Manufacturing Processes

Chapter Ten:

Fundamentals of Metal Casting

Dr. Eng. Yazan Al-Zain
Department of Industrial Engineering

Introduction

- In casting, the starting work material is either a liquid or is in a highly plastic condition, and a part is created through solidification of the material.
- Casting and molding processes dominate this category of shaping processes.
- The solidification processes can be classified according to engineering material processed: :
  - Metals.
  - Ceramics, specifically glasses.
  - Polymers and polymer matrix composites (PMCs).

Introduction

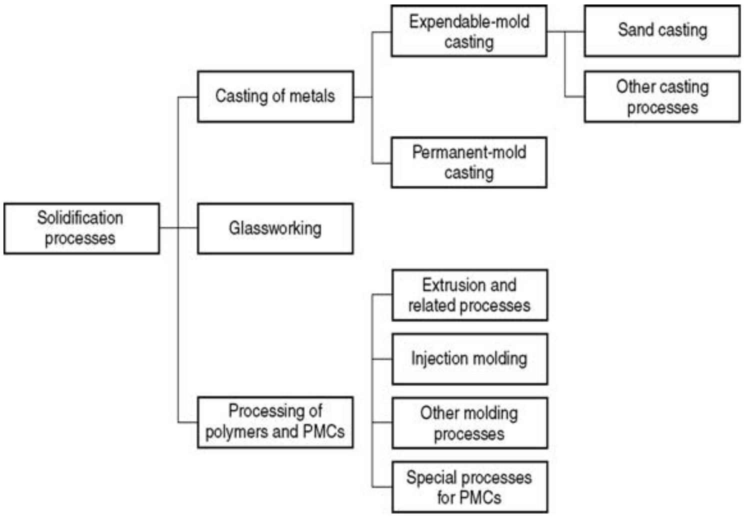


Figure 10.1 Classification of solidification processes.

Introduction

- Casting is the **p**rocess in which molten metal flows by gravity or other force into a mold where it solidifies in the shape of the mold cavity.
- The term *casting* is also applied to the part that is made by this process.
- Principle of casting is pretty simple:
  - Melt the metal.
  - Pour it into a mold.
  - Let it freeze.
- However, to accomplish a successful casting, many variables and factors must be considered.

Introduction

- Casting includes both the *casting of ingots* and the *casting of shapes*.
  - Ingot casting: it describes a large casting that is simple in shape and intended for subsequent reshaping by processes such as rolling or forging.
  - Shape casting: involves the production of more complex geometries that are much closer to the final desired shape.

Introduction

- Casting capabilities and advantages can be summarized as follows:
  - Casting can create complex part geometries, including both external and internal shapes.
  - Some casting processes are capable of producing *net shape;* others are capable of producing *near net shape* (need further processing).
  - Casting can be used to produce very large parts.
  - Can be performed on any metal that can be heated to the liquid state.
  - Some casting processes are suited to mass production.

Introduction

- Casting processes have also disadvantages; different disadvantages for different casting methods:
  - Limitations on mechanical properties.
  - Porosity.
  - Poor dimensional accuracy and surface finish for some processes.
  - Safety hazards to humans when processing hot molten metals.
  - Environmental problems.

Overview of Casting Technology

- Casting is usually performed in a foundry by foundrymen.

  - A *foundry*: a factory equipped for making molds, melting and handling molten metal, performing the casting process, and cleaning the finished casting.

  - *Foundrymen*: are those workers who perform casting.

Overview of Casting Technology; Casting Processes

- Discussion of casting begins with molds.
  - A mold contains a cavity whose geometry determines the shape of the cast part.
  - The actual size and shape of cavity must be slightly oversized to allow for shrinkage that occurs in the metal during solidification and cooling.
  - Amount of shrinkage depends on metal type, so design must be made for the particular metal being cast.
  - Molds are made of a variety of materials, including sand, plaster, ceramic, and metal.

Overview of Casting Technology; Casting Processes

- There are two types of molds:
  - *Open mold*, in which the liquid metal is simply poured until it fills the open cavity.
  - *Closed mold*, in which a passage way, called the gating system, is provided to permit the molten metal to flow from outside the mold into the cavity.

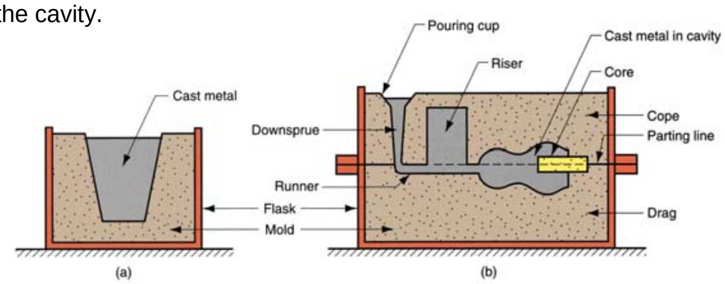


Figure 10.2 (a) Open and (b) Closed molds.

Overview of Casting Technology; Casting Processes

- There are two broad categories of casting:
  - *Expandable mold* casting processes, in which an expendable mold is used and must be destroyed to remove casting. These molds are made out of sand, plaster, whose form is maintained by using binders. Ability to produce complex geometries is an advantage of the expandable mold casting.
  - *Permanent mold* casting processes, in which a permanent mold can be used over and over again. It is made of metal (or, less commonly, a ceramic refractory material). The mold is composed of two sections that can be separated from each other to remove the casting. Example is die casting. Some permanent mold casting processes have certain economic advantages.

Overview of Casting Technology; Sand Casting Molds

- Sand casting is by far the most important casting process.
  - Mold consists of 2 halves; *cope* and *drag*.
    - Cope is the upper half of the mold.
    - Drag is the bottom half of the mold.
  - Cope and drag are contained in a box called *flask*. The flask is also divided into 2 halves; one for the cope and the other for the drag.
  - Parting line: separates the two halves of the mold.

Overview of Casting Technology; Sand Casting Molds

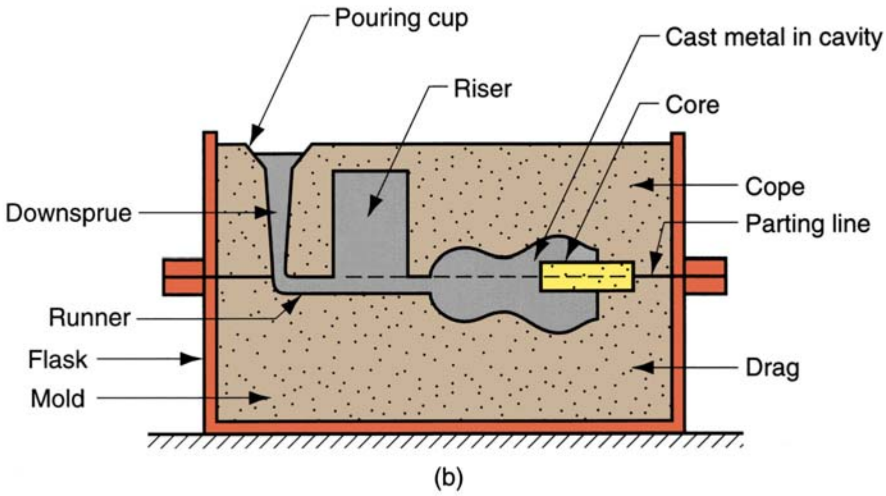


Figure 10.2 (b) Sand casting (closed) mold.

Overview of Casting Technology; Sand Casting Molds

- In sand casting and other expandable mold processes:
  - *Pattern*: the mold cavity is formed by means of a pattern.
    - It is made of wood, metal, plastic, etc, and has the shape of the part to be cast.
    - The cavity is formed by packing sand around the pattern.
    - Usually made oversized to allow for shrinkage as the metal solidifies.
    - The cavity in the mold provides the external surfaces of the cast part.
    - The *core*; the internal surfaces are determined by means of a core, which is a form placed inside the mold cavity to define the interior geometry of the part. “Generally made from sand in sand casting”.

Overview of Casting Technology; Sand Casting Molds

- In sand casting and other expandable mold processes:
  - *Gating system*: is a channel or network of channels, by which molten metal flows into the cavity from outside the mold.
    - The gating system consists of a *downsprue* (or simply *sprue*), through which a metal enters a *runner* that leads into the main cavity.
    - *Pouring cup*, found at the top of the downsprue. It is often used to minimize splash and turbulence as the metal flows into the downsprue.

Overview of Casting Technology; Sand Casting Molds

- In sand casting and other expandable mold processes:
  - *Riser*: is a reservoir in the mold that serves as a source of liquid metal for the casting to compensate for shrinkage during solidification .
    - It is designed to freeze after the main casting in order to satisfy its function

Overview of Casting Technology; Sand Casting Molds

- The air that previously occupied the cavity, as well as hot gases formed by the reactions of the molten metal, must be evacuated so that the metal will completely fill the empty space.
  - In sand casting, 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.

Heating and Pouring Heating the Metal

- Heating furnaces of various kinds are used to heat the metal to a temperature somewhat above its melting temperature for sufficient casting. The heat energy required is the sym of:
  - The heat to raise the temperature to the melting point.
  - The heat of fusion to convert it from solid to liquid.
  - The heat to raise the molten metal to the desired temperature for pouring.
- This can be expressed as:

$$H = \rho V\{C_s(T_m - T_0) + H_f + C_l(T_p - T_m)\}$$

where H = total heat required to raise the temperature of the metal to the pouring temperature, J; ρ = density, g/cm^3; C_s = weight specific heat for solid metal, J/g-ºC; T_m= melting temperature of the metal ºC, T_0 = starting temperature; H_f = heat of fusion, J/g; C_l = weight specific heat of the liquid metal, J/g-ºC; T_p = pouring temperature, ºC; and V = volume of the metal being heated, cm^3.

Heating and Pouring
Pouring the Molten Metal

- For this step to be successful, metal must flow into all regions of the mold, most importantly the main cavity, before solidifying. Factors affecting the pouring operation include:
  - The ***pouring temperature***: temperature of the metal introduced into the mold. Here, *superheat* is important; the difference between the temperature at pouring and the temperature at which freezing begins.
  - The ***pouring rate***: volumetric rate at which the molten metal is poured into the mold. Too slow rates will cause freezing before metal fills the cavity and excessive rates will cause turbulence.
  - ***Turbulence***: sudden variations in the magnitude and velocity throughout the liquid. It tends to accelerate the formation of metal oxides. It also aggravates mold erosion due to impact of the flowing molten metal.

Heating and Pouring
Engineering Analyses of Pouring

- ***Bernoulli's equation*** is an important relationship that governs the flow of liquid metal through the gating system and into the mold. It states that the sum of the energies at any two points in a flowing liquid are equal. This can be written in the following form:

$$h_1 + \frac{P_1}{\rho} + \frac{v_1^2}{2g} + F_1 = h_2 + \frac{P_2}{\rho} + \frac{v_2^2}{2g} + F_2$$

where h = head, cm, P = pressure on the liquid, N/cm^2; v = flow velocity, cm/s; g = gravitational acceleration constant, 981 cm/s/s; and F = head losses due to friction, cm. Subscripts 1 and 2 indicate any two locations in the liquid flow.

Heating and Pouring
Engineering Analyses of Pouring

- Bernoulli's equation may be simplified if we ignore losses due to friction as follows:

$$h_1 + \frac{v_1^2}{2g} = h_2 + \frac{v_2^2}{2g}$$

- Bernoulli's equation may be simplified further. Let's define point 1 at the top of a sprue and point two at its base. If point 2 is used as a reference plane, then $h_2 = 0$ and h_1 is the height of the sprue. When molten metal is poured into the pouring cup and overflows down the sprue, its initial velocity at the top is zero ($v_1 = 0$). Hence the equation becomes:

$$h_1 = \frac{v_2^2}{2g}$$ Solving for flow velocity $$v = \sqrt{2gh}$$

Where v is the velocity of the liquid metal at the base of the sprue, cm/s; and h is the height of the sprue.

Heating and Pouring
Engineering Analyses of Pouring

- Another important relationship during pouring is the ***continuity law***.
- It states that the volume rate of flow remains constant throughout the liquid, and expressed as:

$$Q = v_1 A_1 = v_2 A_2$$

where Q = volumetric flow rate, cm^3/s; and A = cross-sectional area of the liquid, cm^2; and the subscripts refer to any two points in the flow system.

- The time required to fill a mold cavity (*MFT,* in seconds) can be described as:

$$MFT = \frac{V}{Q}$$ V: volume of mold cavity, cm^3.

Heating and Pouring
Fluidity

- ***Fluidity***: (inverse of viscosity) is a measure of the capability of a metal to flow into and fill the mold before freezing. Factors affecting fluidity:
  - Pouring temperature.
  - Metal composition.
  - Viscosity of the liquid.
  - Heat transfer to the surrounding.

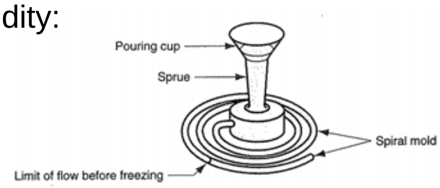


Figure 10.3 Spiral mold test.

- Spiral mold test: a standard test method to asses fluidity, in which fluidity is indicated by the length of the solidified metal in the spiral channel.

Solidification and Cooling
Solidification of Metals

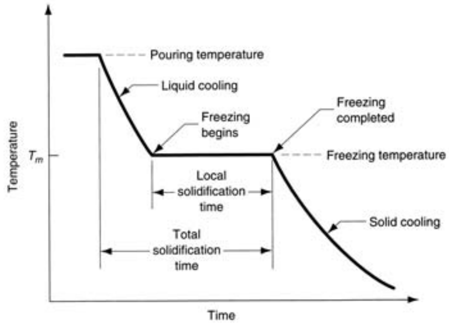
- ***Solidification***: the transformation of the molten metal back into the solid state. (differs depending on composition and purity). Pure metals freeze at a constant temperature while alloys, except for the eutectic compositions, freeze over a temperature range.

- Fluidity of pure metals are better than that of alloys. When solidification occurs over a temperature range, the partially solidified portion interferes with the flow of the liquid portion, hence reducing fluidity.

Solidification and Cooling
Solidification of Metals

(1) Solidification of Pure Metals: the process occurs at constant temperature over time.

- Local solidification time: the time over which actual freezing occurs.
- Total solidification time: the time taken between pouring and solidification.



Note: during local solidification time, the metal's latent heat of fusion is released into the surrounding mold.

Figure 10.4 Cooling curve for the pure metal during casting.

Solidification and Cooling
Solidification of Metals

- Because of the chilling action of the mold wall, a thin skin of solid metal is initially formed at the interface immediately after pouring.
- Skin thickness increases to form a shell around the molten metal as solidification progresses inward toward the center of the cavity.
- Rate of freezing depends on heat transfer into mold, as well as the thermal properties of the metal.

Solidification and Cooling
Solidification of Metals

- The metal which forms the initial skin has been rapidly cooled by the extraction of heat through the mold wall. This causes the grains in the skin to be fine, equiaxed, and randomly oriented.

- Further grain formation and growth occurs in a direction away from the heat transfer. The grains grow inwardly as needles of solid metal since the heat transfer is through skin and mold wall (slower cooling rate). This type of grain growth is referred to as ***dendritic growth***. See Fig. 10.5.

Solidification and Cooling
Solidification of Metals

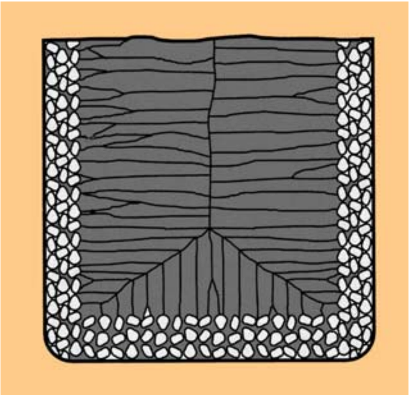


Fig. 10.5 Characteristic grain structure in a casting of a pure metal, showing randomly oriented grains of small size near the mold wall, and large columnar grains oriented toward the center of the casting.

Solidification and Cooling
Solidification of Metals

(2) Solidification of Most Alloys: the process occurs over a temperature range.

- As temperature drops, freezing begins at the temperature indicated by the liquidus, and completed when the solidus is reached.
- The start of freezing is similar to that in pure metals (thin skin and dendritic structure).

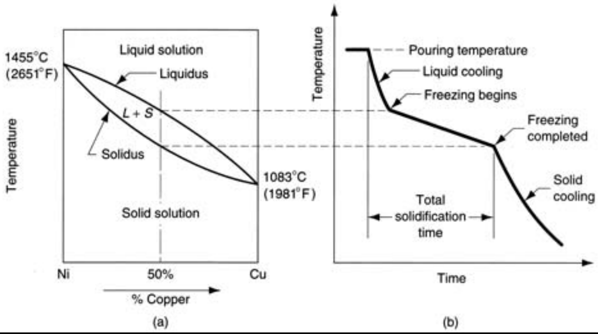


Figure 10.6 Phase diagram for a copper–nickel alloy system and (b) associated cooling curve for a 50%Ni–50%Cu composition during casting.

Solidification and Cooling
Solidification of Metals

- ***Mushy zone***: a solid-liquid region that has a soft consistency.
- The slower the heat transfer and the wider the difference between liquidus and solidus, the broader the mushy zone.
- The liquid islands in the dendritic matrix solidify gradually as the temperature of the casting drops.
- The dendritic structure favors the metal with the highest melting point. In other words, there would become a composition imbalance between the metal that has solidified and the remaining molten metal (variations in chemical composition throughout the casting).
- This leads to segregation of elements in the casting (called ingot segregation).

Solidification and Cooling
Solidification of Metals

Ni-rich (Cu-poor) regions

Assuming a Ni-Cu alloy

Cu-rich (Ni-poor) regions

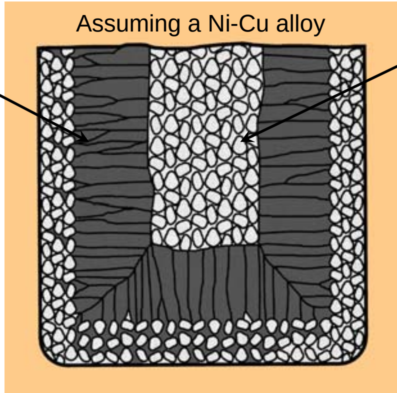


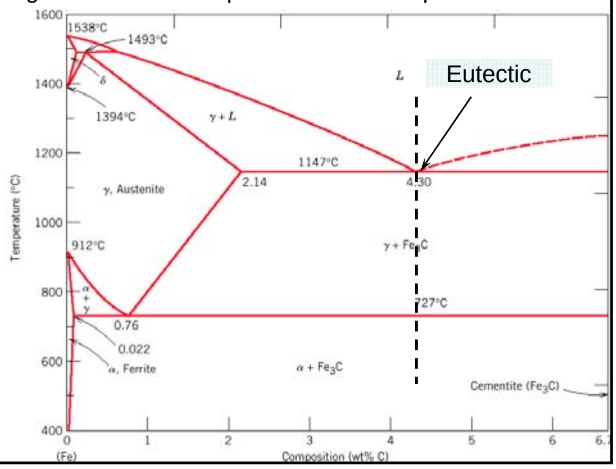
Fig. 10.7 Characteristic grain structure in an alloy casting, showing segregation of alloying components in center of casting.

Solidification and Cooling
Solidification of Metals

(2) Solidification of Eutectic Alloys: in these alloys, the solidus and liquidus are at the same temperature. Hence, the process occurs at constant temperature over time.; e.g. the eutectic composition in Fe-C equilibrium phase diagram.

In the eutectic reaction:
(a liquid transforms into 2 solids)
Liq. → $\gamma + Fe_3C$
Fe_3C: cementite
γ : austenite

In Fe-C system:
-Fe – 4.3 wt.% C is the eutectic composition.
-1147 °C is the eutectic temperature.



Solidification and Cooling
Solidification Time

- Whether the casting is pure metal or alloy, solidification takes time.
- The total solidification time: the time required for casting to solidify after pouring (TST).
- TST depends on size and shape of casting by relationship known as *Chvorinov's Rule*

$$TST = C_m \left(\frac{V}{A} \right)^n$$

Chvorinov's rule indicates that the higher the volume to surface ratio, the more slowly the casting will solidify.

where TST = total solidification time, min; V = volume of the casting, cm^3; A = surface area of the casting, cm^2; n is an exponent usually = 2; and C_m is the mold constant, min/cm^2.

- In the *Riser* design, it is made so that the volume to surface ratio is higher than that of the casting (that's why the riser solidifies after the main casting).

Solidification and Cooling
Shrinkage

- During cooling, shrinkage occurs in three steps:
  - Liquid contraction during cooling prior to solidification.
  - Contraction during the phase change from liquid to solid, called ***solidification shrinkage***.
  - Thermal contraction of the solidified casting during cooling to room temperature.

