Manufacturing processes

1.1 What is manufacturing?

The word manufacture is derived from two Latin words, manus (hand) and factus (make); the combination means made by hand. The English word manufacture is several Centuries old, and ‘‘made by hand’’ accurately described the manual methods.

1.2 manufacturing defined

As a field of study in the modern context, manufacturing can be defined two ways, one technologic and the other economic. Technologically, manufacturing is the application of physical and chemical processes to alter the geometry, properties, and/or appearance of a given starting material to make parts or products; manufacturing also includes assembly of multiple parts to make products. The processes to accomplish manufacturing involve a combination of machinery, tools, power, and labor, as depicted in Figure 1.1.

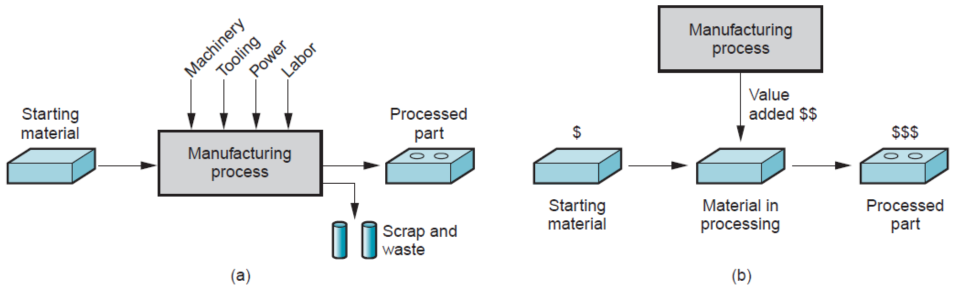


FIGURE 1.1 Two ways to define manufacturing: (a) as a technical process, and (b) as an economic process.

Manufacturing is almost always carried out as a sequence of operations. Each operation brings the material closer to the desired final state.
Economically, manufacturing is the transformation of materials into items of greater value by means of one or more processing and/or assembly operations. The key point is that manufacturing adds value to the material by changing its Shape or properties, or by combining it with other materials that have been similarly altered. The material has been made more valuable through the manufacturing operations performed on it. When iron ore is converted into steel, value is added. When sand is transformed into glass, value is added. When petroleum is refined into plastic, value is added. And when plastic is molded into the complex geometry of a patio chair, it is made even more valuable. The words manufacturing and production are often used interchangeably. The author’s view is that production has a broader meaning than

manufacturing. To illustrate, one might speak of ‘‘crude oil production,’’ but the phrase ‘‘crude oil manufacturing’’ seems out of place. Yet when used in the context of products such as metal parts or automobiles, either word seems okay.

1.3 Importance of manufacturing processes

Manufacturing may produce discrete products, meaning individual parts or pieces of parts or it may produce continuous products. Nails, gears, steel balls, beverage cans and engine blocks are example of discrete products. Metal or plastic sheet, wire, hose and pipe are continuous products that may be cut into individual pieces and thereby become discrete products. Because a manufactured item has undergone a number of changes during which raw material has become a useful product, it has added value, defined as monetary worth in terms of price. For example, clay has a certain value when mined. When the clay is used to make a ceramic dinner plate, cutting tool, or electrical insulator, value is added to the clay; similarly, a wire coat hanger or a nail has added value over and above the cost of a piece of wire.

1.4 Classifications of manufacturing processes

Most of the metals used in industry are obtained as ores. These ores are subjected to a suitable reducing process which gives the metal in a molten form. This molten metal is poured into moulds to give commercial casting, called ingots. These ingots are further subjected to one or more processes to obtain usable metal products of different shapes and sizes. All the further processes used for changing the ingots into usable products can be classified as follows:

1.4.1 Primary Shaping Processes

These processes are of two types. Some of these finish product to its usable form whereas others do not, and require further working to finish the component to the desired shape and size. Casting needs remelting of ingots in cupola or some other foundry furnace and then pouring of this molten metal into metal or sand moulds to obtain the castings. The products obtained through this process may or may not be required to undergo further operation; depending upon the function they have to perform. Same in the case with forging than casting. Many operations like cold rolling die casting, metal spinning and wire drawing etc., lead to the production of directly useful articles. The common operations are:

(1) Casting (2) Forging
(3) Rolling (4) Bending (5) Drawing
(6) Shearing (7) Spinning
(8) Electroforming

1.4.2 Machining Processes

A fairly large number of components are not finished to their usable shapes and sizes through the primary processes. These components are further subjected to one or more of the machining operation called **SECONDARY PROCESSES**, to obtain the desired shape and dimensional accuracy. Thus, the components undergoing these secondary operations are basically the roughly finished products through primary operation. The secondary operation are mainly necessary when a very close dimensional accuracy is required or some such shape is desired to be produced which is not possible through primary operations. These operations require the use of one or more machine tools, various types of cutting tools and cutters, marking and measuring instruments, testing devices and gauges etc. of which a combined application leads to the desired dimensional control. The common machining performed for this purpose are the following:

(1) Turning (2) Threading
(3) Drilling (4) Shaping
(5) Sawing (6) Grinding

1.4.3 Joining Processes

These processes are used for joining metal parts and in general fabrication work. Such requirement usually occurs when larger lengths of standard section are required. In such cases, smaller lengths are joined together to give the desired length. These processes also enable temporary or permanent type of fastening. Most of the processes are require heat for joining of metal pieces. The common processes falling in this category are:

(1) Welding (2) Soldering
(3) Brazing (4) Riveting
(5) Screwing (6) Pressing

1.4.4 Surface Finishing Processes

These processes should not be misunderstood as metal removing processes, in any case as they are primarily intended to provide a good surface finish to the metal surface, although a very negligible amount of metal removal or addition does take place. Thus, these processes will not affect any appreciable variation in dimensions. The common processes are as following:

(1) Buffing (2) Polishing
(3) Sanding (4) Electroplating

1.5 Selecting Manufacturing Processes:

As example for processing methods for materials:

1. Casting
2. Forming and shaping
3. Machining
4. Joining
5. Micromanufacturing and nanomanufacturing
6. Finishing

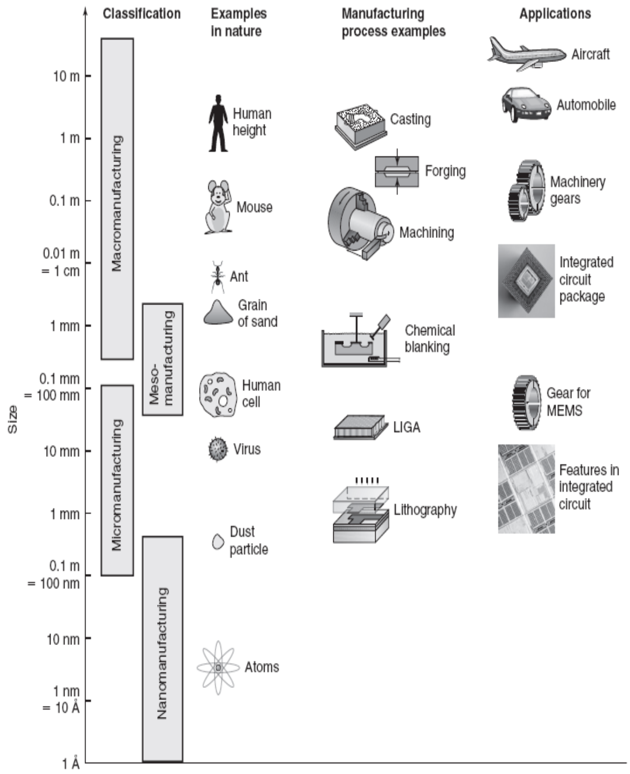
Shapes and Some Common Methods of Production

Shape or feature	Production method[a]
Flat surfaces	Rolling, planing, broaching, milling, shaping, grinding
Parts with cavities	End milling, electrical-discharge machining, electrochemical machining, ultrasonic machining, blanking, casting, forging, extrusion, injection molding, metal injection molding
Parts with sharp features	Permanent-mold casting, machining, grinding, fabricating,[b] powder metallurgy, coining
Thin hollow shapes	Slush casting, electroforming, fabricating, filament winding, blow molding, sheet forming, spinning
Tubular shapes	Extrusion, drawing, filament winding, roll forming, spinning, centrifugal casting
Tubular parts	Rubber forming, tube hydroforming, explosive forming, spinning, blow molding, sand casting, filament winding
Curvature on thin sheets	Stretch forming, peen forming, fabricating, thermoforming
Openings in thin sheets	Blanking, chemical blanking, photochemical blanking, laser machining
Cross sections	Drawing, extrusion, shaving, turning, centerless grinding, swaging, roll forming
Square edges	Fine blanking, machining, shaving, belt grinding
Small holes	Laser or electron-beam machining, electrical-discharge machining, electrochemical machining, chemical blanking
Surface textures	Knurling, wire brushing, grinding, belt grinding, shot blasting, etching, laser texturing, injection molding, compression molding
Detailed surface features	Coining, investment casting, permanent-mold casting, machining, injection molding, compression molding
Threaded parts	Thread cutting, thread rolling, thread grinding, injection molding
Very large parts	Casting, forging, fabricating, assembly
Very small parts	Investment casting, etching, powder metallurgy, nanofabrication, LIGA, micromachining

1.5.1 Part Size and Dimensional Accuracy

- Size, thickness and shape complexity of a part have a major bearing on the process selected

The size and shape of manufactured products also vary widely



1.5.2 Manufacturing and Operational Costs

- Lead time required to begin production and the tool and die life are of major importance.
- Quantity of parts and production rates determine the processes that are used and the economics of production.

1.5.3 Net-Shape Manufacturing

Additional finishing operations might be needed for finished parts or products to desired specifications.

1.6 The main responsibilities of the manufacturing engineers:

a) Plane the manufacturing of the product and the processes to be utilized, this function requires a through knowledge of product, its expected performance and specification.
b) Identify machines, requirement, and tools to carry out the plan.
c) Interact with design and materials engineers to optimize productivity and minimize product costs.
d) Cooperate with industrial engineers for machine arrangements, material-handling, new technologies….etc

Classification Of Engineering Materials, And Their Properties:

1] Material classification:

There are different ways of classifying materials. One way is to describe five groups or families (Table 1-1):

TABLE 1-1 *Representative examples, applications, and properties for each category of materials*

	Examples of Applications	Properties
Metals and Alloys		
Copper	Electrical conductor wire	High electrical conductivity, good formability
Gray cast iron	Automobile engine blocks	Castable, machinable, vibration-damping
Alloy steels	Wrenches, automobile chassis	Significantly strengthened by heat treatment
Ceramics and Glasses		
SiO_2–Na_2O–CaO	Window glass	Optically transparent, thermally insulating
Al_2O_3, MgO, SiO_2	Refractories (i.e., heat-resistant lining of furnaces) for containing molten metal	Thermally insulating, withstand high temperatures, relatively inert to molten metal
Barium titanate	Capacitors for microelectronics	High ability to store charge
Silica	Optical fibers for information technology	Refractive index, low optical losses
Polymers		
Polyethylene	Food packaging	Easily formed into thin, flexible, airtight film
Epoxy	Encapsulation of integrated circuits	Electrically insulating and moisture-resistant
Phenolics	Adhesives for joining plies in plywood	Strong, moisture resistant
Semiconductors		
Silicon	Transistors and integrated circuits	Unique electrical behavior
GaAs	Optoelectronic systems	Converts electrical signals to light, lasers, laser diodes, etc.
Composites		
Graphite-epoxy	Aircraft components	High strength-to-weight ratio
Tungsten carbide-cobalt (WC-Co)	Carbide cutting tools for machining	High hardness, yet good shock resistance
Titanium-clad steel	Reactor vessels	Low cost and high strength of steel with the corrosion resistance of titanium

1. **Metals and alloys**;
2. **Ceramics**, **glasses**, and **glass-ceramics**;
3. **Polymers** (plastics);
4. **Semiconductors**
5. **Composite materials**

1- Metals and Alloys:

Metals and alloys include steels, aluminum, magnesium, zinc, cast iron, titanium, copper, and nickel. An alloy is a metal that contains additions of one or more metals or non-metals. In general, metals have good electrical and thermal conductivity. Metals and alloys have relatively high strength, high stiffness, ductility or formability, and shock resistance. They are particularly useful for structural or load-bearing applications. Although pure metals are occasionally used, alloys provide improvement in a particular desirable property or permit better combinations of properties.

2- **Ceramics:**

Ceramics can be defined as inorganic crystalline materials. Beach sand and rocks are examples of naturally occurring ceramics. Advanced ceramics are materials made by refining naturally occurring ceramics and other special processes. Advanced ceramics are used in substrates that house computer chips, sensors and capacitors, wireless communications, inductors, and electrical insulation. Some ceramics are used as barrier coatings to protect metallic substrates in turbine engines. Ceramics are also used in such consumer products as paints, and tires, and for industrial applications such as the tiles for the space shuttle.

Traditional ceramics are used to make bricks, tableware, toilets, bathroom sinks, refractories (heat-resistant material), and abrasives. In general, due to the presence of porosity (small holes), ceramics do not conduct heat well; they must be heated to very high temperatures before melting. Ceramics are strong and hard, but also very brittle. We normally prepare fine powders of ceramics and convert these into different shapes. New processing techniques make ceramics sufficiently resistant to fracture that they can be used in load-bearing applications, such as impellers in turbine engines. Ceramics have exceptional strength under compression.

Can you believe that an entire fire truck can be supported using four ceramic coffee cups?

3- **Glasses and Glass-Ceramics:**

Glass is an amorphous material, often, but not always, derived from a molten liquid. The term “amorphous” refers to materials that do not have a regular, periodic arrangement of atoms. The fiber optics industry is founded on optical fibers based on high purity silica glass. Glasses are also used in houses, cars, computer and television screens, and hundreds of other applications. Glasses can be thermally treated (tempered) to make them stronger. Forming glasses and nucleating (forming) small crystals within them by a special thermal process creates materials that are known as glass-ceramics. Zerodur™ is an example of a glass-ceramic material that is used to make the mirror substrates for large telescopes (e.g., the Chandra and Hubble telescopes). Glasses and glass-ceramics are usually processed by melting and casting.

4- **Polymers:**

Polymers are typically organic materials. They are produced using a process known as **polymerization.** Polymeric materials include rubber (elastomers) and many types of adhesives. Polymers typically are good electrical and thermal insulators although there are exceptions such as the semiconducting polymers. Although they have lower strength, polymers have a very good **strength-to-weight ratio.** They are typically not suitable for use at high temperatures. Many polymers have very good resistance to corrosive chemicals. Polymers have thousands of applications ranging from bulletproof vests, compact disks (CDs), ropes, and liquid crystal displays (LCDs) to clothes and coffee cups. **Thermoplastic** polymers, in which the long molecular chains are not rigidly connected, have good ductility and formability; **thermosetting** polymers are stronger but more brittle because the molecular chains are tightly linked (Figure 2-1). Polymers are used in many applications, including electronic devices. Thermoplastics are made by shaping their molten form. Thermosets are typically cast into molds. **Plastics** contain additives that enhance the properties of polymers.

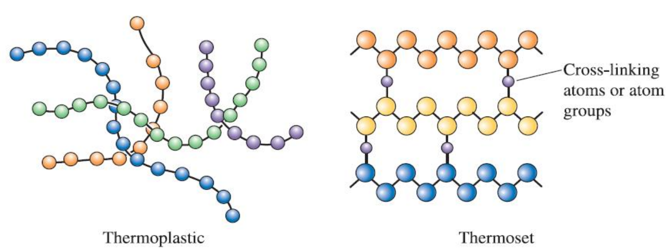


Figure 2-1 Polymerization occurs when small molecules, represented by the circles, combine to produce larger molecules, or polymers. The polymer molecules can have a structure that consists of many chains that are entangled but not connected (thermoplastics) or can form three-dimensional networks in which chains are cross-linked (thermosets)

5- **Semiconductors:**

Silicon, germanium, and gallium arsenide-based semiconductors such as those used in computers and electronics are part of a broader class of materials known as electronic materials. The electrical conductivity of semiconducting materials is between that of ceramic insulators and metallic conductors. In some semiconductors, the level of conductivity can be controlled to enable electronic devices such as transistors, diodes, etc., that are used to build integrated circuits. In many applications, we need large single crystals of semiconductors. These are grown from molten materials. Often, thin films of semiconducting materials are also made using specialized processes.

6- **Composite Materials:**

The main idea in developing composites is to blend the properties of different materials. These are formed from two or more materials, producing properties not found in any single material. Concrete, plywood, and fiberglass are examples of composite materials. Fiberglass is made by dispersing glass fibers in a polymer matrix. The glass fibers make the polymer stiffer, without significantly increasing its density. With composites, we can produce lightweight, strong, ductile, temperature-resistant materials or we can produce hard, yet shock-resistant, cutting tools that would otherwise shatter. Advanced aircraft and aerospace vehicles rely heavily on composites such as carbon fiber-reinforced polymers (Figure 2-2). Sports equipment such as bicycles, golf clubs, tennis rackets, and the like also make use of different kinds of composite materials that are light and stiff.

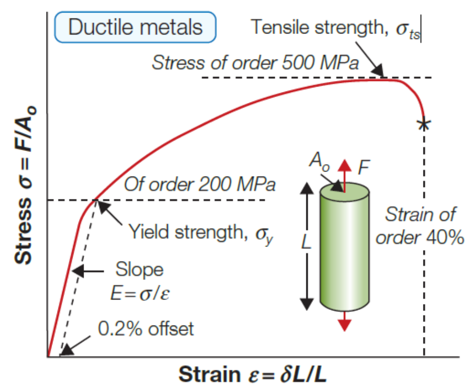
Figure 2-2 The X-wing for advanced helicopters relies on a material composed of a carbon fiber reinforced polymer. (Courtesy of Sikorsky Aircraft Division – United Technologies Corporation.)

2] Material properties:

So what are these properties? Some, like density (mass per unit volume) and price (the cost per unit volume or weight) are familiar enough, but others are not, and getting them straight is essential. Think first of those that have to do with carrying load safely—the *mechanical properties.*

1- Mechanical properties

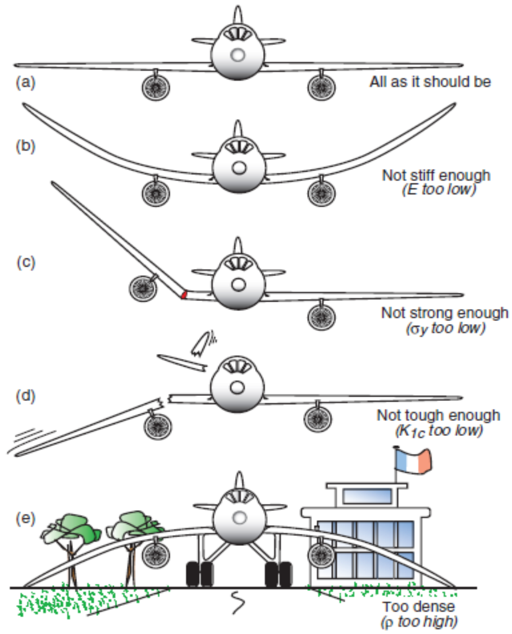
A steel ruler is easy to bend *elastically*—'elastic' means that it springs back when released. Its elastic stiffness (here, resistance to bending) is set partly by its shape—thin strips are easy to bend—and partly by a property of the steel itself: their elastic moduli, E. Materials with high E, like steel, are intrinsically stiff; those with low *E*, like polyethylene, are not. The steel ruler bends elastically, but if it is a good one, it is hard to give it a permanent bend. Permanent deformation has to do with *strength*, not stiffness. The ease with which a ruler can be permanently bent depends, again, on its shape and on a different property of the steel—its *yield strength*, *σ*y. Materials with large *σ*y, like titanium alloys, are hard to deform permanently even though their stiffness, coming from *E*, may not be high; those with low *σ*y, like lead, can be deformed with ease. When metals deform, they generally get stronger (this is called 'work hardening'), but there is an ultimate limit, called the *tensile strength*, *σ*ts, beyond which the material fails (the amount it stretches before it breaks is called the *ductility*). So far so good. One more. If the ruler were made not of steel but of glass or of PMMA (Plexiglas, Perspex), as transparent rulers are, it is not possible to bend it permanently at all. The ruler will fracture suddenly, without warning, before it acquires a permanent bend. We think of materials that break in this way as brittle, and materials that do not as tough. There is no permanent deformation here, so σy is not the right property. The resistance of materials to cracking and fracture is measured instead by the fracture toughness, K1c. Steels are tough—well, most are (steels can be made brittle)—they have a high K1c. Glass epitomizes brittleness; it has a very low K1c. Figure 1.2(d) suggests consequences of inadequate fracture and toughness. We started with the material property density, mass per unit volume, symbol ρ. Density, in a ruler, is irrelevant. But for almost anything



The stress-strain curve for a metal, showing the modulus, E, the 0.2% yield strength, σ_y, and the ultimate strength, σ_{ts}.

that moves, weight carries a fuel penalty, modest for automobiles, greater for trucks and trains, greater still for aircraft, and enormous in space vehicles. Minimizing weight has much to do with clever design is equally to choice of material. Aluminum has a low density, lead a high one. If our little aircraft were made of lead, it would never get off the ground at all (Figure 1.2(e)).These is not the only mechanical properties, but they are the most important ones.

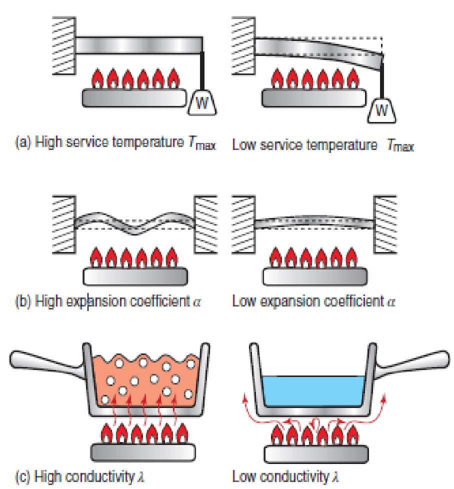
Figure 2-3



2- Thermal properties

The properties of a material change with temperature, usually for the worse. Its strength falls, it starts to 'creep' (to sag slowly over time), and it may oxidize, degrade or decompose (Figure 2.4). This means that there is a limiting temperature called the *maximum service temperature*, *T*max, above which its use is impractical. Stainless steel has a high *T*max—it can be used up to 800°C; most polymers have a low *T*max and are seldom used above 150°C.

Figure 2-4

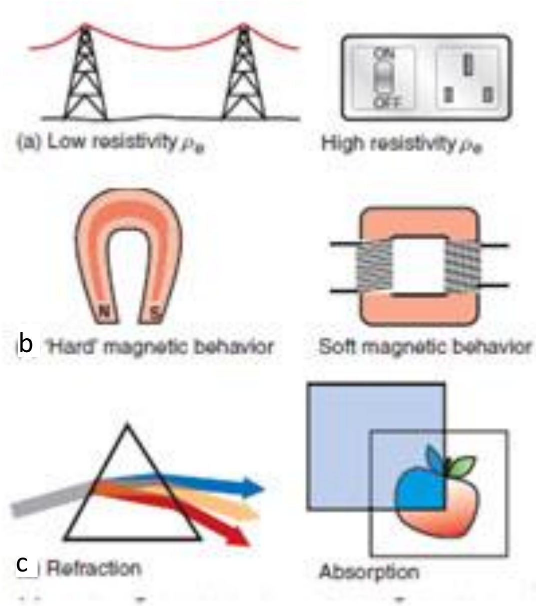


Most materials expand when they are heated, but by differing amounts depending on their thermal expansion coefficient, α. The expansion is small, but its consequences can be large. If, for instance, a rod is constrained, as in Figure 2.4(b), and then heated, expansion forces the rod against the constraints, causing it to buckle. Railroad track buckles in this way if provision is not made to cope with it. Some materials—metals, for instance—feel cold; others—like woods—feel warm. This feel has to do with two thermal properties of the material: *thermal conductivity* and *heat capacity*. The first, thermal conductivity, λ, measures the rate at which heat flows through the material when one side is hot and the other cold. Materials with high λ are what you want if you wish to conduct heat from one place to another, as in cooking pans, radiators and heat exchangers; Figure 2.4(c) suggests consequences of high and low λ for the cooking vessel. But low λ is useful too—low λ materials insulate homes, reduce the energy consumption of refrigerators and freezers, and enable space vehicles to re-enter the earth's atmosphere. These applications have to do with long-time, steady, heat flow. When time is limited, that other property—*heat capacity*, Cp—matters. It measures the Amount of heat that it takes to make the temperature of material rise by a given amount. High heat capacity materials—copper, for instance—require a lot of heat to change their temperature; low heat capacity materials, like polymer foams, take much less

3- Electrical, magnetic and optical properties

We start with electrical conduction and insulation (Figure 2.5(a)). Without electrical conduction we would lack the easy access to light, heat, power, control and communication that—today—we take for granted. Metals conduct well—copper and aluminum are the best of those that are affordable. But conduction is not always a good thing. Fuse boxes, switch casings, all require insulators. Here the property we want is *resistivity*, ρe, the inverse of electrical conductivity κe. Most plastics and glass have high resistivity (Figure 2.5(a))—they are used as insulators—though, by special treatment, they can be made to conduct a little. Electricity and magnetism are closely linked. Electric currents induce magnetic fields; a moving magnet induces, in any nearby conductor, an electric current. The response of most materials to magnetic fields is too small to be of practical value. But a few—called ferromagnets have the capacity to trap a magnetic field permanently. These are called 'hard' magnetic materials because, once magnetized, they are hard to demagnetize. They are used as permanent magnets in headphones, motors and dynamos. Here the key property is the *remanence*, a measure of the intensity of the retained magnetism.

Figure 2-5

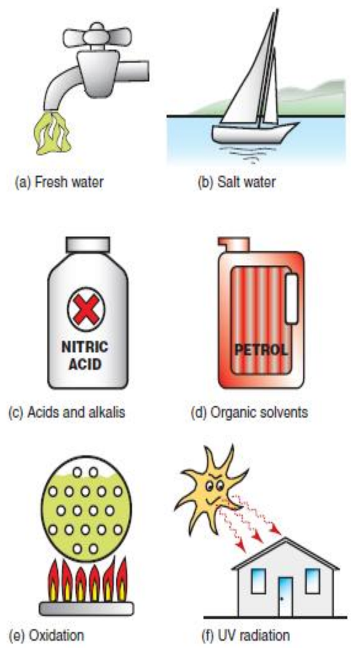


A few others—'soft Magnet materials—are easy to' magnetize and demagnetize. They are the materials of transformer cores. They have the capacity to conduct a magnetic field, but not retain it permanently (Figure 2.5(b)). For these a key property is the *saturation magnetization*, which measures how large a field the material can conduct. Materials respond to light as well as to electricity and magnetism—hardly surprising, since light itself is an electromagnetic wave. Materials that are opaque *reflect* light; those that are transparent *refract* it, and some have the ability to *absorb* some wavelengths (colors) while allowing others to pass freely (Figure 2.5(c)).

