed around the mold to help protest the mold from damage during handling and pouring.

25. The vertically-parted flaskless molding machine produces blocks of sand that contain a cope impression on one side and a drag impression on the other. When assembled side-by-side, they produce a complete pattern, with one complete mold being provided per block of sand. Other methods require separate cope and drag segments, thereby requiring two blocks per mold.

26. Extremely large molds are often constructed in sunken pits, and are often made as an assembly of smaller sections of baked or dried sand.

27. The two major sources of problems with green sand are low strength and high moisture.

28. Dry-sand molds lack popularity because of the long times required for drying, the added cost for the drying operation, and the availability of practical alternatives.

29. In the carbon dioxide-sodium silicate molding method, the carbon dioxide is nontoxic and odorless, and no heating is required for curing. When hardened, however, the sands have poor collapsibility, making shakeout and core removal rather difficult. Here, the heating from the pour actually makes the mold material stronger.

30. No-bake sands use organic resin binders that cure by chemical reactions that occur at room temperature.

31. In the shell molding process, a thermoplastic binder is used to bond the sand grains and the "cure" is provided by the exposure of the sand and binder mixture to patterns that have been heated to temperatures in the range of 300-450^{0}F. The heat then cures a layer

of mold material adjacent to the pattern.

32. Shell molds have thin walls so the length of path for gases leaving the mold is short and mold permeability is high.

When shell molds are heated by the molten material some of the binder burns off. This leaves a weaker, high collapsibility, mold structure.

33. In the V-process, mold strength is obtained through the use of a specially-designed vacuum flask. When a vacuum is drawn, the sand packs to rather high hardness. In contrast, the Ef f-set process uses frozen water as a binder, and the molds are poured while in their frozen condition.

34. Cores are used to produce internal cavities or reentrant sections in a casting. These are features that would be extremely difficult to produce by alternative methods.

35. The major problems with green sand cores is their weakness. If they are long or narrow, they are prone to breaking and may not even be able to support themselves.

36. The binder in the core-oil process is a vegetable or synthetic oil. Oven drying causes the oil to cross-link or polymerize, bonding the grains of sand.

37. In the hot-box core-making process, a liquid thermosetting binder and a catalyst are used to bind the sand. When the sand contacts a heated core box, the elevated temperature induces curing within 10 to 30 seconds.

38. Room-temperature curing is the primary attraction of the cold-box process. No-bake and air-set sands have the same advantage, but use a mixed catalyst in place of permeated gas to induce the cure.

39. Shell-molded cores offer excellent permeability since they are generally hollow.

40. Since cores may be nearly surrounded by molten metal, they generally require greater permeability than the base molding sand. All gases must escape through the core prints. Excellent collapsibility is required to permit the core material to be easily shaken out from the interior of the casting.

41. Chaplets are small metal devices that provide support for cores and prevent them from shifting in the mold. They should be large enough so that they do not completely melt and permit the core to float, and small enough that the surface melts and fuses with the cast metal.

42. When plaster molds are made, plaster is mixed with water and hardening occurs by a hydration process. If a high-melting temperature metal is poured into a plaster mold, the rapid evolution of the hydration water can cause an explosion. Therefore, plaster molds are only used with the lower-melting temperature nonferrous metals and alloys.

43. Process and part characteristics for plaster casting and ceramic mold casting are given in Table 14-4 and Table 14-5. While there are differences in some part characteristics, (e.g., part thickness limit and tolerance) the most striking difference is the greatly different melting temperature of materials that can be cast. Ceramic casting allows high melting temperature metals to be cast.

44. Graphite molds are often specified for use with highly reactive materials, such as titanium, that would interact unfavorably with many of the more common molding materials.

45. The individual patterns for investment casting are usually made from a molten wax, although plastics and mercury have also been used.

46. Investment casting molds are preheated prior to pouring to assure that the molten metal will flow more readily to all thin sections and to give better dimensional control by permitting the mold and the metal to shrink together during cooling.

47. In investment casting a pattern is formed from a low melting temperature, low vaporization temperature material, often wax. The mold is produced by surrounding the pattern with the mold material. The mold cavity is produced when the pattern is removed by melting/vaporizing the pattern. In early process development with porous mold materials the melted wax from the pattern would migrate into the mold material and be lost.

48. Counter-gravity investment casting uses atmospheric pressure, either negative gage pressure vacuum or positive pressure to cause the molten metal to flow into a sprue down-cavity up mold. In contract to using gravity to cause melt flow into the mold, counter-gravity casting enables molten metal to be drawn up into the mold from below the melt surface. This means that
-the molten metal entering the mold is free of slag and dross,
- the molten metal in the mold has low level of inclusions.

Since after the mold cavity fills the melt in the sprue and runner system can flow back to the melt pool, more of the melted metal becomes product than is gravity casting in which the sprue and runner system solidifies.

At low pressure gradients the metal may flow with lower turbulence than in gravity casting processes.
At higher pressure gradients it is possible to fill thinner mold/part sections than in gravity casting.

Since melt fluidity is less of a concern in counter-gravity casting lower melt temperature can be used resulting in improved grain structure and part properties.

49. The necessity of removing a pattern from a mold often requires some design

modifications, a complex pattern, or special molding procedures. When pattern removal is not required, no draft needs to be incorporated on the pattern, complex single-piece patterns can be used, and it is not necessary to use mold segments, such as a cope and drag.

50. In both full-mold and lost-foam casting processes the pattern-sprue-runner system is made from expanded polystyrene. The differences between the processes is in how the pattern system is supported and the mold created. In the full mold process green or chemically bonded sand is used around the pattern and becomes the mold when the pattern is removed. In lost foam casting a thin ceramic layer is formed on the pattern before the pattern-coating is surrounded by unbonded sand.

In essence, in full mold casting a bonded sand mold is made while in lost foam casting a thin ceramic layer-unbonded sand mold is used.

51. The nature of evaporative pattern casting processes leads to advantages compared to other types of casting operations that include
- complex parts can be produced since pattern removal is not a concern,
- with no pattern or core removal necessary mold and part draft can be eliminated,
- cores and parting planes are not required and so simpler processes and less involved process control result,
- with simpler molds simpler runner systems are often possible leading to increased ratio of product weight to weight of metal pored,
- molten material tends to solidify from the furthest point in the mold to the sprue often eliminating the need for risers,
- particularly with lost-foam ceramic layer molds high precision parts with smooth surfaces can be produced,
- if backup sand used in the mold in not bonded it may be directly reused.

52. In shakeout the part, sprue-runner system, cores, etc. are separated from the flask and mold material. Since the mold is designed and made to withstand damage during the entire mold construction-casting process it is a substantial, relatively strong structure. Therefore,
- shakeout entails additional operations to obtain the part,
- the shakeout operations have the potential for damaging the part and so have to be carefully designed and operated.

In general, shakeout implies additional, involved processes.

53. Castings can be cleaned by abrasive means in which particles are caused to impact on the part and so mechanically remove adhering sand, oxide, scale and parting line burrs/flash. The abrasive media can be nonmetallics such as sand, alumina and glass beads or metal shot. The abrasive accelerating system can be high velocity air (sand blasting) of centrifugal force, e.g., produced by feeding shot to the center region of a spinning, vaned wheel.

Problems:

No problems

Case Study:

Moveable and Fixed Jaw Pieces for a Heavy-duty Bench Vise

1. The mechanical properties and size of the piece clearly favor the use of some form of ferrous material, and the size and shape tend to dictate casting. The high elongation can be met by some of the more specialized cast irons, such as ductile cast iron, but also tends to favor the cast steels. Because of the size of the product, some form of expendable-mold sand casting would be likely. While green sand is a possibility the molds will require considerable strength and processes involving stronger molds, such as shell mold will be preferred. Cores will be used to produce the interior channels.

2. Because of the wide variation in section size, the as-cast products would be expected to have high and complex residual stresses and variability of structure and properties. To relax stresses, achieve uniformity, and attain the desired properties, most of the recommended alloys would require some form of heat treatment. Because the properties are not extremely demanding, a furnace anneal may be all that is required. Normalizing may be used if the variability with section size and location can be tolerated. The replaceable jaws would need the higher hardnesses produced by a quench and temper heat treatment process.

3. Corrosion resistance to a shop environment is desirable, and would most likely need to be imparted by paint or other form of surface treatment. If paint is selected, both adhesion and durability (including resistance to various oils and solvents) would be selection conditions. A sand blast treatment may be useful in cleaning the surfaces and producing the roughness necessary for enhanced adhesion.

CHAPTER 15
Multiple-Use Mold Casting Processes

Review Questions

1. The major disadvantage of the expendable-mold casting processes is the requirement that a separate mold be created for each casting. Variations in mold consistency, mold strength, moisture content, pattern removal, and other factors contribute to dimensional and property variation within a production lot.

2. Since the multiple-use molds are generally made from metal, the processes are often restricted to the casting of the lower-melting-point nonferrous metals and alloys. Part size is often limited, and the dies or molds can be rather costly.

3. The reusable molds for permanent mold casting are frequently made from gray cast iron, steel, bronze, or graphite. Aluminum, magnesium, and the copper-based alloys are the metals most frequently cast.

4. Advantages of the permanent-mold casting process include: a reusable mold, good surface finish and dimensional accuracy, the possibility of controlling solidification to give desired properties, and a fast cooling rate to produce a strong structure. Cores can be used to increase the complexity of the castings.

5. Permanent molds, and ancillary equipment, have to be designed to have long lives and so tooling costs for permanent mold casting operations are high. Setup and operating costs are also high. This high process cost cannot be recovered in low part production runs.

6. Permanent mold life depends on part material related characteristics such as melting temperature and melt-mold material compatibility and process related conditions such as pouring temperature and mold temperature.

The primary mold feature that influences mold life is difference in section size through the mold. Different section sizes produce temperature gradients and so differences in mold expansion contraction and also determine the flow patterns as the melt fills the mold.

7. Permanent-mold castings are generally removed from the mold immediately after solidification because the rigid cavity offers great resistance to shrinkage. Tearing might occur if the part is restrained while cooling.

8. Permanent molds are not permeable and usually have smooth mating surface. Venting is usually implemented using slight opening between the mold halves or the addition of small vent holes and passages from the mold cavity to the outside.

9. Slush casting can be used to produce hollow shapes with good surface detail. Wall thickness is variable, so products are largely decorative items, such as candlesticks, lamp bases, and statuary.

10. Low-pressure permanent-mold casting introduces the molten metal into the die by forcing it upward through a vertical tube. The driving force is a low pressure of 5 to 15 psi applied the molten bath.

11. Since no risers are used in the low-pressure permanent-mold process (the pressurized feed tube acts as a riser) and the molten metal in the feed tube can be immediately reused, the yields of the process are generally greater than 85%. The metal is exceptionally clean since it is bottom-fed and never passes through air. Nonturbulent filling further reduces gas porosity and dross, and directional solidification and pressure feeding act to minimize shrinkage problems.

12. Vacuum permanent-mold casting offers all of the advantages of the low-pressure process (clean metal, low turbulence, low dross, compensation for shrinkage, high yields, and good mechanical properties) . In addition, the vacuum produces an even greater cleanliness and low dissolved gas content. Thin-walled castings can be produced with excellent surface quality.

13. In low-pressure permanent-mold casting, the feeding pressures are on the order of 5 to 15 psi. In die casting, the molten metal is forced into the molds by pressures of thousands of pounds per square inch and is held under this pressure during solidification .

14. Most gravity permanent-mold dies are made from gray cast iron. This material has great resistance to thermal fatigue and machines easily. In contrast, die casting dies are generally made from hardened tool steels, since cast iron cannot withstand the casting pressures.

15. Because high pressures might cause turbulence and air entrapment, lower injection pressures may be preferred, followed by higher pressure after the mold has filled completely and the metal has started to solidify.

16. Hot-chamber die-casting machines cannot be used for the higher-melting-point metals, such as brass and bronze, and molten aluminum has a tendency to pick up iron from the casting equipment. Therefore, the hot-chamber machines are generally used with zinc-, tin-, and lead-based alloys.

17. In hot-chamber die-casting machines the molten metal may be in the machine chamber for an extended period. Metals that have high melting temperatures compared to the machine material or react with the machine material are not suitable for hot-chamber die-casting machines. Cold-chamber machine are used to die cast these kinds of materials and examples of such materials are aluminum which picks up iron and magnesium. copper and high-aluminum zinc.

18. Die casting dies fill with metal so fast that there is little time for the air in the mold cavity to escape. To minimize entrapped air problems, such as blow holes, porosity and misruns, the dies must be properly vented, usually by the incorporation of wide, thin vents at the parting line.

19. Since the molten metal is injected into the mold cavity under pressure and this pressure is maintained throughout solidification, risers are not incorporated into the mold design in die casting. Sand cores cannot be used because the pressure of the molten metal would cause them to disintegrate as the metal is injected or produce extensive penetration during the cast. Retractable metal cores can be incorporated into the dies.

20. By introducing the molten zinc directly into the die cavity through a heated manifold and heated nozzles, one can eliminate the sprues, gates and runners normally incorporated into a die-casting die, significantly increasing the yield of the process .

21. Die casting is characterized by extremely smooth surface finishes, excellent dimensional accuracy, and high production rates. A single set of dies can produce many thousand castings without significant changes in dimension.

22. The manufacturing cost of a part includes all the processes needed to produce the part. Typically a series of processes is needed and so if die casting can reduce the number of operations needed and/or simplify the processes, the higher cost of die casting may be offset by lower costs for other, required operations. An example is decreased costs of subsequent finishing (machining to produce specified dimensions and surface finishing to produce desired appearance) for higher cost but more accurate, better surface die cast parts compared to lower cost parts from other types of casting processes that need more or more complicated finishing.

23. In squeeze casting, a precise amount of molten metal is poured into the bottom half of a preheated die set and allowed to partially solidify. An upper die then descends, applying pressure throughout the completion of solidification.

24. A thixotropic material is a semi-solid (liquid plus solid) material that can be handled mechanically like a solid, but shaped at very low pressures because it flows like a liquid when agitated or squeezed. As an alternative to squeeze casting, it eliminates the need to handle molten metal, and reduces or eliminates many of the molten metal problems, such as gas pickup and shrinkage.

25. In semisolid die-casting
- injection temperature is low and so solidification time is short, less substantial machines are needed and machine component life is long,
- the mechanical action breaks up the structure of the semisolid and so a more desirable metallic, isotropic, structure can be produced.

26. In true centrifugal casting, the metal is forced against the outer walls of the mold with

considerable force and solidifies first at the outer surface. Products have a strong, dense exterior surface. Lighter-weight impurities tend to be present on the inner surface, which is frequently removed by a light machining cut.

27. In centrifuging, centrifugal force is used to force metal from a central pouring reservoir into thin, intricate mold cavities removed from the axis of rotation. Thus, the mold cavities fill under the pressure of centrifugal force. In semicentrifugal casting, a single, axisymmetric casting is poured by introducing metal into the centermost region of a rotating mold. The center pouring region is an integral part of the casting .

28. In the electromagnetic casting process there is no interaction with a container, and the electromagnetic stirring promotes a homogeneous, fine-grained structure.

29. Selection of a furnace or melt procedure depends on such factors as: the temperature needed to melt and superheat the metal, the alloy being melted, the desired melt rate and quantity, the desired quality of the metal, the availability and cost of fuels, the variety of metals to be melted, the desire for either batch or continuous melting, the required level of emission control, and the capital and operating costs.

30. Cupolas are used to produce gray, nodular and white cast irons.

31. In cupola-melting operations, temperature and chemistry control is somewhat difficult. The nature of the charged materials and the reactions that occur within the cupola can all affect the product chemistry. Moreover, when the final chemistry is determined by the analysis of the tapped product, there is already a substantial quantity of material within the furnace. Therefore, final chemistry adjustments are often performed in the ladle via ladle metallurgy.

32. In order to increase the melting rate of the metal in a cupola the rate of heating of the incoming air and of the metal have to be increased. Incoming air can be preheated by passing it through a heat exchanger that uses the stack gas as a heat source. Oxygen can be added to blast to increase temperature and increase reaction rate and melting rate. High energy density heat sources can be used, e.g., plasma torches.

33. The stirring action, temperature control, and chemistry control of the indirect fuel-fired furnaces are all rather poor. The major attractive feature is the low capital equipment cost.

34. Arc furnaces offer rapid melting rates, the ability to hold molten metal for any desired period of time to permit alloying (a flux blanket protects the metal), and ease of incorporating pollution control .

35. Channel-type induction furnaces, where the molten metal circulates through a secondary coil loop and gains heat, offer great ability to provide precise temperature control. These make excellent holding furnaces, where the molten metal must be held for long periods of time at a specified temperature.

36. The poring operation has to be designed to insure that the proper pouring temperature is maintained and that only high quality metal gets into the mold. The poring ladle is a critical part of the pouring system.

37. Some of the typical cleaning and finishing operations performed on castings include: removal of cores, gates, risers, fins, and rough spots on the surface, cleaning of the surface, and repairing of any defects.

38. Sand cores are removed by mechanical shaking which may sometimes be preceded by chemically dissolving the binder.

If the runners, risers and gates joining different sections of the part-runner system are small in cross section the part can be broken off of the runner system. If section area is large cutting is necessary using saws, abrasive wheels or oxyacetylene or plasma torches.

39. Some types of casting defects can be repaired readily by arc welding In addition, surface porosity can be filled with a resinous material, such as polyester, by a process known as impregnation.

40. In metal-casting operations, robots can be used to tend stationary, cyclic equipment, such as die-casting machines. They can be used in finishing rooms to remove sprues, gates and runners, perform grinding and blasting operations, and assist in the heat treatment of castings. They can dry molds, coat cores, vent molds, and clean and lubricate dies. In certain processes, they can be used to dip patterns into mold material slurries and position them to dry. Further implementation might include their use to position the pattern, fill the flask with sand, pour the molten metal, and manipulate a cutting torch to remove the sprue.

41. Some of the features affecting the cost of a cast product include: the direct cost ~t material and the energy to melt it, and the indirect cost of patterns, molds, dies, melting and pouring equipment, scrap metal, cleaning, inspection and labor. While the direct costs do not change with the number of castings being produced, the indirect costs must be shared over the production lot. An expensive die may not be justifiable for a small number of castings.

Problems:

No problems

Case Study:

Baseplate for a Household Steam Iron

1. The baseplate must heat to elevated temperatures quickly and cool to room temperature quickly after use. It must sustain repeated thermal cycles without deterioration, be light enough to facilitate ease of use but heavy enough to press out wrinkles without requiring a pushing force, and provide scratch resistance to buttons, snaps, rivets and zippers. The material must be corrosion resistant to steam (and all of the associated contaminants of various waters), as well as a variety of laundry products. It must be fracture resistant to dropping from waist height. The heating element must be thermally-coupled, but electrically-insulated (NOTE: Normally, thermal conductivity and electrical conductivity are proportional properties for metals!). While the key properties are thermal conductivity, corrosion resistance, and light weight, strength, wear resistance, toughness, and resistance to creep and thermal fatigue must all be present at moserate levels. An attractive appearance may be desired for marketability, and machinability may be required to produce the necessary holes, threaded recesses, and dimensional precision .

2. While aluminum would be the primary material to be considered, some possible alternatives might be: Stainless steel (heavy and poorer thermal conductivity), copper alloys (heavier than steel), and cast iron (heavy). Aluminum alloys offer the desired low density, low cost, high thermal conductivity, good corrosion resistance, machinability, and appearance.

Jumping ahead to marry material and process, the most attractive process appears to be die casting, and the family of aluminum die casting alloys is relatively small. Alloy 380 presently accounts for the overwhelming majority of such castings (probably more than 80%). While other alloys may offer better thermal conductivity, the enhancement may not be sufficient to justify deviation from a material that has become the industry norm.

3 . Because of the integral heating element, production would most likely be by some form of casting with a "cast-in insert". Alternative methods include: sand, shell mold, full mold, permanent mold, plaster mold, investment and die casting, as well as various methods of forging or powder metallurgy, for which the insert would have to be a secondary addition.

Within the realm of reasonable production capability, none of the processes could produce the completed part to net-shape directly. Die casting appears to come closest, being capable of producing the narrow webs and 1/8 inch diameter recesses, but is not capable of producing the 1/16 inch holes for the steam vents by means of coring. Surface finish and dimensional precision are excellent for this application.

4. The 1/16 inch holes would most likely be added by some form of secondary machining operation, such as drilling. In addition, the larger holes are threaded, but the simplest means of core removal is simple retraction. Therefore, it is likely that these would be made as smooth-bore cavities in the casting, sufficiently undersized to permit the machining of the threads as a secondary operation.

5. The simple buff and polish may well be the best possible finish. The long-term durability of the teflon coating is questionable, and the anodized layer would produce a

darker dull gray finish on the silicon-containing casting alloy. In addition, this layer has been known to flake off due to the differential thermal expansion characteristics and the brittle nature of the oxide material.

CHAPTER 16
Powder Metallurgy

Review Questions

1. Powder metallurgy processes involve blending of powders, pressing of the powders to a desired shape and sintering.
Since powders are used, the composition of the part can be varied over a wide range and so a wide range of part properties can be produced.
By using a powder component that can be removed after the part is formed permeable parts can be made.
Since powders are compacted in relatively high precision tooling, accurate parts can be produced.
Compaction may require high pressure and in such a case compaction forces will be large and parts will be small.
Sintering enables part characteristics to be controlled by controlling the sintering process.

In general, small, high precision parts that need to have carefully controlled microstructure are candidates for production using powder metallurgy techniques.

2. Some of the earliest mass-produced powder metallurgy products included coins and medallions, platinum ingots, and tungsten wires. These were followed by carbide cutting tool tips, nonferrous bushings, self-lubricating bearings, and metallic filters.

3. Automotive applications currently account for nearly 75% of P/M production. Other major markets include: household appliances, recreational equipment, hand tools, hardware items, business machines, industrial motors, and hydraulics.

4. Iron and low alloy steels are used in about 85% of powder metallurgy production. The large amount of this metal family previously (and currently) used and the workability and experience with working it led to the early and continued development of powder metallurgy processes using it.

5. The powder metallurgy process normally consists of four steps: powder manufacture, mixing or blending, compacting, and sintering .

6. Some important properties and characteristics of metal powders are: chemistry and purity, particle size, size distribution, particle shape, and the surface texture of the particles .

7. The most common means of producing metal powders is by melt atomization where molten metal is fragmented into small droplets and the droplets solidify into particles of metal. Any material that can be melted can be atomized and the resulting particles retain the chemistry of the parent material.

8. Other techniques of powder manufacture include chemical reduction of particulate compounds, electrolytic deposition from solutions or fused salts, pulverization or grinding of brittle materials (comminution), thermal decomposition of hydrides or carbonyls, precipitation from solution, and condensation of metal vapors .

9. Powder production processes based on processes in which elemental forms of material are produced and exist will be practically useful (not overly complicated, time consuming, energy intensive, easily controllable) only for producing elemental powder. For example, as chemical reduction, thermal decomposition and condensation processes occur different elements are obtained at different stages (time, temperature or composition) and so elemental powders are the logical product to be produced using such processes.

10. The production of amorphous and rapidly solidified powders requires large energy density (energy per unit volume of material produced) and so with reasonable energy levels only small particles can be produced. That is, for fixed energy input the requirement of high energy density means that only small volume products can be produced. To make useful products these small particle, powder, raw materials have to be combined and powder metallurgy techniques accomplish this consolidation task effectively and efficiently.

11. To make a powder metal product powder in placed in a die, pressed and then sintered. To describe the ability of the powder to flow into the die and into various, small, sections of the die cavity and to be uniformly distributed in the die, quantitative measures of powder flow are useful. Flow rate tests provide such a powder behavior measure in flow rate.

12. Apparent density is the density of the loose powder to which there has been no application of external pressure. Final density is measured after compaction and sintering and is typically about twice the value of the apparent density.

13. Green strength refers to the strength of the powder metallurgy material after pressing, but before sintering. Good green strength is required to maintain smooth surfaces, sharp corners, and intricate details during ejection from the compacting die or tooling and subsequent transfer to the sintering operation .

14. Mixing or blending is performed to combine various grades or sizes of powders or powders of different compositions, or add lubricants or binders to the powder.

15. The addition of a lubricant improves the flow characteristics and compressibility of the powder at the expense of reduced green strength.

16. While lubricants such as wax or stearates can be removed by vaporization, the graphite remains to become an integral part of the final product. In the production of steel products, the amount of graphite lubricant is controlled so it will produce the desired

carbon content in the final material when it is dissolved in the iron powder.

17. Composites of compatible (easily bonded in sintering) materials should be easy to produce by powder metallurgy techniques.

Since there is a large amount of mechanical working of the powders used in powder metallurgy processes, and since surface areas are high energy regions on material bodies, and since powder surface area is large, the opportunity for producing composites of usually incompatible materials exists. That is the combination of mechanical working and high surface energy may make powder sintering possible and an effective way to create composite materials. Examples are composites composed of an immiscible material dispersed in a matrix and combinations of metals and nonmetals.

18. The goal of the compacting operation is to compress and densify the loose powder into a desired shape. Uniform high density is desired and the product should possess adequate green strength .

19. Compacting pressures generally range between 3 and 120 tons per square inch, with values between 10 and 30 being most common. The total pressing capacity of compacting presses is the feature that generally restricts the cross-sectional area of P/M parts to several square inches.

20. During compaction, the powder particles move primarily in the direction of the applied force. The powder does not flow like a liquid, but simply moves in the direction of pressing until an equal and opposing force is generated through either friction between the particles and die surfaces or by resistance from the bottom punch.

21. When pressing with rigid punches, the maximum density occurs adjacent to the punch and diminishes as one moves away. With increased thickness, it is almost impossible to produce uniform, high density throughout the compact. By using two opposing punches, a more-uniform density can be obtained in thicker pieces.

22.The final density of a P/M product can be reported as either an absolute density in units of weight per volume, or as a percentage of the theoretical density, where the difference between this number and 100% is the amount of void space still present in the product.

23. Conventional powder metallurgy products fall into the classes of
1. Porous or permeable products that are design and produced to small pores or voids that can be filled with another material or to function as porous media as do filters.
2. Complex shaped parts with dimensional and geometric tolerance and surface finish requirements that require only light finishing when produced by powder metallurgy. Such parts can be produced in powder metallurgy dies and so avoid complex machining operations.

3. Product made from high melting point or difficult to machine materials. The mechanical action in compaction and high surface energy of powders make consolidation by sintering practical and avoids difficult machining tasks.
4. Products made from composite materials. Composites can be made from compatible, easily sintered materials and even from some incompatible materials (Question 17).

The use of the concepts of better properties and economic advantage (items 5 and 6 in the text) are useful for describing the advantages of the powder metallurgy processes, but not for describing types of products.

24. Isostatic compaction is the process in which the powder is exposed to uniform compacting pressure on all surfaces, and is usually achieved by encapsulating the powder in a flexible mold and immersing it in a pressurized gas or liquid. The process is generally employed on complex shapes that would be difficult to compact by the faster, more traditional techniques.

25. Warm, elevated temperature, compaction produces more uniform compaction and improved as-compacted and after processing properties, primarily strength. As temperature is increased powder strength decreases. During warm compaction increased deformation of the powder and increased mechanical action makes for more uniform density and increased bonding due to disruption of surface layers on the powder particles. The increased, more intimate contact between powder particles also increases the material consolidation effects of sintering.

26. To increase the powder flow capability, very small particles are used in the powder used in metal injection molding compared to the particle size of powders in conventional powder metallurgy processes.

27. Depending on the binder used, it is removed by
- solvent extraction,
- heating to above the binder volatilization temperature,
- catalytic chemical binder decomposition.

28. During sintering, P/M injection molded parts shrink between
15 and 25% as they achieve their final density and properties.

29. Since small particle size powders are expensive as is binder removal, the ideal geometry for a metal injection molded part is
- a part in which mechanical performance (strength and deformation behavior) is obtained by efficient design rather that by use of a large amount of material, e.g., the ability to get the same performance with less material in an I-beam than with a rectangular cross section beam. Powder cost implies small, complex parts.
- a thin part. Binder removal will be faster and more effective if the binder-surface distance is small. Binder removal implies small, thin parts.

30. P/M injection molding enables the P/M production of small, complex components

that were previously investment cast or machined directly from metal stock. Parts can be made with thin walls and delicate cross sections that would be impossible to compact in a conventional press.

31. The three stages of sintering are: (1) the burn-off or purge -- designed to remove air, volatilize and remove lubricants and binders, and slowly raise the temperature of the compacts; (2) the high-temperature sintering stage, with the temperature being constant; and (3) the controlled cool-down.

32. Most metals are sintered at temperatures between 70 and 80% of their melting point. Certain refractory metals may require temperatures as high as 90% of the melting point.

33. When sintering, one must slowly raise the temperature of the compacts in a controlled manner because rapid heating would produce high internal pressure from heating air entrapped in closed pores and volatilizing lubricants. This would result in swelling or fracture of the compacts.

34. Controlled, protective atmospheres are necessary during sintering because the fine powder particles have large exposed surface areas and, at elevated temperatures, rapid oxidation will occur and impair the properties of the product.

35. During sintering, metallurgical bonds form between the particles. In addition, alloys may form, product dimensions will contract, and density will increase.

36. The purpose of sinter brazing is to join two or more powder metal parts. The brazing process is carried out during the sintering of the individual parts.

37. Products of HIP techniques generally possess full density with uniform, isotropic properties that are often superior to those of products produced by alternative techniques. Near-net shape production is possible, and reactive materials can be processed since they are isolated from the environment.

38. The primary limitations of the HIP process are the cost of "canning" and "decanning" the material, and the long time required for the processing cycle. The sinter-HIP process permits the production of full-density products without the expense and delay of canning and decanning.

39. Sinter-HIP and pressure assisted sintering are intended to produce the same desirable part characteristics as hot isostatic pressing. The main advantage of sinter-HIP and pressure assisted sintering is that the canning and decanning operations in HIP are eliminated.

40. Alternative techniques for the production of high-density P/M products include the various high-temperature forming methods, the Ceracon process, and spray forming (also called the Osprey process).

41. In spray forming
- a stream of molten droplets is produced,
- the droplet stream is sprayed into a collecting container,
- the temperature of the initial material and droplet velocity and flow rate are controlled so that the droplets are in a semisolid or slushy state when they interact with each other in the container,
- the collection of droplets freezes into the part of a structural shape depending on the shape of the collecting container.

High density, fine grain size parts can be made since the interacting droplets are small and can deform extensively in the process since they are in the semisolid state.

42. Repressing, coining or sizing operations are generally used to restore dimensional precision. Only a small amount of metal flow takes place.

43. Repressing cannot be performed with the same tooling that was used for compaction because the compaction tooling is designed to produce an over-sized compact to compensate for the dimensional shrinkage that occurs during the sintering operation.

44. During repressing, only a small amount of metal flow takes place, and the part retains its starting shape. PIM forging, however, imparts a considerable amount of plastic deformation as the material flows from a simple starting shape to a more-complex shape forging.

45. While impregnation and infiltration are both processes that fill the permeable void space with another material, infiltration refers to the filling of the voids with another metal, while impregnation employs a liquid, plastic, or resin.

46. Powder metallurgy product density is directly related to the number and size of the pores in the product. The voids or pores can effect the performance of secondary or finishing operations. The effects are due to the voids in the part and the surface area of the pores.

In heat treatment the part environment during heating and quenching can enter the voids in the part, at least the pores near the surface. Any undesirable reactions between the environment and the part will occur on the part surface and internal to the part in the pores. Protective or nonreacting heating atmospheres may be required. Quenching medium entering the part leads to more extreme temperature gradients in powder metallurgy parts than in solid parts of the same size and shape. Material-quench medium chemical reactions occur not only on the surface but also over the wetted surfaces of the pores. Certain liquid quenching mediums may not be useable.

Both mechanical and fluid-part interactions occur in machining. The density of powder metallurgy parts can indicate potential concerns when machining these parts. When the cutting tool passes through the powder metal workpiece and encounter voids the mechanical loading in the tool edge-work material interaction region changes. Cutting forces become intermittent. The deformation imposed on the work material changes since the tool passes from solid material – to a void – to solid material. The changing cutting forces and deformation patterns lead to a less controlled machining process and potentially a rough, damaged machined surface and increased tool wear. Sharp tools and light cuts can help minimize undesirable mechanical effects in machining. Cutting fluids can enter the pores in the powder metal part and produce undesirable temperature gradients and deleterious fluid-work material chemical reactions.

Surface treatments can involve mechanical, thermal and chemical effects depending on the treatment, e.g., shot peening to produce compressive residual stress, heat-and-quench treatments, carburizing. Powder metal part density, volume of pores, can indicate potential problems with deformation and fracture in mechanical processes and surface-environment problems in thermal and chemical processes as discussed above.

47. The fracture-related properties, such as toughness, ductility, and fatigue life show the strongest dependence on product density.

48. When converting the manufacture of a component from die casting to powder metallurgy, it is important to realize that P/M is a special manufacturing process and provision should be made for a number of unique factors. Products that are converted from other manufacturing processes without modification in design rarely perform as well as parts designed specifically for manufacture by powder metallurgy.

49. The ideal powder metallurgy product has a uniform cross-section, and a single thickness that is small compared to the cross-sectional width or diameter.

50. Powder metal parts provide opportunities for improved part performance since in may be possible to add performance improving additives into the pores in the part. Even with no added material the pores in powder metal parts can be used. By controlling pore size the flow of gases, liquids and particles through the part can be controlled. Examples of products that use part porosity or permeability to advantage are oil impregnated powder metal bearings, powder metal filters and flow regulators.

51. In the electrical industry, copper and graphite are frequently combined to provide both conductivity and lubrication. Electrical contacts frequently combine copper or silver with tungsten, nickel or molybdenum, where the material with high melting temperature provides resistance to fusion during the conditions of arcing and subsequent closure.

52. Machining has two general goals, to produce desired shapes and dimensions and to produce specified surface finish. Finish machining usually is concerned with producing tight tolerance dimensions and low rough ness surfaces. To accomplish these goals high accuracy, rigid, dynamically stable machine tools are required and usually mild cutting conditions are used with resulting low rate of material removal and long machining time. Expensive machine tools and tooling and low material removal rates lead to high cost finish machining operations.

53. In casting materials that are immiscible, that do not form solutions or are outside solubility limits will not form useful continuous solid materials on solidification. While these types of materials cannot be cast, often they can be combined by the mechanical and thermal processes in powder metallurgy processes. An extreme case example is the production of metal-ceramic composites such as aluminum-alumina.

In many forming processes complex shapes are produced and so large deformations are required to form the parts. If the required deformation exceeds the maximum deformation possible before fracture the part cannot be formed or can only be formed in complex, costly processes such as forming-annealing-forming. With the same material in powder form, compacting and sintering can be used to produce the desired shape without the limits imposed by maximum possible deformation. After sintering final sizing by a deformation process to relatively high deformation levels can often be achieved. The residual porosity after sintering effectively increases material ductility as pores are closed in mechanical sizing operations. The conclusion is that powder metallurgy processes may be useful for forming brittle metals such as uranium and zirconium.

Also, composite parts can be made using powder metallurgy processes, Question 17.

54. Because of the high pressures and severe abrasion involved in the compacting process, the dies must be made of expensive materials and be relatively massive. The set-up and alignment of punches and dies is frequently a time-consuming process. Production volumes of less than 10,000 identical parts are rarely practical .

55. The higher cost of the starting material for powder metallurgy is often offset by the absence of scrap formation and the elimination (or reduction) of costly machining operations. Moreover, P/M is usually employed for the production of small parts where the material cost per part is not very great.

56. When compared to cast or wrought products of the same material, conventional P/M products generally possess inferior mechanical properties. This may be an unfair comparison, for if the P/M material and processing is designed to produce a desired product, the desired mechanical properties can often be obtained at lower cost than by alternative techniques. The material, however, is frequently different from that used in wrought or cast equivalents. If full density can be achieved, the properties of PiM products are often superior to their wrought or cast counterparts.

Problems:

1. In addition to chemical purity, the key properties or characteristics for material being used in powder metallurgy are those that affect how the powder will, flow, fill space, compact (i.e. respond to pressure), and sinter, as well as those that will directly affect the final properties. These include:
surface chemistry, particle size and size distribution, particle shape (and shape distribution), surface texture, and microstructure (or mechanical properties) . Since the

material is processed as a solid, all of the geometric and property features of the solid become important.

The characterization of starting material for a powder metallurgy process is far more extensive than specifying the starting material for casting (where the material will be melted and both the geometry and the properties will be significantly altered by the process), and forming (where the properties are important, but the starting geometry will be highly altered) .

2. The hot pressing process would not be attractive for the manufacture of conventional P/M parts because loose powder must be protected from oxidation when it is at the elevated temperature. Conventional P/M permits compaction in air because the powder is at room temperature, and reaction rates are acceptably slow. Protective atmospheres are provided during elevated temperature sintering. In hot pressing, some form of "canning" or isolation must be provided and this brings about additional expense and decreased rate of production.

Case Study:

Impeller for an Automobile Water Pump

1. The relatively low mechanical property, ductility, hardness and wear resistance requirements make this part a candidate for a variety of materials. Because of the presence of coolant and a additional materials in the shaft and housing of the pump, material selection should take into account galvanic corrosion. Possible materials include aluminum, cast iron, copper alloys, stainless steel and others.

2. As designed, the part is a two level part with flat surfaces. With the relatively low surface area and small thicknesses the part can be manufactured by conventional press-and-sinter powder metallurgy using a double acting press. Alternative means of manufacture are some form of casting, such as die casting, permanent mold, shell or investment casting. It would be difficult to use forming processes to form the part because of the lack of draft on the impeller blades. With design changes forging could be used.

3. Possible manufacturing processes are listed in part 2. Each is more compatible with the use of some materials rather than others.

4. Since the part will constantly exposed to water over a range of temperature, the compatibility of polymers with this environment is a major concern. Many polymers absorb water and swell. The change in part dimension in use is unacceptable. This limits the material choice to high performance, engineered polymers which are probably not practical for such a mass produced, low cost part.

CHAPTER 17
Fundamentals of Metal Forming

Review Questions

1. Plasticity is the ability of a solid to flow, plastically deform, without deterioration of its properties. The mathematical description of plastic deformation stresses and strains, and the relations between them is known as the theory of plasticity.

2. Deformation processes shape metal in the solid state through the rearrangement rather than the removal of material. Unfortunately, large forces are required, and the machinery and tooling can be quite expensive. Large quantities may be necessary to justify the capital expenditure.

3. Large production quantities are often necessary to justify the use of metal deformation processes because the large forces require costly machinery and tooling.

4. Independent variables are those aspects of a process over which the engineer has direct control. They are generally selected or specified when setting up the process.

5. The specification of tool and die geometry is an area of major significance in process design. Since the tooling will produce and control the metal flow, the very success or failure of a process often depends upon good tool geometry.

6. It is not uncommon for friction to account for more than
50% of the power supplied to a deformation process. Product quality is often related to friction, and changes in lubrication can alter the material flow and resulting material properties. Production rates, tool design, tool wear, and process optimization all depend upon friction and lubrication. In addition, lubricants often act as coolants, thermal barriers, corrosion inhibitors, and parting compounds .

7. Lubricants, and metal working lubricants in particular, can act as coolants, thermal barriers and corrosion inhibitors. Often lubricants are formulated to include or enhance these functions in addition to their use in reducing friction.

8. If the speed of a metal forming operation is altered, several changes can occur. Many materials are speed-sensitive and will behave differently at different speeds. Ductility may vary, and many materials appear stronger when deformed at faster speeds. In addition, faster speeds promote lubrication efficiency and reduce the amount of time for heat transfer and cooling.

9. Dependent variables are aspects of a process determined by the process itself as a consequence of the values selected for the independent variables.

10. It is important to be able to predict the forces or powers required to perform a specific forming process, for only by having this knowledge can the engineer specify or select the equipment for the process, select appropriate tool or die materials, compare various die designs or deformation methods, and ultimately optimize the process.

11. The engineering properties of a product can be altered by both the mechanical and thermal history of the material. Therefore, it is important to know and control the temperature of the material throughout the process.

12. Metal-forming processes are complex systems composed of the material being deformed, the tooling performing the deformation, lubrication at surfaces and interfaces, and various other process parameters. The number of different forming processes is quite large, and various materials often behave differently in the same process. The independent variables interact with one another, so the effects of any change are often quite complex.

13. The predictive link between independent and dependent variables is generally based on one of three approaches:
experience, experiment, or process modeling.

14. To be truly valid, direct experiments should be full-size at production speeds. Reduced magnitude testing generally alters lubricant performance and thermal effects. Results should be extrapolated to production conditions with caution. In addition, experimentation is costly and time-consuming.

15. Process modeling, particularly numerical modeling and simulation, has experienced greatly expanded use because
- of the availability of computers with continually increasing computational power,
- the accuracy of simulations.

In addition, there are many useful results that can be obtained through use of process models and some of these are listed in the answer to Question 17. below.
- of the use of quantitative results to provide understanding of details of deformation processes,
- obtaining quantitative results that correspond to reality demonstrates process understanding,
-of reductions in production delays and lead times due to having accurate predictions of process performance and part characteristics at the process design stage of manufacturing,
- they can be used as laboratory tools to run numerical experiments to
--- simulate processes using varying processing conditions and tooling to answer “what if?” questions,
--- investigate feasibility of modifications to processes and products and evaluate new processes and products.

16. The accuracy of the various process models can be no better than that of the input

variables, especially those like strength of material and interfacial friction.

17. In general, process models are used to predict process behavior and resulting product properties. Process behaviors such as forces and power required to produce a given deformation pattern and product characteristics such as deformation in surface regions and the resulting residual stress state can be calculated – is accurate process models are available.

In addition, and expanding on the thoughts underlying Question 15:
Process modeling, particularly numerical modeling and simulation, has experienced greatly expanded use because
- of the availability of computers with continually increasing computational power,
- the accuracy of simulations.
- of the use of quantitative results to provide understanding of details of deformation processes,
- obtaining quantitative results that correspond to reality demonstrates process understanding,
-of reductions in production delays and lead times due to having accurate predictions of process performance and part characteristics at the process design stage of manufacturing,
- they can be used as laboratory tools to run numerical experiments to
--- simulate processes using varying processing conditions and tooling to answer "what if?" questions,
--- investigate feasibility of modifications to processes and products and evaluate new processes and products.

18. A constitutive equation for an engineering material is an attempt to mathematically characterize the material's behavior under various conditions of temperature, strain, strain rate, and pressure .

19. Many of the process models describe friction by a single variable of constant magnitude -- i.e. friction is the same at all locations and throughout the entire time of the process.

20. It is important that the metal-forming engineer know the strength or resistance to deformation of the material at the relevant conditions of temperature, speed of deformation, and amount of prior straining. In addition, he would benefit from information on the formability and fracture characteristics, the effect of temperature and variations in temperature, strain hardening characteristics, recrystallization kinetics, and reactivity with various environments and lubricants.

21. Typically interface forces and temperatures are high in metalworking processes. This situation leads to high friction forces. So, friction is important in metalworking processes since high friction forces result in high overall forces (friction and deformation forces) and high energy dissipation. Large forces cause machine and tooling deformation and so the need for large, rigid, expensive forming machines. High energy dissipation rates

cause high temperatures and so increased tool wear and possibly deleterious effects on the workpiece/final part.

22. The friction encountered during metalforming operations is significantly different from that observed in most mechanical operations. In forming, a hard, nondeforming tool interacts with a soft, plastic, workpiece at relatively high pressure. Only a single pass is involved, and the workpiece is often at elevated temperature. Mechanical operations usually involve materials of similar strength, under elastic loading, with a wear-in cycle, and at relatively low temperatures.

23. Two important phenomena in determining resistance to motion of one surface over another, friction force, are
- the plowing of asperities on the harder surface through the softer surface,
- the breaking of bonds between the two surfaces. The bonds form when surfaces are brought into contact since local stresses can be very high and asperity-asperity bonding occurs.

24. Since the workpiece passes over the tooling only once, wear on the workpiece is generally not objectionable, and may actually be desirable as it produces a shiny, fresh-metal surface. Wear on the tooling, however, alters the dimensions and surface finish of the product and increases the power losses due to friction. Replacement of costly tooling may be required along with lost production during the changeover.

25. Lubricants should be selected for their ability to reduce friction and suppress tool wear. Other considerations include:
ability to act as a thermal barrier, coolant, or corrosion retardant; ease of application and removal; lack of toxicity, odor and flammability; reactivity; thermal stability; stability over a wide range of processing conditions; cost; availability, surface wetting; and the ability to flow or thin and still function .

26. If one can achieve full-fluid separation between a tool and workpiece, the required deformation forces may reduce by 30 to 40% and tool wear becomes almost nonexistent.

27. In general, an increase in temperature brings about a decrease in material strength, an increase in ductility, and a decrease in the rate of strain hardening - all effects that would tend to promote ease of deformation.

28. The temperatures required for hot working generally exceed 0.6 times the melting point of the material on an absolute temperature scale. Cold working generally requires temperatures below 0.3 times the melting point, and warm working is the transition region, between 0.3 and 0.6 times the melting point.

29. Hot working is deformation under conditions of temperature and strain rate such that recrystallization occurs simultaneously with the deformation.

30. Hot forming operations do not produce strain hardening and the companion loss of

ductility, permitting the material to be deformed by extensive amounts without the likelihood of fracture or the use of excessive force (elevated temperature lowers the strength and deformation does not increase it) . In addition, diffusion is promoted, pores can be reduced or welded shut, and the metallurgical structure can be altered to improve properties.

31. Disadvantages associated with hot working involve the reactions which may be promoted by elevated temperature, such as rapid oxidation. Tolerances are poorer and the metallurgical structure will be nonuniform if the amount of deformation or thermal history varies throughout the product.

32. If a metal is deformed sufficiently at temperatures above the recrystallization temperature, the distorted structure (of deformation) is rapidly replaced by new, strain-free grains. The final structure of the metal is that produced by the last recrystallization and the any subsequent thermal history. The production of a fine, randomly-oriented, spherical-shaped grain structure can improve not only the material strength, but also the ductility and toughness.

33. While the metal grains recrystallize during hot forming, inclusions and nonmetallic impurities do not and serve to impart an oriented or fiber structure (directional properties) to the product .

34. Heated dies are often used in hot forming operations to reduce the amount of heat loss from the workpiece surface to the tooling and maintain the workpiece temperature as uniform as possible. Nonuniform temperatures may produce surface cracking or nonuniform flow behavior and undesirable properties.

35. When dies or tooling is heated, the lifetime tends to decrease. Therefore, the upper limit to tooling temperature is generally set by some minimum desired lifetime.

36. Compared to hot working, cold working requires no heating, produces a better surface finish, and offers superior dimensional control, better reproducibility, improved strength, directional properties, and reduced contamination problems.

37. Some disadvantages of cold working include: higher forces, required use of heavier and more powerful equipment, less ductility, required surface cleanliness, and the possible need for recrystallization anneals . Detrimental directional properties and undesirable residual stresses may also be produced .

38. Cold working can replace the forming and some strengthening process sequence of operations with only a forming operation - if the required part strength level can be achieved by the strain hardening that occurs during cold working.

39. Key tensile test properties that can be used to assess the suitability of a metal for cold forming include: the magnitude of the yield-point stress, the rate of strain hardening, and the amount of ductility that is available.

40. Springback is an important phenomenon in cold working because the deformation must be carried beyond the desired point by an amount equal to the subsequent springback. Moreover, the amount of springback tends to differ from material to material.

41. Luders bands or stretcher strains are the ridges and valleys that can form on the surface of sheet metal that has undergone a limited amount of stretching. If the total stretch is less than the yield-point runout, some segments of the metal will undergo deformation and thin by an amount consistent with the entire yield-point runout while other regions resist deformation and remain at the original thickness. Both responses can occur since both require the same applied stress.

42. Cold working produces large changes in metal structure and changes the material properties that depend on microstructure. Compared to the same material in the not-cold-worked state, cold worked material will fracture at a lower strain, i.e., ductility decreases, Figure 17-8. The disruption of metallic structure will also make electron transport through the material more difficult and so electrical conductivity will decrease. The increasing number of smaller grains with cold working means that more grain boundaries are formed. Grain boundaries are high energy areas and so will be more sensitive to corrosion and material corrosion resistance decreases and stress corrosion cracking susceptibility increases.

Depending on the processing state and use of the material, increasing strength due to cold working may be a beneficial or deleterious effect. In continuing processing the increased strength means high processing forces and so increasing strength is a decline in material property. An aspect of this is considered in Question 43. If increased strength is beneficial to the product, cold working induced increase in strength is an improvement in properties.

43. In cold working work material strength increases and ductility decreases. Both of these effects can be changed in annealing processes. Intermediate anneals in a series of cold working operations can be used to undo the strain hardening/cold working effects of previous operations and so increase ductility and decrease processing forces in a subsequent operation. The final intermediate anneal (an anneal followed by one or more cold working operations rather than a final anneal after all cold working), combined with the final cold working process, can be used to control the strength and ductility of the final product. The final anneal will increase material ductility and decrease strength while a subsequent cold working process will decrease ductility and increase strength. Design of this final combination of processes being cognizant of the tradeoff allows production of a final part with desired strength and ductility.

44. Compared to hot forming, warm forming offers reduced energy consumption, less scaling and decarburization, better dimensional control, improved surface finish, less scrap, and longer tool life. Compared to cold forming, it offers reduced forces on tooling and equipment, improved material ductility, and a possible reduction in the number of

intermediate anneals.

45. The slow development of warm working processes is due to the lack of knowledge about material behavior in the warm working range and the limited enabling technology developed for use in this working temperature range. Cold and hot working processes have a long history and so the material knowledge bases for low and high temperatures are extensive and materials, machine tools, tooling and lubricants for use in them are well developed. The recent advent of warm working means that material property data for the relevant temperature range is scanty and very effective tooling, lubricants, etc., still need to be developed.

46. The work material characteristic that is the driving force for isothermal forming is a large dependence of material strength on temperature. For materials that are typically hot worked and whose strength increases rapidly with decreasing temperature a decrease in working temperature during processing will produce a large increase in strength and in the associated loads in the process. Such materials are candidates for isothermal forming.

47. Isothermal forming is more expensive than conventional forming since increased forming temperature has to be produced and the temperature and effects of increased temperature on the work and tooling materials have to be controlled. For example,
- work and dies have to be heated which is an increased cost over cold working,
- the increased tooling temperature will cause decreases in tool life,
- the energy dissipated in material deformation is almost all dissipated as heat. So, during forming the work temperature increases and large temperature changes defeat the purpose of isothermal forming. The simplest way to control this deformation work induced temperature rise is to decrease the deformation rate. This leads to lower production rates and increased costs.
- long time exposure of the work and tool materials to elevated temperatures may cause severe enough effects such as scale formation, decrease in strength and corrosion to warrant protecting the forming operation from the environment. Any controlled shielding such as by use of an inert gas will raise the initial cost the manufacturing machine and the operating cost since process complexity in increased.

Problems:

1. The problem deals with the amount of cold work and its effect on material strength and ductility as shown in Figure 17-8. A quantitative measure of "amount of cold work" is needed and one is provided in Chapter 2 in

percent reduction in area R.A. = $\{ (A_o - A_f) / A_o \}$ 100%

This is also a logical measure of deformation imposed in drawing, and is the one used.

The problem setting is

- there is a specified amount of deformation necessary,

  R.A. = $\{ (A_o - A_f) / A_o \}$ 100% = $\{ (0.110 - 0.008) / 0.110 \}$ 100%,

  R. A. = 93%,

- the required final yield strength of at least 50,000 psi means that the material must be subjected to a net amount of cold working of at least 27% - Figure 17-8,
- the required final product ductility of at least 10% elongation implies that the final drawing process in a sequence of draws should impose no more than about 31% cold work – Figure 17-8,

A solution is

- the final drawing process should impose cold work of about 30% on the work material that is in a state approximating its initial undeformed condition,
- assuming that an annealing process can bring the work material back to its initial condition, there should be an anneal before the last draw and the last draw is one imposing a 30% R.A.,
- the entire drawing sequence has to impose an amount of cold work = R.A. of 93%,
- so before the final anneal the previous drawing process(es) have to have produced a 63% amount of cold work,
- the question is then, can this previous 63% R.A. be accomplished in one drawing pass?
  - if so then a possible solution is
    draw to 63% R.A. then anneal then draw to 30% R.A.

I - if not, there is a limit on the amount of reduction that can be imposed in a single draw and a solution is

draw to a reduction less than maximum possible reduction, anneal, draw, anneal, draw etc with the individual draw reductions set to make the total reduction 93% and last draw reduction 30%

The maximum reduction possible in a wire drawing process is not discussed in the text. Quantitative models for maximum possible reduction exist. The general concept is that the drawing force acting on the wire should not result in a drawing stress that is larger than the yield strength of the wire leaving the die. Both the drawing stress and the wire yield strength depend on the amount of reduction, along with other factors such as die-work friction. Setting expressions for drawing stress and yield strength equal to each other gives the maximum reduction condition.

2. a) . Additional costs would include the cost of a heating furnace and the energy costs to achieve the warm working temperature. Tool life would be affected by the combination of increased temperature (decreasing lifetime) and the reduced loads associated with thermal softening (increasing lifetime) . Experience would determine which of the above effects would dominate. The reduction in strain hardening could reduce or eliminate the need for intermediate anneals, but consideration should be given toward attaining the desired final properties. Expanded capabilities in terms of size, complexity, and range of possible materials may expand possible markets.

b) . The conversion from hot forming to warm forming would be accompanied by an obvious savings in energy (heating the workpiece to a lower temperature and heating less material due to higher precision) . Additional energy might be saved if it is possible to achieve the desired final properties without requiring a final heat treatment (there is some strain hardening with warm working) . Improved dimensional precision and surface finish (reduced scaling and decarburization) can mean savings through a reduction in finish machining and the amount of material converted into scrap. Tool life is increased because of the reduced temperatures and the reduction of thermal shock and thermal fatigue. The forces required for forming will increase by 25 to 60%, 50 machinery must be more powerful, or the size of products produced on a given machine must be reduced.

3. Machining operations simply cut through the existing structure, removing the unwanted portion of material. The dimensions of the starting material must be sufficient to contain the crests of the threads. Thread rolling, on the other hand, forms the threads by displacing material from the root of the threads up into the crests. The starting diameter is between that of the root and crest. The benefits of material conservation and oriented flow continue as discussed in the text, but by cold forming the threads, the effects of strain hardening must also be considered. The deformed material will become stronger, but less ductile. The strengthening can be a significant asset, as long as the accompanying loss of ductility does not make the material too brittle. The residual stress pattern imparted by the deformation can be another concern as it can affect fatigue performance and contribute to failure by stress-corrosion cracking. In addition, it should be noted that the increased strength can be lost if the surface is exposed to elevated temperatures during operations such as hot-dip galvanizing.

Case Study:

Repairs to a Damaged Propeller

1). The specific recommendation would depend upon a number of factors: (1) What is the present condition or structure of the metal? Is it as-cast, age hardened, or annealed? ;(2) What is the ductility of this material in this condition? Can it be mechanically reformed without fracture? ;(3) Would elevated temperature aid in the reshaping? ;(4) Would any subsequent treatment be required after reshaping to restore the desired properties?

If the material is in the as-cast or annealed condition (one can determine this by hardness testing), and if the material has sufficient ductility, a reshaping may be possible directly. However, one should keep in mind that the propeller has undergone extensive cold working in the initial bending and may not possess sufficient remaining ductility. If insufficient ductility is present, a softening anneal may be required before the reshaping should be attempted. Depending upon the available ductility and the extent of damage, a series of anneal and deform operations may be necessary.

Finally, consideration should be given to the desired service properties. If the material were directly restored to shape, the bent portions of the propeller would have undergone two rather severe cold forming operations, and would likely be very low in remaining ductility and, therefore, prone to fracture upon any subsequent impact. Since the initial propeller was able to sustain such a severe deformation without fracture, it appears that the initial condition was one with substantial ductility. Therefore, it may be desirable to restore uniform ductility through an anneal after the reshaping.