Solidification and Cooling Shrinkage

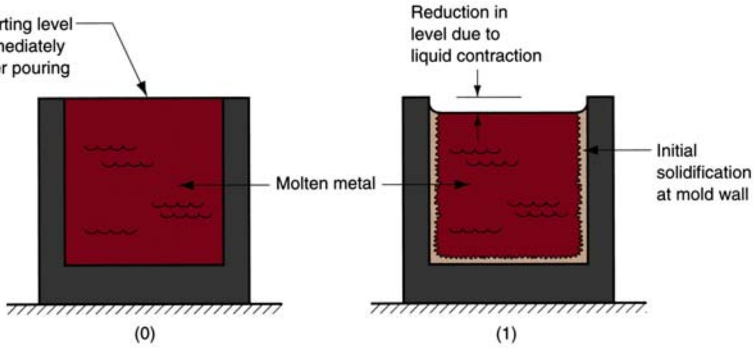


Fig. 10.8 Shrinkage of a cylindrical casting during solidification and cooling: (0) starting level of molten metal immediately after pouring; (1) reduction in level caused by liquid contraction during cooling (the amount of this liquid contraction is ~0.5%).

Solidification and Cooling Shrinkage

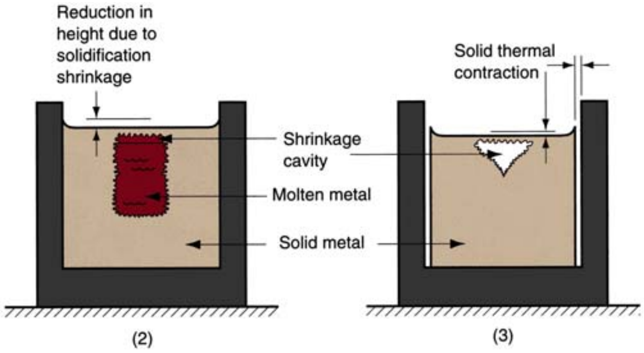


Fig. 10.8 (2) reduction in height and formation of shrinkage cavity caused by solidification shrinkage; (3) further reduction in height and diameter due to thermal contraction during cooling of the solid metal

Solidification and Cooling Shrinkage

- Solidification shrinkage occurs in nearly all metals because the solid phase has a higher density than the liquid phase.
- The phase transformation that accompanies solidification causes a reduction in volume per unit weight of metal.
- Cast iron with high carbon content is an exception as graphitization during final stages of freezing causes expansion that tends to counteract the volumetric decrease associated with the phase change.

Solidification and Cooling Shrinkage

- Patternmakers account for solidification shrinkage and thermal contraction by making the mold cavities oversized.
- The amount by which the mold must be made larger relative to final casting size is called ***pattern shrinkage allowance***.

Solidification and Cooling
Directional Solidification

- In order to minimize the damaging effects of shrinkage, it is desirable for the regions of the casting most distant from the liquid metal supply to freeze first and for solidification to progress from these remote regions toward the riser(s).
- In this way, the molten metal will continually be available from the risers to prevent shrinkage voids during freezing.
- The term ***directional solidification*** is used to describe this aspect of the freezing process and the methods by which it is controlled.

Solidification and Cooling
Directional Solidification

- The directional solidification is achieved by observing Chvorinov's Rule in the design of the casting itself, its orientation within the mold, and the design of the riser system that feeds it.
- For example, by locating sections of the casting with lower V/A ratios away from the riser, freezing will occur first in these regions and the supply of liquid metal for the rest of the casting will remain open until the bulkier sections solidify.

Solidification and Cooling
Directional Solidification

- The directional solidification may also be achieved by the use of ***chills***; internal or external heat sinks that cause rapid freezing in certain regions of the casting.
  - Internal chills: small metal parts placed inside the cavity before pouring so that molten metal will solidify first around these parts.
  - External chills: metal inserts in the walls of the mold cavity that can remove heat from the molten metal more rapidly than the surrounding sand in order to promote solidification.

Solidification and Cooling
Directional Solidification

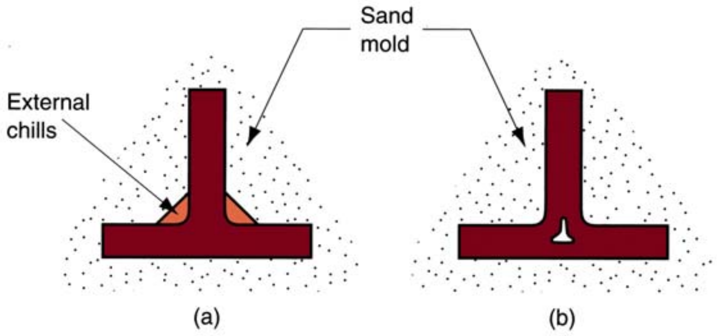


Fig. 10.9 (a) External chill to encourage rapid freezing of the molten metal in a thin section of the casting; and (b) the likely result if the external chill were not used

Solidification and Cooling
Riser Design

- Riser is used in sand casting to feed liquid metal to the casting during freezing to compensate for solidification shrinkage.
- The riser must remain molten until after the casting solidifies.
- Chvorinov's Rule is used to compute the size of the riser that satisfies this requirement.
- As the riser is not a part of the casting, it will be separated from the cast part after casting is finished. Hence, it is desirable for the volume of metal in the riser to be minimum.

Solidification and Cooling
Riser Design

- Risers can be designed in various forms:
  - Side riser: attached to the side of the casting by means of a small channel.
  - Top riser: connected to the top surface of the casting.
- Risers can be open or blind:
  - Open riser: exposed to the outside at the top surface of the cope (disadvantageous as heat will escape faster).
  - Blind riser: entirely closed within the mold.

Solidification and Cooling
Riser Design

- Example 10.3: Riser design using Chvorinov's Rule.

End of Chapter 10

Manufacturing Processes

Chapter Eleven:

Metals For Casting

Dr. Eng. Yazan Al-Zain
Department of Industrial Engineering

Sand Casting

- Sand casting is by far most widely used casting process.
- Nearly all alloys can be sand casted.
- Sand casting is one of the few processes that can be used for metals with high melting points, such as steel and nickel.
- Parts from small to large sizes and quantities from one to millions can be sand-casted.

Sand Casting

- Sand casting consists of:
  - Pouring molten metal into sand mold.
  - Allowing the metal to solidify.
  - Breaking up the mold to remove the casting.
  - Cleaning and inspecting the casting.
  - Heat treatment is sometimes required to improve metallurgical properties

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Sand Casting

- The cavity in the sand mold is formed by packing sand around a pattern, and then separating the mold into two halves to remove the pattern.
- The mold also contains the gating and riser system.
- If casting is to have internal surfaces, a core must be included in the mold.
- A new sand mold must be made for each part produced, since the mold is sacrificed to remove the casting.

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Sand Casting
Patterns and Cores

- The ***pattern*** is a full-sized model of the part, enlarged to account for shrinkage and machining allowances.
- Made of plastic, wood or metals.
- Wood is cheap and easy to machine.
- Wood however, tend to wrap. Thus, limiting the number of times it can be used.
- Metal is more expensive, but it can be a good choice if the number of parts to be made is high.
- Plastic represent a compromise between wood and metal.

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Sand Casting
Patterns and Cores

- There are various types of patterns:
  - ***Solid pattern***: simplest type and easiest to fabricate. However, it is not the easiest to use in making a sand mold (difficult to determine the parting line, also incorporating the raiser and gating system needs high skill).
  - ***Split patterns***: consist of 2 pieces, dividing the part along a line coinciding with the mold's parting line. These patterns are appropriate for complex part geometries and moderate quantities.

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Sand Casting
Patterns and Cores

- There are various types of patterns:
  - ***Match-plate patterns***: appropriate for high production quantities. In these patterns, the two pieces of the split pattern are attached to opposite sides of a wood or metal plate. Holes in the plate allow the cope and drag of the mold to be aligned accurately.
  - ***Cope-and-drag patterns***: appropriate for high production quantities. Similar to match-plate patterns except that split pattern halves are attached to separate plates so that the cope-and-drag sections can be fabricated independently, instead of using the same tooling for both.

Sand Casting
Patterns and Cores

- There are various types of patterns:

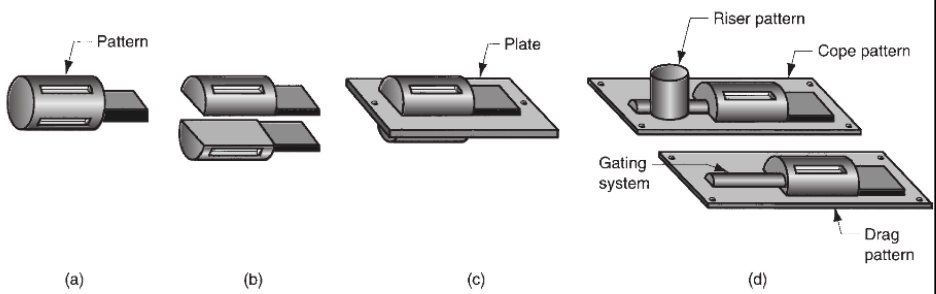

Fig. 11.1 Types of patterns used in sand casting (a) solid pattern, (b) split pattern, (c) match-plate pattern, and (d) cope-and-drag pattern.

Sand Casting
Patterns and Cores

- The ***core*** defines the internal features of a casting.
- Usually made of sand, compacted into the desired shape.
- As with the pattern, the actual size of the core must account for the shrinkage and machining.
- ***Chaplets***: supports for the core. The may or may not be necessary depending on the part's geometry. They are made of metals that have higher melting points than the casting.

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Sand Casting
Patterns and Cores

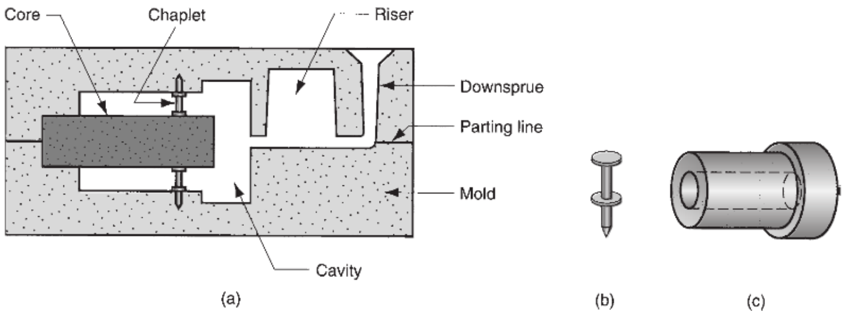

Fig. 11.2 (a) Core held in place in the mold cavity by chaplets, (b) possible chaplet design, and (c) casting with internal cavity .

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Sand Casting
Molds and mold making

- Foundry sands are silica, or silica mixed with other minerals.
- Sand should be able to stand high temperatures without melting or degrading.
- Sand should have appropriate size to provide a good surface finish on the cast part and allow for gases to escape during pouring.
- Small sizes provide a good surface finish but have lower permeability compared to large sizes.
- Sand particles are held together by water and clay (by volume: 90%, 3% and 7%, respectively).

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Sand Casting
Molds and mold making

- The mold cavity is formed by compacting the sand around the pattern for both cope and drag contained in the flask.
- The simplest packing process is hand hammering, accomplished manually by a foundry worker.
- In addition, various machines have been developed to mechanize the packing procedure.

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Sand Casting
Molds and mold making

- The quality of the sand mold is determined by:
  - Strength: the mold's ability to maintain its shape and resist erosion caused by the flow of molten metal. It depends on grain size and shape and binders quality.
  - Permeability: ability of the mold to allow gases to pass through the sand voids.
  - Thermal stability: ability of the sand at the surface of the mold cavity to resist cracking and buckling upon contact with the molten metal.
  - Collapsibility: ability of the sand to give way and allow the casting to shrink without cracking the casting. It also refers to the ability to remove the sand from the casting during cleaning.
  - Reusability: ability to reuse the sand to make other molds.

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Sand Casting
Molds and mold making

- Sand molds classifications:
  - Green-sand molds: made of sand, clay and water. They contain moisture at the time of pouring. They possess good strength, good collapsibility and permeability, good reusability and the least expensive of the molds. Moisture however, can cause some defects in the castings.
  - Dry-sand molds: made of organic binders. The mold is backed in an oven at temperatures between 200 and 320 ºC for strengthening and hardening reasons. Better dimensional accuracy compared to green-sand molds but more expensive.
  - Skin-dried mold: the advantages of dry-sand molds are partially achieved by drying the surface of a green-sand mold to a depth of 10 to 25 mm.

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Sand Casting
The Casting Operation

- After the core is positioned and the two halves of the mold are clamped together, the casting is performed.
- The gating and the riser system in the system must be designed to deliver liquid metal into the cavity, and provide for a sufficient reservoir of molten metal during solidification shrinkage.
- Air and gasses must be allowed to escape.
- Following solidification and cooling, the sand mold is broken away from the casting to retrieve the part.
- The part is then cleaned, gating and riser system is separated and sand is removed.
- Finally, casting is inspected.

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Sand Casting
The Casting Operation

- One of the hazards during pouring is that the buoyancy of the molten metal will displace the core. It results from the weight of molten metal being displaced by the core, according to Archimedes' principle. This force is described as follows:

$$F_b = W_m - W_c$$

where F_b = buoyancy force, N; W_m = weight of molten metal displaced , N; and W_c = weight of the core, N.

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Other Expandable-Mold-Casting Processes

- Other casting processes that have been developed to meet special needs.
- The difference between these methods are in:
  - The composition of the mold material.
  - Or the manner in which the mold is made.
  - Or in the way the pattern is made.

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Other Expandable-Mold-Casting Processes
Shell Molding

- ***Shell molding***: is a casting process in which the mold is a thin shell made of sand held together by thermosetting resin binder.
- Was developed in Germany in the early 1940s.
- Steps of shell molding: (See next figures).

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Other Expandable-Mold-Casting Processes Shell Molding

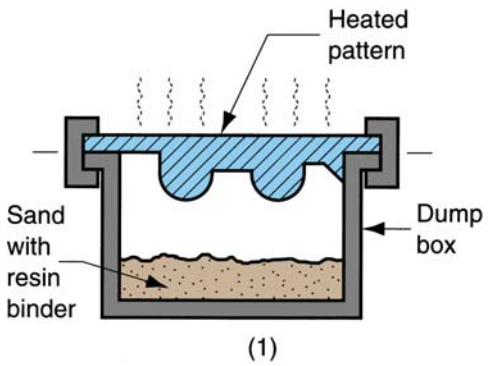

Figure 11.3 − Steps in shell−molding: (1) a match−plate or cope−and−drag metal pattern is heated and placed over a box containing sand mixed with thermosetting resin.

Other Expandable-Mold-Casting Processes Shell Molding

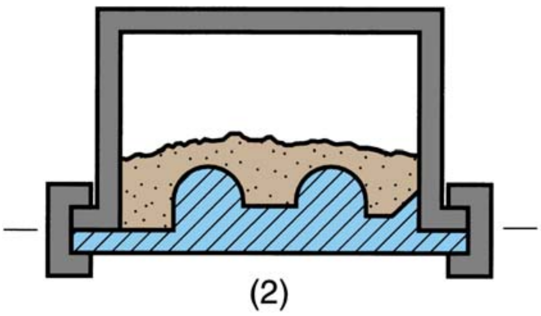

Figure 11.3 − Steps in shell−molding: (2) box is inverted so that sand and resin fall onto the hot pattern, causing a layer of the mixture to partially cure on the surface to form a hard shell.

Other Expandable-Mold-Casting Processes
Shell Molding

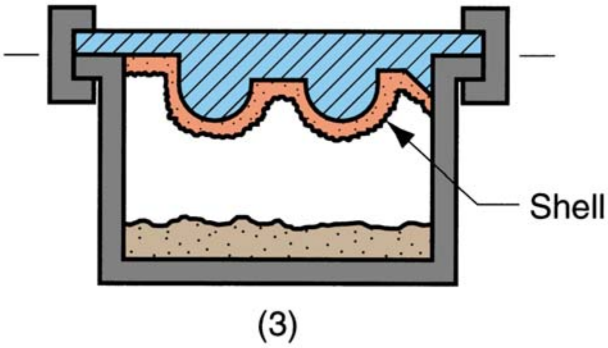

Figure 11.3 − Steps in shell−molding: (3) box is repositioned so that loose, uncured particles drop away.

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Other Expandable-Mold-Casting Processes
Shell Molding

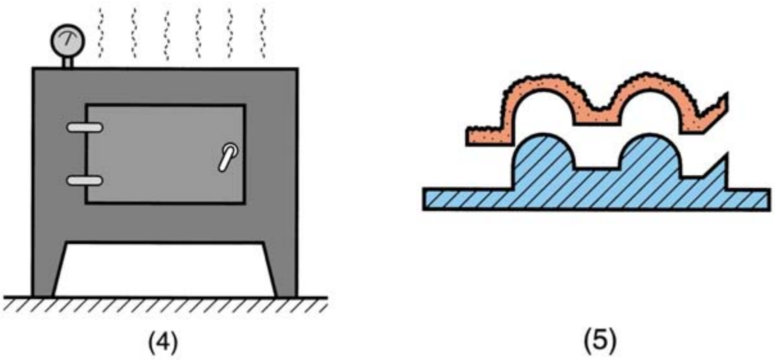

Figure 11.3 − Steps in shell−molding: (4) sand shell is heated in oven for several minutes to complete curing; (5) shell mold is stripped from the pattern.

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Other Expandable-Mold-Casting Processes
Shell Molding

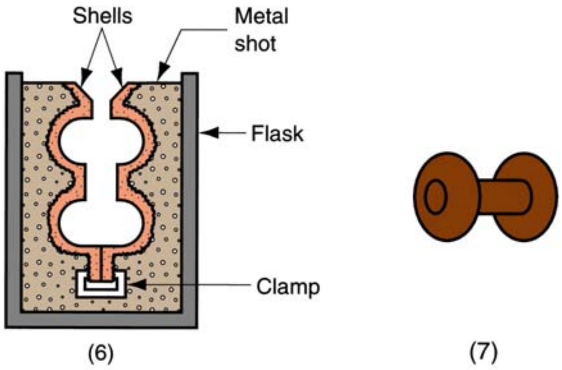

Figure 11.3 − Steps in shell−molding: (6) two halves of the shell mold are assembled, supported by sand or metal shot in a box, and pouring is accomplished; (7) the finished casting with sprue removed.

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Other Expandable-Mold-Casting Processes
Shell Molding

- There are many advantages of shell molding:
  - The surface of the shell mold cavity is smoother than in a conventional green-sand mold.
  - This smoothness permits easier flow of molten metal during pouring and better surface finish on casting.
  - Good dimensional accuracy (due to good finish and accuracy, the need for machining is minimized).
  - Sufficient mold collapsibility to avoid tearing and cracking of casting.
  - Can be mechanized for mass production.
  - Very economical for large quantities.

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Other Expandable-Mold-Casting Processes
Shell Molding

- There are also some disadvantages of shell molding:
  - More expensive metal pattern than the corresponding pattern for green-sand molding. This makes the shell molding difficult to justify for small quantities.
- Examples of parts made using shell molding:
  - Gears.
  - Camshafts.

Other Expandable-Mold-Casting Processes
Expanded Polystyrene Process

- The ***expanded polystyrene process*** uses a mold of sand packed around a polystyrene foam pattern, which vaporizes when the molten metal is poured into the mold.
- Also known as: *lost-foam process*, *lost pattern process*, *evaporative-foam process*, and *full-mold process.*
- The polystyrene pattern includes the sprue, risers, gating system, and may contain internal cores (if needed), thus eliminating the need for a separate core in the mold.
- Since the foam pattern itself becomes the cavity in the mold, considerations of draft and parting lines can be ignored.
- The mold does not have to be opened into cope and drag sections.

Other Expandable-Mold-Casting Processes
Expanded Polystyrene Process

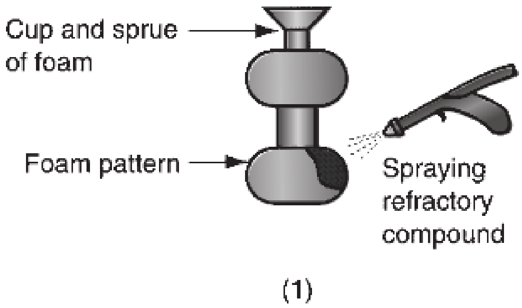

Figure 11.5 ‑ Expanded polystyrene casting process: (1) pattern of polystyrene is coated with a refractory compound (to provide a smoother surface on the pattern and to improve its high temperature resistance).

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Other Expandable-Mold-Casting Processes
Expanded Polystyrene Process

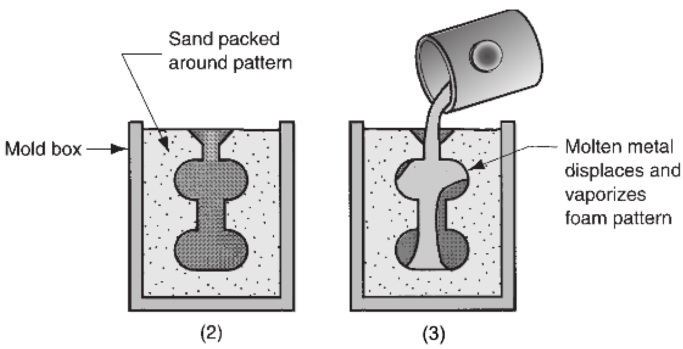

Figure 11.5 ‑ Expanded polystyrene casting process: (2) foam pattern is placed in mold box, and sand is compacted around the pattern; and (3) molten metal is poured into the portion of the pattern that forms the pouring cup and sprue. As the metal enters the mold, the polystyrene foam is vaporized ahead of the advancing liquid, thus allowing the resulting mold cavity to be filled.