4- Chemical properties

Products often have to function in hostile environments, exposed to corrosive fluids, to hot gases or to radiation. Damp air is corrosive, so is water; the sweat of your hand is particularly corrosive, and of course there are far more aggressive environments than these. If the product is to survive for its design life it must be made of materials—or at least coated with materials—that can tolerate the surroundings in which they operate. Figure 2.6 illustrates some of the commonest of these: fresh and salt water, acids and alkalis, organic solvents, oxidizing flames and ultraviolet radiation. We regard the intrinsic resistance of a material to each of these as material properties, measured on a scale of 1 (very poor) to 5 (very good).

Figure 2-6



Chemical properties: resistance to water, acids, alkalis, organic solvents, oxidation and radiation.

Metal Casting processes

3.1 Introduction of casting process:

Casting process is one of the earliest metal shaping techniques. A metal casting may be defined as a metal object produced by pouring molten metal into **mold** containing a cavity which has the desired shape of casting, allowing the molten metal to solidify in the cavity, and then removing the casting. The solidified object is called casting and the process is called founding or casting process. (**Fig.**1) Simplified flow diagram of the basic operations for producing a steel casting

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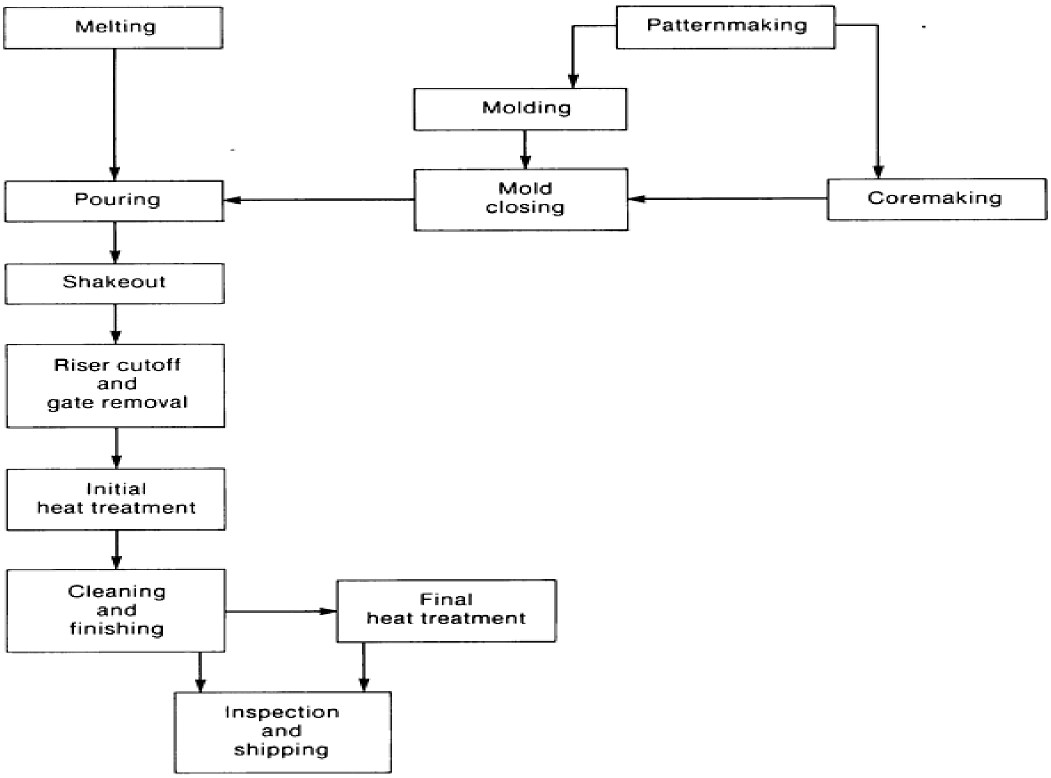


Fig. 1

The important factors in casting process are:

1. The flow of molten metal into mold cavity.
2. Solidification of metal from its molten state
3. Heat transfer during solidification and cooling of the metal in the mold
4. Influence of type of the mold

3.2 Advantages of casting processes

1. Casting can produce complex shapes and can incorporate internal cavities or hollow sections.
2. Very large parts can be produced in one piece.
3. Casting can utilize materials that are difficult or uneconomical to process by other means.
4. The casting process can be economically competitive with other manufacturing processes.

3.3 Good or sound casting producing

Producing a good or sound casting requires a design effort to:

- Create a gating system (which consist from: pouring basin , sprue, and runner) to bring molten metal into the mold cavity
- Provide a riser (feeder) which is a reservoir to feed molten metal to the casting as it solidifies to prevent internal and external shrinkage in the casting. The riser may have to provide up to 5-7% by volume for the casting as it solidifies. The risers should be designed keeping the following in mind (1- the metal in the riser should solidify in the end of the process .2- the riser volume should be sufficient for compensating the shrinkage in the casting.
- Control heat flow , in order to make the last liquid to solidify is in the riser
- Control the rate of heat flow so as to control the nature of the solidified product (microstructure , mechanical properties)

3.4 Significance of fluidity

Fluidity of molten metal helps in producing sound casting with fewer defects. It fills not only the mold cavity completely and rapidly but does not allow also any casting defect like “misrun” to occur in the cast object. Pouring of molten metal properly at correct temperature plays a significant role in producing sound castings. The gating system performs the function to introduce clean metal into mold cavity in a manner as free of turbulence as possible. To produce sound casting gate must also be designed to completely fill the mold cavity for preventing casting defect such as misruns and to promote feeding for establishing proper temperature gradients. Prevent casting defect such as misruns without use of excessively high pouring temperatures is still largely a matter of experience. To fill the complicated castings sections completely, flow rates must be high but not so high as to cause turbulence. It is noted that metal temperature may affect the ability of molten alloy to fill the mold, this effect is metal fluidity. Often, it is desirable to check metal fluidity before pouring using fluidity test. Fig. 2 illustrates a standard fluidity spiral test widely used for cast steel.

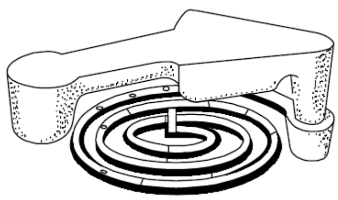


Fig.2

"Fluidity" of an alloy is rated as a distance, in inches, that the metal runs in the spiral channel. Fluidity tests, in which metal from the furnace is poured by controlled vacuum into a flow channel of suitable size, are very useful, since temperature (super-heat) is the most Significant single variable influencing the ability of molten metal to fill mold. This test is an accurate indicator of temperature. The use of simple, spiral test, made in green sand on a core poured by ladle from electric furnace steel melting where temperature measurement is costly and inconvenient. The fluidity test is same times less needed except as a research tool, for the lower melting point metals. In small casting work, pouring is done by means of ladles and crucibles.

3.5 classification of casting processes:

Foundry processes can be classified based on whether the molds are permanent or expendable. Similarly, Sub-classifications can be developed from patterns, that is, whether or not the patterns are expendable. A second Sub-classification can be based on the type of bond used to make the mold. For permanent molding, processes can be classified by the type of mechanism used to fill the mold. Below one possible classification system for the molding and casting processes. Permanent pattern, expendable pattern, and permanent mold processes, are summarized below:

<table>
<tr><th colspan="2">Expendable Mold Processes</th></tr>
<tr><td>• Permanent patterns</td><td>1. Sand casting
2. Shell-mold-casting
3. Plaster-mold-casting
4. Ceramic-mold-casting
5. Vacuum casting</td></tr>
<tr><td>• Expendable patterns</td><td>(1) Expendable- pattern-casting(lost foam)
(2) investment casting(lost- Wax process)</td></tr>
<tr><th colspan="2">Permanent Mold Processes</th></tr>
<tr><td>A. Slush casting
B. Pressure casting
C. Die casting
i) High-pressure die casting
ii) Low-pressure die casting
iii) Gravity die casting (permanent mold)(a)</td><td>D. Centrifugal casting
iv) Vertical centrifugal casting
v)Horizontal centrifugal casting
E. Squeeze casting
F. Semisolid metal casting (rheocasting)
G. Casting technique for single- crystal components
H. Rapid solidification</td></tr>
</table>

3.6 sand casting molds:

Sand casting is by far the most important casting process. A sand-casting mold will be used to describe the basic features of a mold. Many of these features and terms are common to the molds used in other casting processes. Figure 3 shows the cross-sectional view of a typical sand-casting mold, indicating some of the terminology. The mold consists of two halves: cope and drag. The **cope** is the upper half of the mold, and the **drag** is the bottom half. These two mold parts are contained in a box, called a flask, which is also divided into two halves, one for the cope and the other for the drag. The two halves of the mold separate at the **parting line**. In sand casting (and other expendable-mold processes) the mold cavity is formed by means of a **pattern**, which is made of wood, metal, plastic, or other material and has the shape of the part to be cast. The cavity is formed by packing sand around the pattern, about half each in the cope and drag, so that when the pattern is removed, the remaining void has the desired shape of the cast part. The pattern is usually made oversized to allow for **shrinkage** of the metal as it solidifies and cools .The sand for the mold is moist and contains a binder to maintain its shape. The cavity in the mold provides the external surfaces of the cast part. In addition, a casting may have internal surfaces. These surfaces are determined by means of a **core**, a form placed inside the mold cavity to define the interior geometry of the part. In sand casting, cores are generally made of sand, although other materials can be used, such as metals, plaster, and ceramics. The **gating system** in a casting mold is the channel, or network of channels, by which molten metal flows into the cavity from outside the mold. As shown in the figure, the gating system typically consists of a down **sprue** (also called simply the sprue), through which the metal enters a **runner** that leads into the main **cavity**. At the top of the down sprue, a **pouring cup** (pouring basin) is often used to minimize splash and turbulence as the metal flows into the down sprue. It is shown in our diagram as a simple cone-shaped funnel. Some pouring cups are designed in the shape of a bowl, with an open channel leading to the down sprue. In addition to the gating system, any casting in which shrinkage is significant requires a **riser** connected to the main cavity. The riser is a reservoir in the mold that serves as a source of liquid metal for the casting to compensate for shrinkage during solidification .The riser must be designed to freeze after the main casting in order to satisfy its function. As the metal flows into the mold, the air that previously occupied the cavity, as well as hot gases formed by reactions of the molten metal, must be evacuated so that the metal will completely fill the empty space. In sand casting, for example, the natural porosity of the sand mold permits the air and gases to escape through the walls of the cavity. In permanent metal molds, small **vent holes** are drilled into the mold or machined into the parting line to permit removal of air and gases.

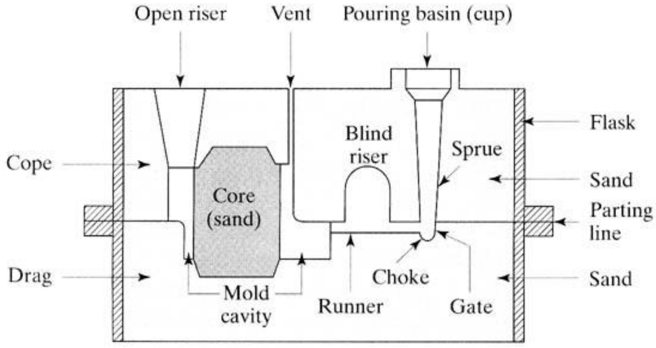


Fig 3 Schematic illustration of a sand mold, showing various features.

- *Flask*: A metal or wood frame, without fixed top or bottom, in which the mold is formed. Depending upon the position of the flask in the molding structure, it is referred to by various names such as drag - lower molding flask, cope - upper molding flask, cheek - intermediate molding flask used in three piece molding.
- *Pattern*: It is the replica of the final object to be made. The mold cavity is made with the help of pattern.
- *Parting line*: This is the dividing line between the two molding flasks that makes up the mold.
- *Core*: A separate part of the mold, made of sand and generally baked, which is used to create openings and various shaped cavities in the castings.
- *Pouring basin*: A small funnel shaped cavity at the top of the mold into which the molten metal is poured.
- *Sprue*: The passage through which the molten metal, from the pouring basin, reaches the mold cavity. In many cases it controls the flow of metal into the mold.
- *Runner*: The channel through which the molten metal is carried from the sprue to the gate.
- *Gate*: A channel through which the molten metal enters the mold cavity.
- *Chaplets*: Chaplets are used to support the cores inside the mold cavity to take care of its own weight.
- *Riser*: A column of molten metal placed in the mold to feed the castings as it shrinks and solidifies. Also known as feed head.
- *Vent*: Small opening in the mold to facilitate escape of air and gases.
- *Chill*: in casting, a metallic chills are used in order to provide progressive solidification or to avoid the shrinkage cavities fig 4.

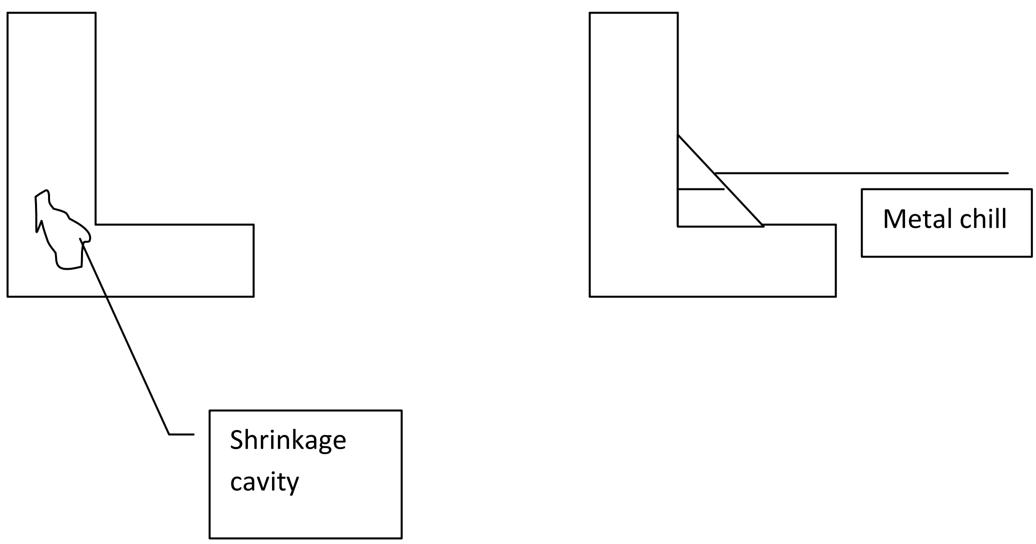


Fig 4

3.7The properties that required in molding materials are:

1. Refractoriness: it is the ability of molding material to withstand the high temperature of molten metal.
2. Green strength: it is refers to the stress required to rupture the sand specimen under compressive loading
3. Permeability: is the property of molding sand which enable air or gas to escape through the sand.

3.8 ENGINEERING ANALYSIS OF POURING

There are several relationships that govern the flow of liquid metal through the gating system and into the mold. An important relationship is Bernoulli's theorem, which states that the sum of the energies (head, pressure, kinetic, and friction) at any two points in a flowing liquid are equal. This can be written in the following form:

$$h_1 + \frac{p_1}{\rho} + \frac{v_1^2}{2g} + F_1 = h_2 + \frac{p^2}{\rho} + \frac{v_2^2}{2g} + F_2 \qquad (3.1)$$

where h:head, cm (in), p:pressure on the liquid, N/cm^2 (lb/in^2); ρ : density; g/cm^3 (lbm/in^3); v = flow velocity; cm/s ́̊(in/sec); g = gravitational acceleration constant, 981 cm/s/s (32.2x12= 386 in/sec/sec); and F= head losses due to friction, cm (in). Subscripts 1 and 2 indicate any two locations in the liquid flow. Bernoulli's equation can be simplified in several ways. If we ignore friction losses (to be sure, friction will affect the liquid flow through a sand mold), and assume that the system remains at atmospheric pressure throughout, then the equation can be reduced to

$$h_1 + \frac{v_1^2}{2g} = h_2 + \frac{v_2^2}{2g} \qquad (3.2)$$

This can be used to determine the velocity of the molten metal at the base of the sprue. Let us define point 1 at the top of the sprue and point 2 at its base. If point 2 is used as the reference plane, then the head at that point is zero (h2 = 0) and h1 is the height (length) of the sprue. When the metal is poured into the pouring cup and overflows down the sprue, its initial velocity at the top is zero (v1 = 0). Hence, Eq. (3.2) further simplifies to

$$h_1 = \frac{v_2^2}{2g}$$

which can be solved for the flow velocity:

$$v = \sqrt{2gh} \qquad (3.3)$$

Where v=the velocity of the liquid metal **at the base of the sprue**, cm/s (in/sec); g=981 cm/s/s (386 in/sec/sec); and h = the height of the sprue, cm (in). Another relationship of importance during pouring is the continuity law, which states that the volume rate of flow remains constant throughout the liquid. The volume flow rate is equal to the velocity multiplied by the cross-sectional area of the flowing liquid. The continuity law can be expressed:

$$Q = v_1 A_1 = v_2 A_2 \qquad (3.4)$$

Where Q = volumetric flow rate, cm^3/s (in^3/sec); v = velocity as before; A = cross sectional area of the liquid, cm2 (in2); and the subscripts refer to any two points in the flow system. Thus, an increase in area results in a decrease in velocity, and vice versa.

Assuming that the runner from the sprue base to the mold cavity is horizontal (and therefore the head h is the same as at the sprue base), then the volume rate of flow through the gate and into the mold cavity remains equal to vA at the base. Accordingly, we can estimate the time required to fill a mold cavity of volume V as

$$T = V/Q \quad \text{or } V/A.v \qquad (3.5)$$

Where T=mold filling time, s (sec); V=volume of mold cavity, cm^3 (in^3); and Q= volume flow rate, A= cross- sectional area of gate (area of sprue base or choke area), v= velocity of liquid metal at the gate, as before. The mold filling time computed by Eq. (3.5) must be considered a minimum time. This is because the analysis ignores friction losses and possible constriction of flow in the gating system; thus, the mold filling time will be longer than what is given by Eq. (3.5). we an calculate the area from:

$$A = W / C\rho t\sqrt{2gh} \qquad (3.6)$$

Where W = casting weight, C= flow efficiency factor (0.4-0.9) for various systems, ρ= density of the metal, t= pouring time

Example1:

A mold sprue is 20 cm long, and the cross-sectional area at its base is 2.5 cm^2. The sprue feeds a horizontal runner leading into a mold cavity whose volume is 1560 cm^3. Determine: (a) velocity of the molten metal at the base of the sprue, (b) volume rate of flow, and (c) time to fill the mold.

Solution: (a) The velocity of the flowing metal at the base of the sprue is given by Eq. (10.4):

$$v = \sqrt{2(981)(20)} = 198.1 \text{ cm/s}$$

(b) The volumetric flow rate is

$$Q = (2.5 \text{ cm}^2)(198.1 \text{ cm/s}) = 495 \text{ cm}^3/\text{s}$$

(c) Time required to fill a mold cavity of **1560 cm^3 at this flow rate**

$$T = 1560/495 = 3.2\text{s}$$

:

Example2:

A mould 60cm x 30 cm x 16 cm is to be filled by liquid metal during sand casting process the sprue head 16 cm. Determine the time taken to fill up the mold cavity? (The cross-sectional area of gate is 6 cm^2)

Solution:

L = length of mould =60 cm

b =width

t = thickness of mould

v = volume of mould

=60x30x16

=28800 cm^3

A= area of gate =6 cm^2

H = head =16 cm

Vg= velocity of liquid metal of gate

$=\sqrt{2gh}$

$= \sqrt{2x981x16}$

= 177.2 cm/sec

T =time taken to fill up the mould

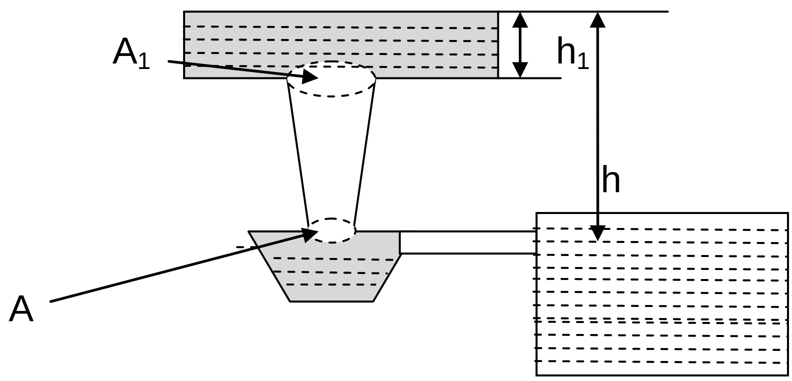
$$\frac{V}{A.v} = \frac{28800}{6x177.2}$$

= 27 sec

Sprue can be of circular or rectangular cross-section.it is tapered downwards to avoid aspiration of air. The cross –sectional area of the bottom is usually the choke area A .therefore the area at the top A1 can be calculated from a sprue taper formula:

$$\frac{\mathbf{A1}}{\mathbf{A}} = \sqrt{\frac{\mathbf{h}}{\mathbf{h1}}} \qquad (3.7)$$

Where A=is the choke area, h= height of metal from top of the pouring basin to the bottom of the sprue, and h1 =is the height from the top of the pouring basin to the top of the sprue



Example 3:

A sprue is 12 in. long and has a diameter of 5 in. at the top, where the metal is poured. The molten metal level in the pouring basin is taken as 3 in. from the top of the sprue for design purposes. If a flow rate of 40 in^3/s is to be achieved, what should be the diameter of the bottom of the sprue? Will the sprue aspirate? Explain. Assuming the flow is frictionless, the velocity of the molten metal at the bottom of the sprue (h = 12 in. = 1 ft) is

$$v = \sqrt{2gh} = \sqrt{2(32.2)(1)}$$

or $v = 8.0$ ft/s = 96 in./s. For a flow rate of 40 in^3/s, the area needs to be

$$A = \frac{Q}{v} = \frac{40 \text{ in}^3/\text{s}}{96 \text{ in./s}} = 0.417 \text{ in}^2$$

For a circular runner, the diameter would then be 0.73 in., or roughly 3/4 in. Compare this to the diameter at the bottom of the sprue based on Eq. (3.7), where h1 = 3 in., h = 15 in., and A1 = 19.6 in2. The diameter at the bottom of the sprue is calculated from:

$$\frac{\mathbf{A1}}{\mathbf{A}} = \sqrt{\frac{\mathbf{h}}{\mathbf{h1}}}$$

$$A = \frac{A1}{\sqrt{h/h1}} = \frac{19.6}{\sqrt{15/3}} = 8.8 \text{ in}^2$$

$$D = \sqrt{\frac{4}{\pi}.A} = 3.34 \text{ in}^2$$

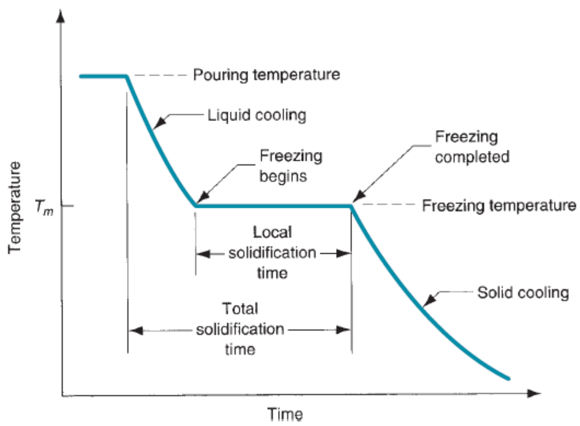
thus, the sprue confines the flow more than is nessessary, and it will not aspirate

3.9 SOLIDIFICATION OF METALS

Solidification involves the transformation of the molten metal back into the solid state. The solidification process differs depending on whether the metal is a pure element or an alloy.

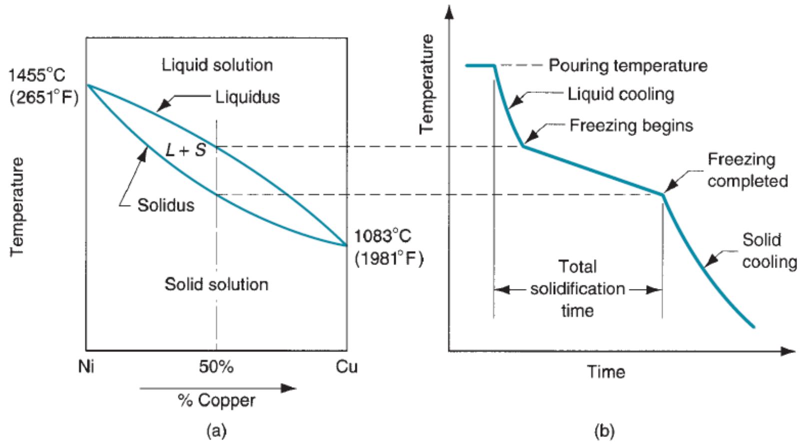
Pure Metals:

A pure metal solidifies at a constant temperature equal to its freezing point, which is the same as its melting point as shown in the figure below. The melting points of pure metals are well known and documented



Alloys:

Most alloys freeze over a temperature range rather than at a single temperature. The exact range depends on the alloy system and the particular composition.



(a) Phase diagram for a copper–nickel alloy system and (b) associated cooling curve for a 50%Ni–50%Cu composition during casting.

Solidification of an alloy can be explained with reference to Figure above which shows the phase diagram for a particular alloy system and the cooling curve for a given composition. As temperature drops, freezing begins at the temperature indicated by the liquidus and is completed when the solidus is reached.

3.10 Solidification Time:

Whether the casting is pure metal or alloy, solidification takes time. The total solidification time is the time required for the casting to solidify after pouring. This time is dependent on the size and shape of the casting by an empirical relationship known as Chvorinov's rule, which states:

$$\text{Solidifiction time (T)} = C\left(\frac{volume}{surface\ area}\right)^{n} \qquad (3.7)$$

Where C = mold constant depend on mold material, metal properties and temperture, n=exponent usually taken 2

Example4:

Three metal pieces being cast have the same volume, but different shapes: One is a sphere, one a cube, and the other a cylinder with its height equal to its diameter. Which piece will solidify the fastest, and which one the slowest?