If the propeller had been age hardened for strength, this heat treatment should be reperformed after the straightening to again produce the strong, homogeneous structure.

Finally, after all heating and cooling, the propeller should be rebalanced to provide smooth running at high RPMs. An out-of-balance propeller can produce excessive loads on bearings and power train components in the engine.

2). In most cases, such a repair can be made, if done properly. The cracked region should be machined out to assure removal of all cracked metal and the exposure of good, clean metal surface. A matching chemistry metal (or near matching to prevent the formation of a galvanic corrosion cell) should then be deposited into the machined groove. Oxyacetylene welding or repair brazing would be the most likely techniques for such a repair.

After deposition, the surface should be rough ground and then fine ground or abraded to produce a smooth surface. Consideration should then be given to the structure of the base metal and the possible effects in the heat-affected zone. If necessary, the entire propeller should be heat treated to produce a uniform structure. Alternately, a stress-relief treatment should be considered to remove potentially damaging residual stresses imparted by the braze. Finally, the propeller should be rebalanced .

If properly performed by an experienced repairman, the repaired propeller will function adequately and will probably cost about half of a new part. Failure to perform a proper repair, however, will result in further cracking problems and the ultimate need to replace the component.

CHAPTER 18
Hot-Working Processes

Review Questions

1. Metal forming probably began with "tools" as simple as rocks being used to shape bits of naturally-occurring metal. Hand tools and muscle power then gave way to machine processes during the industrial revolution. The machinery further evolved, becoming bigger, faster, and more powerful, and the sources of power also changed. Most recently, computer control and automation have been incorporated.

2. Various means have been used to classify metal forming process. These include: (1) primary processes that produce intermediate shapes, and secondary processes that produce finished or semifinished products; (2) bulk deformation processes and sheet-forming operations; and hot-working processes and cold-forming processes .

3 . The division of metal forming processes into hot working and cold working is quite artificial. With increased emphasis on energy conservation, the growth of warm working, and new advances in technology, a temperature classification is often arbitrary. Processes normally considered as hot forming processes are often performed cold and cold-forming processes can often be aided by some degree of heating.

4. At elevated temperatures, metals weaken and become more ductile. With continual recrystallization, massive deformation can take place without exhausting material plasticity. In steels, hot forming involves the deformation of the weaker austenite structure as opposed to the much stronger, room temperature ferrite .

5. Ingots are usually the primary product supplied to rolling mills. Rolling is used to convert the primary product to wrought products that are called by different terms depending on cross section size and shape.

Simple cross section shape products of rolling such as rectangular, square or circular sections are separated by size with
- blooms having thickness greater than 15 cm,
- billets smaller than blooms with rectangular or circular cross section shape,
- slabs have rectangular section shape with width greater than twice the thickness,
- plates, sheets and strips have rectangular cross sections with differing width to thickness ratios.

Blooms and billets can be further rolled to slightly more complex cross section shapes to produce semifinished shapes such as bars and rods that are usually processes further.

Still more complex shapes can be produced by further rolling of billets, bars and rods to produce structural shapes finished products such as channel sections, I-beams and railroad rails.

6. Because the rolls are so massive and costly, and multiple sets of rolls may be required to produce a given product, hot-rolled products are normally available only in standard sizes and shapes for which there is enough demand to permit economical production.

7. In a rolling operation, friction between the rolls and the workpiece is the propulsion force that drives the material forward. If the friction force is insufficient to deform the material, the material remains stationary and the rolls simply skid over the surface. No deformation is achieved.

8. The temperature related concerns in rolling are the rolling temperature or nominal temperature of the work and the variation of temperature over the workpiece. The finishing temperature or the temperature during the final phase of hot rolling must be controlled since temperature affects grain size and the final properties of the rolled product. If finishing t temperature is not adequately controlled undesirable, nonuniform grain structure and properties such as strength will result.

If the rolled product is the final product it will have nonuniform properties and perhaps undesirable shape due to warping and twisting as the product emerging from the rolls responds to its nonuniform structure, properties and stress state. If the rolled product is to be further processes, any nonuniformities in microstructure and properties will affect material behavior in subsequent processing.

9. Early reductions (with thicker pieces) usually utilize two-high or three-high mills with large diameter rolls. The three-high configuration allows the material to be passed back-and-forth through a single mill without having to stop and reverse the direction of roll rotation. Smaller diameter rolls are more efficient when rolling thinner material, but are less rigid and flex into a distorted configuration. To utilize these more efficient rolls and yet provide rigidity, four-high mills are used with support being provided by the more-massive backup rolls.

10. Foil is almost always rolled in a cluster mill because
- small diameter rolls are used to roll thin product since this results in smaller roll-work contact area. The small reductions in rolling foil combined with large diameter rolls gives large, undesirable, rolling forces.
- small diameter rolls have low stiffness and so can deflect to unacceptable extent. To add stiffness to the entire rolling mill backup rolls are used and cluster rolling mills us for thin product such as foil.

11. In a continuous or multi-stand rolling mill, it is important that each stand pass the same volume of material in a given time so as to prevent buildup between the stands or tearing of the material being rolled. As the cross-section is reduced, length increases, so the rolls of each successive stand must turn faster than the preceding one by an amount

equivalent to the cross-sectional area reduction taken by the previous stand.

12. Ring rolling is used to produce rings or hoops having a uniform cross-section throughout the circumference.

13. Hot rolling is expected to produce little or no directionality in product properties and no residual stress. However, if large nonuniformity in structure and/or deformation is produced there will be directional properties, residual stress and the resulting characteristics that these effects produce, e.g., warping of relatively thin, complex shaped product due to residual stresses.

Nonuniform structure can result during hot rolling if nonmetallic inclusion exist in the work material. These inclusions do not recrystallize as the surrounding metallic material does and so nonuniform material and directionality of properties results.

Nonuniform deformation and nonuniform temperature and cooling rate will cause directional properties and residual stress. The extent of recrystallization depends on the amount of initial metal deformation and the time-temperature history of the cooling product. Rolling can produce nonuniform deformation over the rolled section, particularly in sections with varying, thin parts. The deformation pattern near surfaces of the part is different than in regions away from the surfaces (constraint on material deformation is due to surrounding material). So sections such as I-beam are deformed to different extent in different regions of the section.

Variations in cooling rate can produce residual stress. When cooling rate variations are combined with differences in deformation, directional properties and residual stresses can form during cooling from the rolling temperature.

14. The rolling of uniform thickness product requires that the gap between the rolls be uniform. Three-point bending occurs when the rolls are loaded in the middle and supported by bearings on either edge. Attempts to compensate by "crowning" the rolls are designed for a specific load, which may vary with changes or fluctuations in material, temperature, lubrication, and other factors. When the thickness is not uniform, the amount of lengthening will not be constant over the entire width, resulting in such defects as wavy edges, wavy center, fractured edges, or fractured center.

15. Crowned rolls, rolls with varying diameter along the roll length, are used to compensate for roll flexure during rolling. Roll flexure depends on the forces acting on the rolls, the roll cross section shape and the mechanical end or support conditions at the roll end. Since the roll support conditions are constant, the roll design problem is to specify the roll shape to compensate for roll deformation due to the rolling forces. Rolling forces depend on the amount of workpiece deformation, the work deformation pattern, friction and work material properties. That is the rolling forces depend on the particular rolling process and material and so crowned rolls have to be designed for the – particular process and work material.

16. Thermomechanical processing consists of simultaneously performing both deformation and controlled thermal processing so as to directly produce the desired levels of strength and toughness in the as-worked product. The heat for the property modification is the same heat used in the forming operation, and the need for subsequent heat treatment is often eliminated. Product properties can be improved and cheaper materials might be employed .

17. Steam or air hammers use pressure to both raise and propel the hammer. They give higher striking velocities, more control of the striking force, easier automation, and the capability of shaping pieces up to several tons. Computer control can be used to provide specified blows of energy for each step of a process.

18. Open-die forging does not confine the flow of metal in all directions, so the final shape is dependent upon the manipulation and skill of the equipment operator. Impression-die forging operations confine metal flow in all directions to provide good repeatable control of size and shape.

19. Open-die forging is not a practical means for the production of large quantities of identical parts because the shape is produced by manipulation and positioning of the workpiece in the hands of a skilled operator (flow of metal is not controlled) rather than by rigid confinement in a set of shaped dies. Each workpiece, therefore, is a separate entity and is not identical to the others.

20. Because flashless forging involves total confinement of the material within the die cavity, precise workpiece sizing is required along with precise positioning of the workpiece within the cavity and control of the lubrication.

21. In forging the initially very simple shape workpiece is forged to the final shape in series of operations using a series of more complex shape dies. In the intermediate operations the dies are used for blocking the material to close to it final shape and the impressions on the blocking dies are blocking impressions.

22. Because counterblow machines permit the excess energy to be dissipated in the form of recoil, there is a reduction in the amount of noise and vibration, two of the major concerns of regulating agencies concerned with the forging industry.

23. Dimensions contained entirely within a single die cavity can be maintained with considerable accuracy. Dimensions across the parting plane are dependent upon die wear and the thickness of the final flash. While frequently within several hundredths of an inch, these dimensions are noticeably less precise than dimensions set totally within the die cavity.

24. Press forging is often preferred to hammer forging when the workpiece is large or thick and the energy of the hammer is insufficient to produce uniform deformation.

25. Heated dies are usually employed in press forging because the long time of die

contact with the hot workpiece would otherwise permit considerable surface cooling and could produce cracking of the surface.

26. Hammers impart a blow of energy, travel at high speed, and have short time of actual contact. Presses have longer periods of contact and apply a squeezing action or force. Mechanical presses have consistent and reproducible stroke, and are more rapid than hydraulic presses, which are more flexible and can have greater capacity. Since they move in response to fluid pressure, they are controlled by forces or pressures and position is not as reproducible.

27. Upset forging is the term applied when the diameter of a piece of material is increased by compressing its length.

28.Upset forging operations are often used to forge heads on bolts and other fasteners and to shape valves, couplings, and a number of other small components, like those illustrated in Figure 18-15.

29. Automatic hot forging offers numerous advantages. Input material is low cost and production rates are high. Minimum labor is required and scrap production is reduced. The as-forged structure is often suitable for machining. Tolerances are good, surfaces are clean, and draft angles are low. Tool life is nearly double that of conventional forging. On the negative side, however, is the high initial cost of the equipment and the restriction of large production quantities.

30. Roll forging is a process by which round or flat bar stock is reduced in thickness and increased in length. A heated bar is placed between two semicylindrical rolls containing shaped grooves, and as the rolls rotate, the bar is squeezed and rolled out toward the operator.

31. Swaging refers to two kinds of material deformation (in contrast to material removal) manufacturing processes. Swaging can be the hammering of a rod or tube to a final shape by a series of blows from a die that acts as the hammer. The hammer/die can be shaped and the work rotated to produce parts with relatively complex cross sectional shapes. This is usually a cold working process.

Swaging also refers to a process in which a simple cross section workpiece is forced trough a die to change its “diameter” or cross section size. Typically this process is performed at elevated work temperature. This process is conceptually similar to wire or rod drawing but usually applied to large sections with little imposed deformation.

32. The objective of net-shape or near-net-shape forming is to directly form products that are close enough to specified dimensions that few or no secondary operations are required. Cost savings and increased productivity can be attributed to the reduction in secondary machining operations, reduced quantities of generated scrap, and a decrease in the energy required to produce the product.

33. The extrusion process offers a number of attractive features. Almost any cross-sectional shape can be extruded, including many that could not be achieved by rolling. Size limitations are few. No draft is required, and the amount of reduction in a single step is limited only by the capacity of the equipment. Frequently only one die is required for a product. Because only a single die change is required to change products, small production quantities are economically feasible. Dimensional tolerances are quite good.

34. The primary limitation of the extrusion process is that the cross section must be the same for the entire length of the product being extruded.

35. In indirect extrusion there is no relative motion between the sides of the workpiece and the extrusion container. With no motion there is no friction and the primary attraction of indirect extrusion is that no frictional energy dissipation occurs in the process.

36. In extrusion, the final surface area is considerably greater than the surface area of the starting billet. Therefore, as the material is flowing through the extrusion die, the initial layer of lubricant must spread and thin by a substantial amount, while still functioning as an acceptable lubricant.

37. In a spider-mandrel extrusion die, the flow of material divides into several channels and then reforms. If the surfaces are fresh, uncontaminated metal, they can be pressed together to form high-quality, virtually undetectable, welds. If a lubricant were used, the surfaces of the various segments would acquire a coating of lubricant that would prevent the formation of the welds necessary to produce the continuous wall around the hollow shape.

38. Hot drawing can be used to produce tall, thin cups, by several methods. If the wall thickness can be thinner than the base, drawing with ironing can be employed. If uniform wall thickness is desired, one or more redraws, or multiple-die drawing can be used.

39. Ironing is the name given to the process where a cup is placed over a punch and driven through a die where the gap between the punch and die is less than the cup material thickness. The cup wall is thinned and elongated, while the bottom thickness remains unchanged.

40. Steel skelp can be converted into pipe by either butt welding, or lap welding operations. The welding operations occur simultaneously with the hot deformation.

41. In hot-piercing operations, the billet is forced over a pointed mandrel that is held in place in the roll gap. Since the product must flow over the mandrel and the mandrel must be held rigidly in position, the length of product tubing cannot exceed the length of the mandrel (which is rather limited).

Problems:

1. The assignment here is direct and needs no further explanation .

2.

a. S = surface area without ends

$S_{product} = \pi\ d_p\ L_p$

$S_{billet} = \pi\ d_b\ L_b$

$S_{product} / S_{billet} = d_p\ L_p / d_b\ L_b = \{ (0.03\ m)(7.5\ m) \} / \{ (0.15\ m)(0.3\ m) \} = 5$

b. $S_{product}$ = 4 (edge length) (product length) = $4\ a\ L_p$

$S_{billet} = \pi\ d_b\ L_b$

$S_{product} / S_{billet} = 4\ a\ L_p / \pi\ d_b\ L_b$

work material volume is constant so with
cross section area A

$A_b\ L_b = A_p\ L_p$

$L_p / L_b = \{ (\pi/4) (0.15\ m)^2 \} / \{ (\pi/4) (0.03\ m)^2 \} = 25$

same final cross section area so

$a^2 = (\pi/4) (0.03\ m)^2$

$a = 0.0266\ m$

$S_{product} / S_{billet} = \{ 4 (0.0266\ m) (25) \} / \{ \pi (.15\ m) \} = 5.64$

c. The problem says the reduction ratio, R, is 25 => $R = A_b / A_p$
with A being the cross section areas

the surface area ratio is

$Sp / Sb = (\pi\ dp\ Lp) / (\pi\ dp\ Lp)$

since work material volume is constant

$A_b\ L_b = A_p\ L_p$

$L_p / L_b = A_b / A_p = R$

the cross section areas are

$A_b = (\pi/4)\ d_b^2$

$A_p = (\pi/4)\ d_p^2$

and

$d_p / d_b = SQRT(A_p / A_b) = SQRT(R)$

$Sp / Sb = R / SQRT(R) = SQRT(R)$

3. a).Force = (.441) x 50,000 x 3.309 = 73,100 pounds

b) .At maximum force of 60,000 pounds, the pressure will be

= 60,000 / Area of the penny
= 60,000 pounds *I* 0.441 square inches
= 135,900 psi

4. Strip thickness is in the denominator of the equation and so the roll separating force will increase with decrease in strip thickness. For very small thickness as in foil, the roll separating force can become substantial.

One way to minimize the effect of thin materials is to note that the term is proportional to R/t_{av}. Therefore, if the diameter of the rolls can be decreased in proportion to the decrease in thickness, the effect can be canceled.

The various types of rolling mills and their uses, as described in the text, follow this trend. Billets, blooms and thick slabs are rolled in two-high mills with large diameter rolls (often in the range of 22 to 28 inches in diameter). Conventional sheet and strip is rolled on four-high mills with work roll diameters typically in the range of 4 to 10 inches. Foils are rolled on cluster mills with the contact roll being as small as ¼ inch in diameter, and multiple thicknesses may be rolled simultaneously to increase the total thickness being rolled.

5. The area under the direct extrusion curve is proportional to the work required to form the product with billet-chamber friction. The area under the indirect curve is the work required to form the product without frictional resistance. Therefore the "efficiency" of the direct extrusion process could be regarded as the fraction of the total work that is producing deformation. This can be computed as the percentage of the direct curve that is within the indirect region, i.e. the area under the indirect curve, divided by the area under the direct curve, times 100%.

Case Study:

Outboard Motor Brackets

1. The requirements for this part include static strength, corrosion resistance to salt and fresh water, light weight and resistance to vibration. A variety of engineering materials would be possibilities, including aluminum, titanium, magnesium and even the copper-base alloys. Copper is heavier than steel and would only be recommended if other alternatives failed. The corrosion resistance of magnesium is questionable and the cost and fabrication difficulties do not favor titanium. Some form of aluminum alloy would appear to be the attractive choice – either a casting alloy or a wrought alloy, depending on the recommended fabrication process.

2. The geometry (size and shape) is such that impression-die forging or some form of casting process would be the obvious alternatives. The various pros and cons can be evaluated with consideration being given to the estimated production quantity. If forging is selected, the recommended material should be some form of wrought aluminum. If cast, the recommended alloy should be selected for compatibility with the process. NOTE: There are aluminum alloys specifically designed for use with processes such as die casting.

3. If aluminum alloys are used, an age hardening treatment would most likely be required to achieve the desired mechanical strength. This would involve the stages of solution treatment, quenching and aging.

4. The corrosion resistance of aluminum would be adequate for fresh water usage, but might be attacked by salt water. Treatment might be utilized to provide aesthetics as well, and in this case, a color anodizing treatment, such as that commonly seen on aluminum softball bats, might be preferred.

CHAPTER 19
Cold-Working Processes

Review Questions;

1. Attractive features of cold working over hot working include: no heating is required, surface finish is better, dimensional control is superior, reproducibility is better, strength properties are improved so cheaper material may be utilized, directional properties can be imparted, and contamination problems are minimized.

2. Cold-working equipment is usually more powerful that that used for hot-working because the starting material is stronger (no thermal softening), and the material becomes even stronger as it is being formed due to the effects of strain hardening.

3. Sheet or strip is often given a skin-rolled reduction pass to produce a smooth surface and a uniform thickness, and also to improve the yield-point phenomenon that causes the formation of Luders bands.

4. The cold rolling of shaped products generally requires a series of shaping operations, each requiring a separate pass through specially-grooved rolls. Since these rolls are usually expensive, two such rolls are required for each pass, and multiple passes are usually required to produce a product, large production quantities are usually requires to justify the expense of the shape-rolling process.

5. If the starting material is a tube, and a shaped mandrel is inserted before swaging, the metal can be collapsed around the mandrel to simultaneously shape and size the interior and exterior of the product.

6. Viewing material waste as the chips generated in machining a part, if the same shape can be produced by forging, cold forging saves material since chips are not formed.

If machining operations are needed to finish hot formed products, cold forging can reduce material waste if products can be cold forged to within dimensional and shape tolerances. Again, finish machining is not needed.

Depending on the tolerances specified, cold forging can be used to produce parts close enough to required final dimensions so machining in not required and material is not lost to chips.

7. With cold forging, production rates are high, dimensional tolerances and surface finish are excellent, and machining can be reduced. Strain hardening can provide additional strength, and favorable grain flow can be imparted.

8. By combining extrusion and cold heading, the product can be made from a starting stock of intermediate size. Here, the upset head can now be made easily from the starting material size, and the extrusion of the shank reduces the need for extensive machining.

9. In the hydrostatic extrusion process, billet-chamber friction is eliminated, billet-die lubrication is enhanced by the pressure, and in the pressure-to-pressure mode, the pressurized environment suppresses crack initiation and growth and enables the extrusion of relatively brittle materials. Unfortunately, temperatures are limited, sealing problems are common, and complete ejection of the product by the pressurized fluid must be avoided.

10. In pressure-to-pressure hydrostatic extrusion the work material moves from one pressurized chamber to another pressurized chamber. The effect of forming the work material under pressure is to minimize void formation, crack initiation and crack growth. Since the work is always under pressure crack initiation is minimized and the material's ductility is increased.

With increased ductility materials can be deformed to a greater extent in extrusion and normally brittle materials that cannot be extruded may be have enough ductility imparted to them that they can be extruded.

11. Surface friction is the propulsion force in continuous

12. Roll extrusion is typically used to produce thin-walled cylinders with diameters ranging from 3 to 20 inches.

13. When only one side of a joint is accessible, riveting can be accomplished through the use of either explosive rivets, or pull-type or pop-rivets where the shank on the inaccessible side is expanded mechanically.

14. One hardened hub can be used to form a number of identical cavities, so only one part needs to be machined to precision. In addition, it is often easier to machine a male shape on the hub as opposed to a female cavity in the die.

15. During peening, the highly localized blows deform and tend to stretch the metal surface. This surface deformation is resisted by the metal underneath, producing a compressive residual stress in the surface. Since the compressive stresses subtract from applied tensile loads, they serve to impart added fracture resistance to the product.

16. Burnishing involves rubbing a hard object over the surface of a material under considerable applied pressure. Minute surface protrusions are deformed, producing a smooth, deformed surface .

17. "Bending[31] is plastic deformation about a linear axis with little or no change in surface area. When multiple bends are made in a single operation, that operation is often called "forming". If the axes of deformation are not linear, or are not independent, the

process is called drawing".

18. When a material is bent, the material on the outside of the bend is elongated, while that on the inside is compressed. Since the material yields first in tension, more deformation occurs by the tensile mode than the compressive one, and the net result is a thinning of the bend.

19. Springback is the tendency of the metal to unbend somewhat after bending. This is a natural consequence of the outside tension and inside compression of the material and the material seeking to relax these stresses. To form a desired angle, a material must be overbent to compensate for springback

20. Press brakes can be used to produce simple bends, complex bends, seaming, embossing, punching, and other operations.

21.In overview, minimum bend radius is set by the condition that the strain at the material tensile surface becomes equal to the fracture strain of the material in a tensile test.

The minimum bend radius is determined by:
- The ductility of the work material, usually specified by the percent reduction of area at fracture in a tensile test. The higher the ductility the smaller the minimum possible bend radius.

The thickness of the work material. For a given bend radius the thicker the material the smaller the strain at the material surfaces.

The usual bending process-material behavior parameter used to describe bending radius is R/t with R the bend radius and t the material thickness.

22. Whenever possible, the bend axis should be perpendicular to the direction of previous rolling. If two perpendicular bend axes are involved, the metal should be oriented with the rolling direction at 450 to both axes.

23. By designing products to have all of the bends with the same bend radius, manufacturers can significantly reduce setup and tooling costs. The same tooling can then be used to produce all bends.

24. Bottoming dies compress the full area within the tooling, while air-bend dies form the desired geometry through simple. three-point bending. Air-bend tooling is quite flexible since the degree of bend can be varied by a simple change in press position. Bottoming dies, however, produce a more consistent product .

25. Roll bending produced curved shapes when plates, beams, pipe and structural shapes move through a set of closely spaced rolls, Figure 19-29. Although the radius of curvature of the workpiece can be varied as it is being formed by continuously changing roll spacing, usually roll position is fixed. So the type of parts produced are those with

constant curvature. An example is the individual short sections of jet engines that are joined to form the entire engine housing.

26. To prevent flattening at the outside or wrinkling at the inside of a tube when it is bent the tube material can be supported so as not to deform or the imposed deformation state can be altered. Packing an easily removed material such as sand in the tube before bending can support the tube and decrease flattening and wrinkling. Using flexible tooling, e.g., flexible mandrels changes the loading and deformation imposed on the tube in bending and so can reduce flattening and wrinkling.

27. Cold roll forming progressively bends flat strip into complex (but uniform) cross-sectional shapes. Various moldings, channeling, gutters and downspouts, automobile bumpers, and other uniform cross section shapes have been produced. Short lengths of specialized products would be better produced by tools like a press brake, because of the high cost of the roll forming tooling
--multiple sets of profiled rolls.

28. Rod or sheet can be straightened by two techniques: (1) roll straightening (or roller leveling) which involves a series of reverse bends designed to stress the material beyond its elastic limit, and (2) stretcher leveling in which the material is stretched beyond its elastic limit.

29 Shearing is the mechanical cutting of materials without the formation of chips or the use of burning or melting.

30. Sheared or blanked edges are generally not smooth because the cutting tools actually deform the material only to the point where the applied stresses exceed the rupture strength of the remaining material. The remainder of the edge is produced by a metal fracture and has a rough appearance.

31. If the punch and die (or shearing blades) have proper clearance and alignment and are maintained in good condition, the sheared edges can often be sufficiently smooth to avoid the need for further finishing. Edge condition can be further improved by clamping the stock firmly against the die from above and restraining the movement of the piece through the die by an opposing plunger or rubber cushion that applies pressure from below the workpiece.

32. Since fineblanking presses incorporate separate motions and forces for the punch, hold-down or clamping ring, and opposing (or bottom) punch, they are multiple-action machines and are noticeably more complex than presses used in conventional blanking .

33. Progressive shearing involves a smaller volume of material being sheared and so a smaller shearing force than if the entire sheared length is produced at the same time.

The force required for shearing depends on the work material strength and the volume of material being deformed. In shearing the deformation zone thickness perpendicular to the shear is constant so the deformation volume is proportional to the length of the deformation zone in the direction along the shear edge. Progressive shearing takes place in a smaller deformation zone than one long shear.

34. Slitting is the length-wise continuous shearing process used to slice rolls of material into narrower strips. The work material passes between rolls that have grooves that form shearing edges.

35. Piercing and blanking are both shearing operations in which a curved shearing punch pushes material into a die. They both involve the same cutting action, but when the piece being punched out is the scrap the process is piercing, and when the piece being punched out is the product, the process is one of blanking.

36. In the progressive piercing and blanking operation shown in Figure 19-50 the ram holds both the piercing punch and blanking punch so both tools move up and down at the same time. If the piercing and blanking punches were the same length at least two problems would arise. One problem is that the deformation processes occurring in the piercing region and in the blanking region would interact. Control of the deformation processes and so of the accuracy and quality of the part produced would be lost. Another problem is that the mechanisms used to hold down the work during piercing and punching, and the overall machine, would have to be heavier and stiffer to withstand the higher processing forces.

37. Variations of piercing and blanking that have come to acquire separate names include: lancing, perforating, notching, nibbling, shaving, cutoff, and dinking.

38. By grinding a slight angle on the face of a piercing or blanking punch, the maximum cutting force can be reduced. Instead of the entire circumference being sheared simultaneously, the angle allows the cut to be made in a progressive fashion, much like the opening of a pull-tab on a beer or soda can.

39. To produce a uniform cut, it is important that a blanking punch and die be in proper alignment. A uniform clearance should be maintained around the entire periphery.

40. By mounting punches and dies on independent die sets, they can be positioned and aligned prior to insertion into the press, thereby significantly reducing the amount of production time lost during tool change.

41. Standard subpress dies can frequently be assembled and combined to produce large parts that would otherwise require large and costly die sets. In addition, when the die set is no longer needed, the components can be removed and used to construct tooling for another product.

42. When dies are constructed as multipiece assemblies die components can be individually changes into the die or modified. Whether for changing overall die configuration or for repairing or regrinding shearing components of the die, dealing with one component of the die rather that a large one piece die is easier, safer and less expensive.

43. A progressive die set consists of two or more punches and dies mounted in tandem. Strip stock is fed through the dies, advancing incrementally from station to station with each cycle of the press performing an operation at each of the stations. Figure 19-50 illustrates a progressive die operation.

44. In progressive dies one or more punches are mounted in one punch holder and all punches more at the same time. The work material movement is usually linear between the different stations in the die, e.g., sequentially punching of strip work material. In transfer dies usually individual parts are moved from die to die in a single press with the possibility of changing part orientation between the dies that perform one operation each.

45. In compound dies more than one tool is mounted in the die at essentially the same location in the machine tool. The machine motions and tools actuation are such that the punching processes occur sequentially at one location in the machine, Figure 19-51. In progressive dies, Figure 19-50, individual tools are mounted at different locations and the work material moves to each and through a sequence of punch positions.

In progressive dies the punching processes are sequential with all tools moving at the same time and the work moved between punch strokes. In compound dies sequential operations are performed on a stationary working piece with sequectual actuation of different tools.

46. Turret-type punch presses have the capability of holding a large number of punches and to quickly set punch-work position by moving the workpiece. This enables a large number of different size and different shape holes to be placed in complex patterns.

47. The term cold drawing can refer to two different operation. For sheet metal, cold drawing involves plastic flow of material over a curved axis, as in the forming of cup-shaped parts. If the stock is wire, rod, or tubing, the term applies to a process where the cross section of the material is reduced by pulling it through a die.

48. In tube drawing, rigid tooling is used to accurately size both the inner and outer diameters of the product. In tube sinking, only the outside diameter is directly controlled (there is no mandrel or plug to restrict and size the inner diameter) .

49. Tube drawing with a floating plug can be used to produce extremely long lengths of tubular product with a controlled inner diameter .

50. Straight-pull draw benches are normally employed to produce finite lengths of products that cannot be conveniently bent or coiled. Wire, and smaller products that can

be coiled, is generally drawn in a continuous operation on draw blocks where the length of product is limited only by the amount of starting material .

51. Because the reduced section of material is subjected to tensile loading in the wire drawing process, the possible reduction is limited by the onset of fracture. In order to affect any significant change in size, multiple draws are usually required .

52. Since the metal being deformed by spinning deforms under localized pressure and does not flow across the form block under pressure, the form block can be made of relatively inexpensive material, such as hardwood or even plastic.

53. During shear forming, each element of the blank maintains its distance from the axis of rotation. The metal flow is entirely in shear and no radial stretch has to take place to compensate for the circumferential shrinkage. Wall thickness, however, will vary with the angle of that region to the axis of rotation .

54. Stretch forming is used to form large sheet metal components that have relatively small production quantities.

55. In drawing of sheet metal the typical part is, in a very general sense, a closed bottom-open top shaped structure, e.g., cylindrical cans and rectangular automobile oil pans. When the part depth is less than the smallest opening dimension the drawing process is called shallow drawing. Deep drawing processes produce parts with depth greater than the smallest opening dimension.

56. The pressure-ring or hold-down in a deep-drawing operation serves to control the flow of metal and suppress wrinkling, tearing, or undesirable variation in thickness.

57. There are three major reasons that thin material may be difficult to draw into a cup, compared to thicker material.

i. Thin work material is susceptible to tearing. In cup drawing tensile stresses arise in the cup wall as it is being drawn. Tensile stress increases as wall thickness decreases if there is not a corresponding decrease in tensile force. In draw the force acting in the wall of the forming cup is due to stretching, bending and friction. The effects decreasing work thickness on increasing wall stress are greater than the effects of wall thickness on decreasing wall force.
ii. Thin work material is more likely to buckle in the flange region. If the wrinkling extends into the cup wall region it is not likely to be removed when the top edge of the cup is trimmed.
iii. In tensile deformation materials may exhibit tensile instability. This instability is analogous to the nonuniform deformation in necking in the tensile test. Nonuniform deformation is itself a defect in a drawn cup and can act as a site of locally increasing deformation leading to tearing.

58. Draw beads are protrusions and matching grooves on the faces of the die and blankholder or blank holddown plate.

The purpose of drawbeads is to locally impede the flow of the workpiece into the die and so control deformation in drawing processes.

For example, in drawing a rectangular part the material along the straight sections of the die flows more easily into the die that the material around the die corners. To produce more uniform deformation over the forming part the material flow along the straight sections can be restricted by building drawbeads into these sections of the die.

59. Because of prior rolling and other metallurgical and process variables, the flow of metal in deep drawing is generally not uniform in all directions. Excess material is often required to assure desired final dimensions, and a trimming operation is generally employed to establish the final dimensions.

60. The Guerin process employs rubber as the female die, providing the pressure necessary to wrap the sheet metal around a male punch. The hydroform process replaces the female die member with a flexible diaphragm backed by hydraulic pressure. Both processes eliminate the female die member to substantially reduce tooling cost.

61. Bulging using fluid or rubber tooling can be performed by
- holding the workpiece on a machine base so that the hollow workpiece is closed at one end,
- placing fluid or rubber tooling in the part,
- closing the top of the workpiece either with the punch to be used or separate mechanism,
- using a punch to increase fluid pressure or deform the rubber tooling,
- apply enough punch displacement so that the workpiece bulges to a confining split die to form the part,
- release the punch and remove the part from the die.

62. Sheet hydroforming is a process in which a fluid under pressure replaced the solid punch or die in conventional forming. In one process configuration the fluid may act as a punch on one surface of the sheet workpiece to force the work material into a die. In another configuration the fluid may act on the free side of the work material to force it to bend over and conform to a punch.

63. The deformation of the work material in sheet hydroforming is more uniform than in conventional, hard tooling, forming processes. In hydroforming uniform pressure is exerted over the entire workpiece and so deformation is uniform. The uniform strain means that locally nonuniformly strained regions do not exist, and so cannot interact and increase local deformation bringing the material locally closer to its forming or ductility limit. The material is more formable in hydroforming.

64. Regions of the tube that increase in diameter in tube hydroforming experience wall thinning. To compensate for the wall thinning the end of the tube can be compressed. The inward movement of the end plugs is supposed to cause tube compression and help compensate for wall thinning.

65. The high energy-release rates needed by the HERF processes can be obtained by: underwater explosions, underwater spark discharge, pneumatic-mechanical means, internal combustion of gaseous mixtures, and the use of rapidly-formed magnetic fields.

66. Two factors account for the low springback observed during high-energy-rate forming. High compressive stresses are set up when the metal is forced against the die, and some elastic deformation of the die occurs under the high applied pressure, allowing the workpiece to become somewhat overdeformed.

67. Common examples of ironed products include brass cartridge cases and the thin-walled beverage containers. Common embossed products include highway signs (like STOP signs) and industrial stair treads.

68. The intent of superplastic forming is to make it possible to produce very large strains in the workpiece. With regard to workpiece material, ultrafine, uniform grain size increases material ductility and so makes the material suitable for superplastic forming.

Materials are more ductile at higher temperatures and less ductile at higher strain rates. So with regard to processing conditions, superplastic forming is carried out at high temperatures and very low strain rates.

69. The major limitation to superplastic forming is the low forming rate that is necessary to maintain the superplastic behavior. Typical cycle times may be on the order of 5 to 40 minutes per part. on the positive side, superplastic forming has made possible the economical production of complex-shaped parts in limited production quantities. Deep or complex shapes can be made as one-piece, single-operation pressings, rather than multistep conventional pressings or multipiece assemblies. The required forces are low. tooling is relatively inexpensive, precision is excellent, and fine details can be reproduced.

70. By measuring and evaluating the distorted grid pattern, regions where the area has expanded can be detected as locations of sheet thinning and possible failure. Areas that have contracted have undergone thickening and may be sites of possible buckling or wrinkles.

71. A forming limit diagram is a plot of the major strain and related minor strain on the surface of metal sheet, indicating the conditions for which fracture occurs. Deformation in regions below this line (the forming limit) can be performed without fracture. Deformation which induces strains at or above the line will incur fracture.

72. In the right hand section of the forming limit diagram the minor strain measured in a forming deformation experiment is positive. In the left hand region of the forming limit diagram the measured minor strain is negative.

73. Thin complex-shape products can be produced without the use of metalforming techniques through processes such as electroforming, in which metal is electroplated onto an accurately-shaped mandrel and stripped free, and plasma spray forming, where molten metal is sprayed onto a shaped mandrel where it then solidifies.

74. In general, mechanical drives provide faster action and more positive displacement control. Once designed, the stroke of a mechanical press is fixed and cannot be changed. In addition, the available force varies with position and is greatest near the bottom of the stroke. Hydraulic drives offer greater forces and more flexibility of forces, speeds, and strokes. They are generally slower than mechanical drives and do not offer as great a control of position or displacement.

75. Presses with different types of frames are gap-frame presses, open-back presses, inclinable presses and straight-sided presses.

76. Inclinable presses are often tilted to enable ejection of the finished parts to be accomplished with the aid of gravity or compressed air jets.

77. A transfer press is designed to accept a number of die sets, positioned side-by-side to create a multiple station (progressive die-type) operation. With each stroke of the press, each individual station performs its operation on the material positioned between the dies. The strip material then advances forward to the next station, where the press undergoes another cycle. Since all operations are performed simultaneously with each stroke of the press, one product is made per stroke.

Problems:

1. The wire drawing process can be characterized as continuous (provided the various segments of incoming product can be butt welded), but limited in reduction. Since the deformation force is applied as tension to the reduced product, the maximum reduction in area (for perfect frictionless conditions) is 62%, and a typical reduction is between 20 and 50%. The process works for almost all ductile materials and can be performed at high speeds. Because of the large surface area and small volume, the material is rarely heated; most operations are performed at room temperature. Hydrodynamic lubrication is possible because of the high relative speed between the workpiece and die.

Conventional extrusion can perform massive reductions in a single operation (up to a 400 to 1 reduction ratio), but is limited to finite length segments of starting material (i.e. it is a piece-rate process). The process can be performed both hot and cold on both nonferrous and ferrous metals. Because of the large amount of deformation and the conversion of deformation energy into heat, the speed of the process is often rather limited. High strength materials are usually formed hot with special lubricants to prevent pressure welding to the chamber and/or die.

Continuous extrusion is an attempt to achieve the best of both worlds -- namely a continuous, high-reduction process. Present techniques are largely limited to the weaker, nonferrous metals, and are usually conducted with room temperature starting stock. Speeds can be relatively fast, provided adequate cooling can be provided to offset the adiabatic heating induced by the large amounts of deformation being performed in a single operation .

2. Tubular products – advantages and limitations have to do with both the production process and the functioning of the product in use.

Process	Advantages	Limitations	Applications
Extrusion	- high accuracy - small tolerance - uniform properties along length and around circumference - low surface roughness - high strength if cold extruded - no seam	- complicated tooling - limited length due to mandrel - extra operation to join - welded joints, seams have different properties than rest	- high performance tubing such as in heat exchangers
	deformation texture may be advantageous or detrimental - e.g., advantageous for along tube loading, weaker in hoop direction under internal pressure loading		
Seam Welding, Forming and Butt-welding	-simple forming operation - high speed process	- workpiece heating needed - different properties in welded zone - only easily welded materials - internal support needed for large diameters	- common pipe and tube
Piercing	- seamless - large diameter	- limited length - subsequent sizing may be required	- fabrication of small, low pressure, pressure vessels
Drawing	- high strength if cold drawing - accurate	- limited length if mandrel used	- high performance, short tubes as in high pressure hydraulic lines

3. Applications are shown in Figure 19-79.
A cursory search for “hydroforming” gave

www.thefabricator.com/xp/Fabricator/Articles/Experts/Article111/Article111_p1.xml

containing pictures of exhaust manifolds, mention of a rear axel and a description of the advantages accrued in an automobile frames. A list of advantages and disadvantages of hydroforming is provided.

www.cooper-cooper.com.hydroform.htm

contains photographs of several different kinds of products

www.lajonchere.com/hydroform.htm

has a simple animation of the hydroforming process that summarizes the process steps and schematically shows the production of a product, a bellows-like part.

4. The amount of springback depends on the deformation imposed on the material during processing and on the elastic modulus of the work material. This general concept is summarized in Figure 17-6. The typical solution to springback is to overform the workpiece so that it will spring back to the desired final shape.

Given that springback depends only on the modulus of elasticity for a given radius, single axis bend, springback cannot be minimized, but only compensated for, in this case.

To minimize springback in the general case of possibly changing material and part design leads to two general approaches.

i. Changing to a material with larger elastic modulus will result in less springback for the same single axis bend. Changing to a different alloy of the same class of material will have little benefit since alloying has only small effects on elastic properties.

ii. More complex bends can reduce springback since the bends will interact with each other in determining overall springback. This is a radical solution and requires accurate deformation models of complex processes.

5. Residual stresses in cold working result from different amounts of deformation in different regions of the workpiece. Residual stresses will be high, and so important and probably intensely studied, for processes that produce large deformation gradients in the workpiece/product.

One such process is rolling. It is easy to imagine that as the amount of reduction is increased workpiece deformation zones near the surfaces grow and eventually overlap. Conceptually, for light reductions more deformation is expected near the surfaces of the workpiece than further into the work. This will result in compressive residual stress near the surface balanced by tensile residual stresses in the central region of the work. As reduction increases the deformation becomes more complex with frictional constraints at the surface and overlapping deformation. While the net result is not clear, it is clear that the residual stress state will be different.

A short internet search for “residual stress” & “rolling” yields many useful results. The residual stress distributions in both rolling and transverse directions and the distributions after stress relief for a typical rolling operation are shown at www.lanl.gov/projects/residual/alum.html

The results show not only compressive and tensile residual stress regions but also qualitatively different distributions before and after stress relief.

Case Study:

Diesel Engine Fuel Metering Lever

NOTE: This problem is particularly attractive because of the large variety of material-process combinations that can meet the requires geometric, physical, and mechanical properties.

1. As is usually the case, the part could be fully machined from a large piece of metal, such as a rectangular flat. This, however, is usually an inefficient use of material and time and labor considerations may be restrictive, especially for a production run of 10.000 pieces.

The small size of the part, smooth surface finish, and presence of a through hole, make the part attractive for one of several casting processes, including investment, die and, permanent mold. In addition, the part might even be attractive for centrifuging.

Noting that many of the surfaces are flat and parallel (such that if the part were viewed along the hole axis, the cross section would be uniform), one might want to consider extrusion of a shaped section, rolling of a shaped bar, or cold drawing, plus machining to remove the unwanted portions of the metal. This would significantly reduce the amount of machining from the first alternative in this section.

Finally, the prescribed size and small wall thicknesses render the part a candidate for powder metallurgy, or P/M injection molding, as a means of production.

2. These properties are not very restrictive and can be met by a number of metals and alloys, both ferrous and nonferrous. These include most steels, ferrous P/M alloys, copper-base alloys, some heat-treatable aluminum alloys, zinc-aluminum die casting alloys, and a variety of others.

3. The processes listed in part one include both wrought forming and casting, as well as powder metallurgy. This section is designed to get the student to focus on process-material limitations. Almost all metal can be machined, but if 100% machining were to be employed, a free-machining metal or alloy should be seriously considered. Of the cast processes, investment would be the slowest and most costly. This would probably only be considered if ferrous materials were required. Since alternative metal systems can provide the desired properties, die casting of either a copper-base or zinc-aluminum alloy would be an attractive alternative. Ferrous materials cannot be die cast and the higher-melting-point copper-base alloys have a limited die life, so the zinc-aluminum, alloys might be preferred here. Extrusion would require a ductile, wrought alloy, such as an age

hardenable aluminum. Cold drawn bars of low carbon steel would also meet the requirement and copper-base alloys might be considered here. If powder metallurgy were pursued, a ferrous powder would likely be required, but the low hardness and ductility requirements provide ample room for such a solution. The complexity of shape might lead to a preference for P/M injection molding over the conventional press-and-sinter powder metallurgy approach.

4. The conclusion as to which solution is the best is indeed a question of “multiple shades of gray”. Each of the above possibilities has merits and the “best” solution may well be based on the experience, available equipment and expertise, and current economics of the various processes and materials.

In each case, the form of the starting material would be different. Full machining would begin with mill-length bars of standard configuration. Casting would begin with melt quality ingots. If using extrusion or complex cross-section bars, the primary operation would likely be contracted out to a specialist firm and the product could be purchased with a specified degree of cold work amenable to both finish machining and final properties. Powder metallurgy would begin with a specified blend of powder and lubricant.

The necessity for heat treatment again depends on both the material and the method of manufacture. Some of the above systems would require age hardening to attain the desired final properties. Ferrous P/M would require a quench and temper. Other alternatives could meet the goals with cold work.

CHAPTER 20

Review Questions

1. Plastics, ceramics and composites are substantially different from metals in both structure and properties. As a result, the processes of fabrication also tend to be different. Many of the fabrication processes can take the raw material to a finished product in a single operation. Large, complex shapes can be formed as a single unit, often eliminating the need for multipart assembly. Joining and fastening operations are quite different from those used on metals. Color, surface finish and precision can often be obtained directly, eliminating the need for surface finishing.

2. Thermoplastic polymers can be heated to a temperature at or near the melting temperature so that the material becomes either a formable solid or a liquid. The polymer can than be cast, injected into a mold, or forced through a die to produce the desired shape. With thermosetting polymers, once the polymerization has occurred, no further deformation can occur. Thus, the polymerization reaction and the shape-forming process must be accomplished simultaneously.

3. Plastic sheets and plates can be cast between plates of glass. Continuous product can be made by introducing the liquid polymer between moving belts of stainless steel, or into the gap of a rolling mill setup. Tubular products can be made by spinning the liquid against the walls of a rotating mold.

4. Cast plastics generally contain no filler, so they present a distinct lustrous appearance.

5. Blow molding is a process that is used to shape thermoplastic polymers into bottles or other hollow-shape containers. Common thermoplastics for this process include: polyethylene, polyvinyl chloride, polypropylene, and PEEK.

6. In blow molding (and in injection molding) the parts have to harden in the mold before they can be removed from the mold. While parts are hardening the machine cannot be used for forming more parts, it is unproductive time. The part hardening phase of blow molding cycles can be reduced, and production rates increased, by building cooling systems into the molding machine.

7. Compression molding is most economical when it is applied to small production runs requiring close tolerances, high impact strength, and low mold shrinkage. Most products have relatively simple shapes because the flow is rather limited. Parts should not contain regions with thick section because of the long curing times.

8. Mold temperatures for compression molding typically run between 300 and 400^{o}F, but can go as high as 1200^{o}F. They are generally made of tool steel and are polished or chrome plated to improve material flow and product quality.

9. Thin sections, excellent detail, and good tolerances and finish are all characteristic of the transfer molding process. In addition, inserts can be incorporated into the product as the liquid resin is introduced at relatively low pressure.

10. Injection molding is used to produce more thermoplastic products than any other process.

11. Injection molding of thermoplastic polymer is very similar to die casting of metal. Sprues and runners channel molted material to the various closed-die cavities where the material solidifies after mold filling. Injection pressures provide rapid filling and prevent premature solidification. The die segments then separate for easy part ejection.

12. By using a hot runner distribution system, the thermoplastic material is kept in a liquid state until it reaches the gate. The material in the runner does not solidify and can be used in the subsequent shot, thereby reducing the amount of scrap and the amount of material that must be heated for each shot (or product). In addition, quality is improved due to the uniformity of temperature and the absence of recycled material in the melt.

13. The typical molding cycle in the injection molding of thermoplastics takes from 1 to 30 seconds and is very similar to the die casting of molten metal. Because thermosetting plastics must be held at elevated temperatures and pressures for sufficient time to permit curing, the cycle time for the injection molding of these materials in significantly longer than for thermoplastics.

14. In reaction injection molding metered amounts of the materials to be mixed are formed into two high pressure streams. The streams interact in the mixing head of the machine, out side the mold.

15. Since the reaction injection molding is a low temperature, low pressure process the process and the machine have attractive characteristics. In the process itself the solidification time is determined by the curing time of the blend and may be short. This is in contract to processes that use heated polymers such as injection molding. In injection molding solidification time is determined by the time required to remove heat from the heated melt. Depending on the extent of cooling of the mold injection molding cycle times may be long.

The machine and tooling for reaction injection molding can be simpler than for high temperature, high pressure process. Since no heating is required, no heating system in needed in the molding machine. Low pressure means that molds need not be as strong and stiff as molds in high pressure processes. Low temperature and low pressure result in less mold wear than in high temperature, high pressure processes and so mold material requirements are less stringent and less expensive molds may be possible.

16. Plastic products with long, uniform cross sections are readily produced by the extrusion process. Common production shapes include solid forms, tubes, pipes, and even

coated wires and cables. If the emerging tube is blown up by air pressure, allowed to cool, and then rolled, the product can be a double layer of sheet film

17. Twin-screw extruders have advantages associated with the materials that can be extruded and the mixing and heating of the materials. The screws in twin-screw machines enable the extrusion of complex plastics. Since the flow pattern of the plastic is more complex than with single-screw machines better mixing occurs. The greater extent of mixing means that there is more shear heating of the plastic/melt. Shear heating, unless extreme enough to cause high temperatures and plastic degradation, can be an important heat source for melting the feedstock in addition to the heaters built into the extruder.

18. Thermoforming is a process designed to shape thermoplastic sheet material into a uniform-thickness shaped products, similar to those produced by embossing of metal sheet.

19. Rotational molding is used to produce hollow, seamless products of a wide variety of shapes and sizes. These include storage tanks, refuse containers, footballs, helmets, and even boat hulls.

20. Open-cell foams have interconnected bubbles that permit the permeability of gas or liquid. Closed-cell foams have the property of being gas- or liquid-tight.

21. Rigid-type foams plastics are used for structural application, for packaging and shipping containers, as patterns for the full-mold casting process, and for providing rigidity to thin-skinned metal products.

22. In spinning thermoplastic material filaments are formed and several filaments can be spun into twists and wraps similar to cables. Products can be the spun material as it comes out of the machine, e.g., plastic string. Another kind of product is woven twists that resemble cloth.

23. Since plastics are poor thermal conductors, little of the heat that results from chip formation will be conducted away through the material or be carried away in the chips. Consequently, the cutting tools run very hot and may fail more rapidly than when cutting metal. In addition, the high temperature at the point of cutting can cause thermoplastics to soften and swell, possibly binding or clogging the cutting tool.

24. Since bending and recovery of tabs is necessary for effective snap fits material properties related to strength, stiffness and elastic limit are important. Plastics have relatively low values of modulus of elasticity and so small forces are needed to deform the mating sections during assembly of snap fits. While not unusually high the yield strain of plastics is large enough so that mating sections of snap fits will not be permanently deformed during assembly of adequately designed snap fits.

25. Plastics offer designers a number of unique material properties, including light weight, corrosion resistance, good thermal and electrical insulation, and the possibility of

integral color. Some of the design limitations of plastics include" the inability to perform at elevated temperature of operation, poor dimensional stability, and the deterioration of properties with age.

26. Adequate fillets between the adjacent sections of a mold ensure smooth flow of plastic into all section of the mold and also eliminate stress concentrations at sharp interior corners. These fillets also make the mold less expensive to produce and lessen the danger of mold breakage. Rounding exterior edges will act to reduce the possibility of chipping.

27. Uniform wall thickness is desirable in plastic products for several reasons. Since the curing time is determined by the thickest section, it can be optimized for the product if the sections are uniform. In addition, nonuniform wall thickness can lead to serious warpage and dimensional control problems.

28. Dimensions parallel to the parting line are contained entirely within a given section of the mold and can possess good dimensional precision. Larger tolerances are required for dimensions which cross the parting line for they can vary with the fit of the die segments, wear of the dies, and the thickness of any flash that forms.

29. Threaded metal inserts are frequently molded into plastic products because of the difficulty of molding threads in plastic parts and the fact cut threads tend to chip. The inserts provide strength and allow frequent assembly and disassembly.

30. Metal inserts are placed in plastic parts either by forcing the insert into a molded cavity or by molding around the insert. The inserts are held in place by mechanical interactions, not chemical bonding, between the insert and surrounding material. Insert function can be lost if the inserts pull out or rotate. To aid in resisting forces acting along and insert and torques acting to twist the insert inserts are bent, split along their length notched, swaged or formed to produce protrusions and noncircular heads, grooved and knurled, Figure 20-12.

31. Since the mold is the reverse of the product, depressed letters or designs would require these features to be raised above the mold. This would require the entire remainder of the mold to be cut away at a considerable expense. If the details were raised, only these details would have to be machined.

32.A parting line problem is the appearance of the part if flashing occurs during molding and the flash at the parting line has to be removed. Locating the parting line at a sharp corner means that any operation needed to remove possible flash will be performed at an edge, not on a flat surface. Any surface appearance effects of flash removal will be less apparent.

33. Countersinking holes that are to be threaded has two intents.
i. The countersink can aid in locating and starting the tapping or screw insertion operations.

ii. If any damage results from tapping or screw insertion it will be in the countersink and so not visible.

34. Dipping can be used to produce relatively thin elastomeric products with uniform wall thickness, such as boots, gloves, and fairings.

35.Rubber sheets are usually made in calendering processes. Rubber is fed into the gap between two closely spaced rolls. Roll rotation draws the rubber feedstock into the gap forming a sheet of uniform, specified thickness. The rubber sheet leaving the calendering roll gap may be laid onto substrate such as woven fabric.

Dipping of rubber is usually the build up thin layers over a form or mold to produce a shaped product. Dipping using plate is not done to form rubber sheets.

36. Ceramic materials generally fall into two distinct classes, glasses and crystalline ceramics. The glasses are fabricated into useful products by forming a viscous liquid and then cooling it to produce a solid. The crystalline ceramics are fabricated by pressing moist aggregates of powder to a desired shape, followed by drying and bonding by chemical reaction, vitrification or sintering.

37. By rapidly cooling the surfaces of hot glass, a residual stress pattern of surface compression can be induced. The resulting glass is stringer and more fracture resistant. Annealing operations can be used to relieve unfavorable residual stresses when they exist, and heating can also be used to promote devitrification – the precipitation of a crystalline phase from within the glass.

38. Glass ceramics are amorphous, glassy, ceramics that contain regions of ordered, crystalline, structure. A glass ceramic is produced and then subjected to heat treatment to initial and control the formation and growth of crystalline regions.

39. Plasticity can be imparted to the crystalline ceramics in a number of ways. Clay products can be blended with water and various additives to permit shaping. Plastic forming involves the blending of various ceramics with additives to make the mixture formable under pressure and heat. The additive material is subsequently removed by controlled heating before the fusion of the remaining ceramic.

40. In injection molding of plastics
- a one component material, the plastic,
- is heated to a relatively high temperature,
- injected under high pressure into a mold,
- let solidify
- and ejected as a final part.

In injection molding of ceramics
- a two material feedstock is used, ceramic powder and a binder,
- the material is injected at relatively low temperature and pressure,

- after removal from the mold thermal, solvent, catalytic or wicking operation is needed to remove the binder,
- the part is fired to produce final strength and density.

41. Firing or sintering operations provide useful strength to ceramic materials by driving the diffusion processes that are necessary to form bonds between the individual particles. In some cases surface melting or component reactions produce a liquid component that flows to produce a glassy bond.

42. While machining before firing enables the cutting of weaker material, there is usually a greater concern for the dimensional changes that will occur during firing. Therefore, machining performed before firing id usually rough machining designed to reduce the amount of finish machining to be performed after firing establishes both the final properties and dimensions. In both cases, caution should be exercised relating to the handling of brittle materials that will fail by fracture.

43. Since the brittle ceramics cannot be joined by fusion welding or deformation bonding. and threaded assemblies should be avoided because of the brittleness of the material , ceramics are usually joined by some form of adhesive-type bonding. Even here, however, the residual stresses can lead to premature failure of the brittle material. As a result, it is best if ceramic products can be produces as a single piece (monolithic) structures.

44. The overriding characteristic that influences the design of ceramic parts is the brittleness of ceramics. Ceramic part design guidelines emphasize avoiding situations in which cracks are initiated and stresses cause cracks to grow. For example, ceramic parts should be designed so

- tensile and bending stresses (which give rise to tensile stress) are minimized,
- stress raisers due to part shape changes should be minimized so large abrupt changes in section should be avoided,
- sharp corners and edges should be avoided since they are stress raisers,
- corners should be rounded to avoid stress raisers and chipping and crack formation at outside corners,
- secondary or finishing operations are minimized since these operations are difficult and expensive for hard, strong materials such as ceramics,
    - --- features that are difficult to produce in the initial ceramic part production process should be avoided as this will result in additional processing,
    - --- dimensional tolerances should be as large as possible so it may be possible to meet them in the as-fired ceramic part with no secondary processing,
    - --- surface finish specifications should be as loose as possible so it may be possible to meet them in the as-fired ceramic part with no secondary processing.

45.Since particulate composites are composed of discrete, stable solid particles dispersed in a matrix material there is no need for special processes to produce a different kind of structure such as a solution or compound. Processes used to combine other materials and bond different materials into a composite, e.g., mixing, compaction and sintering of powder metal composites, are useful for forming particulate composites.