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Other Expandable-Mold-Casting Processes
Expanded Polystyrene Process

- Advantages of this process include:
  - Pattern need not be removed from the mold.
  - The steps of incorporating cores and gating and riser system, the preparation of two mold halves with a proper parting line, allowances, etc, which are necessary for green-sand molding are built into the foam pattern itself.
- Disadvantage is:
  - A new pattern is needed for every casting.
- An example of parts made with the expanded polystyrene process is automobiles engines.

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Other Expandable-Mold-Casting Processes
Investment Casting

- In ***investment casting***: a pattern made of wax is coated with a refractory material to make the mold, after which wax is melted away prior to pouring the molten metal.
- The term *investment* comes from one of the less familiar definitions of the word *invest* - "to cover completely," this referring to coating of refractory material around the wax pattern.
- It is a precision casting process, as it is capable of making castings of high accuracy and intricate details.
- It dates back to the ancient Egypt, and is also know as the ***lost-wax process***, because the wax pattern is lost from the mold prior to casting.

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Other Expandable-Mold-Casting Processes
Investment Casting

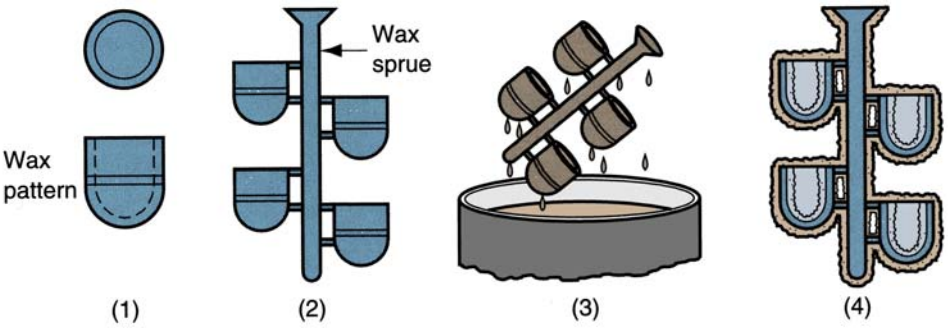

Figure 11.6 − Steps in investment casting: (1) wax patterns are produced; (2) several patterns are attached to a sprue to form a pattern tree; (3) the pattern tree is coated with a thin layer of refractory material; (4) the full mold is formed by covering the coated tree with sufficient refractory material to make it rigid.

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Other Expandable-Mold-Casting Processes
Investment Casting

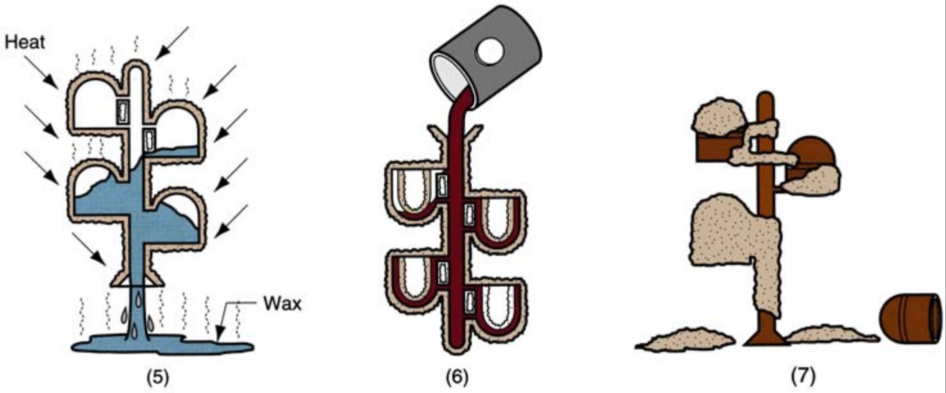

Figure 11.6 − Steps in investment casting: (5) the mold is held in an inverted position and heated to melt the wax and permit it to drip out of the cavity; (6) the mold is preheated to a high temperature, which ensures that all contaminants are eliminated from the mold; it also permits the liquid metal to flow more easily into the detailed cavity; the molten metal is poured; it solidifies; and (7) the mold is broken away from the finished casting. Parts are separated from the sprue.

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Other Expandable-Mold-Casting Processes
Investment casting

- Advantages of investment casting are:
  - Parts of great complexity can be cast.
  - Close dimensional control and good surface finish.
  - Wax can usually be recovered for reuse.
  - Additional machining is not normally required − this is a net shape process.
- Disadvantage are:
  - Since many processing steps are required, it is an expensive process.
  - Parts are usually small in size.
- Examples of parts made with this process are blades and jewelry.

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Permanent Mold Casting Processes

- The economic disadvantage of any of the expendable mold processes is that a new mold is required for every casting.
- In permanent-mold casting, the mold is reused many times.

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Permanent Mold Casting Processes
The Basic Permanent-Mold Process

- Permanent-mold casting uses a metal mold constructed of two sections that are designed for easy, precise opening and closing.
- The molds are commonly made of steel or cast iron. Examples of metals cast in these molds are Al, Mg, Cu-base alloys and cast-iron. For cast iron however, the mold must be made of refractory material.
- To provide good dimensional accuracy and surface finish, the cavity, with gating system are machined into two halves.
- Metallic cores can be used in permanent molds. However, they should be removable, otherwise sand cores can be used. In the later case, the process is referred to as ***semipermanent-mold casting***.
- Steps in the basic permanent-mold casting: see next figures.

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Permanent Mold Casting Processes
The Basic Permanent-Mold Process

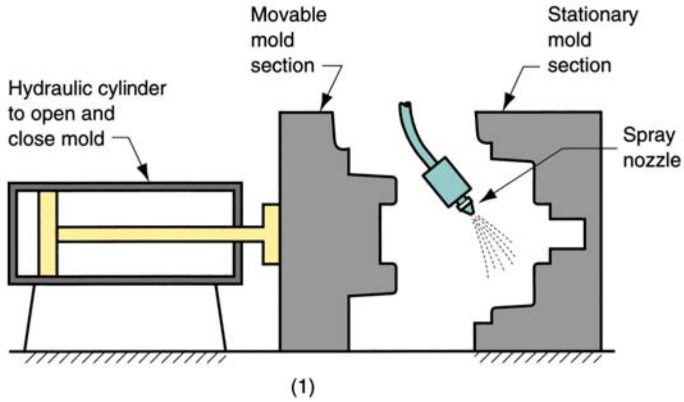

Figure 11.7 − Steps in permanent-mold casting: (1) mold is preheated and coated (preheating facilitates metal flow and coating aid heat dissipation and lubricate the mold surfaces for easier separation of the cast product.

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Permanent Mold Casting Processes
The Basic Permanent-Mold Process

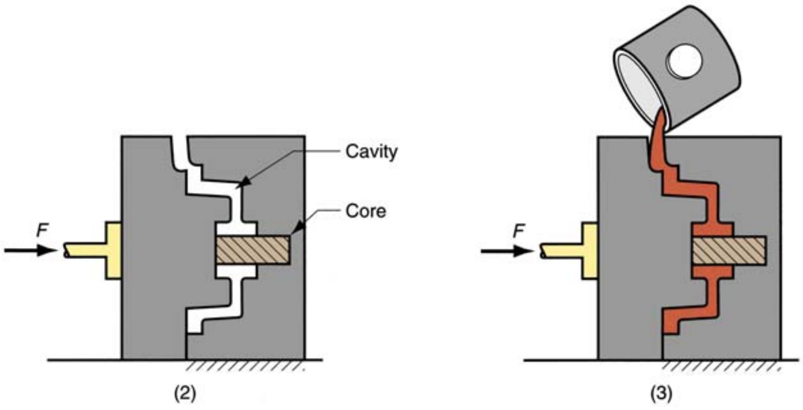

Figure 11.7 − Steps in permanent-mold casting: (2) cores (if used) are inserted and mold is closed; and (3) molten metal is poured into the mold. As the metal solidifies, the mold is opened and the part retrieved.

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Permanent Mold Casting Processes
The Basic Permanent-Mold Process

- Advantages of permanent-mold casting:
  - Good surface finish and close dimensional accuracy.
  - More rapid solidification caused by the metal mold results in a finer grain structure, so stronger castings are produced.
- Limitations:
  - Generally limited to metals of lower melting points.
  - Simple part geometries compared to sand casting because of the need to open the mold.
  - The expense of the mold.
- Examples of castings are automotive pistons and pump bodies.

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Permanent Mold Casting Processes
Die Casting

- ***Die casting*** is a permanent mold casting process in which molten metal is injected into mold cavity under high pressure (7 to 350 MPa).
- The pressure is maintained during solidification, after which the mold is opened and part is removed.
- The molds in this casting operation are called dies; hence the name die casting.
- The use of high pressure to force the metal into die cavity is the most notable feature that distinguishes this process from others in the permanent mold category.

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Permanent Mold Casting Processes
Die Casting

- Die-casting machines are designed to hold and accurately close the two mold halves, and keep them closed while the liquid metal is forced into the cavity.
- There are two main types of die-casting machines, depending on how the molten metal is injected into the cavity:

(1) Hot-chamber.

(2) Cold-chamber.

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Permanent Mold Casting Processes
Die Casting

(1) In hot-chamber machines:

- The metal is melted in a container attached to the machine, and a piston is used to inject the liquid metal under high pressure into the die.
- Production rates up to 500 parts / hour are not uncommon.
- Hot-chamber die casting imposes a special hardship on the injection system because most of it is submerged into the molten metal.
- Hence, the applications are limited to low melting−point metals (Zn, Sn and Pb) that do not chemically attack plunger and other mechanical components.

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Permanent Mold Casting Processes
Die Casting

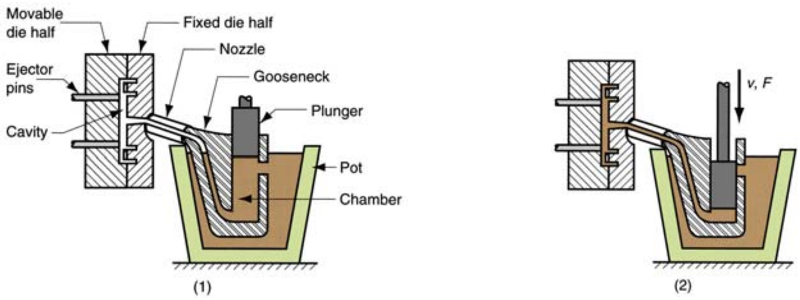

Figure 11.8 − Cycle in hot-chamber casting: (1) with die closed and plunger withdrawn, molten metal flows into the chamber ; and (2) plunger forces metal in chamber to flow into die, maintaining pressure during cooling and solidification. After solidification, plunger is withdrawn, plunger is opened and solidified part is ejected.

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Permanent Mold Casting Processes
Die Casting

(1) In cold-chamber machines:

- The molten metal is poured into an unheated chamber from an external melting container, and a piston is used to inject the metal under high pressure into the die cavity (14 to 140 MPa).
- Compared to hot-chamber machines, cycle rates are not usually as fast because of the need to ladle the liquid metal into the chamber from an external source (still its high production operation).
- Typical for casting: Al, Cu–Zn and Mg alloys.

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Permanent Mold Casting Processes
Die Casting

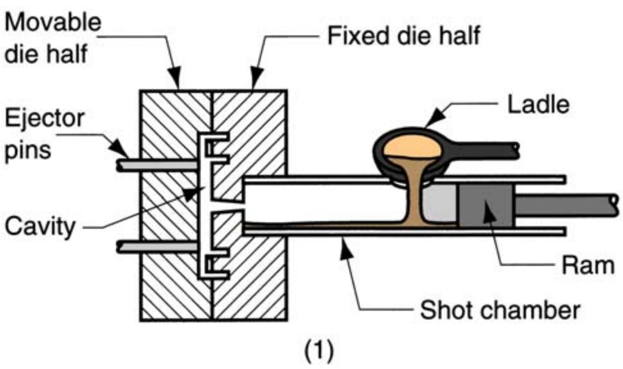

Figure 11.9 − Cycle in cold-chamber casting: (1) with die closed and ram withdrawn, molten metal is poured into the chamber.

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Permanent Mold Casting Processes
Die Casting

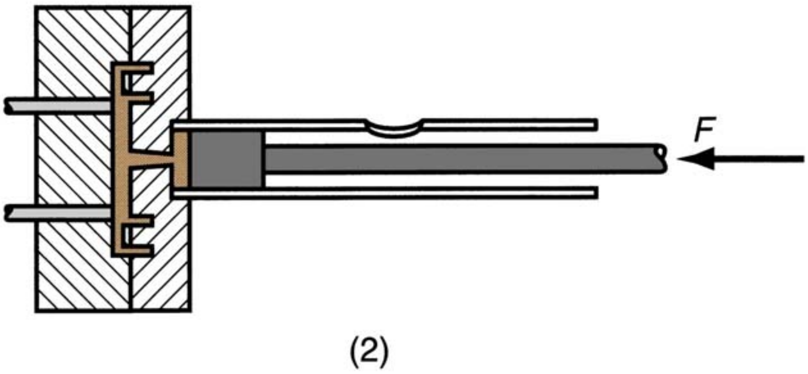

Figure 11.9 − Cycle in cold-chamber casting: (2) ram forces metal to flow into die, maintaining pressure during cooling and solidification. After solidification, ram is withdrawn, die is opened and part is ejected.

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Permanent Mold Casting Processes
Die Casting

- The molds for die-casting are usually made of tool steel or mold steel.
- Tungsten and molybdenum with good refractory qualities are also used.
- Ejector pins are required to remove the part from the die when it opens.
- Lubricants must be sprayed into the cavity to prevent sticking.
- Vent holes built into the mold (since no natural porosity).

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Permanent Mold Casting Processes
Die Casting

- Advantages of die casting:
  - High production rates.
  - Economical for large production quantities.
  - Close tolerance and good surface finish.
  - Thin sections down to 0.5 mm are possible.
  - Rapid cooling provides small grain size and good strength to the casting.
- Limitations:
  - Generally limited to metals of lower melting points.
  - Part geometry must allow removal from die cavity.

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Permanent Mold Casting Processes
Centrifugal Casting

- Centrifugal casting refers to several casting methods in which the mold is rotated at high-speed so that centrifugal force distributes the molten metal to the outer regions of the die cavity.
- The group includes:

  (1) True centrifugal casting.

  (2) Semicentrifugal casting.

  (3) Centrifuge casting.

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Permanent Mold Casting Processes Centrifugal Casting

- In ***True Centrifugal Casting***, molten metal is poured into a rotating mold to produce a tubular part.
- Parts made by this process include pipes, tubes and rings.
- In some operations, mold rotation commences after pouring has occurred rather than beforehand.
- The high-speed rotation results in centrifugal forces that cause the metal to take the shape of the mold cavity. Thus, the outside shape of the casting can be round, octagonal, hexagonal, and so on. However, the inside shape of the casting is (theoretically) perfectly round, due to the radially symmetric forces at work.

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Permanent Mold Casting Processes Centrifugal Casting

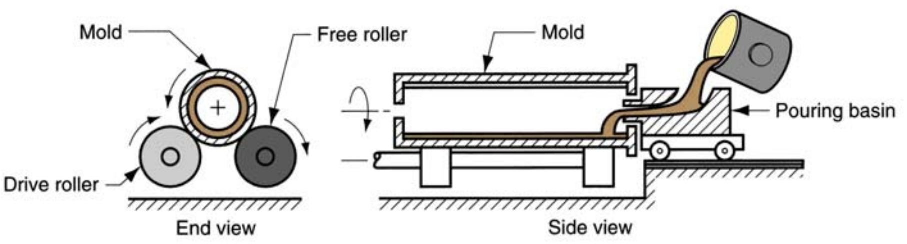

Figure 11.10 − Setup for true centrifugal casting.

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Permanent Mold Casting Processes
Centrifugal Casting

- *How fast must the mold be rotated for the process to work successfully?*

  – Centrifugal force is defined as:

$$F = \frac{mv^2}{R}$$

where F = force, N; m = mass, kg; v = velocity, m/s; and R = inside radius of the mold, m. The force of gravity is its weight $W = mg$, where W is given in N, and g = acceleration of gravity, 9.8 m/s^2.

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Permanent Mold Casting Processes
Centrifugal Casting

- The so-called G-factor GF is the ratio of centrifugal force divided by weight:

$$GF = \frac{F}{W} = \frac{mv^2}{Rmg} = \frac{v^2}{Rg}$$

- Velocity v can be expressed as $2\pi RN/60 = \pi RN/30$, where the constant 60 converts seconds to minutes; so that N = rotational speed, rev/min. Substituting into the above equation, we obtain:

$$GF = \frac{R\left(\frac{\pi N}{30}\right)^2}{g}$$

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Permanent Mold Casting Processes
Centrifugal Casting

- Rearranging this to solve for rotational speed N, and using diameter D rather than radius in the resulting equation,

$$N = \frac{30}{\pi}\sqrt{\frac{2gGF}{D}}$$

where D = inside diameter of the mold, m. If the G-factor is too low in centrifugal casting, the liquid metal will not remain forced against the mold wall during the upper half of the circular path but will "rain" inside the cavity. On an empirical basis, values of GF = 60 to 80 are found to be appropriate for horizontal centrifugal casting.

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Foundry Practice

- In all casting processes, the metal must be heated to the molten state to be poured or otherwise forced into the mold. Heating and melting are accomplished in a furnace.
- The types of furnaces most commonly used in foundries are (1) cupolas, (2) direct fuel-fired furnaces, (3) crucible furnaces, (4) electric-arc furnaces, and (5) induction furnaces.
- Selection of the most appropriate furnace depends on :
  - The casting alloy.
  - Its melting and pouring temperatures.
  - capacity requirements of the furnace.
  - costs of investment.
  - operation, maintenance, and environmental pollution considerations.

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Foundry Practice
Furnaces

- ***Electric-Arc Furnaces***: the charge is melted by heat generated from an electric arc. Power consumption is high, but have high capacity (23,000–45,000 kg/hr). Used primarily for casting steel.

- ***Induction Furnaces***: use alternating current passing through a coil to develop a magnetic field in the metal, and the resulting induced current causes rapid heating and melting of the metal. Induction furnaces are used for nearly any casting alloy; e.g. steel, cast iron, and aluminum alloys.

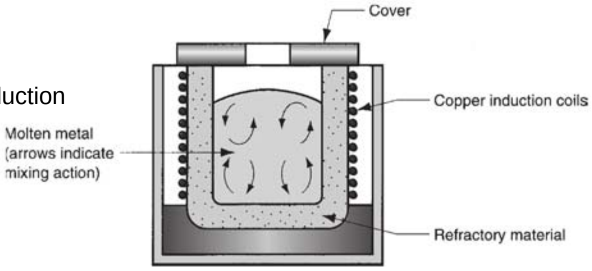

Figure 11.11 – Induction furnace.

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Foundry Practice
Pouring, Cleaning & Heat Treatment

- Moving the molten metal from the melting furnace to the mold is usually done using ladles. These ladles receive the metal from the furnace and allow for convenient pouring into the molds.

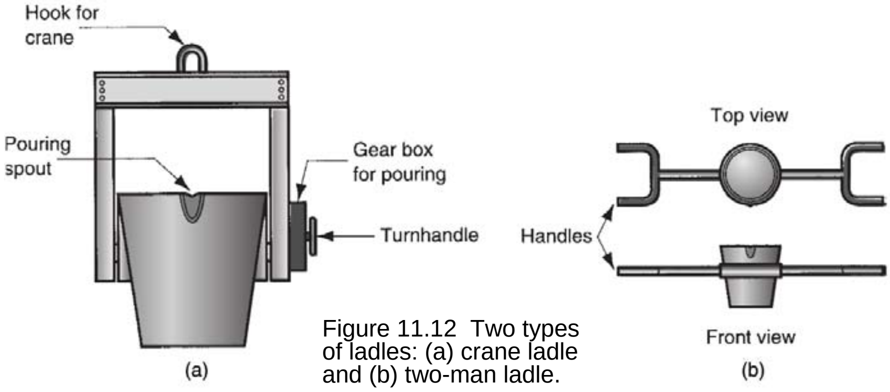

Figure 11.12 Two types of ladles: (a) crane ladle and (b) two-man ladle.

Foundry Practice
Pouring, Cleaning & Heat Treatment

- After the casting has solidified and been removed from the mold, a number of additional steps are usually required: (1) trimming, (2) removing the core, (3) surface cleaning, (4) inspection, (5) repair, if required, and (6) heat treatment. Steps (1) to (5) are referred to as “cleaning”.
- ***Trimming***: involves removal of sprues, runners, risers, parting-line flash, fins, chaplets, and any other excess metal from the cast part.
- ***Core removal***: If cores have been used to cast the part, they must be removed.