Solution The volume of the piece is taken as unity. Thus from Eq. 3.7

$$\text{Solidification time} \propto \frac{1}{(\text{Surface area})^2}.$$

The respective surface areas are as follows:

Sphere:

$$V = \left(\frac{4}{3}\right)\pi r^3,\ r = \left(\frac{3}{4\pi}\right)^{1/3}.$$

$$A = 4\pi r^2 = 4\pi\left(\frac{3}{4\pi}\right)^{2/3} = 4.84.$$

Cube:

$$V = a^3,\ a = 1, \text{ and } A = 6a^2 = 6.$$

Cylinder:

$$V = \pi r^2 h = 2\pi r^3,\ r = \left(\frac{1}{2\pi}\right)^{1/3},$$

$$A = 2\pi r^2 + 2\pi r h = 6\pi r^2 = 6\pi\left(\frac{1}{2\pi}\right)^{2/3} = 5.54.$$

The respective solidification times are therefore

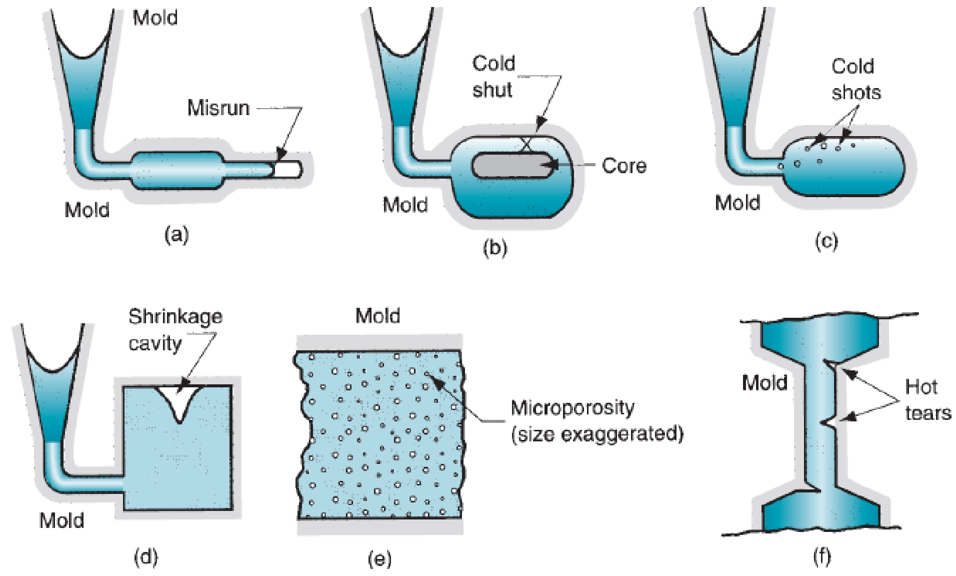
$$t_{\text{sphere}} = 0.043C,\ t_{\text{cube}} = 0.028C,\ t_{\text{cylinder}} = 0.033C.$$

Hence, the cube-shaped piece will solidify the fastest, and the spherical piece will solidify the slowest.

3.11 Defects in castings

The various defects commonly observed in castings are as follows:

Defect	Causes	solutions
Hot tears: these are through or surface cracks in the body of casting,they may be straight or windig form	Abrupt sectional changes and incorrect pouring temperture	Proper directional solidification and even rate of cooling can prevent it
Open blow or blow: holes:small holes below the surface of casting	Low permeablitiy of sand, excessive moisture in sand, insufficiant venting of sand,and sand is rammed to hard	Sand should have proper quantity od moisture
Cold shuts or misruns:its incomplete casting results and mould cavity not filled completely	Imporer gating system ,damaged pattern, slow pouring, and poor fluidity of metal	Designe proper gating system and use theof hotter metal
Cold shots .	which result from splattering during pouring, causing the formation of solid globules of metal that become entrapped in the casting.	Pouring procedures and gating system designs that avoid splattering can prevent this defect
Internal air pockets: it's a small holes inside the casting	Pouring the boiling metal or rapid pouring of the molten metalin the mould	Use a proper pouring velocity with proper meling tempreture
Scales :they are the patches	Slow running of metal, sand having low permeability and moisture, and uneven ramming of sand	Proper ramming of sand and proper feeding liquid metal
Shifting	Core misplacement, mis matching of top and bottom of casting	Proper alignment of pattern and moulding boxes
Warpage: undesirable deformation in a casting	Different rate of solidification in different sectionof the casting	Proper desgin can reduce this defect
Fins :thin projections of metal not required as a part of casting,usually at parting line	Moulds and cores incorrectly assembled	Correct assembly of moulds and cores
Swell : it is an enlargement of the mould cavity by metal pressure	Defective ramming of sand	Sand should be properly rammedkk
Gas porosity:	Hydrogen in molten metal, dissociation of water inside mould cavity	Reduce hydrogen content
Shrinkage porosity: cavity in castings	Non uniform solidification of metal	Proper solidification of metal

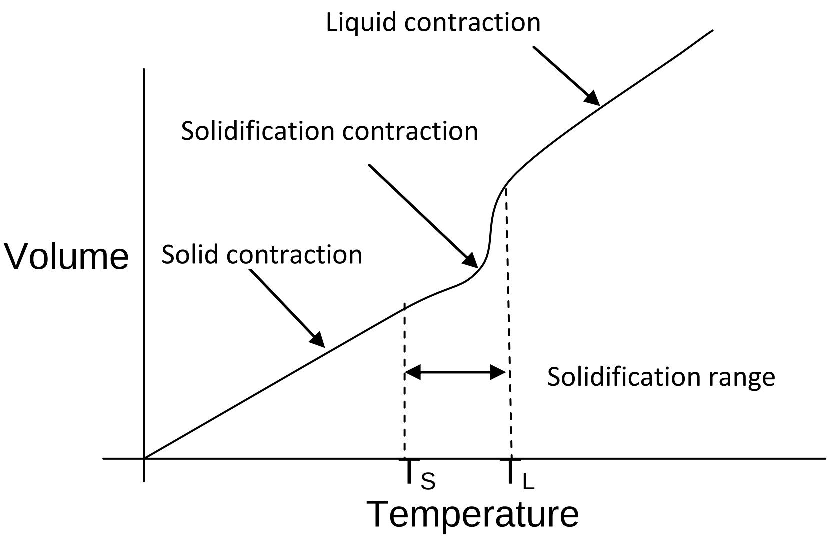


Some common defects in castings: (a) misrun, (b) cold shut, (c) cold shot, (d) shrinkage cavity, (e) microporosity, and (f) hot tearing.

3.12Shrinkage in casting

Because of their thermal expansion characteristics, metals usually shrink (contract) during solidification and while cooling to room temperature. Shrinkage, which causes dimensional changes and sometimes warping and cracking, is the result of the following three sequential events:

I. Contraction of the molten metal as it cools prior to its solidification.
2. Contraction of the metal during phase change from liquid to solid (latent heat of fusion).
3. Contraction of the solidified metal (the casting) as its temperature drops to ambient temperature.



The largest potential amount of shrinkage occurs during the cooling of the casting to ambient temperature. Note that some metals (such as gray cast iron) expand. (The reason is that graphite has a relatively high specific volume, and when it precipitates as graphite flakes during solidification of the gray cast iron, it causes a net expansion of the metal.)

3.13 risers (feeders) design

As described earlier, a riser, Figure 3, is used in a sand-casting mold to feed liquid metal to the casting during freezing in order to compensate for solidification shrinkage. To function, the riser must remain molten until after the casting solidifies. Chvorinov's rule can be used to compute the size of a riser that will satisfy this requirement. The following example illustrates the calculation.

Example5:

A cylindrical riser must be designed for a sand-casting mold. The casting itself is a steel rectangular plate with dimensions 7.5 cm x 12.5 cm x 2.0 cm. Previous observations have indicated that the total solidification time (T) for this casting = 1.6 min. The cylinder for the riser will have a diameter-to-height ratio=1.0. Determine the dimensions of the riser so that it's T = 2.0 min.

Solution:

First determine the V/A ratio for the plate. Its volume V = 7.5 x 12.5 x .0= 187.5 cm^3, and its surface area A= 2 (7.5 x 12.5 + 7.5 x 2.0 + 12.5 x 2.0) = 267.5 cm^2. Given that T = 1.6 min, we can determine the mold constant C from Eq. (3.7), using a value of n = 2 in the equation

$$C = \frac{T}{(V/A)^2} = \frac{1.6}{(187.5/267.5)^2} = 3.26\,\text{min/cm}^2$$

Next we must design the riser so that its total solidification time is 2.0 min, using the same value of mold constant. The volume of the riser is given by

$$V = \frac{\pi D^2 h}{4}$$

and the surface area is given by

$$A = \pi D h + \frac{2\pi D^2}{4}$$

Since we are using a D/H ratio = 1.0, then $D = H$. Substituting D for H in the volume and area formulas, we get

$$V = \pi D^3/4$$

and

$$A = \pi D^2 + 2\pi D^2/4 = 1.5\pi D^2$$

Thus the V/A ratio = $D/6$. Using this ratio in Chvorinov's equation, we have

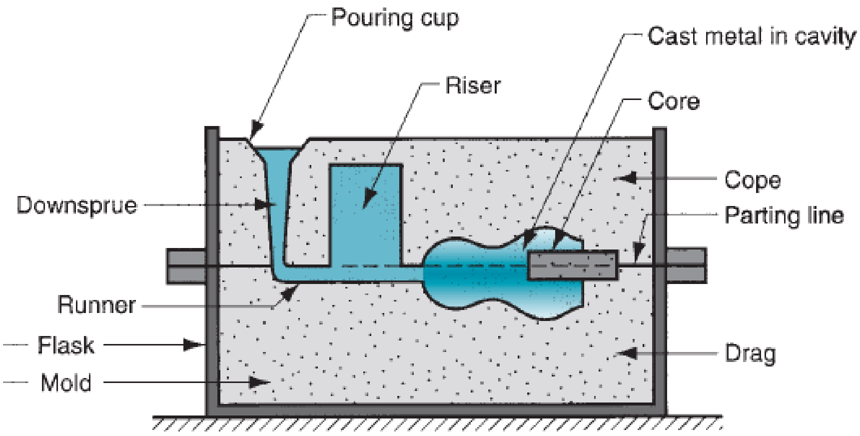
$$T_{TS} = 2.0 = 3.26\left(\frac{D}{6}\right)^2 = 0.09056\,D^2$$

$$D^2 = 2.0/0.09056 = 22.086\,\text{cm}^2$$

$$D = 4.7\,\text{cm}$$

Since $H = D$, then $H = 4.7$ cm also.

The riser represents waste metal that will be separated from the cast part and remelted to make subsequent castings. It is desirable for the volume of metal in the riser to be a minimum. Since the geometry of the riser is normally selected to maximize the V/A ratio, this tends to reduce the riser volume as much as possible. Note that the volume of the riser in our example problem is $V = \pi \cdot 4.7^3/4 = 81.5\ cm^3$, only 44% of the volume of the plate (casting), even though it's total solidification time is 25% longer. Risers can be designed in different forms. The design shown in Figure below is a **side riser**. It is attached to the side of the casting by means of a small channel. A **top riser** is one that is connected to the top surface of the casting. Risers can be open or blind. **An open riser** is exposed to the outside at the top surface of the cope. This has the disadvantage of allowing more heat to escape, promoting faster solidification. A **blind riser** is entirely enclosed within the mold, as in Figure below



Summary of Casting Processes

Process	Advantages	Limitations
Sand	Almost any metal cast; no limit to size, shape or weight; low tooling cost.	Some finishing required; somewhat coarse finish; wide tolerances.
Shell mold	Good dimensional accuracy and surface finish; high production rate.	Part size limited; expensive patterns and equipment required.
Expendable pattern	Most metals cast with no limit to size; complex shapes	Patterns have low strength and can be costly for low quantities
Plaster mold	Intricate shapes; good dimensional accu- racy and finish; low porosity.	Limited to nonferrous metals; limited size and volume of production; mold making time relatively long.
Ceramic mold	Intricate shapes; close tolerance parts; good surface finish.	Limited size.
Investment	Intricate shapes; excellent surface finish and accuracy; almost any metal cast.	Part size limited; expensive patterns, molds, and labor.
Permanent mold	Good surface finish and dimensional accuracy; low porosity; high production rate.	High mold cost; limited shape and intricacy; not suitable for high-melting-point metals.
Die	Excellent dimensional accuracy and surface finish; high production rate.	Die cost is high; part size limited; usually limited to nonferrous metals; long lead time.
Centrifugal	Large cylindrical parts with good quality; high production rate.	Equipment is expensive; part shape limited.

Fundamental of forming process

4-1 introduction

Metal forming includes a large group of manufacturing processes in which plastic deformation is used to change the shape of metal workpieces. Deformation results from the use of a tool, usually called a **die** in metal forming, which applies stresses. Stresses applied to plastically deform the metal are usually **compressive**, **stretch**, **bend**, or **shear stresses** to the metal. To be successfully formed, a metal must possess certain properties. Desirable properties include **low yield strength** and **high ductility**. Metal forming processes can be classified into two basic categories: **bulk deformation processes** and **sheet metalworking,** and these two categories contain many processes as shown in figure 4.1

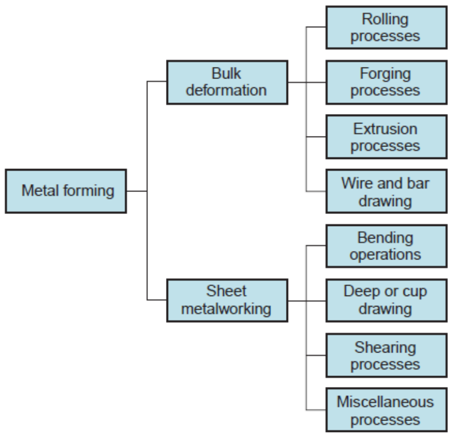


Fig 4-1 Classification of metal forming operations.

Bulk Deformation Processes Bulk deformation processes are generally characterized by significant deformations and massive shape changes, and the surface area-to-volume of the work is relatively small. The term bulk describes the work parts that have this low area to- volume ratio. Figure 4-2 shows some common bulk deformation processes.

Sheet Metalworking Sheet metalworking processes are forming and cutting operations performed on metal sheets, strips, and coils. The surface area-to-volume ratio of the starting metal is high; thus, this ratio is a useful means to distinguish bulk deformation from sheet metal processes. ***Pressworking*** *is the term often applied to sheet metal operations because the machines used to perform these operations are presses*. Sheet metal operations are always performed as **cold working** processes and are usually accomplished using a set of tools called a **punch** and **die**. The basic sheet metal operations are sketched in Figure 4-3.

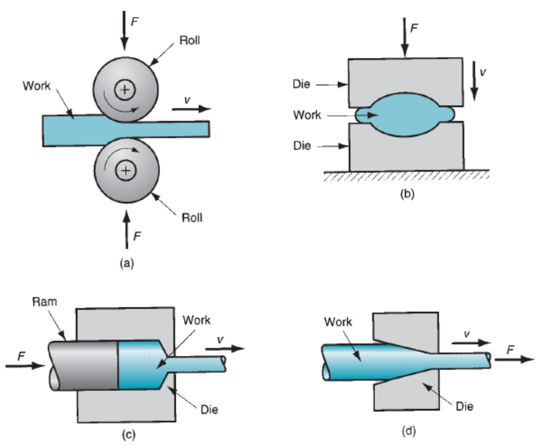


Figure 4-2 Basic bulk deformation processes: (a) rolling, (b) forging, (c) extrusion, and (d) drawing. Relative motion in the operations is indicated by *v*; forces are indicated by *F*.

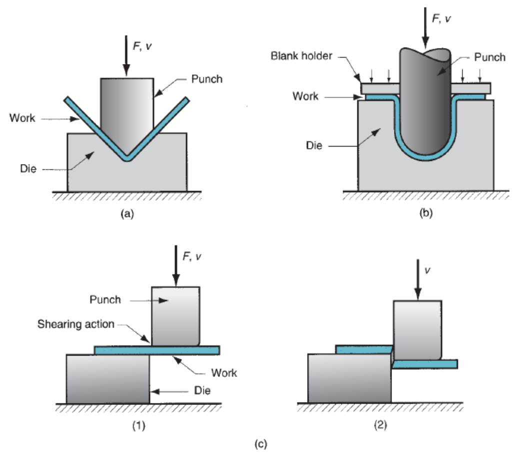


Figure 4-3 Basic sheet metalworking operations: (a) bending, (b) drawing, and (c) shearing: (1) as punch first contacts sheet, and (2) after cutting. Force and relative motion in these operations are indicated by *F* and *v*.

The behavior of metals during forming can be obtained from the stress–strain curve. The typical stress–strain curve for most metals is divided into an elastic region and a plastic region. In metal forming, the plastic region is of primary interest because the material is plastically and permanently deformed in these processes. The typical stress–strain relationship for a metal exhibits elasticity below the yield point and strain hardening above it. In the plastic region, the metal's behavior is expressed by the equation:

$$\sigma = K\varepsilon^n \qquad (4.1)$$

Where K = the strength coefficient, MPa (lb/in2); and (n) is the strain-hardening exponent. The stress s and strain e in the equation are true stress and true strain.

Flow Stress The flow curve describes the stress–strain relationship in the region in which metal forming takes place. It indicates the flow stress of the metal the strength property that determines forces and power required to accomplish a particular forming operation. For most metals at room temperature, the stress–strain plot of Figure 4.4 indicates that as the metal is deformed, its strength increases due to strain hardening. The stress required to continue deformation must be increased to match this increase in strength. Flow stress is defined as the instantaneous value of stress required to continue deforming the material to keep the metal ''flowing.'' It is the yield strength of the metal as a function of strain, which can be expressed:

$$Y_f = K\,\varepsilon^n \qquad (4.2)$$

Where Y_f = flow stress MPa (lb/in^2).

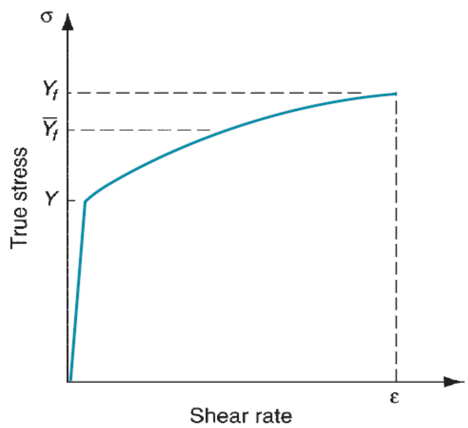


Fig 4-4 Stress–strain curve indicating location of average flow stress $\overline{Y}_f$ in relation to yield strength Y and final flow stress Y_f.

Average Flow Stress The average flow stress (also called the mean flow stress) is the average value of stress over the stress–strain curve from the beginning of strain to the final (maximum) value that occurs during deformation. The value is illustrated in the stress– strain plot of Figure 4.4. The average flow stress is determined by integrating the flow curve equation, Eq. (4.2), between zero and the final strain value defining the range of interest. This yields the equation:

$$Y_f = \frac{K\varepsilon^n}{1+n}$$

Where Y_f = average flow stress, MPa (lb/in2); and ε = maximum strain value during the deformation process.

4-3Temperature in metal forming

For any metal, the values of K and n depend on temperature. Strength and strain hardening are both reduced at higher temperatures. These property changes are important because they result in lower forces and power during forming. In addition, ductility is increased at higher temperatures, which allows greater plastic deformation of the work metal.

Cold Working (also known as cold forming) is metal forming performed at room temperature to 0.3Tm. Significant advantages of cold forming compared to hot working are:

(1) greater accuracy, meaning closer tolerances can be achieved
(2) better surface finish;
(3) higher strength and hardness of the part due to strain hardening
(4) grain flow during deformation provides the opportunity for desirable directional properties to be obtained in the resulting product;
(5) No heating of the work is required, which saves on furnace and fuel costs and permits higher production rates.

There are certain disadvantages or limitations associated with cold forming operations:

(1) Higher forces and power are required to perform the operation.
(2) Care must be taken to ensure that the surfaces of the starting workpiece are free of scale and dirt.
(3) Ductility and strain hardening of the work metal limit the amount of forming that can be done to the part.

Warm working the term warm working is applied to this second temperature range. The dividing line between cold working and warm working is often expressed in terms of the melting point for the metal. The dividing line is usually taken between (0.3 Tm-0.5 Tm), where Tm is the melting point for the particular metal. The advantages of warm working over cold working are:

(1) Lower forces and power.
(2) More intricate work geometries possible.
(3) Need for annealing may be reduced or eliminated.

Hot Working Hot working (also called hot forming) involves deformation at temperatures above the recrystallization temperature. The recrystallization temperature for a given metal is about **one-half** of its melting points on the absolute scale. The range of hot working it's about (0.5Tm-0.75Tm).

The advantages of the hot working are:

(1) shape of the workpart can be significantly altered
(2) lower forces and power are required to deform the metal
(3) metals that usually fracture in cold working can be hot formed

(4) strength properties are generally isotropic because of the absence of the oriented grain structure typically created in cold working
(5) no strengthening of the part occurs from work hardening

Disadvantages of hot working include:
(1) Lower dimensional accuracy.
(2) Higher total energy required (due to the thermal energy to heat the workpiece).
(3) Work surface oxidation (scale).
(4) Poorer surface finish.
(5) Shorter tool life.

Isothermal forming refers to forming operations that are carried out in such a way as to eliminate surface cooling and the resulting thermal gradients in the workpart. It is accomplished by **preheating the tools** that come in contact with the part to the same temperature as the work metal. The variations in temperature and strength in different regions of the workpiece cause irregular flow in metal during deformation, leading to **high residual stresses** and possible **surface cracking**.

4-4 Friction and lubricants

Friction in metal forming arises because of the close contact between the tool and work surfaces and the high pressures that drive the surfaces together in these operations In most metal forming processes, friction is undesirable for the following reasons:
(1) Metal flow in the work is retarded, causing residual stresses and sometimes defect.
(2) Forces and power to perform the operation are increased.
(3) Tool wear can lead to loss of dimensional accuracy.

If the coefficient of friction becomes large enough, a condition known as **sticking** occurs. Sticking in metalworking (also called sticking friction) is the tendency for the two surfaces in relative motion to adhere to each other rather than slide

Considerations in choosing an appropriate metalworking lubricant include:
(1) Type of forming process (rolling, forging, sheet metal drawing, and so on).
(2) Whether used in hot working or cold working.
(3) Work material.
(4) Chemical reactivity with the tool and work metals and Toxicity
(5) Ease of application.
(6) Flammability.
(7) Cost.

Lubricants used for cold working operations include **mineral oils**, **fats** and **fatty oils, water-based emulsions, soaps**. **Hot working** is sometimes performed **dry** for certain operations and materials (e.g., hot rolling of steel and extrusion of aluminum). When lubricants are used in hot working, they include **mineral oils, graphite, and glass**.

Rolling processes

5-1 introduction:

Rolling is the process of reducing the thickness or changing the cross section of a long workpiece by compressive forces applied through a set of rolls, as shown in figure (5-1).

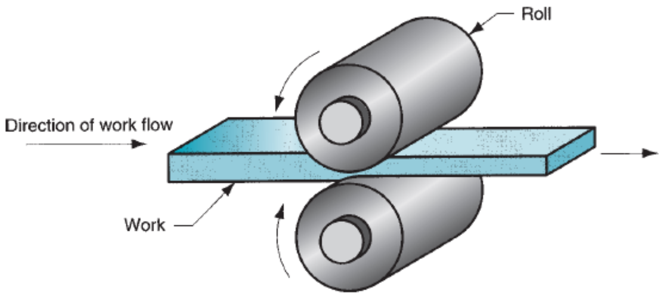


Fig. (5-1)

Most rolling is carried out by hot working, called hot rolling, owing to the large amount of deformation required. Hot-rolled metal is generally free of residual stresses, and its properties are isotropic. Disadvantages of hot rolling are that the product cannot be held to close tolerances, and the surface has a characteristic oxide scale.

Steelmaking provides the most common application of rolling operations. Figure (5-2) illustrates the sequence of steps in a steel rolling mill to show the variety of products made. Similar steps occur in other basic metal industries. The work starts out as a **cast steel ingot** that has just solidified. While it is still hot, the ingot is placed in a furnace where it remains for many hours until it has reached a uniform temperature throughout, so that the metal will flow consistently during rolling. For steel, the desired temperature for rolling is around 1200_C (2200_F). The heating operation is called **soaking**, and the furnaces in which it is carried out are called **soaking pits**. From soaking, the ingot is moved to the rolling mill, where it is rolled into one of three intermediate shapes called blooms, billets, or slabs, as shown in figure (5-2).

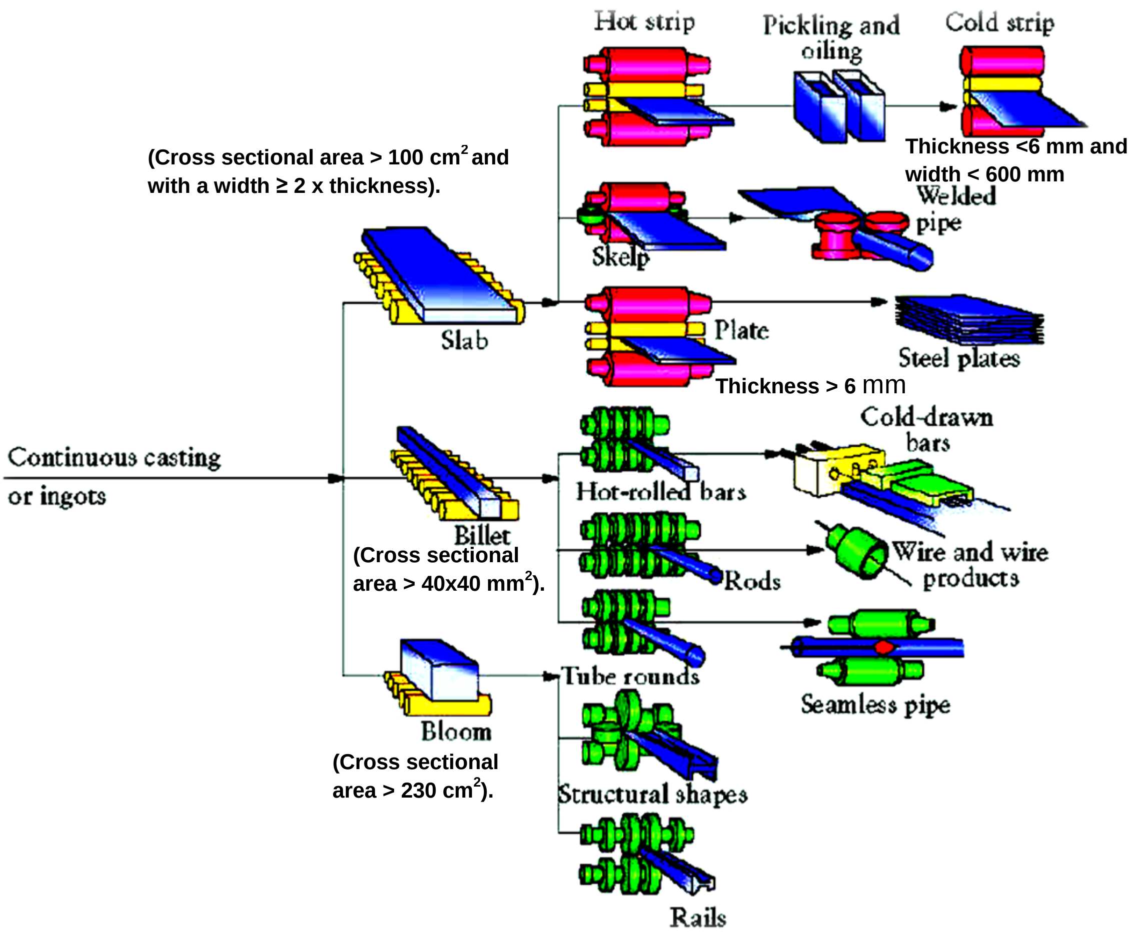


Fig. (5-2)

5.2 Flat rolling and its analysis:

Flat rolling is illustrated in Figures (5-1). It involves the rolling of slabs, strips, sheets, and plates workparts of rectangular cross section in which the width is greater than the thickness. In flat rolling, the work is squeezed between two rolls so that its thickness is reduced by an amount called the **draft**:

$$d = h_\circ - h_f = 2R\,(1\text{-}\cos\alpha) \qquad 5.1$$

Where d = draft, mm (in); $h_\circ$= starting thickness, mm (in); and h_f = final thickness, mm (in).R = roll radius in mm and (α) = bite angle in degree. Draft is sometimes expressed as a fraction of the starting stock thickness, called the **reduction**

$$r = \frac{d}{h_\circ} \qquad 5.2$$

Where r = reduction. When a series of rolling operations are used, reduction is taken as the sum of the drafts divided by the original thickness. In addition to thickness reduction, rolling usually increases work width. This is called spreading, and it tends to be most pronounced with low width-to-thickness ratios and low coefficients of friction, so the volume of metal exiting the rolls equals the volume entering

$$h_{\circ} w_{\circ} L_{\circ} = h_f w_f L_f \qquad 5.3$$

Where w_o and w_f are the before and after work widths, mm (in); and L_o and L_f are the before and after work lengths, mm (in). Similarly, before and after volume rates of material flow must be the same, so the before and after velocities can be related:

$$h_{\circ} w_{\circ} v_{\circ} = h_f w_f v_f \qquad 5.4$$

Where v_o and v_f are the entering and exiting velocities of the work.
The surface speed of the rolls is V_r the velocity of the strip increases from its entry value of V_O as it moves through the roll gap; the velocity of the strip is highest at the exit from the roll gap and is denoted as V_f. The metal accelerates in the roll gap in the same manner as an incompressible fluid flowing through a converging channel.