46. A quality bond can be formed between the distinct layers of a composite through such processes as: roll bonding, explosive bonding, and the various lamination techniques (adhesive bonding, brazing, etc.).

47. Fiber-reinforced composites use the strength of the fibers to impart additional strength to the fiber-matrix whole. The use of fibers means that added strength will be in the fiber length direction. The commonly used fiber forms are
- long, continuous fibers are their use results in increased strength in the fiber length direction,
- fibers woven into fabric layers used in thin sheet composites and they add strength in the two in-plane fiber directions,
- woven fabrics of fibers formed in three dimensions so that when embedded in the matrix strength in three dimensions is increased,
- short, chopped fibers that can be oriented in a particular direction or randomly.

48. Prepregs are segments of woven fabric produced from the fibers, which is then infiltrated with the matrix material. Subsequent fabrication involves stacking the prepreg layers and subjecting them to heat and pressure to complete the cure of the resin. Answer for question.

49. Sheet molding compounds are sheets composed of chopped fibers and resin, the sheets being about 0.1 inch in thickness. These can be press-formed in heated dies to provide an alternative to sheet metal where light weight, corrosion resistance and integral color are desired. Bulk-molding compounds are fiber-reinforced thermoset molding materials containing short fibers in random orientation. They are formed into products using processes like compression molding, transfer molding or injection molding.

50. In pultrusion, bundles of continuos reinforcing fibers are drawn through a resin bath and then through a preformer to produce a desired cross-sectional shape. The material is then pulled through a series of heated dies which further shapes the product and cures the resin. Like wire drawing and extrusion, the product is a long length of uniform cross-section.

51. Filament winding is used to produce hollow, container-like shapes with high strength-to-weight ratio. Small quantities of large parts can often be economically made by the filament winding process. The special tooling for a new product (a new form block) is relatively inexpensive. By making these products as a single piece, additional savings can be obtained through reduction in: labor, total manufacturing time, assembly, and tooling costs.

52. Laminated sheets containing woven fibers can be formed to produce the curves required for products, such as boats, automobile panels, and safety helmets. This fabrication is generally performed by processes, such as vacuum-bag molding or pressure-bag molding. Alternative methods include compression molding, resin-transfer molding, and hand layup.

53. Spray molding utilized chopped fibers mixed with a catalyzed resin. The starting material for sheet stamping is a thermoplastic sheet reinforced with woven fibers. Both chopped and continuous fibers can be used in injection molding using several techniques.

54. Spray molding uses chopped fibers that are mixed with a catalyzed resin.

55. There a number of ways to produce fiber-reinforced, metal-matrix composites. Variations of filament winding, extrusion, and pultrusion have been developed. Sheet materials can be made by electroplating, plasma spraying or vapor deposition onto a fabric or mesh that is then shaped and bonded. Diffusion bonding of foil and fabric sandwiches, roll bonding, and coextrusion are other options. Liquid metal can be cast around fibers through capillary action, pressure casting and vacuum infiltration. Discontinuous fiber products can be made by powder metallurgy techniques or spray forming.

56. In ceramic matrix composites, the matrix is a brittle material and failure occurs by fracture. A primary purpose of the “reinforcement” is often to impart toughness rather than strength. One means of imparting toughness is to prevent (or interrupt) the propagation of cracks across the matrix. By designing weak interfaces, propagating cracks are diverted along the interface, rather than crossing it and continuing their propagation.

57. Fiber reinforced composites are cut using conventional machining processes such as sawing, drilling, routing, tapping, turning and milling. There are problems unique to the cutting of fiber reinforced composites.

Cutting fiber reinforced composites involves cutting through the fibers, the matrix and the fiber-matrix interface regions. Moving a cutting edge through this complex material causes separation of the individual composite material components and the possible separation of the components, e.g., cutting of fibers and separation of the fiber from the matrix. Separation of the material components can result in cracking, splintering, fraying and delamination. To minimize such problems deformation and material separation should be confined to very small regions and so tool sharpness is important. High cutting speeds also help.

The fiber or matrix or the interface material in fiber reinforced composites may be abrasive and call for the use of hard, strong cutting tool materials such as polycrystalline diamond.

Fundamentally different material cutting techniques can be used to cut fiber reinforced composites to circumvent some of the problems associated with conventional machining processes. Water-jet, abrasive water-jet and laser machining can be used.

58. When fiber-reinforced materials must be joined, the major concern is a lack of continuity of the fibers in the joint area. The thermoplastic resins can be welded. Thermoset materials require the use of mechanical joints and adhesives.

Problems:

1. There are a number of possibilities here including the aligning of fibers in the shafts of golf clubs (pultruded or extruded), the laminates of woven sheets in skis, the various sheet type products in racing car bodies, and the continuous fiber reinforcements included in both the frame and handle regions of tennis racquets. Advances are continually being made in both the materials and processes, and sporting goods is one of the most active and competitive markets for the employment of composite materials.

Case Study:

Fabrication of Lavatory Wash Basins

CHAPTER 21

Review Questions

1. The deformation zone in which the chip is produced is not completely bounded. In contrast to drawing for example where the workpiece is deformed in the die, in metal cutting the workpiece has free surfaces. In lathe turning there are free surfaces at the workpiece diameter and on the top of the forming chip. And, the boundaries that do exist (the tool-chip interface and the not well-defined deformation zone boundary in the work material) are difficult to characterize.

Further complications of the process are that the strains are very large and the strain rate is very high. Material properties at such conditions are not typically known. There are also a large number of process variables.

Theoretical solutions or process models have to be validated experimentally. It is difficult to obtain reliable, consistent experimental results that quantitatively describe the local deformation in the chip formation zone. The chip formation zone extends into the workpiece below what will become the finished surface.

2. The input parameters or independent variables for the process include the cutting speed, feed, depth of cut, the cutting tool geometry, cutting tool material and the cutting fluid.

The input parameters determine the process outputs or dependent variables and process performance. e.g.,. material removal rate, machining time, tool wear, finished surface roughness, surface integrity (finished surface and subsurface deformation state), cutting zone temperature, cutting forces, chip formation and machine tool dynamics.

Other process variables may be constrained so as to be not completely defines or fixed. There may or may not be complete control over such process characteristics such as the work material, machine tool, workholding device.

3. Single point:
turning, facing, boring, shaping, planing, fly cutter milling, some modes of deep hole drilling and other variations of lathe operations such as cutoff, recessing plunge or form turning.

The rest of the machining processes are multiple point and include drilling, milling, broaching, sawing, filing and many forms of abrasive machining.

4. In turning the feed rate is the speed of the cutting tool along the workpiece longitudinal direction. If the lathe carriage is driven independently of the spindle (inch/minute or mm/min) there is no necessary relation between feed speed and cutting speed. There are the practical considerations of cutting forces, machine vibration, etc. In many lathes one motor drives both the spindle and the carriage. The carriage is usually driven through a gearbox and so feed rate is in inches or millimeters per revolution of the spindle. In this case the linear feed speed and the feed rate in units of distance/revolution are related as

feed rate (in/min or mm/min) = N_s (rev/min) f_r (in/rev or mm/rev)
$f = N_s f_r$

In contrast to the linked spindle speed-feed rate lathe turning operation, in other machining operations there may be no relationship between cutting speed and feed rate.

For example in end milling the spindle and table are driven independently. If the feed rate is the table speed past the spindle, v, it is set by the table feed motor-drive system. The spindle is driven by the spindle motor and the cutting speed, V, is the speed of the cutting edge through the workpiece. For spindle rotational speed N rpm the cutting speed at the cutter periphery is

V = (N) (cutter circumference) = N π (cutter diameter)
V = N (rev/min) π d (in or mm)

The description of the amount of material being removed is usually given by the advance of an individual cutting edge into the workpiece in one revolution of the cutter. This is the bite per tooth or the chip load. Bite/tooth is dependent on both spindle speed and table speed. For a cutter with A flutes or cutting edges, the bite/tooth, B, is

B = advance of one cutting edge per revolution of the cutter
B = { (v in/min or mm/min) (time for one cutter revolution) } / (edges / revolution)
B = (v in/min or mm/min) (1 / N rev/min) (1 / A teeth/rev)

In some machining processes the feed rate is set by the tool, in broaching the feed is built into the tool, rise per tooth as shown in Figure 26-6. Feed will be the same regardless of cutting speed.

There may be only indirect influences between feed and cutting speed in machining operations. In power sawing using a horizontal saw such as shown in Figure 26-17 and Figure 26-12 it may be that the saw in acted on only by gravity, that is, the vertical force is not controlled or the mechanism controlling this force is inactive. The net downward force will be due to gravity and the cutting forces acting. If the cutting forces change with cutting speed the net downward force will change and so the feed rate changes. In sawing soft materials or materials with definite anisotropic structure with a high tooth rake angle saw the cutting action may pull the saw down into the work.

5. The machine motion related to feed in milling is the table speed or table feed and combined with the spindle speed gives the feed per tooth or bite per tooth as explained in 4 immediately above.

So, the two feeds in milling are the table feed (in/min, mm/min) and the feed per tooth (in/tooth, mm/tooth). The table feed is the direct input to the machine. Spindle speed is a machine input that is used to set the cutting speed.

6. A shear-front lamella structure is developed by very narrow shear fronts which segment the chip material into very narrow lamellae. The mechanism is developed out of the compression deformation which precedes the shear. If the material is already cold worked, very little additional compression deformation is needed to activate the shear

process. If the material is annealed (or as-cast), the compression deformation is extensive, causing the workpiece to bulge and upset prior to shearing. The shear fronts have micron-spaced periodicity and are the result of many dislocations moving at the same time. The onset of shear begins at the shear plane (defined by ϕ) and moves at the angle φ to form the chip. This process is microscopic and not visible to the naked eye, except in very special circumstances. The primary dislocation mechanism appears to be one of dislocation pileups against the cell structure produced by compression deformation or prior work hardening of the workpiece material.

7. The metalcutting process has been labeled as an adiabatic shear instability, meaning that heat input and heat dissipated are balanced, or that there is excess heat which results in softening (lowering the strength of the material) so that the shear instability can take place. However, the metalcutting observed in Figure 21-12 is taking place at such low speeds, that such a mechanism appears to be unlikely. At faster cutting speeds, adiabatic shear may be responsible for the large saw-tooth structures seen in chips as the elastic energy is rapidly dissipated over the shear front.

8. In orthogonal cutting the cutting speed direction and cutting edge are perpendicular to each other. This is not the case in oblique cutting.

Oblique cutting is what is typically done in machining processes, with the exception of experimental setups designed to eliminate one cutting force, thus converting oblique (3 forces) cutting to orthogonal (2 force) cutting. The exceptions to this in industrial practice are broaching and slab milling with a straight tooth cutter. Orthogonal machining can be converted to oblique machining simply by canting the cutting edge with respect to the direction of motion of the tool.

9. The approximate equation for turning is (21-4):

$$MRR = 12\ V\ f_r\ d$$

base on the assumption that the depth of cut d is small compared to the workpiece diameter, D_1.

The exact equation for turning is:

$$MRR = \text{volume removed / time}$$

$$MRR = \{ (\pi D_1^2 - \pi D_1^2)\ L \} / \{ 4\ L / f_r\ N \}$$

$$N = 12\ V / \pi D_1$$

$$MRR = 12\ V\ fr\ (D_1^2 - D_2^2) / 4\ D1$$

10. The mechanics of the chip formation process can become quite complicated when a radius is used rather than an edge. Almost all of the analysis work in metalcutting assumes a zero radius cutting edge.

11. The magnitude of the strain and strain rates are very large for metal cutting compared to tensile testing. Metal cutting strain is on the order of 1 to 2 compared to tensile testing's 0.20 to 0.40 and metal cutting strain rates are 10^5 to 10^9 in/in/sec compared to tensile testing's 10^{-2}.

12. Titanium is very strain rate sensitive. The faster it is deformed, the stronger it behaves. This causes problems because of the high strain rates in metal cutting.

13. Cast iron has a structure that is filled with flake graphite. These flakes produce regions that act like sharp-cornered flaws or voids which concentrate the compression stresses. The shear fronts cannot cross these regions. Under the large strains, the metal fractures through the flake and the chips come out segmented or in fractures chunks.

14. In metal cutting shear stress is a material constant. This means that it is not sensitive to changes in cutting parameters or cutting process variations. Once this value is known for a metal, it can be used in basic engineering calculations for machining statics (forces and deflections) and dynamics (vibrations and chatter).

15. The primary or largest force is always the cutting force, F_c which is in the direction of the cutting speed vector, V. The cutting speed is much larger than the feed speed and the radial speed.

16. The energy F_cV is divided into shear (actually compression and shear) to form the chips (about 75%) and secondary shear and sliding friction at the tool/chip interface.

17. The energy that produces plastic deformation does so through the production of dislocations, which multiply and move. The energy in the dislocations is returned to the metal as heat when the dislocation absorb each other (annihilate). In short, energy is converted to heat. Only a very small portion of the input energy is stored in changes in metallic structure.

18. F_c can be estimated from:
   a) the unit power, eqn (21-12)
) the specific energy, eqn (21-15)
   b) the shear stress, eqn (21-30) with an estimate for F_t
      usually Ft is estimated at F_c / 2

19. The rate of wear (on both the flank and the rake face) of the tool is most directly influenced by cutting speed. The higher the cutting speed, the shorter the life of the tool. This is because increasing V directly drives up the temperature, and increasing the temperature of a tool rapidly increases wear rates.

Question 17 is concerned with the heat generated in machining. The power dissipated in machining is FV (the sum of the products of all cutting forces and corresponding velocities) and so increasing V increases power, increasing heat generation and increasing tool temperature.

Tool wear is discussed in Sections 22.5, 22.6.

20. As temperature goes up, the hardness (resistance to penetration) decreases. See Figure 22-3.

21. The case of constant cutting force with increasing cutting speed, Figure 21-11, can be due to either

- cutting speed has no effect on the machining process and on work material behavior/properties,
- or that the effects of cutting speed increase on the process and/or material offset each other to produce no net effect.

Specifying the effect of cutting speed, V, on cutting force, F_c, can be approached from two starting points.

i. The power for machining as described in Section 21.3 can be used.
Using the definition of power $P = F_c V$,
and the machining process model $P = HPs\ MRR$ relating power and unit power and material removal rate gives

$$F_c = P / V = HPs\ MRR / V$$

$MRR = V fr\ d$ with fr being feed advance d the depth of cut

then

$$F_c = HPs\ fr\ d$$

Feed advance and depth of cut do not depend on cutting speed. This implies that that for constant F_c, HP_s does not depend on cutting speed. That is, unit power is constant with increasing cutting speed.

However, more careful consideration of the unit power may lead to a different conclusion. If unit power is determined by work material properties and chip formation process mechanics then a balance of competing effects may result in constant unit power. For example, if

- work material shear strength increases with cutting speed (the strength of many materials increases with strain rate)
- and the amount of deformation to form the chip decreases with increasing cutting speed due to formation of a smaller shear zone,
- and work material strength decreases with increasing cutting speed due to increased temperature in the shear zone,

perhaps these effects will combine to produce a constant value of unit energy. In reality a more realistic statement is that they combine to produce a small enough change in unit energy so that cutting force appears to be constant.

ii. The force model of machining can be used to add more detail to explaining constant cutting force in terms of process and material interactions.

The process model, force system is shown in Figure 21-20.
From Figure 21-20

$$F_c = R \cos(\beta - \alpha)$$

again from Figure 21-20 $F_s = R \cos(\beta - \alpha + \phi)$

or $R = F_s / \cos(\beta - \alpha + \phi)$

now known material behavior is introduced by putting shear force in terms of shear strength

$$F_s = \tau\ As$$

$$As = t\, w / \sin \phi$$

$$F_s = \tau\, t\, w / \sin \phi$$

$$R = (\tau\, t\, w) / \{ \sin \phi \cos (\beta - \alpha + \phi) \}$$

and finally

$$F_c = \{ \tau\, t\, w \cos(\beta - \alpha) \} / \{ \sin \phi \cos (\beta - \alpha + \phi) \}$$

If cutting force is to remain constant then all terms on the right hand side of the equation should not change with cutting speed or the effects of changing process and material parameter values have to compensate, i.e., cancel each other.

The width of cut, *w*, the depth of cut or uncut chip thickness, *t*, and the tool rake angle, α do not change with cutting speed. The changes with cutting speed of the remaining parameters, τ, β, ϕ, are not so clear-cut.

It seems reasonable as a first approximation to assume that the work-tool coefficient of friction is constant and so the friction angle β = constant. The shear angle ϕ is given in the Merchant chip formation model by

$$\phi = 45^o + \alpha / 2 - \beta / 2$$

and the shear angler does not depend on cutting speed for constant friction coefficient.

The revised description of shear angle in Section 21.7 is

$$\phi = 45^o + \alpha / 2 - \psi$$

with ψ dependent on material hardness.

So, what is left is the explanation that cutting force is constant with increasing cutting speed since the work material shear strength, τ, is constant with increasing cutting speed. The argument that increase in τ with increasing strain rate is balanced by decrease in τ with increasing temperature as cutting speed increases leads to the conclusion that cutting force remains constant with increasing cutting speed.

(An Aside: The development of the initial Merchant model of chip formation was based on the independence of friction and shear strength from shear angle. Subsequent models developed by Merchant and others explicitly included consideration of the work material strength.)

22. In overview, the cutting force increases with increasing feed or depth of cut since the amount of material being removed increases.

The same cutting force equation as immediately above can be used and the argument is

$$F_c = \{ \tau\, t\, w \cos(\beta - \alpha) \} / \{ \sin \phi \cos (\beta - \alpha + \phi) \}$$

and if *t* and/or *w* increases, F_c increases.

Problems:

1. Excel spreadsheet solution

shear angle $\phi = \tan^{-1}\ \{ r_c \cos \alpha / (1 - r_c \sin \alpha) \}$

shear stress $\tau_s = F_s / A_s$

$F_s = F_c \cos \phi - F_t \sin \phi$

$A_s = t\, w / \sin \phi$

coefficient of friction $\mu = F / N$

$F = F_c \sin \alpha + F_t \cos \alpha$

$N = F_c \sin \alpha - F_t \cos \alpha$

In the orthogonal metal cutting model the only nonzero velocity is the cutting velocity and so the only power is (cutting force)(cutting velocity)

HP_s = Power / Material Removal Rate

$HP_s = = \{ (F_c \text{ lb}) (V \text{ ft/min}) (12 \text{ in/ft}) \} / \{ (t \text{ in}) (w \text{ in}) (V \text{ ft/min}) (12 \text{ in/ft})$

$HP_s = \{ F_c / t\, w \ \ \text{inlb/min} / \text{in}^3\text{/min} \}\{ \text{hp} / 396{,}000 \text{ inlb/min} \}$

$HP_s = F_c / t\, w \ \ \text{hp/ in}^3\text{/min}$

	w	0.2	in												
	alpha	0	deg												
	V	530	sfpm												
Run	F_c (lb)	F_t (lb)	Feed (ipr)	r_c		**phi (deg)**		F_s (lb)	A_s (in^2)	**tau (psi)**		F (lb)	N (lb)	**mu**	**HP_s**
1	330	295	0.00489	0.331		**18.3**		221	0.00311	**70874**		295	330	**0.89**	**0.85**
2	308	280	0.00489	0.381		**20.8**		188	0.00275	**68487**		280	308	**0.91**	**0.80**
3	410	330	0.00735	0.426		**23.0**		248	0.00375	**66084**		330	410	**0.80**	**0.70**
4	420	340	0.00735	0.426		**23.0**		253	0.00375	**67492**		340	420	**0.81**	**0.72**
5	510	350	0.00981	0.458		**24.5**		318	0.00471	**67478**		350	510	**0.69**	**0.66**
6	540	395	0.00981	0.453		**24.3**		329	0.00475	**69171**		395	540	**0.73**	**0.70**

Figure 21-21 shows shear stress for annealed 1018 steel = 75,000 psi

- this is close to the results of the calculations for 1020 steel
  - while it is not definite, sometimes it is said that the effects of increasing work strength with strain rate are offset by decreasing strength due to increasing

temperature and the room temperature shear strength of the work can be used for approximate calculations of machining variables.

The calculated unit power values of about 0.7 – 0.8 hp/in3/min seem lower than the values in Table 21-3. This is probably due to the simplifications in the orthogonal model of chip formation.

In actual machining there is a feed direction velocity that when multiplied by the feed direction force gives a power dissipation. Calculation of this power with typical values will show that it is negligible with respect to the cutting force power.

2. rc = t / tc

weight density = ρ = weight / volume = $Wt / (l_c\ w_c\ t_c)$
with l_c = chip length, w_c = chip width, t_c = chip thickness
$t_c = Wt / (l_c\ w_c\ \rho)$

$rc = t\ Wt / (l_c\ w_c\ \rho)$

Know Wt, l_c, ρ

t is the uncut chip thickness in the orthogonal model and is the feed in conventional turning and should be known since a machining process was run to obtain the chip.

w_c is the chip width and in the orthogonal cutting model is the width of workpiece and is constant since two-dimensional deformation is a basis for the model. In conventional turning the deformation is often close to plane strain and then the chip width is the depth of cut.

3. $U_s = F_s\ V_s$ / Material Removal Rate
$= F_s\ V_s / (V\ t\ w)$

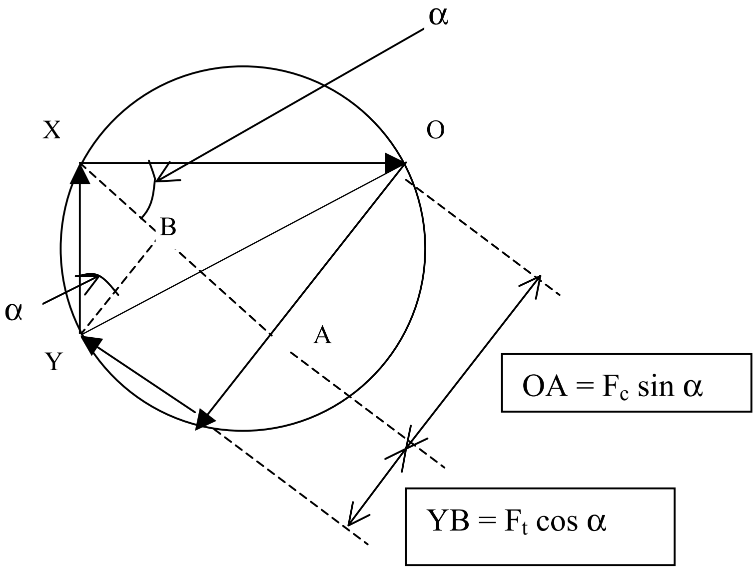
$F_s = F_c \cos \phi - F_t \sin \phi$
$V_s = V \{ \cos \alpha / \cos(\phi - \alpha\}$
V = cutting speed
t = uncut chip thickness = feed advance per revolution
w = width of cut

$U_f = F\ V_c$ / Material Removal Rate
$= F\ V_c / (V\ t\ w)$

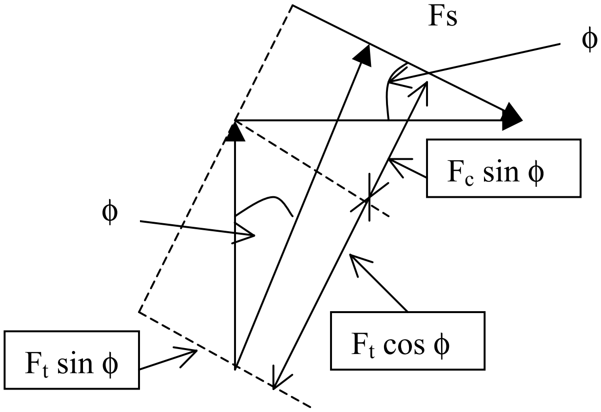
$F = F_s = F_c \sin \alpha + F_t \cos \alpha$
$V_c = V\ r_c$

	w	0.2	in									
	alpha	0	deg									
	V	530	sfpm									
Run	F_c (lb)	F_t (lb)	Feed (ipr)	r_c		phi (deg)	F_s (lb)	V_s (ipm)	**Us (inlb/in^3)**	F (lb)	V_c (ipm)	**U_f (inlb/in^3)**
1	330	295	0.00489	0.331		18.3	220.6	6699	**237582**	295	2105	**99842**
2	308	280	0.00489	0.381		20.8	188.1	6806	**205849**	280	2423	**109080**
3	410	330	0.00735	0.426		23.0	247.9	6913	**183279**	330	2709	**95633**
4	420	340	0.00735	0.426		23.0	253.1	6913	**187184**	340	2709	**98531**
5	510	350	0.00981	0.458		24.5	317.9	6995	**178236**	350	2913	**81702**
6	540	395	0.00981	0.453		24.3	328.9	6982	**184029**	395	2881	**91200**

4.



5.



6. shear strain = $\gamma = \cos\alpha / (1 + \sin\alpha)$

	w	0.2	in				
	alpha	0	deg				
	V	530	sfpm				
Run	F_c (lb)	F_t (lb)	Feed (ipr)	r_c		**shear strain**	**1 / rc**
1	330	295	0.00489	0.331		**2.00**	**3.02**
2	308	280	0.00489	0.381		**2.00**	**2.62**
3	410	330	0.00735	0.426		**2.00**	**2.35**
4	420	340	0.00735	0.426		**2.00**	**2.35**
5	510	350	0.00981	0.458		**2.00**	**2.18**
6	540	395	0.00981	0.453		**2.00**	**2.21**

The inverse of the chip thickness ratio 1 / rc = tc / t decreases with increasing feed rate. This indicates that the chip is relatively less deformed, i.e., the chip thickness goes from about three times the uncut chip thickness to about twice the uncut chip thickness. Given the change in deformation, the constant value of shear strain is surprising.

7 With cutting conditions known (except for cutter rake angle) and a chip formation mechanics model available, what remains to be obtained is material property values. The candidate sources of material behavior are material strength and the unit machining power for the particular work material.

The rake angle is presumably known as it is measurable. For a strong tough material a low rake angle, and so strong, tool is probably used, say $\alpha = 0^o$. (Lacking specific information, one way to proceed is to consider several realistic possibilities, i.e., a range of rake angle values. However, using the force data provided that is for one case with different rake angles implies that cutting force is independent of rake angle. This is not the case.)

i. eqn (21-30) gives

$F_c = \{ \tau_s\, t\, w + F_t \sin 2\phi \} / \{ \sin\phi \cos\phi \}$

given $F_t = F_c / 2$

$F_c = (\tau_s\, t\, w) / (\sin\phi \cos\phi - ½ \sin 2\phi)$

$\phi = \tan^{-1} \{ r_c \cos\alpha / (1 - r_c \sin\alpha) \}$

$r_c = t / t_c = 0.020$ in / 0.080 in = 0.25

$\phi = 14^o$

Figure 21-21 shows τ_s for Inconel 600 to be 105,000 lb/in^2

t = 0.020 in

w = 0.25 in

$F_c = 2555$ lb

An alternative problem solution is to use tabulated values of unit machining power such as Table 21-3.

For Iconel 700, HP = 1.4 hp/(in^3/min)

Power = F V

in turning $P = F_c V + F_t V_{feed} + F_r V_r$

in turning a straight shaft the radial velocity $V_r = 0$

the feed direction force Ft is given as Ft / 2 but this component of power will not be included since tool velocity in the feed direction is small compared to the cutting speed.

e.g., even at 1000 rpm spindle speed

V_{feed} = (1000 rev/min)(0.020 in/rev) = 20 in/min = 1.7 fpm

Power = F_c V

P = F_c V = HPs (Material Removal Rate)

Fc = P / V

MRR = V f d = (250 ft/min)(0.020 in)(0.250 in)(12 in/ft)

MRR = 15 in3/min

P = { 1.4 hp/(in^3/min) } { 15 in^3/min } = 21 hp

V = 250 ft/min = 3,000 in/min

Fc = { 21 hp / 3,000 in/min }{ 396,000 (inlb/min) / hp } = 2,772 lb

8. For rough machining typical ranges of cutting conditions are:

Cutting speed, 200 sfpm to 800 sfpm

Feed rate, 0.010 ipr to 0.085 ipr

Depth of cut, 0.125 in to 0.675 in

MRR = 12 V f d

MRR_{min} = 12 (200 ft/min) (0.010 in) (0.125 in) = 3 in^3/min

MRR_{max} = 12 (800) (0.085) (0.675) = 550 in^3/min

For finishing

MRR_{min} = 12 (700 ft/min) (0.005 in) (0.0125) = 0.525 in^3/min

MRR_{max} = 12 (1600) (0.015) (0.0675) = 19.44 in^3/min

9. HP = Fc V ftlb/min/ 33,000 ftlb/min/hp

V can be obtained from the MRR

MRR = 12 V fr d = 550 in3/min

V = 550 in^3/min { (12) (.005 in) (0.675 in)

V = 13,580 ft/min

HP = (10,000 lb) (13,500 ft/min) / 33,000 ftlb/min/hp

HP = 4090 hp

The 4000 hp value calls for investigation of this unreasonable number. Although the cutting speed seems high it might be possible. The difficulty is probably with the 10,000 lb “measured” force.

10. HP_s = Power / MRR

Power = 24 hp
MRR = 550 in^3/min

HPs = 0.0436 hp/in^3/min

Table 21-3, Steel (200 BHN)
HPs = 1.50 hp/in^3/min & 0.73 hp/in3/min

The calculated value is well out of the expected range.

Case Study:

No case study

CHAPTER 22

Review Questions

1. The most important material property for cutting tools is hardness. The tool must be harder than the material being machined to prevent rapid wearing and early failures.

2. Hot hardness is the ability to sustain hardness at elevated temperatures. See Figure 21-22.

3. Impact strength is a material property which reflects the ability of a material to resist sudden impact loads without failure. It is a combination of strength and ductility and is measured by the energy absorbing capability of the material. The two tests used for impact testing are the Charpy and the Izod Impact test. The general term for impact strength is toughness.

4. Many cutting tools experience impacts during routine cutting processes. Interrupted cuts are common in milling. Cutting tools may also impact on hard spots or hard surfaces of a material .

5. RIP is hot isostatic pressing, a powder metallurgy process used to make cutting tools, particularly carbides. See Chap. 16.

6. Primary considerations in tool selection include: What material is going to be machined, what process is going to be used, what are the cutting speeds, feeds, and depths of cut needed, what is the tool material, and what are lubricants going to be used. See Figure 22 - 2 for complete answer.

7. A hard, thin, wear-resistant coating is placed on a tough, strong, tool material. Such composites have good impact strength and good wear resistance.

8. Cermets are a relatively new cutting tool material compared to composed of ceramic materials in a metal binder. See Figure22-10 for a comparison of cermets to other tool materials.

9. CBN is manufactured by the same process used to make diamonds. The powder is used as a coating for carbide blanks in the same way poly-crystalline diamonds are made. CBN powder is sintered and compacted onto a carbide substrate, diced with a laser into segments and the segments brazed into pockets in a standard tungsten carbide insert. The CBN layer is about 0.020 inches thick.

10. F. W. Taylor developed the experiments which lead to the Taylor tool life equation, developed the principles of scientific management and stop watch time study, developed the tool grinder methodology for grinding specific angles on cutting tools, and is considered to be one of the founders of Industrial Engineering. He was also the first

United States tennis doubles champion, dispelling the myth he had bad eyesight.

11. Cast cobalt alloy tools would be made by investment casting, due to the high temperatures of the alloys.

12. The compacted powders are compressed into a solid of uniformly fine grains. If cobalt is used as a binder, the solid cobalt dissolves some tungsten carbide, then melts and fills the voids between the carbide grains. This step is called sintering.

13. When the cobalt powders melt and fill the voids between the carbide grains, they "cement" the carbide grains together. This is an old term still used in the cutting tool industry to describe sintered, powder metallurgy tools.

14. The ground inserts are more precise - have less variability from tool insert to tool insert -- so that there is very little difference between tools. This is important when changing tools in automatic equipment or rotating the insert in an indexing tool holder. Therefore, the tool does not have to be reset when the insert tip is changed. Pressed inserts may vary in size as much as .005 inches and may carry this size change into the process.

15. The chip groove is placed on the rake face directly behind cutting edge. Depending upon the depth of cut, the chip groove can make the land in front of the groove act as a controlled contact surface and modify the cutting process. It can cause the shear angle to increase and therefore reduce the power and cutting forces. It can also cause the chips to bend sharply and fracture into short segments which makes chip disposal easier. See Figure 22-9.

16. As shown in Figure 22-13, a groove forms at the outer edge of the cut during the machining of materials with a hard surface or a surface with hard particles in it. The groove is called the depth of cut line or the DCL since it forms at a distance from the cutting edge equal to the depth of cut.

17. a) High speed steel will deflect the most - smallest E
b) Ceramic will resist penetration the most - hardest
c) High speed steel is the most ductile
d) Carbides are the strongest in compression.

18. Tools get hot and expand during machining. Different materials have different coefficients of expansion. The layers are graded with respect to thermal coefficients of expansion to reduce the probability of thermal cracking of the coats. Some layers are also used to promote bonding between the materials.

19. For high-speed steel, black oxide and nitriding are quite common but TiN of RSS is becoming very popular. Coating carbides with TiN and TiC and other materials is popular now using CvD. Aluminum oxide coating is becoming more popular. Ceramics are usually not coated or surface treated.

20. The reaction forms hydrogen chloride which can affect the impact strength and other material properties.

21. Lowering the coefficient of friction at the tool/chip interface reduces the secondary deformation. This has the effect of reducing the friction force, F. The reduction of F results in rotation of the force circle (or an increase in the shear angle). For a given cutting geometry, this means a reduction in F_s (because $F_s = {}_sA_s = \sim t\, w/\sin\phi$) and F_c (because F_c is a function of F_s). Thus, the tools run at lower forces and lower temperatures and last longer.

22. CBN tools are used when other factors, such as interrupted cutting, do not mitigate against using as high a cutting speed as possible. An example is lathe turning of low strength materials. The machining processes amenable to the use of CBN cutters are similar to machining situations in which diamond cutters are used – with the exception of ferrous workpieces. Diamonds react chemically with ferrous materials while CBN does not.

23. Diamond reacts chemically with ferrous materials while CBN does not.

24. The coefficient of variation is the ratio of the standard deviation of a statistic distribution to the mean of the distribution. A large value indicates that the process which produced the data for the distribution has a large amount of process variability .

25. Tool life varies from tool to tool even when the tools are being used under identical conditions. Lifetime is a random variable, whether we are talking about tools, people, tires, or light bulbs. The random variable nature of tool life means that predicting tool death will be very difficult.

26. Metal cutting tool life data tends to be log-normal and have a coefficient of variation of .3 to .4. Compare this to values for yield strength data or UTS data which have values of
.03to .05.

27.Machinability is defined many different ways. The two most common ways are: <u>machining specific horsepower</u> (RP~) which reflects the power needed to remove a cubic inch of metal per minute - the more difficult metals will have higher numbers for specific horsepower; and <u>machinability numbers based on tool life comparisons</u>. A material is selected as the standard. A material which can be machined faster with the same tool life as the standard material has a higher rating than the standard. So the first measure is based on equal volume of material removed and ignores tool life, and the other on equal tool lives, ignoring power consumed. Other measures of machinability have been proposed using ease of chip removal and surface quality as criteria .

In the 1970's, one of the authors (Black) tried (without much success) to get people to think about flow stress, τ_s, as a machinability standard (like UTS) and developed a prototype machine to determine flow stress values for various materials. Many of the values given in Figure 21-21 came from this research.

28. From the earliest measurements of F. W. Taylor, it has been known that cutting fluids provide a cooling action for the tool. Because of the nature of the process, few usable cutting fluids provide a lubrication action to the tool/chip interface but this

29. Carbide tools are made in press and sinter operations. The compositions of the carbide constituents and the binder are important in determining tool mechanical properties and hence performance when cutting different work materials.

Powder metallurgy techniques are described in Chapter 16.

30.High-speed steel tools are coated to increase their useful life by covering them with a more highly wear resistant material. Physical vapor deposition is used since it is a relatively low temperature process and so has little effect on changing the HSS substrate material. Subsequent heat treatment to restore HSS properties after coating may not be required.

31. The is no universal cutting tool material since the requirements for the cutter vary widely with the material being machined and the kind of machining process being used.

At one extreme is the cutting of tough work material in an intermittent or interrupted cutting process such as milling. In this situation tool material resistance to impact loading and thermal cycling is required. High cutting speed is secondary to simply accomplishing the process and so high speed steel tools may be used in preference to other tool materials that have higher hot hardness but are more susceptible to chipping and fracture. At the other extreme are smooth, continuous machining processes such as finish lathe turning of low strength materials with small feed rate and depth of cut. In this situation, high hardness, high wear resistance tool materials can be used at high cutting speed. e.g., diamond tooling. The factors that make these tools materials susceptible to failure do not exist.

32. 18-4-1 or T1 high-speed steel is composed of iron, carbon and 18% tungsten, 4% chromium and 1% vanadium.

33. The most notable mechanical property of high-speed steel compared to other cutting tool materials is its higher toughness. It can also be more easily ground and so complex tool shapes can be produced. These characteristics make high speed steel tools useful for severe cutting situations requiring form tools, e.g., interrupted cutting processes such as milling using form cutters and gear cutting.

34. High hot hardness, high wear resistance cutting tool materials are usually brittle and so sensitive to changing forces and temperature, i.e., fluctuating forces and temperatures

cause varying stress fields and can lead to chipping and fracture. Non-rigid machine tools can cause dynamic, as opposed to constant level, forces and so adversely affect tool life.

35. While hardness is one indication of wear resistance, it is not the only one, and may be only an indirect indication of the resistance of the material to a particular wear mechanism.

Perhaps the most obvious shortcoming of hardness as a measure of wear resistance is in the chipping/fracture of cutting tools. Hard brittle materials are susceptible to chipping at the tool edge. So the tool material may be hard but still exhibit high wear rate if the work material, machining process and cutting conditions result in local, small-scale fracture and edge wear.

Also at a local level, hard inclusions in the nominally soft workpiece may abrade the tool and cause wear of the macroscopically much harder tool.

At high cutting speed, even with soft work material, high temperature is produced in the chip formation zone. The high temperature can result in diffusion of certain phases of the tool and tool wear. More specifically, for cemented carbide cutting tool materials the binder material may diffuse out of the tool exposing the brittle carbide structure to fracture and wear. This same type of tool weakening and wear can be due to chemical effects. In cutting green (moist) wood chemical action may remove the carbide tool binder. Then even relatively small cutting forces may cause fracture of the carbide phase.

36.A honed edge, or the chamfer shown in Figure 22-11, is the result of removing a small region at the tool cutting edge. The intent is to make the tool stronger. Much as negative rake angle increases tool strength by decreasing the wedge angle (θ in Figure 22-12) and changing the force at the tool edge to a more compressive stress pattern, honing has the same goals.

Problems:

1. With tool life equation $V\,T^n = K$ and K a constant,
can choose two data points and set the values for K equal,
Using the 3 min and 60 min tool life data points

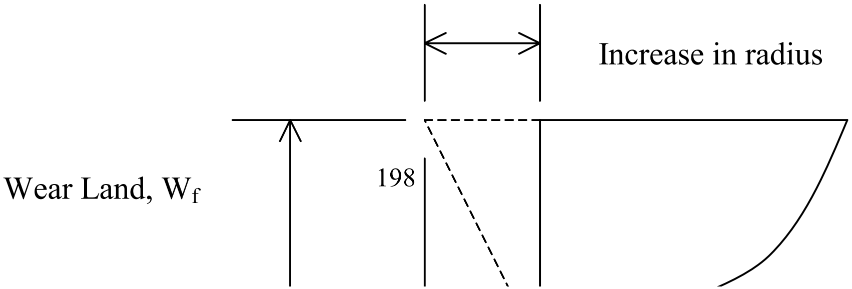
$$(V\,T^n)_3 = (V\,T^n)_{60}$$

$$(40.6) (3)^n = (26.8) (60)^n$$

$n = 0.14$

V Tn = (40.6) (3).14 = 47.4 = K
Values for n in Table 22-6 indicate material is high speed steel, but there is a low value for K

2.



Increase in radius = (Wf)(tan 5^o) = (0.020 in)(tan 5^o)= 0.002 in
Increase in diameter = -.004 in

There may be other significant effects on machined diameter, e.g., workpiece and tooling deflection.

3.

A =	side rake angle
B =	side relief angle
C =	end relief angel
D =	back relief angle
E =	nose radius
F =	side cutting edge angle
G =	end cutting edge angle

4. $V\ T^n = K$
For sand casting – diamond
$731\ (20)^n = 642\ (30)^n$
$731\ (20)^n = 514\ (60)^n$
$642\ (30)^n = 514\ (60)^n$
gives n = 0.32 and $K = 731\ (20)^{0.32} = 1907$

For permanent mold casting – diamond
$591\ (20)^n = 517\ (30)^n$
$591\ (20)^n = 411\ (60)^n$
$517\ (30)^n = 411\ (60)^n$
gives n = 0.33 and $K = 517\ (30)^{0.33} = 1588$

For PMC – diamond will coolant
$608\ (20)^n = 554\ (30)^n$
$608\ (20)^n = 472\ (60)^n$

$554\ (30)^n = 472\ (60)^n$

gives $n = 0.23$ and $K = 472\ (60)^{0.23} = 1210$

For sand casting – WC – K-20

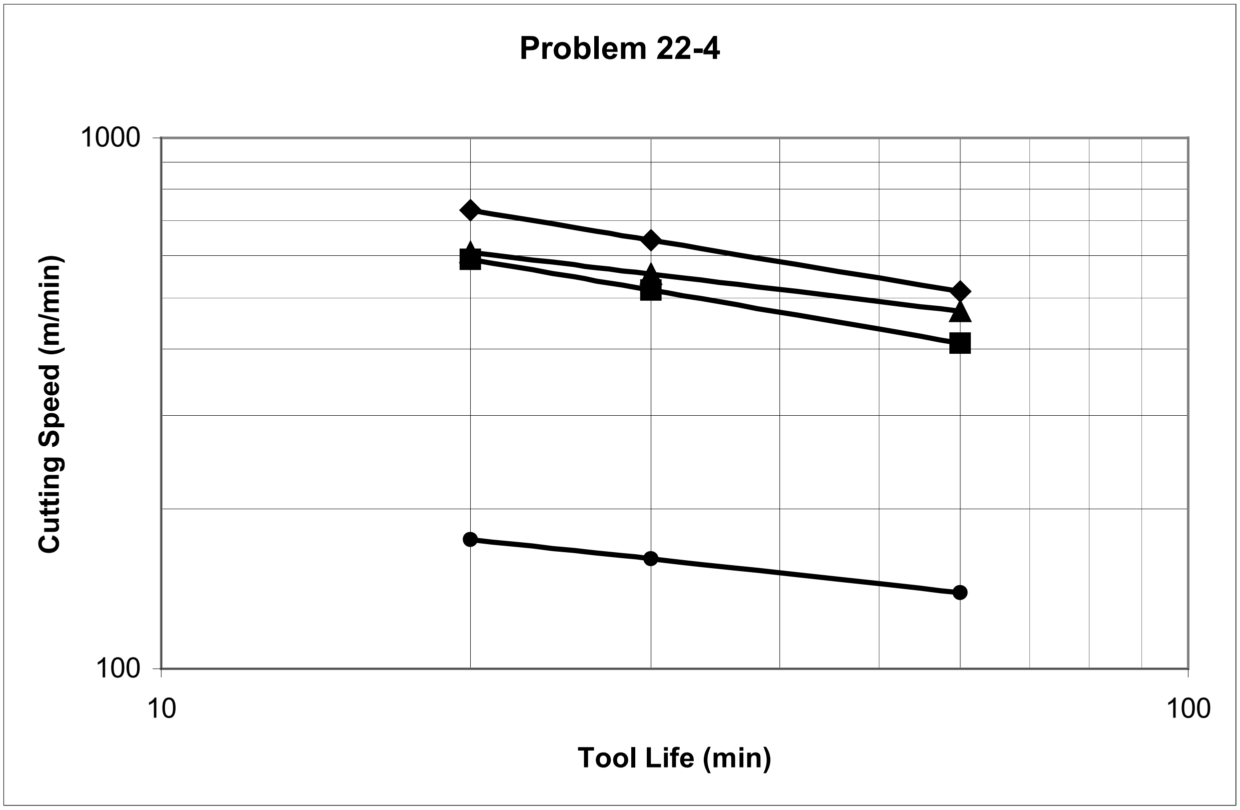
$175\ (20)^n = 161\ (30)^n$

$175\ (20)^n = 139\ (60)^n$

$161\ (30)^n = 139\ (60)^n$

gives $n = 0.21$ and $K = 161\ (30)^{0.21} = 329$

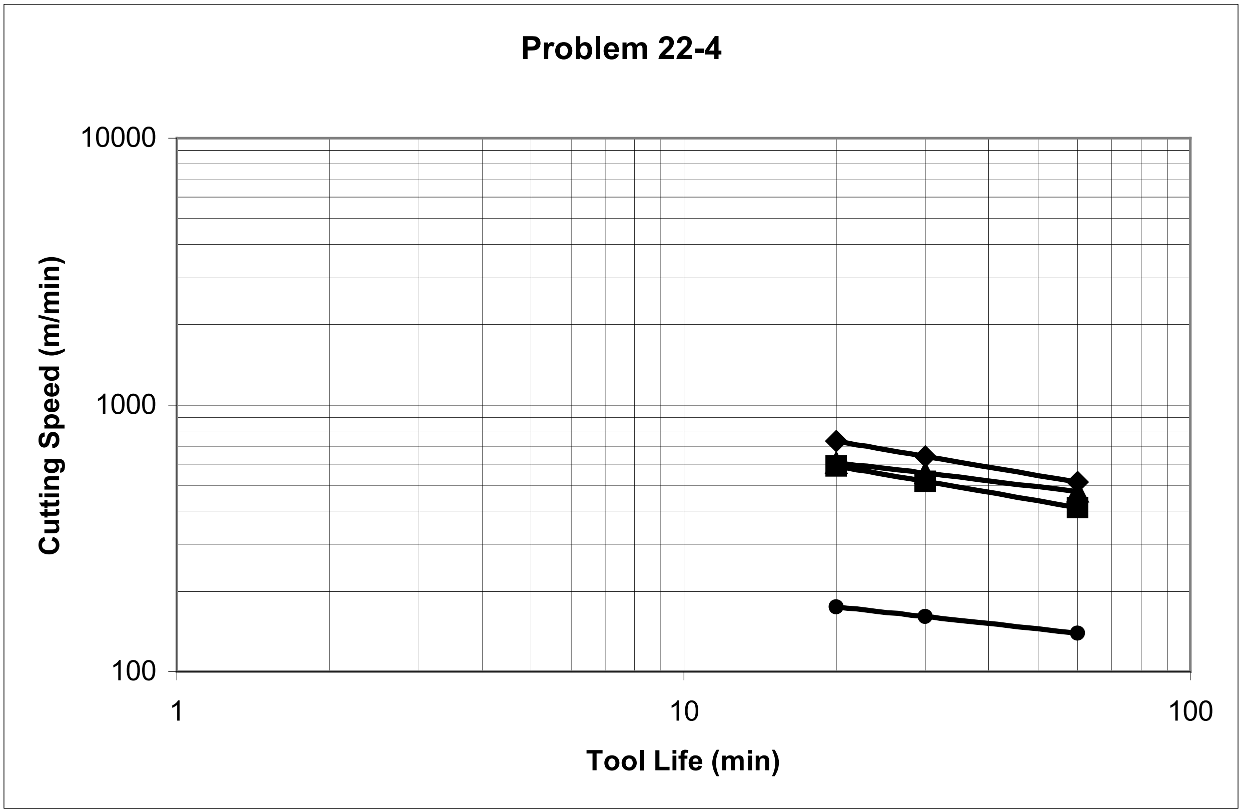
Problem 22-4								
		V (m/min) for tool life T (min) of				Log of V and T values		
Work	Tool	20	30	60		1.30	1.48	1.78
Sand Casting	Diamond	731	642	514		2.86	2.81	2.71
Mold Casting	Diamond	591	517	411		2.77	2.71	2.61
PMC	Diamond	608	554	472		2.78	2.74	2.67
Sand Casting	WC-K-20	175	161	139		2.24	2.21	2.14



Slope		
for example		
Sand Casting	WC-K20	n = (log(330) - log(140)) / (log(60) - log(1))
		n = (2.519 - 2.146) / (1.778 - 0)
		n = 0.21
Sand casting	Diamond	n = (log(1900)-log(510)) / (log(60) - log(1))
		n = (3.279 - 2.708) / (1.778 - 0)
		n = 0.32

with the T = 1 intercepts, that are the values for K, determined by extaoplating the following plot

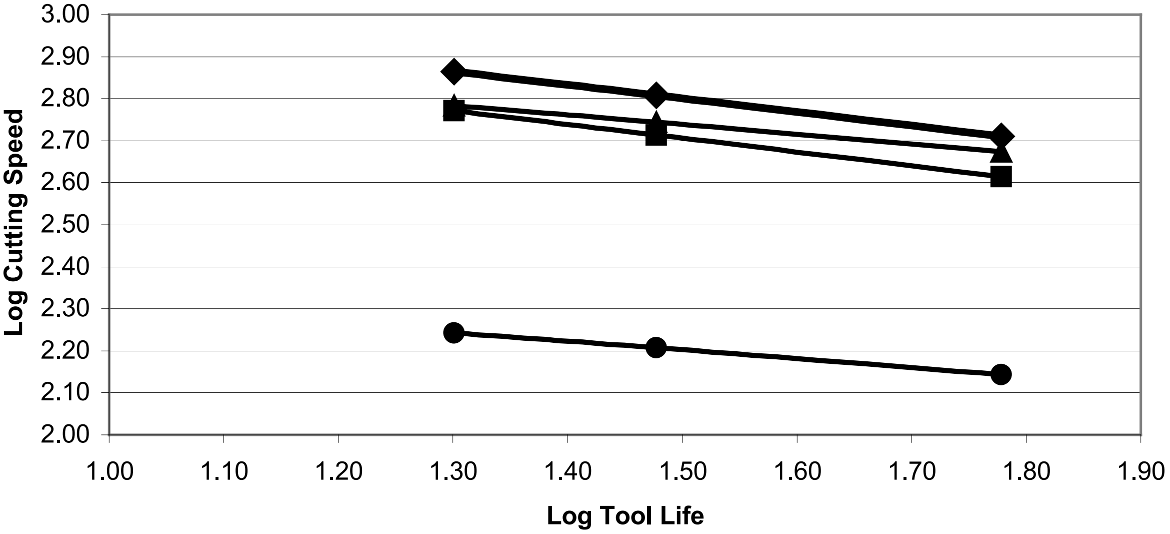
		V (m/min) for tool life T (min) of				Log of V and T values		
Work	Tool	20	30	60		1.30	1.48	1.78
Sand Casting	Diamond	731	642	514		2.86	2.81	2.71
Mold Casting	Diamond	591	517	411		2.77	2.71	2.61
PMC	Diamond	608	554	472		2.78	2.74	2.67
Sand Casting	WC-K-20	175	161	139		2.24	2.21	2.14



		V (m/min) for tool life T (min) of				Log of V and T values		
Work	Tool	20	30	60		1.30	1.48	1.78
Sand Casting	Diamond	731	642	514		2.86	2.81	2.71
Mold Casting	Diamond	591	517	411		2.77	2.71	2.61
PMC	Diamond	608	554	472		2.78	2.74	2.67
Sand Casting	WC-K-20	175	161	139		2.24	2.21	2.14

Or
plotting log T vs log V

Problem 22-4

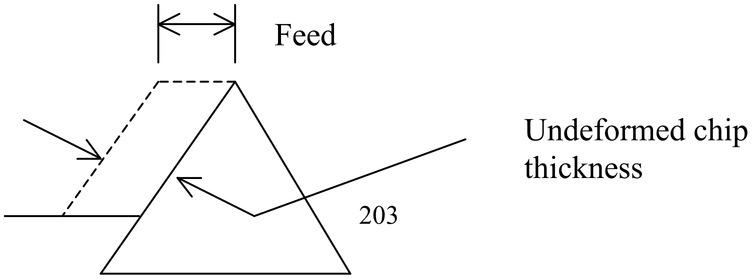


Slope		
Sand Casting	Diamond	n = (2.87 - 2.71) / (1.78 - 1.30) = 0.33
PMC	Diamond	n = (2.78 - 2.67) / (1.78 - 1.30) = 0.23
PMC	D + fluid	n = (2.77 - 2.61) / (1.78 - 1.30) = 0.33
Sand Casting	Diamond	n = (2.25 - 2.14) / (1.78 - 1.30) = 0.23

K		
for example		
Sand Casting	Diamond	extrapolate lowest line to Log Tool Life = 1, T = 10
	Log Cutting Speed = 2.3, V = 199	
	VTn = K = 199 (10)0.23 = 338	

5. a. cos(SCEA) = = 0.250 in / 0.289 in = 0.865 => SCEA = 30.1^{o}

b)



Undeformed chip thickness = (feed distance)(cos(SCEA)
Undeformed chip thickness = (0.010 in)(cos(30.1^o) = 0.009 in

c) When SCEA goes from 0o to a different value the orthogonal, essentially two-dimensional deformation and force situation changes to three-dimensional. A radial force arises producing work and tooling deflection and may cause chatter. A SCEA increases the chip becomes thinner, more heat is dissipated and notching wear at the work outer diameter is decreased.

6.

	SiN	PCBN
Tips/part	12	12
Tool life parts/tool	200	4700
Cost/tip	$1.25	$28.50
Tool cost/part	(12)($1.25)/200 = $0.075	(12)($28.50)/4700 = $0.073
Tool cost/yr	($0.075)(312,000 = 23,400	($0.073)(312,000) = $22,776

There are costs with making change and these may very well be greater than the $624 tool cost savings. However, There be other than cost advantages to adopting the new tools, e.g., part surface finish, less tool change time.

b. If there is to be a change it will be based on tool cost and other, important, factors. The finished cylinder bores are critical elements of the part. Changes in the product – over its entire life – that are related to changing tooling have to be evaluated. For example, changing cutting tools may affect bore surface finish and surface integrity and so affect engine performance in terms of power produced and cylinder bore wear.

7. The tool life equation is $V T^n = K$ and so the straight line relation is on a log-log plot, e.g., Figure 22-16 and n and K have constant values.