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Foundry Practice
Pouring, Cleaning & Heat Treatment

- ***Surface cleaning***: involves removal of sand from the surface of the casting and otherwise enhancing the appearance of the surface; e.g. using sand blasting.
- ***Inspection***: to detect the presence of defects, and ***repairing*** the castings if possible.
- ***Heat treatment***: often done to enhance the properties of the castings, either for subsequent processing operations such as machining or to bring out the desired properties for application of the part.

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Casting Quality

- There are numerous opportunities for things to go wrong in a casting operation, resulting in quality defects in the cast product.
- Some of the defects are common to any and all casting process. They include: *Misruns, Cold shuts, Cold shots, Shrinkage cavities, Microporosity, and Hot tearing*.
- Other defects found primarily in sand casting include: *Sand blows, Pinholes, Sand wash, Scab, Penetration, Mold shifts, Core shifts, and Mold Cracks*.

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Casting Quality

- ***Misruns***: castings that solidify before completely filling the mold cavity. Typical causes include (1) fluidity of the molten metal is insufficient, (2) pouring temperature is too low, (3) pouring is done too slowly, and/or (4) cross section of the mold cavity is too thin.

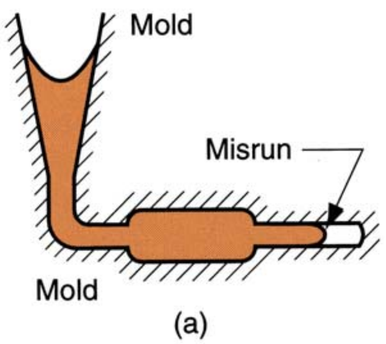

Figure 11.13 (a) Misruns.

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Casting Quality

- ***Cold shuts***: occurs when two portions of the metal flow together but there is a lack of fusion between them due to premature freezing. Its causes are similar to those of a misrun.

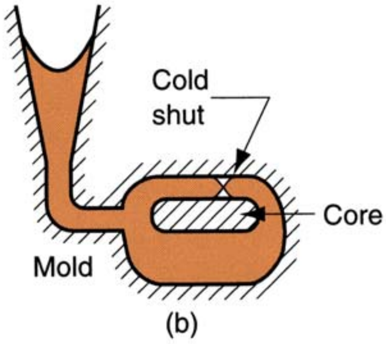

Figure 11.13 (b) Cold shuts.

Casting Quality

- ***Cold shots***: 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.

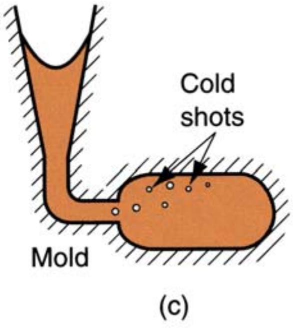

Figure 11.13 (c) Cold shots.

Casting Quality

- ***Shrinkage cavities***: is a depression in the surface or an internal void in the casting, caused by solidification shrinkage that restricts the amount of molten metal available in the last region to freeze. It often occurs near the top of the casting, in which case it is referred to as a "pipe". The problem can often be solved by proper riser design.

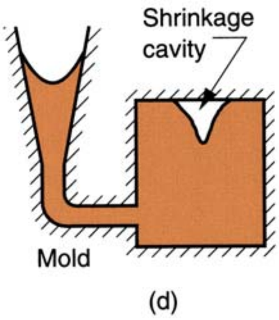

Figure 11.13 (d) Shrinkage cavities.

Casting Quality

- ***Microporosity***: consists of a network of small voids distributed throughout the casting caused by localized solidification shrinkage of the final molten metal in the dendritic structure. The defect is usually associated with alloys, because of the protracted manner in which freezing occurs in these metals (solidification over a temperature range).

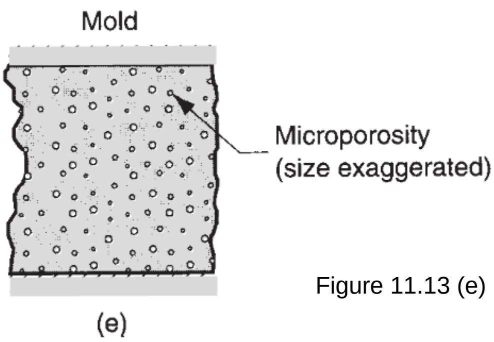

Figure 11.13 (e) Microporosity.

Casting Quality

- ***Hot tearing (hot cracking)***: occurs when the casting is restrained from contraction by an unyielding mold during the final stages of solidification or early stages of cooling after solidification. In sand-casting and other expendable-mold processes, it is prevented by compounding the mold to be collapsible. In permanent-mold processes, hot tearing is reduced by removing the part from the mold immediately after solidification.

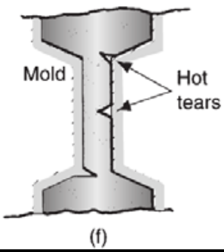

Figure 11.13 (f) Hot tearing.

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Casting Quality

- ***Sand blow***: is a defect consisting of a balloon-shaped gas cavity caused by release of mold gases during pouring. It occurs at or below the casting surface near the top of the casting. Low permeability, poor venting, and high moisture content of the sand mold are the usual causes.

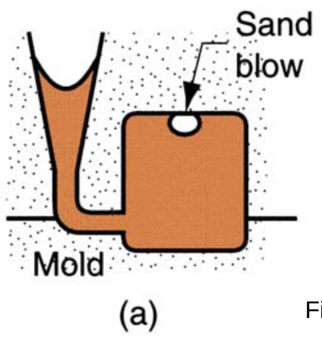

Figure 11.14 (a) Sand blow.

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Casting Quality

- ***Pinholes***: also caused by release of gases during pouring, consist of many small gas cavities formed at or slightly below the surface of the casting.

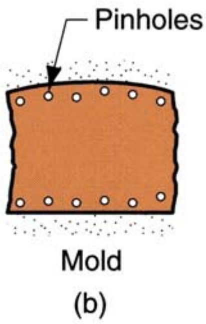

Figure 11.14 (b) Pinholes.

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Casting Quality

- ***Sand wash***: an irregularity in the surface of the casting that results from erosion of the sand mold during pouring, and the contour of the erosion is formed in the surface of the final cast part.

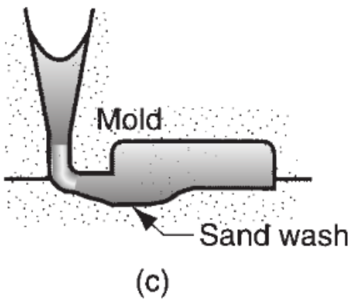

Figure 11.14 (c) Sand wash.

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Casting Quality

- ***Scabs***: are rough areas on the surface of the casting due to encrustations of sand and metal. It is caused by portions of the mold surface flaking off during solidification and becoming imbedded in the casting surface.

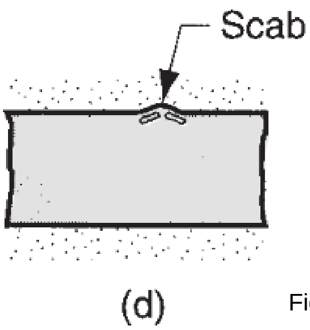

Figure 11.14 (d) Scabs. 69

Casting Quality

- ***Penetration***: refers to a surface defect that occurs when the fluidity of the liquid metal is high, and it penetrates into the sand mold or sand core. Upon freezing, the casting surface consists of a mixture of sand grains and metal. Harder packing of the sand mold helps to alleviate this condition.

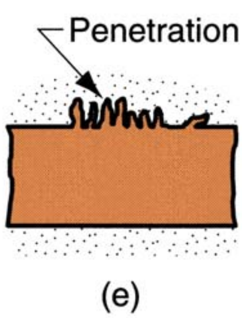

Figure 11.14 (e) Penetration. 70

Casting Quality

- ***Mold shift***: refers to a defect caused by a sidewise displacement of the mold cope relative to the drag.

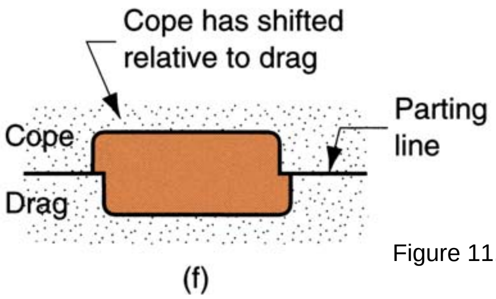

Figure 11.14 (f) Mold shift.

Casting Quality

- ***Core shift***: similar to mold shift, but it is the core that is displaced, and the displacement is usually vertical. Core shift and mold shift are caused by buoyancy of the molten metal.

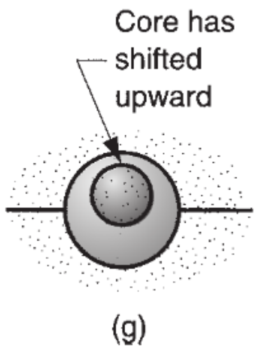

Figure 11.14 (g) Core shift.

Casting Quality

- ***Mold crack***: occurs when mold strength is insufficient, and a crack develops, into which liquid metal can seep to form a "fin" on the final casting.

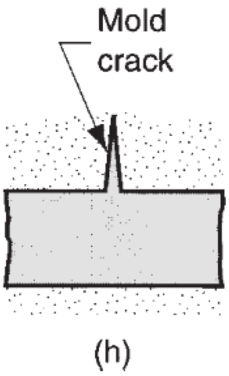

Figure 11.14 (h) Mold crack.

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Casting Quality

- Inspection methods include:
  - Visual inspection to detect defects such as misruns, cold shuts and severe surface flows.
  - Dimensional measurements to ensure that tolerances have been met.
  - Metallurgical, chemical, physical and other tests concerned with the inherent quality of the cast material.

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Metals for Casting

- Most commercial castings are made of alloys rather than pure metals.
- Alloys are generally easier to cast, and the properties of the resulting product are better.
- Casting alloys can be classified as:
  - Ferrous (steel and cast iron).
  - Nonferrous.

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Metals for Casting
Ferrous Casting Alloys

- ***Cast Iron***: is the most important of all casting alloys. The tonnage of cast iron castings is several times that of all other metals combined.
- There are several types of cast iron:
  - Gray cast iron.
  - Nodular iron.
  - White cast iron.
  - Malleable iron.
- Typical pouring temperatures for cast iron are around 1400 ºC, depending on composition.

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Metals for Casting
Ferrous Casting Alloys

- ***Steel***: the mechanical properties of steel make it an attractive engineering material, and the capability to create complex geometries makes casting an appealing process. However, great difficulties are faced by the foundry specializing in steel:
  - The melting point of steel is considerably higher than for most other metals that are commonly cast.
  - The solidification range for low-carbon steels begins at ~1540 ºC.
  - The pouring temperature required for steel is very high (1650 ºC).
  - Due to high pouring temperature, steel readily oxidizes, so special procedures must be used during melting and pouring to isolate the molten metal from air.
  - Molten steel has relatively poor fluidity, and this limits the design of thin sections in components cast out of steel.

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Metals for Casting
Ferrous Casting Alloys

- However, Several characteristics of steel castings make it worth the effort to solve these problems:
  - Tensile strength is higher than for most other casting metals, ranging upward from about 410 MPa.
  - Steel castings have better toughness than most other casting alloys.
  - The properties of steel castings are isotropic; strength is virtually the same in all directions.
  - Steel castings can be readily welded without significant loss of strength.

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Metals for Casting
Nonferrous Casting Alloys

- ***Aluminum alloys***: generally considered to be very castable.
  - The melting point of pure aluminum is 660 ºC, so pouring temperatures for Al casting alloys are low compared to cast iron and steel.
  - Their properties make them attractive for castings: light weight, wide range of strength properties attainable through heat treatment, and ease of machining.

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Metals for Casting
Nonferrous Casting Alloys

- ***Copper alloys***: include bronze (Cu–Sn), brass (Cu–Zn), and aluminum bronze.
  - Good corrosion resistance.
  - Attractive appearance.
  - Good bearing (strength) properties.
  - However, the high cost of Cu is a limitation on the use of its alloys.

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Product Design Considerations

- In casting, certain guidelines should be followed to facilitate production of the part and avoid many of the defects discussed earlier.
- These include: (1) ***Geometric Simplicity***, (2) ***Corners***, (3) ***Section Thicknesses***, (4) ***Draft***, (5) ***Use of Cores***, (6) ***Dimensional Tolerance and Surface Finishes*** and (7) ***Machining Allowances***.

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Product Design Considerations

(1) ***Geometric Simplicity***:

- Simplifying the part design will improve its castability. Avoiding unnecessary complexities simplifies mold making, reduces the need for cores, and improves the strength of the casting.

(2) ***Corners***:

- Sharp corners and angles should be avoided, because they are sources of stress concentrations and may cause hot tearing and cracks in the casting. Generous fillets should be designed on inside corners, and sharp edges should be blended.

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Product Design Considerations

(3) ***Section Thicknesses***:

- Should be uniform in order to avoid shrinkage cavities. Thicker sections create hot spots in the casting (greater volume requires more time for solidification and cooling). These are likely locations of shrinkage cavities.

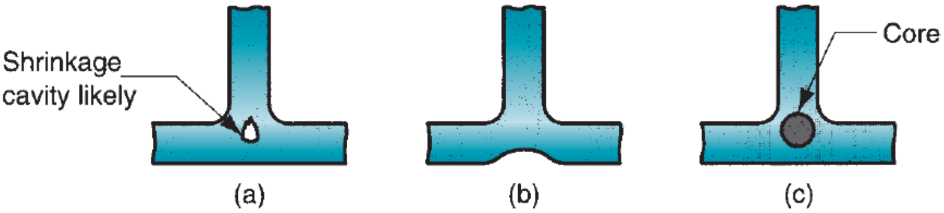

Figure 11.15 (a) Thick section at intersection can result in a shrinkage cavity. Solutions include (b) redesign to reduce thickness and (c) use of a core.

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Product Design Considerations

(4) ***Draft***:

- Drafts are created to aid in removal of the part from the mold. The required draft need only be about 1º for sand casting and 2º to 3º for permanent-mold processes.

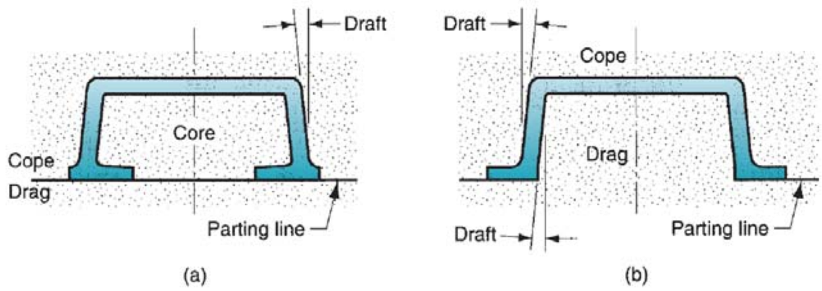

Figure 11.15 (a) Thick section at intersection can result in a shrinkage cavity. Solutions include (b) redesign to reduce thickness and (c) use of a core.

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Product Design Considerations

(5) ***Use of Cores***:

- Minor changes in part design can reduce the need for coring, as shown in Figure.

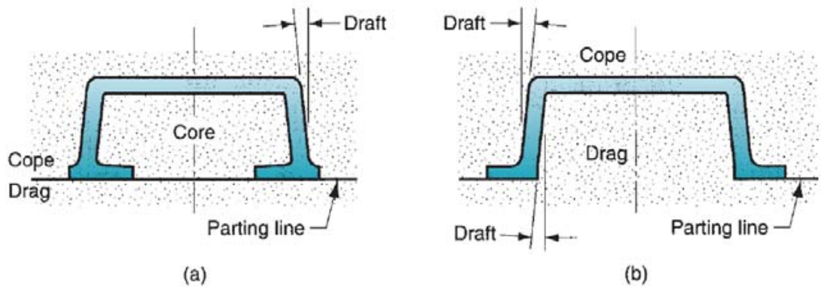

Figure 11.15 (a) Thick section at intersection can result in a shrinkage cavity. Solutions include (b) redesign to reduce thickness and (c) use of a core.

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Product Design Considerations

(6) ***Dimensional Tolerance***:

- Depending on the process, there are significant differences in the dimensional accuracies that can be achieved in castings.

TABLE 11.2 Typical dimensional tolerances for various casting processes and metals.

Casting Process	Part Size	Tolerance mm	Tolerance in	Casting Process	Part Size	Tolerance mm	Tolerance in
Sand casting				Permanent mold			
Aluminum[a]	Small	±0.5	±0.020	Aluminum[a]	Small	±0.25	±0.010
Cast iron	Small	±1.0	±0.040	Cast iron	Small	±0.8	±0.030
	Large	±1.5	±0.060	Copper alloys	Small	±0.4	±0.015
Copper alloys	Small	±0.4	±0.015	Steel	Small	±0.5	±0.020
Steel	Small	±1.3	±0.050	Die casting			
	Large	±2.0	±0.080	Aluminum[a]	Small	±0.12	±0.005
Shell molding				Copper alloys	Small	±0.12	±0.005
Aluminum[a]	Small	±0.25	±0.010	Investment			
Cast iron	Small	±0.5	±0.020	Aluminum[a]	Small	±0.12	± 0.005
Copper alloys	Small	±0.4	±0.015	Cast iron	Small	±0.25	±0.010
Steel	Small	±0.8	±0.030	Copper alloys	Small	±0.12	±0.005
Plaster mold	Small	±0.12	±0.005	Steel	Small	±0.25	±0.010
	Large	±0.4	±0.015				

Product Design Considerations

(6) ***Surface Finish***:

- Typical surface roughness achieved in sand casting is around 6 μm. Similarly poor finishes are obtained in shell molding, while plaster-mold and investment casting produce much better roughness values: 0.75 μm.

- Among the permanent-mold processes, die casting is noted for good surface finishes at around 1 μm

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Product Design Considerations

(7) ***Machining Allowances***:

- Tolerances achievable in many casting processes are insufficient to meet functional needs in many applications (sand casting is the worst). So machining is required.

- Therefore, additional material, called the machining allowance, is left on the casting for machining those surfaces where necessary. Typical machining allowances for sand castings range between 1.5 and 3 mm.