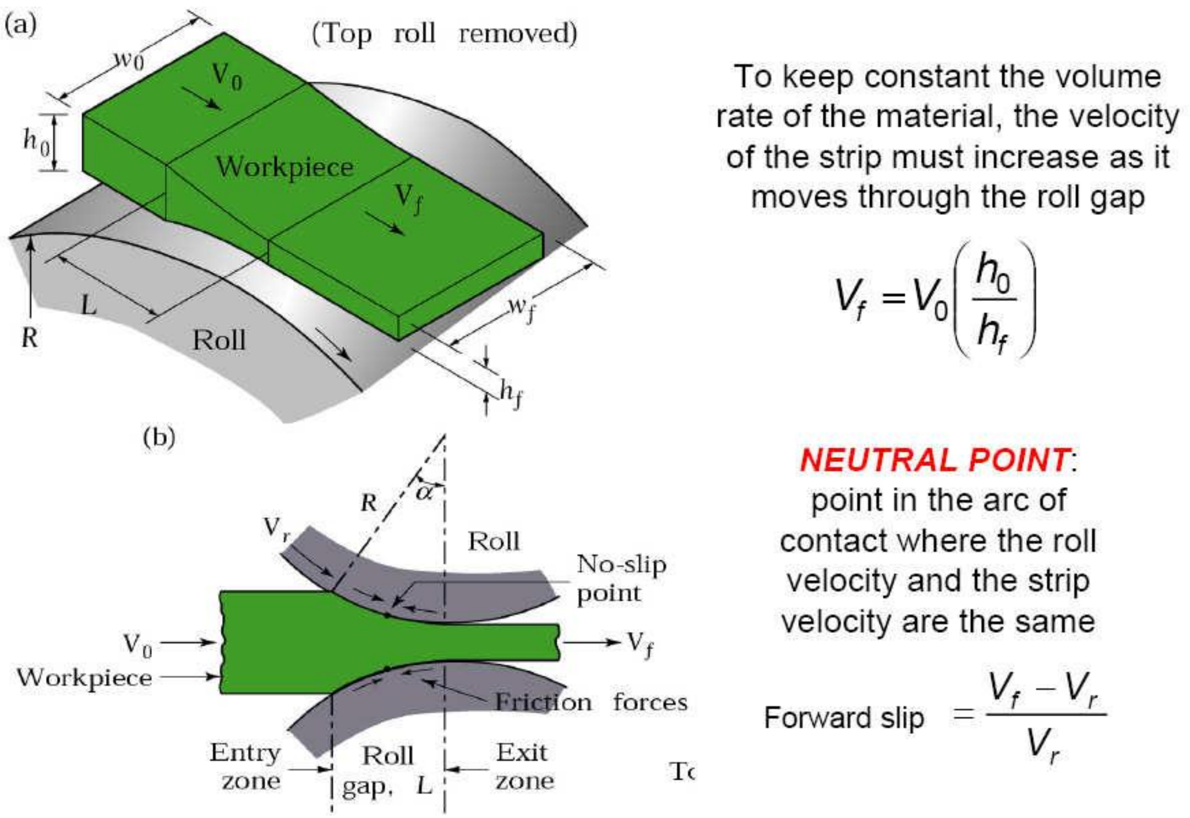


Fig. (5-3)

Because the surface speed of the rigid roll is constant, there is relative sliding between the roll and the strip along the arc of contact in the roll gap, **L**. At one point along the contact length **(called the neutral point or no-slip point) the velocity of the strip is the same as that of the roll**. To the left of this point, the roll moves faster than the strip; to the right of this point, the strip moves faster than the roll. Consequently, the frictional forces-which oppose motion between two sliding bodies-act on the strip as shown above. On either side of this point, slipping and friction occur between roll and work. The amount of slip between the rolls and the work can be measured by means of the forward slip, a term used in rolling that is defined:

$$\boldsymbol{S} = \frac{\boldsymbol{V_f - V_r}}{\boldsymbol{V_r}} \qquad 5.5$$

Where $\boldsymbol{S}$ = forward slip; $\mathbf{v_f}$ = final (exiting) work velocity, m/s (ft/sec); and $\mathbf{v_r}$ = roll speed, m/s (ft/sec).

The rolls pull the material into the roll gap through a net frictional force on the material. Thus, the net frictional force must be to the right in Fig. (5-3 b). This also means that the frictional force to the left of the neutral point must be higher than the friction force to the right. Although friction is necessary for rolling materials (just as it is in driving a car on a road), energy is dissipated in overcoming friction. Thus, increasing friction also increases rolling forces and power requirements. Thus, a compromise is made in practice: Low and controlled friction is induced in rolling through the use of effective lubricants.

The maximum possible draft is defined as in equation below; it can be shown that this quantity is a function of the roll radius, R, and the coefficient of friction, μ, between the strip and the roll by the following relationship:

$$d_{max} = \mu^2 R \qquad 5.6$$

Thus, as expected, the higher the friction and the larger the roll radius, the greater the maximum possible draft becomes. Note that this situation is similar to the use of large tires (high R) and rough treads (high, μ.) on farm tractors and off-road earthmoving equipment, thus permitting the vehicles to travel over rough terrain without skidding.

Coefficient of friction in rolling depends on lubrication, work material, and working temperature. In cold rolling, the value is around 0.1; in warm working, a typical value is around 0.2; and in hot rolling, m is around 0.4. Hot rolling is often characterized by a condition called sticking, in which the hot work surface adheres to the rolls over the contact arc. This condition often occurs in the rolling of steels and high-temperature alloys. When sticking occurs, the coefficient of friction can be as high as 0.7. The consequence of sticking is that the surface layers of the work are restricted to move at the same speed as the roll speed v_r; and below the surface, deformation is more severe in order to allow passage of the piece through the roll gap.

The true strain experienced by the work in rolling is based on before and after stock thicknesses. In equation form,

$$\varepsilon = \ln \frac{h_\circ}{h_f} \qquad 5.7$$

The true strain can be used to determine the average flow stress Y_f applied to the work material in flat rolling. Recall from eq. (4.3)

$$\bar{Y}_f = \frac{K\varepsilon^n}{1+n} \qquad 5.8$$

The minimum number of passes= $h_\circ - h_f / d_{max}$

5.3 roll force, torque, and power requirements:

The rolls apply pressure on the flat strip in order to reduce its thickness, resulting in a roll force, F, as shown in Fig. 5-4.

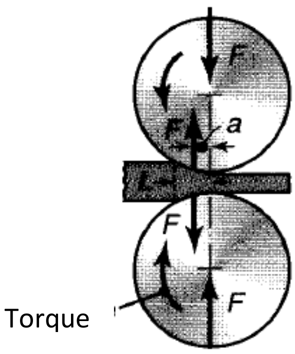


Fig. 5-4

Note that this force appears in the figure as perpendicular to the plane of the strip, rather than at an angle. This is because, in practice, the arc of contact is very small compared with the roll radius, so we can assume that the roll force is perpendicular to the strip without causing significant error in calculations. The roll force in flat rolling can be estimated from the formula

$$F = \bar{Y}_f \; w \, L \qquad 5.9$$

(For a frictionless situation; however, an estimate of the actual roll force, including friction, may be made by increasing this calculated force by about 20%). Where $\bar{Y}_f$ = average flow stress from Eq. (5.8), MPa (lb/in^2); and the product (wL) is the roll-work contact area, mm^2 (in^2). Contact length can be approximated by

$$L = \sqrt[2]{R(h_\circ - h_f)} \qquad 5.10$$

The torque in rolling can be estimated by assuming that the roll force is centered on the work as it passes between the rolls, and that it acts with a moment arm of one-half the contact length L. Thus, torque for each roll is

$$T = 0.5FL \qquad 5.11$$

The power required per roll can be estimated by assuming that (F) acts in the middle of the arc of contact; thus, in Fig. (5-4), a = L/2. Therefore, the total power (for two rolls), in S.I. units, is

$$\text{Power (in Kw)} = \frac{2\pi FLN}{60000} \qquad 5.12$$

Where F is in newtons , L is in meters, and N is the revolutions per minute of the roll.

In traditional English units, the total power can be expressed as

$$\text{Power (in hp)} = \frac{2\pi FLN}{33000} \qquad 5.13$$

Where F is in pounds and L is in feet.

Example:

A 300-mm-wide strip 25-mm thick is fed through a rolling mill with two powered rolls each of radius = 250 mm. The work thickness is to be reduced to 22 mm in one pass at a roll speed of 50 rev/min. The work material has a flow curve defined by K = 275 MPa and n = 0.15, and the coefficient of friction between the rolls and the work is assumed to be 0.12. Determine if the friction is sufficient to permit the rolling operation to be accomplished. If so, calculate the roll force, torque, and horsepower.

Solution:

The draft attempted in this rolling operation is

$$d = 25 - 22 = 3\text{mm}$$

From equation (5.6) we can find the maximum draft

$$d_{max} = (0.12)^2(250) = 3.6\text{mm}$$

Since the maximum allowable draft exceeds the attempted reduction, the rolling operation is feasible. To compute rolling force, we need the contact length L and the average flow stress Yf . The contact length is given by Eq. (5.10)

$$L = \sqrt[2]{R(h_\circ - h_f)}$$

$$L = \sqrt[2]{250(25 - 22)} = 27.4 \text{ mm}$$

Y_f is determined from the true strain:

$$\varepsilon = \ln \frac{h_\circ}{h_f}$$

$$\varepsilon = \ln \frac{25}{22} = 0.128$$

$$\overline{Y_f} = \frac{275X0.128^{0.15}}{1+0.15} = 175.7 \text{ MPa}$$

Rolling force is determined from Eq. (5.9)

F =175.7(300) (27.4) =1. 444. 254 N

Torque required to drive each roll is given by Eq. (5.11):

T = 0.5(1. 444.254) (27. 4) (10^{-3}) = 19. 786 N-m

And the power is obtained from Eq. (5.12):

Power (in Kw) = $\frac{2\pi X 1.444.786 X 0.274 X 50}{60000}$ = 207.284 Kw

(We note that one horsepower =745.7 W):→ Power in hp =$\frac{207284}{745.7} = 277.97 = 278$ hp

It can be seen from this example that large forces and power are required in rolling. Inspection of Eqs. (5.9) and (5.12) indicates that force and/or power to roll a strip of a given width and work material can be reduced by any of the following: (1) using hot rolling rather than cold rolling to reduce strength and strain hardening (K and n) of the work material; (2) reducing the draft in each pass; (3) using a smaller roll radius R to reduce contact area and then reduce the force; and (4) using a lower rolling speed N to reduce power.

5.4 Shape rolling:

In shape rolling, the work is deformed into a contoured cross section. Products made by shape rolling include construction shapes such as I-beams, L-beams, and U-channels; rails for railroad tracks; and round and square bars and rods (see Figure 5.5). Most of the principles that apply in flat rolling are also applicable to shape rolling. Shaping rolls are more complicated; and the work, usually starting as a square shape. Designing the sequence of intermediate shapes and corresponding rolls is called roll-pass design. Its goal is to achieve uniform deformation throughout the cross section in each reduction.

Fig. 5.5

5.5 rolling mills:

Various rolling mill configurations are available to deal with the variety of applications and technical problems in the rolling process. The basic rolling mill consists of two opposing rolls and is referred to as a two-high rolling mill, shown in Figure 5.6 (a). The rolls in these mills have diameters in the range of 0.6 to 1.4 m (2.0–4.5 ft). The two-high configuration can be either reversing or nonreversing. In the nonreversing mill, the work always passes through from the same side. The reversing mill allows the direction of roll rotation to be reversed, so that the work can be passed through in either direction. This permits a series of reductions to be made through the same set of rolls, simply by passing through the work from opposite directions multiple times. The disadvantage of the reversing configuration is the significant angular momentum possessed by large rotating rolls and the associated technical problems invol

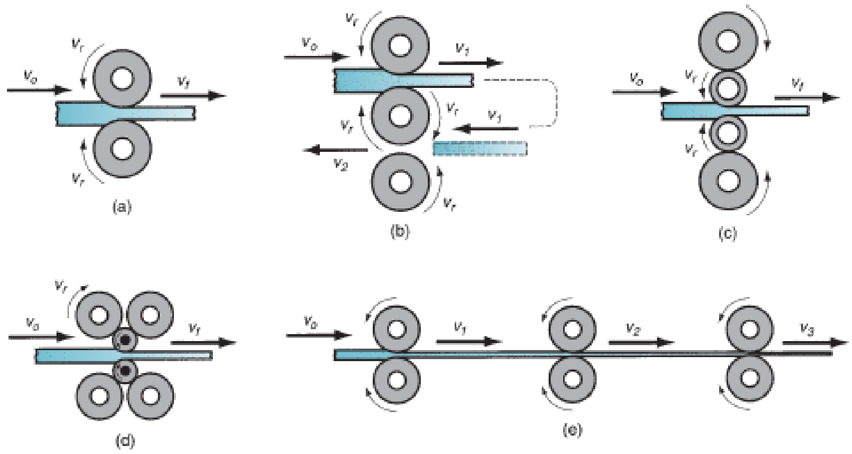


Fig (5.6) various configurations of rolling mills: (a) 2-high, (b) 3-high, (c) 4-high, (d) cluster mill, and (e) tandem rolling mill.

Several alternative arrangements are illustrated in Figure 5.6. In the three-high configuration, Figure 5.6 (b), there are three rolls in a vertical column, and the direction of rotation of each roll remains unchanged. To achieve a series of reductions, the work can be passed through from either side by raising or lowering the strip after each pass. The equipment in a three-high rolling mill becomes more complicated, because an elevator mechanism is needed to raise and lower the work.

As several of the previous equations indicate, advantages are gained in reducing roll diameter. Roll-work contact length is reduced with a lower roll radius, and this leads to lower forces, torque, and power. The four-high rolling mill uses two smaller-diameter rolls to contact the work and two backing rolls behind them, as in Figure 5.6 (c). Owing to the high roll forces, these smaller rolls would deflect elastically between their end bearings as the work passes through unless the larger backing rolls were used to support them.

Another roll configuration that allows smaller working rolls against the work is the cluster rolling mill (Figure 5.6(d)).

To achieve higher throughput rates in standard products, a tandem rolling mill is often used. This configuration consists of a series of rolling stands, as represented in Figure 5.6(e). Although only three stands are shown in our sketch, a typical tandem rolling mill may have eight or ten stands, each making a reduction in thickness or a refinement in shape of the work passing through.

5.6Various Rolling Processes and Mills:

Several other bulk deformation processes use rolls to form the workpart. The operations include thread rolling, ring rolling, and roll piercing….etc

5.6.1 Transverse rolling or Roll forging in this operation (also called cross rolling), the cross section of a round bar is shaped by passing it through a pair of rolls with profiled grooves (Fig. 5.7). Roll forging typically is used to produce tapered shafts and leaf springs, table knives, and hand tools; it also may be used as a preliminary forming operation, to be followed by other forging processes.

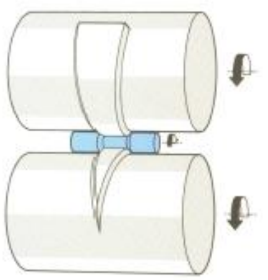


Fig 5.7

5.6.2 Skew Rolling. A process similar to roll forging is skew rolling, typically used for making ball bearings (Fig. 5.8). Round wire or rod is fed into the roll gap, and roughly spherical blanks are formed continuously by the action of the rotating rolls.

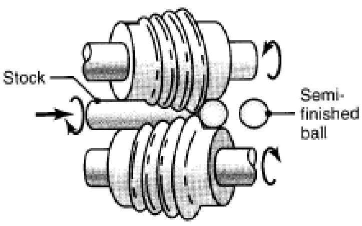


Fig 5.8

5.6.3 Ring Rolling. In ring rolling, a thick ring is expanded into a large-diameter thinner one. The ring is placed between two rolls, one of which is driven while the other is idle (Fig. 5.9). Its thickness is reduced by bringing the rolls closer together as they rotate. Since the volume of the ring material remains constant during plastic deformation (volume constancy), the reduction in ring thickness results in an increase in its diameter. Typical applications of ring rolling are large rings for rockets and turbines.

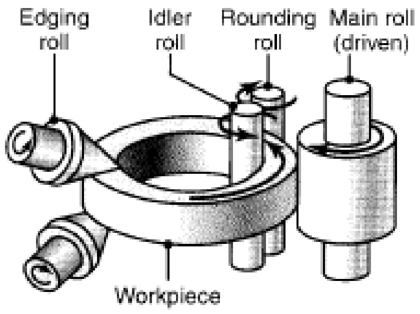


Fig 5.9

5.6.4 Thread Rolling. Thread rolling is a cold-forming process by which straight or tapered threads are formed on round rods or wire. The threads are formed on the rod or wire with each stroke of a pair of flat reciprocating dies (Fig. 5.10). In another method, threads are formed with rotary dies (Fig. 5.11), The thread-rolling process has the advantages of generating threads with good strength (due to cold working) and without any loss of material (scrap). The surface finish produced is very smooth, and the process induces compressive residual stresses on the workpiece surfaces, thus improving fatigue life.

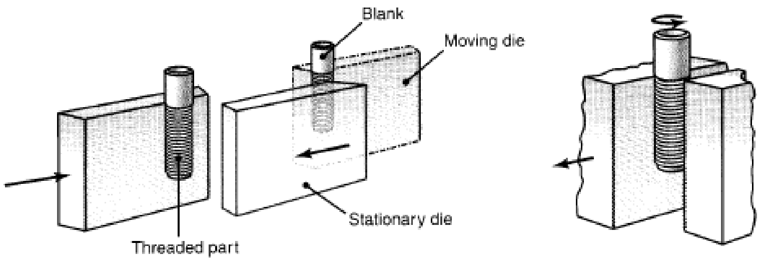
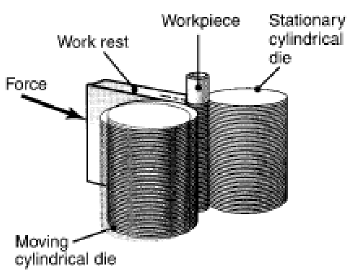


Fig 5.10



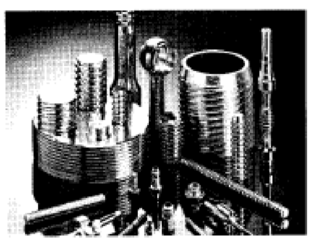


Fig 5.11

5.6.5 Rotary Tube Piercing or Roll Piercing: Ring rolling is a specialized hot working process for making seamless thick-walled tubes. It utilizes two opposing rolls, and hence it is grouped with the rolling processes. The process is based on the principle that when a solid cylindrical part is compressed on its circumference, as in Figure 5.12(a), high tensile stresses are developed at its center. If compression is high enough, an internal crack is formed. In roll piercing, this principle is exploited by the setup shown in Figure 5.12(b).

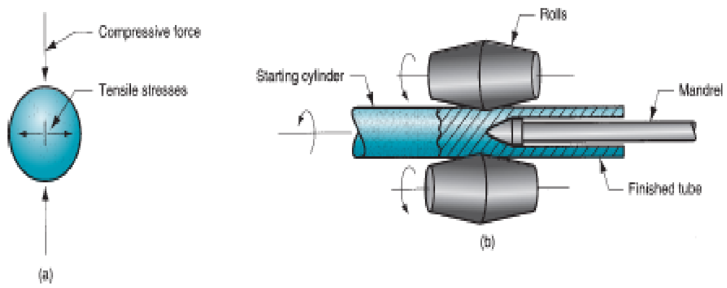


Figure 5.12 Roll piercing: (a) formation of internal stresses and cavity by compression of cylindrical part; and (b) setup of Mannesmann roll mill for producing seamless tubing.

5.7 Roll bending

Because of the forces acting on them, rolls undergo changes in shape during rolling. Just as a straight beam deflects under a transverse load, roll forces tend to bend the rolls elastically during rolling (Fig. 5.13). As expected, the higher the elastic modulus of the roll material, the smaller the roll deflection. As a result of roll bending, the rolled strip tends to be thicker at its center than at its edges (crown). The usual method of avoiding this problem is to grind the rolls in such a way that their diameter at the center is slightly larger thanat.their edges (camber).

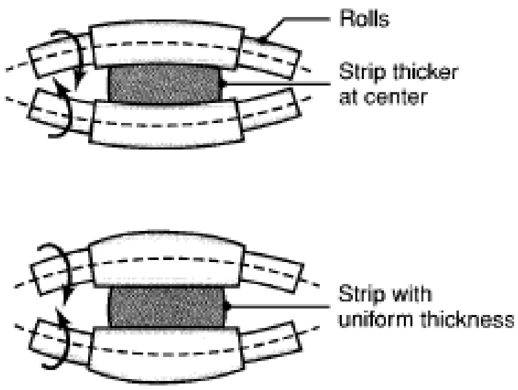


Fig 5.13

The results of insufficient camber are shown in Figure 5.14. The thicker center requires the edges to be elongated more. This can cause edge wrinkling or warping of a plate. The center is left in residual tension and center cracking can occur.

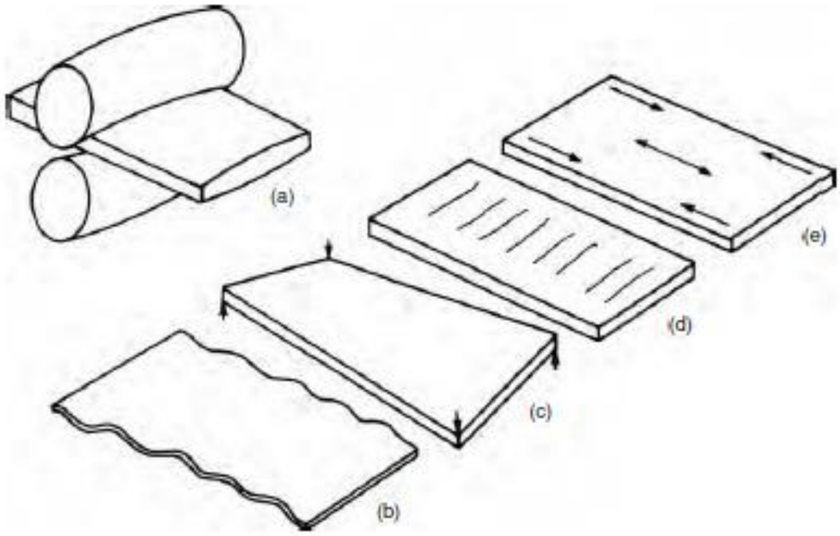


Fig 5.14 Possible effects of insufficient camber (a): edge wrinkling (b), warping (c), centerline cracking (d), and (e) residual stresses.

If the rolls are over-cambered, as shown in Figure 5.15, the residual stress pattern is the opposite. Centerline compression and edge tension may cause edge cracking, lengthwise splitting, and a wavy center.

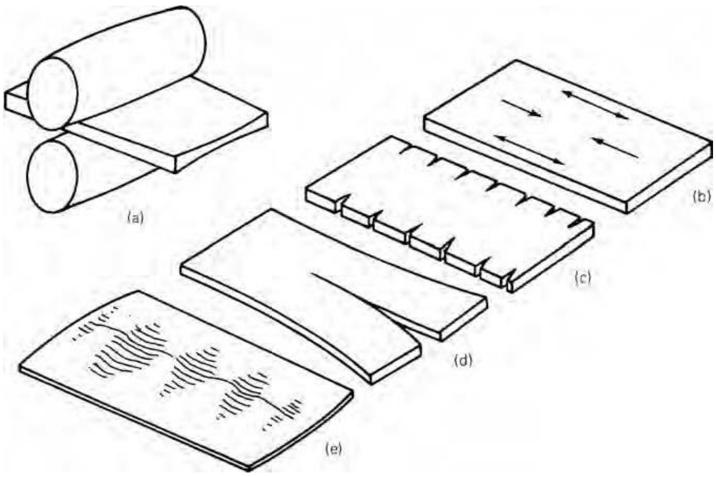


Fig 5.15Effects of over-cambering (a): wavy center (b), centerline splitting (c), edge cracking (d), and (e) residual stresses**.**

Extrusion Process

6.1 Introduction:
Extrusion is a compression process in which the work metal is forced to flow through a die opening to produce a desired cross-sectional shape. As shown in figure (6.1)

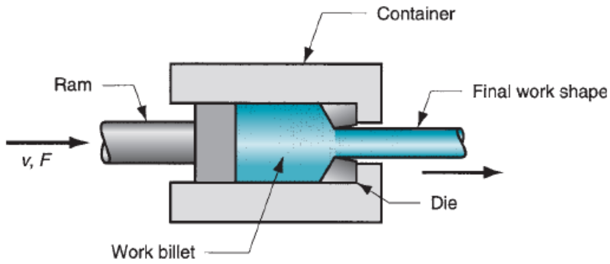


Figure (6.1) Extrusion process (direct extrusion)

6.2 advantages of the extrusion process:
There are several advantages of the modern extrusion process

1. A variety of shapes are possible, especially with hot extrusion.
2. Grain structure and strength properties are enhanced in cold and warm extrusion.
3. Fairly close tolerances are possible, especially in cold extrusion.
4. Little or no wasted material is created.