Given 2 in diameter the cutting speeds and tool lives are

Spindle Speed (rpm)	Cutting Speed, V (ft/min)	Tool Life, T (min)
284	149	10
132	69	30

With the two (V,T) points the values of n and K can be calculated and used in the tool life equation to calculate the cutting speed for a tool life of 60 min

for constant K,

$69 (30)^n = 149 (10)^n$ and n = 0.7

with n = 0.7, K = 746.5

for 60 min life, $V T^n = K$ is V (60)0.7 = 746.5 and V = 42.5 ft/min

Solving the problem by plotting the given values on log-log paper or if linear graph paper is used the given point are

(V, T) point	(logV, logT) point
(149, 10)	(2.17, 1)
(69,30)	(1.84, 1.78

Drawing a line between the point and picking the point on the line corresponding to tool life of 60 min (log 60 = 1.78) gives a log cutting speed value of about 1.62 and a cutting speed of $(10)^{1.62}$ = 41.7 ft/min

If the straight line relationship is interpreted erroneously as a linear relation between V and T rather than $V T^n = K$,
then
the slope of the line is $\Delta V / \Delta T$ = (69 – 149) ft/min / (30 – 10) min = - 4
extrapolating from the V = 149 ft/min, T = 10 min point to T = 60 min gives
V = 149 ft/min + (-4 ft/min/min)(60 – 10) min = - 51 ft/min

8. The machining process dependent variables are:
a) eqn(21-18)
Chip thickness ratio = $r_c = t / t_c$ = 0.010 in / 0.022 in = 0.455
b) eqn(21-19)
Shear plane angle = $\phi = \tan^{-1}\{ r_c \cos\alpha / (1 - r_c \sin\alpha) \}$
$\phi = \tan^{-1}\{ 0.455 \cos 10^o / (1 - .455 \sin 10^o) \} = 25.9^o$
c) Friction angle = see below
d) Coefficient of friction = see below
e) Friction force = see below
f) Shear force = see below
g) Shear stress on shear plane = see below
h) eqn(21-21)
Shear velocity = $V_s = V \{ \cos\alpha / \cos(\varphi - \alpha)$
V_s = 500 ft/min $\{ \cos(10^o) / \cos(26^o - 10^o)$ = 512 ft/min
i) Shear strain eqn(21-31)
$\gamma = \cos\alpha / [\sin(\phi+\psi) \cos(\phi+\psi-\alpha)$
eqn(21-34) $\psi = 45^o - \phi + \alpha/2$
gives corrected eqn(21-35) as shown in the center of page 503
eqn(21-22) corrected
Shear strain = $\gamma = 2 \cos\alpha / (1 + \sin\alpha)$
$\gamma = 2 \cos(10^o) / (1 + \sin(10^o)) = 1.68$
j) Specific shear energy = see below

Parts c, d, e, f, g, j require information in addition to that given in Problem. Specifically,
- a value for cutting force can lead to solution,
- a value for material shear strength can lead to solution,
- some other possibilities that enable use of concepts in Section 21-6

For example, Figure 21-21 shows a value for shear strength of 1018 steel, using a value of τ_s = 75,000 lb/in2 for 1015 steel gives

(f) eqn(21-28) $F_s = \tau_s A_s$

eqn(21-29) $A_s = t\ w / \sin\phi = (.0100\text{in})(.100\text{ in}) / \sin(26^o) = 0.0023\text{ in}^2$

F_s = 75,000 lb/in2 (0.0023 in 2) = 171 lb

(e) eqn(21-23) $F = F_c \sin\alpha + F_t \cos\alpha$

eqn(21-26) $F_s = F_c \cos\phi - F_t \sin\phi$

$F_c = (F_s + F_t \sin\phi) / \cos\phi = (171\text{ lb} + 140\text{ lb} (.438)) / 0.899 = 258\text{ lb}$

F = 183 lb

(c) eqn(21-22) β = tan-1(F/N)

N = Fc cosα - Ft sinα = 230 lb

β = 38.5o

(d) $\mu = \tan\beta = 0.796$

(j) eqn(21-16) $U_s = F_s V_s / V f d$

U_s = (171 lb)(512 ft/min)(12 in/ft) / (500 ft/min)(0.01 in)(0.1 in)(12 in/ft)

U_s = 175,104 inlb/in^3

9. Figure 21-32 shows that temperature increases with cutting speed and that wear increases with temperature. The general conclusion is that wear increases with cutting speed. With regard to the data in Problem 1, the data show that as cutting speed increases the tool life (given amount of wear) decreases.

10. $V\ T^n = K$

n = 0.25, K = 1300

using the units of minute for T and ft/min for cutting speed

Spindle speed = N rpm

V = (N rev/min) (26.25π in/rev) (ft / 12 in) = 6.88 N ft/min

T = work length / feed speed = 48 in / { .01 in/rev) (N rev/min) } = (4800 / N) min

$(6.88\ N) (4800/N)^{.25} = 1300$

N = 64 rpm

V = (64 rev/min) (26.25π in/rev) (ft / 12 in) = 439 ft/min

11. For the turning operation described in Problem 10

Horsepower = F_c V + Ft V_{feed}

V = 500 ft/min = N rev/min (26.25 π in/rev)(ft/ 12 in)

N = 72.8 rpm

V_{feed} = 0.010 in/rev (72.8 rev/min)(ft/12 in) = 0.061 ft/min

F_c = 258 lb estimated in Problem 8

negligible with respect to cutting speed

HP = 258 lb (500 ft/min)(hp / 33,000 ftlb/min) = 3.9 hp

12. It's not clear that how a cutting force comparison can be discussed since it seems that only one tool geometry is specified, i.e., in Figure 22-D.

Case Study: no case study

CHAPTER 23

Review Questions

1. In turning, the work rotates and the tool is fed parallel to the axis of rotation. In facing the tool is fed in the radial direction, toward or away from the axis of rotation..

2. In turning cylindrical, conical, contoured, tapered, and knurled surfaces can be produced externally. Internal turning is called boring. In facing a flat surface is produced.

3. In form turning, the shape of the tool defines the shape of the surface and the tool is usually fed perpendicular (or plunged) to the axis of rotation. See Figure 23-28 for examples of form turning.

4. Facing employs a tool that is wider than the desired cut width and the workpiece is not separated into two parts by the process as is the case in a cutoff operation. In both cutoff and facing, the tool feeds perpendicular to the axis of rotation.

5. Knurling, a common lathe operation, usually does not make chips - it cold forms the pattern into the surface.

6. It is not possible to provide the proper rake angles on all portions of a complex form tool. Typically, small or even zero back angle tools are used, so the cutting forces will be large. In addition, small increases in depth of cut result in very large force increases because the cutting volume is large (long cutting edge in contact); so depth of cut must be set (and held) small to prevent large deflections and chatter during machining.

7. $MRR = 12\ V\ f_r\ d$ uses V which is the speed at the outer, unmachined surface of the workpiece to calculate material removal rate. In reality cutting speed varies with radial position and V is the maximum value. So, the calculated MRR using V does not include the variation of cutting speed in the calculation.

8. A hollow spindle permits long bar stock to be fed through it into the workholding device (chuck or collet) much more quickly than if individual piece parts are used. The drawbar for the collet also must pass through the spindle. See Figures 23-4 and 23-38.

9. The carriage supports the toolholder and provides the feed motion to the tool.

10.

11. Either the feed rod or the lead screw drives the carriage. The feed rod system usually has a friction clutch in which slippage can occur. The lead screw provides positive ratios between carriage movement and spindle rotation and no slippage is allowed. The lead screw is for thread turning.

12. Work in a lathe can be held between centers, held on mandrels which are then held

between centers, held in 3 or 4 jaw chucks, or held in collets. Workpieces can also be directly mounted on a faceplate attached to the spindle and are occasionally mounted on the carriage and even in the tailstock assembly (very rarely) .

13. A device called a dog is attached to the work and the tail of the dog fits into a hole in the faceplate, which is directly attached to the spindle. See Figure 23-30.

14. After the work has been turned, the surfaces will be tapered rather than cylindrical. See Figure 23-11.

15. Hot rolled stock usually has an oxide scale on it, which is rough. Clamping on nonround, rough surfaces like this can damage the collet jaws and destroy the accuracy of the collet.

16. A steady rest is mounted on the ways and is stationary while a follow rest is mounted on the carriage and thus translates with it as it carries the tool. Both are commonly used on long, cylindrical workpieces.

17. A four-jaw independent chuck can be adjusted to clamp work of almost any shape within its capacity. Such a chuck requires more time to adjust than a three-jaw chuck, and it is not self-centering .

18. Minimizing the overhang of the tool improves the rigidity of the setup and reduces the tendency of the tool to deflect which in turn reduces the tendency to chatter and vibrate. Remember, deflection is a function of length of overhang cubed in cantilever beams, so a small change in overhang length can greatly change deflection and vibration tendencies.

19. Figure 23-12. On a ram-type turret lathe the ram holding the turret moves on the saddle – ram and saddle can move independently. On a saddle-type turret lathe the turret is fixed to the saddle – there is no movable ram between the saddle and turret and so the saddle-type turret lathe is stiffer with respect to tool and tool holding structures..

20. Tapers may be turned by: (1) use of the compound rest, (2) set-over of the tailstock, (3) use of a taper attachment.

21. The material removal rate is a function of speed x feed x depth of cut. Assuming speed is kept constant, heavier depths of cut or heavier feeds will reduce the number of cuts or passes that have to be made, which reduces the number of adjustments or resettings of the tool which have to be made. Increasing either feed or depth of cut will increase the cutting force. Increasing depth of cut will have less effect on tool life than increasing the feed. Either way, the total machining time is usually less. In addition, the surface finish is usually better with the lighter feed.

22. The rpm of a facing cut is based on the largest diameter of the workpiece, utilizing

the correct (selected) cutting speed.

23. See response to question number 18 above. Boring tools have large overhangs and are thus more subject to deflection, vibration, and chatter problems. Reducing the feed (or the depth of cut) reduces the cutting forces and thereby the deflection problems .

24. As the cutting rate increases, the surface finish usually improves - See Figure 23-7. However, large nose radius tools tend to chatter more.

25. The BUE will cause the tool to make heavier depth of cuts than expected, so the part may come out undersize.

26. In tooling a multiple spindle screw machine, it is important to have the machining operations at each spindle require the same amount of time. As shown in Figure 23-18, this time balancing can be very difficult to do. There will be one operation having a processing time larger than any of the other operations. The 2nd position drill or the 4th position tap are probably the operations with the longest operation times (about 5-7 seconds) .

27. The C-axis is the rotational position of the spindle on the lathe. For turning centers that have capabilities in addition to turning the workpiece may have to be held stationary in a certain orientation – the C-axis position – so that the other type of machining process can be done. For example, if a turning center has milling capabilities a turned shaft with two slots can be produced in one setup. The shaft can be turned and then held in specified positions, C-axis positions, while the milling of the slots is done.

28. In drilling, the drill can drift or shift off center. This is due to the chisel end of the drill not cutting and the drill being deflected as it starts the cut. In boring, the hole is the result of the rotation of the workpiece about its axis, which remains fixed.

29. On vertical boring machines, the weight of the workpiece is down on, and supported by, the table; whereas, in a lathe, it must be supported and rotated about a horizontal axis. Large, heavy workpieces will deflect the spindle, causing a loss in accuracy and precision.

30. On a horizontal boring machine, the workpiece does not rotate. In other words, workpiece rotation limits the number of surfaces which can be machined in a single setup. Thus, horizontal boring machines are more flexible. This machine was one of the first to be converted to NC. On this machine: (1) Several types of machining operations can be performed with a single setup, and (2) the workpiece does not move, thus it is easy to clamp and hold large workpieces. Finally, chip disposal is easier than on vertical spindle machines (for boring blind holes for example) .

31. Figure 32-14.

32. In a collet.

33. Figures 23-2, 23-11, 23-30, 23-38

34. Figures 23-11, 23-31

35. a. Three-jaw chuck; Figures 23-6, 23-14, 23-34: Figure 23-33
b. Collet; 23-17, 23-36
c. Faceplate; Figures 23-30, 23-38
d. Four-jaw chuck; Figure 23-5: Figure 23-33

36. Three form tools are used in this setup. The shaving tool is a form tool.

37. Since the intent of most operations is to machine a complete part in one setup all the machining operations have to be completed on one machine. If one tool fails the part cannot be completed and so the tool has to be replaced. The question then is whether to replace all the tools at this time. The general answer is that if the tool failed unexpectedly, i.e., after a very short time the other tools are expected to keep performing adequately and so only the failed tool is replaced. To do otherwise is disposing of useable tooling. The other extreme is if one tool fails at about the same time as the other tools are approaching the end of their expected lives. Then all tools are changes. The large middle ground is difficult to quantify since tool life is a stochastic variable, Figures 22-15, 22-18.

38. The tools to be used are shown in the turret in Figure 23-29. The last operation is to separate the final part from the remaining stock and so cutoff operation with tool 9 is the last one.

There may be rare exceptions but usually turrets are indexed sequentially from one tool holder to the very next one. This being the case the questions are what is the first turret operation, whether the turret rotates clockwise or counter-clockwise and whether there are operations between those performed using the tools in the turret.

The workpiece has to be positioned, so
1. Stock stop used to set extension of work out of collet
    An accurate initial diameter is needed so
2. Turn B using tool 3 which may include turning the entire part length
    Diameter D is needed and Figure indicates it is produced by
3. Turn D using turrep position 2
    An accurate initial diameter is needed for tread production so
4. Turn F using turret position 3
    The end face needs to be chamfered and center drilled and this will also aid in starting threading so
5. End face and chamfer – turret position 4
6. Center drill – turret 6
    Thread the end before reducing final part diameter since work will be stiffer so
7. Thread – turret position 7
    Machine diameters furthest from supported end first since work is stiffer and
8. Turn C and E with tool 5
9. Form cut with tool 8

10. Cutoff with tool 9.

Problems:

1. V = N rev/min (π 3 in/rev)(ft / 12 in) = 200 ft/min
N = 255 rpm

2. CT = (L + A) / (feed x N)
CT = (8 in + 1 in) / {(255 rev/min)(0.020 in/rev) = 1.76 min

3. Material Removal Rate – exact:
i. MRR = Volume removed / time

Volume = $\pi/4$ (work length)($d_o^2 - d_f^2$)
change in diameter = 2 (depth of cut) = 0.25 in
V = $\pi/4$ (8 in){ $(3\text{ in})^2 - (2.75)^2$) } = 9.03 in3
time = distance / feed speed
feed speed = N rev/min (0.020 in/rev)
V = 200 ft/min = N rev/min (π 3 in/rev)(ft/ 12 in)
N = 254.6 rpm
feed speed = 5.09 in/min
t = 8 in / 5.09 in/min = 1.57 min

MRR = 5.75 in^3/min = 94,225 mm^3/min

ii. Or
using do – ½(depth of cut) to calculate cutting speed
MRR = V f d
V = 254.6 rev/min (π 3 in/rev) = 2350 in/min
MRR = 2350 in/min (0.020 in)(0.125 in) = 5.875 in^3/min = 96,274 mm^3/min

Material Removal Rate – approximate:
MRR = V f d = 200 ft/min (0.020 in)(0.125 in)(12 in / ft)
MRR = 6 in^3/min = 98,332 mm^3/min

4. a). Engine lathe cost TC_{EL} = (0 .5 Q + 0.5) 18 + 0
Turret lathe cost TC_{TL} = (0.083 Q + 3) 20 + 300
Equate TCEL = TCTL at BEQ
(0.5 Q + .5) 18 = (0.083 Q + 3) 20 + 300
9 Q + 9 = 1.67Q + 60 + 300
Q = 351 / 7.33 =41.9 or42 units

b). 0.5 (18) + (0.5 x 18) / 41.9 = 9 + .21 = $9.21/part

5. The feed given in the problem (for boring) is 0.5 mm/rev or

about 0.02 ipr. The depth of cut is (112) x (89-76) or 6.5 mm or 0.255 inches. Assuming that for 1340 steel, the BHN would be in the low range (175 to 225), Figure 42-11 on page 1179 recommends a cutting speed of 80 sfpm or 24.4 m/min.

Drilling RPM for 18 mm drill = (24.4 x 1000)/(18 x 3.14) = 431
Drilling RPM for 76 mm drill = (24.4 x 1000)/(76 x 3.14) = 102.2
Boring RPM = (24.4 x 1000)/(89 x 3.14) = 87.3
Drilling time for 18 mm drill = (200 + 18/2)/(431 x 0.25) = 1.94 min.
Drilling time for 76 mm drill = (200 + 76/2)/(102.2 x 0.64) -3.64 min.
Boring time = 200/(87.3 x 0.5) = 4.58 min.
Center drill time = 0.5 min.
Four changes of speed and tool settings require 4 x 1 mm = 4 min.

6. a) Taking "fixed cost" completely literally, i.e., not varying with production quantity, the fixed cost is the constant cost per unit part of the curves. Estimating costs from the log Cost per unit axis
Engine lathe; 30 - 40
NC lathe; 6 - 7
Single spindle automatic; 2 - 3

7. The derivation of the approximate equation 23-5 for the MRR for turning requires an assumption regarding the diameters of the parts being turned. The derivation is:
$MRR = 12 (D_1^2 - D_2^2)$ fr $V / 4 D_1$
$MRR = 12 \{ (D_1 - D_2) / 2 \} \{ (D1 + D2) / 2 D1 \}$ fr V
$V \simeq 12 V f t$
where $(D_1 - D_2) / 2 = t$ and
$(D_1 + D_2)/ 2 D_1 = (D_1 + D_1 - 2t) / 2 D_1 = 1 - t / D_1 \simeq 1$ for $t / D1 \simeq 0$
which assumes t, the depth of cut, is small and negligible compared to the uncut diameter, D_1, so that $t / D_1 \simeq 0$.

Case Study: New "Estimating the Machining Time for Turning"

Total machining time is
CTT = (machining time for one pass)(number of cutting passes) + tool change time
The problem comes down to determining the machining time for one pass and the number of passes required. The machining time for one pass will be determined by the feed rate, f, along with the length of the workpiece, L, and the allowance, A. The number of passes necessary will be determined by the depth of cut, doc. There are three concerns that set limits on feed rate and depth of cut and they are available power, workpiece deflection and tool wear.

Cutting time for one pass over the forging is CT = (L + Allowance) / feed speed
the feed speed is (spindle speed rev/min)(feed rate in/rev) = N f

A starting place is to choose a tool life based either on desired tool cost if more than one tool can be used or life long enough to complete the machining operation with one tool. This tool life will give a cutting speed and cutting speed is needed in the analysis to follow. After the results are calculated the tool life chosen can be reassessed and is it is not consistent with the results obtained, the analysis can be repeated with a different tool life.

Tool life = 30 min

- tool life equation $VT^n = K$
- using given data in part 1 and *noting feed rate = 0.020 ipr and* $\alpha = 10^o$

$(VT^n)_{60} = K = (VT^n)_{85}$

$60 (100)^n = 85 (10)^n$

$K = 120, n = 0.15$

For 30 min tool life: $V (30)^{0.15} = 120$

V = 72 ft/min

Power Available constraint:

power available = power required

50 hp (0.75) = HPs (MRR)

HPs from Table 21-3 and BHN = 300 – 400

for steel with BHN = 300 the larger unit power is 1.87 hp/in^3/min

say HPs = 2 hp/in^3/min

V = 72 ft/min = 864 in/min

37.5 hp = (2 hp/in^3/min)(f)(doc)(864 in/min)

(f)(doc) = 0.022 in^2

- this is a large area, e.g., feed rate of 0.020 ipr and depth of cut = 1.1 in
- and so power will not be a limiting factor

The power required can also be calculated using the cutting force, Fc, and thrust force, Ft,

power available = Fc V + Ft Vfeed

The machining forces are calculated below.

Deflection constraint:

- the radial force is said to cause deflection and the machining process models can be used to relate feed and depth of cut to cutting force Fc and thrust force Ft
- two machining process models are available; the specific power model used above and the machining forces model
- the cutting forces model will be used since material shear strength data and measured chip deformation (chip thickness) information are available
- model workpiece supported between centers as a simply supported beam
- deflection will be maximum when force applied is at midlength and diameter is minimum so D = 6 in
- deflection, δ (= 0.005) in of a simply supported, circular cross section beam with load P applied at mid length is

$\delta = PL^3 / 48\ EI$

$E = 30E6\ lb/in^2$ is typical value for steel

$I = \pi\ D^4 / 64 = 63.6\ in^4$

$0.005\ in = Fr\ (\ 96\ in\ )^3 / [\ (\ 48\ )(\ 30E6\ lb/in^2\ )(\ 63.6\ in^4\ )\ ]$

$Fr = 518\ lb$

and with the given force relationships

$Ft = 2\ Fr = 2\ (\ 518\ lb\ ) = 1036\ lb$

$Fc = 2\ Ft = 2\ (\ 1036\ lb\ ) = 2072\ lb$

The cutting force and thrust force are functions of feed rate and depth of cut and the shear strength is known

eqn(21-30) $tw = (\ Fc \sin\phi \cos\phi - Ft \sin^2\phi\ ) / \tau$

shear angle was measure – chip thickness ratio – *at feed rate = 0.020 ipr*

at $V = 20$ ft/min, $rc = 0.4$: at $V = 80$ ft/min, $rc = 0.6$

at $V = 72$ ft/min, $rc = 0.4 + [\ (\ 0.6 - 0.4\ ) / (\ 80 - 20\ )\ ][\ 72 - 20\ ] = 0.57$

$\tan\phi = rc \cos\alpha / (\ 1 - rc \sin\alpha\ ) = [\ (\ 0.57\ )(\ .985\ )\ ] / [\ 1 - (\ 0.57\ )(\ 0.174\ )\ ]$

$\phi = 32^o$

$tw = [\ 2072\ lb\ (\ 0.53\ )(0.85\ ) - 1036\ lb\ (\ 0.53\ )^2\ ] / 125{,}000\ lb/inb^2 = 0.0051\ in^2$

the data was developed for *feed of 0.020 ipr* so

$t = doc = 0.26$ in

For the limiting doc = 0.26 in based on workpiece deflection the number of passes is

NP = (change in radius) / depth of cut = [(10 – 6) / 2] in / 0.26 in

NP = 8

The feed speed depends on spindle speed and if the cutting speed is to be maintained at 72 ft/min the spindle speed will have to be changed for the different machining passes. The average diameter during production is 8 in and the average spindle speed is

$V = 72\ ft/min = N\ rev/min\ (\ 8\pi\ in/rev\ )(\ ft/12\ in)$

$N = 34.4$ rpm

and the feed speed is

$S = 34.4\ rev/min\ (\ 0.020\ in/rev\ ) = 0.7\ in/min$

For a half-inch allowance the machining time per pass is

$CT = (\ 96\ in + 0.5\ in\ ) / 0.7\ in/min = 137.9\ min$

It is reasonable to expect that the eight passes will be used to bring the diameter to close to the specified finished diameter and then a finishing cut made. If the finishing cut is made with a feed rate of 0.005 ipr the feed speed is on fourth of the roughing feed speed and the machining time for the finish cut is

$CTF = (\ 96\ in + 0.5\ in\ ) / [\ (\ 0.7\ in/min\ ) / 4\ ] = 551.4\ min$

For the eight roughing passes and one finish pass the total machining time is

$CTT = 8\ (\ 137.9\ min\ ) + 551.4\ min = 1654.6\ min$

This time is far in excess of the starting estimate of 30-minute tool life and so re-evaluation of the analysis procedure is not needed.

For the 30 minute tool life there will be 1655 min / 30 min/tool = 55 tool changes and a tool change time of

TCT = 55 (time to change tool)

should be added to the total machining time.

CHAPTER 24

Review Questions

1. The flutes form the rake angle of the cutting edges, permit coolant to get to the cutting edges, and serve as channels (elevators) through which the chips are lifted out of the hole.

2. The rake angle of the drill is determined by the helix angle of the drill at the outer extremities - the tips - and gradually changes to a zero rake angle at the inner extremities- the chisel edge. The center core drill shown in Figure 24-4 has a small, uniform rake angle.

3. The helix angle is mostly determined by the material being drilled .

4. The smaller hole provides a guide for the cone portion of the point of the larger drill, of sufficient size so the chisel point of the latter does not contract the workpiece at the start and thus cannot cause the drill to wander. In addition, larger drills can drill faster if the central region of the hole is drilled out first as the negative point is removed from the operation, lowering the cutting torque and thrust considerably. Of course, an extra operation is needed (i.e. drilling the smaller hole first) .

5. <u>Area of the hole</u> times <u>the feed rate</u>, where (f_r)N is the feed rate.

6. Spade drills typically are operated at slower speeds (lower rpms) and higher feeds than twist drills.

7. The hole will generally be oversize as the drill will not be cutting properly and will probably use more torque and thrust.

8. The drill selected to machine the hole generally has a diameter equal to the nominal hole size, so unless the drill has excessively worn, the hole will typically be equal to the nominal size or greater.

9. Two primary functions of a combination center drill are:
(a) To start the hole accurately at the desired location, and
(b) to provide a tapered guide for the drill to be used.

10. The margins bear or rub against the drilled hole and help to guide the drill and prevent it from bending. This rubbing action also produces heat which expands the drill and increases the rubbing and friction which can increase the torque. Proper lubrication is advised to reduce the friction at the walls of the hole.

11. Drift is a particular problem with small drills and deep holes. If the rake angles or the lengths of the cutting edges between the two sides are not equal (this is usually due to improper regrinding of the drill), a force imbalance can cause the drill to drift off line. Hard spots in the workpiece can also cause the drill to move off line, as can a large void

or other material nonhomogeneities.

12. The holes provide a way to get cutting fluid to the cutting zone and so aid in cooling and lubricating the chip formation zone. Such drills are usually employed for long, deep holes.

13. The deeper the hole, the greater the surface area of the drill in contact with the hole wall (the margin) and in contact with the chips coming out the flute. The chips can also pack in the flute and increase the friction and thus the torque.

14. Cutting fluids have lubricants to reduce the rubbing friction between the drill margins, and the chips, as they contact the walls of the hole.

15. Figures 24-6, 24-11, 24-12

16. A gang-drilling machine has several independent spindles mounted on a common base, and usually has a common table. A multiple-spindle drilling machine has several spindles driven and fed in unison by a single powered head.

17. The thrust force (the force 900 to the cutting force or torque) increases with increasing feed. See Figure 24-4.

18. Holding the workpiece by hand may result in broken hands, fingers, or even arms as the workpiece may catch on the drill, particularly at breakthrough, causing the workpiece to rotate at the drill rpm.

19. Centering insures that the drill will start at the right location and not walk off the desired spot. Drilling creates the hole itself. Boring produces a sized and properly aligned hole over the entire length, correcting for any drift problems. Reaming provides for final finish and exact hole size.

20. The slot-point drill reduces the thrust significantly compared to other drills by eliminating the chisel end of the drill. The material in the center of the hole is left undrilled and is periodically fractured away as the drill advances. See Figure 24-4.

21. Spot facing produces a smooth surface normal to the hole axis, as a bearing surface, usually for a bolt head, washer, or nut.

22. Counterboring produces a second hole of larger diameter and with a smooth bearing surface as its bottom, which is normal to the axis of the hole. See Figure 24-22.

23. Reaming provides for excellent hole finish and more exact size.

24. Shell reamers are cheaper, because the arbor is made of ordinary steel and may be used with more than one shell. Only the shells are made from HSS or coated HSS.

25. First, the geometry of a drill for plastics will be very different than a drill for cast iron. It will have much larger helix angles and therefore larger rakes. Also, plastic is a very poor heat conductor compared to cast iron so the frictional heat will remain in the drill, causing it to overheat.

26. The drill should be withdrawn from the hole at frequent intervals to remove the chips and permit the drill to cool. This procedure is called pecking. Ample coolant should be used. See also Figure 29-15.

27. A spade drill requires a much smaller amount of the expensive cutting tool material, and it can be made more rigid than a comparable twist drill. Also, the different point geometries allow these drills to start more accurately. They are really more like milling cutters than drills, and are used for large holes that are not too deep (there are no flutes to carry the chips out of a deep hole) .

28. The drill bit is repeatedly withdrawn from the hole during the drilling process in order to clear the flute of chips. This procedure is invoked whenever the hole depth to drill diameter exceeds 3 to 1. See also Figure 29-15.

29. Recall the equation which relates rpm to cutting speed:

$$V = \pi D N / 12$$

Write the N term as the ratio of drill rate (in./min.) divided by the feed rate (in./rev.)

$N = f_m / f_t$. Therefore, $V = \pi D fm /(12 ft)$

In order to keep the cutting velocity at the drill tips constant (keep V constant), while maintaining the same penetration rate(keep fm constant), the feed rate must increase in proportion to the drill diameter, D.

$$D / f_t = 12 VI (\pi f_m)$$

30. If the feed is too large, one could experience drill fracture up the middle of the drill, chipping of the cutting edge, and rough walls on the drilled hole. See Table 24-7.

Problems:

1. The selection of proper speeds and feeds is the first step in any process analysis or planning. Someone has to decide the cutting parameters. Since this is an indexable-insert drill, Table 24-1 can be used. Otherwise, standard references like the 1(machinability Data Handbook can be used. For 1020 cold rolled steel, the recommended speeds and feeds are 400-550 sfpm and 0.004-0.007 ipr respectively. The allowance would typically be D/2. You might want to use a spade drill here as it is less expensive and ideal for shallow, large-diameter holes - See Figure 24-13.

2. Problem 1 is solved here using a cutting speed of 410 sfpm and a feed of 0.005 ipr. The allowance used is one half of the drill diameter.

CT = (Hole depth + Allowance) / fr N

CT = (2 +0.75) in / { (0.005 in/rev) [(12)(410)] / [π 1.5] rev/min}
CT = 2.75 in / 5.22 in/min = 0.527 min

3. Cutting speed = 200 fpm
N = (12 x 200)1 3.14 x 1.5 = 509 rpm
MRR = π D^2 /4 N f_r
MRR = (3.14 x 1.52)14 x 509x 0.010
MRR = 1.76 x 509 x 0.010
MRR = 8.99 cu.in./min. or 9 in^3/min

4. HP = (0.9 hp/in^3/min)(9.0 in^3/min) = 8.1 horsepower

5. 1 hp = 0.7457 kW so 1.5 kW -= 2 hp
CS = 200 fpm
N = 509 rpm
MRR = π D^2 /4 N f_r
MRR = [3.14 $(2)^2$ / [4 (509)(0.010)

Also, HP = HP_s (MRR)
So, MRR = HP/HP_s = (2) (75) / 0.70 = 2.14
Therefore, 2.14 = 3.14 x 509 f_r
f_r = 0.0013
f_r (max) = 0.0013 ipr
The process is severely limited to light feeds.

6. MRR = (πD^2 L/4) / (L / frN) = (πD^2 / 4) (f_rN)
MRR = (πD^2 /4) f_r (12 V / πD)
MRR = 3 D f_r V

7. Yes. f_rN = feed rate in inches/minute

8. The time to change the drill is spread over the total number of holes drilled between tool changes. The units are time per hole.

9. Spade drill:
Feed rate = 204 x 0.009 = 1.836 in./min.
Holes/mm = 1.836 *1* 3 in/hole = 0.612
Cost/hole = (45/60)1.612 + 160.90/ X (where X = holes/tool)

Indexable-insert drill
Feed rate = 891 x 0.007 = 6.237 in./min.
Holes/mm = 6.237 1 3 in/hole = 2.079
Cost/hole = (45/60)12.079 + 285.80/ X

Equating:
1.225+ 160.90/X = 0.36 + 285.90/X

BEQ:
X= (2.85.80 - 160.90)/(1.225-0.36)
X = 124.90 I 0.865 = 144

If you were doing more than 144 holes, the extra cost of the indexable-insert drill may be justified.

Why is it a “reasonable assumption” to assume that both tools make the same number of holes? The cutting speeds selected here are from tables of recommended speeds, and these tables typically recommend speeds that give 60 minutes of tool life.

Of course, the decision to change from one process to another is made on the basis of many factors in addition to tool cost.

10. a). The tolerances between the holes is based on ± 1 degree Converting degrees into inches, ± 1 degree = (3.14 x 6)/360 = 0.05 inches.

b) Yes, a multiple spindle drill setup can meet this tolerance specification, as such a setup would have a process capability for hole location of ~ 0.030 to 0.050 inches, assuming good drills are being used.

c). Using a drill jig would improve the situation by an order of magnitude to * 0.003 to * 0.005 inches.

Case Study: “Bolt Down Leg on a Casting”

1). The machining difficulty was in starting the drill for machining the bolt hole on the inclined, rough cast iron surface. The drill point would tend to “walk” down the surface, and drill breakage would result due to bending of the drill bit.

2) Assuming the fixture used is accurate, the varying distance between holes is due to the drill walking to a location other than the specified hole location.

3). The failures were in the form of cracks, at location as shown in Figure CS-24. These failures were caused by sharp corners (produced by the counterboring operation) which created a stress concentration when the leg was placed in service and received a moment bending load. The sharp corner was placed in tension, and cast iron is weak in tension. NOTE: This problem could be further aggravated if white cast iron were produced in this region as a result of rapid cooling rates in the thinner leg segments.

4). One solution would be to redesign the part so that the present curved surface is flat. This will eliminate the counterbore and sloped surface from the processing. Another alternative would be to use a start drill, drill and counterbore sequence with the counterbore enlarged somewhat and given a large radius to eliminate the sharp corner. If possible, drilling from the bottom would eliminate the drill “walking”.

5). To stop failures in the field, it will be necessary to eliminate the sharp corner. The same oversize counterbore operation can be manually performed on units in the field if they have not been installed. Those that have been installed and failed must be replaced since cast iron cannot readily be repaired. The company should replace these at no cost to the customer. Other installed units should be repaired (and/or replaced) as rapidly as possible, particularly if failures in the field could lead to personal injury.

CHAPTER 25

Review Questions

1. Since multiple-edge cutters are used material removal rate can be high in milling. If sufficient power and tool strength is available along with allowable surface finish requirements, large feed rates and depths of cut are possible for the multiple cutting edges.

2. In peripheral milling the surface produced is parallel to the cutter axis of rotation, Figure 25-1. In face milling, Figure 25-2, the generated surface is perpendicular to the cutter axis. For mass-production machining material removal rate is the primary concern. Assuming sufficient power is available, wide peripheral milling cutters or large diameter face milling cutters can be used to achieve high material removal rate.

3. If the volume of metal removed is the same and the only difference is the direction of rotation, one would think the power (FcV) would be the same. In climb milling, a component of the cutting force is in the same direction as the feed force which lowers the power requirements on the feed motor.

4. Casting surfaces can be quite hard (due to rapid cooling) or contain hard spots (rapid cooling around grains of sand) as well as abrasive grains (in sand castings). These factors can lead to more rapid tool wear when the cutter tooth comes down into the surface from above versus from below as in up milling.

5. The material removal rate is given by equation (25-5)

$$MRR = W\ f_m\ DOC$$

and depends on the width of the cutter of workpiece, W, the depth of cut DOC, and the cutting time, T = length of cut / machining time. Machining time depends on the table speed.

Material removal rate in milling can be viewed as the rate at which the cross section of material being removed is advancing through the workpiece. The area being removed is

(depth of cut)(width of cut)

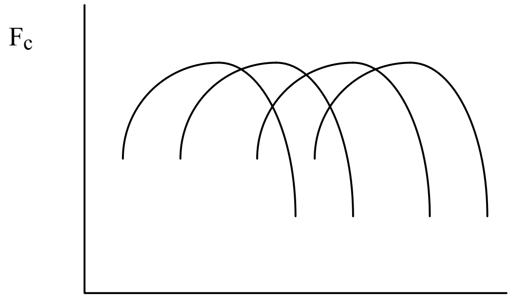
and it is being removed at a speed equal to the speed of the cutter through the workpiece or the

table speed.

6. You would have end milling, and you would be milling a slot.

7. Helical toothed cutters enter the workpiece progressively. Thus, the impact of initial tooth contact is less, and, overall, the cutting forces are smoothed out as two or three teeth are engaged in the work at the same time.

8. Imagine all the F_c patterns superimposed on each other which forms a steady F_c with small scallops.



9. No. The cutting edge on the insert shown in Figure 25-7can produce only a flat, horizontal surface. Production of a T-slot requires machining of horizontal and vertical surfaces.

10. The teeth are staggered so that the teeth can be given a side rake angle in addition to a back rake. This reduces the impact at entry and the cutting forces overall.

11. The table on a plain column-and-knee milling machine cannot be swiveled to permit cutting a helix, as required for the flutes of a twist drill. A special attachment to hold a ball end mill and a universal dividing head can be used as shown in Figure 25-17.

12. The block has to be mounted on the machine table, either directly clamped of in a vise or fixture. This means that the two sides of the block available for simultaneous milling are perpendicular to the machine table. So, two side milling cutters, Figure 25-8 could be mounted on the arbor of the horizontal milling machine as shown in Figure 25-9 and two sides of the block machined.

13. The most distinctive feature of the column-and-knee type milling machine is the combination of the column that supports a movable knee. The knee then supports the saddle and table. In contrast, in a bed-type mill the table is supported by a stationary part of the machine frame.

14. The table can move horizontally, left, and right. The table sits in a saddle, which can move horizontally, in and out. The saddle sits on the knee which can raise and lower the saddle-table assembly.

15. The rate ring limits the amount of deflection of the stylus. See Figures 25-16.

16. The vertical spindle Bridgeport was (and still is) a very versatile machine, and it was very accurate and precise.

17. The dividing head uses a worm-gear reduction assembly. See Figure 25-17. When you turn the crank one revolution, the spindle on the other end rotates 1/40 of a revolution. The index plate is designed such that a workpiece can be rotated through almost any desired number of equal arcs.

18. Connecting the input end of a universal dividing head to the feed screw of the milling machine causes the workpiece to be rotated a controlled amount as the table moves longitudinally. see Figure 25-17.

19. The hole-circle plate (or the index plate) is to control the rotation of the workpiece through a desired angle. See Question 20.

20. The only hole circle that can be used is the 27-hole circle. All others do not give a whole number of holes. The calculation is (40 x 27)118 = 60 holes. Thus a tooth gap would be milled and then the gear blank rotated by cranking through 60 holes or about 2.22 revolutions of the crank, and then the next tooth gap milled. The setup is shown in Figure 31-7 for cutting helical gears.

21. As in all machining processes, the cutting speed (V) is selected based on the cutting tool material and work material. The feed (f_t) is also selected in terms of how much each tooth will remove during each pass over the work -- the feed per tooth (See Table 25-1). The RPM is computed from the selected speed by:

$N = (12 \times V)/(3.14 \times D)$ where D is the cutter diameter

Then, the table speed is calculated from:
$f_m = f_t\, n\, N$ where n is the number of teeth in the cutter .

22. See answer to question 24. The important aspect of milling feed is the amount of material removed per cutting edge and this depends on spindle speed, table speed and number of teeth.

23. The large cutting forces in slab milling must be considered. These forces tend to dislodge the part in slab up milling. In vertical spindle milling, the chip engagement (chip thickness) tends to stay more uniform and overall the cutting forces are not as large.

24. A cutting speed of 50 to 100 fpm and a feed per tooth of 0.005 to 0.010 ipt are quite reasonable values. The student must go to a handbook or similar source to find the values. See also Table 25-1.

Problems:

1. $V = \pi . D N / 12$, so
$N = 12 V / (\pi D) = [12 (200)] / (3.14 \times 8)$
$N = 95.5$rpm
$f_m = n N f_t = 10 (95.5)(0.01) = 9.55$ ipm

2. $N = 12 (70) / [(3.14)(6)]= 44.5$ rpm

f_m = n N f_t = 8 (44.5) (0.012 ipt) = 4.28 ipm

CT (L +All) / f_m = (12 + 3 + 3) / 4.28 = 4.2 min.

3. MRR = Vol / CT = W t f_t = 5 (0.35) (4.28) = 7.49 cu.in./min.

4. HP = MRR (HP_s)= 7.49 (0.67) = 5 horsepower

5. The axially symmetric sections of the part would be made in lathe turning operations. The left end face would probably be produced in a facing cut on the lathe.

Flat surfaces can be milled and for the slot some options are:

Process	Tool	Cutting Conditions	
Slotting Figure 25-8	width equal to slot width	- spindle speed - depth of cut - table speed	- slotting cutters stiffer than end mills - slotting typically done in one pass
End milling Figure 25-3	diameter equal to or less than slot width	- spindle speed - axial depth of cut - table speed - radial depth of cut for finishing pass if diameter less than slot width	- end milling may require more than one pass
End milling on a turning center Figure 23-14	same as end milling		- use lathe C-axis Question 27, Chapter 23 - turning and slotting on one machine

6. The first step in the problem is the selection of a cutting speed. From Table 25-1, the student might select anything from 40-130 sfpm. Let's say 120 sfpm is selected.

For face milling:

RPM of cutter = [(120)(12)] / [(3.14)(8) = 57.3 rev/mm

Table feed, f_m = n N f_t = (10)(57.3)(0.010) = 5.73 in/mm

CT = Machining time where A = D/2

= (L + A) / f_m = (18 + 4) /5.73 = 3.83 mm/part

Setup time (a one time operation) = 60.0

min.

Load and unload fixture (very conservative) = 2 min

Total time for one part is = 65.83 min

Cost to make one = (60.00 / 60)(33.25 / 1) + (33.25)(5.83) / 60 = \$37.03/part

Cost to make 10 = (60.00 / 60)(33.25 / 10) + (33.25)(5.83) / 60= \$6.55/part

Cost to make 100 = … = \$3.56/part

For shaping, use V= 120 sfpm (high but used for comparison):

$V = 2\ 1\ Ns / 12\ R_s$

where is the fraction of the total stoke during which cutting occurs and is typically about $R_s = 200^o / 360^o = 5/9$, Equation (26-1)Figure 26-1

l = 6 (Equation 26-3)

$N_s = 66.6$ This is RPM of the bull wheel (See Figure 26-1)

CT = 18/ [(66.6)(0.015)] = 18 min/part (no allowance)

Cost to make one = (10 / 60)(25.25 / 1) + [(25.25)(18.00)] / 60 = \$12.77/part

Cost to make 10 = = \$7.99/part

Cost to make 100 = ... = \$7.61/part

The shaper is cheaper when the lot size is very small. At some higher number of parts, the milling machine will be the better choice. Note that the reduction or elimination of setup time could make milling the choice even for a lot size of one.

7. For milling, the percentage of time spent in nonmachining activities is

[60 + (2)(10)] / { [(5.83)(10)] + 60 } = 80 / 118.3 =or 67.6%

For shaping, the percentage of time spent in nonmachining activities is

[(10 + (2.0)(10)] / [(18.0)(10) + 10] = 30/191 or15.8%

8. Figure 25-10 and equation (25-2)

$f_m = ft\ N_s\ n$

$V = 125$ ft/min = Ns rev/min (π 5 in/rev)(ft/12 in)

Ns = 95.5 rpm

f_m = 0.006 in/tooth (95.5 rev/min)(8 teeth/rev) = 4.58 in/min

9. MRR = W d fm = (2)(0.5)(4.58) = 4.58 cu.in./min.

Up milling is shown in Figure 21-5.

10. $N = 12\ V / \pi\ D = (12)(500) / (3.14)(6) = 318$ rpm

$f_m = n\ N\ ft = (8)(318)(0.010) = 25.44$ inch/min

$CT = (L + \text{Allowances}) / f_m$ where $\text{Allow} = \{ 35 (6 - .35) \}^{1/2}$
$CT = (12 + 1.4) / 25.44 = 0.53$ min

This cutting time is considerably less due to the high cutting speed for carbide cutting tools. The MRR is greater than for face milling with HSS tools.

Case Study: no case study

CHAPTER 26

Review Questions

1. The feed is built into the teeth of the broach -- the rise per tooth is the feed. It is also as close to orthogonal machining as one finds in industry.

2. The saw blade has no "step" or rise per tooth between successive teeth, so a saw blade is not a broach.

3. These machines use straight line movement and the feed is built into the tool, so the machine tools are much simpler, mechanically speaking.

4. Why broaching is suited for mass production -- Accuracy and precision are built into the process. No machine adjustment is needed after the initial setup. The rapid, single stroke or one pass completion of parts leads to easy A(2) or A(3) levels of automation. Roughing and finishing are built into the same tool.

5. The pitch or the distance between each tooth. This is needed to determine how long the broach must be to remove the material. See question 6.

6. Because all metal removal (depth of cut) is built into the tool, the design of the tool must relate to the amount of material to be removed, chip thickness per tooth, tooth-spacing (pitch and gullet size), and the length of available stroke in the machine.

7. Methods for reducing force and power requirements in broaching are rotor-tooth design, double-cut construction, and progressive-tooth design .

8. The rotor-tooth broach would be longer.

9. In designing a broach, the distance between the teeth (the pitch) and the shape of the gullet (the radius) must be such that the chip can be fully contained and allowed to curl properly, so that the chips do not rub the machined surface.

10. Since the entire surface is machined in one pass, the operation is very fast without resorting to high cutting speeds. High speed would consume more power and also generate more heat, thereby greatly shortening the life of the broach. Because these tools are usually quite expensive, they must have a long life to make the cost per part low and the entire process economical.

11. Shell-type construction reduces the cost of the broach because the main shaft can be made of inexpensive steel, and also the shaft can be used with various sizes and types of shells. Also, worn or broken teeth can be removed and replaced and the entire broach does not have to be replaced.

12. Because the cutting speeds are low, carbides are not needed. In addition, the cutting

forces tend to put the broach tooth geometries in tension, where carbide is not as strong and reliable as steel. Carbides and ceramics can be used for the burnishing rings (i.e. finishing teeth).

13. TiN-coated HSS broaching tools will cut with less power and lower forces because of the lower tool/chip interface friction condition. The lower interface friction condition produces larger shear angles and lower shear forces. The TiN-coated tools also last longer.

14. It is easier to feed pull-up machines, and the work falls free after the operation is completed.

15. The roughing teeth are shorter and varying in height. In finishing broaches the finish teeth are of the same height.

16. No. There would be no place for the chips to go, and the first tooth on the broach would have to be full size, permitting no feed being built into the tool.

17. Such sockets usually have a recess, larger than the finished size of the broached hole, beyond the end of the surface to be broached. Such recesses can be made by forging, casting, or machining.

18. Sawing is relatively efficient because only a small amount of material is formed into chips.

19. (1) Tooth spacing controls the size of the teeth, (2) the spacing determines the space into which the chips must be contained, (3) tooth spacing determines how many teeth are in contact with the work (cutting) at a given time. Tooth spacing is the same as pitch in broaching.

20. The tooth gullet is the space between the teeth. It must be large enough to hold all the chips from a single pass over the workpiece.

21. “Set” is the manner in which the teeth are offset from the centerline of the saw blade so as to produce a cut that is slightly wider than the thickness of the blade. The width of the cut is called the "kerf". See Figure 26-12 and 26-13.

22. Set is the offset of the tooth corner from the plane of the saw surface, Figure 26-12. Cutting at the tooth corners determines the kerf and so kerf is determined by saw thickness and set. In the ideal case for a straight set saw (Figure 26-13) the kerf is equal to the saw plate thickness plus twice the tooth set.

23. If the band were hardened throughout its width, it would be brittle and would break when flexing around the guide wheels.

24. Circular saws are limited in the depth of cut that can be made with them. Also they

are more expensive than bandsaws. Advantages: they can be made stronger, more accurate cuts can be made, and they have teeth made from a variety of cutting materials.

25. Bandsawing machines can operate at higher cutting speeds and cut continuously (no reciprocating) and are thus able to make the same cuts faster than hack saws.

26. A hole is drilled into the workpiece. The bandsaw blade is broken, inserted into the workpiece, and welded. The cuts (holes) are then made. The blade is broken and removed. This process is good for small volumes of parts.

27. The machining time Tm is the distance the saw edge moves divided by the rate of movement.

Tm = distance / speed

For a horizontal saw cutting a 3 inch diameter round section with downfeed rate of f_d

$Tm = 3 \text{ in} / f_d$

The downfeed rate is probably not known with any precision.

Attaching a value to the feed rate is difficult. If there is a power feed on the saw then the feed rate can be set to a specified value. Establishing the value is not straightforward. The cutting speed along with the feed rate will determine cutting forces, cutting zone temperature and tool wear. Starting with a desired tool life the effects of cutting speed and feed rate would have to be determined and the feed rate set. The length of cut along the work varies over time since the saw is moving through a circular cross section. This means that the best feed rate will vary during the process.

If the feed is provided by gravity (or gravity and an additional load) the estimation of the feed rate is even more complicated. A force balance can be set up in which the downward gravitational force is balanced by the cutting forces. In a two-dimensional model the cutting force and thrust force act to separate the work material and balance the gravitational force. It seems unlikely that the force situation could be modeled accurately enough to be able to predict the rate of advance of the cutting edges in the feed direction into the work material. And, the net force and perhaps forces at each tooth vary during cutting since the length of work being cut varies since the workpiece has a circular cross section.

28. If feed is by gravity, the feed force is constant. As the cut proceeds, the length of the cut increases. The force resisting the feed increases in proportion to the length of the cut. Thus, the feed rate slows down and speeds up in proportion to the diameter of the round bar.

29. The file is much wider than the saw blade and the teeth may have negative rakes, but these are the only real differences.

30. A safe edge on a file means that the file has no teeth on the edge. The user is less likely to be injured while using it and metal won't be filed from undesired locations.

31. On a band filing machine, the cutting motion is continuous, i.e. no reciprocation.

32. The teeth on a rasp-cut file are formed by being plastically deformed outward from the body of the file, whereas those of other types are formed by cutting.

33. In a shaper, the tool reciprocates and the work feeds perpendicularly to the tool motion. In a planer, the work reciprocates and the tools feed perpendicular to the work movement. Both make straight line cuts. Shapers are best suited for flat surfaces on small workpieces in small quantities as in the tool room or for special one-of-a-kind jobs. Planers are used for large workpieces. Because the workpieces machined on planers are large and heavy, it is difficult to reciprocate the work and table rapidly and to block the workpiece so as to hold them against the high acceleration and deceleration forces occurring at the ends of the strokes. It is good practice to cut on a shaper with as little overhang of the ram arm as possible. The arm is a moving cantilever beam and the cutting forces will greatly increase the amount of deflection in the arm as the length of overhang is increased. The planer does not have the cantilever beam design of the shaper, so it can make long straight cuts without suffering deflection problems, and therefore can take advantage of the cutting time saved.

34. Shaper feed is in millimeters or inches per stroke, while milling is in inches per tooth. In shaping, the cutting time is relatively slow and the setups, while usually simple, can take as long as the setup on a milling machine, which will have a faster cutting time. Thus, milling is generally able to show an economic advantage over shaping and has about the same or better precision. See Problem 6 in Chapter 25.

35. On planers, two tables are often used, so one is being used while the other is machining. On planers, the setups and cuts are designed so that cuts are made during both the forward and return strokes, while on shapers, cuts are made only on the forward stroke and feed occurs after the tool has returned. (On both shapers and planers, feed is in inches per stroke.) on planers and shapers, the table cannot be reciprocated at high speeds, so cutting speeds are relatively low and cutting time is large. On planers, simultaneous cuts can reduce the cutting time. These methods cannot be used on a shaper.

Problems:

1. The length of the cut times the feed is 12 x 0.0047 = 0.0564 cu.in. per gullet. This would be the minimum cross section of the gullet. The gullet would have a larger cross section than this to allow the chip to curl.

2. The formula used to estimate the pitch is an empirical expression based on English units, the metric units must not be used. $P = (Lw)^{1/2} =$).35 (17.75 $)^{1/2}$ = 1.47 inches. The number of teeth needed is 0.25 / 0.004 = 62.5 teeth. The length of the roughing section is then 63 (147) = 92.6 inches.

3. For gray cast iron, HP_s = 0.5 HP/ cu. in./ min

10 m/min = 32.75 ft/min
The horsepower needed per tooth:
HP = HP_s K MRR = .5 (12) (0.004) (3) (32.75)
HP = 4.716 horsepower

The number of teeth in contact: = 17.75 / 1.47 = 12

The maximum HP is = 12 x 4.716 = 56.59 hp, a rather large value, suggesting that the broach be redesigned if the machine does not have sufficient horsepower.

4. The approximate force per tooth can be estimated by:
HP = Fc V/ 33,000. Therefore, $F_c \simeq$ 4.716 **(** 33,000) / 32.75 = 4752 lbs per tooth.
For 12 teeth, this requires 57,024 pounds. This is very large. The student should be concerned.

5. The cutting speed selected should be around 55 m/min. = 180 ft/mm. The pitch is 0.05 inch or 0.00417 ft.
The number of teeth which pass over the workpiece per minute =180 / 0.00417 = 43165.5 teeth/min.
The CT = 6/ (43,165.5)(0.0001) = 1.39 min with no allowances.

6. Allowable pull = (A_{min})(Y.S.) / S where S = factor of safety
Allowable pull = ((πD^2 / 4 - DpW)(200,000)/ 1.25
where DpW = the area of the slot in the pull end.

7. First determine the Stroke Ratio, R_s = 200 / 360 = 0.55
N = 12 V R_s *I* 2 1 where we let 1 = 2 L to allow for overrun at both ends of the stroke and allow the ram to reach full cutting speed before it enters the workpiece
N = 12 **(** 25)(0.55) / (2)(4) = 165/ 8 = 20.6 rpm or 20.6 bull wheel strokes per minute

Cutting time = CT = W/(N_s f_c) = 7/(20.6 x.1) = 3.39 min.
Note that shapers are rather slow.

Metal removal rate = MRR = L w t / CT = [(4)(7)(0 .25)] / 13.39 = 2.06 cu. in./min.

8. R_s = 0.55; N_s = 11.78 for 1 = 7 inches; CT = 3.39 minutes Thus, this setup does not take less time, but requires a much greater overhang on the ram and a possible loss of accuracy and precision due to deflection.

N_s = 12 V R_s / (2 1) = (12)(25) (0.55) / (2)(7) = 11.78
CT = w / (N_s f_c) = 3.39 min

9. Let V_{avg} = average velocity of the ram produced by N rpm of the crank with a R_s stroke ratio.
V_{avg} = distance / time = length of stroke / time of stroke
V_{avg} = 1 in / [(1/Ns)(R_s) min

Since $V = 2\ V_{avg}$

$V = (2)(1)(Ns)$ ft / $(12)(R_s)$ min

10. For $R_s = 220 / 360 = 0.611$

$N_s = [(12)(120)(0.61)] / [(2)(10)] = 43.92$ strokes/min

or $N_s = [(6.11.1)(36.6)] / [(2)(254)] = 44.03$ (metric units)

where 611.1 = R (1000 mm/meter)

so, $N_s = 44$ strokes/min

11. $N_s = (12\ V\ Rc) / (2\ 1)$ but $R_5 = 2/3$ for hydraulic shapers with a 2:1 cut to return ratio and = L + 1 inch allowance instead of 2.

Therefore:

$N_s = 8\ V / 1 = [(8)(150)] / (8 + 1) = 133.3$ strokes/min

$CT = W/(Ns\ f_c) = 10 / [(133.3)(0.020) = 3.75$ min.

12. MRR = L W t / CT = (10)(8)(0.25) / (3.75) = 5.33 cu.in./min.

13. Assuming gray cast iron has a specific horsepower of 0.30 HP/ cu.in./min,

$HP = HP_s$ (MRR) = (0.30 hp/in^3/min)(5.33 cu.in./min) = 1.59 HP

14. Power available = Power required for machining

10 hp (0.75) = (0.67 hp / in3/min) (material removal rate)

7.5 hp = (0.67 hp / in3/min)(0.25 in)(180 ft/min)(12 in/ft)(doc)

doc = 0.021 in

15. Planing: Problem Definition: For a one tool planer, cutting occurs and then a return stroke, say at the same speed. The planing action starts off the edge of the workpiece (say 25 mm, which is related to the tool size) and moves off the other edge. So the "surface machined" is (25 + 305 + 25) mm wide. The tool moves the length of the work piece (305 mm) and returns so there are two stokes per each cutting pass. Tool acceleration to cutting speed and deceleration and reversal times will be ignored. There is an allowance at both ends, say 1/10(workpiece length) = 30.5 mm. The length of travel is then 2(366 mm) per cutting stroke. The tool is fed across the workpiece at 6.35 mm/stroke. Cutting speed is 180 ft/min = 55 m/min.

Machining time =(time per tool pass)(number of tool passes)

Process parameters

work length plus allowance = 366 mm

tool travel per feed step = 2(366 mm) = 732 mm

time per feed step = time per stroke = travel / cutting speed

= 0.732 m / 55 m/min = 0.013 min = 0.8 sec

number of feed steps = (width of cut surface + allowance) / feed per stroke

number of feed steps = (355 mm / 6.35 mm/stroke) = 56 strokes

Tc = (56 feed steps)(0.8 sec/feed step) = 45 sec

Milling: Process: A more than 305 mm = 12 in long peripheral milling cutter seems unreasonable, so a face milling operation, Figure 25-2 is planned. The realistic choice is probably use of a large diameter, carbide insert face mill, Figure 25-7. The work can be machined on both forward and return passes.