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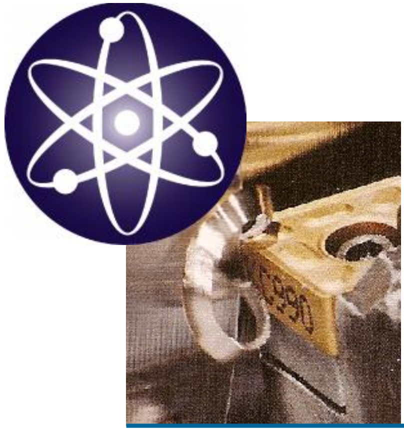

Manufacturing Processes

Chapter Twenty one:

Theory of Metal Cutting

Dr. Eng. Yazan Al-Zain
Department of Industrial Engineering

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THEORY OF METAL CUTTING

1. Overview of Machining Technology
2. Theory of Chip Formation in Metal Machining
3. Force Relationships and the Merchant Equation
4. Power and Energy Relationships in Machining
5. Cutting Temperature

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Material Removal Processes

A family of shaping operations, the common feature of which is removal of material from a starting workpart so the remaining part has the desired geometry

- Machining – material removal by a sharp cutting tool, e.g., turning, milling, drilling
- Abrasive processes – material removal by hard, abrasive particles, e.g., grinding
- Nontraditional processes - various energy forms other than sharp cutting tool to remove material

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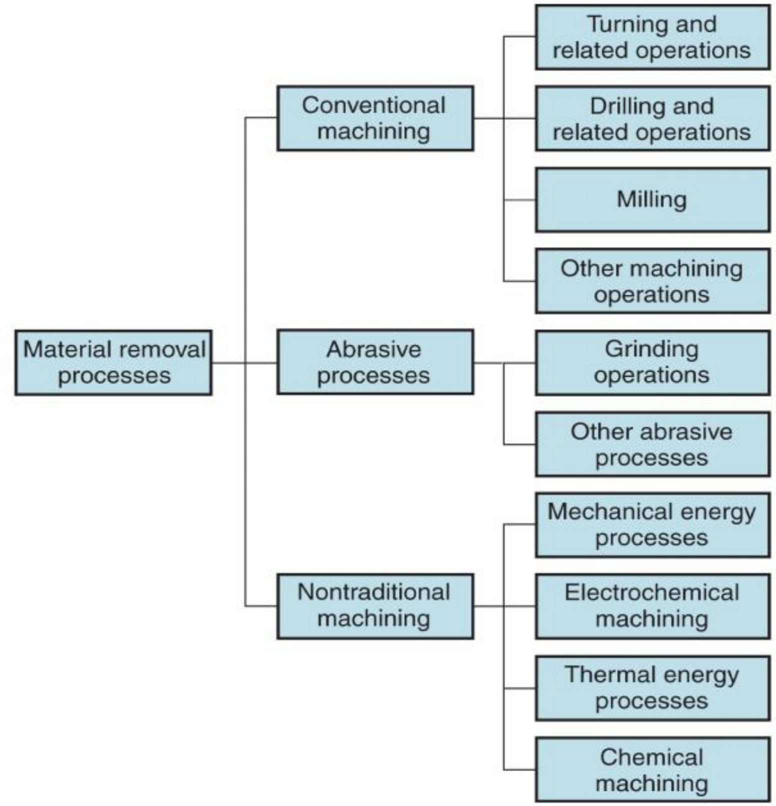
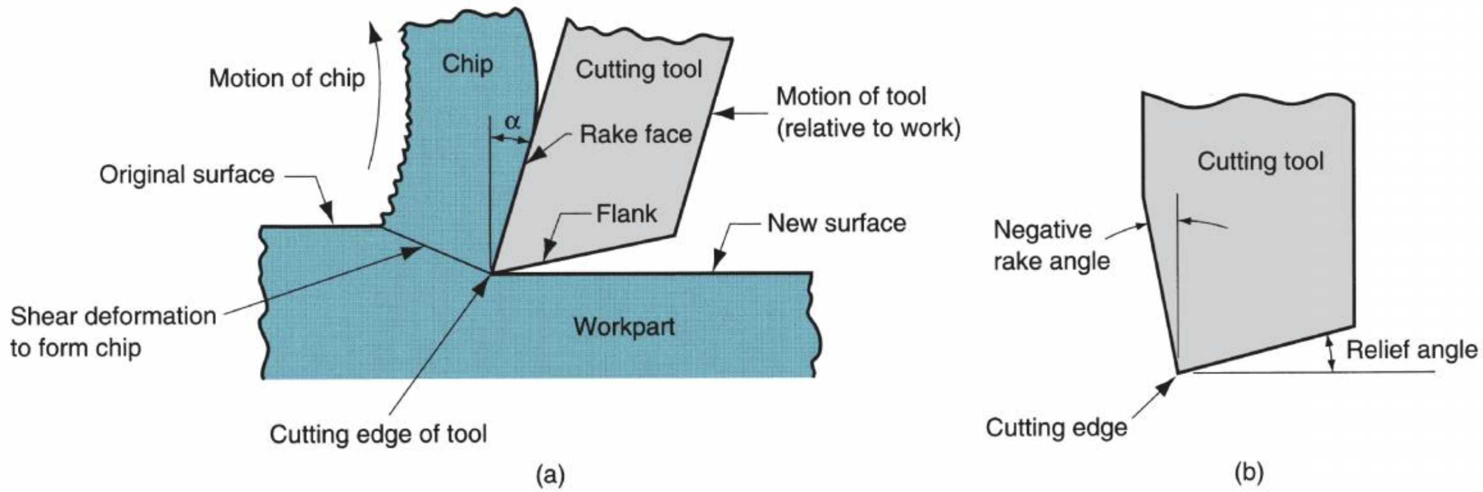
Material Removal Processes

- The family tree



Machining

- Cutting action involves shear deformation of work material to form a chip, and as chip is removed, new surface is exposed: (a) positive and (b) negative rake tools



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Why Machining is Important

- Variety of work materials can be machined
  - Most frequently used to cut metals
- Variety of part shapes and special geometric features possible:
  - Screw threads
  - Accurate round holes
  - Very straight edges and surfaces
- Good dimensional accuracy and surface finish

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Disadvantages with Machining

- Wasteful of material
  - Chips generated in machining are wasted material
    - At least in the unit operation
- Time consuming
  - A machining operation generally takes longer to shape a given part than alternative shaping processes

Machining in the Manufacturing Sequence

- Generally performed after other manufacturing processes, such as casting, forging, and bar drawing
  - Other processes create the general shape of the starting workpart
  - Machining provides the final shape, dimensions, finish, and special geometric details that other processes cannot create

Machining Operations

- Most important machining operations:
  - Turning
  - Drilling
  - Milling
- Other machining operations:
  - Shaping and planing
  - Broaching
  - Sawing

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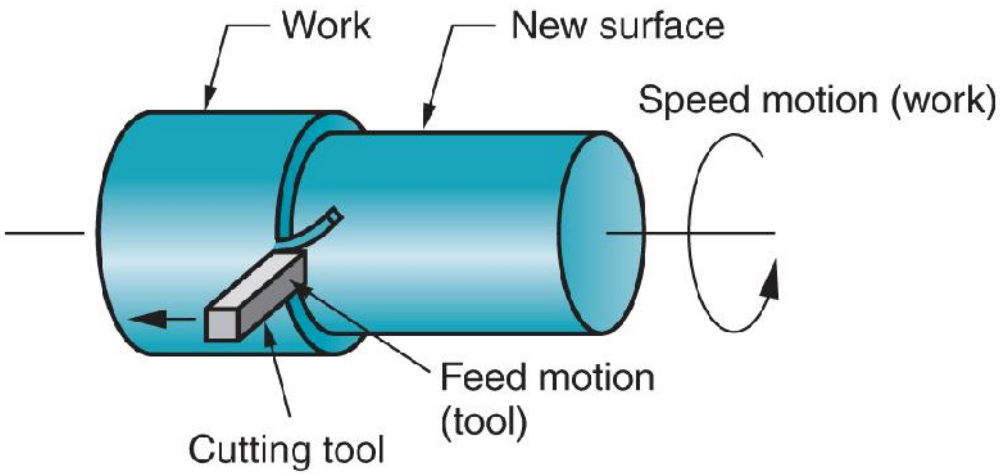
Turning

- Single point cutting tool removes material from a rotating workpiece to form a cylindrical shape



(a)

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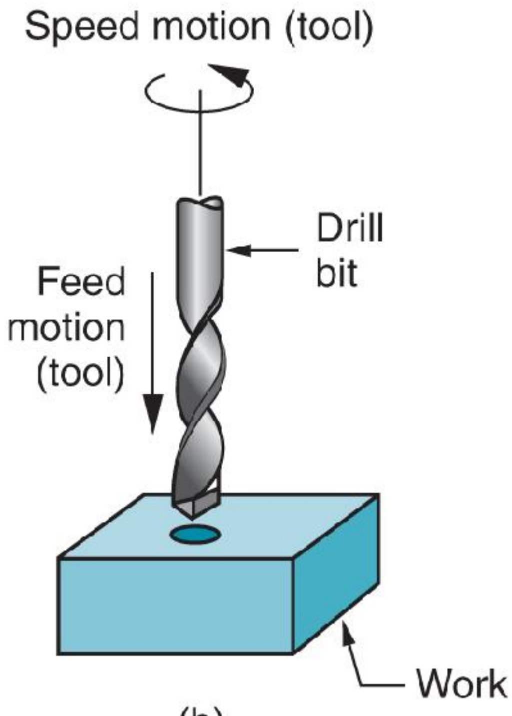
Drilling

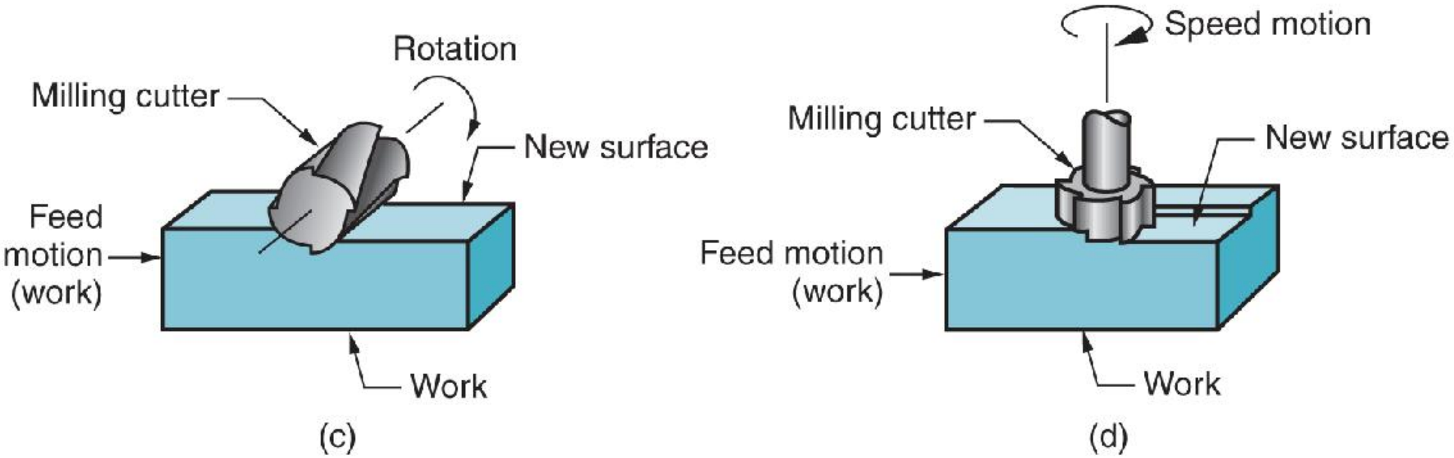
- Used to create a round hole, usually by means of a rotating tool (drill bit) with two cutting edges



(b)

Milling

- Rotating multiple-cutting-edge tool is moved across work to cut a plane or straight surface
- Two forms: (c) peripheral milling and (d) face milling



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Cutting Tool Classification

1. Single-Point Tools
   - One dominant cutting edge
   - Point is usually rounded to form a nose radius
   - Turning uses single point tools
2. Multiple Cutting Edge Tools
   - More than one cutting edge
   - Motion relative to work achieved by rotating
   - Drilling and milling use rotating multiple cutting edge tools

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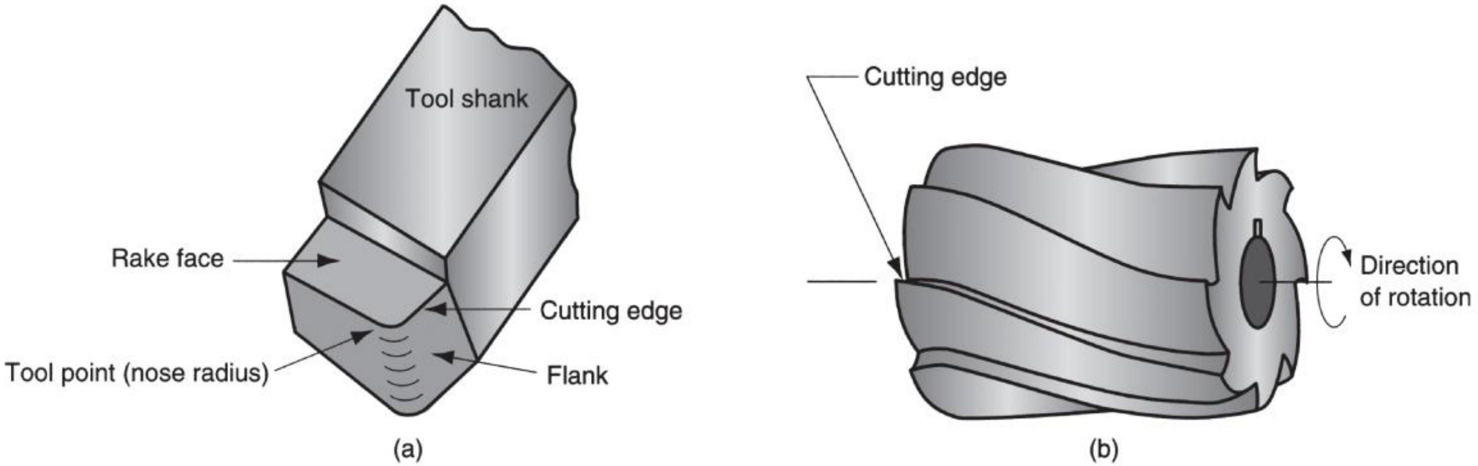
Cutting Tools

- (a) Single−point tool showing rake face, flank, and tool point; and (b) a helical milling cutter, representative of tools with multiple cutting edges



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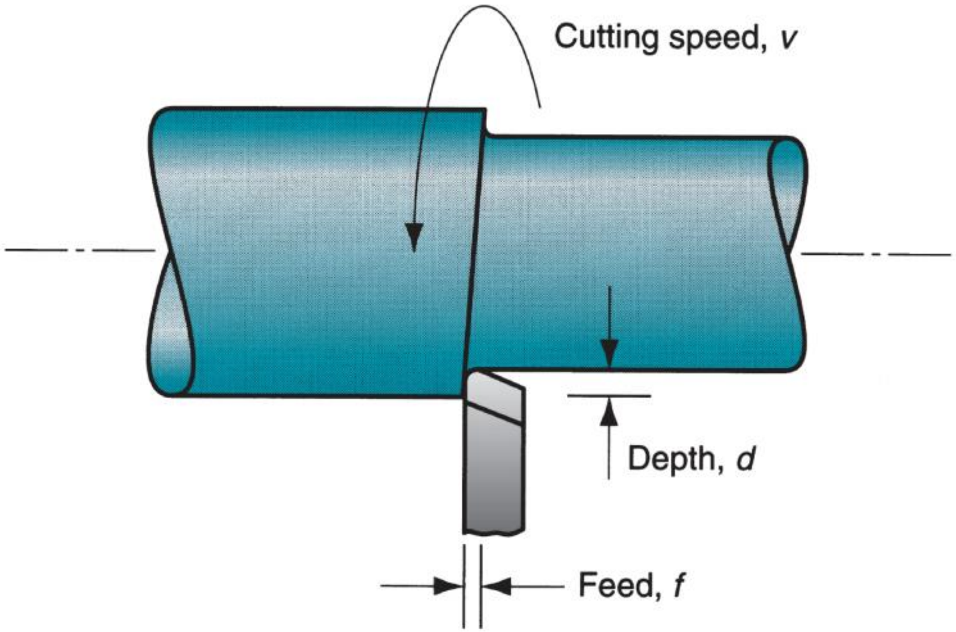
Cutting Conditions in Machining

- Three dimensions of a machining process
  - Cutting speed *v* – primary motion
  - Feed *f* – secondary motion
  - Depth of cut *d* – penetration of tool below original work surface
- For certain operations (e.g., turning), material removal rate R_{MR} can be computed as

$$R_{MR} = v\ f\ d$$

Cutting Conditions in Turning

- Speed, feed, and depth of cut in a turning operation



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Roughing vs. Finishing Cuts

- In production, several roughing cuts are usually taken on a part, followed by one or two finishing cuts
  - Roughing - removes large amounts of material from starting workpart
    - Some material remains for finish cutting
    - High feeds and depths, low speeds
  - Finishing - completes part geometry
    - Final dimensions, tolerances, and finish
    - Low feeds and depths, high cutting speeds

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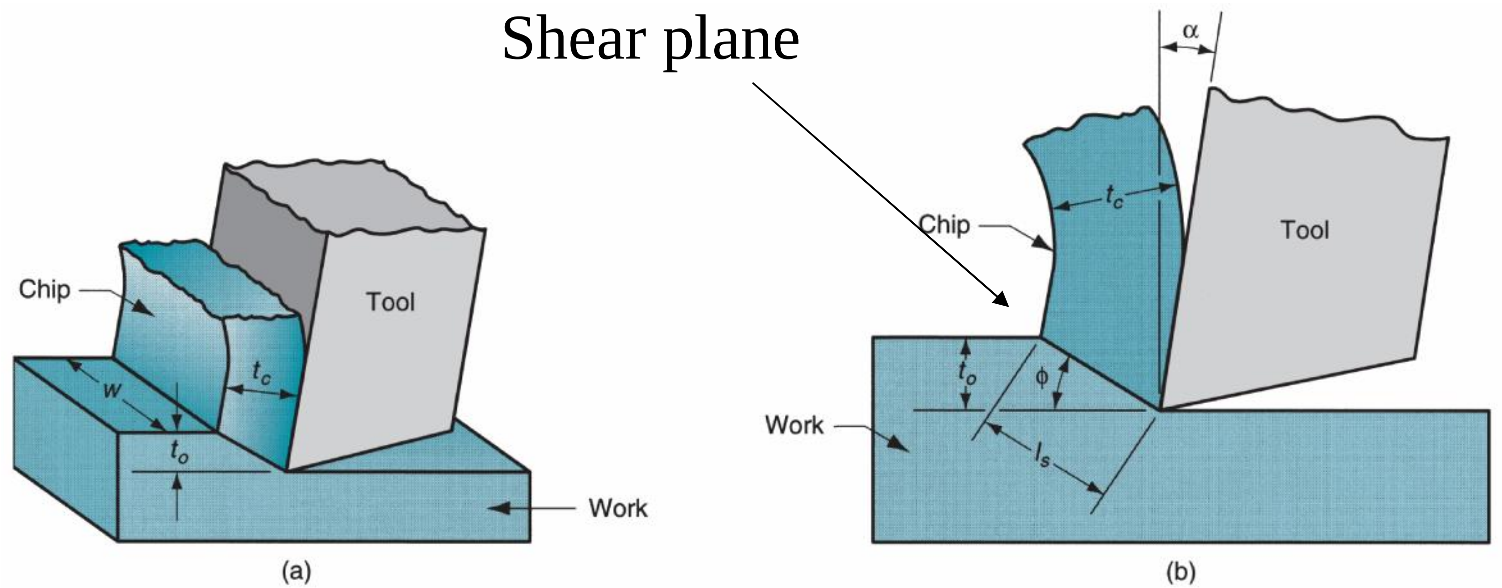
Machine Tools

A power−driven machine that performs a machining operation, including grinding

- Functions in machining:
  - Holds workpart
  - Positions tool relative to work
  - Provides power at speed, feed, and depth that have been set
- The term also applies to machines that perform metal forming operations

Orthogonal Cutting Model

- Simplified 2-D model of machining that describes the mechanics of machining fairly accurately



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Chip Thickness Ratio

$$r = \frac{t_o}{t_c}$$

where r = *chip thickness ratio*; t_o = thickness of the chip prior to chip formation; and t_c = chip thickness after separation

- Chip thickness after cut is always greater than before, so chip ratio is always less than 1.0

Determining Shear Plane Angle

- Based on the geometric parameters of the orthogonal model, the shear plane angle ¤ can be determined as:

$$\tan ¤ = \frac{r \cos \sim}{1 - r \sin \sim}$$

where r = chip ratio, and ~ = rake angle

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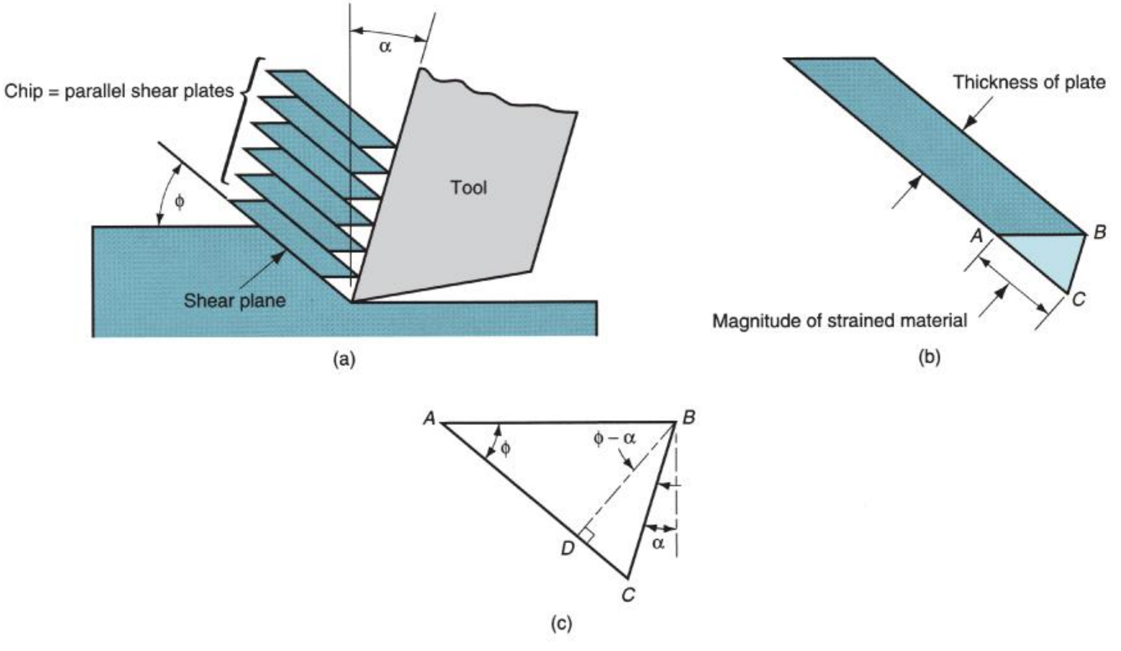
Shear Strain in Chip Formation

- (a) Chip formation depicted as a series of parallel plates sliding relative to each other, (b) one of the plates isolated to show shear strain, and (c) shear strain triangle used to derive strain equation



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Shear Strain

Shear strain in machining can be computed from the following equation, based on the preceding parallel plate model

¥ = tan(¤ - ~) + cot ¤

where ¥ = shear strain, ¤ = shear plane angle, and ~ = rake angle of cutting tool