However, a limitation is that the cross section of the extruded part must be uniform throughout its length.

6.3 types of extrusion process:
There are many classifications for the extrusion processes, it may classify depending on the extrusion direction as direct and indirect another classification is by working temperature as cold or warm or hot extrusion.

6.3.1 Direct extrusion (also called forward extrusion) is illustrated in Figure(6.1). A metal billet is loaded into a container, and a ram compresses the material, forcing it to flow through one or more openings in a die at the opposite end of the container. As the ram approaches the die, a small portion of the billet remains that cannot be forced through the die opening. This extra portion, called the butt, is separated from the product by cutting it just beyond the exit of the die. One of the problems in direct extrusion is the significant **friction that exists between the work surface and the walls of the container** as the billet is forced to slide toward the die opening. This friction causes a substantial increase in the ram force required in direct extrusion.
In hot extrusion, the friction problem is aggravated by the presence of an oxide layer on the surface of the billet. This oxide layer can cause defects in the extruded product. To solve these problems, a **dummy block** is often used between the ram and the work billet. The diameter of the dummy block is slightly smaller than the billet diameter, so that a narrow ring of work metal (mostly the oxide layer) is left in the container, leaving the final product free of oxides.
Hollow sections (e.g., tubes) are possible in direct extrusion by the process setup in

Figure (6.2). The starting billet is prepared with a hole parallel to its axis .This allows passage of a mandrel that is attached to the dummy block. As the billet is compressed, the material is forced to flow through the clearance between the mandrel and the die opening

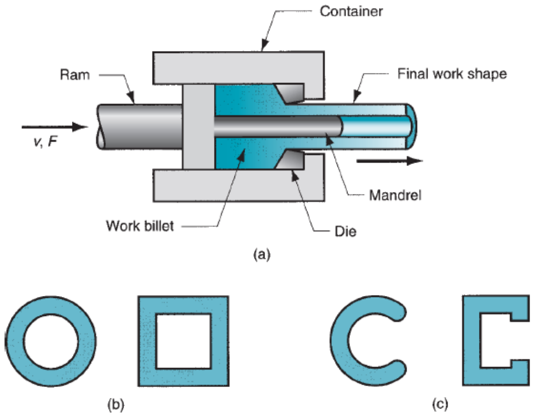


Figure (6.2) (a) Direct extrusion to produce a hollow or semi –hollow cross section;
(b) Hollow and (c) Semi-hollow cross sections.

6.3.2 Indirect extrusion, also called backward extrusion and reverse extrusion, Figure 6.3(a), the die is mounted to the ram rather than at the opposite end of the container. As the ram move, the metal is forced to flow through the clearance in a direction opposite to the motion of the ram. Since the billet is not forced to move relative to the container**, there is no friction at the container walls**, and the ram force is therefore lower than in direct extrusion. **Limitations** of indirect extrusion are imposed by **the lower rigidity of the hollow ram and the difficulty in supporting the extruded product as it exits the die**.

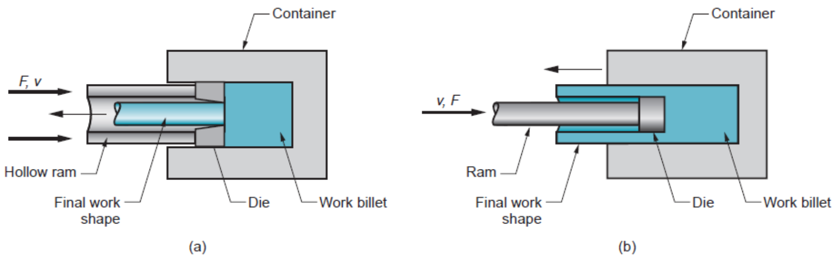


Figure (6.3) indirect extrusion to produce (a) a solid cross section and (b) a hollow cross section

Indirect extrusion can produce hollow (tubular) cross sections, as in Figure 6.3(b)**.** There are practical limitations on the length of the extruded part that can be made by this method. Support of the ram becomes a problem as work length increases.

6.3.3. Hot extrusion involves prior heating of the billet to a temperature above ($0.5T_m$). This **reduces strength and increases ductility of the metal**, **permitting more extreme size reductions and more complex shapes** to be achieved in the process. Additional advantages include **reduction of ram force**, **increased ram speed**. Cooling of the billet as it contacts the container walls is a problem, and **isothermal extrusion** is sometimes used to overcome this problem.

6.3.4. Cold extrusion and warm extrusion are generally used to produce discrete parts, often in finished (or near finished) form. Some important **advantages** of cold extrusion include **increased strength due to strain hardening, close tolerances, improved surface finish**, **absence of oxide layers**, and **high production rates**. Cold extrusion at room temperature also eliminates the need for heating the starting billet.

6.4 Analysis of extrusion:

Let us use Figure 6.4 as a reference in discussing some of the parameters in extrusion. The diagram assumes that both billet and extrudate are round in cross section. One important parameter is the **extrusion ratio**, also called the **reduction ratio**. The ratio is defined:

$$r_x = \frac{A_\circ}{A_f} \qquad 6\text{-}1$$

Where r_x= extrusion ratio; A_o= cross-sectional area of the starting billet, mm^2 (in^2); and A_f = final cross-sectional area of the extruded section,mm^2 (in^2). The ratio applies for both direct and indirect extrusion the value of r_x can be used to determine true strain in extrusion, given that ideal deformation occurs with <u>**no friction and no redundant work**</u>:

$$\epsilon = \ln r_x = \ln \frac{A_\circ}{A_f} \qquad 6\text{-}2$$

Under the assumption of ideal deformation (no friction and no redundant work), the pressure applied by the ram to compress the billet through the die opening depicted in our figure can be computed as follows:

$$p = \bar{Y}_f \ln r_x \qquad 6\text{-}3$$

Where Y_f = average flow stress during deformation, MPa (lb/in2)

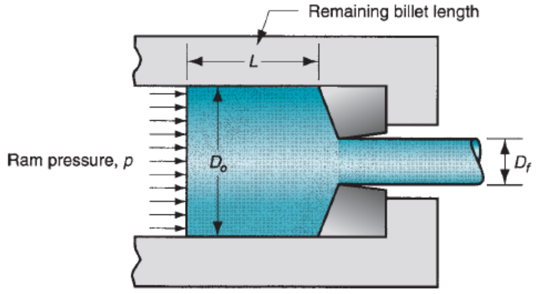


Figure (6.4) Pressure
And other variables in direct extrusion.

Friction exists between the die and the work as the billet squeezes down and passes through the die opening. In direct extrusion, friction also exists between the container wall and the billet surface.
The following empirical equation proposed by Johnson for estimating extrusion strain (in friction condition):

$$\epsilon_x = a + b \ln r_x \qquad 6\text{-}4$$

Where $\boldsymbol{\epsilon_x}$ = extrusion strain; and **a** and **b** are empirical constants for a given die angle. Typical values of these constants are: a = 0.8 and b = 1.2 to 1.5. Values of a and b tend to increase with increasing die angle.

Indirect extrusion the ram pressure to perform can be estimated based on Johnson's extrusion strain formula as follows:

$$p = \bar{Y}_f \epsilon_x \qquad 6\text{-}5$$

Where $\bar{Y}_f$ is calculated based on **ideal strain from Eq. (6-2)**, rather than extrusion strain in Eq. (6-4).

In direct extrusion, the effect of friction between the container walls and the billet causes the ram pressure to be greater than for indirect extrusion, the following formula can be used to compute ram pressure in direct extrusion:

$$p = \bar{Y}_f \left(\epsilon_x + \frac{2L}{D_\circ}\right) \qquad 6\text{-}6$$

Where the term 2L/Do accounts for the additional pressure due to friction at the container–billet interface. L is the portion of the billet length remaining to be extruded, and Do is the original diameter of the billet. Note that **p** is reduced as the remaining billet length decreases during the process.
Ram force in indirect or direct extrusion is simply pressure p from Eqs. (6-5) or (6-6), respectively, multiplied by billet area A_o:

$$F = pA_\circ \qquad 6.7$$

Where F = ram force in extrusion, N (lb).

Example: A billet 75mmlong and 25mmin diameter is to be extruded in a direct extrusion operation with extrusion ratio r_x = 4.0. The extrudate has a round cross section. The die angle (half angle) = 90° The work metal has a strength coefficient = 415 MPa, and strain-hardening exponent = 0.18. Use the Johnson formula with a = 0.8 and b = 1.5 to estimate extrusion strain. Determine the pressure applied to the end of the billet as the ram moves forward.
Sol.:
Let us examine the ram pressure at billet lengths of L= 75mm (starting value),
L= 50 mm, L= 25 mm, and L= 0.We compute the ideal true strain, extrusion strain using Johnson's formula and average flow stress:

$$\epsilon = \ln r_x = \ln 4.0 = 1.3863$$

$$\epsilon_x = 0.8 + 1.5(1.3863) = 2.8795$$

$$\bar{Y}_f = \frac{415(1.3863)^{0.18}}{1.18} = 373 \text{ MPa}$$

L=75mm,With a die angle of 90°, the billet metal is assumed to be forced through the die opening almost immediately; thus, our calculation assumes that maximum pressure is reached at the billet length of 75mm. For die angles less than 90°, the pressure would build to a maximum as the starting billet is squeezed into the cone-shaped portion of the extrusion die.

$$p = 373\left(2.8795 + 2\frac{75}{25}\right) = 3312 \text{ MPa}$$

$$L = 50 \text{ mm: } p = 373\left(2.8795 + 2\frac{50}{25}\right) = 2566 \text{ MPa}$$

$$L = 25 \text{ mm: } p = 373\left(2.8795 + 2\frac{25}{25}\right) = 1820 \text{ MPa}$$

L=0, Zero length is a **hypothetical value** in direct extrusion. In reality, it is impossible to squeeze all of the metal through the die opening. Instead, a portion of the billet (the ''butt'') remains unextruded and the pressure begins to increase rapidly as L approaches zero.

$$p = 373\left(2.8795 + 2\frac{0}{25}\right) = 1074 \text{ MPa}$$

6.5 Other extrusion processes:

6.5.1Impact Extrusion: Impact extrusion is performed at higher speeds and shorter strokes than conventional extrusion. It is used to make individual components. As the name suggests, the punch impacts the work part rather than simply applying pressure to it. Impacting can be carried out as forward extrusion, backward extrusion, or combinations of these. Some representative examples are shown in Figure (6.5). Impact extrusion is usually done cold on a variety of metals. Backward impact extrusion is most common. Products made by this process include toothpaste tubes and battery cases. As indicated by these examples, very thin walls are possible on impact extruded parts. The high-speed characteristics of impacting permit large reductions and high production rates, making this an important commercial process.

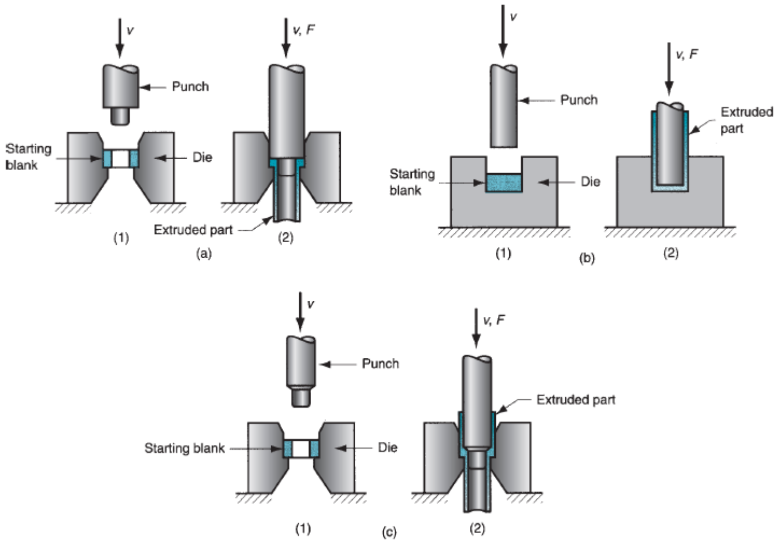


Fig (6.5) several examples of impact extrusion: (a) forward,
(b) Backward, and (c) combination of forward and backward.

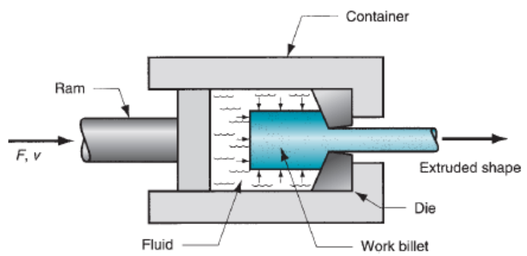
6.5.2Hydrostatic Extrusion

One of the problems in direct extrusion is friction along the billet– container interface. This problem can be addressed by surrounding the billet with fluid inside the container and pressurizing the fluid by the forward motion of the ram, as in Figure 6.6

This way, there is no friction inside the container, and friction at the die opening is reduced. Consequently, ram force is significantly lower than in direct extrusion. The fluid pressure acting on all surfaces of the billet gives the process its name. It can be carried out at room temperature or at elevated temperatures. Special fluids and procedures must be used at elevated temperatures. Hydrostatic extrusion is an adaptation of direct extrusion. Hydrostatic pressure on the work increases the material's ductility. Accordingly, this process can be used on metals that would be too brittle for conventional extrusion operations.

Ductile metals can also be hydrostatically extruded, and high reduction ratios are possible on these materials. One of the **disadvantages** of the process is the **required preparation of the starting work billet.** The billet must be formed with a taper at one end to fit snugly into the die entry angle. This establishes a seal to prevent fluid from squirting out the die hole when the container is initially pressurized.

Fig (6.6) Hydrostatic extrusion



6.6. Defects In Extruded Products

Owing to the considerable deformation associated with extrusion operations, a number of defects can occur in extruded products. The defects can be classified into the following categories, illustrated in Figure 6.7

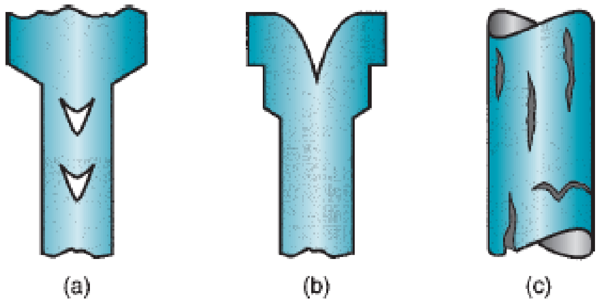


Fig (6.7) Some common defects in extrusion: (a) centerburst, (b) piping, and (c) surface cracking.

(a) Centerburst. This defect is an internal crack that develops as a result of tensile stresses along the centerline of the work part during extrusion. Although tensile stresses may seem unlikely in a compression process such as extrusion, they tend to occur under conditions that cause large deformation in the regions of the work away from the central axis. The significant material movement in these outer regions stretches the material along the center of the work. If stresses are great enough, bursting occurs. Conditions that promote centerburst are high die angles, low extrusion ratios, and impurities in the work metal that serve as starting points for crack defects. The difficult aspect of centerburst is its detection. It is an internal defect that is usually not noticeable by visual observation. Other names sometimes used for this defect include **arrowhead fracture**, **center cracking**, and **chevron cracking**.

(b) Piping. Piping is a defect associated with direct extrusion. As in Figure 6.7(b), it is the formation of a sink hole in the end of the billet. The use of a dummy block whose diameter is slightly less than that of the billet helps to avoid piping. Other names given to this defect include **tailpipe** and **fishtailing.**

(c) Surface cracking. This defect results from high workpart temperatures that cause cracks to develop at the surface. They often occur when extrusion speed is too high, leading to high strain rates and associated heat generation. Other factors contributing to surface cracking are high friction and surface chilling of high temperature billets in hot extrusion.

Wire Drawing

7.1 Introduction:

In drawing, the cross section of a long rod or wire is reduced or changed by pulling (hence the term drawing) it through a die called a draw die (Fig. 7.1). Thus, the difference between drawing and extrusion is that in extrusion the material is pushed through a die, whereas in drawing it is pulled through it. Although the presence of tensile stresses is obvious in drawing, compression also plays a significant role because the metal is squeezed down as it passes through the die opening. For this reason, the deformation that occurs in drawing is sometimes referred to as indirect compression. Drawing is a term also used in sheet metalworking. The term wire and bar drawing is used to distinguish the drawing process discussed here from the sheet metal process of the same name. Rod and wire products cover a very wide range of applications, including shafts for power transmission, machine and structural components, blanks for bolts and rivets, electrical wiring, cables,..Etc.

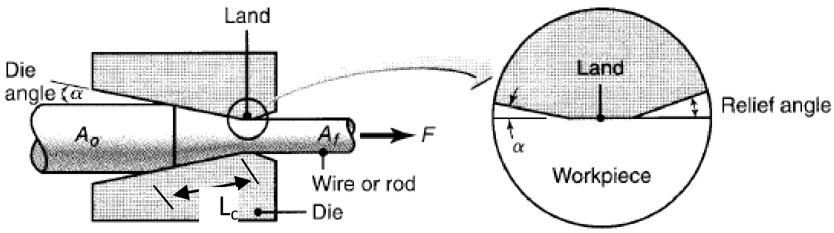


Fig (7.1) Process variables in wire drawing. The die angle, the reduction in cross sectional area per pass, the speed of drawing, the temperature and the lubrication all affect the drawing force, F.

The major processing variables in drawing are similar to those in extrusion that is, reduction in cross-sectional area, die angle, friction along the die-workpiece interface, and drawing speed. The die angle influences the drawing force and the quality of the drawn product.

The basic difference between bar drawing and wire drawing is the **stock size** that is processed. Bar drawing is the term used for large diameter bar and rod stock, while wire drawing applies to small diameter stock. Wire sizes down to 0.03 mm (0.001 in) are possible in wire drawing.

Bar drawing is generally accomplished as a single-draft operation—the stock is pulled through one die opening. Because the beginning stock has a large diameter, it is in the form of a straight cylindrical piece rather than coiled. This limits the length of the work that can be drawn. By contrast, wire is drawn from coils consisting of several hundred (or even several thousand) feet of wire and is passed through a series of draw dies. The number of dies varies typically between 4 and 12.

In a drawing operation, the change in size of the work is usually given by the area reduction, defined as follows:

$$r = \frac{A_\circ - A_f}{A_\circ} \qquad 7\text{-}1$$

Where r=area reduction in drawing; A_o=original area of work, mm^2 (in^2); and A_f=final area, mm^2 (in^2). Area reduction is often expressed as a percentage.

In bar drawing, rod drawing, and in drawing of large diameter wire for upsetting and heading operations, the term draft is used to denote the before and after difference in size of the processed work. The draft is simply the difference between original and final stock diameters:

$$d = D_\circ - D_f \qquad 7\text{-}2$$

Where d = draft, mm (in); D_o = original diameter of work, mm (in); and D_f = final work diameter, mm (in).

7.2 Analysis of drawing:

Mechanics of Drawing: If no friction or redundant work occurred in drawing, true strain could be determined as follows:

$$\epsilon = \ln\frac{A_\circ}{A_f} = \ln\frac{1}{1-r} \qquad \text{7-3}$$

Where A_o and A_f are the original and final cross-sectional areas of the work, as previously defined; and r = drawing reduction as given by Eq. (7-1). The stress that results from this ideal deformation is given by:

$$\sigma = \bar{Y}_f\epsilon = \bar{Y}_f \ln\frac{A_\circ}{A_f} \qquad \text{7- 4}$$

Where $\bar{Y}_f = \frac{K\epsilon^n}{1+n}$ = average flow stress based on the value of strain given by Eq. (7-3). Because friction is present in drawing and the work metal experiences inhomogeneous deformation, the actual stress is larger than provided by Eq. (7-4). In addition to the **ratio A_o/A_f** , other variables that influence draw stress are **die angle** and **coefficient of friction** at the work–die interface. A number of methods have been proposed for predicting draw stress based on values of these parameters. We present the equation suggested by **Schey**:

$$\sigma_d = \bar{Y}_f\left(1+\frac{\mu}{tan\,\alpha}\right)\emptyset\ln\frac{A_\circ}{A_f} \qquad \text{7-5}$$

Where σ_d = draw stress, MPa (lb/in^2); μ = die-work coefficient of friction; α = die angle (approach angle) (half-angle) as defined in Figure (7.1); and $\emptyset$ is a factor that accounts for inhomogeneous deformation which is determined as follows **for a round cross section**:

$$\emptyset = 0.88 + 0.12\frac{D}{L_c} \qquad \text{7-6}$$

Where D= average diameter of work during drawing, mm(in); and L_c = contact length of the work with the draw die in Figure (7.1),mm(in).Values of D and L_c can be determined from the following:

$$D = \frac{D_\circ+D_f}{2} \qquad \text{7-7}$$

$$L_c = \frac{D_\circ-D_f}{2sin\alpha} \qquad \text{7-8}$$

The corresponding draw force is then the area of the drawn cross section multiplied by the draw stress:

$$F = A_f\sigma_d = A_f\overline{Y}_f\left(1+\frac{\mu}{\tan\alpha}\right)\phi\ln\frac{A_o}{A_f} \qquad \text{7-9}$$

Where F = draw force, N (lb); and the other terms are defined above. The power required in a drawing operation is the draw force multiplied by exit velocity of the work.

Example:
Wire is drawn through a draw die with entrance angle=15°. Starting diameter is 2.5 mm and final diameter =2.0 mm. The coefficient of friction at the work–die interface = 0.07. The metal has a strength coefficient K = 205 MPa and a strain-hardening exponent n = 0.20. Determine the draw stress and draw force in this operation?

Solu:
The values of D and L_c for Eq. (7.6) can be determined using Eqs. (7-7 &7-8).
D= 2.25 mm and L_c = 0.966 mm. Thus,

$$\emptyset = 0.88 + 0.12\frac{2.25}{0.966} = 1.16$$

The areas before and after drawing are computed as A_o=4.91mm^2 and A_f= 3.14mm^2. The resulting true strain ϵ =ln (4.91/3.14)= 0.446 and the average flow stress in the operation is computed:

$$\bar{Y}_f = \frac{205X0.446^{0.2}}{1+0.2} = 145.4\ Mpa$$

Draw stress is given by Eq. (7-5)

$$\sigma_d = 145.4\left(1+\frac{0.07}{tan\ 15}\right)(1.16)(0.446) = 94.1Mpa$$

Finally, the draw force is this stress multiplied by the cross-sectional area of the exiting wire:

F=94.1(3.14) = 295.5 N

7.3 Tube Drawing:
Drawing can be used to reduce the diameter or wall thickness of seamless tubes and pipes, after the initial tubing has been produced by some other process such as extrusion. Tube drawing can be carried out either with or without a mandrel. The simplest method uses no mandrel and is used for diameter reduction, as in Figure 7.2. The term tube sinking is sometimes applied to this operation.

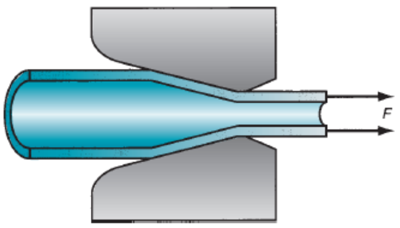
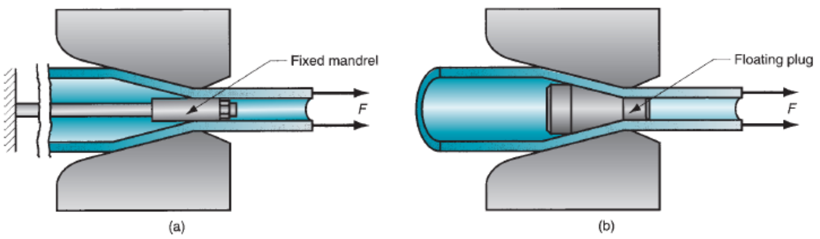


Figure 7.2 Tube drawing with no mandrel (tube sinking).

The problem with tube drawing in which no mandrel is used, as in Figure 7.2, is that it lacks control over the inside diameter and wall thickness of the tube. This is why mandrels of various types are used, two of which are illustrated in Figure 7.3.The first, Figure 7.3 (a) Uses a fixed mandrel attached to a long support bar to establish inside diameter and wall thickness during the operation. Practical limitations on the length of the support bar in this method restrict the length of the tube that can be drawn. The second type, shown in (b), uses a floating plug whose shape is designed so that it finds a ''natural'' position in the reduction zone of the die. This method removes the limitations on work length present with the fixed mandrel.

Figure 7.3 (a) Fixed mandrel
(b) Floating plug.



7.4 Drawing Practice

Drawing is usually performed as a cold working operation. It is most frequently used to produce round cross sections, but squares and other shapes are also drawn. Wire drawing is an important industrial process, providing commercial products such as electrical wire and cable; wire stock for fences; and rod stock to produce nails, screws, rivets, springs. Bar drawing is used to produce metal bars for machining, forging, and other processes.

Advantages of drawing in these applications include:
(1) Close dimensional control.
(2) Good surface finish
(3) Improved mechanical properties such as strength and hardness.
(4) Adaptability to economical batch or mass production.

Drawing speeds are as high as 50 m/s (10,000 ft/min) for very fine wire. In drawing, reductions in the cross-sectional area per pass range up to about 45 %. **Usually, the smaller the initial cross section, the smaller the reduction per pass**. Fine wires usually are drawn at 15 to 25% reduction per pass and larger sizes at 20 to 45%.
A light reduction (**sizing pass**) also may be taken on rods to improve their surface finish and dimensional accuracy.

7.5 Bundle Drawing:

Although very fine wire can be produced by drawing, the cost can be high. One method employed to increase productivity is to draw many wires (a hundred or more) simultaneously as a bundle.
Bundle drawing produces wires that are somewhat polygonal, rather than round, in cross-section. In addition to producing continuous lengths, techniques have been developed to produce fine wire that is chopped into various sizes and shapes. These wires are then used in applications such as electrically conductive textiles. The wires produced can be as small as 4 µm in diameter and can be made from such materials as stainless steels, titanium, and high-temperature alloys.

7.6 Drawing Equipment:

Bar drawing is accomplished on a machine called a draw bench, consisting of an entry table, die stand (which contains the draw die), carriage, and exit rack.
The arrangement is shown in Figure 7.4.The carriage is used to pull the stock through the draw die. It is powered by hydraulic cylinders or motor-driven chains. The die stand is often designed to hold more than one die, so that several bars can be pulled simultaneously through their respective dies.