Since the problem asks for comparison of machining times for high speed steel, an 8-cutting edges, 4 inch diameter face mill will be used with HSS inserts. The central issue is choice of bite per tooth. Table 25-1 suggests feed of 0.005 – 0.015 in/tooth and cutting speed of 60 – 100 ft/min. Choosing central values of chip load of 0.010 in/tooth and cutting speed of 80 ft/min and

- mill step over distance is typically 1/3 –1/2 cutter diameter, choose 1/3 diameter,
- indexing (step over) time between cutting passes is at rapid traverse speed and will be ignored,
- allowances at each end of work are 1.5(cutter diameter),
- cutter starts off end of work by 1.5(diameter) and is set for initial pass so cutter axis is set for a 1/3(diameter) first pass and 8 passes are required, i.e., 12 in / (4/3) in/pass less the starting point position that is one step over,
- to pass completely off of work 3 additional passes are need, i.e., 1/3(diameter) step over,

T_c = length of tool travel / table speed

length of tool travel = (length per pass)(number of passes)
length per pass = work length + 2 (allowance)
length per pass = 12 in + 2 [1.5 (cutter diameter)
length per pass = 12 in + 2 [6 in] = 24 in
number of passes = 11
length of tool travel = (24 in/pass)(11 machining passes) = 264 in

table feed speed, v, for the selected bite per tooth
For the 8-edge cutter and bite per tooth = 0.010 in/tooth
(table speed)(time for 1/8 revolution) = 0.010 in/tooth
(v) [(1/8 rev/tooth) / (N rev/min)] = 0.010 in/tooth
$V = N$ rev/min (π 4 in/rev)(ft/12 in) = 80 ft/min
$N = 76.4$ rpm
v [(1/8 rev/tooth) / 76.4 rev/min)] = 0.010 in/tooth
v = 6.1 in/min

Time per pass = 24 in / 6.1 in/min = 4 min which is much larger than the planing stroke time of 0.8 sec.

T_c = 264 in / 6.1 in/min = 43.3 min

Case Study: “The Socket with the Triangular Hole”

After getting over your initial reaction to "who the heck designed this part?" and "I don't think that this part can be made!", you would find that there are really many ways to make the part. Clearly, it could be made by powder metallurgy or investment casting. It could be made in two pieces -- a flat disk and cylinder with a broached triangular hole -- with an appropriate joining process, perhaps friction welding. The hole could be machined into the cylinder by EDM, ECM, or ultrasonic machining. With the latter three approaches, a hole should initially be drilled of a diameter about 5 and 1/2 mm in the center of the cylinder. Two EDM tools are used: a triangular hollow tool followed by a solid triangular tool to finish the hole to size. One might want to follow initial drilling with end milling, to make the initial hole flat bottomed. Drilling and milling before EDM, ECM, or ultrasonic will greatly enhance the overall processing time.

If you can get the designer to relent a bit on the 0.8 mm radius, you can use the Watts method of drilling angular holes. The Watts method consists of a Watts Patented Pull-floating Chuck, Angular Drill, and Guide Plate and is kind of a Wankel engine that machines. Triangular, square, and hexagonal holes

can be drilled on conventional lathe, mill, or drill press equipment. Again, a regular round hole is drilled first in harder metals as a lead hole, but this probably won't be necessary of aluminum is selected as the metal for the part. These tools are sold by the Watts Bros. Tool Works, Inc., Wilmerding, PA.

It may be possible to make this part by backward impact extrusion, since the material is aluminum and the part is not that large. The final selection as to which processes are most economical would likely come down to impact extrusion, powder metallurgy, and investment casting. The quantity here is quite large and all of these processes can be automated. Die life may be a problem for impact extrusion because of the small radius that will have to be placed on the punches to get those 0.8 mm corners .

CHAPTER 27

Review Questions

1. Abrasive machining processes. Grinding, honing, lapping, and ultrasonic machining are four processes that use abrasive grits for cutting tools.

2. Attrition is caused by the dulling of the edges and flattening of the grits, and the glazing of the wheel surface that is caused by the abrasive wear action of the grits. The grits are pulled out of the surface of the wheel as the forces on the worn grits increase.

3. Friability is the ability of the grits to fracture and expose new cutting edges, which results in more cutting surfaces continuously becoming available.

4. The smaller the grit size, the better the surface finish.

5. Both are quite hard, but aluminum oxide is tougher than silicon carbide, and is less reactive with materials. Therefore, it is the more general purpose abrasive.

6. CBN is harder and does not react with certain work materials at the elevated temperatures of grinding (particularly steel).

7. The common bonding agents are vitreous ceramics, plastics, rubber, and silicate of soda.

8. Grade expresses the strength of bonding material. It controls how freely grits will pull out of the wheel – the stronger the bond, the more difficult it is for grits to pull out of the wheel.

9. Structure refers to the spacing - how far apart are the abrasive grains. An open structure has widely-spaced grains compared to a dense structure. Either structure could use a high strength bonding material.

10. In crush dressing, the grains in an abrasive wheel are crushed, oz broken, by means of a hardened roller, to expose sharp edges and, usually, to impart a desired contour to the wheel. It is the easiest practical way to impart a desired contour to an abrasive wheel. See Figure 27-14.

11. A glazed wheel is one in which the grits are worn flat and polished; whereas, a loaded wheel is one in which chip material has packed in between the grains so that the entire surface of the wheel is smooth, rather than just the tops of the grains.

12. Grinding is a mixture of cutting, plowing, and rubbing processes, all occurring at different places at the same time. Grits with large negative rakes may just plow a groove in the surface rather than form a chip. Other grits may simply rub or burnish the surface (depth of cut very small or cutting edges very rounded or worn) . The grits that are

making chips do so in exactly the same manner as a single point cutting tool.

13. In dressing a grinding wheel, dulled abrasive grains are broken (thereby exposing sharp edges) or are pulled from the wheel to expose new grains.

14. In abrasive machining, heavy feeds and large abrasive grits are used to rapidly remove material. Cutting dominates the process but, fundamentally, it is not really different from grinding.

15. The grinding ratio is the ratio of the volume of metal removed versus the volume of wheel lost (abrasive material used) or worn away (attrition).

16. Feed is controlled by tilting the regulating wheel. The angle of inclination provides a force in the feed direction. The part feeds at
$F = dN \sin\theta$ (Equation 27-1)

17. There must be spacing between the grains to make room for the chips. To a certain extent, spacing or structure, along with the grain size, also dictates the surface finish.

18. The cutting fluid carries away the chips and keeps the workpiece and grinding wheel cool. The very high grinding speeds convert considerable energy into heat energy. The grinding area is very limited and the localized heating can easily damage the workpiece .

19. The wheel is fed radially into the rotating workpiece.

20. The dust resulting from grinding contains fine, hard abrasive particles which can become airborn and get embedded in the softer, moving parts of other machines, causing these parts to act as laps, which thereafter would ruin the accuracy of the machines. In manufacturing cells, where grinders are often placed near other machines, it is important to put good dust control devices on the grinders and use lots of cutting fluids.

21. The purpose is to produce a surface which is free of residual stresses or a surface in which tensile and compressive stresses are nicely balanced. Cutting results in residual tension, while rubbing and burnishing produce residual compression.

22. Wheel speed is reduced, the down feed is reduced, and sulpherized cutting oil is used for low stress grinding. See Figure 27-11.

23. The larger the grains, the fewer that can be packed into a given area, so on the average, fewer grains will contact the workpiece during a pass.

24. Centerless grinders are faster, have better work support, require very little operator skill, have the possibility of continuous infeed, give excellent size control, and can be automated with regard to part loading and unloading. wheel adjustment for wheel wear can be automatic as well.

25. Electron microscopes are roughly analogous to light microscopes with electrons, rather than light, used to create the image. This requires an electron source, electromagnetic lenses and operation in vacuum. In scanning electron microscopy secondary electrons emitted from the surface under observation are used to form the image. An explanation of these general ideas is provided at *www.mos.org/sin/sem/intro.html*

26. The grinding forces are much lower than the forces used in milling and usually are directed downward into the vacuum chuck. Killing has larger forces, and the force may be directed up, away from the vacuum check, as in up milling.

27. The typical grinding operation makes many passes at very small depths of cut and relatively large feeds. In creep feed grinding the depth of cut is large, the feed is very slow, and the cut is often made in one pass over the workpiece. Creep feed grinding is grinding at very slow feed rates. See Figure 27-20.

28. In lapping, the abrasive grits become embedded in the soft material of the lap. This is referred to as "charging the lap". The material to be lapped is machined or rubbed by the abrasive grits, not the soft material of the lap.

29. In honing stones, additional materials, such as sulfur, resins, or wax are added to the bonding agents to modify the cutting operations. The grits themselves are very fine or small.

30. "Charging" a lap is loading it up with abrasive materials.

31. Honing is intended to smooth and size the hole, not to alter the position or angle of the axis, so a rigid setup is not what is desired in this tool.

32. In most coated abrasive belts, the abrasive grains do not pull out so as to expose new, sharp grains. They thus have no self-sharpening action.

33. The chips are small, of the same order of size as the abrasive grits. So, the bottoms of the individual chip slid on one abrasive grit. If the bottom of the chip appears smooth it is because the abrasive grain surface was smooth or the resolution of the microscope was insufficient to show the features on the chip bottom surface.

With the 4800x magnification including enlargement of the photograph from the original micrograph the chip thickness is a measured chip thickness on the photograph divided by 4800. The upper left potion of the chip labeled “T” shows the top and side of the chip. The chip thickness in the photograph is about 7 mm and so the actual chip thickness is about 0.002 mm = 2 μm.

34. The angle is a function of the rate of rotation (rpm) of the honing head versus the rate of oscillation.

35. Four major causes of grinding accidents are:

- a) operating at too high of a rpm.
- b) operating a wheel that has been dropped or struck so as to produce a crack
- c) operating the wheel improperly
- d) operating the wheel with the safety guards removed.

36. A surface grinder resembles a horizontal spindle milling machine.

37. A residual stress is a stress that is left in a piece of material after external loading is removed from the material.

38. Infeed and crossfeed usually refer to surface grinding operations, Figure 27-19. Infeed is the distance that the wheel is advanced into the workpiece in the direction perpendicular to the work surface. Crossfeed is the distance that the wheel is traversed parallel to the work surface and perpendicular to the infeed and grinding directions between grinding passes.

Problems:

1. a) The wear of the stairs is produced by the hard particles of material embedded in the soles of people's shoes. The leather or rubber soles are softer but act as laps, charged with fine grits of abrasives. The bottom of the stairs are nearest the outside.
b) The grits get dull as the stairs are ascended so less stair wear occurs at the top than the bottom. Grits are removed from the soles while ascending. Soles get charged while walking outside the building, not inside the building.

2. The small particle will tend to have fewer defects (dislocations) per unit volume and will thus act stronger. The small particle may also be more work hardened than the bulk material.

3. In surface grinding, the MRR is controlled by the table feed, V_w. See Table 27-5.

For a 1-inch wide wheel removing 0.004 inches of metal,
MRR = (12) (150) (0.004) (1) = 7.2 in^3/min.if the entire face of the wheel were engaged.

However, the wheel is crossfed over the workpiece at a rate of 0.060 in per pass, so the MRR = (7.2)(0.060) = 0.43 in^3/min.

Generally speaking, MRR's in grinding are an order of magnitude less than other multiple-tooth machining processes.

Case Study: “Aluminum Retainer Rings”

Several possibilities exist here:

One method might be to purchase tubing with the correct internal diameter or wall thickness (if possible) and slice the rings of f the tube with a sawing or cutoff operation. This would be followed by a milling operation to cut the opening in the ring. A tumbling operation might be needed to eliminate sharp edges and burrs on the ring. If tubing of the proper size cannot be located and additional machining of the OD and ID are needed, this method will not be the most economical.

A very economical procedure would be to purchase this material (5052 aluminum half hard) in a wire form, and convert the wire into a rectangular shape by pulling it through a device called a Turks Head. A Turks Head is a roll forming device with four rollers which form the four sides of the needed rectangle. The wire would thus be given the 1.60 x 2.36 cross section. Next, a round mandrel would be made. The mandrel diameter would be something less than the 89,71 ring diameter. The rectangular wire would be wound up on the mandrel like a big spring, forming a continuous coil. This operation would be done on a lathe and could provide the pulling means to pull the round wire through the Turks Head. The mandrel, with the coil clamped in place, is then placed in a milling machine and a slitting saw is used to form the individual rings. Some calculations (regarding springback) and experimentation would be necessary to determine the correct diameter of the mandrel and the width of the slitting saw so that, when the coil is cut, the individual rings will come out with the appropriate diameter with the correct opening.

If an extrusion press is available, the square wire can be formed by extrusion, since a rectangular extrusion is fairly easy to do in aluminum, and the dies might not be overly expensive. However, if the die costs exceed $500, it would be advisable to go to the Turks Head method, as Turks Heads do not cost much more than this and can be adjusted and used for other applications at a later time.

CHAPTER 28

Review Questions

1. Four types of NTM processes are: chemical, electrochemical, mechanical, and thermal.

2. The materials used in the future will be harder and stronger, making traditional machining more difficult. A large amount of energy in metal cutting goes into heat which can cause damage to the material of the part. Delicate workpieces are extremely difficult to machine by traditional methods.

3. Material removal rates on Nontraditional machining processes are typically much lower than in conventional metal cutting with some notable exceptions. The exceptions are when MRR = volume removed / time = (penetration rate)(area being machined) becomes large due to very high penetration rates or, more likely working of a large area. For example,
- in cutting operations where penetration rates may be comparable to or larger than mechanical processes such as sawing, and
- in processes with small penetration rates but that act over large areas such as is possible in electrochemical milling.

Material removal measures are given in Table 28-1.

	Feed rate (mm/min)	
Process		
Chemical milling Photochemical milling	0.013 – 0.076	MRR = (penetration rate)*(area)
Electrochemical machining	2.5 – 12.7	MRR = (penetration rate)*(area)
Abrasive-jet machining	76	
Abrasive waterjet machining	15 - 450	MRR = (penetration rate)*(area) area ~ kerf -> small
Ultrasonic machining	0.5 – 3.8	small penetration, small area
Waterjet machining	250- 200,000	high penetration, small area
Electrical-discharge machining	0.5	MRR = (penetration rate)*(area)
Electon-beam machining	30 - 1500	very small area
Laser-beam machining	100 - 2500	small area
Plasma arc cutting	250 - 5000	high penetration, kerf can be large
Wire electrical discharge machining	100 - 250	MRR = (penetration rate)*(area) area = wire-work area -> small

4. The six basic steps are: (1) preparation of the artwork, (2) photographic production of

the negative, (3) application of the emulsion to the workpiece, (4) exposing the workpiece to light passing through the negative, (5) developing the exposed workpiece, and (6) application of the reagent to the workpiece.
In chemical milling, one often wants to selectively etch certain parts of the material. The material is coated with a coating, called a resist, which, when exposed to certain wavelengths of light, chemically changes and hardens or sets. The unexposed region can be washed away, leaving an exposed region which can be chemically milled or etched. The resist or mask protects the rest of the surface. This technique allows for complex, minute, detailed masks to be developed. The technique is used in microelectronics.

5. Spraying continuously washes away the debris and keeps the process progressing evenly.

6. Very thin parts can be blanked.
Parts with varying thickness can be blanked.
Many parts can be blanked at the same time.
No press or expensive die sets are needed.
No tools to wear out.

7. The area having the greatest depth is exposed to the reagent first. Next the resist is removed from the area having the next greatest depth, and the work is again exposed to the reagent. This step-by-step procedure is repeated as often as desired.

8. No. The ratio of the depth to width is too great.

9. The width of the groove = width of the maskant + (213) depth. The width of the mask should therefore be 21 mm.

10. Yes, but not very satisfactorily. There would be too much variation in the geometry and metallurgy in and adjacent to the weld.

11. Tapered sections are produced by slowly withdrawing the workpiece vertically from the chemical bath.

12. Deburring by vaporizing burrs and fins on cast and machined parts.

13. ECM is not really related to chemical machining since ECM is a deplating process that utilizes an electrolytic circuit with an external power supply.

14. Hardness is not a factor in ECM and should have no effect on MRR.

15. The current density in a material is obviously a function of the geometry of the part. Small projections, corners, and things like burrs will have a current density which is higher than the bulk regions. The MRR is a function of the current density. The higher the current density, the faster the MRR. Thus, geometries like burrs preferentially etch faster.

16. There is no tool wear to speak of in ECM as the tool is protected cathodically during the process. There may be some chemical reaction between the tool and the electrolyte when the power is off, depending upon the materials involved.

17. Shaped-tube electrolytic machining is similar to electrochemical machining and electrostream drilling in that the same material removal process is used – electrochemical action. It is different in the tooling used to deliver the electrolyte to the material removal area. In STEM the electrolyte is delivered in a very controlled way to the working area by use of a tube.

18. ECG is not suitable for grinding ceramics because they are not conductors. Ultrasonics can be effectively used to machine ceramics, but the process is quite slow (low MRR).

19. The MRR in ECM depends mainly upon the current density which is influenced by the geometry of the tool. For example, the current density at sharp corners will be greater than flat surfaces, so corners will cut faster.

20. The amount of material removed is a function of exposure time. As the tool advances down into the work, the sides of the tool would continue to machine the sides of the hole, giving it a taper (largest at the top) which in this case is not desired. Thus, the tool is insulated to prevent the passage of current.

21. In ultrasonic machining small parts of the work material are removed by coalescence of fractures cause by the impact of the abrasives on the work, and a small amount of ductile chip formation where very small depths of cut (deformation zone size) occur. If chips are viewed as the result of (ductile) shear deformation as in metal cutting then ultrasonic machining is chipless. If chips are viewed as an identifiable particle from the workpiece then ultrasonic machining produces chips.

22. The acceleration is greatest at the ends of the stroke so the forces acting on the grits in the slurry are greatest here as well. Actually, the grits in the slurry are driven by the wave action of the vibrating tool against the workpiece. The tool acts to focus this wave action into the desired regions.

23. The surface is heated by the sparks to either melt or even vaporize metal. The melted metal is washed away by the dielectric. The sparks cut small, spherical shaped, cups into the surface. The surface is covered with recast (melted and resolidified) metal. Thus, there will always be a hard, brittle, surface layer on EDM part surfaces.

24. The moving wire electrode can cut straight or angled slots through plates under CNC control. The thin wire allows relatively complex geometries to be cut into dies and stripper plates, for example, with virtually the same program being used to make parts which will later mate with the die set. The principal advantage is that it can produce "saw-like" cuts in hard, delicate materials which would be difficult to bandsaw. There are

no tool forces on the wire. A hole can be drilled in the part and the wire passed through the hole.

25. The effect would not be great. The MRR is controlled by adjusting the amperage (higher amperage, higher MRR) while the surface finish is controlled by the frequency of the spark (higher frequency with amperage constant yields smaller craters and smoother finish).

26. ECM is probably preferred to EDM in this case because the recast layer produced by EDM may serve as a source for fatigue cracks in the already brittle base material.

27. Of the four processes, laser beam machining is the easiest to automate into large volume production provided the laser can do the job. Lasers leave recast surfaces like EDM. Both ECM and EDM can be automated but are more oriented toward batch processes. If the parts are small and a large number can be loaded into a machine at the same time, EDM or ECM could be used, with ECM holes having less damage and EDM usually having slightly faster MRRs in most materials. LBM and EBM have very low MRRs which may exclude them from large volume production.

28. Again, LBM is good for small holes in hard metals and since they are being used for venting, the recast layer should not be a problem. The low MRR rate may make for long machining cycles, so ECM may be preferred. EDM is not preferred for small holes.

29. Specific power may be high for LBM because the spot area or volume is very small and the coherent beam energy is very large.

30. The spark in an EDM process literally blasts molten metal out of the crater. These globs of material try to assume the lowest energy state which is spherical. They cool from the outside to the inside, so the inside can form a shrink cavity, making the spheres hollow. The spheres may also trap gases to make them hollow.

31. In waterjet cutting a high speed stream of water is used. This requires machines to generate high pressure, pumps to move the fluid, the flow of water through piping at high speed, and a high speed stream leaving a nozzle (Figure 28-16). These are all sources of noise.

32. In abrasive waterjet cutting nozzle wear occurs due to the interactions of the abrasives and the nozzle. Wear can be minimized if abrasive-nozzle contact is minimized (few particles and low contact stress) and if the speed of the abrasives through the nozzle is small. One way to accomplish decreased nozzle wear in to use controlled streams of water to keep the abrasives away from the nozzle wall and to inject the abrasive particles into the central part of the water streams.

33. Abrasive flow machining appears to be useful for finishing internal passages in engine blocks AFM is useful for finishing complex, internal, difficult-to-access regions of parts. However, the AFM process will become very complicated since there are so

many openings that need to be closed, different kinds and size passages and so large variations in media pressure and long passages and so large media pressure drops in cylinder blocks.

34.Thermal deburring is a process in which a hot, corrosive gas is directed onto a burr and the burr is removed by vaporization. Part of the deburring process is due to chemical action, oxidation of metals, breakdown of the chemical bonds of thermosetting plastics. While thermoplastics have low thermal conductivity the increase in temperature will have a less severe effect on the material. Thermoplastics are characterized by a glass transition temperature that indicates gradual changes in molecular behavior. Rather that breaking the material down chemically thermal deburring is expected to cause a softening of the material, and not only in the burr but also in the surrounding material.

Problems: no problems

Case Study: no case study

CHAPTER 29

Review Questions

1. The work holding device locates the part in the machine tool with respect to the cutting tools and holds the part (clamps it) so it does not move due to cutting forces or inertial forces.

2. A jig determines location dimensions while a fixture does not. A fixture is a special workholding device -- that is, specially designed to accomplish a specific job. Jigs have the layout of geometric shapes built into them, and thus they automatically transfer this layout to the workpiece as operations are performed with their use.

3. The definition was incorrect, in that some jigs do not hold the work (as in clamp-on jigs), and some jigs do not guide the tool (as in welding jigs). Welding jigs are used to locate one (or more) parts with respect to another part and hold them in the right orientation and location while welding is performed.

4. A vise is a general purpose workholding device and is not a specially designed workholding device. This answer may sound picky but it is important to distinguish between a vice used in general purpose milling and a fixture used in a milling machine. Why? The latter may have many special features designed into it to enhance or speed up production, reduce setup time, or reduce time to load or unload parts. The fixture may have a pokayoke built into it, meaning that it cannot be operated if parts are loaded into it incorrectly (pokayokes prevent defects from occurring - See Chapter 43).

5. Some basic factors in designing jigs and fixtures are: (1) clamping the work to resist the cutting forces; (2) supporting the work during cutting so that it does not deflect under the load of the cutting forces; (3) location to provide the desired dimensional control; (4) guidance of the tool$_1$ if required; (5) provision for chip removal or clearance during or after operation; and (6) rapid, easy, safe operation.

6. The critical surfaces (often 3 perpendicular planes) are surfaces on the part that are vital to the parts function or operation. Other surfaces are dimensioned from the critical surfaces, and these surfaces are established early in the processing sequence.

7. The clamping forces can distort the workpiece. The workpiece is machined in the distorted configuration. When the clamping forces are removed, the workpiece returns to its unstressed shape, but now the machined surface is distorted and the dimensions produced by the machining operations will be incorrect .

8. Three points are required to locate the workpiece in one plane. Two points are required to locate the workpiece in a second plane, perpendicular to the first plane. One point is required to locate the workpiece in a third plane, perpendicular to the first two.

9. Supporting the work against the cutting forces of the process often requires that

additional points or bearing supports be placed in the three perpendicular surfaces, beyond the 3-2-1 points .

10. Reasons for not having the drill bushings actually touch the workpiece include:
(1) Chips may become tangled in the drill bushing if there isn't sufficient clearance between the bushing and the workpiece,
(2) the end of the bushing may contact an oversize workpiece and not permit the piece to be located or held properly, and
(3) the chips will be passed through the bushing and may wear and score it.

11. Down milling pushes the workpiece down into the location surfaces, which are solid, unmoving surfaces; up milling tends to lift the workpiece out of the fixture, so clamping forces must be greater to hold the workpiece against the location points during machining.

12. Flexibility means versatility. Workholding devices can be made move flexible by making them modular, i.e., made of combinations of standard elements that are combined in different ways for use in making different parts.

13. Forces acting against the floor caused the jig to deflect, which, in turn, caused the jig to twist. By having a rigid jig with only three points of support, the jig would not twist.

14. If a machine is costly and has a high production rate, time lost in setting up and clamping a workpiece is very costly. Thus a small amount of time saved each cycle by use of a fixture easily repay the cost of the fixture. A machine that is not costly or highly productive may not offer sufficient return to pay for the same fixture.

15. Jigs that can be flipped over to permit drilling from more than one side are called roll-over jigs. They: (1) usually eliminate the cost of a second jig, (2) reduce the amount of clamping time, and (3) may reduce possible clamping error due to clamping stresses.

16. The spherical washer permits minor deviations in the parallel surface to readily be absorbed. The strap clamp does not have to be exactly parallel to the surface holding the D stud. This allows for variations in the thickness of the workpiece .

17. Strap clamps, C clamps and toggle clamps are all commonly used.

18. The strap clamps can be bought in different sizes. The letters are used in a table in the clamp catalog to define the sizes but the basic design of the clamp does not change, just the size.

19. There is no control over how many points the part will rest on if it is set on the flat plate. Plates are not perfectly flat. Using locator buttons assures that the number and location of part support points are known.

20. The X plane is the largest plane and would ordinarily take 3 buttons. However, this

would place the thrust of the drilling process for the two mounting holes outside the area defined by the three buttons. Therefore, 4 buttons are used in the X plane and the drilling thrust is inside the region defined by these 4 points. The bottom of the bearing block would be milled flat and true prior to insertion in the jig.

21. The Z location buttons establish the "A" dimension.

22. The front and back could be straddle milled first, then the base milled perpendicular to the front or back and finally the right end. The end is milled solely for the purpose of establishing dimension "B" and "C: The right end must rest against button"Y" in the jig. The base could be milled first and then the front and back milled, using the base as a locating surface .

23. The surfaces which locate the holes are milled first to properly establish dimensions "A", "B", and "C". It is more difficult to locate surfaces to be milled from surfaces that were drilled than it is to locate (and drill) holes with respect to milled surfaces. While the drawing does not say so specifically, the holes are perpendicular to the flat bottom.

24. Drill bushings (K) must be removable so the holes can be countersunk with the workpiece still in the jig. Drill bushings are made removable for any number of reasons. You may want to replace it if it wears. You may want to remove it so that the drilled hole can be reamed, tapped, or countersunk --the reamer, tap, or countersink being larger than the drill diameter. You may be drilling two holes of different diameter in the same location, so you need two different drill bushings.

Problems:

1. Same as 8th edition Chapter 28

1. $(\$5.75 + \$4.50)(2.25) - (\$4.50 + \$4.50)(1.25) = (\$3.000 / N)(1 + (3)(0.1)) / 2$

$N = 292+$ or 293 pieces

2. The cost of the jig is:

$$Ct = [\ \$100 + (4)(12)\ ] / N + [\ \$600 / N\ ]\ [\ 1 + (3)(16) / 2\ ]$$

Assuming the design and assembly costs are one-time costs and the modular elements are written off over three years;

$$Ct = \$148 / N + (600 / N)(1.24)$$

$$(8.00 + 8.75)(.5) - (6.50 + 8.75)(0.2) = 148 / N + (600 / N)(1.24)$$

$$8.375 - 3.05 = 148 / N + 744 / N$$

$$N = 892 / 5.325 = 167.51$$

The modular fixture has a lower breakeven quantity.

3. The cutting force, F_c of 1800 lb. is assumed to be going to the left, and the thrust force of 900 lb. is assumed to be going down. The clamping forces, F_R and F_L are required so that the clamps can be designed.

For a static condition, the sum of forces in the X-direction (horizontal) equals zero, the sum of forces in the Y-direction (vertical) equals zero, and the sum of moments around any point is zero.

$F_x = R_1 + \mu(F_L + F_R + 1500 + 900) - 1800 = 0$
$F_y = R_2 + R_3 - F_L - F_R - 900 - 1500 = 0$

M_A = moment about point A on left side
$= (900 \times 5) + (1500 \times 15) + (F_R \times 30) + (R_3 \times 30) - (1800 \times 34) = 0$

Let $R_3 = 0$ (assume part is barely touching) and
$F_L = 0$ (assume there is no tendency to lift on the left side).

So:
if $R_3 = 0$; $F_L = 0$

$2F_x = R_1 + 0.19\ (FR = 1500 + 900) - 1800 = 0$

$2Fy = R_2 - F_R - 900 - 1500 = 0$

$M_A = 4500 + 1500(15) + F_R\ 30 - 1800(34) = 0$

$F_R = [\ 1800(34) + 900 + 1500(15)\ ] / 30 = 1140$ lb

$R_2 = 1140 + 900 + 1500 = 3540$ lb.

$R_1 = 1800 - .19\ (1140 + 1500 + 900) = 1127.4$ lb.

4. Current cost to drill holes
1 minute machining time + 0.5 minute unload/load time = 1.5 min/part
40 parts/hr
(\$42 / hr) / (40 parts/hr) = \$1.05 / part

With toggle clamp
experiment shows advancing screw about ½ in takes about 4 sec
and working toggle takes less than 1 sec
=> part in and out of jig about 30 sec – 2(4 sec) for one screw at a time
new unload/load time is 22 sec part handling + 2 sec clamping = 24 sec
1 minute drilling time + (24/60) unload/load time = 1.4 min/part
43 parts/hr
(\$42 / hr) / 43 parts/hr) = \$0.98 / part

Cost change = $0.07 /part

Cost to implement change

cost per clamp = $3.85 – catalog data

cost to modify jig = (shop cost)(shop time) = ($70 /hr)(7 hr) = $490

current University shop rate

University shop estimate of construction time

design cost = ?

lost production time while jig is modified = 7 hrs + transportation and queue time = ?

Considering only purchase of clamps and jig modification cost the number of parts that must be drilled to recoup cost is ($490 + $7.70) / $0.07 / part = 7,110 parts

Case Study: "Overhead Crane Installation"

This study actually involves two location problems: the location of the holes with respect to themselves and the location of the hole patterns with respect to each other. The former problem can be solved by making a simple ring jig. The jig can be secured to the column using magnets or a hole can be drilled at the point (+) on the column, tapped, and used to hold the jig plate while the bolt holes are drilled. The holes can be drilled with a hand electric drill.

The second problem, locating the drill jig properly on each column so that the hole pattern centers all come out on the same plane, is a bit more difficult. Here is one possible solution. A fine cross (+) is placed on the jig. On the day that the job is to be done, a surveyor's transit or level is set up in the center of the eight columns at the required height. A painter's scaffold should provide adequate height. When the transit is properly leveled, each column can be "shot" so that, when the jig is mounted on each column for hole drilling, the jig will always be at the same height with respect to all other columns (without regard to the floor itself).

The equipment needed would be: a drill jig, magnet, drills, portable electric drill with long extension cord, scaffold, and surveyor's level.

CHAPTER 30

Review Questions

1.The major diameter is the over-all, outside diameter of the thread. The pitch diameter is a smaller, theoretical diameter upon which all the design elements of a thread are based.

2. The pitch and lead are the same for a single-pitch thread.

3. The helix angle is the angle between the slope of the screw thread and a line perpendicular to the axis of the screw.

4. Pipe threads are made on a taper so that as the threaded joint is tightened it will form a liquid-tight joint.

5. The basic methods for making external threads are: machining (grinding), forming, and casting. In plastics, threads can be molded.

6. 1/4"-20 UNC-3A designated an external thread of the Unified, or American, form, 1/4" nominal diameter, having 20 threads per inch, and a Class 3 fit.

7. M20 x 2.5-6g6g designates a metric thread; the nominal size is 20 mm; the pitch is 2.5 mm; #6 tolerance grade and "g" tolerance position on the crest diameter. The x means "by".

8. Fine-series threads are being used less because of the wide availability and use of self-locking plastic inserts on fasteners and special locking coatings.

9. Pitch is controlled by controlling the longitudinal motion of the lathe carriage relative to the rotation of the spindle, by means of the lead screw and clamp nut. Comment on threading on a lathe: Cutting threads on a lathe is a slow and expensive process. The design should specify standard threads which can be made by the most economical process whenever possible. Can thread rolling be used? If machined threads are needed and if the threads are of standard diameter, they can be cut with a die. Dies come in standard sizes. Nonstandard size threads would require operator controlled functions and great time delay in the cycle to make the threads. This is typically how they are made on the engine lathe, but engine lathe work is only for very small lots. The use of a die allows the turret lathe operations to be performed rapidly, without adjustment. An NC lathe can do threads quickly and repeatably.

10. The threading dial assures that the cutting tool will exactly

"track" in the previous thread groove during successive cuts.

11 Figures 23-8 (not labeled) & 23-9 show threading dials.

12.The lead is built into the cutting die. It twists itself on to the shaft just like a nut.

13. The purpose of a self-opening die head is to permit the die head to be withdrawn linearly from the completed thread without having to be unscrewed from it.

14. The shape of a taper tap aids in properly aligning the tap in the hole. It is much more difficult to align a plug tap properly if it is not preceded by a taper tap.

15. If full threads are specified to the bottom of a dead-end hole, it is necessary to follow the usual plug tap with a bottoming tap, which must be used with care to avoid breaking off the tap in the hole.

16. A fluteless tap produ6es threads by plastic flow of the material, requiring a ductile material. Gray cast iron is brittle, and therefore does not plastically flow. Threads in gray cast iron must be machined.

17. If possible, have the hole drilled deeper than actually needed so that it can be threaded to the desired depth without having to use a bottoming tap.

18. A spiral-point tap projects the chips ahead of the tap, thereby avoiding chips from becoming entangled in the cutting tap. (Another reason to drill the hole deeper than the threaded portion.)

19. No, a fluteless tap forms threads progressively, thus requiring several partially formed threads ahead of the fully formed threads, therefore it can not be used to thread a dead-end hole to the bottom.

20. Yes, it is not only desirable but necessary in most materials that the cutting fluid be a good lubricant. There will be large friction forces between the teeth of the tap and the tapped hole as the tap progresses. A lubricant will also reduce the friction between the chips and the work material and the tap.

21. Threads are milled (machined) using form cutters - either single or multiple-form cutters are used. Because the cutter has multiple teeth, the thread can be fully machined in one pass of the cutter past the rotating workpiece. So this process is faster than thread turning, which

uses a single point tool.

22. By grinding, threads can be made on hardened materials and the threads will be more precise (less variability) and have a better surface finish.

23. Thread rolling is much faster than any of the machining processes and the properties of the threads are improved -- stronger and smoother. The materials to be thread rolled must be ductile and full-form threads cannot be obtained by rolling. Also, the threads will not have any sharp radius. The surface of the bar must have a good surface finish.

24. Examine the thread. Machined surfaces are very different from rolled surfaces.

25. With the involute tooth form, there is only rolling contact between the gear tooth surfaces, thus eliminating sliding friction.

26. The diametral pitch of a gear is the ratio of the number of teeth to the pitch diameter, or is the number of teeth per inch of pitch diameter.

27. The module and the pitch diameter are the same.

28. See Figures 30-14 and 30-15.

29. (1) The actual tooth profile must coincide with the theoretical profile; (2) tooth spacing must be uniform and correct; (3) the actual pitch circle must be coincident with the theoretical circle and be concentric with the axis of rotation; (4) the face and flank surfaces must be smooth and adequately hard; (5) the shafts and bearings must assure that center-to-center distances are maintained under load. Notice that most of these requirements are determined solely by manufacturing of the gears.

30. The tooth engagement of helical gears is gradual, and more teeth are in contact at a given time. This tends to provide smoother and quieter operation. (Do you think that helical gears are used in car transmissions?)

31. Helical gears cause side thrust and are more difficult to manufacture than straight tooth gears.

32. A hob has to extend past the point being cut on the gear teeth. On herringbone gears this would cause the hob to extend, and cut into the teeth beyond the centerline of the gear.

33. Full-herringbone gears can be cut only on a Sykes gear generating machine .

34. A clearance groove is machined around the center of the gear

to provide clearance for the hob, or two helical gears, having opposite helix angles, may be machined separately and joined together.

35. A different, and very expensive, broach has to be made for each size and type of gear.

36. A crown gear will mate properly with any bevel gear having the same diametral pitch and tooth form.

37. Three basic processes for machining gears are: form cutting, generating, and template machining.

38. The Fellows gear shaper uses generation, meaning the tooth profile is made in progressive passes. See Figure 31-10.

39. The feed screw of the milling machine table is geared to the dividing head so as to cause the spindle of the dividing head, which holds and rotates the gear blank, to rotate in relationship to longitudinal movement of the table.

40. A hob has almost continuous cutting action, there are multiple teeth, and the action does not have to be stopped to index the gear blank.

41. The tooth profiles are produced by successive cuts of the cutter past a slowly rotating workpiece.

42. Cold-roll forming is a very rapid process, the faces of the resulting teeth are very smooth and somewhat hardened, and the gear may be stronger.

43. Cold-roll forming requires a ductile material; gray cast iron is not ductile.

44. Shaving cannot be used on hardened gears.

45. Cold-roll forming produces work hardening and thus provides a better wearing surface on the face of the teeth.

46. Cast iron is soft, and the lapping abrasive would become embedded in the gears, resulting in them not being lapped but rather the teeth would become laps.

47. Gear inspection checks: hardness; tooth thickness, spacing and depth; tooth profile; surface roughness; and noise.

48.Gear finishing is accomplished by gear shaving, roll finishing, grinding (good for hardened gears) and lapping for final finishing.

Problems:

1. For 30 fpm, the RPM will be N = (12 x 30)1(3.14 x 0.75) = 152.8rpm.
The cutting time CT = (2 + 0.75)/(0.1 x 152.8) =0.179 min.
where 10 thread per inch = 0.1 inches/thread or 0.1 inches per revolution and 0.75 inches is the allowance for overtravel to insure that full threads are cut.

2. The recommendation is based on the favorable cutting time of the chipless tap over the normal tapping process. The engine blocks may be made out of cast iron, in which case fluteless tapping will not work because cast iron is a brittle material. In addition, tapping deep, dead-end holes with fluteless taps is a difficult process. If these are aluminum engine blocks, then the suggestion should be given serious consideration. P.S. Do not forget to ask the operator and the foreman in the area what they would recommend, as they are going to have to implement any suggestions you make.

3. RPM of hob = (27.4 x 1000) / (76.2 x 3.14) = 114.5
RPM of gear blank = 114.5 / 36 = 3.18

4. Effective width = 76.2 + (2 x 38) = 153.2 mm
Time = 153.21(3.18 x 1.9) = 25.4 minutes

5. For the HSS cutter milling 4340 steel, selected values for
V = 100 fpm and f_t = 0.007inches per tooth would be reasonable.

f_m= n N Ft, where N = 12 V / (πD) = 12 x 1001(3.14 x 4) = 95.4
f_m= 11 x 95.4 x 0.007 = 7.35 ipm

CT = (L + A) / fm = (1 + 2~4) / fm for a 1 inch thick gear
CT = 3.4 / 7.35 = 0.46 min.
where A = allowance = $2L_A = 2 \{ t (D-t) \}^{1/2} = 2 \{ 0.6(3.0 - 0.6) \}^{1/2}$ for t=0.6, scaled from Figure 31-19

Each pass takes about 1/2 minute. From Figure 31-19 one can determine that there are 12 teeth which require 12 passes. Assuming that it takes 30 seconds to return the cutter to the start position and index the gear blank 30 degrees, the job would take about 12 minutes. Down milling will be used to get the best finish on the teeth.

6. The broach has 10 sets of progressive tooling, so assume the cost of the tooling is $2500. Assume labor costs $10 per hour and machine overhead is 100%. Assume the milling cutter cost is $100 or so. The milling time is 12 minutes per part versus 15 seconds per part for broaching.

Savings estimate (12-.25) x (20 / 60) = $3.91/part

Assuming all other costs remain the same,
Additional cost = $2500 - 100 = $2400 for the broach versus the milling cutter

BEQ = 2400 / 3.91 = 613 parts

If the company is making over 613 gears and has both machines, the switch is justified.

Comparing to shaping, assume a 1 minute cycle time for shaping.

Savings estimate (1-.25) x (20 / 60) = $0.25/part
BEQ = 2400/0.25 = 9600 parts

Broaching would only be preferred to shaping if there were over 9600 gears to be machined. The broach can easily cut that number of gears and the cost of TiN coating is also justified. For example, adding $100 to each broach,

BEQ = 3400/3.91 = 869 parts

7., 8. The gear manufacturing processes described in the chapter are listed in the table along with some important characteristics of each related to making 1.125 inch diameter, 70-30 brass gears.

Process			Consider for
Form Milling	standard cutters standard milling machine	slow	3
Broaching	complex machine complex tooling	short cycle time	10,000
Gear Generating			
- shaping	specialized machine can make multiple gears simultaneously	short cycle time	10,000
- hobbing	general purpose machine can be adapted specialize machine for high production		3, 10,000
Cold-Roll Forming	specialized machine high quality tooling	short cycle time high quality gears	10,000
Casting	probably requires finishing		
Blanking	for thin gears		NA
Powder Metallurgy	specialized equipment and materials		don’t consider
Flame machining	little accuracy		NA

8. Above

9. The hole is larger than the internal thread minor diameter.

A closer look at machinists' handbooks will show not only 75% threads but also 60% threads that call for larger drill sizes than the 75% thread drill size which is still larger than the minor diameter.

While an oversimplification an explanation of thread strength is that it is determined by the shear of threads and so the width of the thread is the important issue and thread depth is secondary. With regard to thread manufacture there is work material deformation in addition to the metal removal. Too small a prepared hole will lead to very little room for deformed material flow, tap seizing and tap breakage. Machinists working on prototypes and special projects have been know to use drill sizes slightly larger than recommended for low stress applications so as to ease machining problems.

Case Study: "Vented Cap Screws"

The redesigned part would need a hole 0.024 inches in diameter, 1/2 inch deep. This is a hole diameter to hole depth ratio of 1 to 20, clearly not a conventional drilling process.

The hole or the slot, as designed, could be made by EDM or ultrasonic machining, or perhaps laser machining, depending upon the available equipment. If none of this equipment is available, ask the designer if the slot needs to be of uniform cross section throughout, or only in some region to control the pressure buildup. This is probably the case, and would allow the slot to be redesigned as shown in the sketch below. This design can be slot milled using a one-inch-diameter slot milling cutter.

CHAPTER 31

Review Questions

1. Some of the possible objectives of surface modification processes are: clean surfaces and remove surface defects, modify a product's appearance, improve resistance to wear or corrosion, reduce friction or adhesion, and conserve costly materials.

2. When selecting a surface modification process, one should consider the common factors of time, labor, equipment, and material handling. In addition, consideration should be given to such features as: the size of the part, the shape of the part, the quantity to be processed, the temperatures required for processing, the temperatures encountered during subsequent use, and any dimensional changes that might occur due to the treatment.

3. Two general concepts apply. One is the shape or geometry or topography of the machined surface. Machining processes produce surface profiles that are not exact replicas of the tool shape. The deformation of the work surface results in roughness at a more local level than the size of the cutting edge and nose radius. This is the roughness usually measured and referred to as "surface roughness."

The other aspect of the machined surface is the modification of the structure, properties and residual stress state of the machined surface layer. These changes in material characteristics can affect the part performance in use. The term "surface integrity" refers to this aspect of machined surface characteristics.

4. Manufactured products frequently contain foreign material on the surfaces. Sand from casting molds and cores often adheres to surfaces. Scale can be produced when metals are processed at elevated temperatures. Oxides can form during storage.

5. Blasting or other abrasive cleaning operations utilize abrasives such as: sand, steel grit, metal shot, fine glass shot, walnut shells, dry-ice pellets, and even baking soda.

6. Barrel finishing operations are most effective when large quantities of small parts are to be processed.

7. In barrel finishing, the rotation of the barrel causes the material to rise until gravity causes the uppermost layer to cascade downward in a "landslide" movement. If the barrel is too full, the relative motion between the work and the abrasive will not adequate. Increasing the speed causes the material to rise higher in the barrel, but if the speed is too high, centrifugal forces cause the parts to adhere to the outside of the barrel, thereby eliminating the cascading action.

8. In barrel finishing, most of the finishing occurs when the parts slide down over the media. In vibratory finishing the entire load is in constant agitation, and there is virtually constant relative motion between the work and the media.

9. Synthetic abrasive media, formed by combining abrasive material and a binder, are manufactured, and have consistent and reproducible size and shape.

10. The compounds that are used in abrasive finishing operations can perform a variety of functions, including:
deburring, burnishing, abrasive cutting, cleaning, descaling, and corrosion inhibition.

11. The ideal geometry for belt sanding is a flat surface. The process is more difficult with curved surfaces, and is extremely difficult to apply when the geometry includes recesses or interior corners.

12. Electropolishing is the reverse of electroplating, since material is removed from the surface rather than being deposited.

13. Alkaline cleaning can remove a variety of soils, including oils, grease, wax, fine particles of metal, and dirt. The actual cleaning occurs through one or more of: (1) saponification, (2) displacement, (3) dispersion or emulsification, and (4) dissolution.

14. Solvent cleaning cannot be used to remove insoluble contaminants, such as metal oxides, sand, scale, and the inorganic fluxes used in welding, brazing and soldering.

15. Environmental issues have made vapor degreasing rather unattractive. The standard solvents have been identified as ozone-depleting compounds, and have been banned from use. Replacement solvents usually lack one or more of the qualities that are desirable for the process.

16. Acid pickling operations are generally used to remove oxides and dirt that remain on the surface of metals after other processing operations.

17. During milling of most of the slot the work material ahead of the cutter is supported by more work material ahead of the deformation zone. As the free surfaces of the workpiece are approached this support decreases. Very near the free surfaces the workpiece deformation zone is not strongly bounded. The deforming material is not cleanly sheared and deforming material can move into free space forming burrs.

18. During thermal energy deburring, the parts are loaded into a chamber, which is then filled with a combustible gas mixture. when the gas is ignited, the short-duration wavefront heats the small burrs to extremely high temperatures, while the rest of the part remains cool. The burrs are vaporized, including those in inaccessible or difficult-to-reach locations .

19. While both coating and cladding are deposition processes, coatings are deposited as a liquid or a gas (or from a liquid or gas medium), while the added material is solid during cladding.

20. Paints are used for a variety of reasons, including providing protection and decoration, filling or concealing surface irregularities, changing the surface friction, and modifying the light or heat absorption or radiation characteristics.

21. In a painted surface, the prime coat serves to promote adhesion, fill minor porosity or surface blemishes (leveling), and improve corrosion resistance. The more highly pigmented final coats are designed to provide color and appearance.

22. In airless spraying, mechanical pressure forces the paint through an orifice under pressure. The resultant velocity is sufficient to produce atomization and propel the particles toward the workpiece.

23. Industrial robots can mimic the movements of a human painter, while maintaining a uniform separation distance and minimizing waste. Monotonous and repetitious movements can be performed with consistent results, and the human operator is freed from an undesirable working environment.

24. Electrostatic spraying greatly reduces paint loss and the generation of airborne particles, and provides for more uniform coverage of the workpiece.

25. In electrostatic spray painting, the workpiece must act as one of the electrodes. Wood and plastic are not electrically conductive and cannot serve as an electrode.

26. The most common metallic coatings that are applied by hot dipping are: zinc, tin, aluminum, and terne (a lead-tin alloy).

27. The two most common types of chemical conversion coatings are chromate and phosphate.

28. Nonconductive materials, such as plastic, can be electroplated provided that they are first coated with an electrically-conductive material. Processes, such as the electroless deposition of nickel can be used.

29. Hard chrome plate offers Rockwell C hardnesses between 66 and 70, and can be used to build up worn parts, and coat tools and other products that can benefit from the reduced surface friction and good resistance to wear and corrosion.

30. Some of the process variables in an electroplating cell include: the electrolyte and the concentrations of the various dissolved components, the temperature of the bath, and the electrical voltage and current.

31. Ordinarily only one type of workpiece is plated at a time, since the details of solutions, immersion times, and current densities are usually changed with changes in workpiece size and shape.

32. In the electroforming process, the coating is stripped from the substrate and becomes

the final product. In electroplating, the coating and substrate remain intact.

33. when anodizing aluminum, if the oxide is not soluble in the anodizing solution, the oxide will grow until the resistance of the oxide prevents the current from flowing. If the oxide is partially soluble, dissolution competes with oxide growth and a porous coating is produced. As the coating thickens, the growth rate decreases until it achieves a steady state where the growth rate is equal to the rate of dissolution.

34. In color anodizing, a porous oxide is first produced, which is then immersed in a dye solution. The dye is then trapped in place by a sealing operation.

35. Electroless plating will provide uniform thickness on complex shapes and it requires much less energy. In addition, metallic platings can be directly applied to nonconducting surfaces.

36. When minute particles are codeposited with the electroless metal, electroless plating can be used to produce composite coatings. Commercial applications have used diamond, silicon carbide, aluminum oxide, and teflon particles dispersed in the metal matrix.

37. Mechanical plating is an adaptation of barrel finishing in which coatings are produced by cold-welding soft, malleable metal powder onto a substrate.

38. Porcelain enamel coatings can be used to impart resistance to corrosion and abrasion, decorative color, electrical insulation, and the ability to function in a high-temperature environment.

39. See the Case Study below.

40. Since machining processes are surface region removal processes there is a difference in the deformation or structure between the worked surface region and the underlying un-worked material so there is always residual stress of some level. In the chip formation type of machining such as turning and grinding deformation gradients can be high and residual stresses are high. In very mild machining operations such as electrochemical machining there are still differences between worked surfaces and the bulk of the material, although such differences can be very small.

41. The extent of deformation below machined surfaces depends on the magnitude of the forces acting and the direction of the forces. A way to understand the effect of tool rake angle on depth of subsurface effects is to consider the resultant force of the cutting forces, R, in Figure 21-20. The magnitude of r is

$$R = \{ F_c^2 + F_t^2 \}^{1/2}, \quad \text{eqn (21-25)}$$

and the direction of R with respect to the finished surface is

$$\eta = \beta - \alpha$$

For constant coefficient of friction, as rake angle α becomes more negative the direction of R rotates so that R is directed more into the work material.

As rake angle decreases the cutting forces increases. A qualitative explanation is,
- as α decreases the shear angle ϕ decreases, eqn(21-19)
- decreasing ϕ means that the shear plane length and area increase, Figure 21-17,
- the shear strain also increases as ϕ decreases, eqn(21-31)
- as the amount of deformation increases the cutting forces increases if the work shear strength is constant, increases or does not decrease enough to compensate for the increase in cutting forces due to increased deformation

42. Fatigue failure involves crack initiation and growth. Crack are more likely to initiate at surfaces than in interior region of manufactured parts because,
- the manufacture of surfaces results in surfaces that are not perfectly smooth and small sharp irregularities in surfaces act as stress raisers,
- in extreme cases the irregularities in the surface may be small cracks,
- manufacturing operations may produce tensile residual stress in the surface region that then can act in consort with applied tensile stress to raise the net stress acting,
- the change in stress state from the interior of the material to the plane stress state at the surface can result in stresses that aid crack initiation.

43. Stress raisers are changes in material shape, part geometry, that result in the local stress near the change in shape being increased. At changes in geometry the material remains continuous so the stress changes and increased local stress can result.

44. The two types of surface effects due to machining are surface profile effects and subsurface region effects – see Question 3.

45. The residual stress combines with the stress due to applied loading to give the net stress acting, locally, in the part. If tensile stresses result and are undesirable in use then the residual compressive stress acts to reduce the net tensile stress acting and can improve part performance.

Problems:

1. Because of the wide variety of finishes desired, a number of processes can be considered. Of particular importance is the need to retain the necessary mechanical properties that were set by the heat treatment. Exposure to high elevated temperatures will overtemper the hook, making it prone to possible unwanted deformation. In addition, the need to maintain sharpness of the points and barbs significantly restricts the thickness of any applied coatings. The shape and the presence of the barbs may well make any mass treatment process rather difficult.

The ideal process would produce a durable, thin, uniform-color coating under low temperature conditions. Among the attractive possibilities are chemical conversion treatments, the various PVD methods, and blackening or coloring treatments.

2. This is a rather open-ended problem offering a wide variety of base materials, sizes,

shapes and requirements. It is designed to expose the student to the wide variety of surface treatment methods that are encountered in everyday products.

The extent to which the problem is treated can vary greatly. For example, part k) - the automobile muffler offers the option of having to integrate surface treatment and manufacturing process. For example, spot or seam welds are quite difficult if the sheet material has an existing galvanized (zinc) coating. Low-carbon sheet steel, however, can be readily seam welded. Therefore, if the sheet material is pre-galvanized, then assembly might utilize some form of mechanical (such as roll-lock) seam. If uncoated material is selected with the intent of subsequent coating, the student should realize that the presence of inlet and outlet tubes, and internal components or baffles, would preclude the possibility of approaches such as hot-dip galvanizing after assembly.

Case Study: “Burrs on Tonto’s Collar”

1). Here is a listing of deburring techniques commonly used in industry (as contributed by L.K. Gillespie and J.G. Bralla):

- Barrel tumbling. A large group of parts with burrs are placed in a rotating barrel with small pebble-like media, a fine abrasive powder, and water, and the barrel and its contents are slowly rotated until the burrs wear off, typically 4-12 hr.
- Centrifugal barrel tumbling, similar to barrel tumbling except that the barrel is placed at the end of a rotating arm. The addition of centrifugal force up to 25G to the weight of the parts in the barrel makes the process 25-50 times faster than conventional barrel tumbling.
- Spindle finishing, also similar to barrel tumbling except that the workpiece is fastened to the end of a rotating shaft and then placed in a barrel rotating in the opposite direction. The abrasive media gently wears off the burrs and produces a smooth radius on the edges. Although each part must be handled individually, deburring requires only 1-2 mm. per part.
- Vibratory deburring, also similar to barrel tumbling except that parts and media are vibrated rather than rotated.
- Abrasive-jet deburring. A high-velocity stream of small abrasive particles or miniature glass beads is sprayed at the burrs, and a combination of impact, abrasion, and peening actions breaks or wears away the burrs. Deburring takes from 30 sec to 5 mm, depending on workpiece size and complexity. This process is essentially a refined sand-blasting process.
- Water-jet deburring. A 0.25-mm-dia (0.010-in.-dia) jet of water at very high velocity cuts burrs and flash from the workpiece. In nonmetals, this process can deflash contours at a rate of 250 mm/s (600 ipm).
- Brush deburring. Motorized rotating brushes abrade burrs from parts at a rate from 10 sec to 5 mm per part. At least 50 different types of brushes are in common use.
- Sanding. Belt sanders deburr flat parts and disks, and flap wheels deburr contoured parts, at a rate of 600 stamped parts per hour. Although heavy burrs are

removed, the process itself often produces a very small burr.

- Mechanical deburring. A variety of specialized machines are equipped with chamfering tools, knives, or grinding wheels to mechanically remove cut burrs. Automotive gears, for example, can be deburred at a rate of 400 gears per hour.
- Abrasive-flow deburring. Hydraulic cylinders force an abrasive-laden putty-like material over burrs at a rate of 30 parts per hour. Deburring at up to 400 parts per hour is possible with automation. Some dimensional changes occur on surfaces contacting the putty-like material.
- Liquid-hone deburring. A 60-grit abrasive suspended in water is forced over burr-laden edges, removing very fine burrs in a 5-mm cycle and producing minimal edge radii.
- Chemical deburring. Buffered acids dissolve burrs from large groups of small parts in 5-30 mm, depending on the part. Because acids attack all surfaces, some dimensional changes of the entire part occur.
- Ultrasonic deburring. A combination of buffered acids and a fine abrasive media is ultrasonically agitated to wear and etch minute burrs, such as those produced in honing.
- Electropolish deburring. Reverse electroplating operation uses electrolysis in a mild acid solution to remove burrs from all surfaces, producing excellent surface finish.
- Electrochemical deburring, similar to electropolish deburring except that a salt solution and a shaped electrode are required. Stock is removed only at the edges, although some light etching occurs at other places on the part. Surface residues on the part have to be brushed or wiped off.

  Deburring typically requires 2 min per part, without automation.
- Thermal-energy deburring. A high-temperature wavefront -produced by igniting natural gas in a closed container -vaporizes burrs. The short-duration wavefront exposes components to only 95C (200F) while burrs are exposed to as much as 3300C (6000F). Up to 80 parts per hour can be deburred by this process.
- Manual deburring. Workers with special knives, files, scrapers, and other tools cut burrs from parts.