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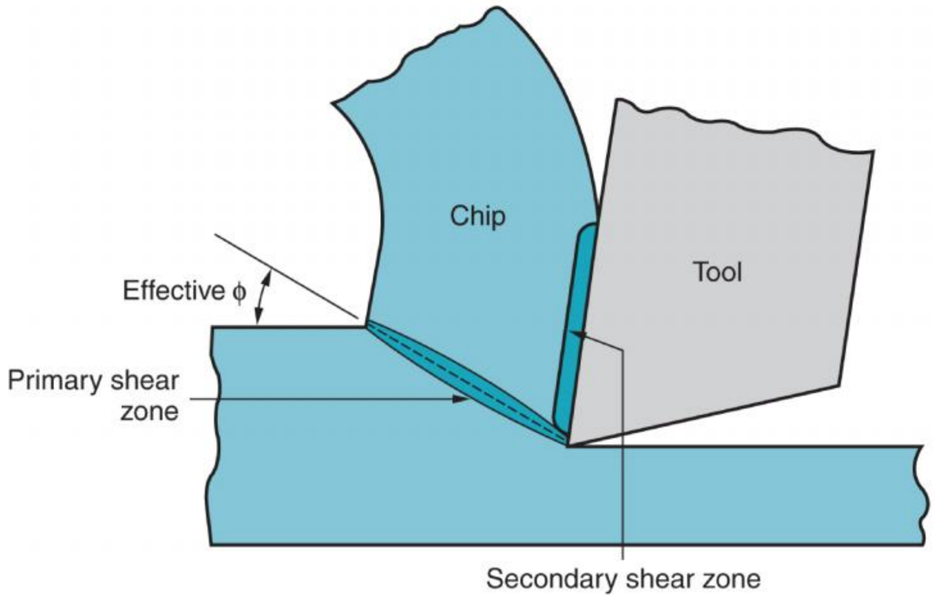
Chip Formation

- More realistic view of chip formation, showing shear zone rather than shear plane
- Also shown is the secondary shear zone resulting from tool–chip friction



Four Basic Types of Chip in Machining

1. Discontinuous chip
2. Continuous chip
3. Continuous chip with Built-up Edge (BUE)
4. Serrated chip

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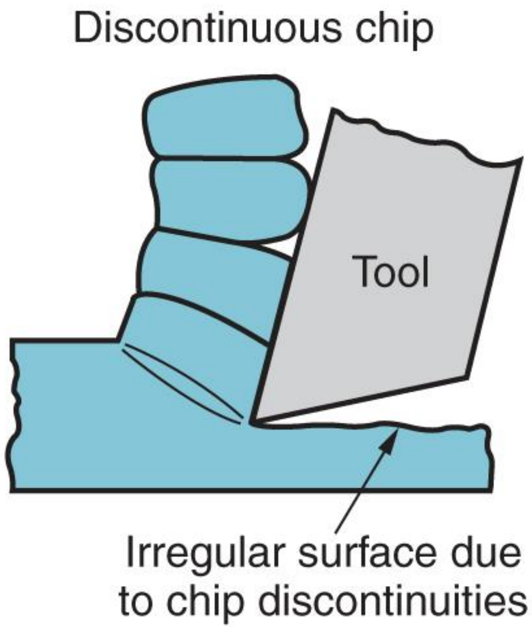
Discontinuous Chip

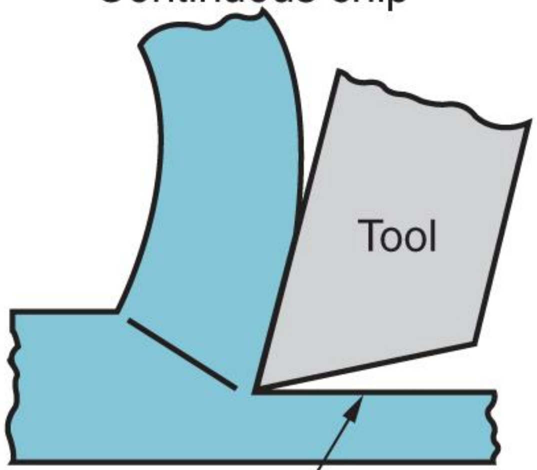
- Brittle work materials
- Low cutting speeds
- Large feed and depth of cut
- High tool−chip friction



(a)

Continuous Chip

- Ductile work materials
- High cutting speeds
- Small feeds and depths
- Sharp cutting edge
- Low tool–chip friction



(b)

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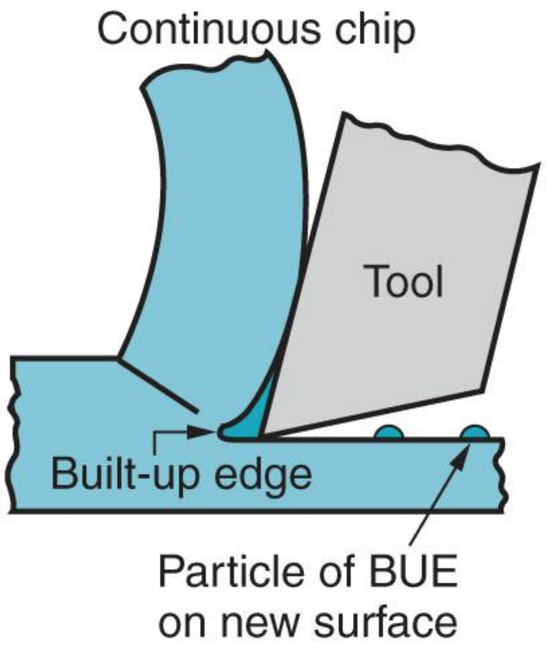
Continuous with BUE

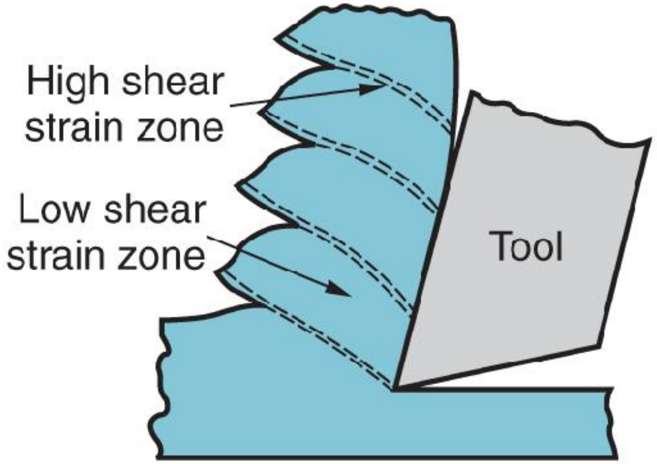
- Ductile materials
- Low−to−medium cutting speeds
- Tool-chip friction causes portions of chip to adhere to rake face
- BUE forms, then breaks off, cyclically



(c)

Serrated Chip

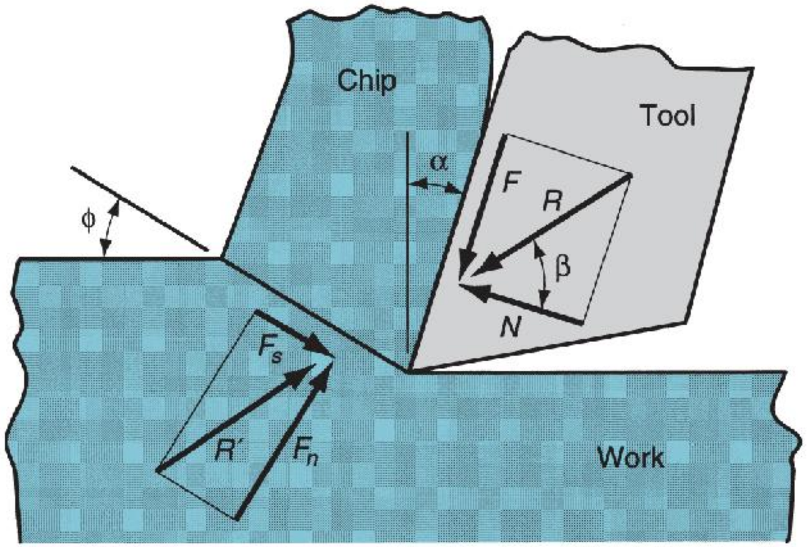
- Semicontinuous - saw-tooth appearance
- Cyclical chip forms with alternating high shear strain then low shear strain
- Associated with difficult-to-machine metals at high cutting speeds



(d)

Forces Acting on Chip

- (a) Friction force *F* and Normal force to friction *N*
- (b) Shear force F_s and Normal force to shear F_n



(a)

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Resultant Forces

- Vector addition of *F* and *N* = resultant *R*
- Vector addition of F_s and F_n = resultant *R*’
- Forces acting on the chip must be in balance:
  - *R*’ must be equal in magnitude to *R*
  - *R*’ must be opposite in direction to *R*
  - *R*’ must be collinear with *R*

Coefficient of Friction

- Coefficient of friction between tool and chip

$$\text{«} = \frac{F}{N}$$

- Friction angle related to coefficient of friction as

$$\text{«} = \tan$$

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Shear Stress

- Shear stress acting along the shear plane

$$S = \frac{F_s}{A_s}$$

where A_s = area of the shear plane

$$A_s = \frac{t_o w}{\sin\phi}$$

- Shear stress = shear strength of work material during cutting

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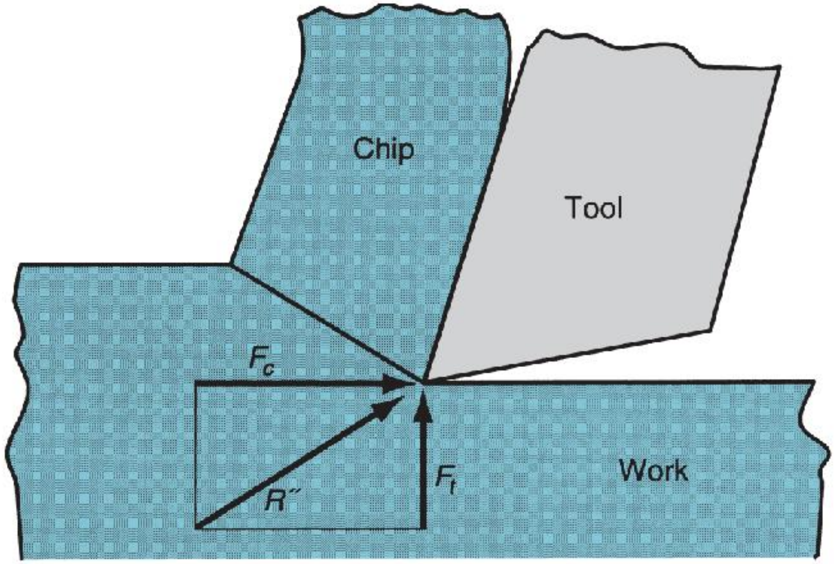
Cutting Force and Thrust Force

- F, N, F_s, and F_n cannot be directly measured
- Forces acting on the tool that can be measured: Cutting force F_c and Thrust force F_t



(b)

Forces in Metal Cutting

- Equations to relate the forces that cannot be measured to the forces that can be measured:

$$F = F_c \sin\sim + F_t \cos\sim$$

$$N = F_c \cos\sim - F_t \sin\sim$$

$$F_s = F_c \cos\text{¤} - F_t \sin\text{¤}$$

$$F_n = F_c \sin\text{¤} + F_t \cos\text{¤}$$

- Based on these calculated force, shear stress and coefficient of friction can be determined

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The Merchant Equation

- Of all the possible angles at which shear deformation can occur, the work material will select a shear plane angle ¤ that minimizes energy

$$¤ = 45 + \frac{\sim}{2} - \frac{\quad}{2}$$

- Derived by Eugene Merchant
- Based on orthogonal cutting, but validity extends to 3-D machining

What the Merchant Equation Tells Us

$$\text{¤} = 45 + \frac{\sim}{2} - \frac{\;}{2}$$

- To increase shear plane angle
  - Increase the rake angle
  - Reduce the friction angle (or reduce the coefficient of friction)

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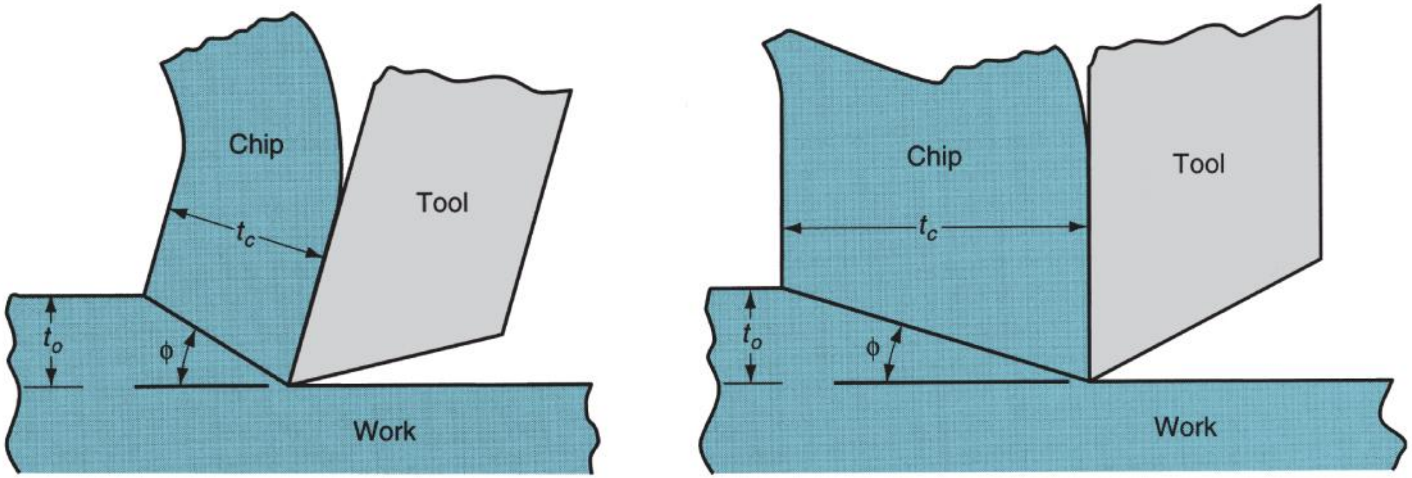
Effect of Higher Shear Plane Angle

- Higher shear plane angle means smaller shear plane which means lower shear force, cutting forces, power, and temperature



(a) (b)

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Power and Energy Relationships

- A machining operation requires power
- The power to perform machining can be computed from:

$$P_c = F_c v$$

where P_c = cutting power; F_c = cutting force; and v = cutting speed

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Power and Energy Relationships

- In U.S. customary units, power is traditionally expressed as horsepower (dividing ft−lb/min by 33,000)

$$HP_c = \frac{F_c v}{33{,}000}$$

where HP_c = cutting horsepower, hp

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Power and Energy Relationships

- Gross power to operate the machine tool P_g or HP_g is given by

$$P_g = \frac{P_c}{E} \quad \text{or} \quad HP_g = \frac{HP_c}{E}$$

where E = mechanical efficiency of machine tool

- Typical E for machine tools $\sim$ 90%

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Unit Power in Machining

- Useful to convert power into power per unit volume rate of metal cut
- Called *unit power*, P_u or *unit horsepower*, HP_u

$$P_U = \frac{P_c}{R_{MR}} \quad \text{or} \quad HP_u = \frac{HP_c}{R_{MR}}$$

where R_{MR} = material removal rate

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Specific Energy in Machining

- Unit power is also known as the *specific energy U*

$$U = P_u = \frac{P_c}{R_{MR}} = \frac{F_c v}{v t_o w}$$

where units for specific energy are typically N−m/mm^3 or J/mm^3 (in−lb/in^3)

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Cutting Temperature

- Approximately 98% of the energy in machining is converted into heat
- This can cause temperatures to be very high at the tool‑chip
- The remaining energy (about 2%) is retained as elastic energy in the chip

Cutting Temperatures are Important

High cutting temperatures

1. Reduce tool life
2. Produce hot chips that pose safety hazards to the machine operator
3. Can cause inaccuracies in part dimensions due to thermal expansion of work material

Cutting Temperature

- Analytical method derived by Nathan Cook from dimensional analysis using experimental data for various work materials

$$T = \frac{0.4U}{\rho C}\left(\frac{vt_o}{K}\right)^{0.333}$$

where T = temperature rise at tool−chip interface; U = specific energy; v = cutting speed; t_o = chip thickness before cut; ρC = volumetric specific heat of work material; K = thermal diffusivity of work material

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Cutting Temperature

- Experimental methods can be used to measure temperatures in machining
  - Most frequently used technique is the *tool−chip thermocouple*
- Using this method, Ken Trigger determined the speed−temperature relationship to be of the form:

$$T = K v^m$$

where T = measured tool−chip interface temperature, and v = cutting speed

Manufacturing Processes

Chapters Nineteen:

Bulk Deformation Processes in Metal Working

Dr. Eng. Yazan Al-Zain
Department of Industrial Engineering

Introduction

- Bulk deformation processes in metal working include:
  - Rolling.
  - Other deformation processes related to rolling.
  - Forging.
  - Other deformation processes related to forging.
  - Extrusion.
  - Wire and Bar Drawing.

Introduction

- Bulk deformation processes accomplish significant shape change in metal parts whose initial form is bulk rather than sheet.
- The starting forms include (1) cylindrical bars and billets, (2) rectangular billets and slabs, and (3) similar elementary geometries.
- The bulk deformation processes **refine the starting shapes**, sometimes improving mechanical properties, and **always** adding commercial value.
- Deformation processes work by **stressing** the metal sufficiently to cause it to plastically flow into the desired shape.

Introduction

- Bulk deformation processes are performed as (1) cold, (2) warm, and (3) hot working operations.

- Cold and warm working is appropriate when the shape change is less severe, and there is a need to improve mechanical properties and achieve good finish on the part.

- Hot working is generally required when massive deformation of large workparts is involved.

Introduction

- The commercial and technological importance of bulk deformation processes derives from the following:
  - When performed as hot working operations, they can achieve significant change in the shape of the workpart.
  - When performed as cold working operations, they can be used not only to shape the product, but also to increase its strength through strain hardening.
  - These processes produce little or no waste as a byproduct of the operation. Some bulk deformation operations are near net shape or net shape processes; they achieve final product geometry with little or no subsequent machining.

Rolling

- ***Rolling***: is a deformation process in which the thickness of the work is reduced by compressive forces exerted by two opposing rolls.

- The rolls rotate to pull and simultaneously squeeze the workpart between them.

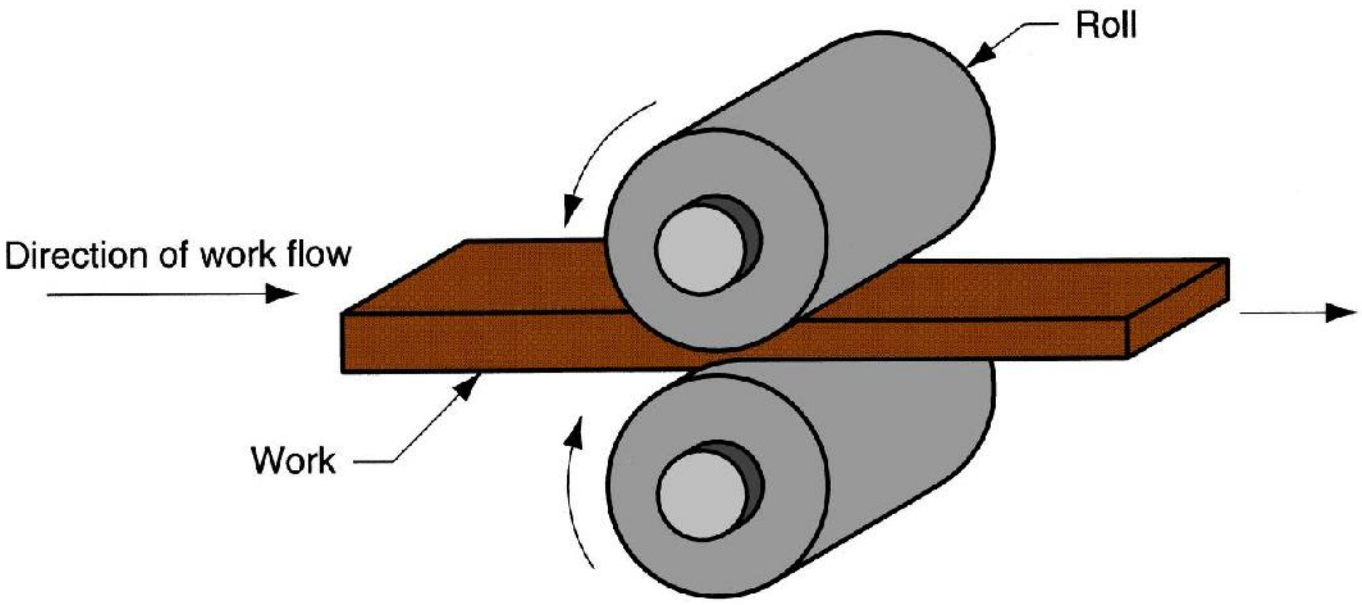


Figure 19.1 The rolling process (specifically, flat rolling).