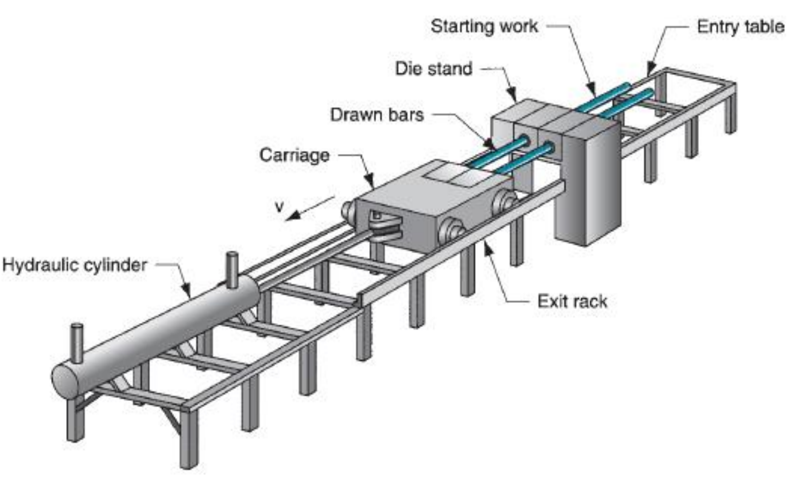


Figure 7.4
Hydraulically operated draw bench for drawing metal bars.

Wire drawing is done on continuous drawing machines that consist of multiple draw dies, separated by accumulating drums between the dies, as in Figure 7.5. Each drum, called a capstan, is motor driven to provide the proper pull force to draw the wire stock through the upstream die. It also maintains a modest tension on the wire as it proceeds to the next draw die in the series. Each die provides a certain amount of reduction in the wire, so that the desired total reduction is achieved by the series. Depending on the metal to be processed and the total reduction, annealing of the wire is sometimes required between groups of dies in the series.

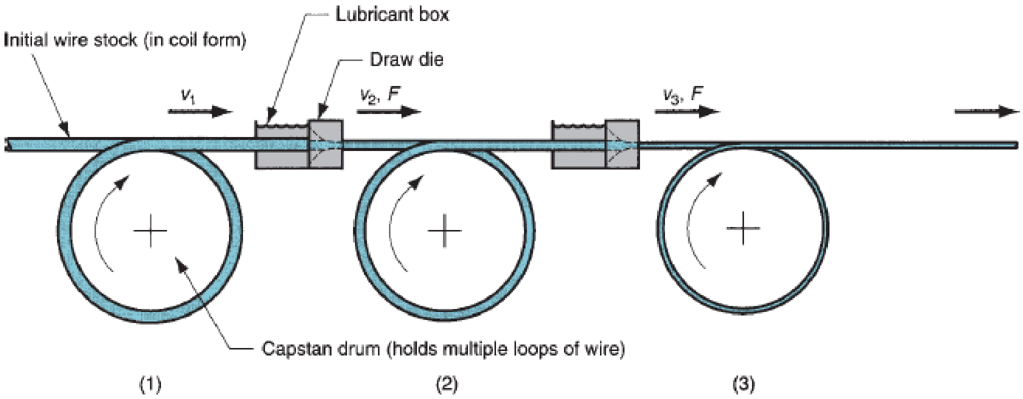


Figure 7.5 Continuous drawing of wire.

7.7 Draw Dies:

Figure 7.6 identifies the features of a typical draw die. Four regions of the die can be distinguished: (1) entry, (2) approach angle, (3) bearing surface (land), and (4) back relief. The entry region is usually a bell-shaped mouth that does not contact the work. Its purpose is to funnel the lubricant into the die and prevent scoring of work and die surfaces.

The approach is where the drawing process occurs. It is cone-shaped with an angle (half angle) normally ranging from about 6° to 20°. The proper angle varies according to work material. The bearing surface, or land, determines the size of the final drawn stock. Finally, the back relief is the exit zone. It is provided with a back relief angle (half-angle) of about 30°. Draw dies are made of tool steels or cemented carbides. Dies for high-speed wire drawing operations frequently use inserts made of diamond (both synthetic and natural) for the wear surfaces.

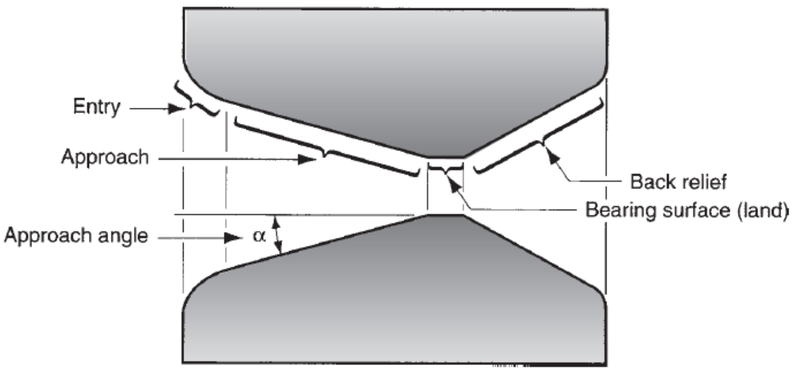


Figure 7.6 Draw die for drawing of round rod or wire.

7.8 Preparation of the Work:
Prior to drawing, the beginning stock must be properly prepared. This involves three steps: (1) annealing, (2) cleaning, and (3) pointing. The purpose of **annealing** is to increase the ductility of the stock to accept deformation during drawing. As previously mentioned, annealing is sometimes needed between steps in continuous drawing. **Cleaning** of the stock is required to prevent damage of the work surface and draw die. It involves removal of surface contaminants (e.g., scale and rust) by means of chemical pickling or shot blasting. In some cases, prelubrication of the work surface is accomplished subsequent to cleaning. **Pointing** involves the reduction in diameter of the starting end of the stock so that it can be inserted through the draw die to start the process. This is usually accomplished by swaging, rolling, or turning. The pointed end of the stock is then gripped by the carriage jaws or other device to initiate the drawing process.

7.9 Die Material:
Die materials for drawing typically are tool Steels and carbides. For hot drawing, cast-steel dies are used because of their high resistance to wear at elevated temperatures. Diamond dies are used for drawing fine wire with diameters ranging from 2 µm to 1.5 mm. They may be made from a single-crystal diamond or in polycrystalline form with diamond particles in a metal matrix (compacts). Because of their very low tensile strength and toughness, carbide and diamond dies typically are used as inserts or nibs, which are supported in a steel casing. Figure (7.7)

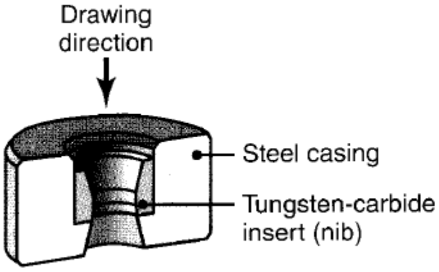


Figure (7.7) tungsten-carbide die insert in a steel casting.
Diamond dies used in drawing thin wire are encased in a similar manner

7.10 Drawing Defects and Residual Stresses:
Typical defects in a drawn rod or wire are **similar to those observed in extrusion** especially center cracking another major type of defect in drawing is **seams**, which are longitudinal scratches or folds in the material. Seams may open up during subsequent forming operations (such as upsetting, heading, thread rolling, or bending of the rod or wire), and they can cause serious quality-control problems. Various other surface defects (such as scratches and die marks) also can result from improper selection of the process parameters, poor lubrication, or poor die condition.
Because they undergo nonuniform deformation during drawing, cold-drawn products usually have residual stresses. For light reductions, such as only a few percent, the longitudinal-surface residual stresses are compressive (while the bulk is in tension) and fatigue life is thus improved. Conversely, heavier reductions induce tensile surface stresses (while the bulk is in compression). Residual stresses can be significant in causing stress-corrosion cracking of the part over time. Moreover, they cause the component to warp if a layer of material subsequently is removed such as by slitting, machining, or grinding.
Rods and tubes that are not sufficiently straight (or are supplied as coil) can be straightened by passing them through an arrangement of rolls placed at different axe.

Electromagnetic Forming (magnetic pulse forming)

8.1 Process description:

The EMF process uses a capacitor bank, a forming coil , a field shaper , and an electrically conductive workpiece to create intense magnetic fields that are used to do the useful work. This very intense magnetic field, produced by the discharge of a bank of capacitors into a forming coil, lasts only a few microseconds. The resulting eddy currents that are induced in a conductive workpiece that is placed close to the coil then interact with the magnetic field to cause mutual repulsion between the workpiece and the forming coil. The force of this repulsion is sufficient to stress the work metal beyond its yield strength, resulting in a permanent deformation.

8.2 speed of forming:

The conductivity of the workpiece and the eddy currents which interact with the magnetic field of the coil result in a net pressure on the surface of the workpiece. As the workpiece surface moves inward under the influence of this pressure, it absorbs energy from the magnetic field. To apply most of this available energy to forming, and to reduce energy loss due to permeation of the workpiece material (which wastes energy by resistance heating), the forming pulse is kept short. In most forming applications, pulses have duration of between 10 and 100 second.

8.3 formation methods:

Electromagnetic formation can usually be applied to three forming methods: compression, expansion, and counter forming. As shown in figure (8-1 a), a tubular workpiece is compressed by an external coil, usually against a grooved contoured insert, plug, tube or fitting inside the workpiece. A tubular workpiece is expanded by an internal coil as shown in figure (8-1 b), usually against a collar or other component surrounding the workpiece .flat stock is almost always contour-formed against a die as seen in figure (8-1 c).

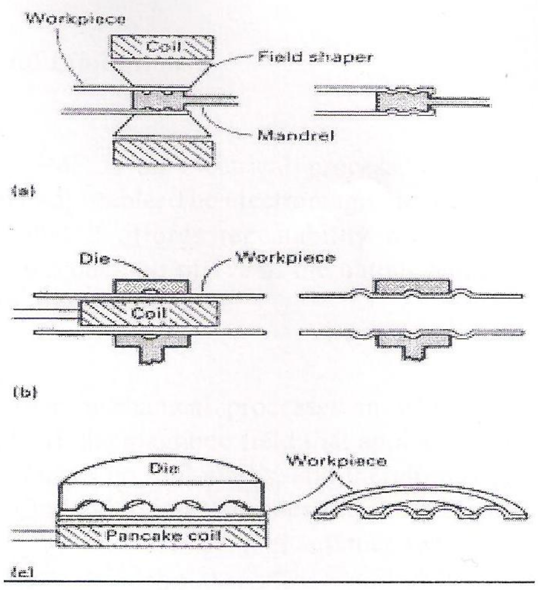


Figure (8-1) Three basic methods of EMF. (a) Compression. (b) Expansion. (c) Contour forming.

This process is primarily applied in the forming of good conducting materials such as: copper, aluminum, silver and low carbon steel. It can also be used to form a poor conductor like stainless steel. T he efficiency of the magnetic pulse forming depends upon the resistivity of metal being formed. For good results the resistivity of the material should be less than 15 micro-ohm-centimeters.

8.4advantages and limitations:

1. It gives a high rate of production
2. Non contact: unlike other mechanical processes in which a tool contacts a workpiece, in EMF the magnetic field that applies the pressure requires no lubrication, leaves no tool marks and therefore requires no cleanup after forming. One exception that does require lubrication is when the workpiece is driven against a mandrel and then removed.
3. Springback: the material is loaded into its plastic region , resulting in permanent deformation, so that the springback often associated with mechanical processes is virtually eliminated , because there is no mechanical contact.
4. Strength: joints made by this process are typically stronger than the parent material.
5. The EMF process allows increased ductility for certain aluminum alloys because of the lack of mechanical stress and friction normally encountered with mechanical processes.

6. Tooling: the tooling for process is relatively inexpensive .the machine and the work coils can be viewed as general –purpose tooling.

General limitations

The speed of joining or formation also represents one of the limitations of the process. Because forming take place in such a short period, the material does not lend itself to deep drawing of materials. The process is also limited to those materials that are electrically conductive .materials with an electrical resistivity of 0.15 micro –ohm- meter or less are ideal candidates for the process. Included in this group are such materials as copper, aluminum, brass, and mild steels.

Pressure limit:

The maximum pressure that can be applied by standard compression coils is approximately 340 Mpa, thus the process is restricted to relatively thin –wall tube or sheet products.

8.5 Applications:

Electromagnetic forming is chiefly used to expand, compress, or form tubular shapes. It is occasionally used to form flat sheet, and it is often used to combine several forming and assembly operations into a single step.

8.6 die materials:

The die used in electromagnetic process should be made of low electrical conductivity to minimize the magnetic cushion effect. Dies are generally made of the following materials: **Steel or epoxy resin**. Steel dies have longer life .but the disadvantage of steel dies is that magnetic cushion effect is not entirely prevented. Air is often evacuated from the die to ensure good reproduction of detail, and prevent distortion caused by entrapped air, which is particularly likely to occur with thin gauge material.

Sheet metal forming processes

9.1Introduction
Products made of sheet metals are all around us. They include a very wide range of consumer and industrial products, such as **beverage cans, cookware, file cabinets, metal desks, appliances, car bodies** figure (9.1). The term **pressworking** or **press forming** is used commonly in industry to describe general sheet-forming operations, because they typically are performed on presses.

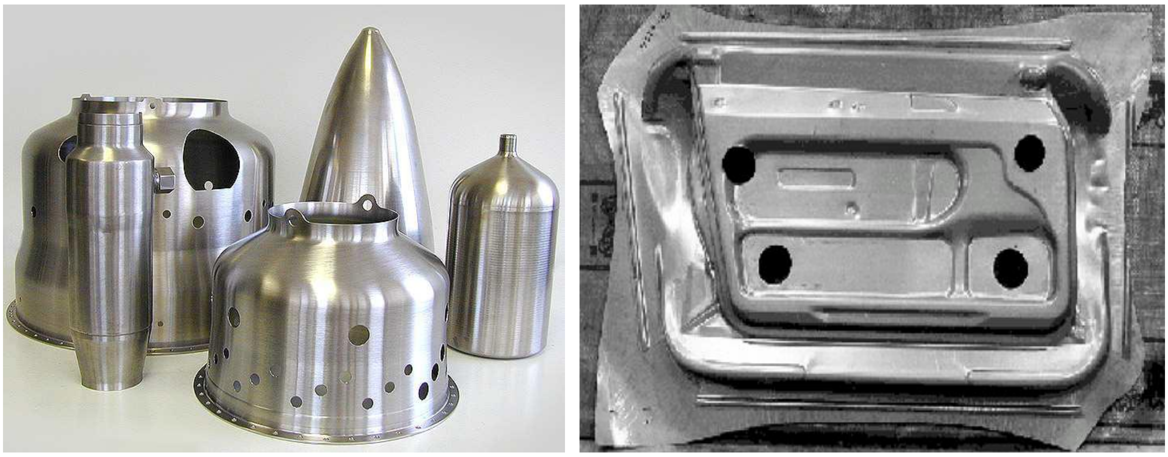


Figure (9.1) shows some sheet metal applications

9.2 Material in sheet metal forming processes:
Low-carbon steel is the most commonly used sheet metal because of its low cost and generally good strength and formability characteristics. Aluminum is the most common material for such sheet-metal applications as beverage cans, packaging, kitchen utensils, and applications where corrosion resistance is a concern. The common metallic materials for aircraft and aerospace applications are aluminum and titanium.

9.3 Temperature and sheet metal forming:
Most manufacturing processes involving sheet metal are performed at room temperature. Hot stamping is occasionally performed in order to increase formability and decrease forming loads on machinery. Typical materials in hot stamping operations are titanium alloys and various high-strength steels.

9.4 Types of metal forming operations:
The three major categories of sheet-metal processes are **(1) cutting, (2) bending, and (3) drawing** as shown in figure (9.2). Cutting is used to separate large sheets into smaller pieces, to cut out part perimeters, and to make holes in parts. Bending and drawing are used to form sheet-metal parts into their required shapes.

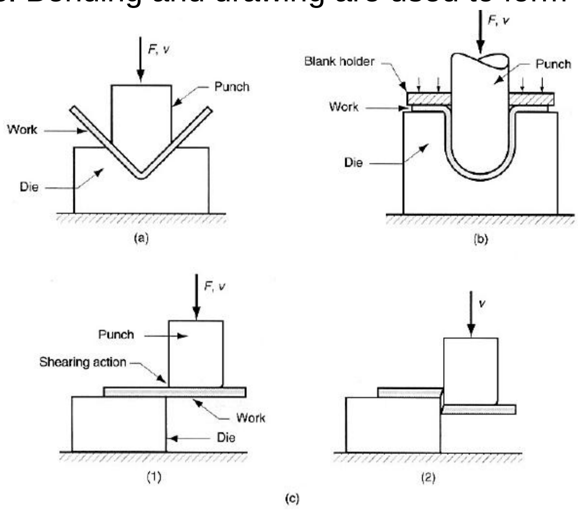
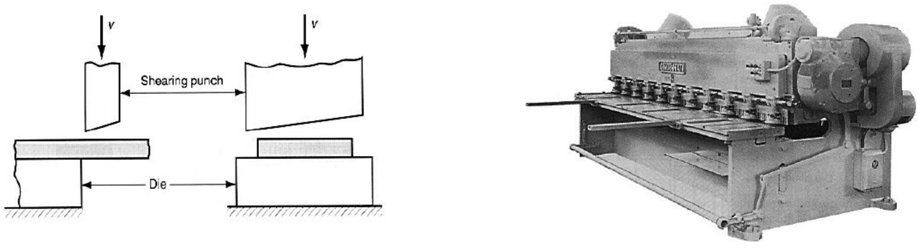


Figure (9.2) Basic sheet metalworking operations:
(a) bending, (b) drawing, and (c) Shearing;
(1) as punch first contacts sheet and (2) after cutting. Force and relative motion are indicated by F and v

9.4.1 Cutting operations:

The three most important operations in pressworking that cut metal by the shearing mechanism just described are shearing, blanking, and punching.

A)Shearing: Shearing is a sheet metal cutting operation along a straight line between two cut-ting edges by means of a power shear see figure (9.3).



Shearing operation   3-m power shear for 6.5-mm steel

Figure (9.3) show the shearing operation and its equipment

B) Blanking and punching

Blanking and punching are similar sheet metals cutting operations that involve cutting the sheet metal along a closed outline. **If the part that is cut out is the desired product, the operation is called *blanking* and the product is called *blank*. If the remaining stock is the desired part, the operation is called *punching*** as shown in figure (9.4). Both operations are illustrated on the example of producing a washer:

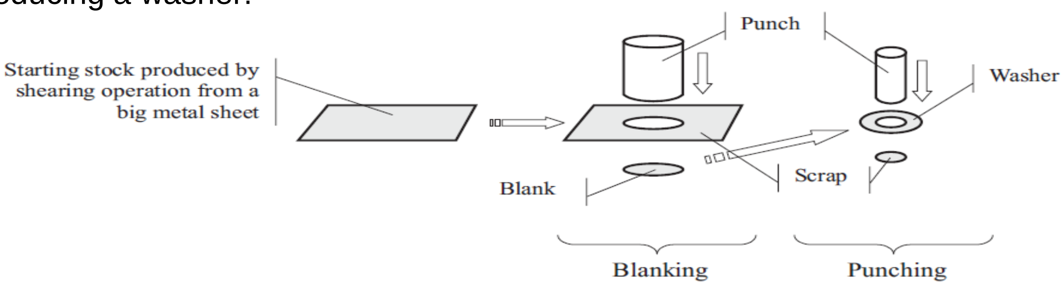
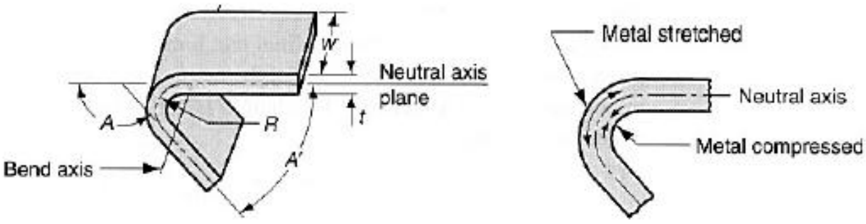


Figure (9.4) shows the blanking and punching operations

9.4.2 Bending operation:

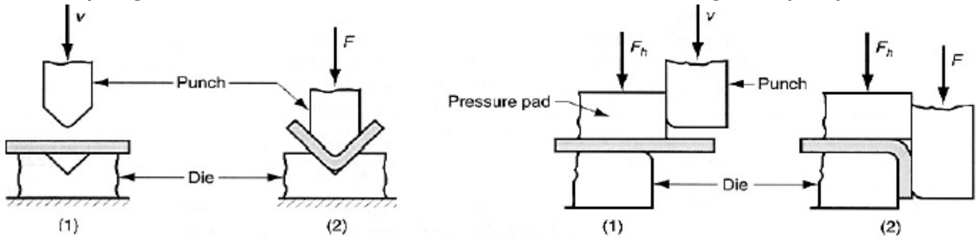
Bending in sheet-metalwork is defined as the straining of the metal around a straight axis, as in Figure (9.5)



Bending of sheet metal

Figure (9.5) show bending of sheet metal

Bending operations are performed using punch and die tooling. The two common bending methods and associated tooling are V-bending, performed with a V-die; and edge bending, performed with a wiping die. These methods are illustrated in Figure (9.6)



(*Left*) V-bending, and (*Right*) edge bending; (1) before and (2) after bending

Figure (9.6) types of bending operations

In V-bending, the sheet metal is bent between a V-shaped punch and die. Included angles ranging from very obtuse to very acute can be made with V-dies. It is often performed on a press brake, and the associated V-dies are relatively simple and inexpensive.
Edge bending involves cantilever loading of the sheet metal. A pressure pad is used to apply a force to hold the base of the part against the die, while the punch forces the part to yield and bend over the edge of the die. In the setup shown in Figure (9.6 right), edge bending is limited to bends of 90° or less. More complicated wiping dies can be designed for bend angles greater than 90°. Because of the pressure pad, wiping dies are more complicated and costly than V-dies and are generally used for high-production work.

Springback When the bending pressure is removed at the end of the deformation operation, elastic energy remains in the bent part, causing it to recover partially toward its original shape. This elastic recovery is called springback, defined as the increase in included angle of the bent part relative to the included angle of the forming tool after the tool is removed. This is illustrated in Figure (9.7)

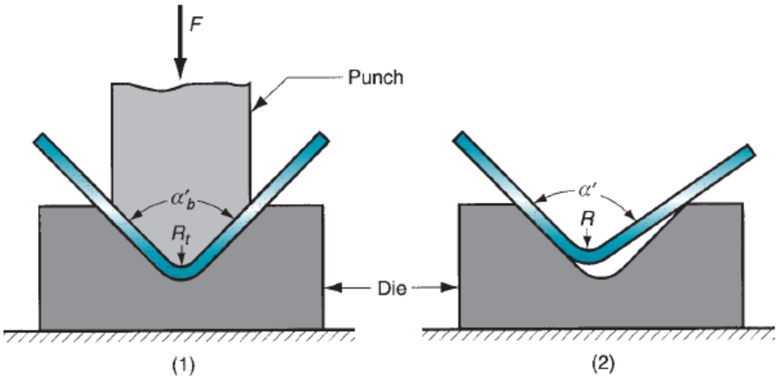


Figure (9.7) Springback in bending shows itself as a decrease in bend angle and an increase in bend radius: (1) during the operation, the work is forced to take the radius R_t and included angle α'_t = determined by the bending tool (punch in V-bending); (2) after the punch is removed, the work springs back to radius R and included angle α'. Symbol: F = applied bending force.

Compensation for springback can be accomplished by several methods. Two common methods are overbending and bottoming.

Overbending—the punch angle and radius are smaller than the final ones.
Bottoming—squeezing the part at the end of the stroke.

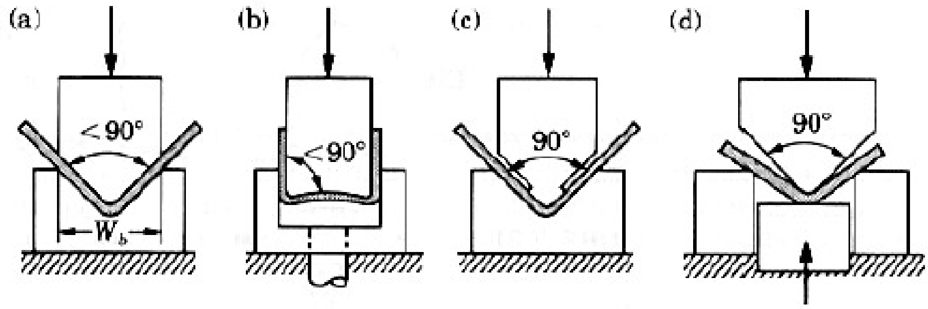


Figure 9.8 Compensation of springback by:
(a) and (b) overbending; (c) and (d) bottoming

9.4.3 Drawing operation:

Drawing is a sheet-metal-forming operation used to make cup-shaped, box-shaped, or other complex-curved and concave parts. It is performed by placing a piece of sheet metal over a die cavity and then pushing the metal into the opening with a punch, as in Figure 9.9. The blank must usually be held down flat against the die by a blankholder.
Common parts made by drawing include beverage cans, ammunition shells, sinks, cooking pots, and automobile body panels.

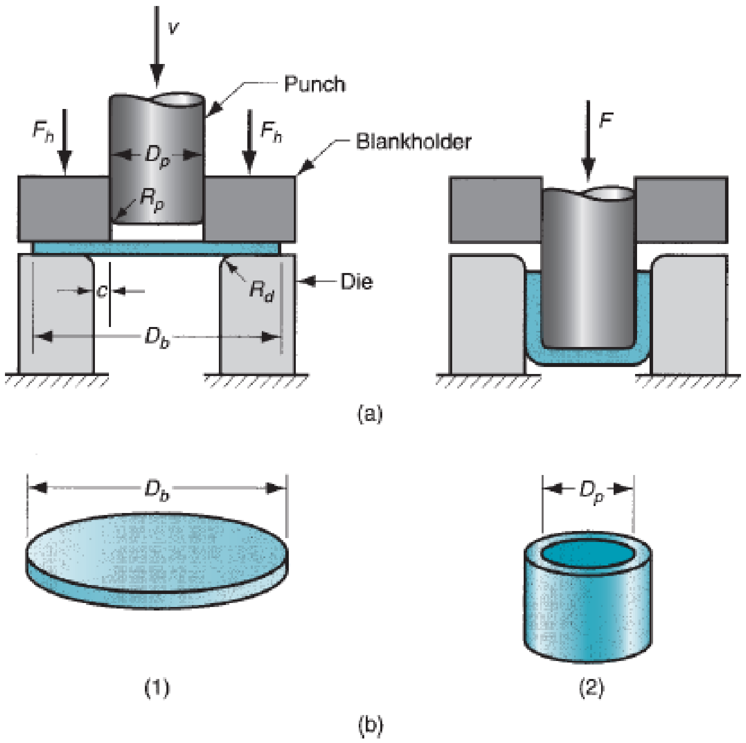


Figure 9.9
(a) Drawing of a cup-shaped part: (1) start of operation before punch contacts work, and (2) near end of stroke; and (b) corresponding workpart: (1) starting blank, and (2) drawn part. Symbols: *c* = clearance, D_b = blank diameter, D_p = punch diameter, R_d = die corner radius, R_p = punch corner radius, *F* = drawing force, F_h = holding force.