2). The screw machine operation has six steps:

I. Use form tool to turn the 12.7 mm diameter (The original diameter is 17.46 mm.)
II. Slot the end. (Rotation must be stopped to form the slot.)
III. Turn the 16 mm diameter. (The original diameter is 17.46 mm. This operation removes the slotting burrs.)
IV. Drill 6.4 mm hole. (This operation uses the part of the hole remaining from the previous part as a start.)
V. Thread the 12.7 mm diameter. (Use a thread-forming tool.)
VI. Cut off.
(Cut to the specified 12.7 mm length.)

Drilling and turning after slotting eliminates most of the burrs. This part takes about 20 seconds, so the machine can make 180 per hour. The total run takes about 138 hours or 17-18 days, assuming one 8-hour shift per day. The part would cost about 10 or 11 cents, exclusive of material to make on the screw machine.

3). The collars could also be made by powder metallurgy. It is likely that powder metallurgy would be somewhat cheaper for the quantity required, but much would depend on local conditions as to competition between suppliers.

The collars could also be made by on cold heading machines followed by thread rolling. Quantities may be a bit too small to justify the dies.

The collars could also be investment cast. The cost here would likely be higher than the other alternatives that can take advantage of the geometric symmetries.

The collars cannot be die cast because the melting temperature of the material (AISI 304 stainless steel) is too high.

CHAPTER 32

Review Questions

1. Table 32-1 shows human attributes replaced
A(0) - none
A(1) – energy – power other than human powers machine
A(2) – dexterity – machines manipulate material
A(3) – diligence – machine runs without attention, but not closed-loop
A(4) – judgement – closed-loop control in response to measurements

2.A(1) powered machines – power hand tools
A(2) machine runs itself over single cycle – cooking ovens, clothes and dish washing machines
A(3) automatic repeat of cycles – clocks repeat mechanical and electronic actions cyclically
A(4) closed-loop control – refrigerators, freezers, home furnaces acting on thermometer measurements

3. Windmills are A(4) self-adjusting machines since the direction is set into the wind in response to changing wind direction. Changes in wind direction act to produce changes in force on the windmill rudder and motion of the mill to a desired, defined direction.

4. Feedback control includes an active action in response to a change in system operation. So, the overflow plumbing in sinks is not a typical feedback control system since no active control action is taken to stop water flow – water flow is simply diverted not controlled. Modern temperature and pressure controlling shower valves do operate based on measured flow rate to control flow. The water level in toilets is measured with simple mechanical mechanisms and water flow is allowed to continue or stopped based on feedback information.

5. Line balancing refers to time balancing - making the time for each station in a transfer line as close to the same as possible. This requires the balancing of the specific operations that are done at each station so the machining time at each station is the same.

The operations shown in Figure 32-6 are five machining operations. If each operation requires the same amount of time, then all operations finish at the same time and indexing occurs. The next set of operations are carried out in the same time and indexing to the next operation occurs, etc. If individual operation times are not equal then the system must wait for the longest operation to be completed before indexing and the start of the next step.

6. The machining center can automatically change tools to permit operations and processes other than just milling to take place. Both machines can be numerically controlled. The machining center will often be able to change pallets automatically with one pallet being in the machine and the other pallet being outside the machine having a workpiece mounted on it. This reduces the machine down time by doing the setup

externally - the machine does not have to be stopped during setup, only during part exchange.

In 1958, Kearney and Trecker marketed a NC machine tool that could automatically change tools, thus making it a multiprocess machine tool and the first machining center.

7. Parsons conceived of the idea of a machine tool controlled by inputting numbers. He demonstrated his idea to the U.S. Air Force by having three men stand at the controls of a 3-axis milling machine with three more people calling out numbers to them simultaneously. The machine then produced a complex contour. The USAF gave Parson's company a grant to develop a NC machine. Parson subcontracted KIT and the rest is history.

8. DNC as first practiced means direct numerical control and described a system wherein numerical control machines where hardwired to a large digital computer. Programs were sent directly to the machine tool and paper tapes were not needed. Recently, DNC stands for distributed NC were programs are distributed to the on-board computers at the CNC machine tools. That is, the CNCs are networked to a large computer which provides enhanced memory and computational capacity.

9. An adaptive control system, A(S), must be able to evaluate the process, and modify the inputs in order to optimize the process in some way. In order to do this, the machine tool must have a computer, and that computer must have in it a mathematical model which describes "how the process works". The process is going to adapt itself to improve or optimize itself, or its cost, or some other feature. To be specific, the house thermostat controls the temperature in the house. To make this system A(S), it would have to adjust fuel and air mixtures to improve the heat yield and burn more efficiently. It may even be programmed to change from oil to gas, depending upon the cost of fuel, in order to optimize cost.

10. Feedforward is sensing something about the product on the input side of the process and altering the process to meet these changing input parameters. For example, in hot rolling, the temperature and size (thickness) of the plate entering the rolling stand influences the strength and needed opening between the rolls to accomplish the desired thickness on the output side.

11. The machine tool builders had to learn how to build more accurate and precise machine tools, removing friction and backlash from the mechanical drives, often through the implementation of ball lead screwdrivers. The machines also had to be made more rigid, so that elastic deflections were less of a problem. A good machinist could compensate for such problems on a regular machine tool.

12. Interpolation refers to the situation wherein paths not on the X-Y axes of movement of the table must be approximated with a series of connected short (X,Y) movements. The shorter the increment (the X or Y distance moved), the better will be the interpolation but the program will be longer.

13. Cutter offset refers to the condition where the path of tool centerline must be offset from the desired surface by half the diameter of the tool. This means that the geometry of the path will be different from that of the desired surface. In terms of Figure 32-A the cutter path when machining the bottom edge must be 0.75 in / 2 = 0.375 in away from the intended edge of the part, the tool path will be along the y = 1 in – 0.375 in = 0.625 in line. On the right edge the cutter must run along the x = 6 in + 0.375 I in = 6.375 in line to produce the desired part edge.

14. The operator performs part loading and unloading, inspection, deburring, part transportation, reorientation (turn part end for end), and process monitoring. Any function which requires thinking on the part of the operator will be difficult to automate. In addition to the above functions, the operator may perform setups, improve setups, control the process capability and maintain the machines. Therefore, he may be very multifunctional. The higher the level of function, the more difficult it will be to automate it.

15.Open-loop control means reliance on the machine to execute the commands precisely with no feedback information, e.g., no information as to actual position or velocity. In essence there must be no errors in the motions performed. This means more accurate, more precise machines and so removal of friction and backlash, stiffer drive components and structure. There is no provision in open-loop systems for adjustments either by the machinist as in use of manual machines or by the machine system as in closed-loop machines.

16. There is no reason why it cannot be open-loop. The problem is, however, in contouring, where one must control the velocities in the X and Y (and Z) simultaneously within a certain tolerance or variation. This is difficult to accomplish without feedback.

17.A shaper is not really a production-type machine and a broach is a straight-line cutting machine wherein the tool geometry dictates the geometry of the surface to be machined.

18. It takes too long to manually generate all the points needed to describe a contoured path, even in two dimensions. Suppose you have a one inch long curved path and the contouring requires a tolerance of 0.001 inches. This means you might have to generate 1000 sets of points to program the tool to travel one inch.

19. The feedback detection or sensor can be placed on the motor, on the ballscrew of the table or on the table itself. See Figure 32-9.

20. The machine tool has a point in space that is its zero point - where X,Y, and Z dimensions are zero. This point is fixed in the machine tool. The zero reference point is selected by the part programmer or machine tool operator as some point on the part from which all the part dimensions are made. See Figures 29-7 and 29-8 for examples.

21. An encoder is a feedback sensor (a device) which generates pulses as it rotates. The source of the pulses is often an interrupted light beam. See Figure 29-S and 29-10.

22. In continuous-path or contouring control, both velocity and position must be controlled at all times in order to keep the tool on the desired path. In three-dimensional contouring, the cutter is required to move in three directions simultaneously. That is, the movement is the resultant of X,Y, and Z components. The curved path is broken up into short straight segments or arcs.

23. Pecking is a software routine that is already programmed into the machine which permits the drill to be periodically raised out of the hole to clear the flutes of the drill or chips. See figure below.

24. Pocket milling is a form of contouring wherein a hole (usually square or rectangular) is milled into a solid block of metal. This is often done to reduce the weight of the finished product. The cutting tool first feeds down to the desired depth and then feeds in a contouring path to produce the pocket. End mills with spiral flutes are commonly used for pocket milling. See the following figure.

25. Recalling that process capability refers to the accuracy and precision of a process, suppose a part is being turned in a CNC machine. The probe can detect the current size of the part. The correct depth of cut necessary to bring the part to size can be calculated by the computer. This depth of cut will account for variations in tool size and tool wear and deflections in the machining system.

26. The preparatory or G functions (also called G words) precedes the dimension words and prepares the control system for the information that is to follow in the block of information. G codes range from GOO to G99.

27. Transfer lines rely on mechanical mechanisms to control and produce workpiece motion from one station to the next. Changing motions or speeds or reconfiguring the line requires changing the inherent characteristics of machines and structures. In flexible manufacturing systems changing system behavior and performance is produced by much simpler re-programming of more sophisticated devices, e.g., changing machine tool programs, rerouting AGV guides, re-programming robot and moving sections of conveyors.

28. Even if the basic structure of a transfer line is fixed - a given configuration of machines and the mechanisms used to transfer work between them – it is desirable to be able to change operating conditions of individual machines. Programmable machines and PLC’s provide a relatively easy means for controlling and changing the behavior of component machines in a transfer line. Not all transfer lines are necessarily the extreme lock-step, fixed time step stereotypes. Adjustments and changes can be made to individual stations and programmable machines and PLC’s are useful.

29. In finite element problem formulations a continuous field is modeled by a set of discrete elements. The behavior of each element is defined, elements combined to describe the entire domain of interest and the overall behavior calculated.

Finite element analysis in based on replacing the continuous description of a field, e.g., strain or temperature, with a local description for each of a number of elements making up the entire domain of interest. The specification of the behavior of the variable of interest in the individual elements and the continuity between elements is given in the "shape function." The use of discrete elements and an algebraic shape function results in a system of algebraic equations describing the field rather than a differential equation as in continuum models. The solution of the usually large system of algebraic equations is simpler than the solution of a complicated differential equation that results for complex geometry, material behavior, loading and boundary conditions.

30. The two types of computer-aided process planning are variant CAPP and generated CAPP. The difference between them is that
- in variant process planning the plan is developed from an existing plan for a similar part while
- in generated, or generative, process planning a new plan is developed based on part geometric characteristics, design rules and logic and process characteristics and capabilities.

31. Computer graphics can be used to verify the NC program. In addition, a sample part machined out of plastic or machinable wax can be used to check actual dimensions, although cutting forces and therefore defections may be different when cutting metals than when cutting plastics.

32. Robots are used in materials processing (mainly welding, painting, and machining like drilling and boring) and materials handling (load/unload castings, forgings, and plastic processing machines and machine tools for metal cutting in cells). Robots, as they become more precise with long term repeatability, are being used in electronic and mechanical assembly. Very shortly, we will be seeing dedicated robots attached to machine tools for the purpose of changing tools as well as loading and unloading functions.

33. The typical industrial robot has a manipulator arm, a hand, a power source, and a control system. Depending upon the level of the robot, it will have feedback devices in the various joints, in the manipulator arm and hand, and perhaps sensors for tactile or visual sensory systems.

34. Spherical, rectangular, cylindrical, and jointed-arm are common work envelopes.

35. Positional feedback can be obtained by resolvers or stepper motors or other feedback devices in the joints of the robot arm. Proximity sensors are being developed as well to give positional feedback to the controller. Robots with visual sensors are being introduced into industry in a limited fashion. Many of these systems use vision systems for finding the position or orientation of workpieces so that the robot knows where to go to fetch the part.

36. The rotary transfer device not only moves the part from machine to machine, but also

serves as the workholder. The robot does not serve as the workholder, only a material handler doing load/transport/unload functions. The rotary transfer machine is setup to run one part in large volume. The unmanned cell is designed to handle a family of parts in very small lots. The machines in the cell are computer NC while the machines in the transfer machine or automatic repeat cycle with no feedback - fixed or hard automation or programmable NC machines.

37. The human worker can think, has superior vision and tactile feel, and in addition can walk. The human can also detect odors and hear funny sounds coming from the machines. Compared to humans, robots are quite handicapped but are superior in their ability to work in hazardous or dangerous or nasty environments and are very repeatable, having less cycle time variability when the cycles are long.

38. Tactile sensing is giving machines the sense of feel. No examples readily come to mind.

39. Most robots in automobile body assembly lines are doing spot welding. Some are doing arc welding, other painting. These operations entail moving through well-defined, relatively simple paths. Production of these kinds of motions with robots is easy, inexpensive and replaces people in repetitious tasks in unpleasant environments.

40. Ultra high-speed machining centers have to produce high spindle speed, high feed rates and high rapid travel moves between cutting passes. This leads to the following requirements and the continued development of
- high speed, high stiffness spindles,
- high speed, high performance (acceleration, deceleration) drives,
- high performance controller (high bandwidth),
- high stiffness machine structures.

Problems:

1. The X and Y locations / dimensions for hole #2 are +6.7118 and +8.6563.
The X and Y dimensions / locations for hole #3 are +7.9445 and +4.0555

2. 2π r = 3600 = 2π 5 in = 31.42 inch
$\cos(\theta/2) = (5 - T) / 5 = (5-0.001) / 5 = 4.999 / 5$
where θ = the span angle

Therefore, $\theta/2 = 1.1459^o$ and $\theta = 2.292^o$
AB = (31.42) (2.292) / 360 = 0.2 inches

3. $\text{Cos}(\theta/2) = (5 - T) / 5 = (5 - 0.0001) / 5 = 0.99998$
$\theta/2 = 0.36^o$;
$\theta = 0.7247^o$
AB = (31.42) (0.7247) / 360 = 0.060 in

4.

PT	X	Y
1	0	-0.5
2	12.5	-0.5
3	12.5	12.5
4	-0.5	12.5
5	-0.5	-0.5
6	0	-0.5

5.

PT	X	Y
1	0	-0.5
5	-0.5	-0.5
4	-0.5	12.5
3	12.5	12.5
2	12.5	-0.5
1	0	-0.5

6. From the drawing:
- the center of the bolt hole circle is at X = 12 in, Y = 10 in, the radius of the bolt hole circle is 6 in and the angle between holes is 45^o.

The X and Y directions the distances, d, of the center of hole 6 from the center of the bolt hole circle are

in the X direction, $d_x = -(6\text{ in})\sin45^o = -4.243$ in
in the Y direction, $d_y = -(6\text{ in})\cos45^o = -4.243$ in

And hole 6 center position with respect to the Zero Reference is

X = 12 in – 4.243 in = 7.757 in
Y = 10 in – 4.243 in = 5.757 in

Interpreting the English Program

```
INDEX/GO TO/ 18, 10, 1, 40
```

go to position x = 18 in, y = 10 in z = 1 in with respect to zero ref. i.e., center position of first hole

then instructions for drill in a hole and to copy the hole every 45^o for seven holes

```
GO DELTA/MINUS 1, 12
GO DELTA/ 1, 12
COPY/ 1 XY ROT, 45, 7
```

7.

	2^7	2^6	2^5	2^4	2^3	2^2	2^1	2^0
	128	64	32	16	8	4	2	1
Given binary number	1	0	1	1	0	1	1	0
	1x128	0x64	1x32	1x16	0x8	1x4	1x2	0x1
	128	0	32	16	0	4	2	0
SUM	182							

8. [NOTE: This case study was developed from real factory data for a real part. Therefore the findings represent the real situation in the job shop where the machines are often employed. In this environment, you assume that each machine has one operator doing the job.]

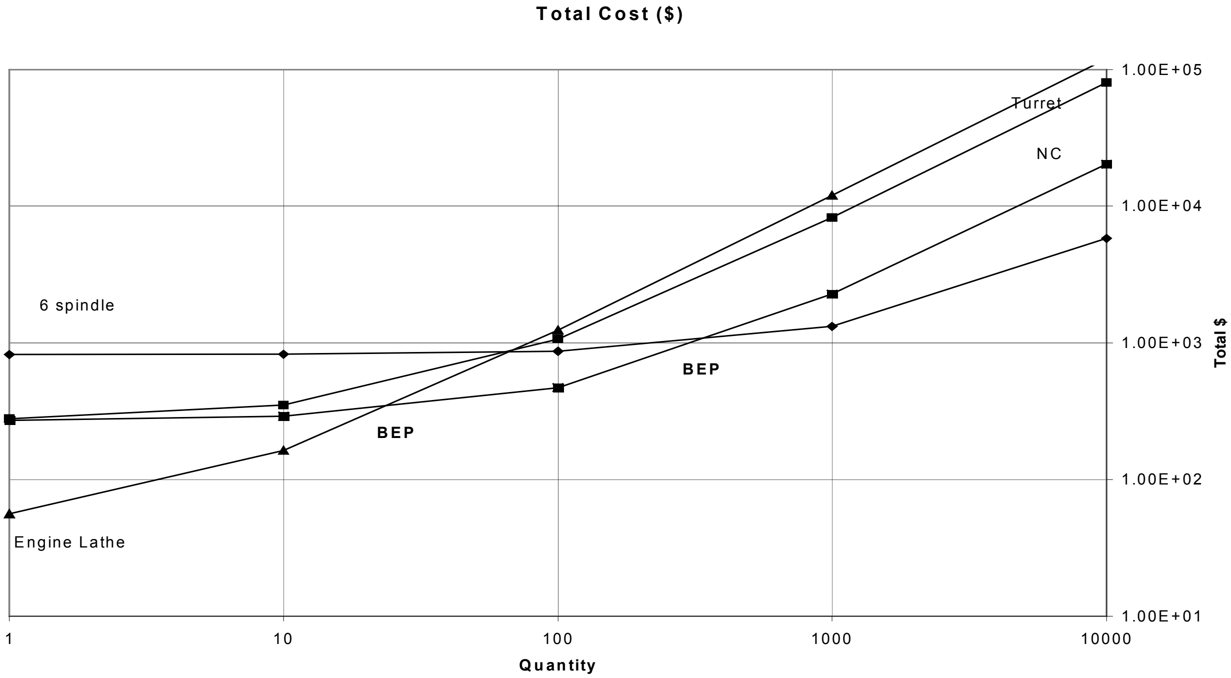
1. The fixed costs, which do not change with make quantity, are: engineering, tooling and setup. The variable costs are the run cost and the material cost (which was not listed).

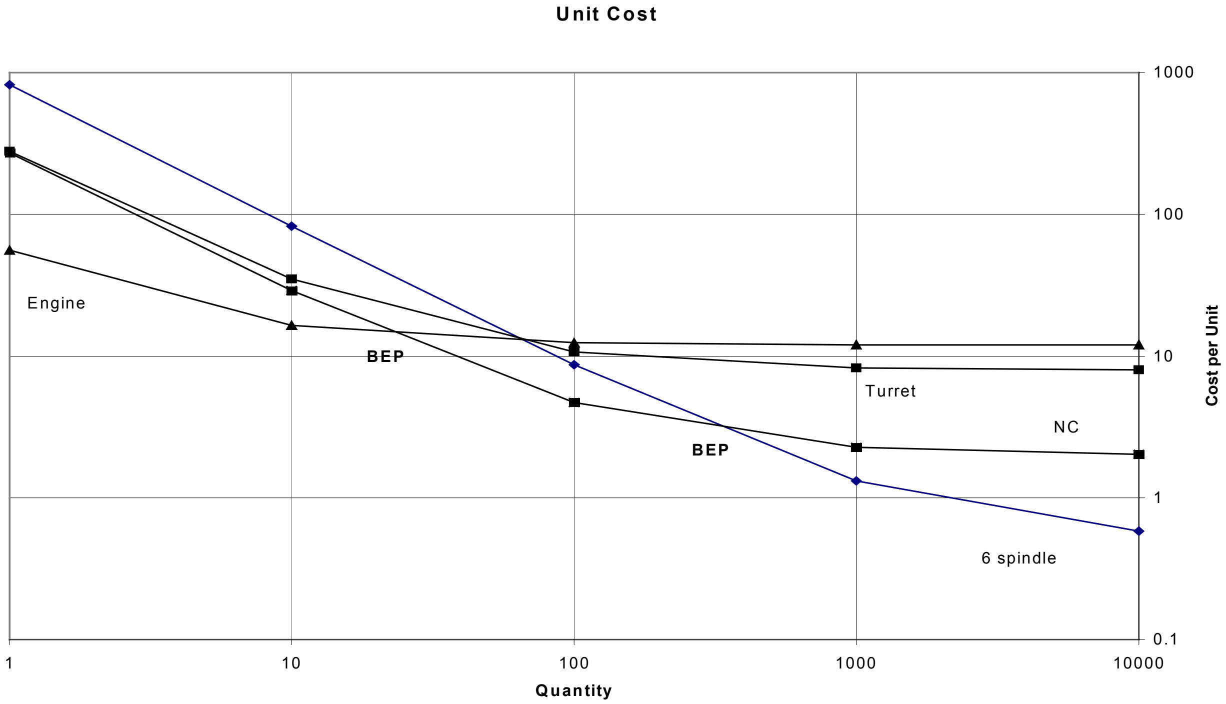
2. In order to find the run cost, one has to compute the CT from the equations found in the chapter and then add to that the time needed for part loading/unloading, tool changing and adjusting, inspection, and so forth during each cycle. See references on cost estimating.

3. The nonmachining portions can be estimated from other similar jobs done on these machines, or one can use techniques like MTM. One cannot use time study, since these jobs are not yet setup and running.

4. This time estimate is multiplied by the labor cost per hour, which can include a factor for factory overhead.

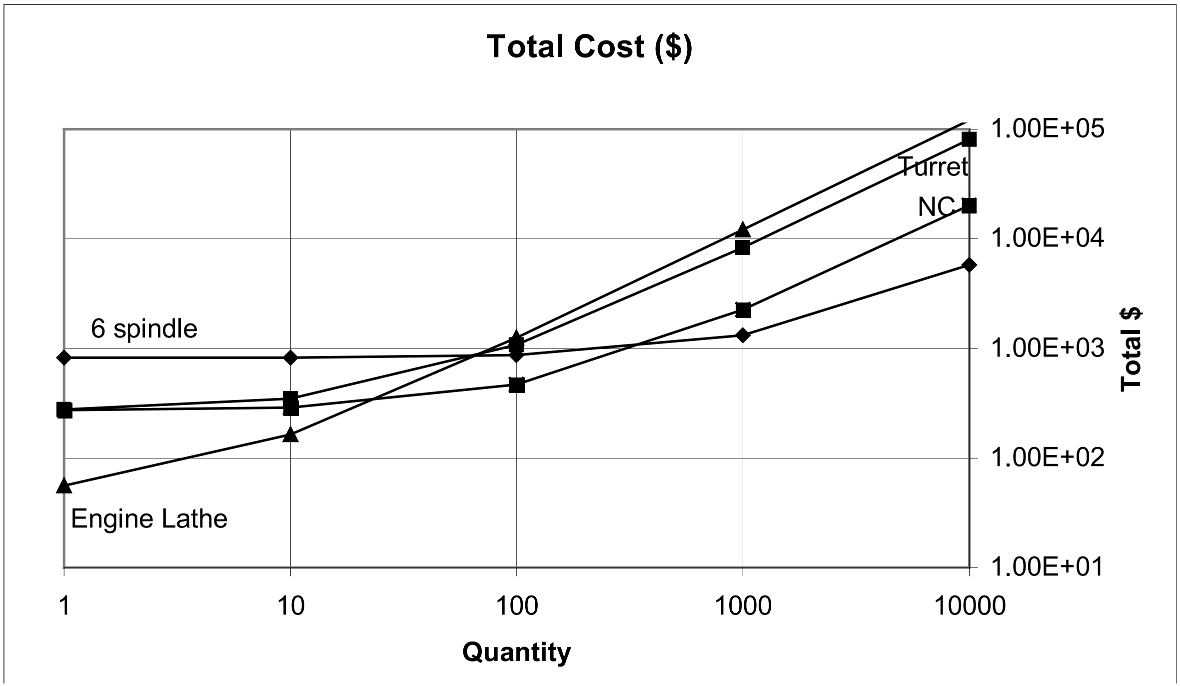
5 and 6. These are the plots shown below followed by the worksheets.


Total Cost ($)
Turret
NC
6 spindle
BEP
BEP
Engine Lathe
1.00E+05
1.00E+04
1.00E+03
1.00E+02
1.00E+01
Total $
1
10
100
1000
10000
Quantity


Unit Cost
Engine
BEP
Turret
NC
BEP
6 spindle
1000
100
10
1
0.1
Cost per Unit
1
10
100
1000
10000
Quantity

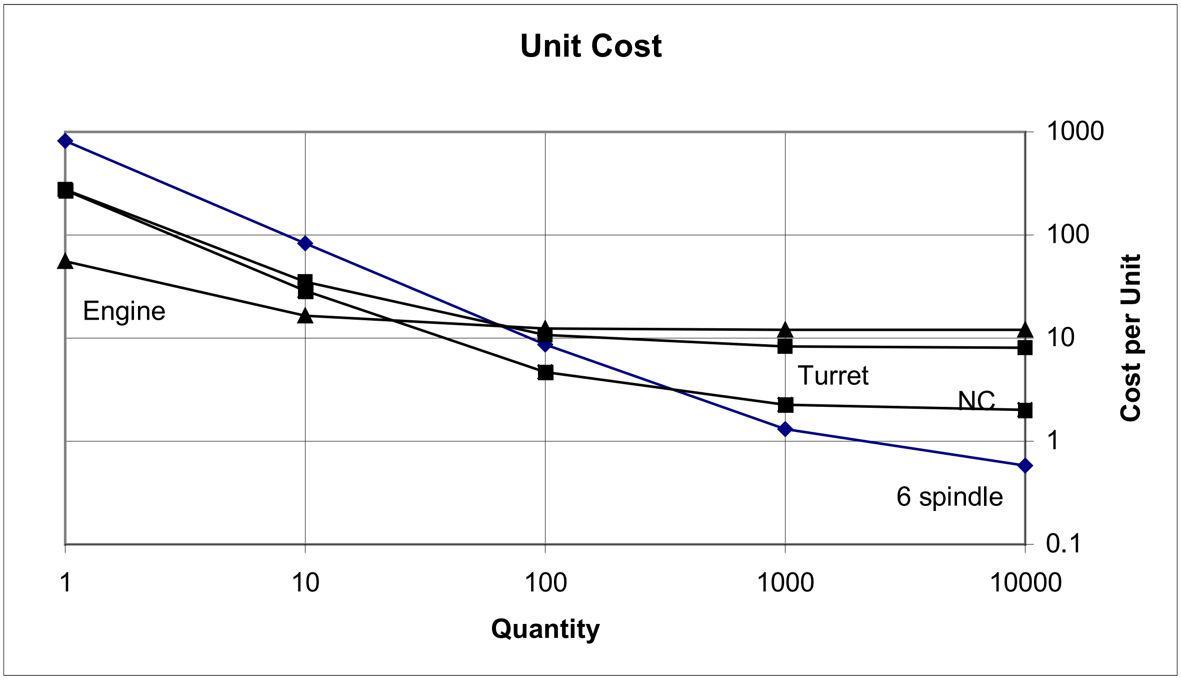
Prob. 32-8

				10000	1000	100	10	1
6-Spindle	Time (hr)	Rate ($/hr)	Run ($/piece)					
Total Cost				5820	1320	870	825	820.5
Engineering	2.5	40		100	100	100	100	100
Tooling				600	600	600	600	600
Setup Cost	8	15		120	120	120	120	120
Run Cost			0.5	5000	500	50	5	0.5
Cost each				0.582	1.32	8.7	82.5	820.5
Turret Lathe								
Total Cost				80270	8270	1070	350	278
Engineering	2	20		40	40	40	40	40
Tooling				150	150	150	150	150
Setup Cost	4	20		80	80	80	80	80
Run Cost			8	80000	8000	800	80	8
Cost each				8.027	8.27	10.7	35	278
EngineLathe								
Total Cost				120044	12044	1244	164	56
Engineering	1	20		20	20	20	20	20
Tooling				0	0	0	0	0
Setup Cost	2	12		24	24	24	24	24
Run Cost			12	120000	12000	1200	120	12
Cost each				12.0044	12.044	12.44	16.4	56
NC Lathe								
Total Cost				20270	2270	470	290	272
Engineering				150	150	150	150	150
Tooling				100	100	100	100	100
Setup Cost	1	20		20	20	20	20	20
Run Cost			2	20000	2000	200	20	2
Cost each				2.027	2.27	4.7	29	272



Prob. 32-8

				10000	1000	100	10	1
6-Spindle	Time (hr)	Rate ($/hr)	Run ($/piece)					
Total Cost				5820	1320	870	825	820.5
Engineering	2.5	40		100	100	100	100	100
Tooling				600	600	600	600	600
Setup Cost	8	15		120	120	120	120	120
Run Cost			0.5	5000	500	50	5	0.5
Cost each				0.582	1.32	8.7	82.5	820.5
Turret Lathe								
Total Cost				80270	8270	1070	350	278
Engineering	2	20		40	40	40	40	40
Tooling				150	150	150	150	150
Setup Cost	4	20		80	80	80	80	80
Run Cost			8	80000	8000	800	80	8
Cost each				8.027	8.27	10.7	35	278
EngineLathe								
Total Cost				120044	12044	1244	164	56
Engineering	1	20		20	20	20	20	20
Tooling				0	0	0	0	0
Setup Cost	2	12		24	24	24	24	24
Run Cost			12	120000	12000	1200	120	12
Cost each				12.0044	12.044	12.44	16.4	56
NC Lathe								
Total Cost				20270	2270	470	290	272
Engineering				150	150	150	150	150
Tooling				100	100	100	100	100
Setup Cost	1	20		20	20	20	20	20
Run Cost			2	20000	2000	200	20	2
Cost each				2.027	2.27	4.7	29	272



7. The breakeven quantities are shown on the plots. The engine lathe performs best for quantities of about 1 -> 35, the NC lathe for 35 -> 350 and the 6 Spindle Automatic for quantities larger than about 359. The turret lathe is never an economical alternative, being technologically replaced by the NC lathe. We observe that the turret lathe had a very narrow region over which it was economical if one ignored the NC lathe curve. In addition, we observe that none of these processes display an economic minimum, but rather there are regions in which one process is economically preferred. As the build quantities increase and the processes become more automated, the cost per unit continues to decrease, approaching the variable cost per unit as a limit.

8. The turret lathe is never an option. However, if the NC lathe is removed from the solution, the turret lathe has breakeven quantities at about 50 units and 75 units (a very narrow range). Turret lathes are being used far less in production operations due to the greater flexibility, capability, and productivity of numerical control lathes.

9.Use 0.500 in end cutting end mill to cut keyway and to drill (plunge cut) holes
Spindle speed in rpm, feed rate in in/min

N01	GO G17 X1.00 Y3.00	rapid traverse, in x-y plane to x = 1.000, y = 3.000, point 1
N02	G20 Z-0.75 F2.87 S573 M3	move along z axis to location z = -0.750 spindle speed = 573 rpm start spindle (drill hole from initial z to final z gives hole depth, from z=0.25 -> z=-0.75, hole depth 0.5 in)
N03	G20 20.00	move along z axis to retract drill retract position z=20.000
N04	G0 G17 x-0.50 T2.00	rapid traverse in x-y plane to x = -0.500, y=2.000 above work surface location for start of keyway point 2
N05	G20 Z-0.50	move along z axis to z=-0.5 setting keyway depth (z=0.25 -> z=-0.5 keyway depth = 0.25 in)
N06	G17 X5.25 F2.67 S383	move in x-y plane to x=5.25 at feed rate = 2.67 in/min spindle speed = 382 rpm milling of keyway to point 3 at bottom of keyway
N07	G20 20.00	move along z axis to above work surface to z=20.000
N08	G0 G17 x3.00 Y1.00	rapid traverse in x-y plane to x=3, y=1, point 4
N09	G20 Z-0.75 F2.87 S573	move along z axis to z=-0.75 at feed rate = 2.87 in/min, spindle speed = 587 rpm (drill hole from z=0.25 -> z=-0.75)
N10	G20 20.00	move along z axis - retract
N11	M5	stop the spindle
N12	M2	end of program

c. Holes are 0.500 inch deep – see line No2 in table

Case Study: “Steam Line Holes”

1. The holes (cuts or slits) in the outer casing occurred where the edges of the U-shaped supporting legs contacted the casing. Essentially the entire weight of the outer casing rested on the upper vertical leg during transportation. During operation, the weight of the inner line and the steam will rest on the two lower legs.

2. A design error as explained below.

3. The designer of this line was not sufficiently familiar with cold forming operations to realize that when flat bar stock is bent to form the U-shaped support legs, a sharp corner will be produced on each outer corner of the bent pieces due to the stretching-contraction of the bars about the center line. This will create a line contact where the legs contact the outer casing, and the weight of the casing will be great enough to cause the load per unit area to exceed the strength of the casing wall in these regions. This was a design error. (The designer never went out to look at the line being fabricated or he might have caught this condition at the plant.)

4. Two design modifications are suggested. Grind off the sharp corners of the legs and shape the contour of the leg to conform to the interior curvature of the outer casing. This will reduce the unit loads to an acceptable level. The second design modification might be to eliminate the legs altogether and let the steam line simply lie on the bottom of the return line with a layer of appropriate insulation material placed between the two. This eliminates the legs and their fabrication and installation altogether.

5. The line must be totally disassembled and these modifications made even though no damage was visible or detectable. An entire new outer casing should be obtained since it appears that the damage was caused during shipping, not installation. Once operational, however, similar damage to the outer casing will be produced by the bottom legs, unless modifications are made.

CHAPTER 33

Review Questions

1.A prototype is the first physical model of a part or product.

2.The prototype can be used to verify the form, fit and function of part. Adding importance to prototyping is that the prototype is the first physical realization of the part and so is important for product and manufacturing process development.

3. Prototyping is expensive because only a small number of parts are made leading to high cost per part. Also, the total cost is high because usually specialized tooling and equipment are used to produce the prototype, possibly by highly skilled personnel. And, since the prototype is important many aspects of manufacturing personnel from many manufacturing functions will be involved in evaluating the prototype.

4. Rapid prototyping is used in software development and in printer circuit board and microelectronic product and process development.

5. *i*. Desktop Manufacturing: many rapid prototyping machine are about of desktop size, at least in terms of the machine footprint.
ii. 3D Printing: Inkjet printers build essentially 2-d structures using a buildup of ink spots. Some rapid prototyping techniques build 3d structures by the buildup of 3d particles of material analogous to the ink spots.
iii. Freeform Fabrication: Since structures can be built up of particles (for example, 3D printing) or streams of material that hold their shape and quickly solidify, there is no mold needed to contain the material. During part production there is a free surface(s), no container, and the ability to direct the material and so “freeform” fabrication.
iv. Layered Manufacturing: Layers of the final part can be built up by depositing particles or streams, parts can be made from a set of layers, e.g., similar to gaskets with slightly different shape for each layer and a number of layers forming a prototype part.
v. Tool-less Manufacturing: If particles are used to buildup a prototype as in freeform fabrication described in part iii there is no typical or traditional tool in the process.

6.*i*. Preprocessing to convert the part design into a sequence of tool paths.
ii. The fabrication of the part
iii. Postprocessing possibly involving curing, cleaning the part, surface finishing, etc.

7. Freeform fabrication processes are additive in the sense that the part is built up by continually adding material to the forming part until it is complete

8. Concepts modelers produce parts for verification of general concepts such as form, shape appearance and fit into final products. The parts are less durable than parts produced on functional modelers that are more robust and are intended for some level of use such as measurement, testing and perhaps short term use of the part.

9. The four basic groups of freeform processes are
i. Photopolymer-based processes in which material addition is by light curing of selected regions of a polymer bath.
ii. Deposition-based in which material is directly deposited onto the forming part.
iii. Powder-bonding using various kinds of bonding mechanisms to form layers or three-dimensional shapes by selective bonding of powder particles.
iv. Lamination-based processes in which layers of material are bonded together, in contrast to some photopolymer-based process in which the individual layers are form sequentially.

10. In turning, a part is produced by material removal using relatively strong, rigid work and tool materials. In freeform fabrication processes the tool is usually less well-defined and controlled, part production is by the addition of small amounts of material per time and the work material is soft and even fluid in some cases. This results in parts produced in freeform fabrication processes having poorer accuracy, rougher surfaces and larger tolerances than turned parts. In addition production times are longer for freeform fabrication and the work materials that can be used are much more limited.

11. Tessellation refers to a simple shape such as a triangle used to numerically model a surface, and it also can mean the process of using the discrete surface elements to model a continuous surface.

12. Preprocessing involves creating a manufacturing part model from the design model, converting the part shape into a sequence of tool paths and generating machine tool code from the tool path information.

Postprocessing has to do with the part itself rather than preparing input data to fabricate the part. Postprocessing may involve curing, cleaning and surface finishing.

13. The three components of freeform fabrication build time are preprocessing time, fabrication time and postprocessing time. Fabrication time is the longest (50% - 90% of total time) since for most processes material addition rates are low. While not always the case, in many operations small increments of material are added in a sequential manner leading to long build times. In contrast, if all parts of the work are processed at one time, parallel processing, high part production rates can be obtained, e.g., conventional casting solidification and sintering and solid ground curing rapid prototyping.

14. A voxel is a volume element. Voxels are significant in freeform fabrication processes since many of the processes can be modeled using the concept of adding voxels to the emerging part. Part build rate is then related to voxel deposition rate and voxel size. Part surface geometry is determined by voxel shape and size. Voxel size and shape depend on the process parameters - operating conditions.

15. In freeform fabrication material is added sequentially to the emerging part. As layers are built up a stair-step surface is created and this stair-stepping is the dominant surface effect in freeform fabrication. Stair-stepping can be minimized by orienting the part so that adjacent layers match better, meaning that the part orientation might have to be

continually changed during production requiring sophisticated machines and controls. Decreasing added layer thickness will decrease step height, but at the cost of added production time.

16. Random noise shrinkage is the non-deterministic part of the shrinkage that occurs on solidification. Random noise shrinkage is due to random variability in phase change shrinkage.

Random noise shrinkage is a factor in determining prototype dimensions for two reasons. First, shrinkage occurs and so part dimensions change and the change in dimensions depends on the amount of shrinkage. Second, and an important implication, is that since random noise shrinkage is non-deterministic the amount of shrinkage cannot be predicted and so cannot be compensated for by process and prototype part design.

17. Starting with the belief that a known amount of shrinkage can be compensated for and so does not influence final part accuracy, only the random noise shrinkage determines prototype dimensional accuracy. However, equation (33-1) states that the degree of random noise shrinkage is linearly proportional to mean process shrinkage so the material with the largest shrinkage will present the most problems with random noise shrinkage. The material with the largest volumetric shrinkage in Table 33-2 is B F Goodrich / Laserite, LN-4000.

18. In addition to random noise shrinkage, the dimensional accuracy available in freeform fabrication processes depends on shrinkage anisotropy, temperature gradients and the resulting residual stresses and warping, and shrinkage variations over the part due to constraints imposed by part shape (variations in amount of shrinkage in different part sections that have different thicknesses for example).

19. In stereolithography patterning is accomplished by scanning a laser over a phtotocuring polymer so that the polymer solidifies along the laser path. Layering is accomplished by raising the liquid polymer level to above the previously formed solid layer and then patterning the liquid layer to produce the next solid layer.

20. In postprocessing of stereolithography parts the excess, non-polymerized material is cleaned off the part and then the part is post or final cured to assure complete polymerization.

21. Stereolithography layering processes are descending platform, ascending suspension, ascending surface and masked-lamp descending platform.

22. In stereolithography first the boundary the layer is exposed and so cured. This setting of the layer boundary is followed by hatching in which in which the remained of the layer is exposed and solidified.

23. In photopolymerization processes the idealized parallelepiped voxel will not be formed because

- laser beam intensity varies over the beam diameter so there is no sharp laser beam edge to form a sharp edge on the voxel,
- the absorption of laser energy in the polymerizing material decreases with depth into the polymer voxel and so the solidification process varies with depth.

24. If power is decreased less energy is available for curing and so the line of voxels will be thinner and less deep. If scanning speed is increased the energy input per time to any voxel is less and so the voxel (line) will be less wide and less high.

25. The advantages of stereolithograhphy processes include high, repeatable dimensional accuracy (0.03% over 60 mm) and good surface finish (below 16 μm). Disadvantages include the need for expensive, sometimes toxic or irritating, polymers, the need for supports which leads to more complicated part designs, more involved preprocessing and the need to remove supports from the finished part and the need for post or final curing of the part.

26. In solid ground curing the pattern of a photopolymer layer is produced by exposing the polymer through a photomask. The photomasks are used for individual layers then cleaned and re-made with a different pattern to be used in making another layer. Layering is composed of a number of steps. For each layer, unexposed resin is removed, liquid wax is applied to fills voids in the layer and then the layer is milled to final thickness. Another layer is then built onto the structure.

27. In photopolymerization certain parts of the entire polymer bath are polymerized and layers are formed. This leads to three general types of postprocessing operations; cleaning to remove excess polymer, surface finishing to remove unacceptable stair-stepping and final curing to improve part strength through complete polymerization.

28. Lamp photopolymerization can produce dimensionally accurate prototypes and relatively smooth surfaces if layer thickness is small. Complex parts can be produced with supports, e.g. pre-assembled structures.

The disadvantages include small material addition rates and so long build times, the need for specialized materials and usually postprocessing to produce acceptable surface quality. If large parts are required the machine can be very large and this is a move away from the ideal of having to invest little time and expense in making prototypes.

29. Solid ground curing does not require supports for the part being built up. This means more of the working area is available for producing parts.

30. In fused deposition model creation an extrusion head is robotically guided and the extruded material forms a layer pattern. Another layer is extruded onto the previous layer to build up the part.

31. Extruded deposition prototypes do not have smooth surfaces but are usually not postprocessed. Deposition conditions are usually set so that an acceptable, even if relatively rough, surface is produced.

32. Extruded deposition processes use much conventional technology (robots and thermoplastics) and so machines are inexpensive, do not require any special shielding and venting and operator skill is minimal.

Materials used have to be easy to extrude and so the limited number of useful materials is a disadvantage. The material used is in filament form and so more costly than might be expected when quoting typical thermoplastic resin cost. The process is slow and rough surfaces are produced.

33. In inkjet deposition the layer pattern is formed by scanning an inkjet printing head over a surface or support. The small droplets coalesce to form a layer. Layers are produced by additional scans over the emerging part and supporting structure.

34. Depending on prototype requirements, inkjet deposition can produce parts that require no postprocessing. If high surface quality, high accuracy, relatively strong parts are required each layer is treated to fill voids and/or milled before the next layer is laid down.

35. The major advantages of the inkjet deposition process arise due to the small drop size and droplet spacing available. High dimensional accuracy and the ability to produce small structures are results.

With the small droplet size the disadvantage of very long build time is typical of inkjet deposition. Materials that can be used are limited.

36. In selective laser sintering the pattern of each layer is produced by scanning a laser over a powder layer. Layering is accomplished by adding another layer of powder to the layer previous sintered, leveling the powder layer and scanning the laser over this next layer.

37. Scanned laser fusion and sintering produces parts with surface roughness typical of bonding powder particles together. Postprocessing involves cleaning the part and, depending on intended use, perhaps surface finishing by processes such as sanding.

38. Scanned laser fusion and sintering is complicated but high strength materials can be processed and so high strength, directly useable products can be produced, e.g., injection molding molds and die casting dies.

The sintering of powder particles leads to rough surfaces and voids and these can be major disadvantages. Since relatively high temperatures compared to other prototyping processes are needed for sintering, high power lasers and perhaps preheating of the powder are needed and these are disadvantages. The need to heat the powder to sintering temperature leads to slow scan rates and long build times. High temperature is also conducive to oxidation and material contamination and so neutral atmosphere may be required. Shrinkage can lead to poor dimensional accuracy. As in other layering processes, stair-stepping can be a problem depending on the surface smoothness required. Often a final densification heat treatment is needed.

39. Fusing of powder particles involves melting of at least part of the powder and re-solidification. Sintering is carried out below the material melting temperature. Particles bond due to atomic diffusion and viscous flow under pressure.

40. In scanned laser fusion and sintering of amorphous thermoplastics the particle surfaces soften and bond forming a solid structure possessing substantial porosity. In crystalline polymers (parts of the polymer having a well ordered or crystalline structure) melting and bonding of particles occurs. In scanned laser fusion and sintering of metal and ceramics the powder is coated with a binder material which acts to bond particles together when first exposed to the patterning laser. The green structure produced is further processed in final sintering and densification, to form the final strong, dense part.

41. In selective inkjet binding (three-dimensional printing) the pattern of the layer to be produced is formed by injection of a binder between powder particles by a scanning head moving over the powder surface. The injected binder bonds powder particles together and the bonded powder pattern and any unbonded powder serves as the surface for the next scan that produces the next layer of the emerging part.

42. Postprocessing operations are different for selective inkjet binding depending on the material used. Ceramics and metals can be sintered to achieve full strength. Further processing can include infiltration of relatively lower melting temperature metals in to the sintered part to increase density.

43. The initial, green part produced in selective inkjet binding is made from a powder and a binder and is formed at low temperature. This leads to the advantages of being able to process a variety of materials using a variety of binders. The result is the possibility of making high strength parts and using the binder as a component that stays in the part.

The disadvantages of selective inkjet binding are associated with the number of operations needed to produce the desirable part properties. The green part has to be produced and then heat treated and infiltrated to achieve high strength and high density.

44. The individual laminations are cut (usually by laser) in desired patterns from a solid sheet. Layering is by stacking and bonding the individual laminations, usually sequentially immediately after the laminations are produced.

45. Post processing of prototypes from lamination based freeform fabrication processes includes edge finishing and perhaps sealing of hygroscopic materials

46. Lamination-based processes offer the advantages of using easy to cut material (although this limits material selection), no need for complicated support structures and relatively simple machines. The laminates are not severely deformed as they are produced and so warping and residual stress in not a large problem in the assembled parts. Since large laminations can be produced easily, large parts can be produced.

The laminations are produced by material removal – cutting – and so as in all material removal processes material that cannot be used, and must be disposed of, is produced.

Only small batches of parts can be produced so build time is long. Build time is also increased if only thin laminations can be produced and used to build up the entire part.

47. Rapid tooling is immediately usable tooling that can be produced quickly and inexpensively. Tooling is often complex in shape. Since freeform fabrication processes can produce complex shapes in a large variety of materials they form a set of attractive processes for tooling production. This is especially true for tooling that does not have to be extremely hard and strong.

48. Rapid tooling can extend from soft tooling to prototype tooling to production tooling. Soft tooling is used for producing small quantities of parts from easy to work materials, for example molds for casting reacting or low temperature curing polymers. Prototype tooling is destined for the production of small numbers of parts. The parts may be prototypes of real products and so made from more difficult to work materials. Production tooling is used to produce high volumes of high quality parts and so the more complicated freeform fabrication processes such as those involving sintering will probably be used for making production tooling.

49. Engineering tooling assemblies, ETA, are assemblies in which the shaped surface of the tooling is not built into a large block. In contrast to forging dies for example in which the die cavity is sculpted from a die block, in a tooling assembly the contoured surface is formed as a thin shell and is supported by a backing material in a frame to produce the entire tooling assembly. ETA's are significant for several reasons. The contoured shell can be made using freeform fabrication processes that are inexpensive and fast. The backing material and frame are not expected to be expensive compared to standard tooling materials. It may be possible to construct a set of modular tooling with only the shaped part of the ETA produced for different parts.

50.Freeform fabrication can be used for making conceptual prototypes to demonstrate ideas, for functional prototypes that can be used for dimensional and performance evaluation and for the production of real products, e.g., hard tooling such as injection molding molds.

Problems: no problems

Case Study: Flywheel for a High-Speed Computer Printer

NOTE: This part is somewhat unique in the relative absence of mechanical requirements (strength, ductility, fracture resistance, etc.) and the need to concentrate high mass in a small part (i.e. the desire to use a heavy material).

1. While a prototype does not have to serve all the functions required of the production part, the important aspects of function should be reproduced in the prototype. The weight of the part is a major requirement and so is should be included in the prototype. This

removes polymers from consideration and focuses attention on the metallic powder-based rapid prototyping techniques. Selective laser sintering with its ability to use metals and to infiltrate parts to achieve high density is the choice.

2. The above requirements, coupled with the need for high dimensional precision tend to restrict the possibilities. Since all axial surfaces are parallel, and the presence of gear teeth and a non-circular section add complexity in this plane, powder metallurgy seems extremely attractive. The thickness of the part is rather high for powder metallurgy, but the mechanical properties are sufficiently low that the absence of high-density pressing should not be a major limitation. The processing of ferrous materials has become routine for powder metallurgy, and heavier copper-based alloys could be used if even greater mass is desired within a given shape. Machining from bar stock would be another alternative, especially in view of the specified precision. Casting processes could be considered, but those that are compatible with ferrous materials would likely require secondary processing to attain the desired dimensional precision.

Since the mechanical properties are largely unspecified, powder metallurgy part and process design is free to select a material based on minimization of expense and ease of fabrication. An unalloyed iron powder, possibly an iron-carbon to utilize the benefits of the graphite as a lubricant, would seem attractive. Another alternative might be the iron-copper powders, since copper additions enhance P/M fabrication and the copper will actually add additional mass, possibly off-setting the presence of voids within the P/M product. Fabrication by machining would probably utilize some form of free-machining steel bar. Casting processes would best utilize one of the more fracture-resistant cast irons, since the part is a spinning flywheel, and the brittleness of the cheapest gray cast iron may be a detriment.

The "best" alternative here appears to be powder metallurgy because of the suitability of the size and shape, the low or absent mechanical properties, the desirability of ferrous material, and the minimization of scrap and labor (compared to machining). Fabrication would be by the conventional press-and-sinter method.

Consideration might be given to the need for enhanced corrosion or wear resistance. The part contains numerous small gear-type teeth -- might they experience wear? If ferrous material is used, is corrosion a possibility? If either of these become a concern, surface modification, such as the popular steam treatment of ferrous powder metallurgy products might be considered. Such a treatment would enhance surface properties without significantly altering the surface dimensions or finish.

CHAPTER 34

Review Questions

1. Electronics is primarily concerned with producing desired functions through production and manipulation of electrical signals by controlling the flow of electrons.

2.Integrated circuits have all the electrical components and interconnections on a single piece of material. This provides the advantages of a single structure and low cost per functional element since the cost of producing larger integrated circuits does not rise rapidly with the number of elements produced.

Electronic assemblies are combinations of electrical devices, including integrated circuits. Electronic assemblies can have greater flexibility in that elements can be combined to produce more and different functions or applications.

The less complex and less flexible (although still able to perform a variety of tasks) integrated circuits are less expensive that the more expensive, but more flexible assemblies.

3. The three levels of electronic manufacturing are;
i. integrated circuit manufacturing,
ii. integrated chip packaging for connection that leads to,
iii. printed circuit board fabrication and assembly.

4. A semiconductor is a material that can be either an electrical conductor or insulator depending on the impurity atoms in the overall atomic structure.

5. Three common semiconductor materials are silicon, gallium arsenide and germanium.

6. Doping is the introduction of impurity atoms into a semiconductor material to produced desired electrical behavior.

7. In n-type semiconductors electrical conduction is by the movement of electrons, negative charge carriers. In p-type semiconductors electrical conduction results from the movement of positive charge carriers – the movement of holes representing a lack of electrons in the valence level of the atoms.

8. The lack of a full complement of electrons in the valence level of the atoms in a semiconductor represents a positive or p-type charge carrier called a hole.

9. Silicon is the most important semiconductor used today because;
i. it is plentiful
ii. it is readily produced in single crystal form needed for electronic manufacture,
iii. the native oxide that forms is useful in electronic device manufacture.

10. A p-n junction is the interface region between a p-type semiconductor region and a n-type region. A p-n junction can be used as an electrical circuit element by controlling charge carrier flow across it – Question 11.

11. In a semiconductor p-n junction the electrons and holes that are characteristic on the n-type and p-type materials on either side of the junction combine to form region with no mobile charge carriers – the depletion region. The difference in potential across the junction is the potential barrier. Electron flow across the junction can be controlled by the imposition of an external potential and switching flow on and off can be the basis for an electronic device. The manufacture of such devices is outlined in Question 12

12. The steps in producing a bipolar diode are (Figure 34-2)
- production of a silicon wafer by cutting, lapping and polishing a section of a large crystal,
- growing an oxide layer on the wafer in an oven (this oxide layer will be used as a mask in the doping process),
- producing a lithography mask over the oxide layer,
- etching of the oxide layer,
- removal of the lithography mask,
- doping, (another doped layer(s)r will be produced above the first one),
- removal of the oxide mask,
- growing of another oxide layer,
- Patterning of the next layer,
- doping,
- deposition of a conducting metal layer to connect the semiconductor layers produced,
- create masks for lithography of metal film to produce leads and contacts,
- etching of metal layer to produce pattern,
- apply passive, protective coating.

13. ULSI is ultra-high-scale integration of electrical elements to form a device. ULSI and very-large-scale integration, VLSI, differ in the number of components per circuit.

14. Level of integration of electronic components required increased miniaturization of integrated circuit components. Initially new technologies were required, recently better control over processes has led to advances.

15. A silicon boule is a single crystal silicon ingot.

16. Impurity additions while growing a single crystal can serve as initial sites for the congregation and segregation of any additional impurities that may enter the process, see Question 20.

17. The electrical properties of the single crystal depend on crystal orientation and type of dopant used. The single crystal ingot is ground to cylindrical form for use. To provide an indication of crystal orientation and dopant type a flats are ground on the cylindrical

surface. The primary, largest, flat indicates crystal orientation. After processing the grinding affected region is removed chemically – a low stress process.

18. Smaller single crystal ingots have flats ground on them to indicate crystal orientation and type of doping. Grinding easily identifiable easily produced flats on large diameter ingots reduces the surface area available on this high cost stock and so to increase available area for devices notches are used.

19. Since high-precision planar devices are to be produced on the wafer, the wafer surface has to be flat and smooth. Geometric concerns in wafer production are the roughness of the wafer surface and the flatness of the wafer.

20. In wafer production gettering is the intentional addition of hard to move impurities into the wafer material in areas away from regions to be used for component production. The intent is to trap other impurities and defects at the gettering sites, Question 16.

21. Silicon wafers can be doped by;
i. alloying during production of the bulk material.
However to produce desirable, useful structure, composition gradients and behavior for electronic devices selective doping is required. Selective doping can be done by;
i. thermal diffusion,
ii. ion implantation.

22. For doping of semiconductor material ion implantation offers better control of the depth of dopant penetration and so dopant concentration and concentration gradient than thermal diffusion. Also, ion implantation provides better control over the impurities that may work their way into the diffusion process.

23. Ion implantation takes place as the high kinetic energy diffusing species impact with and enters the semiconductor. Mechanical damage results and this affects electrical and chemical properties. To remove or minimize the damage annealing processes are used.

24. In annealing, and other thermally driven processes, the effects produced depend on temperature and time of the workpiece at elevated temperature. In annealing of doped semiconductors the high temperature drives the decrease in mechanical damage but also increases energy available for movement and redistribution of dopant atoms. Rapid thermal processing technologies are advantageous since their use results in less change in the electrical properties of the material being processed.

25. In microelectronics manufacturing silicon dioxide is used as;
i. a dielectric material component of electronic elements, e.g., the gate in field effect transistors,
ii. an insulating material between electron element components such as isolation layers between metal conductors.

26. In wet oxidation the furnace atmosphere contains oxygen and water vapor. The diffusion rate of water molecules into the forming diffusion mask is greater that for oxygen molecules and so diffusion layers grow faster in wet oxidation processes. Two advantages of this faster growth rate are less processing time for a given layer thickness and the ability to grow thicker layers in reasonable time.