Rolling

- According to the part geometry, the rolling processes can be divided into:
  - ***Flat rolling***: used to reduce the thickness of a rectangular cross section.
  - ***Shape rolling***: related to flat rolling, in which a square cross section is formed into a shape such as an I-beam.

Rolling

- Rolling can be carried out at high or low (ambient) temperatures.
  - ***Hot rolling***: most rolling is carried out by hot working, due to the large amount of deformation required.
  - Hot-rolled metal is generally free of residual stresses, and its properties are isotropic (similar properties in different directions).
  - Disadvantages of hot rolling are that the product cannot be held to close tolerances, and the surface has a characteristic oxide scale.

Rolling

- Rolling can be carried out at high or low (ambient) temperatures.
  - ***Cold rolling***: less common than hot rolling.
  - Cold rolling strengthens the metal and permits a tighter tolerance on thickness.
  - the surface of the cold-rolled sheet is absent of scale and generally superior to the corresponding hot-rolled product.

Rolling

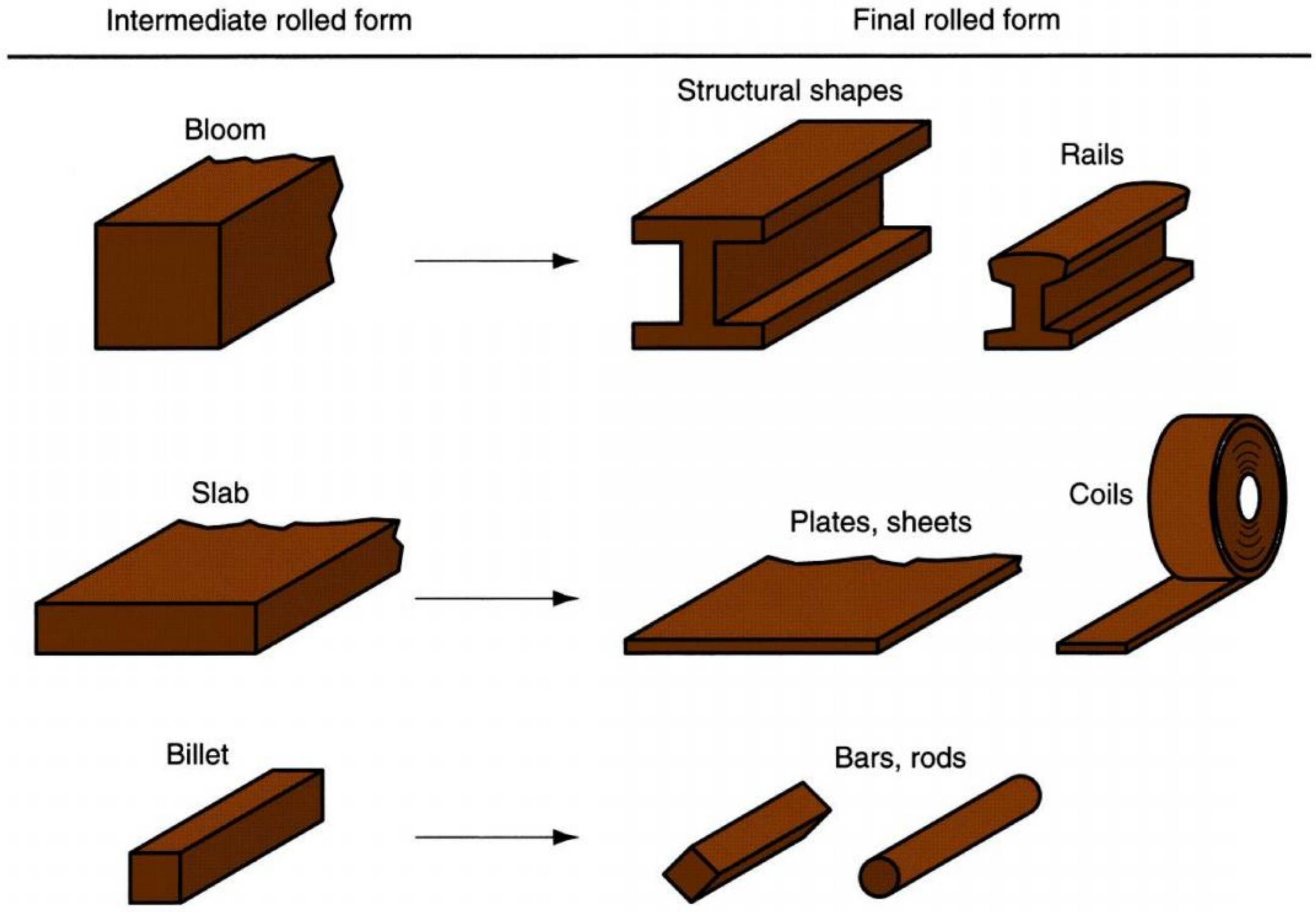


Figure 19.2 Some of the steel products made in a rolling mill.

Rolling
Flat Rolling and Its Analysis

- Flat rolling involves the rolling of workparts of rectangular cross section in which the width is greater than the thickness; e.g. slabs, strips, sheets and plates.

- ***Draft*** is amount of thickness reduction and described as:

$$d = t_0 - t_f$$

where d = draft, mm; t_0 = starting thickness, mm; and t_f = final thickness, mm.

- Draft is sometimes expressed as a fraction of the starting stock thickness, called the ***Reduction*** (r):

$$r = \frac{d}{t_0}$$

Rolling
Flat Rolling and Its Analysis

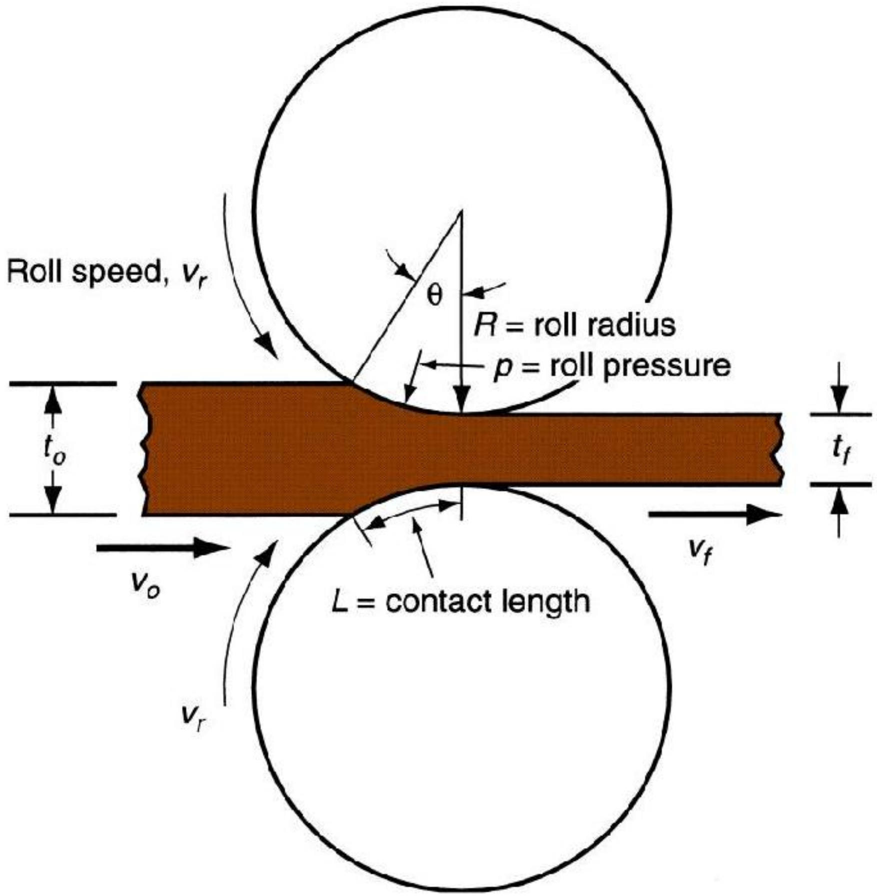


Figure 19.3 Side view of flat rolling, indicating before and after thicknesses, work velocities, angle of contact with rolls, and other features.

Rolling
Flat Rolling and Its Analysis

- ***Spreading***: the increase in width due to rolling, described as:

$$t_o w_o L_o = t_f w_f L_f$$

where w_o and w_f are the before and after work widths, mm; and L_o and L_f are the before and after work lengths, mm.

- Similarly, before and after volume rates of material flow must be the same, so the before and after velocities can be related:

$$t_o w_o v_o = t_f w_f v_f$$

where v_o and v_f are the entering and exiting velocities of the work.

Rolling
Flat Rolling and Its Analysis

- True strain is expressed by:

$$£ = \ln \frac{t_o}{t_f}$$

- The true strain can be used to determine the average flow stress $\overline{Y_f}$ (MPa) applied to the work material in flat rolling:

$$\overline{Y_f} = \frac{K£^n}{1+n}$$

The average flow stress is used to compute estimates of force and power in rolling.

Rolling
Flat Rolling and Its Analysis

- There is a limit to the maximum possible draft that can be accomplished in flat rolling with a given coefficient of friction, defined by:

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

where d_{max} = maximum draft, mm; μ = coefficient of friction; and R = roll radius, mm.

- Rolling force (F, N) can be expressed as:

$$F = \overline{Y}_f wL$$

- Contact length (L, mm) is described as:

$$L = \sqrt{R(t_o - t_f)}$$

- The torque (T) and the power required to drive each roll (P, J/s) are:

$$T = 0.5FL \quad \text{and} \quad P = 2\pi NFL$$

where P = power, J/s or W; N = rotational speed, 1/s; F = rolling force, N; and L = contact length, m.

Rolling
Shape Rolling

- In shape rolling, the work is deformed into a contoured cross section.
- Products include construction shapes such as I-beams, L-beams, and U-channels; rails for railroad tracks; and round and square bars and rods.
- The process is accomplished by passing the work through rolls that have the reverse of the desired shape.
- 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, requires a gradual transformation through several rolls in order to achieve the final cross section.

Rolling
Rolling Mills

- Rolling mill configurations:
  - ***Two-high***: consists of two opposing rolls, and the configuration can be either reversing or nonreversing.

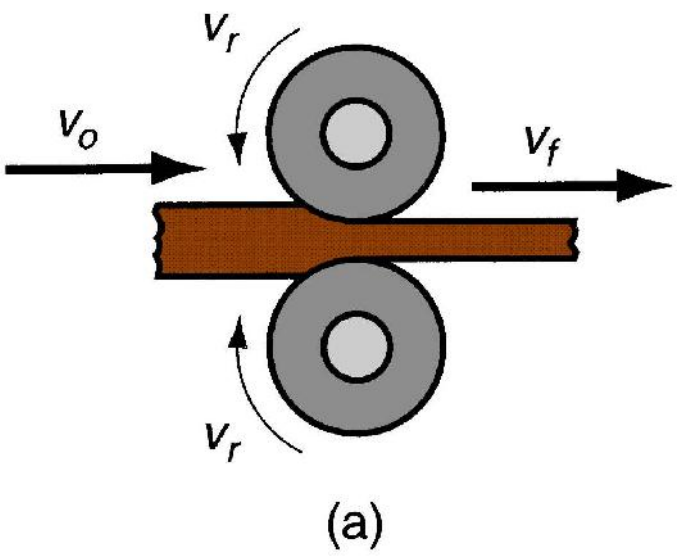


Figure 19.4 Various configurations of rolling mills: (a) two-high rolling mill.

Rolling
Rolling Mills

- Rolling mill configurations:
  - ***Three-high***: three rolls in a vertical column, and the direction of rotation of each roll remains unchanged.

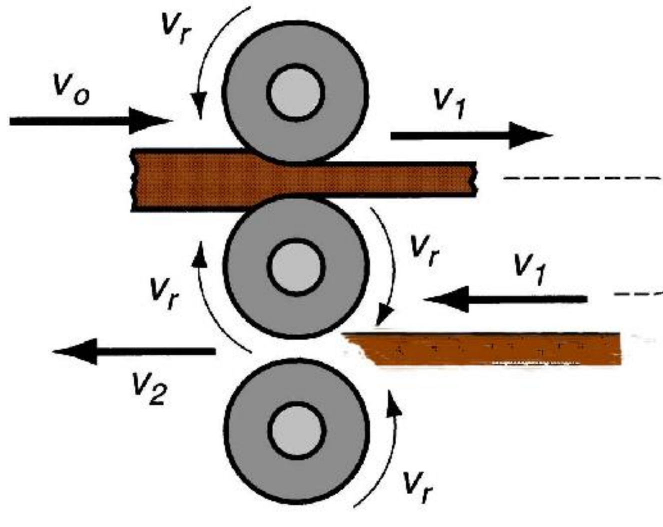


Figure 19.4 Various configurations of rolling mills: (b) three-high rolling mill.

Rolling
Rolling Mills

- Rolling mill configurations:
  - ***Four-high***: uses two smaller-diameter rolls to contact the work and two backing rolls behind them.

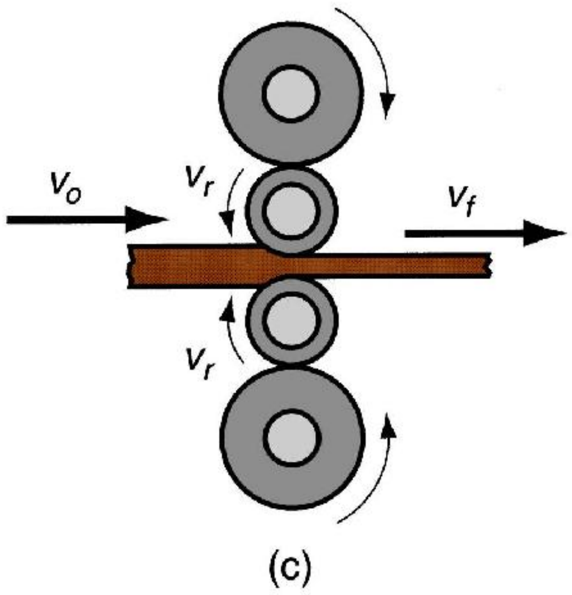


Figure 19.4 Various configurations of rolling mills: (c) four-high rolling mill.

Rolling
Rolling Mills

- Rolling mill configurations:

  - ***Cluster mill***: roll configuration that allows smaller working rolls against the work (smaller than in four-high mills).

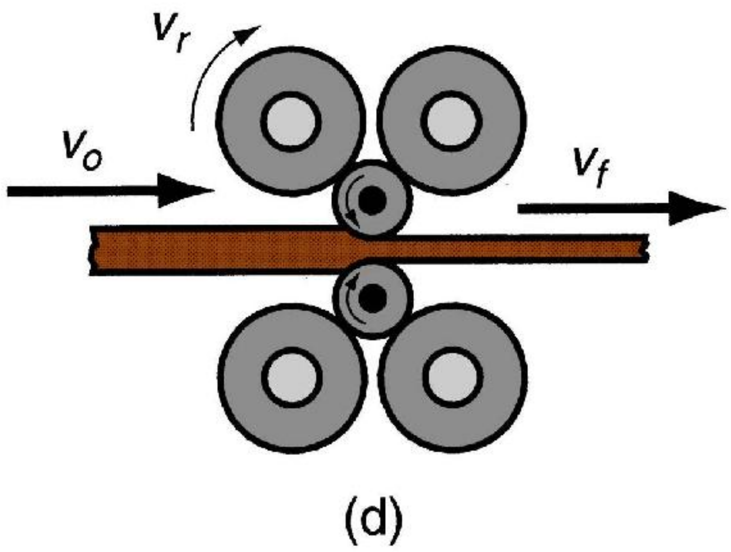


Figure 19.4 Various configurations of rolling mills: (d) cluster mill.

Rolling
Rolling Mills

- Rolling mill configurations:
  - ***Tandem rolling mill*** : consists of a series of rolling stands, aimed at higher throughput rates.

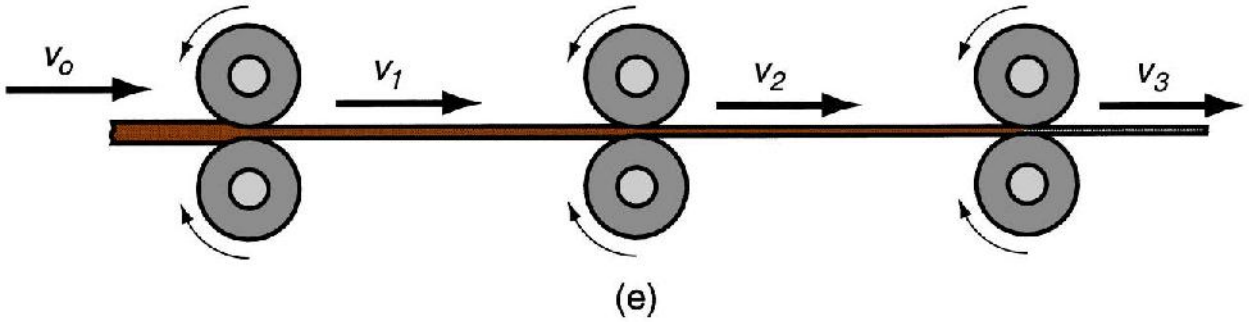


Figure 19.4 Various configurations of rolling mills: (e) tandem rolling mill.

Other Deformation Processes Related to Rolling

- ***Thread Rolling***:
  - Used to form threads on cylindrical parts by rolling them between two dies.
  - The most important commercial process for mass producing external threaded components.
  - Performed by cold working in thread rolling machines. These are equipped with special dies that determine the size and form of the thread.
  - Advantages of thread rolling over thread cutting and rolling include:
    - Higher production rates.
    - Better material utilization.
    - Smoother surface.
    - Stronger threads and better fatigue resistance due to work hardening.

Other Deformation Processes Related to Rolling

- ***Thread Rolling***:

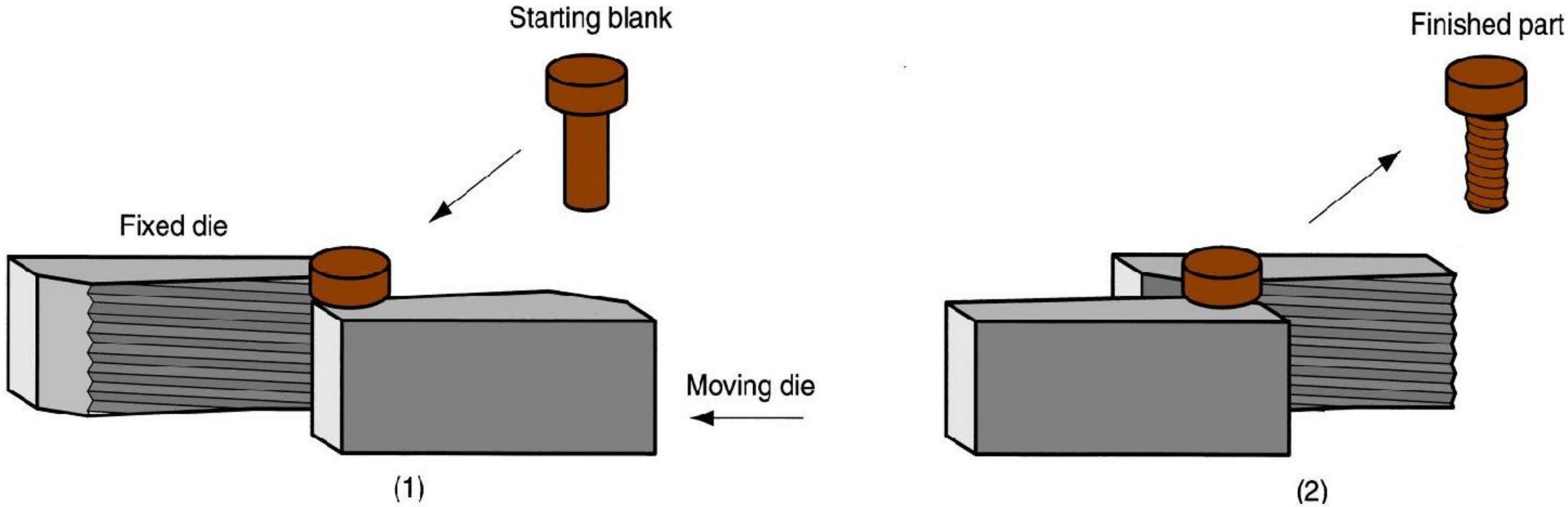


Figure 19.5 Thread rolling with flat dies: (1) start, and (2) end of cycle.

Other Deformation Processes Related to Rolling

- ***Ring Rolling***: a deformation process in which a thick-walled ring of smaller diameter is rolled into a thin-walled ring of larger diameter.
  - As the thick-walled ring is compressed, the deformed material elongates, causing the diameter of the ring to be enlarged.