9.4.3.1 Mechanic of drawing:
Drawing of a cup-shaped part is the basic drawing operation, with dimensions and parameters as pictured in Figure 9.9. A blank of diameter D_b is drawn into a die cavity by means of a punch with diameter D_p. The punch and die must have corner radii, given by R_p andR_d. If the punch and die were to have sharp corners (R_p andR_d=0), a hole-punching operation (and not a very good one) would be accomplished rather than a drawing operation. The sides of the punch and die are separated by a clearance c. **This clearance in drawing is about 10% greater than the stock thickness**:

$$c=1.1t \qquad 9.1$$

The punch applies a downward force F to accomplish the deformation of the metal, and a downward holding force F_h is applied by the **blankholder**, as shown in the sketch.

9.4.3.2 ENGINEERING ANALYSIS OF DRAWING:

Measures of Drawing:
One of the measures of the severity of a deep drawing operation is the **drawing ratio DR**. This is most easily defined for a cylindrical shape as the ratio of blank diameter D_b to punch diameter D_p. In equation form:

$$DR= D_b/D_P \qquad 9.2$$

The drawing ratio provides an indication of the severity of a given drawing operation. The greater the ratio, the more severe the operation. An approximate upper limit on the drawing ratio is a value of **2.0**. The actual limiting value for a given operation **depends on punch and die corner radii**

(Rp and Rd), friction conditions, depth of draw, and characteristics of the sheet metal (e.g., ductility, degree of directionality of strength properties in the metal).
Another way to characterize a given drawing operation is by the **reduction r**, where

$$r = \frac{D_b - D_p}{D_b} \qquad \textbf{9.3}$$

It is very closely related to drawing ratio. Consistent with the previous limit on DR (**DR ≤ 2.0**), the value of reduction **r** should be less than **0.50**.
A third measure in deep drawing is the **thickness-to-diameter ratio** t/D_b (thickness of the starting blank t divided by the blank diameter D_b). Often expressed as a percentage, it is desirable for the t/D_b ratio to be greater than **1%**. **As t/D_b decreases, tendency for wrinkling increases.**
In cases where these limits on drawing ratio, reduction, and t/D_b ratio are exceeded by the design of the drawn part, the blank must be drawn in two or more steps, sometimes with annealing between the steps.

Example:
A drawing operation is used to form a cylindrical cup with inside diameter = 75 mm and height = 50mm. The starting blank size = 138mmand the stock thickness = 2.4mm. Based on these data, is the operation feasible?

Solution: To assess feasibility, we determine the drawing ratio, reduction, and thickness-to-diameter ratio.

$$DR = 138/75 = 1.84$$

$$r = (138 - 75)/138 = 0.4565 = 45.65\%$$

$$t/D_b = 2.4/138 = 0.017 = 1.7\%$$

Forces
The drawing force required to perform a given operation can be estimated roughly by the formula:

$$F = \pi D_p t (TS)\left(\frac{D_b}{D_p} - 0.7\right) \qquad 9.4$$

Where F = drawing force, N (lb); t = original blank thickness, mm (in); TS = tensile strength, MPa (lb/in2); and D_b and D_p are the starting blank diameter and punch diameter, respectively, mm (in). The constant 0.7 is a correction factor to account for friction.

The holding force is an important factor in a drawing operation. As a rough approximation, the holding pressure can be set at a **value = 0.015 of the yield strength of the sheet metal**. This value is then multiplied by that portion of the starting area of the blank that is to be held by the blankholder. In equation form

$$F_h = 0.015 Y \pi \left\{ D_b^2 - \left(D_p + 2.2t + 2R_d\right)^2 \right\} \qquad 9.5$$

Where F_h = holding force in drawing, N (lb); Y = yield strength of the sheet metal, MPa (lb/in2); t = starting stock thickness, mm (in); R_d = die corner radius, mm (in); and the other terms have been previously defined. The holding force is usually about one-third the drawing force.

Example:
For the drawing operation of Example above, determine (a) drawing force and
(b) Holding force, given that the tensile strength of the sheet metal (low-carbon steel) = 300 MPa and yield strength = 175 MPa. The die corner radius = 6 mm.

Solution:

$$F = \pi(75)(2.4)(300)\left(\frac{138}{75} - 0.7\right) = 193,396 \text{ N}$$

9.4.3.3 D

(b) Holding force is estimated by Eq. (20.13):

(a) **Wrink** that form radially ir

$$F_h = 0.015(175)\,\pi(138^2 - (75 + 2.2 \times 2.4 + 2 \times 6)^2) = 86,824 \text{ N}$$

(b) **Wrinkling** in the wall. If and when the wrinkled flange is drawn into the cup, these ridges appear in the vertical wall.
(c) **Tearing**. Tearing is an open crack in the vertical wall, usually near the base of the drawn cup, due to high tensile stresses that cause thinning and failure of the metal at this location. This type of failure can also occur as the metal is pulled over a sharp die corner.
(d) **Earing**. This is the formation of irregularities (called ears) in the upper edge of a deep drawn cup, caused by anisotropy in the sheet metal. If the material is perfectly isotropic, ears do not form.
(e) **Surface scratches**. Surface scratches can occur on the drawn part if the punch and die are not smooth or if lubrication is insufficient.

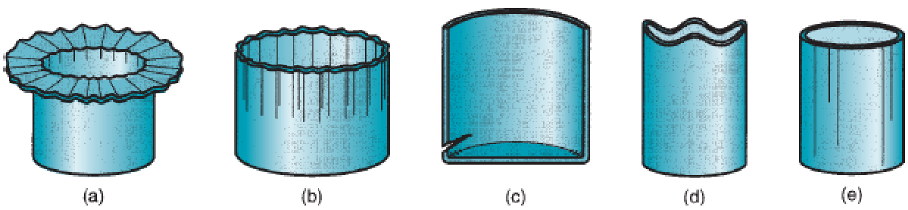


Figure 9.10 Common defects in drawn parts: (a) wrinkling can occur either in the flange or (b) in the wall, (c) tearing, (d) earing, and (e) surface scratches.

Fundamental of Welding processes

12.1 Introduction

Welding is a materials joining process in which two or more parts are coalesced at their contacting surfaces by a suitable application of heat and/or pressure. Many welding processes are accomplished by **heat alone,** with no pressure applied; others by **a combination of heat and pressure**; and still others by **pressure alone**, with no external heat supplied. In some welding processes a filler material is added to facilitate coalescence. The assemblage of parts that are joined by welding is called a **weldment**. Welding is most commonly associated with metal parts, but the process is also used for joining plastics.

12.2 Advantages of welding process

1. Welding provides a permanent joint.
2. The welded joint can be stronger than the parent materials if a filler metal is used and if proper welding techniques are used..
3. Welding is usually the most economical way to join components.
4. Welding is not restricted to the factory environment.

12.3 Disadvantages of welding processes

1. Most welding operations are performed manually and are expensive.
2. Most welding processes are inherently dangerous.
3. Since welding accomplishes a permanent bond between the components, it does not allow for convenient disassembly.
4. The welded joint can suffer from certain quality defects that are difficult to detect.

12.4 Types of joints

There are five basic types of joints for bringing two parts together for joining. The five joint types are not limited to welding; they apply to other joining and fastening techniques as well. With reference to Figure 11.3., the five joint types can be defined as follows:

a. Butt joint. In this joint type, the parts lie in the same plane and are joined at their edges.
b. Corner joint. The parts in a corner joint form a right angle and are joined at the corner of the angle.
c. Lap joint. This joint consists of two overlapping parts.
d. Tee joint. In a tee joint, one part is perpendicular to the other in the approximate shape of the letter ''T.''
e. Edge joint. The parts in an edge joint are parallel with at least one of their edges in common, and the joint is made at the common edge(s).

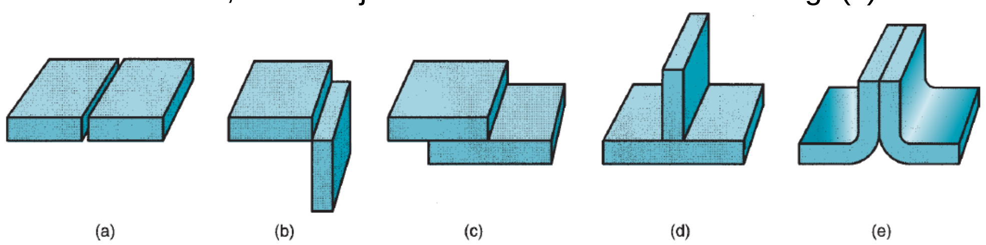
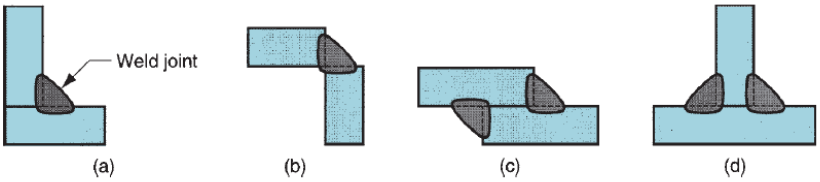


Figure 12.1 Five basic types of joints: (a) butt, (b) corner, (c) lap, (d) tee, and (e) edge.

12.5 weld types:

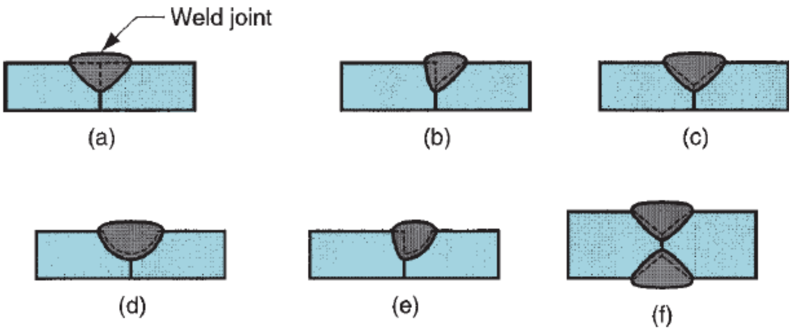
A fillet weld is used to fill in the edges of plates created by corner, lap, and tee joints, as in Figure 12.2. Filler metal is used to provide a cross section approximately the shape of a right triangle. It is the most common weld type in arc and oxyfuel welding because it requires minimum edge preparation—the basic square edges of the parts are used. Fillet welds can be single or double (i.e., welded on one side or both) and can be continuous or intermittent (i.e., welded along the entire length of the joint or with unwelded spaces along the length).

Figure 12.3 Various forms of fillet welds: (a) inside single fillet corner joint; (b) outside single fillet corner joint; (c) double fillet lap joint; and (d) double fillet tee joint. Dashed lines show the original part edges.



Groove welds usually require that the edges of the parts be shaped into a groove to facilitate weld penetration. The grooved shapes include square, bevel, V, U, and J, in single or double sides, as shown in Figure 12.4. Filler metal is used to fill in the joint, usually by arc or oxyfuel welding. Preparation of the part edges beyond the basic square edge, although requiring additional processing is often done to increase the strength of the welded joint or where thicker parts are to be welded. Although most closely associated with a butt joint, groove welds are used on all joint types except lap.

Figure 12.4 Some typical groove welds: (a) square groove weld, one side; (b) single bevel groove weld; (c) single V-groove weld; (d) single U-groove weld; (e) single J-groove weld; (f) double V-groove weld for thicker sections. Dashed lines show the original part edges.



Plug welds and slot welds are used for attaching flat plates, as shown in Figure 12.5, using one or more holes or slots in the top part and then filling with filler metal to fuse the two parts together. **Spot welds** and seam welds, used for lap joints, are diagrammed in Figure 12.6. A spot weld is a small fused section between the surfaces of two sheets or plates. Multiple spot welds are typically required to join the parts. It is most closely associated with resistance welding. A seam weld is similar to a spot weld except it consists of a more or less continuous fused section between the two sheets or plates.

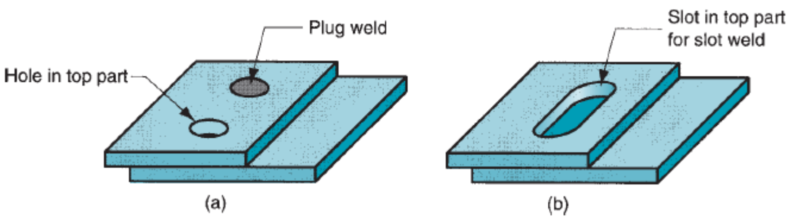


FIGURE 29.5 (a) Plug weld; and (b) slot weld.

Figure 12.5

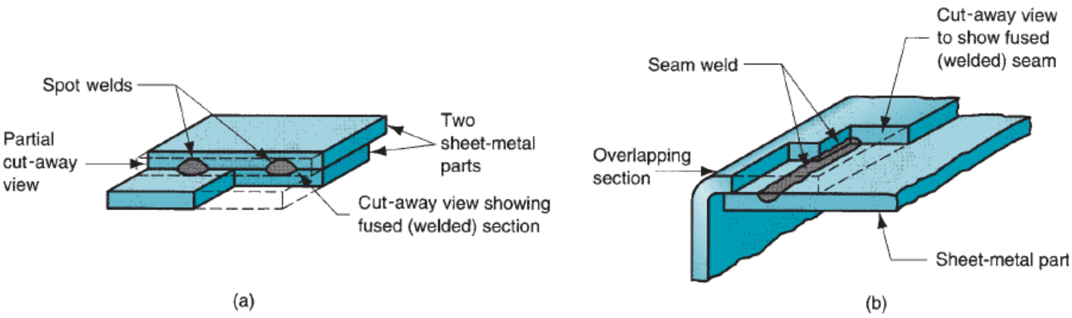


Figure 12.6 (a) Spot weld; and (b) seam weld.

12.6 physics of welding:

We first examine the issue of power density and its importance, and then we define the heat and power equations that describe a welding process.

12.6.1power densities:

To accomplish fusion, a source of high-density heat energy is supplied to the faying surfaces, and the resulting temperatures are sufficient to cause localized melting of the base metals. If a filler metal is added, the heat density must be high enough to melt it also. **Heat density can be defined as the power transferred to the work per unit surface area, W/mm^2 (Btu/sec-in^2). The time to melt the metal is inversely proportional to the power density**. At low power densities, a significant amount of time is required to cause melting. If power density is too low, the heat is conducted into the work as rapidly as it is added at the surface, and melting never occurs. It has been found that the minimum power density required to melt most metals in welding is about 10 W/mm^2 (6 Btu/sec-in^2). As heat density increases, melting time is reduced. If power density is too high—above around 105 W/mm^2 (60,000 Btu/secin^2), the localized temperatures vaporize the metal in the affected region. Thus, there is a practical range of values for power density within which welding can be performed.

Differences among welding processes in this range are
(1) The rate at which welding can be performed and/or (2) The size of the region that can be welded. As example Oxyfuel gas welding is capable of developing large amounts of heat, but the heat density is relatively low because it is spread over a large area. For metallurgical reasons, it is desirable to melt the metal with minimum energy, and high power densities are generally preferable. Power density can be computed as the power entering the surface divided by the corresponding surface area:

$$PD = \frac{P}{A} \qquad 12.1$$

Where PD = power density, W/mm^2 (Btu/sec-in^2); P = power entering the surface, W (Btu/sec); and A= surface area over which the energy is entering, mm^2 (in^2). The issue is more complicated than indicated by Eq. (12.1). One complication is that the power source (e.g., the arc) is moving in many welding processes, which results in preheating ahead of the operation and postheating behind it. Another complication is that power density is not uniform throughout the affected surface; it is distributed as a function of area, as demonstrated by the following example.

EXAMPLE1: A heat source transfers 3000W to the surface of a metal part. The heat impinges the surface in a circular area, with intensities varying inside the circle. The distribution is as follows: 70% of the power is transferred within a circle of diameter=5mm, and 90%is transferred within a concentric circle of diameter = 12 mm. What are the power densities in (a) the 5-mm diameter inner circle and (b) the 12-mm-diameter ring that lies around the inner circle?

Solution: (a) The inner circle has an area $A = \frac{\pi(5)^2}{4} = 19.63 \text{ mm}^2$.

The power inside this area $P = 0.70 \times 3000 = 2100$ W.

Thus the power density $PD = \frac{2100}{19.63} = 107 \text{ W/mm}^2$.

(b) The area of the ring outside the inner circle is $A = \frac{\pi(12^2 - 5^2)}{4} = 93.4 \text{ mm}^2$.

The power in this region $P = 0.9\,(3000) - 2100 = 600$ W.

The power density is therefore $PD \frac{600}{93.4} = 6.4 \text{ W/mm}^2$.

a

Observation: The power density seems high enough for melting in the inner circle, but probably not sufficient in the ring that lies outside this inner circle. 1 inch

and 75% is transferred within a concentric circle of diameter = 0.25 in. What are the power densities in (a) the
0.1-inch diameter inner circle and (b) the 0.25-inch diameter ring that lies around the inner circle? (c) Are these power densities sufficient for melting metal?

Solution: (a) Area $A = \pi(0.1)^2/4 = 0.00785$ in^2

150 Btu/min = 2.5 Btu/sec.

Power $P = 0.50(2.5) = 1.25$ Btu/sec

Power density PD = (1.25 Btu/sec)/0.00785 in^2 = **159 Btu/sec-in^2**

(b) $A = \pi(0.25^2 - 0.1^2)/4 = 0.0412$ in^2

Power $P = (0.75 - 0.50)(2.5) = 0.625$ Btu/sec

Power density PD = (0.625 Btu/sec)/0.0412 in^2 = **15.16 Btu/sec-in^2**

(c) Power densities are sufficient certainly in the inner circle and probably in the outer ring for welding.

Heat Balance In Fusion Welding

The quantity of heat required to melt a given volume of metal depends on:

(1) The heat to raise the temperature of the solid metal to its melting point

(2) The melting point of the metal

(3) The heat to transform the metal from solid to liquid phase at the melting point.

To a reasonable approximation, this quantity of heat can be estimated by the following equation:

$$U_m = K\mathrm{T}_{\mathrm{m}}^2 \qquad 13.1$$

Where Um = the unit energy for melting (i.e., the quantity of heat required to melt a unit volume of metal starting from room temperature), J/mm^3 (Btu/in^3); Tm = melting point of the metal on an absolute temperature scale, K$^\circ$ (R$^\circ$); and K=constant whose value is 3.33x10^{-6} when the Kelvin scale is used (and K = 1.467 x 10^{-5} for the Rankine temperature scale). Not all of the energy generated at the heat source is used to melt the weld metal.

There are two heat transfer mechanisms at work, both of which reduce the amount of generated heat that is used by the welding process. The situation is depicted in Figure 13.1**. The first mechanism involves the transfer of heat between the heat source and the surface of the work. This process has a certain heat transfer factor f_1, defined as the ratio of the actual heat received by the workpiece divided by the total heat generated at the source**. **The second mechanism involves the conduction of heat away from the weld area to be dissipated throughout the work metal, so that only a portion of the heat transferred to the surface is available for melting. This melting factor f_2 is the proportion of heat received at the work surface that can be used for melting**. The combined effect of these two factors is to reduce the heat energy available for welding as follows:

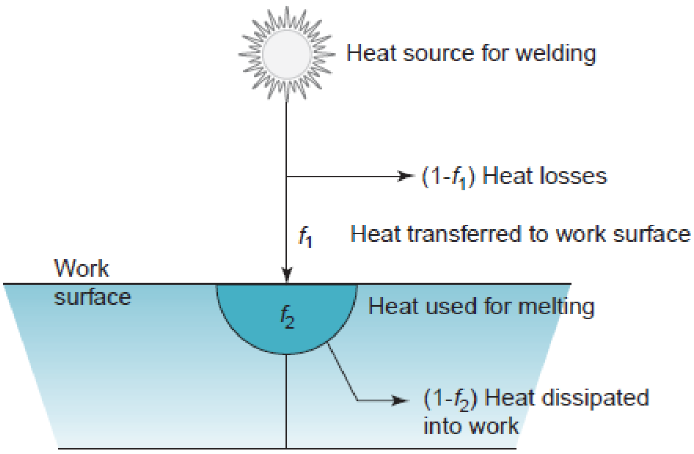


Figure 13.1 Heat transfer mechanisms in fusion welding.

$$H_w = f_1 f_2 \mathrm{H} \qquad 13.2$$

Where H_w = net heat available for welding, J (Btu), f_1 = heat transfer factor, f_2 = the melting factor, and H = the total heat generated by the welding process(welding source) , J (Btu).

The factors f_1 and f_2 range in value between zero and one. **It is appropriate to separate f_1 and f_2 in concept,** even though they act in concert during the welding process. The heat transfer factor f_1 is determined largely by the welding process and the capacity to convert the power source (e.g., electrical energy) into usable heat at the work surface. Arc-welding processes are relatively efficient in this regard, while oxyfuel gas-welding processes are relatively inefficient.

The melting factor f_2 depends on the welding process, but it is also influenced by the thermal properties of the metal, **joint configuration, and work thickness.** Metals with high thermal conductivity, such as aluminum and copper, present a problem in welding because of the rapid dissipation of heat away from the heat contact area. The problem is exacerbated by Welding heat sources with low energy densities (e.g., oxyfuel welding) because the heat input is spread over a larger area, thus facilitating conduction into the work. In general, a high power density combined with a low conductivity work material results in a high melting factor. We can now write a balance equation between the energy input and the energy needed for welding:

$$H_w = U_m V \qquad 13.3$$

Where R_{Hw}=rate of heat energy delivered to the operation for welding, J/s= W(Btu/min); H_w = net heat energy used by the welding operation, J (Btu); Um = unit energy required to melt the metal, J/mm^3 (Btu/in^3); and V= the volume of metal.

In the welding of a continuous bead, the volume rate of metal welded is the product of weld area A_w and travel velocity v. the rate balance equation can now be expressed as

$$R_{Hw} = f_1 f_2 R_H = U_m A_w v \qquad 13.4$$

Where f_1 and f_2 are the heat transfer and melting factors; R_H = rate of input energy generated by the welding power source, W (Btu/min); A_w = weld cross-sectional area, mm^2 (in^2); and v = the travel velocity of the welding operation, mm/s (in/min).

Example1

The power source in a particular welding setup generates 3500W that can be transferred to the work surface with a heat transfer factor = 0.7. The metal to be welded is low carbon steel, whose melting temperature is 1760K. The melting factor in the operation is 0.5.A continuous fillet weld is to be made with a cross-sectional area=20mm^2. Determine the travel speed at which the welding operation can be accomplished.

Sol:

Let us first find the unit energy required to melt the metal U_m from Eq. (13.1)

$$U_m = 3.33(10^{-6}) \times 1760^2 = 10.3 \text{ J/mm}^3$$

Rearranging Eq. (13.5) to solve for travel velocity, we have $v = f_1 f_2 R_H / U_m A_w$; and solving for the conditions of the problem

$$v = \frac{0.7\,(0.5)\,(3500)}{10.3\,(20)} = 5.95 \text{ mm/s.}$$

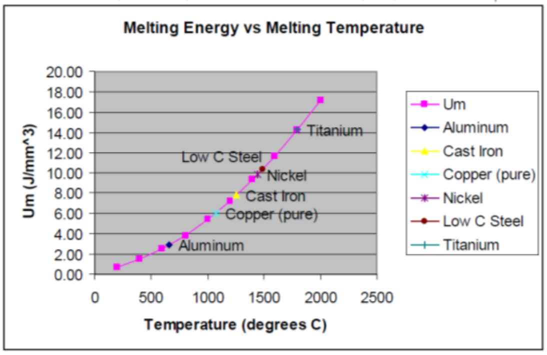
Example 2

Make the calculations and plot on linearly scaled axes the relationship for unit melting energy as a function of temperature. Use temperatures as follows to construct the plot: 200°C, 400°C, 600°C, 800°C, 1000°C, 1200°C, 1400°C, 1600°C, 1800°C, and 2000°C.

Sol:

Um = 3.33×10^{-6} Tm^2, The plot is based on the following calculated values.

For Tm = 200°C = (200 + 273) = 473°K: Um = $3.33 \times 10^{-6} (473)^2$ = 0.75 J/mm^3
For Tm = 400°C = (400 + 273) = 673°K: Um = $3.33 \times 10^{-6} (673)^2$ = 1.51 J/mm^3
For Tm = 600°C = (600 + 273) = 873°K: Um = $3.33 \times 10^{-6} (873)^2$ = 2.54 J/mm^3
For Tm = 800°C = (800 + 273) = 1073°K: Um = $3.33 \times 10^{-6} (1073)^2$ = 3.83 J/mm^3
For Tm = 1000°C = (1000 + 273) = 1273°K: Um = $3.33 \times 10^{-6} (1273)^2$ = 5.40 J/mm^3
For Tm = 1200°C = (1200 + 273) = 1473°K: Um = $3.33 \times 10^{-6} (1473)^2$ = 7.23 J/mm^3
For Tm = 1400°C = (1400 + 273) = 1673°K: Um = $3.33 \times 10^{-6} (1673)^2$ = 9.32 J/mm^3
For Tm = 1600° C = (1600 + 273) = 1873° K: Um = $3.33 \times 10^{-6} (1873)^2$ =11.68 J/mm^3
For Tm = 1800° C = (1800 + 273) = 2073° K: Um = $3.33 \times 10^{-6} (2073)^2$ = 14.31 J/mm^3
For Tm = 2000° C = (2000 + 273) = 2273° K: Um = $3.33 \times 10^{-6} (2273)^2$ = 17.20 J/mm^3



Example 3:

A U-groove weld is used to butt weld 2 pieces of 7.0-mm-thick titanium plate. The U-groove is prepared using a milling cutter so the radius of the groove is 3.0 mm. During welding, the penetration of the weld causes an additional 1.5 mm of material to be melted. The final crosssectional area of the weld can be approximated by a semicircle with a radius of 4.5 mm. The length of the weld is 200 mm. The melting factor of the setup is 0.57 and the heat transfer factor is 0.86. *Tm* for titanium is 2070°K (a) What is the quantity of heat (in Joules) required to melt the volume of metal in this weld (filler metal plus base metal)? Assume the resulting top surface of the weld bead is flush with the top surface of the plates. (b) What is the required heat generated at the welding source?

Sol:

$Um = 3.33 \times 10^{-6} (2070)^2 = 14.29$ J/mm^3

$A_w = \pi r^2/2 = \pi(4.5)^2 /2 = 31.8$ mm^2

$V = A_w L = 31.8(200) = 6360$ mm^3

$H_w = U_m V = 14.29(6360) =$ **90,770 J**

(b) $H = H_w/(f_1 f_2) = 90{,}770/(0.86 \times 0.57) =$ **185,200 J**

Example4

A fillet weld is used to join 2 medium carbon steel plates each having a thickness of 5.0 mm. The plates are joined at a 90° angle using an inside fillet corner joint. *Tm* = 1700°K , The velocity of the welding head is 6 mm/sec. Assume the cross section of the weld bead approximates a right isosceles triangle with a leg length of 4.5 mm, the heat transfer factor is 0.80, and the melting factor is 0.58. Determine the rate of heat generation required at the welding source to accomplish the weld.