27. The lateral geometry, or pattern of the planar structures in integrated circuits, are produced by lithography and etching. Question 12 outlines the general steps in which lithography is used to produce patterns on a surface and etching is used to remove material to produce the patters in a material.

28. The most complicated, expensive and critical step microelectronics manufacture is lithography. Large numbers of very precise, high resolution patterns must be produced.

29. For pattern transfer in microelectronic manufacturing photolithography is most widely used. Additional lithography methods are;
i. X-ray lithography,
ii. electron-beam lithography,
iii. ion-beam lithography

In the different lithography processes different physical phenomena are used and so different equipment must be used. Electromagnetic radiation and particles are used and these are controlled and patterned differently.

30. To produce a photoresist mask on a silicon substrate a mask layer must be formed and a pattern produced on it. The steps are
the creation of a photomask,
- a thin film of opaque material is deposited on an optical purity, high stability quartz plate to be used in creating the photomask,
- the thin film is patterned by etching to form the photomask,

the creation of the photoresist
- liquid photoresist material is applied to the silicon substrate,
- the coated substrate is soft baked to evaporate solvents and case photoresist-substate adhesion,
- the photoresist is exposed to electromagnetic radiation through the photomask producing a stable, “hardened” pattern on the photoresist,
- the substrate is moved, indexed, stepped below the photomask to expose and pattern sequential areas of the photoresist,
- the photoresist is developed, the exposed areas of the photoresist remain and the unexposed areas are removed,
- the patterned photoresist on the substarate is hard baked to remove all solvents and harden the photoresist.

31. The two major classifications of photoresist materials are positive photoresists and negative photoresists. With negative photoresists the incident radiation in photoresist film production cause cross-linking in the polymer and making the photoresist less soluble in the developer.

32. A photoresist should
i. be resistant to down stream etching and diffusion or implantation, i.e., after it is applied and hard baked,
ii. have high resolution,
iii. have high sensitivity,
iv. adhere well to the substrate.
Resolution and sensitivity determine the accuracy and precision of the patterns that can be produced.

33. The two standard, and therefore important, wavelengths in photolithography using a mercury arc lamp are
i. the 436 nm, blue, g-line,
ii. the 365 nm, UV, I-line.

34. The three types of exposure methods used in photolithography are
i. contact printing which gives very high resolution,
ii. proximity printing which has higher throughput than the other methods,
iii. projection printing which result in no process induced resist-mask damage.

35. Wet etching uses a liquid chemical to remove material. Dry etching used a physical means to remove material, e.g., a plasma.

36. Undercutting is the removal of material under the photoresist, in the lateral direction for the typical horizontal photoresist-substrate configuration. Undercutting increases with time and so the lateral extent of undercutting varies with depth below the substrate surface. A quantitative measure of the amount of undercut is the etch bias, Figure 34-10.

37. If the photoresist-substrate is underetched the desired pattern is not produced and defects such as exposure or unexposure of doped and electrical contact regions occur and faults such as opens in doped regions and shorts in electrical result.

Overetching results in larger than allowable undercutting (Question 36) and possible damage as change in properties of the substrate and mask.

38. *i*. Etchant composition is the material content of the etchant and determines what interactions occur between it and the substrate and mask.
ii Etchant concentration is the relative proportion of the constituents of the etchant.

Important parameters of the etching process are etchant temperature and workpiece immersion time.

39.

Process	Etch mechanism	Advantages
Plasma etching (gaseous phase chemical etching)	partially ionized gas chemically reacts with the target surface removing material and producing gaseous by-products	high etch rate relatively simple process - low excitation energy - low radiation damage
Reactive ion etching (ion-assisted etching)	physical interaction between ions and target increasing rate of chemical action	etch rate higher than in sputter etching little undercutting in some situations
Sputter etching (ion milling)	impact between ions and target physically remove material	little undercutting

40. Thin films are layers of material less than about 1 μm thick. Thin film are important in microelectronic manufacturing because
- many of the structures and devices produced are built up as a series of thin films,
- thin films are used in many manufacturing processes, e.g., the photoresist in lithography.

41.

Type of Process	Mechanism	Advantages
Evaporative	condensation of metal vapor on substrate	simple - machines and equipment non-severe processing conditions
Sputtering	ions impact on charge material ejecting atoms toward and to the wafer	good step coverage can deposit metals, alloy, dielectrics

42.

Form of CVD	Applications
Atmospheric pressure CVD	producing microelectronic device layers, e.g., - passivation layers - smoothing and gettering layers e.g. producing components of devices - polysilicon gate electrodes
Low pressure CVD	producing microelectronic device components, e.g., - polysilicon gate electrodes
Plasma enhanced CVD	depositing passivating and protective layers on devices

43. In atmospheric chemical vapor deposition undesirable gas-phase reactions are controlled by using dilute gases. In low pressure chemical vapor deposition undesirable gas-phase reactions are controlled by using gas pressure.

44. Reactor designs are based on the fundamental physical process that controls and limits the deposition process. The reactions that occur at the deposition surface depend on the rate of reaction and the availability of reacting material. In atmospheric pressure chemical vapor deposition a large amount of the reacting gas is available at the surface and so the rate of deposition is controlled by the reaction rate – it is reaction rate limited. In low pressure chemical vapor deposition the availability of reacting material at the deposition surface controls the rate of reaction – it is mass transport rate to the surface limited.

For the reaction rate limited low pressure chemical vapor deposition process the important reactor characteristics are assuring uniform temperature over the entire gas mass in the reactor. This means and tight control over reactor temperature leading to heated wall reactors. For mass flow rate limited processes the control issue is assuring an adequate, uniform flow of gas over the entire deposition area. The flow of the reacting gas controls reactor design – nonuniform temperature in the reactor also can influence flow.

45. Two types of chemical vapor deposition reactor design are cold wall and heated wall reactors.
Hot-wall reactors keep the entire reaction zone at a uniform temperature providing good process temperature and flow control resulting in the advantage of uniformity of the deposited layer. The disadvantages of hot-wall reactors arise from deposition on the reactor walls. This may cause contamination of ongoing processes as aged deposits flake off the wall providing contaminants for the new or different material films. If reactors are dedicated to certain materials flexibility in types of materials that can be deposited is lost.

Cold-wall reactors are simpler than hot-wall reactors and so less expensive and easier to operate and maintain. The major disadvantage of them is the relatively less well controlled process temperature uniformity compared to hot-wall reactors. This leads to less temperature control and less uniform deposited layers.

46. The plasma enhanced chemical vapor deposition process an be run at lower temperatures than other chemical deposition processes. This has the advantage of allowing the desired reactions to occur while minimizing the effect of other temperature dependent processes, e.g., allowing deposition with minimizing diffusion of previously deposited material.

47. Epitaxy is the growth of a single crystal thin film on a surface with the film having the same crystal orientation as the surface. Epitaxial layers can be produced with fewer defects than doped layers, higher purity, more uniform dopant distribution and sharper transitions so that their use produces better electronic performance. Also, epitaxial layers can be used to ease geometric transitions between device layers since they maintain their desirable characteristics as layer thickness increases.

48. Contacts are the access points between the first metal layer of conduction lines and the underlying semiconductor. Vias are access points for contacts between the different layers of conduction lines.

49. Planarizarion is the production of a flat or planar surface on one or more of the layers that are built up during the production of integrated circuits. Plararization is needed because as the layers are produced distinct topography associated with each layer forms. If the topography becomes too uneven the structure and performance of subsequent layers becomes problematic. Non-flat surface can lead to short in the conducting layers and other problems.

50.Interconnect layers can be plararized by;
i. using a layer material that flows easily and inherently forms a planar surface, e.g., p-glass,
ii. etching with an etchant that preferentially etches high regions of the surface,
iii. chemical mechanical polishing which uses a combination of mechanical and chemical actions to remove material.

51. Electromigration is the movement of atoms over time due to an applied current. Electromigration is a concern in integrated circuit processing and use since the size and shape of conducting paths change. As conductor size and spacing are decreased the effects of electromigration increase and can even cause open circuits and short circuits

52. Wafer testing is intended to remove any defective dies or chips from the production stream. That is, defective dies are identified and removed and so resources are not spent on packaging dies that will not function.

53. A chip is an individual integrated circuit that is cut from the wafer on which many chips are produced.

54. Driving the increase in component density and die area is the desire to increase the number of chips produced on each wafer. This drives down the cost per chip.

55. Very small scale, or point, defects have large detrimental effects on integrated circuit yield. These small defects can be cause by atmospheric particles and to minimize this source of product contamination manufacturing is conducted in clean rooms.

56. Integrated circuit packages are made up of;
i. components to distribute electronic signals and power and provide interfacing to test equipment and the entire system in which the circuit will reside,
ii. components to protect the devices and circuitry.

57. In through-hole connections discrete electronic components are inserted into metal plated holes in the printed circuit board. Through hole technology provides the advantages of high joint strength and the ability to use many different kinds of components.

With surface mount technology electronic components are placed onto solder paste pads on the printed circuit board and soldered. Compared to through hole technology surface mount techniques provide the advantages of easily automated production and higher circuit board density. This leads to cost-effective manufacturing.

58. The two main classes of through-hole packages are dual in-line packages (DIP) and pin grid arrays (PGA).

59. The four types of surface mount lead geometries are;
i. butt lead or I-lead that has the advantages of cost savings if through-hole components have to be converted for use in surface mount processes,
ii. gull wing leads that provide the advantages of thinner packages, smaller leads, fine pitch, compatibility with most re-flow soldering processes, and that they can be self-aligning during soldering,
iii. J-leads have the advantages of ruggedness, easy inspection since solder joint are more visible and easier cleaning since the components have higher stand offs from the circuit board,
iv. solder balls used in ball grid arrays have the advantages of high lead density, self-aligning and they are less susceptible to deviations in parallelism between the component and board.

60. The major steps in conventional integrated circuit packaging are
- attachment of the die to the package,
- sealing of the package using either premolded or postmolded packages,
- formation of leads.

61. Three techniques for attaching and electrically connecting dies to integrated circuit packages are;
i. wire bonding or chip-and-wire attachment using an adhesive to attach the chip to the package and a wire to connect bonding pads on the chip and package,

ii. tape-automated bonding in which a polymer tape holding the lead circuitry is aligned with the die and bonded using raised temperature and applied pressure,
iii. flip-chip technology in which the chip and package bonding pads face each other.

62. Direct chip attachment or chip-on-board or direct mounting is a process in which the chip is directly attached to the circuit board. It differs from other integrated circuit packaging in that the chip itself is assembled onto the circuit board rather than a packaged chip. Disadvantages of this process are that it involves the shipping and handling of bare chips and the need for equipment to handle die-attachment while manufacturers have package-level equipment.

63. Chip scale packages are packages that add no more than 20% of additional board area to the chip. Chip scale packages are physical packages, not attachment methods. Direct chip attachment interconnection techniques are used with chip scale packages.

64. Multichip modules are chip carriers that package of more than one chip through direct chip attachment to fine line, thin film conductors within a ceramic carrier. They are advantageous in integrated circuit packaging because reduced distances between integrated circuits is possible

65. Printed circuit boards are the carriers that hold and connect the elements of a circuit. Printed circuit boards consist of a board composed of
i. laminated dielectric sheets comprising the base,
ii. metallic circuits or tracks for connecting the electronic components to be placed on the base
iii. pads of conducting material that serve as junctions for circuit elements.

66. Three alternative materials for the dielectric components of printed circuit boards are
i. epoxy-impregnated fiberglass which is the least expensive of the alternatives,
ii. polyamide which can be mechanically flexible and so can be made into flexible circuits,
iii. alumina or other ceramic which can be used to minimize thermal shock because of relatively high thermal conductivity compared to the other materials.

67. Plated through holes are holes that are plated with electrically conducting materials and serve as insertion points for circuit components. Via holes are plated holes that are connect the circuit on one side of the board to the circuit on the other side of the board.

68. Printed circuit boards are composed of layers of circuits. The circuits on different layers or different sides of an individual layer are connected by vias. Blind or partially buried vias extend from one side of the board to a layer in the interior of the board, they do not extent to the other free side of the board. Buried vias connect layers with in the interior of the board, they to not extent to either free side of the board. Through vias extend from the outermost circuit track on one side of the board to the outermost track on the other side of the board.

69. The four major steps in producing a multilayer printed circuit board are
i. production of circuits on inner layer laminations, (Question 70),
ii. lamination of layers,
iii. drilling and preparation of via holes,
iv. production of circuits on outer layers.

70. The two methods of circuitization of inner layers of printed circuit boards are
i. Subtractive circuitization in which
- the starting structure is a double sided copper coated laminate, panel,
- to which a dry photoresist is applied,
- followed by photolithographic exposure and development to produce the circuit pattern,
- and etching of the copper coating to produce the circuit,
- and stripping of the photoresist,
- then drilling of registration holes used in board assembly.

This process is less involved and more economical than the alternative additive circuitization.

ii. Additive circuitization is different than subtractive circuitization in that the circuit is formed by producing the circuit pattern directly by material deposition rather than by etching the circuit into a metal layer. Additive circuitization involves
- starting with a laminate in which registration holes have been drilled,
- drilling of any required via holes,
- exposing and developing an etch mask that exposes the underlying dielectric,
- preparing the dielectric for electroless deposition by adsorbing a catalyst on to it, the buttercoating or seeding process,
- deposition of a thin layer of electroless copper on the seeded dielectric,
- electroplating of thicker layers
- stripping of the resist.

This process provides higher resolution circuitry (finer lines and higher density) than subtractive circuitization.

71. Built-up multilayers are circuit boards that are produced by deposition and processing of one dielectric layer at a time. Vias are plated passageways used to connect one circuit layer to another. Microvias are via holes that are smaller than the approximately 200 micrometers diameter holes than can be produced by conventional mechanical drilling.

Laminates start with a dielectric layer and produce the circuit on it. Built-up multilayer manufacturing includes the deposition and processing of the dielectric as an integral, controllable part of the process.

Microvias are different from vias in size and production methods. Vias are larger than microvias and are usually produced by mechanical drilling and limited in size by the minimum drill size of about 200 micrometers. Micro vias are smaller than drilled vias and are produced by photoimaging, laser ablation and plasma etching.

72. The four major steps in assembling a through hole printed wiring assembly are
i. insertion of the circuit components,
ii. clinching and trimming of leads,

iii. soldering,
iv. postsolder cleaning.

73. Leads are trimmed and clinched after through hole insertion to decrease the effective size of them and so decrease the possibility of bridging of adjacent solder joints. Solder joint bridging produces electrical shorts in the circuit.

74. Four major steps in assembling surface mount printed wiring assemblies are
i. application of solder paste to the lands on the printed circuit board by screening, stenciling or dispensing,
ii. placement of the surface mount components,
iii. reflow of solder paste in an oven (or, less commonly, vapor phase soldering or condensation soldering),
iv. cleaning

75. Four methods for feeding components to robotic manipulators in pick-and-place robots are
i. tape or reel feeding which is widely used and most appropriate to high volume placement or where protective handling to minimize lead damage is needed,
ii. bulk feeding as with vibratory bowls is useful for prototyping of production processes,
iii. tube or stick feeders which are primarily used in smaller volume assemblers,
iv. waffle packs that hold different kinds of chips in specific locations so that pick-and-place robots can be programmed for positioning to pick the correct chip.

76. Startup and operation cost of surface mount assembly processes is most affected by the component placement step in the process.

Large costs are associated with component placement since the equipment cost is high (high startup costs) and this stage in the assembly process is the source of most product defects.

77. The four necessary zones in a surface mount solder reflow thermal profile (time-temperature trajectory) are
i. preheating to drive off nonflux volatiles from the solder paste,
ii. soaking to bring the entire assembly up to a temperature just below reflow temperature of the paste,
iii. a rapid rise in temperature to bring the solder paste temperature to above the reflow temperature for fluxing and wetting,
iv. cooling of the assembly.

Problems: no problems

Case Study: no case study

CHAPTER 35

Review Questions

1. Manufacture as a joined structure composed of several pieces is favored when the product needs to be large, composed of several parts with different properties or have a complex shape.

2.Consolidatin processes are those in which different material bodies are joined to produce the part or product. Examples of consolidation processes are welding of relatively large pieces together to form a part, powder metallurgy with the sintering of particles together and additive rapid prototyping techniques such as inkjet and 3-D printing.

3. Welding is the permanent joining of two material bodies by coalescence produced by temperature, pressure and metallurgical conditions.

4. The ideal metallurgical bond requires: (1) perfectly smooth, flat or matching surfaces, (2) clean surfaces, free from oxides, absorbed gases, grease, and other contaminants, (3) metals with no internal impurities, and (4) two metals that are both single crystals with identical crystallographic structure and orientation.

5. Surface roughness is overcome either by force, causing plastic deformation of the asperities, or by melting the two surfaces so that fusion occurs. In solid state welding, contaminated layers are removed by mechanical or chemical cleaning prior to welding or by causing sufficient metal to flow along the interface so that they are squeezed out of the weld. In fusion welding, the contaminants are removed by fluxing agents. Welding in a vacuum also serves to remove contaminants.

6. When high temperatures are used in welding, the metals may be adversely affected by the surrounding environment. If actual melting occurs, serious modification of the metal may result. The metallurgical structure and properties of the metal can also be adversely affected by the heating and cooling cycle of the weld process.

7. Thermal cutting is the separation of a piece of material into two pieces by the imposition of localized thermal energy such as with a flame, electric arc, laser beam, electron beam or the impingement of an oxygen stream onto a hot material.

8. Some common weld defects are cracks, cavities, inclusions, incomplete fusion between the weld and base materials, incomplete penetration of the weld into the materials to be joined, unacceptable weld shape, surface defects due to arc strikes, blemishes due to spatter, metallurgical changes that are detrimental to product performance and warping and distortion.

9. The four basic types of fusion welds are bead welds, groove welds, fillet welds, and plug welds, as illustrated in Figure 35-3.

10.Fillet welds are used for tee, lap, and corner joints. These configurations are shown in Figure 35-6.

11. The cost of making a weld is affected by the required edge preparation, the amount of weld metal that must be deposited, the type of process and equipment that must be used, and the speed and ease with which the welding can be accomplished.

12. When two pieces are welded together, they become one piece. Cracks in one segment can then cross the weld and continue propagation throughout the structure. Also, one segment constrains the others, so that properties such as fracture resistance and ductility can change appreciably.

13. The notch-ductility characteristics of metal can change markedly with a change in the size of the piece. While a small piece, such as a Charpy impact specimen, exhibits ductile behavior and good energy absorption down to low temperatures, a large structure of the same metal exhibits brittle behavior at higher temperatures. Because of the added constraint of mass, deformation and fracture modes that may absorb energy may be forbidden, resulting in a product with reduced fracture resistance, reduced ductility, and an elevated ductile-to-brittle transition temperature.

14. Excessive rigidity in a welded structure can restrict the material's ability to redistribute stresses, and thereby avoid failure. Structures and joints should be designed to have some flexibility.

15. In a fusion weld, a pool of molten metal is created, contained, and solidified within a metal mold formed by the segments being welded. This is actually a casting in a metal mold and has all of the structural and property features of such a casting.

16. The chemistry of a weld fusion zone may be complex because it is a combination of the filler metal and melted-back metal from the material being welded. See Figure 35-9.

17. Since the solidified weld will be in an as-cast condition, its properties and characteristics will not be those of the same metal in the wrought state. Therefore, electrode or filler metals are usually not selected on the basis of matching chemistry, but on the basis of having properties in the as-solidified or as-deposited condition that equal or exceed those of the base metal.

18. Fusion weldments may exhibit all of the problems and defects observed with castings, including: gas porosity, inclusions, blowholes, cracks, and shrinkage. Rapid solidification and cooling may lead to: inability to expel dissolved gases, chemical segregation, grain-size variation, grain shape problems, and orientation effects.

19. In the heat-affected zone, temperature and its duration vary widely with location. This variation in thermal history produces a variety of microstructures and a range of properties.

20. Structure and property variations in heat-affected zones can include: phase transformations, grain growth, precipitation (or overaging), embrittlement, and even cracking.

21. Due to possible changes in structure, the heat-affected zone may no longer possess the desirable properties of the parent metal, and, since it was not molten, it does not have the selected properties of the weld metal. Consequently, it is often the weakest area of the weld in the as-welded condition. Except when there are obvious defects in the weld deposit, most welding failures originate in the heat-affected zone.

22. Low heat input rate to welding processes heat a large area of the workpieces and so produce high total heat content, slow cooling rates, large heat affected zone. The resulting structures can have low strength and hardness and high ductility (analogous to annealing). Residual stresses are expected to be lower than high heal input rate processes that produce localized, small, high temperature zones interacting with surrounding cooler zones.

23. When attempting to heat-treat products after welding, numerous problems can arise in producing controlled heating and cooling in the often large, complex-shaped structures that are typically produced by welding. Furnaces, quench tanks, and related equipment may not be available to handle the full size of the welded assembly.

24. Pre- and post-heating operations can reduce the variation (and sharpness in the variation) in microstructure. The cooling rate in both the weld deposit and adjacent heat-affected zone is reduced, producing more gradual changes in microstructure.

25. In brazing and soldering, the base and filler metals are usually of radically different chemistry. The elevated temperatures of joining can promote interdiffusion. Intermetallic phases can form at the interface and alter the properties of the joint - usually imparting loss of both strength and ductility .

26. Residual stresses can produce several kinds of undesirable effects including
- residual stress states that act in combination with applied stresses to raise the effect stress acting in a part to above the failure stress,
- change of part shape, warping, as the residual stresses produced during processing of a held or fixed part rearrange themselves when the part is released from the fixture,
- change in dimensions locally.

27. Reaction-type residual stress is caused by restraining the parts during welding. If the parts are not free to move in response to loads applied during welding when the entire structure is assembled there is rearrangement of the stress state. Reaction stresses result.

28. The magnitude of the reaction stresses is an inverse function of the length between the weld joint and the point of fixed constraint.

29. The amount of distortion in a welded structure can frequently be reduced by: forming the weld with the least amount of weld metal necessary to make the joint; use faster welding speeds to reduce the amount of heating of adjacent metal; use the minimum number of welding passes; permit the base metal segments to have as much freedom of motion as possible; and, weld to the point of greatest freedom (as from the center to the edge) . Weld surfaces can be peened to induce offsetting compression.

30. If plastic flow can occur in response to residual stresses the effects of the residual stress is mitigated. A plastic flow zone forms, plastic flow occurs, stress is relieved or surrounded by an elastic zone constraining the plastic zone. Residual stresses will have harmful effects if the residual stress acts along with a stress raiser such as a notch and if the structure is very rigid and no or very little plastic flow can occur.

31. When welded structures are subsequently machined, the material removal frequently unbalances the residual stress equilibrium, and the material distorts to achieve a new balance of forces. In essence, it distorts during machining. Weldments that are to undergo appreciable machining should be given a stress-relief heat treatment prior to the machining operation.

32. The cracking of weldments can be reduced by designing joints to keep restraint to a minimum, and selecting metals and alloys with welding in mind. Thin materials are more resistant to cracking than thicker sections. The size and shape of the weld bead should be properly selected and maintained. Weld profile (penetration depth) can affect cracking. By slowing the cooling of the weld area and inducing plasticity into the material, the tendency to crack can be further reduced. Preheats, postheats, and stress reliefs can be used, along with efforts to remove hydrogen from the weld area.

33. Weldability and joinability are nebulous terms since the performance of a process depends on a number of material and process characteristics. A material may produce a very good quality weld in one process and so be weldable, while in a different welding process the results may be unacceptable and the material is not weldable. Similarly, and even more extreme, a material may be easy to weld and produce a good quality joint at one set of welding conditions and unacceptable results in the same welding process using different conditions.

Problems:

1. The assessment is not fair, because a subsequent examination of the riveted ships revealed a number of similar cracks. These cracks, however, simply traveled to the edge of the plate and stopped. Welding, on the other hand, produces monolithic structures. The cracks can cross the welds and continue into and through adjacent pieces. While the problem was a material problem, it became far more apparent when welding was used to produce the large, one-piece assemblies.

The problem was later identified as a metallurgical one related to the high ductile-to-brittle transition temperatures of the steel being welded. Additional knowledge of the phenomena, coupled with the selection of materials with lower transition temperatures, has permitted the safe use of welded-hull ships under most of the temperatures likely to be encountered.

(NOTE: While not a welded-hull ship, it is this same ductile-to-brittle transition phenomena that is suspected a playing a significant role in the sinking of the Titanic.)

2. Some possible corrective measures to eliminate or reduce cracking include: (1) possible use of a lower carbon steel, (2) substitution of a low-hydrogen type electrode, and (3) use of preheating and possibly some post-heating if the carbon content of the steel cannot be reduced.

3. a. Based on the desire to minimize constraint, one should resist the natural tendency to fabricate the exterior box and then insert the interior subsections. Instead, the preferred sequence would begin with the innermost welds and progress outward. The initial welds might be 4 and 5 -- then 8 and 9. Welds 3, 7, 6 and 10 would follow, and then on to the final assembly at 1 and 2 and 11 and 12.

b. Various "rules" could be proposed, each designed to reduce the amount of restraint on the weld or the number of welds that must be made under restraint. When restrained welds must be made, efforts could be made to maximize the length of material, or distance to the restraint. (NOTE: If 3/100-inch elastic stretching must be provided to compensate for weld shrinkage, this would require a 3% stretch for a 1-inch segment, 0.3% for a 10-inch segment, and 0.03% for a 100-inch segment.)

Case Study: no case study

CHAPTER 36

Review Questions

1.The combustion of oxygen and acetylene involves a two-stage reaction. In the first stage,

$$C_2H_2 + 02 \longrightarrow 2\,CO + H_2$$

And in the second stage,

$$2C0 + 02 \longrightarrow 2C0_2 \quad H_2 + 1/2\ 02 \longrightarrow H_20$$

The outer flame region preheats the metal and protects it from the surrounding atmosphere. The inner part of the flame produces the required high temperature.

2. The maximum temperature in an oxyacetylene flame occurs at the end of the inner cone where the first stage of combustion is complete.

3. The outer zone of an oxyacetylene flame serves to preheat the metal and provides shielding from oxidation, since some of the oxygen from the surrounding air is used in the secondary combustion.

4. The three types of oxyacetylene flames that can be produced by varying the oxygen-to-acetylene ratio are: a neutral flame, oxidizing flame (with excess oxygen), and a carburizing or reducing flame (with excess fuel).

5. MAPP, while providing a slightly lower temperature flame, is more dense than acetylene, providing more energy for a given volume. It can be stored safely in ordinary pressure tanks.

6. The tip size of the torch can be varied to control the shape of the inner cone, the flow rate of the gases, and the size of the material that can be welded. Larger tips permit greater flow of gases, resulting in greater heat input without requiring higher gas velocities that might blow the molten metal from the weld puddle. Thicker metal requires larger tips.

7. A filler metal is extra metal added between the two parts being welded. Filler metal is needed since there are usually gaps between the edges being welded and these gaps need to be filled. It is better to add metal to fill the gaps than to use metal from the pieces being welded because that would change the welded section size and shape.

8. Welding flux
- cleans the surfaces to be welded,
- removes contaminants, primarily oxides,
- produces a gaseous shield around the welding zone preventing oxidation,
- produces a slag that as it solidifies protects the cooling weld pool.

9. The low heat input rate in oxyfuel gas welding leads to large heated areas that can cause distortion and changes in metal properties in areas removed from the welded region.

10. The use of oxyfuel processes is attractive since the equipment is portable, inexpensive and versatile. For example, oxyfuel processes can be used in welding, brazing, soldering, cutting and as the heat source for bending, forming, straightening and hardening.

11. When torch cutting nonferrous metals, the metal is merely melted by the flame and blown away to form a gap, or kerf. When ferrous material is being cut, it is heated to a sufficient temperature that the iron will then oxidize (burn) rapidly in the stream of oxygen that flows from the torch. Thus, the oxyfuel flame first raises the temperature of the metal and then the oxygen content is raised to continue the cutting, the iron oxide being expelled from the cut by the gas pressure of the torch.

12. When ferrous metal emerges from a continuous casting operation, its temperature will already be above the necessary 2200^0F, so only a supply of oxygen through a small pipe is necessary to start and maintain cutting. This is known as oxygen lance cutting (LOC).

13. The tip arrangement in an oxyacetylene, cutting torch is different from that of an oxyacetylene welding torch. The cutting torch contains a circular array of holes through which the oxygen-acetylene mixture is supplied for the heating flame. A larger hole in the center supplies a stream of oxygen to promote the rapid oxidation and blow the formed oxides from the cut.

14. Cutting torches can be mechanically manipulated by a number of means, including driven carriages (as for straight cuts), template-tracers, CNC machines, and industrial robots.

15. In order to cut underwater, a supply of compressed air must be added to the torch to provide the secondary oxygen for the oxyacetylene flame and keep the water away from the zone where the burning of the metal occurs.

16. If a curved plate is to be straightened by flame straightening, the heat should be applied to the longer surface of the arc. The hot metal will be upset and will contract upon cooling, reducing the length of that region.

17. Flame straightening cannot be used on thin materials because the metal adjacent to the heated area must have sufficient rigidity to resist transferring the buckle from one area to another.

Problems: no problems

Case Study: no case study

CHAPTER 37

Review Questions

1.Early attempts to develop arc welding were plagued by instability of the arc, requiring great amount of skill to maintain it, and contamination and oxidation of the weld metal resulted from atmospheric exposure at such high temperatures. In addition, the metallurgical effects of such a process were not well understood.

2. The three types of current and circuit conditions used in arc welding are: alternating current, straight polarity direct current (workpiece is positive), and reversed polarity direct current (workpiece is negative).

3. In the consumable electrode processes, the electrode melts to supply the needed filler metal to fill the voids in the joint. With a nonconsumable electrode, such as tungsten, a separate metal wire must be used to supply the filler metal.

4. The three modes of metal transfer that can occur in arc welding are: globular, spray, and short circuit. They are illustrated in Figure 34-2.

5. Arc welding processes require the specification of: welding voltage, welding current, arc polarity, arc length, welding speed, arc atmosphere, electrode or filler material, and flux.

6. The four primary consumable electrode arc welding processes are;
i. shielded metal arc welding,
ii. flux cored arc welding,
iii. gas metal arc welding,
iv. submerged arc welding.

7. Electrode coatings can play a number of roles, among them:

> (1) provide a protective atmosphere, (2) stabilize the arc, (3) act as a flux to remove impurities from the molten metal, (4) provide a protective slag to accumulate impurities, prevent oxidation, and slow the cooling of the weld metal, (5) reduce weld metal spatter and increase the efficiency of deposition, (6) add alloy elements, (7) affect arc penetration, (8) influence the shape of the weld bead, and (9) add additional filler metal.

8. Coated electrodes are classified by the tensile strength of the deposited weld metal, the welding position in which they may be used, the type of current and polarity (if direct current), and the type of covering. A four or five-digit system of designation is used, as presented in Figure 34-3.

9. Shielded metal arc electrodes are baked just prior to welding to remove all moisture from the coating, a source of hydrogen in the welds.

10. The gases that form when the electrode coating melts and vaporizes
- provide a protective atmosphere for the welding zone,
- provide ionizing elements to help stabilize the arc,
- help reduce weld spatter,
- increase deposition efficiency,
- influence weld bead shape.

11. The slag coating in a shielded metal arc weld serves to entrap impurities that float to the surface, protect the cooling metal from oxidation, and slow down the cooling rate of the weld metal to prevent hardening.

12. Electrodes having iron powder in the coating significantly increase the amount of metal that can be deposited with a given-size electrode wire and current.

13. Continuous shielded metal arc welding faces the problem of providing electrical contact (through the coating) to the center filler-metal wire. Electrode length is limited because the current must be applied near the arc to prevent the electrode from overheating and ruining the coating. Thus, while some continuous arc welding processes have been developed, most shielded metal arc welding is performed with finite length stick electrodes.

14. With the flux in the center of an electrode, the electrode is less bulky (since no binder is required to hold it onto the outside) and electrical contact can be maintained directly with the surface of the electrode. Thus, flux-cored arc welding becomes something like continuous shielded metal arc welding.

15. The current in fluxed-core arc welding can be higher than in shielded metal arc welding since overheating of the electrode is less of a problem. With less concern about overheating current can be increased.

16. Compared to shielded metal arc welding, gas metal arc welding provides the advantages of
- there being no need for flux and so the electrode can an uncoated, continuous wire,
- it can be applied to all metals,
- the heat transfer and weld penetration can be controlled to some extent by choice of shielding gas.

17. In gas metal arc welding helium produces the hottest arc and deepest weld penetration and carbon dioxide provides the lowest arc temperatures and shallowest penetration. Argon produces temperatures and penetrations intermediate between helium and carbon dioxide.

18. In the pulsed-arc gas metal arc welding process, a low welding current is first used to create a molten globule on the end of the filler wire. A burst of high current is then applied, which "explodes" the globule and transfers the metal across the arc in the form of a spray.

19. Because of the reduced heat input and temperatures of the pulsed arc technique: thinner material can be welded, distortion is reduced or eliminated, workpiece discoloration is minimized, heat-sensitive parts can be welded, high-conductivity metals can be joined, electrode life is extended, electrode cooling techniques may not be required, and fine microstructures are

20. Some of the primary process variables in gas metal arc welding are type of gas, welding current/voltage and rate of electrode advancement.

21. In submerged arc welding, the flux provides excellent shielding of the molten metal and a sink for impurities. In addition, the unmelted flux provides a thermal blanket to slow down the cooling of the weld area and produce a soft, ductile weld.

22. Submerged arc welds can be performed at high welding speed, with high deposition rates, deep penetration, and high cleanliness. However, submerged arc welds are generally restricted to flat welds because of the need to form an area of molten slag and keep it in place over the molten weld metal. Extensive flux handling, possible contamination of the flux by moisture, the large volume of slag that must be removed, the high heat inputs that promote large grain sizes, and the slow cooling rates are other negative features of the process. The process is not suitable for high-carbon steels, tool steels, aluminum, magnesium, titanium, lead or zinc.

23. In bulk welding, iron powder is deposited into the prepared gap (beneath the flux blanket but on top of the backing strip) as a means of increasing the deposition rate. A single pass can deposit as much weld metal as seven or eight conventional submerged arc passes.

24. Stud welding is a special adaptation of arc welding that has been developed to weld fasteners into place.

25. The ceramic ferrule placed over the stud in stud welding acts to concentrate the arc heat and simultaneously protect the heated metal from the atmosphere. It also serves to confine the molten or plastic metal to the weld area and shapes it around the base of the stud.

26. Carbon dioxide cannot be used in gas tungsten arc welding because it does not adequately protect the tungsten electrode.

27. Since filler metal deposition rate increases with increasing wire temperature, Figure 37-13, deposition rate can be increased by increasing wire temperature. This can be done by electrically preheating the filler wire and oscillating the hot wire in the high temperature zone.

28. Some of the attractive features with gas tungsten arc welding are the production of high quality, clean, localized, symmetric welds without use of flux. Many of the

advantages accrue due to the ability to use various shielding gases and shielding gas efficiency.

29. In gas tungsten arc spot welding the weld nugget begins to form at the surface of the work, In most resistance spot welding processes the weld nugget forms at the interface between the two workpieces, where the resistance is the highest.

30. In plasma arc welding, it is the flow of hot gases that actually transfers heat to the workpiece and melts the metal.

31. In plasma arc welding there is a flow of inert gas through the nozzle where it is heated to form a plasma, called orifice flow. This gas flow is the source of heat to the weld zone. There is also a flow inert gas around the welding zone that provides weld pool shielding.

32. Plasma arc welding offers greater energy concentration, fast welding speeds, deep penetration, a narrow heat-affected zone, reduced distortion, less demand for filler metal, higher temperatures, and a process that is insensitive to arc length. Nearly all metals and alloys can be welded.

33. The primary difference between plasma arc welding and plasma arc cutting is the pressure of the gas flowing out of the orifice. At lower pressures, the molten material simply flows into the joint and solidifies to form a weld. At higher pressures, the molten material is expelled form the region and the process becomes plasma cutting.

34. The kerf in thermal cutting processes is the slit or separation region between the parts of the workpiece being cut.

35. In the oxygen arc cutting process, the stream of oxygen is directed onto the hot, incandescent metal. It reacts with the oxidizable metal, liquifies, and is expelled, producing the cut.

36. Plasma arc cutting is used to cut high-melting-point metals because this process produces the highest temperature available from any practical source. Virtually any material can be melted and blown from the cut.

37. Radial impingement of water on the arc was found to provide the necessary constriction of the arc, producing the intense, highly-focused arc needed to make a narrow, controlled cut in plasma arc cutting. Magnetic fields have also been used to constrict the arc.

38. Compared to the oxyfuel technique, plasma cutting is more economical, more versatile, and much faster. Narrow kerfs and smooth surfaces are produced, and surface oxidation is almost eliminated by the cooling water spray. The size of the heat-affected zone is significantly reduced and heat-related distortion is virtually eliminated.

39. Because of the low rate of heat input, oxyacetylene cutting will produce a rather large heat-affected zone. Arc cutting produces effects similar to arc welding. Plasma arc cutting is so rapid that the heat-affected zone is less than 1/16 inch.

40. Cutting tends to produce surfaces in residual tension. If subsequent machining removes only a portion of the total surface, the resulting imbalance of stresses may cause warping.

41.In addition to the effect of residual stresses, Flame- or arc-cut edges are rough and contain geometrical notches that can act as stress raisers and reduce the fatigue performance and toughness of a product. Thus, it is suggested that the cut surface and heat-affected zone should be removed (or at least subjected to a stress relief) on a highly-stressed machine part.

Problems: no problems

Case Study: "Bicycle Frame Repair"

The adhesive bonding employed in the original construction was selected because the material properties are heat-sensitive, and the heat of an elevated-temperature joining method would significantly diminish the strength of the tubing material.

a.

1. If the material were cold-drawn tubing, the heat-affected zone created by the weld repair would contain regions of recovery, recovery and recrystallization, and possibly recovery, recrystallization and grain growth. (These phenomena are discussed in Chapter 3, and the heat affect section of Chapter 35-39) These structures are significantly weaker than the original cold-drawn material, and would be subject to failure by the ductile overload mechanism. While the weld itself was not really defective, the failure occurred as a result of the welding process -- namely the creation of a heat-affected zone that adversely altered the properties of the base material. Therefore, the second failure was indeed the result of the welding repair.

2. If the tubing had been age hardened material, regions of the heat affected zone would have been hot enough to re-solution treat (and then produce a totally new structure upon subsequent cooldown), while other locations would have been reheated enough to permit overaging. These effects also serve to reduce the strength of the material, and increase the likelihood of ductile overload failure. Once again, the weld itself may have been of high quality, but the welding process was responsible for the alteration of the base material, and the subsequent failure.

3 . The repair of these materials would be limited to low temperature methods, such as adhesive bonding or possibly brazing. Both of these methods gain strength by increasing the area of bonding, so the use of some form of large area internal lug or external sleeve

would be desirable, as opposed to a simple butt joint repair.

b. Bicycle frames could be constructed from titanium or magnesium. Titanium offers clear advantages over magnesium and some advantages over steel. While more costly than steel, titanium has density of about 60% that of steel, modulus of elasticity of about half that of steel and can have comparable strength of steel depending on alloy and heat treatment. The strength-to-weight ratio is attractive for a high performance bicycle engineered for minimum weight. Titanium is very corrosion resistant and so the bicycle frame would not have to be coated, and perhaps the bare metal look would be a selling point. Most likely the titanium tubes would be produced by extrusion and the finished tubing frame members welded. Adhesive joining is possible.

Titanium bicycle frames are in production, e.g.,
www.vanguardtitanium.com
www.morati.com
www.biam.com/ti_bicycle.htm

Magnesium has density about 25% that of steel and a modulus of elasticity of 20% - 25% that of steel. The strength to weight ratio is attractive but to achieve strength near that of a steel bicycle frame thick sections might be required. The use of several different metals in the bicycle could be a problem since magnesium is susceptible to galvanic corrosion. Magnesium has a hexagonal close packed structure so is relative less ductile than metals with other structures and so the tubes for the frame would be extruded in the hot working region. Benefits of strain hardening would no be available. The frame would be assembled by welding under inert gas. Adhesive joining is also possible.

c. With its light weight, modulus of elasticity of about 50% greater than that of steel and strength comparable to steel, beryllium is a likely candidate for a bicycle frame based on mechanical properties. Practical limitations work against its use. It is very expensive in forms useful for bicycle frame construction, is so stiff that it is probably not useful for a bicycle frame and it is toxic.

d. In addition to joining the design of the tubes should be considered. Specifically, the orientation of the reinforcing fibers needs to specified. Bicycle frames are rigid in the plane of the frame due to the geometric design. Torsion of the frame components has to be considered and so fiber orientation in the fiber-reinforced composite tubes should be such as to make the tubes torsionally rigid. The tubes can be assembled into the frame using adhesives and plugs just as the original frame in this case study.

CHAPTER 38

Review Questions

1.In resistance welding, pressure is applied initially to hold the workpieces in contact and thereby control the electrical resistance at the interface. After the proper temperature is attained, the pressure is increased to bring about coalescence of the metal.

2. Because pressure is applied, coalescence occurs at a lower temperature than required for other forms of welding. Many resistance welds are formed without any melting of the base metal.

3. Applying additional pressure after coalescence in resistance welding provides some forging action with some grain refinement due to the deformation, and possibly some strain hardening. Additional heating can also be applied with the intent of tempering and/or stress relieving the weld zone.

4. Fluxes and shielding gases are used in welding to protect the welding zone form undesirable effects due to the ambient, native atmosphere. Since the pressure exerted between the workpieces in resistance welding precludes the introduction of the surrounding atmosphere, no flux or shielding gas is needed.

5. The total resistance between the electrodes consists of three components: (1) the resistance of the workpieces, (2) the contact resistance between the electrodes and the work, and (3) the resistance between the surfaces to be joined, known as the faying surfaces.

6. The resistance between the electrodes and the workpiece can be minimized by using electrode materials that are excellent electrical conductors, by controlling the shape and size of the electrodes, and by using proper pressure between the work and the electrodes .

7. If too little pressure is used, the contact resistance is high and surface burning and pitting of the electrodes can result. If the pressure is too high, molten or softened metal may be squirted or squeezed from between the faying surfaces or the work may be indented by the electrodes.

8. Ideally, moderate pressure should be applied to hold the workpieces in place and establish proper resistance at the interface prior to and during the passage of the welding current. The pressure should then be increased considerably to complete the coalescence and produce the forged, fine-grain structure.

9. The current applied in resistance welding varies through the process. A welding current is used and later in the process a postweld heating current is applied, Figure 38-3. The welding current is usually large, up to about 100,000 A.

10. Resistance spot welding is the simplest and most widely used form of resistance

welding.

11. Spot weld nuggets typically have sizes between 1/16 and 1/2 inch in diameter.

12. The two basic types of stationary spot welding machines are the rocker-arm machine and the press-type machine. The rocker-arm design is used for light-production work where complex current-pressure cycles are not required. Larger machines and those used at high production rates are generally of the press-type design.

13. Spot welding guns allow the process to become portable. The welding unit can now be brought to the work, greatly extending the use of spot welding in applications where the work is too large to be positioned on a welding machine (such as automobiles).

14. A transgun is a spot welding gun with an integral transformer. When accurate positioning is required in an articulated arrangement, such as an industrial robot, transguns may not be attractive because of the added weight of the integral transformer at the end of the arm.

15. The functions of resistance welding electrodes are to conduct current, set current density, apply force and dissipate heat. The electrode should not combine, alloy, with the work materials. In order to effectively accomplish these functions resistance welding electrodes must have appropriate values of electrical and thermal conductivity, hot compressive strength, melting temperature and composition. While not a physical, mechanical or chemical property, electrode shape also is a consideration in electrode selection.

16. Steel is clearly the most common spot-welded metal.

17. The practical limit of thicknesses that can be spot-welded by ordinary processes is about 1/8 inch (3 mm), where each piece is the same thickness. When thicknesses vary, a thin piece can be easily welded to another piece that is much thicker than 1/8 inch.

18. When metals of different thickness or different conductivities are to be welded, they can generally be brought to the proper temperature in a simultaneous manner by using a larger electrode or one with higher conductivity against the thicker or higher-resistance material.

19. In roll-spot welding, the seam is actually a series of overlapping spot welds, generally produced by two rotating disk electrodes. Continuous seam welding, on the other hand, applies a continuous current through rotating electrodes.

20. Projection welding enables multiple spot-type welds to be made simultaneously, and reduces the problems associated with electrode maintenance.

21. The number of projections is limited only by the ability of the machine to provide the required current and pressure.

22. Some of the attractive features of resistance welding processes as techniques for mass production include: (1) they are very rapid, (2) the equipment is semiautomatic or fully automated, (3) they conserve material (no filler metal is required), (4) Skilled operators are not required, (5) Dissimilar metals can be easily joined, and (6) a high degree of reliability and reproducibility can be achieved.

23. The primary limitations to the use of resistance welding are: (1) the high initial coat of the equipment, (2) limitations to the type of joints that can be made, (3) skilled maintenance personnel are required to service the control equipment, and (4) some materials require special surface preparation prior to welding.

24. Because of the rapid heat inputs, short welding times, and rapid quenching by both the base metal and the electrodes, the cooling rates in spot welds can be extremely high. In medium-and high-carbon steels, martensite can readily form, and a post-weld heating is generally required to temper the weld.

25. The forge welds of a blacksmith were somewhat variable in nature and highly dependent on the skill of the individual because his heat source was somewhat crude, temperatures were uncertain, and it was difficult to maintain metal cleanliness.

26. Coalescence is produced in cold welding by only the application of pressure. No heating is used, the weld resulting from localized pressures that produce 30 to 50% cold deformation.

27. By coating portions of one sheet with a material that prevents bonding and then roll bonding with another sheet, products can be made that are bonded only in selected regions. If the no-bond region is then expanded, the expanded regions can form flow channels for fluids.

28. Inertia welding differs from friction welding in that the moving piece is now attached to a rotating flywheel. The flywheel is brought to speed, separated from the driving motor, and the rotating assembly is pressed against the stationary member. The kinetic energy is converted to heat during the deceleration.

In friction welding, the contact is made while the driven piece is connected to the motor, all rotation is stopped, and the pieces are further pressed together.

29. In the friction and inertia welding processes, surface impurities tend to be displaced radially into a small upset flash that can be removed after welding, if desired.

30. Friction and inertia welding is restricted to joining round bars or tubes of the same size, or connecting bars or tubes to flat surfaces. In addition, the ends of the workpieces must be cut true and be fairly smooth.

31. In friction welding one piece of the two-piece workpiece pair is rotated while in contact with the other. The resulting heat and pressure produce welding between the two

workpieces. In friction stir welding there is a three-piece system, two plates or workpieces to be joined and a non-consumable probe, analogous to a tool. The probe rotates while in contact with both workpieces, softened work material flows around the probe and into the workpiece joint area and the workpieces joined.

32. Ultrasonic welding is restricted to the joining of thin materials, such as sheet, foil, and wire, or the attaching of thin sheets to heavier structural materials.

33. Ultrasonic welding can be used to join a number of metals and dissimilar metal combinations (even metals to nonmetals). Since temperatures are low, the process is an attractive one for heat-sensitive materials. The equipment is simple and reliable, and only moderate operator skill is required. Surface preparation and energy requirements are less than for competing processes.

34. Diffusion welding is a solid state bonding that occurs when properly prepared surfaces are maintained in contact under pressure and time at elevated temperature. Quality of the bond is highly dependent upon surface preparation.

35. If the interface of an explosive weld is viewed in cross section, it would exhibit a characteristic wavy configuration at the interface. See Figure 38-20.

36. A thermit weld is quite similar to a metal casting in that molten metal is produced externally and is introduced into a prepared cavity. In the case of the thermit weld, the super-heated metal is produced from the reaction between iron oxide and aluminum, and then flows into a prepared joint providing both heat and filler metal. Runners and risers must be provided, as in a casting, to channel the molten metal and compensate for solidification shrinkage.

37. In thermit welding, heat comes from the superheated molten metal and slag obtained from the exothermic reaction between a metal oxide and aluminum.

38. Thermit welding can be used to join thick sections of material, particularly in remote locations where more sophisticated welding equipment is not available.

39. In electroslag welding, heat is derived from the passage of electrical current through a liquid slag. Resistance heating within the slag causes the temperature increase.

40. In electroslag welding, the molten slag serves to melt the edges of the metal being joined, as well as the fed electrodes supplying the filler metal. In addition, the slag serves to protect and cleanse the molten metal.

41. Electroslag welding is most commonly used to vertical or circumferential joints because of the need to contain the pool of molten slag. The process is particularly attractive for the joining of thick plates (up to 36-inches thick).

42. High vacuum is required in the electron beam chamber of an electron beam welding

machine because electrons cannot travel well through air. In many operations, the workpiece is also enclosed in the high-vacuum chamber and must be positioned and manipulated in this vacuum.

43. In addition to having to position and manipulate production pieces in a high vacuum, there are size and shape restrictions imposed by the size of the actual vacuum chamber. The high vacuum must be broken and reestablished as pieces are inserted and removed, significantly impairing productivity. If welding is performed on pieces that are outside of the vacuum chamber, high capacity vacuum pumps must be used to compensate for leakage through the electron-emitting orifice. The penetration of the beam and the depth-to-width ratio of the molten region are considerably reduced as the pressure increases.

44. High-voltage electron beam welding equipment emits a considerable quantity of harmful X-rays and thus requires extensive shielding and indirect viewing systems for observing the work.

45. Almost any metal can be welded by the electron beam process. Dissimilar metals can be welded. The weld geometry offers a narrow profile and remarkable penetration. Heat input and distortion are low, and the heat-affected zone is extremely narrow. Welding speeds are high, and no shielding gas, flux, or filler metal is required.

46. Compared to electron beam welding, laser beam welding: (1) does not require a vacuum environment, (2) generates no X-rays, (3) can employ reflective optics to shape and direct the beam, and (4) does not require physical contact between the workpiece and the welding equipment (the beam can pass through transparent materials).

47. Laser beams are highly concentrated sources of energy and the resulting welds can be quite small. While the power intensity is quite high, the weld time is extremely small and the total heat input can be quite low. For these reasons, laser beam welds are quite attractive to the electronics industry.

48. In the laser beam cutting process, a stream of "assist gas" is often used to blow the molten metal through the cut, cool the workpiece, and minimize the heat-affected zone.

49. Through the use of a fiber-optic cable, laser energy can be piped to the end of a robot arm, eliminating the need to mount and maneuver a heavy, bulky tool that would produce elastic flexing of the components of the robot arm and affect the accuracy of positioning. Cutting and welding can then be performed with the multiple axes of motion of an industrial robot or CNC machine.

50. Laser spot welding can be performed with access to only one side of the joint. It is a non-contact process, involves no electrodes, and produces no indentations. Weld quality is independent of material resistance, surface resistance, and electrode condition. The total heat input is low, and the heat-affected zone is small.

51. The flashing action in flash welding must be long enough to provide heat for melting

and to lower the strength of the metal to allow for plastic deformation. Sufficient upsetting should occur that all impure metal is squeezed out into the flash and only sound metal remains in the weld.

52. Only the thermoplastic polymers can be welded, since these materials can be melted and softened by heat without degradation. The thermosetting polymers do not soften with heat but tend only to burn or char.

53. Thermoplastic polymers can be welded by methods that use mechanical movement or friction to generate the required heat (such as ultrasonic welding, friction welding, and vibration welding), and methods that employ external sources of heat (such as hot-plate welding, hot-gas welding, and resistive or inductive implant welding) .

54. Surfacing methods are usually used to apply;
- carbon and low-alloy steels,
- high-alloy steels and irons,
- cobalt-based alloys,
- nickel-based alloys,
- copper-based alloys,
- stainless steels,
- ceramics,
- refractory carbides, oxides, borides, silicates.

55. Surfacing materials can be deposited by nearly all of the gas-flame or arc welding methods, including: oxyfuel gas, shielded metal arc, gas metal arc, gas tungsten arc, submerged arc, and plasma arc. Laser hardfacing has also been performed.

56. Several of the thermal spray processes are adaptations of oxyfuel welding equipment involving some form of material feed. Electric arcs can be used to melt the material and produce the molten particles, and plasma spray processes are also quite common .

57. Thermal spraying is similar to surfacing and is often applied for the same reasons. The thermal spray coatings are usually thinner, and the process is more suited for irregular surfaces and heat sensitive substrates.

58. In metallizing, the bond between the deposited material and the base metal is a purely mechanical one. To enhance mechanical interlocking, the surface can be roughened by a variety of methods, including: grit blasting or the machining of grooves followed by deformation to roll over the crests or mushroom the flat upper surfaces.

59.In spraying coatings a material layer is formed so material can be added to a substrate and the material properties of the coating can be controlled to produce desirable surface behavior in use. Applications include
- restoring worn parts to original dimension by spraying material followed by finishing operations,
- producing protective coating such as for corrosion protection,

- hard surfacing to produce wear resistant surface layers while maintain the desirable properties of the substrate, including economic consideration or characteristics,
- applying thin coatings in situations where establishing a plating operation is not warranted,
- applying electrically conduction coatings,
- applying optical coatings,
- applying decorative coatings,
- producing tailored surface characteristics such as specified surface profile or layered structure.

Problems:

1. This is really an open-ended library-type research assignment, and the results will vary considerably with the specific process chosen to investigate.

2. Thermosetting polymers can be joined by such processes as:
adhesive bonding, threaded fasteners, riveting, and other types of mechanical joining. Similar restrictions apply to the elastomers, but threaded fasteners are not as viable. For ceramic materials, the most common method of joining is adhesive bonding. Mechanical joining requires the use of large washers or load distributing devices, and rivets are seldom employed.

Case Study: Field Repair to a Power Transformer Case

1. The primary restriction here is the need for portability. A process, such as oxyacetylene welding requires only bottled gas, flow regulators and an appropriate torch. These can be scaled and are readily portable. The arc welding methods require a power supply, and an AC, plug-in outlet is not likely to be available. Thus, the electrical capabilities will be limited to those that can be provided by a portable generator. These can be truck-mounted and powered by gasoline motor. The finite-length stick electrodes of the shielded-metal arc process would be quite appropriate for this application because of the wide variety of materials, geometries, and applications encountered in field repair. Gas tungsten arc and gas metal arc are also possibilities. The size and geometry (fillet joint) would not be attractive for the electroslag, submerged arc, or thermit processes, and the equipment required for other alternatives would not be sufficiently portable.

2.- 4. This information can be found by surveying various texts and handbooks. Selection is really a matter of preference, with due consideration to material, the need to weld in both downward and upside-down fillet positions, and the probability of oil contamination and possibly even paint (this is a field repair on an installed item).

CHAPTER 39

Review Questions

1.Low-temperature production joining methods include: brazing, soldering, adhesive joining, and the use of mechanical fasteners.

2. The characteristic feature of brazing, and so important in its definition, is the use of a filler material with melting temperature above 450^o but below the melting temperature of the materials to be joined. Many processes use heat and filler metal, but brazing implies a certain use (capillary flow into the braze joint) and type of filler material.

3. Brazing employs a filler metal whose melting point is below that of the metals being joined. It differs from welding in that: (1) the composition of the brazing alloy is significantly different from the base metal, (2) the strength of the brazing metal is substantially lower than the base metal, (3) the base metal is not melted during joining, and (4) bonding requires capillary action.

4. Since neither of the base metals are melted during the brazing operation, and the bond is formed by introducing a lower melting temperature metal into the gap, the brazing process is attractive for the joining of dissimilar metals, such as ferrous to nonferrous or metals of widely different melting points.

5. Because brazing introduces a filler metal of different composition from the materials being joined, and the process can be used to join dissimilar metals, brazing can result in the formation of a two-component or three-component galvanic corrosion couple.

6. Braze joint clearance is the most important factor determining joint strength. Joint clearance determines if capillary action will be effective in filling the joint gap. Capillary action is the movement of a fluid into a small space driven by surface attraction force.

If the joint clearance is too small, the filler metal may be unable to flow into the gap and the flux material may be unable to escape. If the gap is too great, capillary action may be insufficient to draw the metal into the joint and hold it in place during solidification.