Sol:

: $A_w = bh/2 = 4.5(4.5)/2 = 10.125$ mm^2

$U_m = 3.33 \times 10^{-6} (1700)^2 = 9.62$ J/mm^3

$R_H = U_m A_w v/(f_1 f_2) = 9.62(10.125)(6.0) / (0.8 \times 0.58) =$ **1260 J/sec = 1260 W.**

Plasma Arc Welding

14.1 Plasma arc welding (PAW) is a special form of gas tungsten arc welding in which a constricted plasma arc is directed at the weld area. In PAW, a tungsten electrode is contained in a specially designed nozzle that focuses a high-velocity stream of inert gas (e.g., argon or argon–hydrogen mixtures) into the region of the arc to form a high velocity, intensely hot plasma arc stream, as in Figure 14.1. Argon, argon–hydrogen, and helium are also used as the arc-shielding gases. Temperatures in plasma arc welding reach 17,000_C (30,000_F) or greater, hot enough to melt any known metal. The reason why temperatures are so high in PAW (significantly higher than those in GTAW) derives from the constriction of the arc. Although the typical power levels used in PAW are below those used in GTAW, the power is highly concentrated to produce a plasma jet of small diameter and very high power density.

Plasma arc welding was introduced around 1960 but was slow to catch on. In recent years its use is increasing as a substitute for GTAW in applications such as **automobile subassemblies, metal cabinets, door and window frames, and home appliances**. Owing to the special features of PAW, its advantages in these applications include **good arc stability, better penetration control than most other AW processes, high travel speeds, and excellent weld quality. The process can be used to weld almost any metal, including tungsten.**

Difficult-to-weld metals with PAW include bronze, cast irons, lead, and magnesium. Other limitations include high equipment cost and larger torch size than other AW operations, which tends to restrict access in some joint configurations.

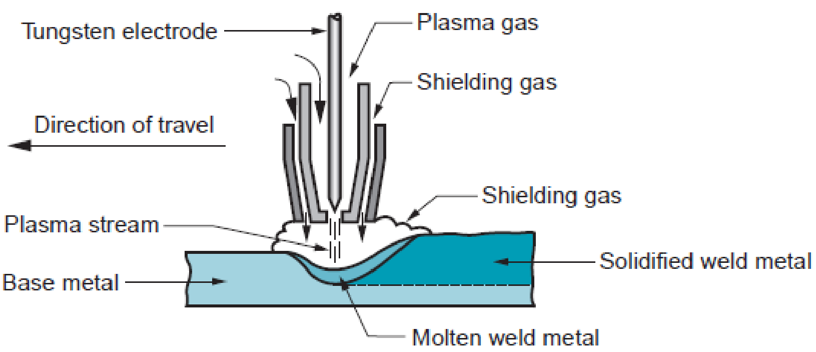


Figure 14.1 Plasma arc welding (PAW).

14.2 other fusion-welding processes

Some fusion-welding processes cannot be classified as arc, resistance, or oxyfuel welding. Each of these other processes uses a unique technology to develop heat for melting; and typically, the applications are unique.

14.2.1 Electron Beam Welding:

Electron-Beam Welding Electron-beam welding (EBW) is a fusion-welding process in which the heat for welding is produced by a highly focused, high-intensity stream of electrons impinging against the work surface. The electron beam gun operates at high voltage to accelerate the electrons (e.g., 10–150 kV typical), and beam currents are low (measured in milliamps). The power in EBW is not exceptional, but power density is.

High power density is achieved by focusing the electron beam on a very small area of the work surface, so that the power density PD is based on

$$PD = \frac{f_1\, EI}{A} \qquad 14.1$$

Where PD = power density, W/mm^2 (W/in^2, which can be converted to Btu/sec-in^2 by dividing by 1055.); f_1 = heat transfer factor (typical values for EBW range from 0.8–0.95); E = accelerating voltage, V; I = beam current, A; and A = the work surface area on which the electron beam is focused, mm^2 (in^2). Typical weld areas for EBW range from 13 X 10^{-3} to 2000 X10^{-3} mm^2 (20 X 10^{-6} to 3000 X 10^{-6} in^2).

The process had its beginnings in the 1950s in the atomic power field. When first developed, welding had to be carried out in a vacuum chamber to minimize the disruption of the electron beam by air molecules. This requirement was, and still is, a serious inconvenience in production, due to the time required to evacuate the chamber prior to welding. The pump-down time, as it is called, can take as long as an hour, depending on the size of the chamber and the level of vacuum required. Today, EBW technology has progressed to where some operations are performed without a vacuum.

Three categories can be distinguished: (1) high-vacuum welding (EBW-HV), in which welding is carried out in the same vacuum as beam generation; (2) medium-vacuum welding (EBW-MV), in which the operation is performed in a separate chamber where only a partial vacuum is achieved; and (3) non vacuum welding (EBW-NV), in which welding is accomplished at or near atmospheric pressure. The pump-down time during work part loading and unloading is reduced in medium-vacuum EBW and minimized in non vacuum EBW, but there is a price paid for this advantage. In the latter two operations, the equipment must include one or more vacuum dividers (very small orifices that impede air flow but permit passage of the electron beam) to separate the beam generator (which requires a high vacuum) from the work chamber. Also, in non vacuum EBW, the work must be located close to the orifice of the electron beam gun, approximately 13 mm (0.5 in) or less. Finally, the lower vacuum processes cannot achieve the high weld qualities and depth-to-width ratios accomplished by EBW-HV. Any metals that can be arc welded can be welded by EBW, as well as certain refractory and difficult-to-weld metals that are not suited to AW.

Work sizes range from thin foil to thick plate. EBW is applied mostly in the automotive, aerospace, and nuclear industries. In the automotive industry, EBW assembly includes aluminum manifolds, steel torque converters, catalytic converters, and transmission components. In these and other applications, **electron-beam welding is noted for high-quality welds with deep and/ or narrow profiles, limited heat-affected zone, and low thermal distortion. Welding speeds are high compared to other continuous welding operations. No filler metal is used, and no flux or shielding gases are needed**. **Disadvantages of EBW include high equipment cost, need for precise joint preparation and alignment, and the limitations associated with performing the process in a vacuum**. In addition, there are **safety concerns** because EBW generates X-rays from which humans must be shielded.

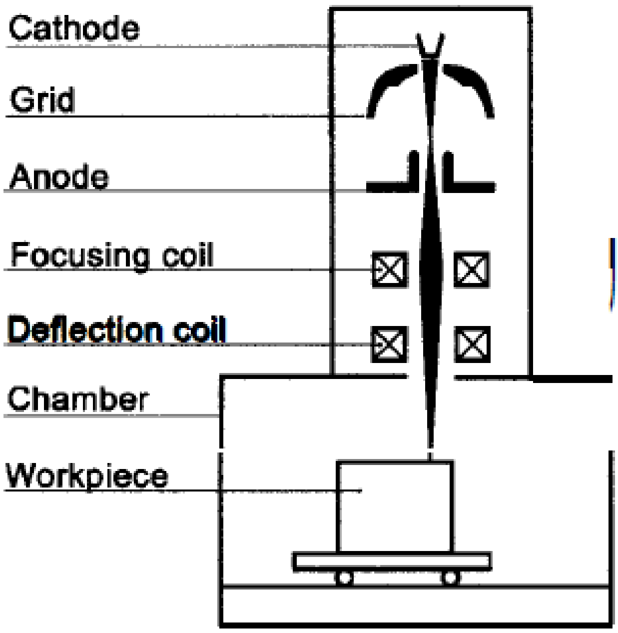


Figure 14.2: *The electron gun.*

14.2.2 Laser Beam Welding:

Laser-beam welding (LBW) is a fusion-welding process in which coalescence is achieved by the energy of a highly concentrated, coherent light beam focused on the joint to be welded. The term laser is an acronym for light amplification by stimulated emission of radiation. LBW is normally performed with shielding gases (e.g., helium, argon, nitrogen, and carbon dioxide) to prevent oxidation. Filler metal is not usually added. LBW produces welds of high quality, deep penetration, and narrow heat-affected zone. These features are similar to those achieved in electron-beam welding, and the two processes are often compared. There are several advantages of LBW over

EBW: no vacuum chamber is required, no X-rays are emitted, and laser beams can be focused and directed by optical lenses and mirrors. On the other hand, LBW does not possess the capability for the deep welds and high depth-to-width ratios of EBW. Maximum depth in laser welding is about 19 mm (0.75 in), whereas EBW can be used for weld depths of 50 mm (2 in) or more; and the depth-to-width ratios in LBW are typically limited to around 5:1. Because of the highly concentrated energy in the small area of the laser beam, the process is often used to join small parts.

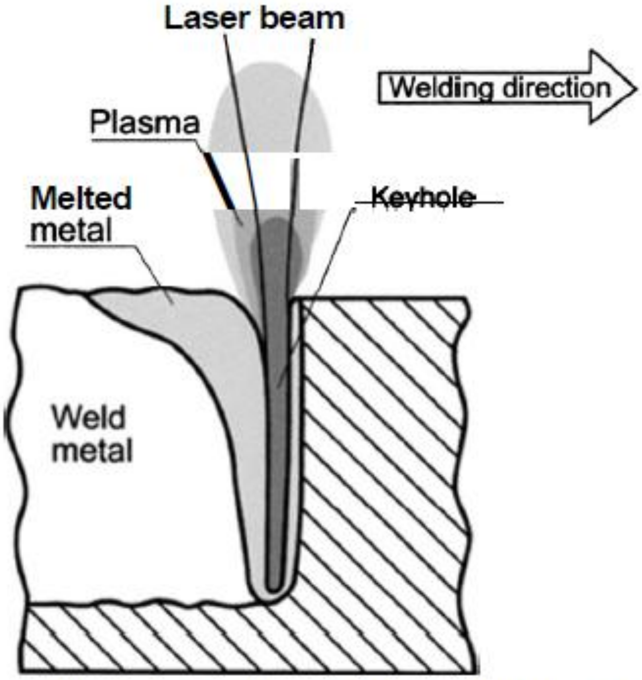


Figure 14.3 *Penetration of a laser welding beam.*

Solid-state welding

15.1 Introduction:

In solid-state welding no liquid or molten phase is present in the joint. The principle of solid-state welding is demonstrated best with the following example: If two clean surfaces are brought into close contact with each other under sufficient pressure, they form bonds and produce a joint.
To form a strong bond, it is essential that the interface be free of oxide films, residues, metalworking fluids, other contaminants, and even adsorbed layers of gas. Solid-state bonding involves one or more of the following phenomena:

- Diffusion: The transfer of atoms across an interface; thus, applying external heat improves the strength of the bond between the two surfaces being joined, as occurs in diffusion bonding. Heat may be generated internally by friction (as utilized in friction welding), through electrical-resistance heating (as in resistance-welding processes, such as spot welding), and externally by induction heating (as in butt-welding tubes).

- Pressure: The higher the pressure, the stronger is the interface (as in roll bonding and explosion welding), where plastic deformation also occurs. Pressure and resistance heating may be combined, as in flash welding, stud welding, and resistance projection welding.

- Relative interfacial movements: When movements of the contacting surfaces (faying surfaces) occur (as in ultrasonic welding), even very small amplitudes will disturb the mating surfaces, break up any oxide films, and generate new, clean surfaces-thus improving the strength of the bond.

15.2 Forge Welding

Forge welding is of historic significance in the development of manufacturing technology. The process dates from about 1000 BCE, when blacksmiths of the ancient world learned to join two pieces of metal **. Forge welding is a welding process in which the components to be joined are heated to hot working temperatures and then forged together by hammer or other means.** Considerable skill was required by the craftsmen who practiced it in order to achieve a good weld by present-day standards. The process may be of historic interest; however, it is of minor commercial importance today except for its variants that are discussed below.
Forge welding requires the application of pressure by means of either a hammer (hammer welding), rolls (roll welding), or dies (die welding). Joint configurations differ depending on whether the joints are to be produced

manually or using automatic equipment. Typical joint designs used in manual forge welding operations are shown in Fig. 1. The joint surfaces in Fig. 1 are slightly rounded or crowned to ensure that the centerline region of the components joined will be welded first to force any contaminants (for example, slag, dirt, or oxide) present on the surfaces out of the joint. Typical joint configurations used for automatic forge welding operations are shown in Fig. 2.

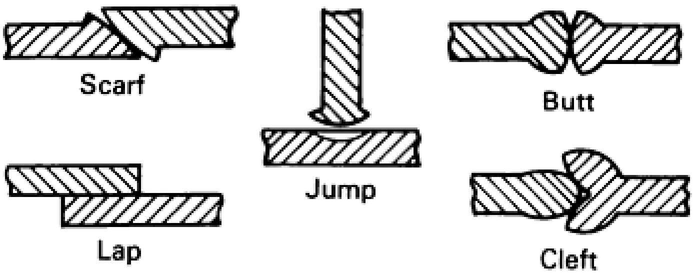


Figure (1) TYPICAL JOINT CONFIGURATIONS USED FOR MANUAL FORGE WELDING APPLICATIONS

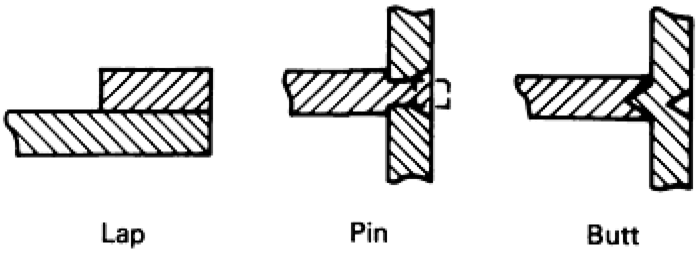


Figure (2) RECOMMENDED JOINT CONFIGURATIONS USED IN AUTOMATIC FORGE WELDING APPLICATIONS

Hydraulic presses are typically employed to apply pressure. Presses are often highly automated, featuring microprocessor control of pressure and temperature cycles.

The normal welding sequence is to:

(1) Apply sufficient pressure to firmly seat the faying surfaces against one another,

(2) Heat the joint to welding temperature.

(3) Rapidly apply additional pressure to upset the weld zone.

Forge welding is most commonly applied to carbon and low-alloy steels, with typical welding temperatures of about 1125 °C (2060 °F). Low-carbon steels can be used in the as-welded condition, but medium-carbon steels and low-alloy steels normally are given full heat treatments following welding Applications of this process include welding rods, bars, tubes, rails, aircraft landing gear, chains, and cans.

15.3 Cold Welding (also known as cold pressure welding)
Cold welding (CW) is a solid-state welding process accomplished by applying high pressure between clean contacting surfaces at room temperature. The faying surfaces must be exceptionally clean for CW to work, and cleaning is usually done by degreasing and wire brushing immediately before joining. Also, at least one of the metals to be welded, and preferably both, must be very ductile and free of work hardening. Metal such as soft aluminum and copper can be readily cold welded. The applied compression forces in the process result in cold working of the metal parts, reducing thickness by as much as 50%; but they also cause localized plastic deformation at the contacting surfaces, resulting in coalescence. For small parts, the forces may be applied by simple hand-operated tools. For heavier work, powered presses are required to exert the necessary force. No heat is applied from external sources in CW, but the deformation process raises the temperature of the work somewhat. Applications of CW include making electrical connections.

15.4 Friction Welding
Friction welding is a widely used commercial process, amenable to automated production methods. The process was developed in the (former) Soviet Union and introduced into the United States around 1960. Friction welding (FRW) is a solid state welding process in which coalescence is achieved by frictional heat combined with pressure. The friction is induced by mechanical rubbing between the two surfaces, usually by rotation of one part relative to the other, to raise the temperature at the joint interface to the hot working range for the metals involved. Then the parts are driven toward each other with sufficient force to form a metallurgical bond. The sequence is portrayed in Figure 3 for welding two cylindrical parts, the typical application. The axial compression force upsets the parts, and a flash is produced by the material displaced. Any surface films that may have been on the contacting surfaces are expunged during the process. The flash must be subsequently trimmed (e.g., by turning) to provide a smooth surface in the weld region. When properly carried out, no melting occurs at the faying surfaces. No filler metal, flux, or shielding gases are normally used.
Nearly all FRW operations use rotation to develop the frictional heat for welding. There are two principal drive systems, distinguishing two types of FRW: (1) **continuous drive friction welding**, and (2) **inertia friction welding**. *In continuous-drive friction welding, one part is driven at a constant rotational speed and forced into contact with the stationary part at a certain force level so that friction heat is generated at the interface.*
When the proper hot working temperature has been reached, braking is applied to stop the rotation abruptly, and simultaneously the pieces are forced together at forging pressures. *In inertia friction welding, the rotating part is connected to a flywheel, which is brought up to a predetermined speed. Then*

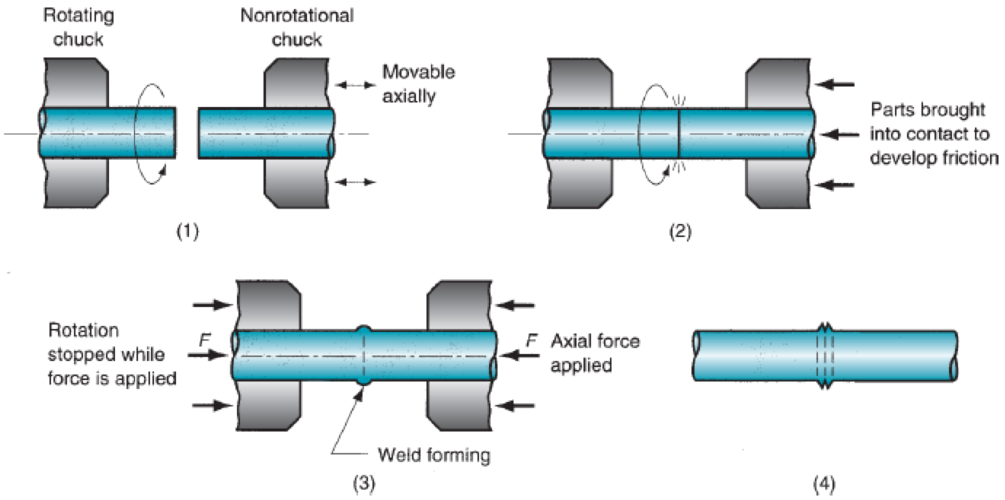


Figure (3) Friction welding (FRW): (1) rotating part, no contact; (2) parts brought into contact to generate friction heat; (3) rotation stopped and axial pressure applied; and (4) weld created.

The flywheel is disengaged from the drive motor, and the parts are forced together. The kinetic energy stored in the flywheel is dissipated in the form of friction heat to cause coalescence at the abutting surfaces. The total cycle for these operations is about 20 seconds.

Machines used for friction welding have the appearance of an engine lathe. They require a powered spindle to turn one part at high speed, and a means of applying an axial force between the rotating part and the nonrotating part. With its short cycle times, **the process lends itself to mass production**. It is applied in the welding of various shafts and tubular parts in industries such as automotive, aircraft, farm equipment, petroleum, and natural gas. **The process yields a narrow heat-affected zone and can be used to join dissimilar metals.** However, at least one of the parts must be rotational; flash must usually be removed, and upsetting reduces the part lengths (which must be taken into consideration in product design).

The conventional friction welding operations discussed above utilize a rotary motion to develop the required friction between faying surfaces. A more recent version of the process is linear friction welding, in which a linear reciprocating motion is used to generate friction heat between the parts. This eliminates the requirement for at least one of the parts to be rotational (e.g., cylindrical, tubular).

Diffusion welding (bonding)

16.1 introduction

Although this process was developed in the 1970s as a modern Welding technology, the principle of diffusion bonding dates back centuries to when goldsmiths bonded gold over copper to create a product called filled gold. First, a thin layer of gold foil is produced and placed over copper, and a Weight is placed on top of the foil. Finally, the assembly is placed in a furnace and left until a strong bond is obtained; hence, the process is also called hot-pressure welding (HPW).

Is only one of many solid-state joining processes wherein joining is accomplished without the need for a liquid interface (brazing) or the creation of a cast product via melting and resolidification (welding). That produces solid-state coalescence between two materials under the following conditions:

1. Joining occurs at a temperature below the melting point , *T*M
2. Coalescence of contacting surfaces is produced with loads below those that would cause macroscopic deformation to the part.
3. A bonding aid can be used, such as an interface foil or coating ,to facilitate the bonding.

Thus, diffusion bonding facilitates the joining of materials to produce components with no abrupt discontinuity in the microstructure and with a minimum of deformation.

It should be noted that the preferred term for this process, according to the American Welding Society, is diffusion *welding.* However, because diffusion *bonding* is used more commonly in industry. Figure(1)

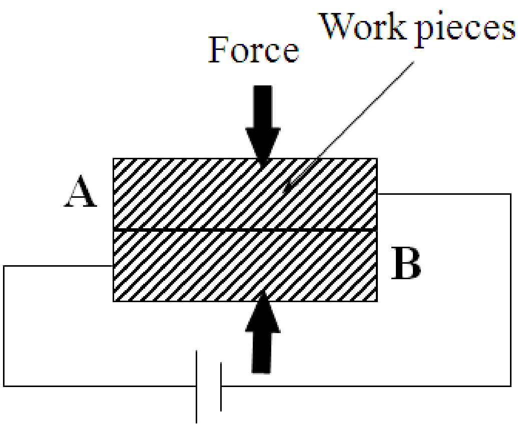


Figure (1) representation of diffusion welding using Electrical resistance for heating

The bonded interface in diffusion welding has essentially the same physical and mechanical properties as the base metal. Its strength depends on:
(a) Pressure, (b) temperature, (c) time of contact, and (d) how clean the faying surfaces are**.**

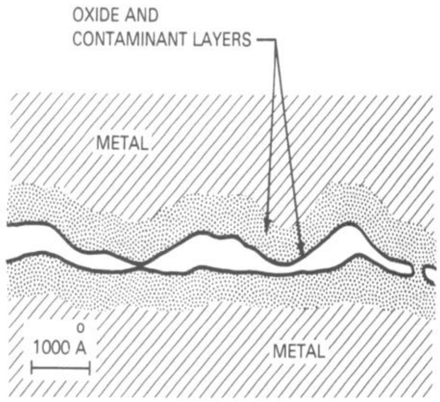
Diffusion bonding generally is most suitable for joining dissimilar metals. It also is used for reactive metals (such as titanium, beryllium, zirconium, and refractory metal alloys) and for composite materials such as metal-matrix composites. Diffusion bonding is also an important mechanism of sintering in powder metallurgy. Because diffusion involves migration of the atoms across the joint, the process is slower than other Welding processes.

16.2 Diffusion Bonding Process

The DB process, that is, the application of pressure and temperature to an interface for a prescribed period of time, is generally considered complete when cavities fully close at the faying surfaces. Relative agreement is found for the mechanisms and sequence of events that lead to the collapse of interface voids, and the discussion below describes these metallurgical processes. Although this theoretical understanding of the DB process is universally applicable, it should be understood that parent metal strength is only approached for materials with surface conditions that do not have barriers to impede atomic bonding such as the absence of surface oxides or absorbed gases at the bonding interface.
In practice, oxide-free conditions exist figure (2) ,only for a limited number of materials. Accordingly, the properties of real surfaces limit and impede the extent of diffusion bonding. The most notable exception is titanium alloys, which, at DB temperatures greater than 850 °C (1560 °F), can readily dissolve minor amounts of adsorbed gases and thin surface oxide films and diffuse them away from the bonding surfaces, so that they will not impede the formation of the required metallic bonds across the bond interface
Similarly, the joining of silver at 200 °C (390 °F) requires no deformation to break up and disperse oxides, because silver oxide dissociates completely at 190 °C (375 °F). Above this temperature, silver dissolves its oxide and also scavenges many surface contaminants. Other examples of metals that have a high solubility for interstitial contaminants include tantalum, tungsten, copper, iron, zirconium, and niobium. Accordingly, this class of alloy is easiest to diffusion bond.
A second class of material, that is, metals and alloys that exhibit very low solubility for interstitials (such as aluminum-, iron-, nickel-, and cobalt-base alloys) are not readily diffusion bondable. Special consideration must be given to remove surface barriers to atomic diffusion prior to joining and subsequently prevent their reformation during the joining process.

This is not an easy processing matter. Accordingly, the potential for high-strength bond interfaces for alloys with low interstitial solubility should be considered on an individual alloy basis.

Figure (2)



16.3 Mechanism of Diffusion Bonding

In diffusion bonding, the nature of the joining process is essentially the coalescence of two atomically clean solid surfaces. Complete coalescence comes about through a three-stage metallurgical sequence of events. Each stage, as shown in Fig. 2, is associated with a particular metallurgical mechanism that makes the dominant contribution to the bonding process. Consequently, the stages are not discretely defined, but begin and end gradually, because the metallurgical mechanisms overlap in time. During the first stage, the contact area grows to a large fraction of the joint area by localized deformation of the contacting surface asperities. Factors such as surface roughness, yield strength, work hardening, temperature, and pressure are of primary importance during this stage of bonding. At the completion of this stage, the interface boundary is no longer a planar interface, but consists of voids separated by areas of intimate contact. In these areas of contact, the joint becomes equivalent to a grain boundary between the grains on each surface. The first stage is usually of short duration for the common case of relatively high-pressure diffusion bonding.

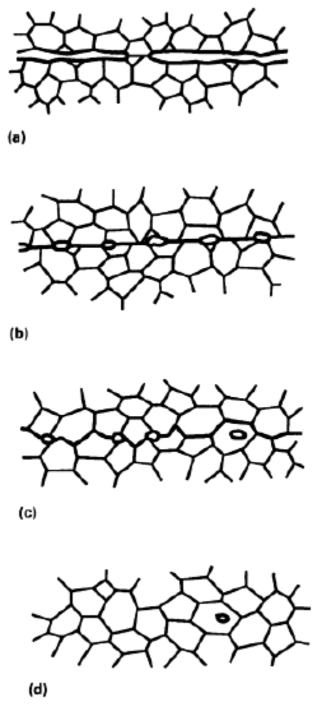


Figure (3) shows the mechanism of diffusion bonding

During the second stage of joint formation, two changes occur simultaneously. All of the voids in the joints shrink, and most are eliminated. In addition, the interfacial grain boundary migrates out of the plane of the joint to lower-energy equilibrium. Creep and diffusion mechanisms are important during the second stage of bonding and for most, if not all, practical applications, bonding would be considered essentially complete following this stage. As the boundary moves, any remaining voids are engulfed within grains where they are no longer in contact with a grain boundary. During this third stage of bonding, the voids are very small and very likely have no impact on interface strength. Again, diffusional processes cause the shrinkage and elimination of voids, but the only possible diffusion path is now through the volume of the grains themselves.

Although diffusion welding is used for fabricating complex parts in low quantities for the aerospace, nuclear, and electronics industries, it has been automated to make it suitable and economical for moderate-volume production. Unless the process is highly automated, considerable operator training and skill are required.