7. The clearances necessary for good flow and wetting of the joint are those that are present at the temperature of the brazing process. The effects of thermal expansion should be compensated when specifying the dimensions of the joint components.

8. The two most common types of brazed joints are butt joints and lap joints. Butt joints are attractive since they do not require additional joint thickness in the braze region. Lap joints are attractive since the relatively large area compared to butt joints results in high joint strength.

9. Some of the considerations when selecting a brazing alloy include: compatibility with the base materials, brazing temperature restrictions, restrictions due to service or

subsequent processing temperatures, the brazing process to be used, the joint design, anticipated service environment, the desired appearance, the desired mechanical properties, the desired physical properties, and the cost.

10. The most commonly used brazing metals are copper and copper alloys, silver and silver alloys, and aluminum alloys.

11. Silver solder is a brazing filler material.

12. In brazing, a flux is used to: (1) dissolve oxides that may have formed on the metal surfaces, (2) prevent the formation of new oxides during the heating, and (3) lower the surface tension of the molten brazing metal and promote its flow into the joint.

13. Clean surfaces are needed for brazing and while fluxes can remove some surface oxides they are not designed to be exclusively cleaners. To provide a "clean enough" surface so the flux can act as a fluxing agent and secondarily as a cleaner, precleaning by chemical and/or mechanical means is necessary.

14. Brazing is done to provide a joint between materials and one of the functions of the joint is to provide proper geometric relationships between the components of the entire structure. If the geometric relationships are important, positioning of the pieces to be joined before and during brazing can be maintained using jigs and fixtures. Brazing jigs and fixtures are especially important for complex structures since without proper support movements in the joints can produce large errors in final structure configuration.

15. The primary attraction of furnace brazing is that a number of parts/products can be processed simultaneously and so production rates can be high.

16. In furnace brazing, reducing atmospheres or a vacuum are frequently used to prevent the formation of surface oxide and possibly reduce any existing oxides and eliminate the need for a brazing flux. If reactive metals must be brazed, a vacuum may be required.

17. In dip brazing, the entire assemblies are immersed in a bath of molten brazing metal. The braze metal will usually coat the entire workpiece, so such a process is wasteful for all but very small assemblies.

18. Some of the attractive features of induction brazing are: (1) heating is very rapid, (2) the operation can be made semiautomatic (requiring only semi-skilled labor), (3) the heating can be confined to a localized area (reducing scale, discoloration, and distortion), (4) uniform results are readily obtainable, and (5) by changing coils, a wide variety of work can be performed with a single power supply.

19. Since most brazing fluxes are corrosive, the residue should be removed from the work immediately after brazing is completed.

20. Braze welding differs from straight brazing in that capillary action is not used to

distribute the filler metal. Low melting temperature filler metal is simply deposited into a joint by gravity.

21. The distinction between soldering and brazing is one of temperature, soldering being a brazing-type operation where the filler metal has a melting point below 840^0F (450^0C).

22. Solder joints are not strong because low melting temperature, weak materials are used for solders, low soldering temperatures are used and the bonding of the solder to the pieces to be joined is primarily mechanical. There is no strong metallurgical bonding developed as in the case of welding where the work material and filler material are melted and recombine.

23. The most common soldering alloys are composed of lead and tin.

24. Health and environmental concerns about lead are driving the search for and development of leadfree solders.

25. A successful conversion to leadfree solders means that the functions of the solder must be effectively and efficiently provided by the new solder material. Properties related to useful solder characteristics are melting temperature, wettability, electrical and thermal conductivity, thermal expansion coefficient, strength, ductility, creep resistance, thermal fatigue resistance, corrosion resistance, manufacturability and cost. Obtaining adequate solder characteristics and behavior involves a large number of factors and so a number of difficulties. Other difficulties in conversion to leadfree solders are the development of useful fluxes and the design of processes that will use the new solder.

26. Any of the heating methods used for brazing can be used for soldering, but most soldering is still done with electric soldering irons or small torches. For the low-melting-point solders, infrared heaters can be used.

Problems:

1. a. The corroding member of the corrosion cell is the component that gives up electrons (oxidation) – the anode. The driving force for the electrochemical reaction is the voltage that develops between the anode and the cathode at which the reduction reaction occurs. Standard electrochemical cells are used to measure the voltage between a sample material and a standard, platinum, electrode in a standard cell at standard conditions. The electromotive force series is developed from such tests. The metals that are lower on the electromotive series experience oxidation, corrosion, with respect to metals higher on the series. A similar, widely-used indication of corrosion susceptibility is the galvanic series which presents the relative reactivity (no electromotive voltages are provided) of materials in seawater. Again, the more cathodic materials are at the top of the series and more anodic materials toward the bottom of the series.

Electromotive force and galvanic series are available in many textbooks and handbooks (e.g., Corrosion Engineering, M. G. Fontana, McGraw-Hill, 1986) and show that for
i. low-carbon steel – copper-based brazing alloy the anode will be steel
ii. copper wire – steel sheet – lead-tin solder the anode will be steel
iii. tungsten carbide - carbon-steel the anode will be steel since most brazing materials are lead and tin alloys.

2. The tin-antimony and tin-copper solders are expected to be more cathodic than the lead-based solders since lead is below copper and tin (slightly) on the galvanic series.

3. The three general ways to change interactions between materials in a galvanic corrosion situation are to change materials, to change the surrounding environment and to change the galvanic cell by introducing another material(s). The material changes possible are changing the materials that are joined and/or the braze material. The function of the joint will determine if this is feasible. Changing the environment is problematic since this will probably entail significant, qualitative changes in the system in which the brazed joint must function. Inserting a sacrificial body (anodic with respect to all other materials in the joint) into the system may be a possibility.

Case Study: no case study

CHAPTER 40

Review Questions

1. The ideal adhesive bonds to any material, needs no surface preparation, cures rapidly, and maintains a high bond strength under all operating conditions.

2. Structural adhesives are bonding materials that can be stressed to a high percentage of their maximum load for extended periods of time without failure.

3. Some newer applications of adhesive bonding are medical and dental applications (e.g., cosmetic dentistry), bonding composite materials (laminates) and joining major components of automobiles (body panels).

4. Some types of industrial adhesives are epoxies, cyanoacrylates, anaerobics, acrylics, urethanes, silicones, phenolics, polyamides and thermoplastics.

5. Curing of the structural adhesives can be performed by the use of heat, radiation or light (photoinitiation), moisture, activators, catalysts, multiple-component reactions, or combinations thereof .

6. Typical epoxies have use temperatures of –50o C to 250o C (-60^{o} F - 500^{o} F), shear strength of 10 MPa to 70 MPa (1500 psi – 10,000 psi) with strength dependent on temperature and curing time of minutes to days.

7. Trace amounts of moisture on the surfaces promote the curing of cyanoacrylates. The anaerobic adhesives remain liquid when exposed to air. However, when confined to small spaces and shut off from oxygen, as in a joint to be bonded, the polymer becomes unstable. In the presence of iron or copper, it polymerizes into a bonding-type resin.

8. The silicone adhesives form low-strength joints, but can withstand considerable expansion or contraction. Flexibility and sealing ability are other attractive properties. Numerous materials can be bonded, and the bonds resist moisture, hot water, oxidation, and weathering, and retain their flexibility at low temperatures.

9. Nonstructural adhesives include
- evaporative adhesives that are usually organic or water base solvents containing vinyls, acrylics, phenolics, polyurethanes and various kinds of rubber,
- pressure-sensitive adhesives that use rubber compounds as the adhesive media,
- delayed-tack adhesives that usually use rubber based adhesive that require heat activation,
- conductive adhesives that are adhesive binder containing conductive particles,
- radiation curing adhesives such as photocuring polymers used in rapid prototyping and dental applications.

10. Conductive adhesives can be produced by incorporating selected fillers, such as

silver, copper or aluminum flakes or powder. Certain ceramic oxides can provide thermal conductivity.

11. Temperature considerations relating to the selection of adhesives relate to both the temperature required for the cure and the temperatures likely to be encountered in service. Consideration should be given to the highest temperature, lowest temperature, rates of temperature change, frequency of change, duration of exposure to extremes, the properties required at the various conditions, and the differential expansions or contractions.

12. Environmental conditions that might reduce the performance or lifetime of a structural adhesive include: exposure to solvents, water, or humidity, fuels or oils, light, ultraviolet radiation, acid solutions, or general weathering.

13. The stress state in a bonded joint can be tension, shear, cleavage, or peel, as shown in Figure 38-1. Since most adhesives are much weaker in peel and cleavage, joints should be either shear or tension. Looking further, the shear strengths are greater than the tensile strengths, so the best adhesive joint would be one in which the stress state is pure shear.

14. The strength of an adhesive joint depends on the strength of the bond between workpieces and adhesive and the area of adhesion. Butt joints are undesirable since the contact area is small giving relatively low strength joints compared to other joint configurations.

15. Surface preparation procedures vary widely, but frequently employ some form of cleaning to remove contaminants and grease. Chemical etching, steam cleaning, or abrasive techniques may be used to further enhance wetting and bonding.

16. Almost all materials or combinations of materials can be joined by adhesive bonding. The low curing temperatures permit heat sensitive materials and thin or delicate materials to be joined. The resulting bond can tolerate the thermal stresses of differential expansion or contraction.

17. The primary property of structural adhesives is strength. Other attractive properties of various adhesives are

- low curing temperature and so the ability to join temperature sensitive materials and no production of a heat affected zone,
- mechanical flexibility and so the capability to adapt to differential expansion and contraction between the joined components,
- flow during application and mechanical flexibility and so the possibility of reducing susceptibility to fatigue which usually is initiated at sharp surface irregularities,
- low thermal and electrical conductivity and so the ability to be used as insulators,
- high damping compared to solid interfaces and so good shock, noise and vibration insulation,
- low corrosion susceptibility,
- flow during joint formation and so the ability to be used as a sealant,

- potentially low cost.

Some desirable characteristics of the adhesive joint are

- high strength if large areas are joined,
- large adhesion areas and so the ability to distribute load,
- small or no stress raisers.

18. From a manufacturing viewpoint, joint formation does not require the flow of material, as with brazing and soldering, but the adhesive is applied directly to the surfaces. The adhesives can be applied quickly, and useful strengths are achieved in a short period of time. Surface preparation may be reduced, since bonding can often occur with a oxide film on the surface. Rough surfaces are an asset; tolerances are less critical; and no prior holes have to be made. In addition, the process lends itself to robotics and automation.

19. Most industrial adhesives are not stable at temperatures above ~50^{0}F. Oxidation reactions are accelerated, thermoplastics soften and melt, and thermosets decompose.

Since most adhesives are not stable above 350^{0}F, the structural adhesives would not be attractive for applications that involve exposure to elevated temperatures. At low temperatures, some of the adhesives become brittle.

20. Adhesives bond the entire joint area. Force equals strength times area. By providing large contact areas, the relatively low strength structural adhesives can be used to produce joints with load-bearing abilities comparable to most alternative methods of joining or attachment.

21. Selection of a specific fastener or fastening method depends primarily upon the materials to be joined, the function of the joint, strength and reliability requirements, weight limitations, dimensions of the components, and environmental considerations. Other considerations include cost, installation equipment and accessibility, appearance, and the need or desirability for disassembly.

22. If there is a need to disassemble and reassemble a product, threaded fasteners or other styles that can be removed quickly and easily should be specified.

23. Integral fasteners are regions of components that are specifically formed to be used as parts of fasteners. An example is the formed parts of the top and tabs on aluminum beverage containers. The top and tab have formed regions that are produced as the top and tab are being manufactured. These regions are aligned and further deformed when the top and tab are joined.

24. A press fit differs from a shrink or expansion fit in that mechanical force produces the assembly, not differential temperatures and thermal expansions and contractions. Both involve a strong interference fit to produce a high-strength mechanical joint.

25. The most common causes for the failure of mechanically fastened joints relate to joint preparation and fastener installation. Hole manufacture and alignment, installation with too much or too little preload, misalignment of surfaces, insufficient area under load-

bearing heads, and vibrations that can lead to further loosening of the joint (and fastener fatigue) are all areas of concern.

26. The use of standard fasteners would enable ready access at reasonably attractive cost. Nonstandard fasteners require scheduled production, possible delays and additional expense. By minimizing the variety of fasteners within a given product, there is a reduced likelihood of mix-up or exchange of pieces during a disassembly and reassembly, or even within the initial production and assembly line. Moreover, inventory costs could be reduced, and by using larger quantities of a given fastener, a reduced price might be available.

Problems:

1. An interesting opportunity is available if elevated temperature can be used to bake coatings and also influence material characteristics such as mechanical properties of the material to be coated. Data is provided at *ussautomotive.com/auto/tech/grades/dual_ten.htm* that shows typical paint-bake temperature of 177° C (350° F) and that there is a change in yield strength due to bake-hardening.

In addition to bake temperature the bake time has to be considered since adhesive curing time, as well as temperature, is a concern.

Given the adhesive cure temperatures in Table 40-1, and the belief that using too high a temperature will degrade the adhesive and produce unacceptable joints, the possible adhesives are epoxies, phenolics and urethanes.

The primary pro of such an integration of paint baking and adhesive curing is the elimination of individual operations with separate tooling, facilities and personnel and replacement with a combined, simpler operation. The major con is that with the loss of an individual process the relatively tight control, operation and optimization available for the process is compromised as the integrated process is designed operated and optimized to accomplish two or more operations.

2. When iron (steel) is galvanically coupled with passive aluminum, iron becomes the anode and undergoes preferential corrosion. (Aluminum is below steel in the galvanic series - see Problem 1, Chapter 39) With moisture being the electrolyte that completes the electrical circuit, we have a corrosion cell with very small corroding anodes (the heads of the iron nails) and large cathodic surfaces (the aluminum siding). The heads of the nails will rapidly corrode and the siding will eventually separate from the house. Aluminum siding should be installed with aluminum nails.

3. Hole preparation would be a major area of concern, because we must now produce holes in a fiber-reinforced material. Mechanical means will tend to produce frayed surfaces. Thermal means may damage the fibers and matrix.

Joint design is also a concern. While the composite material may offer attractive strength properties, these properties may not be present around a fastener where the continuity of the fibers has been disrupted. Screws and similar threaded fasteners will be limited by the strength of the polymeric matrix. Compression fasteners, such as bolts and rivets, may require the use of large washers to spread the load over a larger area. A variety of service-type failures could be considered.

Case Study: Golf Club Heads with Insert

1. Since the club head is a martensitic stainless steel, it achieves its strength by a quench and temper heat treatment. Subsequent exposure to temperatures in excess of the tempering temperature will result in a further loss of strength and hardness. In addition, exposure to temperatures near 1000OP will enable the atomically-dispersed carbon and chromium atoms to diffuse and unite to form chromium carbides. The depletion of chromium will leave the adjacent regions with less than 12% chromium free to react with oxygen to form the protective (corrosion-resistant) oxide. The stainless steel is no longer "stainless" and will be subject to red rust. For these reasons, coupled with possible warping of the thin insert, the joining method is limited to low temperature methods. While brazing or, more preferably, soldering might be possibilities, these methods provide metallic joint, and the electrical conductivity coupled with the presence of two or more dissimilar metals creates a galvanic corrosion cell in a product that may be exposed to humidity and moisture as they are stored in car trunks and other locations. Rivets, screws and other fasteners are possible, but the joining becomes localized, and the possibility of gaps and related dampening is a real one. Among the low-temperature methods, it appears that some form of adhesive bonding would be the most preferred means of assembling the components.

2. The same problems with the martensitic stainless steel restrict the temperature of the joint. Most of the above methods continue as options, with brazing or soldering being eliminated because of the polymeric shaft, and shrink or press fits becoming additional alternatives. If the shaft were metallic, brazing or soldering reenter the picture. If the shaft is sufficiently solid, some form of hole and rivet is a possibility.

3. If the same procedure is to be applied to both joints, one between dissimilar metals, and the other between stainless steel and fiber-reinforced epoxy, then some form of adhesive would appear to be preferred. NOTE: It may also be desirable to consider alternative means of creating the composite club face, such as flame-spray deposition of the carbide-containing surface -- which would eliminate the need to bond two dissimilar metals.

4. The general process being proposed is the removal of material from around the carbide particles. The alternative is to add carbide particles to the club face. Particle deposition processes are limited to those that will form a strong bond at the carbide particle-substrate interface and not have adverse effects on the substrate to which the particles are applied.

Adhesives will not be useful since they will not supply strong adhesive forces over the small particle-surface contact areas. Spraying processes such as plasma spraying will not be useful since they will affect club face properties and performance.

Starting with the proposition that using an insert does not affect club performance, it is probably less expensive to produce inserts and add them to the club face, rather than trying to produce a one-piece club head with a specially prepared face. Inserts can be produced in batches. Inserts can be finished by specially designed processes without concern about affecting the rest of the club head, e.g., edge smoothing by sanding without concern about the sanding process extending to the parts of the club face surrounding the inserts.

If there are performance advantages to a single piece club head, and there may very well be effects of the insert-club head interface on performance, then entire club heads should be produced and the hard particles added to only the club face. In addition to selecting the process, process control concerns arise. The particle deposition process must not extend to regions beyond the club face area of interest. This approach probably will be more expensive than producing separate inserts and bonding them to club faces.

The low process temperature, high bond strength requirements lead to consideration of what are fairly exotic processes for mass produced consumer goods, but are much less unrealistic for high end golf clubs that are semi-custom products. Possible processes are,
- electroless composite plating and variations of such processes, Chapter 31,
- laser sintering, Chapter 33,
- low temperature furnace brazing ,Chapter 39

Club heads can be produced in batch mode in plating and brazing processes so unit cost can be low.

The performance of the raised parts/particles themselves is an issue. If these regions wear or are removed, the benefits of them being on the face are lost. Inspection of used clubs with abrasive particles in the face will show a worn region. The carbides are not expected to wear. But they will be removed from the club face either by fracture of the hard, brittle carbide or by separation at the carbide-metal interface. Again the strength of the particle-face bond is critical.

CHAPTER 41

Review Questions

1. The production system includes design engineering, manufacturing engineering, sales, advertising, production, inventory control and the manufacturing system.

2. a. The route sheet is a document which describes the route or path that the parts must take in the production job shop. Each machine is indicated on the route sheet and the parts are transported from machine to machine in tote boxes or carts.
b. The function of the route sheet is to specify the sequence of operations and processes needed to convert the part from raw material into a finished product.
c. Cooking recipes contain route sheets. They are also partly a bill of materials and an operation sheet.
d. The route sheet is also called a traveler since it moves with the parts.

3. Examples of a process flow chart and a bill of materials are given in Figure 41-18. This type of process flow chart outlines the sequence of manufacturing steps to produce the final product in terms of components of the product and their order of use. This description is in contrast to specifying the processes and machines used to produce, manipulate and assemble the components.

The bill of materials lists the materials and components needed to produce one unit of final product. The process flow chart is related to the bill of materials in that it shows where (time and location) in the process the items in the bill of materials are used. This indicates when the items will be needed and determines not only the items to be obtained but also when they are needed enabling rational procurement and production planning.

4. An operations sheet gives more specifics with regard to the processes needed to make the part while the route sheet, a production control device for the job shop, provides information about where the part is to go next for more operations. In the visual factory, operations sheets are posted right at the machine for all to see.

5. The master production schedule is a document that specifies the products to be produced, the quantity to be produced and the delivery date.

6. MRP can mean material requirements planning and is a tool for calculating the quantities of items and/or amounts of material needed for use in each stage in the production process and when they will be needed. Manufacturing resource planning MRP encompasses the same general idea but expands it to include consideration of all resources, not just materials. For example, it is used to specify materials, labor, machines, etc. that are needed and the time and location of the requirements.

The master production schedule specifies products and their time of production and so sets the outcomes, or dependent variables or dependent demands, that are in the production system. Material requirement or resource planning specifies the materials and other resources and when they must be available to meet the dependent demands specified in the master production schedule.

7. The economic order quantity usually refers to materials and components, not to such manufacturing resources as labor, and so is used in material requirements planning. In material requirements planning the amount of material and time it is needed is set. This is an overall system or global set of requirements. The economic order quantity calculation provides a way to decide on the best way to obtain the materials within the larger MRP framework. Materials must be available to the production system when they are needed. However, the cost of the materials depends many factors and the economic order quantity specifies the best way to order the materials that have to be in the system at specified times.

8. The functional objectives of production control are to produce the timing and coordination to ensure that product delivery meets customer demands.

9. The function of inventory control is to ensure that enough products of each type are available to satisfy customer demand. This concept can be applied at any level of the enterprise by changing the definition of the customer. For example, a single machine station can be a customer relying on inventory control to assure that the workpieces supplied to it from the previous step in the process are available when needed.

10. Production control refers to controlling the movement of the materials to the right machines at the right times. Production control deals with when to make the products (scheduling) on which machines in what quantities. Inventory control deals with having the right amounts of materials in the system available at the right places at the right times.

11. The design determines which manufacturing alternatives will be available to make the part. The design along with the needed volume and the material selected for the part all influence the choice of the manufacturing processes. For example standardizing the design of the thread type and hole size greatly simplifies the design of manufacturing cells. Suppose the design calls for 16 RMS finish. The manufacturing system will probably need a grinding operation to meet this design specification. The manufacturing cell design would have to include grinding capability. Design also influences the production system in many ways. Designing things that customers want to buy, that can be readily inspected for quality, that are reliable, and that are safe for the customer to use are all design aspects that impact the production system. Because design occurs before all the other functions described in the manufacturing and production systems, it obviously is the driving force.

12. This statement means that a large expensive piece of software adds a large fixed cost to the total cost of making something in the same way a large expensive piece of hardware adds a large fixed cost to the total. Both costs will require a large volume of parts to be made to cover the cost. The problem is that while hardware (equipment) can be depreciated and some of its cost recaptured through tax savings, software costs are not depreciated and are generally hidden in the overhead costs of the company .

13. The part described in Figure 41-20 is a simple turned part and for a quantity of 25 is produced on an engine lathe, a general purpose machine. As production quantity increases the use of more special purpose machines can be justified based on unit cost to produce the parts. The more specialized machines for this type of turned and threaded part are, in increasing order of specialization, turret lathes, screw machines and turning followed by thread rolling machines. It is doubtful that any advance past use of a turret lathe would be warranted, and perhaps not even use of a turret lathe if one was not already available.

This same kind of question is considered in more detail in Problem 8, Chapter 32.

14. A route sheet lists the processes that are required to produce a part, the sequence of processes and the machines and tooling to be used. An operations sheet lists the sequence of operations to be performed on a single machine, at a single work station or on a given workpiece in a specified group of machines. The operation sheet provides the details needed to carry out the individual processes specified on the route sheet.

15. Ergonomics deals with the mental, physical and social requirements of work and how the work is designed or modified to accommodate human limitations, Section 43.7. The Ergonomics Society (*www.ergonomics.org.uk*) says that, Ergonomics is the application of scientific information concerning humans to the design of objects, systems and environment for human use.

16. The mrp generates orders for the shop, which generates the orders for purchased parts (from the vendors) and the orders for subassembly and component manufacturing. The MPS uses the information in the BOM as one of its inputs. The BOM lists all the parts that are in the product. The MPS uses the information regarding the capacity of the systems compared to the orders for the components and products to generate a master schedule.

17. Computer integrated manufacturing is the use of computers to run machines and to store all the information needed to manufacture a product and to manipulate all the data and information in any activity related to the manufacture of the product. Manufacturing of the product is defined in the very broadest sense, all the way from market study and conceptual design to disposal or recycling.

18. A manufacturing system is a sequence of processes and people that actually produce the desired product(s), Section 41.3.

Manufacturing system characteristic	Comparison in university
processes	lectures laboratory activities research outreach
sequence	progression form lower level to upper level courses
people	faculty staff students
products	education new knowledge service to various communities

Internal customers for faculty are students, internal customers for staff are faculty and students.

Products are educated people, new knowledge and service to communities such as theater and sporting event audiences and professional societies.

19. In a project shop the critical path is the longest path in terms of time through the sequence of steps that are needed to produce a product. The paths show activities needed to produce the product and are formulated on diagrams that show the manufacturing steps, their sequence, interrelationships and the time needed for each.

20. For example, the work boot of a foundry worker has steel toes and a strong arch to protect his toes from heavy objects being dropped on them and provide good support on the hard concrete floors of the foundry. One doesn't wear sandals in the foundry as these are designed for entirely different purposes.

21. The overhead costs include all those costs necessary to run the factory but which are not tied directly to the product. The cost of the foreman or the forklift truck drivers, power, light, heat, indirect materials, and so forth are all totaled into the overhead cost.

22. Manufacturing systems are systems composed of subsystems that interact with each other and with the entire system. Manufacturing systems have inputs such as materials, energy, customer demands social pressure and capital. The system contains people, material being worked, machines, equipment, supplies, information and data systems. Areas of control in the system are production rate, product mix, inventory, quality and machines. The system outputs are goods, services, information and unusable material and data.

Stability usually means a system response that is small compared to the input causing it and that the response to the disturbance decreases rapidly over time. System stability is usually increased in two ways. One is to include feedback into the system controller and operate the system so as to drive the difference between desired behavior and the measured actual behavior to zero. In terms of manufacturing systems this implies producing feedback from the overall system output of product characteristics and quantity, etc. and also from subsystem components such as production and inventory control system and establishing a control system that acts on these feedback signals.

The second way that system stability is increased is at the system design level. It is to design and implement system components and systems that are relatively insensitive to disturbances and/or to operate systems away from operating points that are sensitive to disturbances. The general concept is to design and use subsystems that have a flat response to changes in operating conditions. For example, in terms of cost, inventory systems that have holding cost per unit that does not change appreciably with held quantity are more stable than inventory systems with large dependence of unit holding cost on in-stock quantity. The lower, more constant holding cost system is more stable in the sense of decreasing the importance of uncertainty in economic order quantity considerations for example.

There is also the possibility of decreasing variability of inputs to the system. This is a way to influence system behavior but is not a way to make the system inherently more stable

23. Since there are critical paths in all systems that include preference relations, there is a critical path through the academic job shop.

24.

	Quality	Cost	Delivery	Flexibility
Job shop	high based of worker skill	high product cost due to high throughput time, large inventories, general purpose machines	long due to production of many different kinds of small batch parts and so long many, long changeovers	high due to functional design
Flow shop	high if system stable	high plant cost due to use of specialized machines and equipment	short due to use of specialized equipment and dedication to few products	low due to specialized production and materials handling equipment
Lean shop	high due to local control at cell level	low plant cost due to low inventory		high since cells can be reconfigured and worker flexibility

25. A high-volume transfer line for machining is characterized primarily by a lack of flexibility. The product mix is extremely small and so little flexibility is needed in the individual processes or in the material handling equipment between the processes.

Given the true function of a transfer line as the production of very similar parts at high rate there does not appear to be a reason for considering lean manufacturing concepts that are intended to capitalize on flexibility

However, there are some reasons to expect the need for flexibility to be important in high volume products. Product life in terms of changing product characteristics, not product failure, is becoming shorter. Flexibility in changing large production systems is needed. Product semi-customization is becoming a customer demand calling for production system flexibility. The possibilities for incorporating lean manufacturing concepts into high volume production situations are expanding.

There are some counter-trends. For example, building several car models on one platform is a move toward reducing product variations and so less flexible manufacturing systems are required. The number of models may increase but certain aspects of them become less variable.

26. Mass production plants have been evolving into lean plants designed for flexibility through the
- development of manufacturing and assembly cells linked to each other and to final assembly by specific material control systems,
- production of functionally integrated systems for inventory and production control,
- grouping of cells according to the sequence of operations needed to produce the part.

The intent is to convert the linear, fixed arrangement of flow lines into easily reconfigurable cells with short cell and machine setup times.

27. One way to quantify manufacturing system performance is in terms of profits generated. For a particular product the profit can be calculated from

profit per part = selling price – unit cost

and if this is put in terms to include the production rate and sales rates

profit = (selling price)(number sold) – (unit cost)(number produced).

This indicates that to increase profit efforts should be made to
- increase the selling price, perhaps by controlling production or providing customization,
- increase the number of units sold, perhaps by appealing to, or creating, new markets,
- decreasing the unit cost, as in the best use of mass production, flow lines,
- bring the number of units produced into line with the number sold requiring accurate forecasting of demand.

28. The Ford system was the refinement of the mass production system. The system relied on division of labor, moving assembly lines, real-time stock control and reliance on assembly cycle time predictability and control. A large part of the usefulness and efficiency of such a system is similarity of parts, bordering on complete interchangeability.

The essential feature of the Toyota Production System is a linked-cell manufacturing system with the linking generated by material control systems. With respect to the Ford or mass production system the similarity is that the control of material flow drives the system. The difference is in the way material flow is controlled. Another similarity is the importance of part quality in making the systems successful. Implicit in the mass production, interchangeable part system is the reliance on truly interchangeable parts. In the initial fit and function sense, if not in life cycle performance, this can be viewed as high quality. And this high quality made it possible to assemble a large number of cars in a short time. Quality is also a mark of the Toyota system, but is produced in a different way, based on in-process control, rather than being assumed for the input to work stations on the mass production line.

29. If the unit cost of each operation needed to produce a product is minimized the impact
a. on machine design is minimal whether the machine is considered to be the product or the production machine,
b. on workers' is minimal, unless there is profit-sharing,
c. on the factory as a manufacturing system is probably improved performance since total system production cost may be reduced since it is reasonable to assume that the plant has been run by competent people. However, in the true system wide view this may not be so clear or always the case. The system cost is much more than the sum of the process unit costs. There are costs associated with the factory and parts of it that are not directly related to individual processes. For example, the complexity of the system has a cost and so machines grouped in different ways with produce different costs for the system, even if the unit costs of all individual operations remain the same.

30. The Ford system was the refinement of the mass production system. The system relied on division of labor, moving assembly lines, real-time stock control and reliance on assembly cycle time predictability and control. A large part of the usefulness and efficiency of such a system is similarity of parts, bordering on complete interchangeability. Part interchangeability is a hallmark of the first industrial revolution and the Ford system built on it.

Problems: no problems

Case Study: Fire Extinguisher Pressure Gage

1. A number of questions come to mind. How many failures have been recorded? Are they all from the same batch or production run? How long have the failed components been in service? Under what conditions of temperature, humidity, corrosive environment, etc.? Have they been serviced or recharged? If so has the maintenance been performed properly? what gases or chemicals might be present in the interior of the tube? Are these potentially dangerous or might they react with the tubing? what is the normal internal pressure? Could the chemicals present in the extinguisher have played a role? How was the tube manufactured? Was the starting tubing seamless or seamed tubing? How much cold work was imparted to the tubing? Was a stress relief or anneal incorporated after forming? what was the likely ductility of the tubes when put into service? Were the tubes inspected? If so, how? In the failed components, is the failure by a single crack or multiple cracks? Do the cracks have a branching appearance? Do they follow the flow lines of deformation? Are they intergranular or transgranular? Are any corrosion products observable? Is there evidence of any plastic deformation, such as would be present if the

tubing had burst? Could mishandling have caused the damage?

2. The tubing could have been defective as it came from the original supplier. If the tubing was seamed tubing, this could be the location of a poor bond. Massive inclusions, seams, laps, and other metallurgical defects could produce failures of this sort. If this were the case, there should be some correlation to tubing supplier, date of manufacture or batch, etc. Also, metallographic examination should reveal features that confirm the presence of metallurgical defects in the tubing. In this case, the cracks should have formed as the bourdon tube was being manufactured. Defects of this type should have been detected by the manufacturer.

An overpressurization could have occurred, causing the tubing to burst. In this case, plastic deformation should be observable and the fractured regions should be flared toward the outside of the tubing. A single burst should be present, and the fracture would most likely be transgranular.

Copper-base alloys are also susceptible to stress-corrosion cracking, especially when present in moist or humid environments. If this were the case, metallography would reveal the crack to be brittle in appearance, following grain boundaries in the direction of prior working, and be a branching crack (most likely, multiple cracks should be present). The absence of a prior anneal or stress relief would be noted. Standard tests could be conducted to determine the susceptibility of the particular material to stress-corrosion cracking.

Mechanical abuse might also be considered, but for an expectedly ductile material, there should be signs of plastic deformation that would have preceded final fracture.

3. Of the mechanisms proposed above, only stress-corrosion cracking would account for a satisfactory product being made at the manufacturer and the defect forming at a later time when the product is in service. Cracking due to defective tubing should have occurred during the process of forming the bourdon tube. Overpressurization would likely have occurred during either the initial manufacture (failure should have been noted), or during recharging (a correlation of failures and service record should be noted) . Mechanical abuse should come with accompanying signs of prior deformation.

4. Assuming that the failure mechanism is indeed stress-corrosion cracking, possible alternatives would be to subject all formed bourdon tubes to a stress-relief or anneal heat treatment. Elimination of the corrosive environment would be extremely difficult, so the problem should be addressed through the stress approach. Another alternative would be to change the material in the bourdon tube to a metal or alloy with reduced susceptibility to this particular mode of failure.

CHAPTER 42
System and Cell Design

Review Questions

1. An enterprise or production system is a system that supports the value-adding work of the manufacturing system, see Question 2.

2. A manufacturing system is a system that converts a product of material from one state to another with higher value. Manufacturing systems consist of people, machines, equipment, facilities, etc.

3. Manufacturing system design is using system design principles (logic) and system implementation processes (definite actions or steps) to create a manufacturing system.

At a very general level, part design can be viewed as using principles to specify materials and their distribution in space to fulfill a function. Analogously, manufacturing system design is the use of principles to specify manufacturing system content, configuration and operation and the steps needed to implement it.

4. The enterprise system supports the manufacturing system, even though the manufacturing system exists within the enterprise, see Question 1. The enterprise system provides support to make possible the value-adding activity in manufacturing.

5. The six functional requirements of a stable manufacturing system are,
i. Right quantity
ii. Right mix
iii. Right quality
iv. Robust
v. Rapid problem solving
vi. Safe, Ergonomically sound

a. Standardized work (Question 9) is the definition of work methods to be used to operate the manufacturing system. It specifies what to do, how to do it and why it is being done. With clear definitions of what is expected, abnormal situations are easily identified as those not fitting with the specific, definite expectations.

b. In order for a system to be robust it must contain components that are
- inherently insensitive to disturbances, to the extent possible,
- system elements specifically designed to deal with, and minimize the effects of disturbances, such as process, subsystem and total system control systems.

c. For stable systems cost is reduced by
- focusing on what the system is to achieve, not simply on the end results of the system,
- realizing that the operation's cost is not simply the sum unit cost for each operation,
- considering the effects of flow complexity on cost.

6. A value stream map depicts the processes and activities in material and information flows in the system.

McDonalds is typical, and prototypical, of many fast food restaurants.

Functional Requirement	Function Requirement Achieved?
Right quantity	At the store, products are produced individually at time of order and so, yes the right quantity is produced. However, products are available from store inventory and so the question of inventory level arises. From observation of one store there is no way to judge enterprise quantity management.
Right mix	As above, that is there is no easy way to judge store and enterprise inventory mix.
Right quality	Yes, success of the business attests to this – the acceptable quality is based on definite expectations held by the customers.
Robust	No – disturbances in the form of large rushes of customers are seen to have large effects on line length – probably due to size of staff.
Rapid problem solving	Yes, returned items are quickly replaced with quick disposal of returned items.
Safe, Ergonomically sound	Yes, most obviously in heights of work areas and drive through service window.

7.

Functional Requirement	Function Requirement Achieved?
Right quantity	Yes, given acceptance of curriculum planners expertise and seemingly similar quantity worldwide.
Right mix	Yes with specific and “broadening” courses in curriculum, given acceptance of curriculum planners expertise.
Right quality	Yes, the institution remains open – individual course quality depends greatly on instructor.
Robust	Yes, establishment of new programs, departments occurs slowly except in cases of truly new disciplines or large changes in demand.
Rapid problem solving	Yes, instructors and advisors available at least five days per week.
Safe, Ergonomically sound	Yes, most universities have security and environmental health and safety divisions.

8. System designs should be robust since perturbations or disturbances of the system are to be expected. The system should continue to function effectively in realistic situations and these include disturbances around the steady state.

9. Standardized work is the definition of work methods to be used to operate the manufacturing system. It specifies what to do, how to do it and why it is being done. Standardized work covers all aspects of system operation, e.g., how to handle problem situations as well as normal work.

10. Takt time is the length of time set to accomplish a task so that the task fits into a planned, controlled system. In part manufacturing takt time is the time set to produce a part and is

available daily production time / daily part demand

11. Given that the cell has to meet the necessary cycle time and the general rule that all individual processing times in a cell must be less than the cell cycle time, the part that the machine is producing has to be made in less time. The alternatives are to reduce the machine’s processing time to below the cell cycle time or to decrease the part production time by adding processing capabilities, probably by the addition of another machine(s).

12. Single piece flow is necessary in a cell because it is the basis for production control in the cell. Single piece flow enables

- implementation of checking the output of each processing and assembly step before the part is moved to the next step and
- ability of workers to move through the cell doing different operations.

13. The machines in cells have to operate in such a way that the individual process time is less than the cell cycle time, single piece flow is possible and operators can run the cell, rather than individual machines. This means operators load, unload and inspect parts at several machines and so the individual machines must run automatically between loading and unloading. Machine design requirements include walkaway switches meaning the machine is started and it runs through its cycle and switches off, indicators that show the machine as running or not, machine fault indicators showing premature stopping and cycle completion indicators. The machine should have part checking capabilities and workpiece loading devices where warranted. Machines have to meet all health and safety requirements.

More general machine requirements are described in Section 43.5.

14. The key role of the worker in the cell is to control production by implementing single-piece flow.

15. a. The finishing process can be removed from the cell and included in the decoupler between the cell and the next cell, or perhaps included in the subsequent cell if there is another processing cell for the product. The decoupler would have to be designed to be capable of doing the finishing process in a processing time amenable with the rest of the manufacturing system.

b. Compared to the total cost of the cell and its operation $5000 seems very small and so calls for only a quick analysis of the machine based on added cost per part. Present cost per part is known and new cost per part can be estimated from the known machine cost and part production rate. The overarching cell design rule that individual process times have to be less than cell cycle time provides real impetus to new machine acquisition and may over ride some cost concerns.

c. With the increased cost a more detail cost analysis is required. A cost-benefit analysis should include consideration and quantification of the benefit of adhering to the all-process-times-less-than-cell-cycle-time rule.

16. Parts are pulled through a cell. That is, what drives part movement through the cell is the demand for a part from a process further down stream.

17. a. A mistake-proof device is one designed so that mistakes, or the production of defects in manufacturing, cannot occur. The device can be operated only in ways that make mistakes impossible without completely overriding certain aspects of the device. See Figure 43.12

b. Mistakes result in defective parts and/or machine malfunctions. Lost time and lost quality can be avoided is mistakes can be kept from happening.

18. The number of products per year should be estimated since even for short lived products there may be a large demand and so the need for large scale available

automation. That is, it may be necessary to achieve very high production rates in a very short time to take advantage of a new, large, expected short life product market. This will require the use of available automation, rather than the development of automation. Process automation development is unrealistic for the short time of one year.

A reasonable starting point for dicsussiion is the typical situation of one year life meaning relatively small demand and the availability of machines and equipment to set up a manufacturing cell to meet the demand.

a. There is probably no need or advisability for automation. Designing automation, specifying equipment, setting it up and testing and qualifying it in less than one year is a dubious undertaking.

b. In a machine cell the major, general functions are providing parts to the cell, moving parts between machines, loading parts on machines, unloading parts from machines, inspecting parts and moving parts out of the cell. Depending on the part value (precision, material, cost of failure in use, etc.) part inspection requirements and inspection equipment can vary widely. The other cell functions are easier to assess.

The simplest tasks to automate, and those with equipment that is most likely to be generally useful after the five year product life, are the candidates for automation. These are

- machine loading and unloading. Given the machines will probably remain after the five years the automated loading and unloading equipment will probably be general purpose, reconfigurable.
- inspection equipment. Again, this automated equipment may be useful after initial product life, especially it can be on-machine probing or inspection.

Material handling equipment usually involves larger, more complicated, more expensive equipment with little flexibility with respect to different products – it should not be automated. Movement of work into and out of the cell should not be automated since it probably interacts with other parts of the manufacturing system and those may not be concerned with the particular product of interest.

c. For reasonable, consistent annual demand over fifty years probably all the automation opportunities listed above should be implemented.

19. Fine furniture, boats and buildings have long product lives and are built in large annual quantities. They are made in variations of the general job shop, Section 41.4.

20. Single-cycle automatic machines are used in cells so that the worker(s) can load, unload and inspect parts at several machines. After one machine is loaded it has to run automatically so the worker can move to another machine to perform one of the required functions before returning to unload the machine.

Problems:

1.Takt time = available production time / daily demand
Takt time = { (480 min/shift)(2 shifts/day) } / { (160 + 120 + 200) products / day }
Takt time = 2 min

a. With 97% yield the number of products that have to be made to meet demand is
(160 + 120 + 200) products / day / 0.97 = 495 products
and the cell cycle time is 960 min/day / 495 products/day = 1.94 min = 116 seconds

b. With no unload times and assuming one worker follows each part through the cell and waits for the processing of it to be completed at each machine the time is 283 seconds – this is essentially the time that the part spends in the cell.

Operation	Time Increment	Cumulative Time
Start		0
Load M1	3	3
Process at M1	42	45
Walk to 2	3	48
Process at 2	17	65
Walk to M2	3	68
Load M2	4	72
Process at M2	53	125
Walk to 4	3	128
Process at 4	4	132
Walk to M3	3	135
Load M3	4	139
Process at M3	18	157
Walk to M4	3	160
Load M4	6	166
Process at M4	50	216
Walk to M5	3	219
Load M5	9	228
Process at M5	47	275
Walk to 8	3	278
Process at 8	5	283

Once a flow of parts through the cell is established, i.e., steady state operation, then the worker can move parts and do the manual operations while the machines are running. The order of the worker's moves is not orchestrated by the table above. That is, the worker can move between various tasks while the machines are running. What is necessary is that parts on which to work be available

c. The takt time almost assuredly cannot be met. Consider the truly ideal situation of perfect synchronization. The sum of the times for the manual operations is (17 + 4 + 5) = 26 seconds and the machine load times are (3 + 4 + 4 + 6 + 9) = 26 seconds. There has to be at least one set of moves through the system so walking time is (7 walks)(3 sec/walk) = 21 seconds. The ideal worker time is then 73 seconds and this can only occur if parts are finished and available at just the right time at all machines. The large variation on processing times between the machines means this will not happen and the takt time will not be met.

d. A possible improvement is to decrease the processing times for the long processing time operations to approach the degree of synchronization necessary.

e. The implementation of the improvement should be based on a factory simulation. That is, with the available data and using different processing times the operation of the cell can be easily simulated, including expected variability in all the operations. The results used to justify committing to the improvement.

f. The cell design depends on the improvements proposed. What should be done is a quantitative description of the cycle time with the proposed cell design.

2. a. Yes this is a problem. An important, necessary aspect of cell design and operation is standardized work. With no provision for moving material into and out of the cell this aspect of the cell operation is not standardized work and so not part of the cell and so the cell will not function.

b. There are two parts to the solution to the problem. The first is to include running the input and output in the list of standard work for the cell. The second part of the solution is to have workers A and E operate the input and output stations. When there is insufficient input material a control signal has to be sent to preceding parts of the system to supply more material, this type of pull system is described in detail in Chapter 43. When cell output is sufficient finished parts has to be moved out. With the U-shaped ccell layout both workers A and E can be involved with both input and output stations since these stations are close together.

Case Study:

Snowmobile Accident

This case was fictionalized from an actual case in which one of the authors of the text was involved as an expert witness. In real cases of this sort, there will always be conflicting evidence and many explanations presented for the same set of evidence. Often, the truth may never be presented to the jury and the actual cause of the accident may never be known. Such was the situation here.

The tierod sleeve did actually fail prior to the accident. The cause: the tierod sleeve broke under impact when the right ski of the snowmobile hit a deep rut. At twenty below zero, low carbon steel has low impact strength and behaves as a brittle material. The original designer erred in his choice of materials for this application. The failure was not due to the reasons the lawyer stated, although in combination, such was certainly possible. Nor did the tierod break when the snowmobile hit the tree, although this was also possible. In cases like these, there are frequently no winners, except the lawyers.

CHAPTER 43
Implementation of Lean Manufacturing Systems and Cells

Review Questions

1. If the first step in moving away from a job shop design is to form single-piece flow cells the hidden variations in the job shop design will be exposed. The use of single-piece flow results in selection and study of only those processes, machines and layouts used in part production. Extraneous aspects of the job shop are not considered. Any variations in the processes and machines that were hidden by using the machines for making different kinds are parts at different times will be identified.

2. There are many steps in preparing the workforce for the conversion to a lean shop including
- explain why a change is desirable,
- education in lean production philosophy and concepts,
- involving the entire company,
- assure that system designers include all the workforce into system design,
- explain accounting and financial concepts that are different, or apply differently to the lean shop compared to the existing shop
- explain the measurable parameters that will be used to assess shop performance and how and why these might be different than those presently used,
- describe best in class operations and the performance measure values obtained by them.

3. Before cell formation, and during cell use, cycle time variation can be reduced by decreasing variations is materials, machines, product characteristics, product output rate and cost.

4. Two groups have the best ideas about how to improve work in cells. The people working in the cell have the most immediate knowledge of all aspects of cell operation and so can be expected to have the best ideas about very detailed parts of the work that can be improved. The other group is people who understand cell work principles and implementation of them to assure the cells are designed and operated properly.

On top of this foundation of individuals is general concept that all people can and should add to improvements of all kinds.

5. The manufacturing engineer should maintain the standardized work instructions. Changes in the standardized work instructions will involve several groups from cell designed to workers in the cell.

6. Integrated quality control includes setting specifications, producing measures over time and assuring that the workers involved in checking quality. Integrated preventive maintenance involves knowing maintenance schedules, maintaining records of maintenance actions and involving the machine user in carrying out some preventive

maintenance. The common elements are observing changes over time and involving the people most involved with the products and machines in the processes.

7. Leveling is the attempt to eliminate variations in final assembly. It involves mixed models, or mixed final products.
Balancing is making the output of the cells match the demands for parts downstream and needs of final assembly.

8. Sequencing in the placing of parts and subassemblies in the order necessary so that they arrive at assembly operations in the correct order and at the right time.
Synchronization is concerned with the time of manufacture of all items needed in the final product. It is the process of making sure production of subassemblies starts when needed.

9. A kanban pull system is the production process that uses a card system, standard container sizes and pull versus push production to accomplish just-in-time production. A kanban system is a visual control system for providing control over the routes that parts must take, the amount of material flowing between parts of the system and specifying when parts are needed at processing sites.

All the cells, processes, subassemblies and assemblies in a plant are connected by definite links in the manufacturing system design. The parts and materials move only over these definite links and only at specified times. The kanban system is run by use of part containers. Parts are used out of containers and when the cart is empty it is sent back up stream to be loaded with the parts needed. The arrival of an empty container up stream results in the production of parts. loading them in the container and sending them to the downstream stage based on the kanban card in the container.

With the movement of container to and from different parts of the plant a total oeratin pull system is established. The times for material, part, subassembly production and moves is determined. See also Question 17.

A kanban system is a control system for inventory. The maximum inventory is the number of of parts held in a container times the number of containers. The kanban system can be used to lower inventory levels by reducing the number of containers, observing the effects on system operation, curing any problems that occurred with the reduction in number of containers and operating the system with the new number of containers. The process can be repeated.

10. The advantages to users of building and customizing their own equipment is that then the user has a unique process technology and complete control over it. Others do not have the same proprietary capability. But it comes at the cost of research and development.

Using purchased equipment can lead to temporary advantage if the equipment is new. However this advantage is lost very quickly as markets are open. A strategy that can be used is to buy equipment and modify it in-house to provide better, perhaps unique, capabilities.

11. See also Question 2 Chapter 41. A manufacturing system is a system that converts a product or material from one state to another with higher value. The manufacturing

system is a complex arrangement of physical elements characterized by measurable parameters that is intended to add value in the production of a product. It consists of people and expertise, materials, machines, tooling, equipment, supplies, facilities and the systems needed to control the entire, system-wide process.

12. The functional requirements of the lean shop can be deduced from the implementation methodology of Table 43-1. They are
- material and part flow and part quality controlled by inherent manufacturing system design,
- integration of quality control into the manufacturing system,
- integration of inventory control into the system,
- integration of preventive maintenance into manufacturing,
- synchronization, leveling and balancing of manufacture,
- supplier integration into the system.

13. The objective of manned Linked-Cell Manufacturing System Design is to provide flexibility to the cell by including one or more people in the operation of the cell. This objective is maintained in two primary ways. One is to design the cell layout and workstations so that people in the cell can easily work the entire cell. The other is by providing for the possibility of adding additional people to the cell.

14. Internal elements or parts of the entire setup operation can be done only when the machine is not running, e.g., changing from a milling fixture that holds prismatic workpieces to one that hold cylindrical workpieces.

External elements of setup can be done while the machine is running, e.g., presetting milling cutter length for the next machine setup.

15. Some of the advantages of integrated quality control are that people immediately involved in making the part and involved in quality control, problems are identified as they occur not later, defective parts are immediately removed from the system and corrective action at the site of the problem might be immediately possible.

In a lean system quality control in implemented in the cell at the operation level as the part is produced. In other systems quality control and inspection are typically functions performed separately, far down stream from the operation or part production site.

16. In real physical processes there is a variability that is a part of the nature of the process and cannot be removed from it, it is inherent in the procecss.

17. Production control is the scheduling of the manufacturing system in terms of routing materials and parts, scheduling the use of materials and setting the quantities. Production control is accomplished in lean manufacturing by designing the system to inherently include a process that generates a call for parts or materials. An example, is the pull system built into the system by use of Kanban, see Question 9.

The production routing and part manufacture scheduling in the sequencing and synchronization part of the manufacturing system design and operation, see Question 8.

18. Build schedule stability is the existence of only little variation in scheduled production rates. The schedule of when and where to built parts is stable in that it is not subjected to large, rapid changes.

19. A pokayoke device is one that prevents an operators from making a wrong move or mistake. On a car pokayoke devices range widely over the problem they are intended to prevent, for example,
- with an automatic transmission the car cannot be started it it is in gear,
- anti-lock brake system are intended to prevent the incorrect application of brake pedal force,
- a true can't do it wrong device is the two edged key.

20. The cycle time is the time to produce a part, the single-piece flow cell is defined this way. And, the rule is that processing time for all the processes in a cell has to be less than the cell cycle time. So, the drying process in the cell can be at most 60 seconds. However, drying time can be increased by treating the drying oven as a process that is truly decoupled from the cell and then the cycle time does not set a limit on the drying time.

Problems:

1.Single-minute exchange of die is analogous to tire changing if the change of a setup in a manufacturing process is viewed as having elements or processes that are similar to changing a tire.
The major work elements in changing a tire are
obtain jack and spare tire -> move to flat/worn tire -> remove wheel cover -> loosen lug nuts -> place jack -> raise jack/car -> remove lug nuts -> remove wheel/tire -> place new wheel/tire -> tighten lug nuts -> lower jack/car -> tighten lug nuts -> replace wheel cover -> stow replaced wheel/tire.

The definition of external elements of setup change is those that can be done while the machine is running. None of the tire change process elements are external elements.

In a NASCAR race tire change the tire change time for one tire has been reduced by (there are no wheel covers for reasons other than reducing tire change time)
- having new wheels/tires readily available (not in the car and close to the pit wall)
- involving two people in the operation,
- using specially designed wheels (fixtures),
- using power tools,
- using a fast acting, long stroke, single action jack,
- providing incentives fro fast tire changes.

2. The seven tools of quality control are
Flow diagram
Histogram
Pareto chart

Scatter diagram
Fishbone diagram
Run chart
Control charts

The presentation can include the general intents of quality control, which of the general intents is addressed in use of the tool, the concepts underlying the tool, how the tool is used and what it shows. Three minutes is a very short time so probably these issues would simply be listed on graphic with almost all of the three minutes dedicated to describing what is shown on a particular tool, how the data is obtained and how useful information is obtained from the data, i.e. how the tool is used.

3. The parts under discussion have to be defined. For example, wheels are probably parts while spokes on wheels that use the traditional thin wire spokes are not parts. Similarly the bicycle chain is a part while the links are not. Bicycle wheel bearings are probably considered to be parts while the individual balls and races are probably not. Just as part count for an automobile will not typically include ever screw, bolt, nut or piece of fabric thread.

A typical mountain bike may have about 50 parts.

Synchronizing, or producing in sequence, means that parts prepared for a specific bicycle arrive at assembly when the particular bicycle does. For example, if custom bicycles are being produced, then the particular seat that goes with a particular frame based on the size of the buyer of the particular bicycle must arrive at the assembly work site at the same time. Synchronization may not be a realistic topic of discussion for custom mountain bicycle production operations since these specialty items will not be assembled using sequenced flow of parts to assemble. They are really one-of-a-kind products not manufactured in typical lean production systems but in craft type operations. The majority of parts are probably made in manufacturing operations.

4. It’s not clear what the manager’s current plan is, other than to take immediate action to implement a kanban system. The details of the plan are missing.

A suggested plan of action could be

Emphasize that the change to lean production will require a change in philosophy and that interest and the new view will have to be maintained throughout the changeover process
Draw up an outline of the steps required and add the right level of detail to the plan so that everyone at the plan presentation is able to understand what will be done. The outline and topics could be
- everyone has to be involved and committed to change
- how cost and financial considerations have to be addressed
- reconfigure the manufacturing system
- describe the kinds of machines that will be needed and if they are currently available

- establish production control based on the pull concept using kanban
- integrate inventory control into the production control system
- integrate quality control into the manufacturing system
- integrate preventive maintenance in the manufacturing system
- integrate suppliers into the system
- a proposed initial system design
- a plan for reviewing the initial design involving as many people as possible
- an implementation plan and schedule
- continuous evolution of the system is needed and processes must be established to assure it

Present the plan making sure to get as large an audience as possible

Discuss why moves to lean production might fail

- there is no champion(s) for the process
- failure to achieve zero-defect production
- there are hesitations about effects on individuals and hidden agendas
- middle management is fearful of loosing influence and control
- change is usually threatening
- funds are not committed for expenditures over long times
- loss of management interest if quick results are not apparent

Case Study:

Automobile Water Pump Impeller

1. This is another part that can be produced in a variety of ways. As designed, the part is a two-level part with flat surfaces. This, coupled with the relatively small surface area and small thicknesses, would make the part attractive for manufacture by conventional press-and-sinter powder metallurgy using a double-action press. Alternative means of manufacture would probably involve some form of casting, such as die casting, permanent mold, shell, or investment. It would be difficult for forming processes to produce the existing design because of the lack of draft or taper on the impeller blades. With design modifications, impression-die forging might be a possibility.

2. The relatively low mechanical properties, the low ductility, and the absence of a hardness or wear requirement make this part a candidate for a variety of materials. Because of the presence of coolant (an electrolyte material) and additional materials in the shaft and housing of the pump, material selection might be based as much on galvanic corrosion as on mechanical performance. Possible materials include aluminum, cast iron, copper alloys, stainless steel, and others.

3 - 5. Again, the spectrum of possibilities is great. If conductive material (i.e. a metal) is specified, consideration should be given to galvanic compatibility with what will likely be a steel shaft and the material to be used in the housing. Heat treatments would not likely be to produce enhanced strength, but may be specified to effect a stress-relief. Surface treatments might be such as anodizing, if aluminum were specified .

6. Since this part will be constantly exposed to water-based solutions over a range of temperatures, the response of polymers to water immersion would be a major consideration. Many polymers absorb water and exhibit dimensional swelling. By proper selection of resin, and the use of appropriate fillers and/or reinforcements, it would appear that a polymeric solution to the above requirements would indeed be feasible. Fabrication would be by one of the polymeric molding techniques. By selecting a nonconductive polymer, galvanic concerns would be removed, and the major concerns would now relate to mechanical durability -resistance to swelling, cracking and erosion.