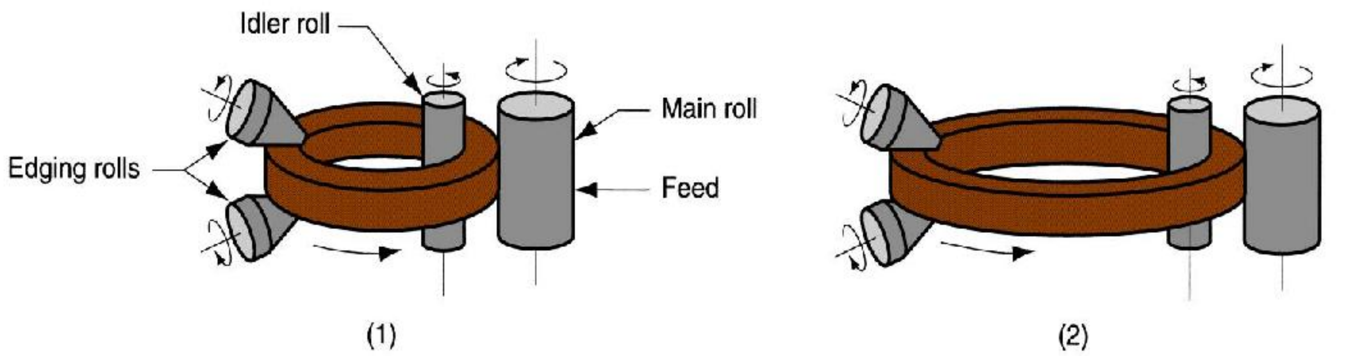


Figure 19.6 Ring rolling used to reduce the wall thickness and increase the diameter of a ring: (1) start, and (2) completion of process.

Other Deformation Processes Related to Rolling

- ***Ring Rolling***:
  - Usually performed as a hot-working process for large rings and as a cold-working process for smaller rings.
  - Applications include ball and roller bearing races, steel tires for railroad wheels, and rings for pipes, pressure vessels, and rotating machinery.
  - Advantages over processes producing similar products include: (1) raw material savings, (2) ideal grain orientation for the application, and (3) strengthening through cold working.

Other Deformation Processes Related to Rolling

- ***Roll Piercing***: a specialized hot working process for making seamless thick-walled tubes.
  - Based on the principle that when a solid cylindrical part is compressed on its circumference, high tensile stresses are developed at its center. <u>If compression is high enough, an internal crack is formed</u>.
  - Compressive stresses on a solid cylindrical billet are applied by two rolls, whose axes are oriented at slight angles (6º) from the axis of the billet, so that their rotation tends to pull the billet through the rolls. A mandrel is used to control the size and finish of the hole created by the action.

Other Deformation Processes Related to Rolling

- ***Roll Piercing***:

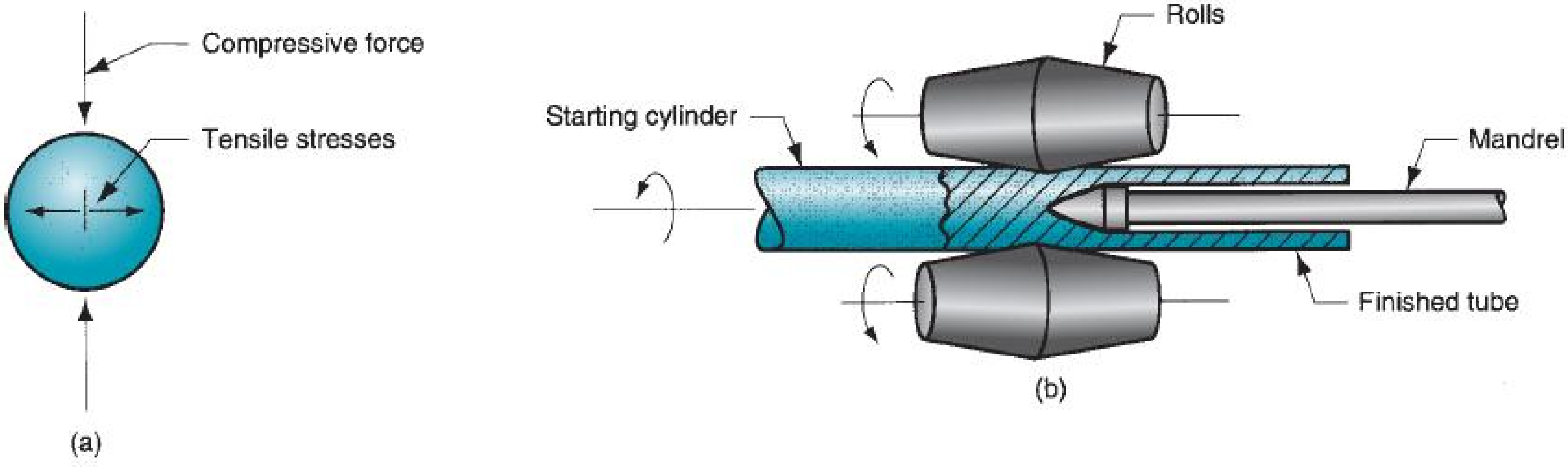


Figure 19.7 Roll piercing: (a) formation of internal stresses and cavity by compression of cylindrical part; and (b) setup of Mannesmann roll mill for producing seamless tubing.

Forging

- ***Forging***: a deformation process in which the work is compressed between two dies, using either impact or gradual pressure to form the part.
  - Dates back to perhaps 5000 BCE.
  - Today, forging is an important industrial process used to make a variety of high-strength components for automotive, aerospace, and other applications.
  - These components include engine crankshafts and connecting rods, gears, aircraft structural components, and jet engine turbine parts.
  - In addition, steel and other basic metals industries use forging to establish the basic form of large components that are subsequently machined to final shape and dimensions.

Forging

- Forging can be classified in many ways, one is working temperature.
  - ***Hot*** or ***warm forging***: done when significant deformation is demanded by the process and when strength reduction and increase of ductility is required.
  - ***Cold forging***: its advantage is the increased strength that results from strain hardening of the component.
- The other way is by the way the forging is carried out:
  - ***Forging hammer***: a forging machine that applies an impact load.
  - ***Forging press***: a forging machine that applies gradual load.

Forging

- Forging can be also classified according to the degree to which the flow of the work metal is constrained by the dies.
  - ***Open-die forging***: the work is compressed between two flat dies, thus allowing the metal to flow without constraint in a lateral direction relative to the die surfaces.
  - ***Impression-die forging***: the die surfaces contain a shape or impression that is imparted to the work during compression, thus constraining metal flow to a significant degree. Here, flash will form.
  - ***Flashless forging***: the work is completely constrained within the die and no excess flash is produced.

Forging

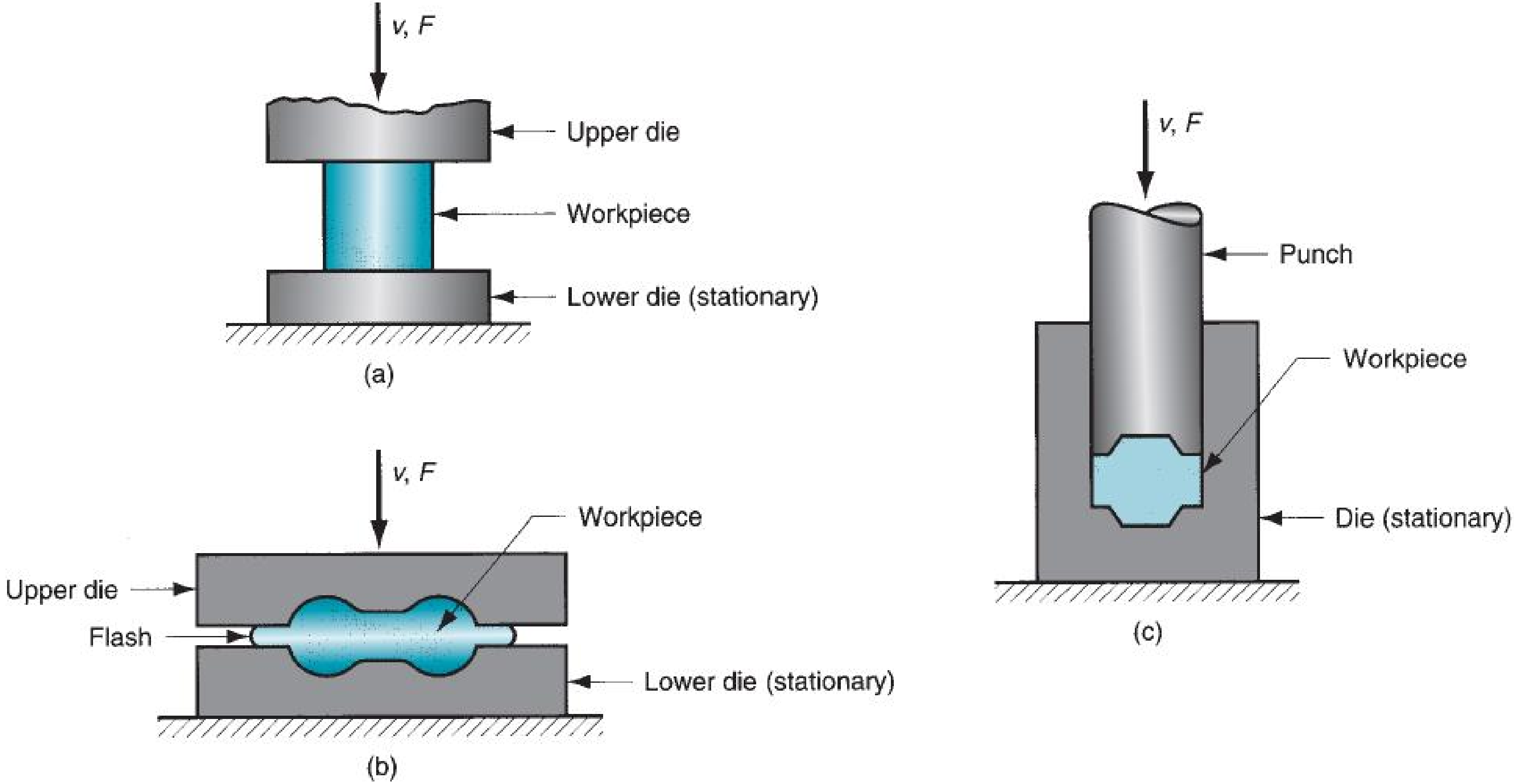


Figure 19.8 Three types of forging operation: (a) open-die forging, (b) impression-die forging, and (c) flashless forging.

Forging
Open-Die Forging

- Known as ***upsetting*** or ***upset forging***.

- Involves compression of a workpart of cylindrical cross section between two flat dies, much in the manner of a compression test.

- It reduces the height of the work and increases the diameter.

Forging
Open-Die Forging

- Analysis of Open-Die Forging:
  - If carried out under ideal conditions of no friction between work and die surfaces, then homogeneous deformation occurs, and the flow of the material is uniform throughout its height.

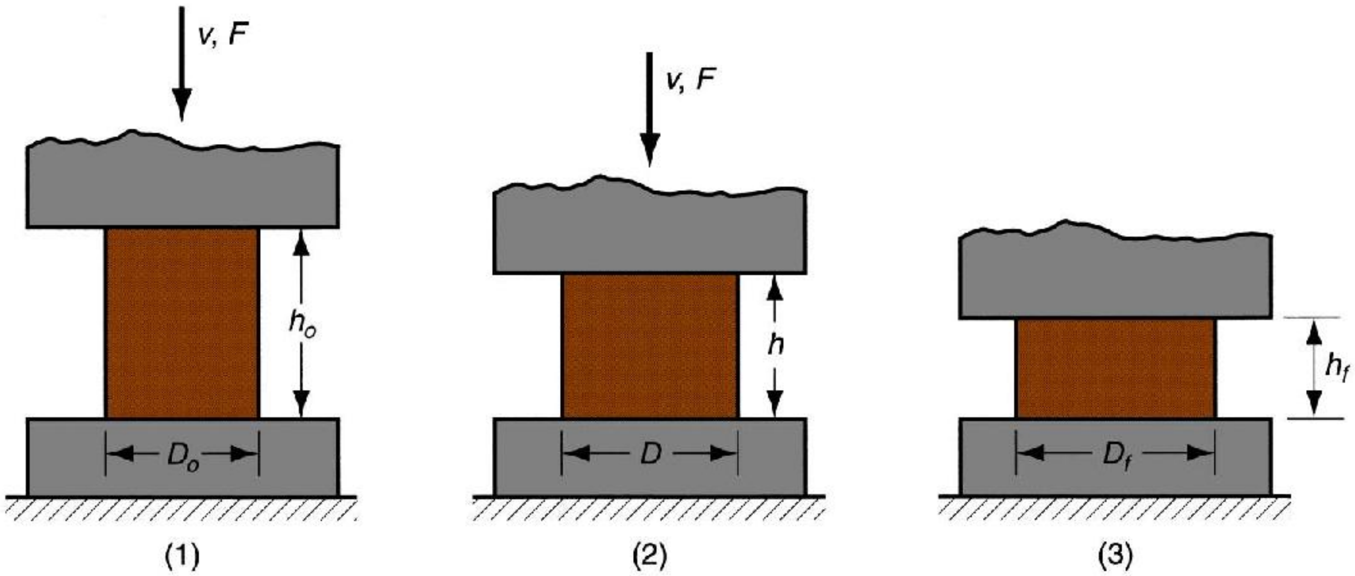


Figure 19.9 Homogeneous deformation of a cylindrical workpart under ideal conditions in an open−die forging operation: (1) start of process with workpiece at its original length and diameter, (2) partial compression, and (3) final size.

Forging
Open-Die Forging

- Analysis of Open-Die Forging:
  - Under these ideal conditions, the true strain experienced by the work during the process can be determined by:

$$\pounds = \ln \frac{h_o}{h}$$

  - The force to perform upsetting at any height is given by:

$$F = Y_f A$$

where F = force, N; A = cross-sectional area, mm^2; and Y_f = flow stress, MPa.

Forging
Open-Die Forging

- Analysis of Open-Die Forging:
  - If carried out under conditions where friction between work and die surfaces is accounted for, a barreling effect is created.

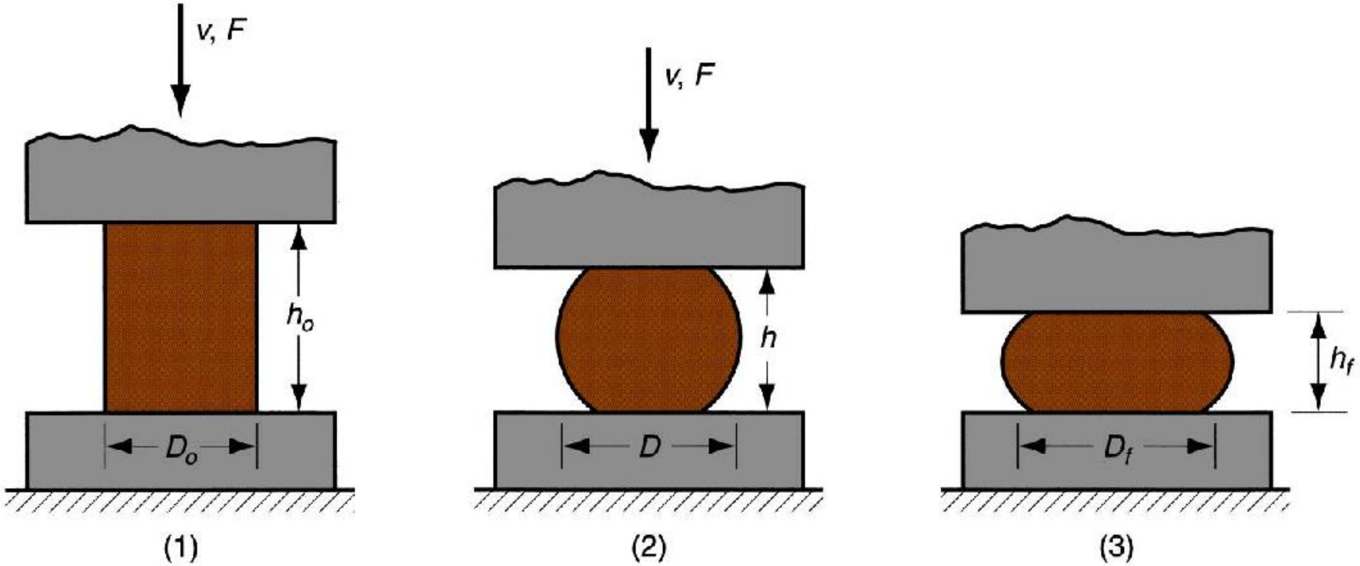


Figure 19.10 Actual deformation of a cylindrical workpart in open-die forging, showing pronounced barreling: (1) start of process, (2) partial deformation, and (3) final shape.

Forging
Open-Die Forging

- Analysis of Open-Die Forging:

  – Friction causes the actual upsetting force to be greater than what is predicted the previous equation:

$$F = K_f Y_f A$$

where K_f is the forging shape factor, defined as:

$$K_f = 1 + \frac{0.4«D}{h}$$

where μ = coefficient of friction; D = workpart diameter or other dimension representing contact length with die surface, mm; and h = workpart height, mm.

Forging
Open-Die Forging

- In practice, open-die forging can be classified into:
  - ***Fullering***: a forging operation performed to reduce the cross section and redistribute the metal in a workpart in preparation for subsequent shape forging (dies have convex surfaces).
  - ***Edging***: similar to fullering, except that the dies have concave surfaces.
  - ***Cogging***: consists of a sequence of forging compressions along the length of a workpiece to reduce cross section and increase length.

Forging
Open-Die Forging

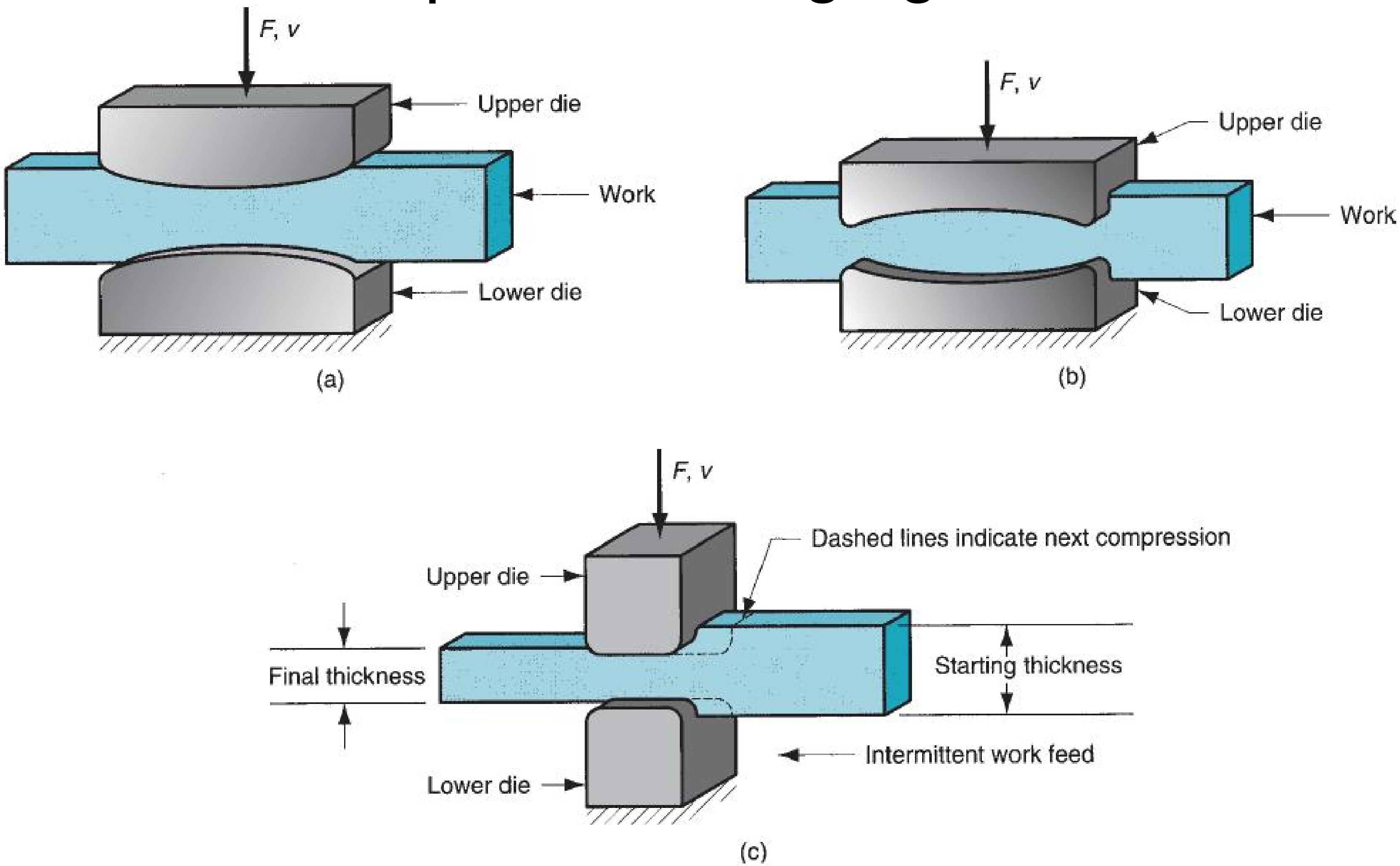


Figure 19.11 Several open-die forging operations: (a) fullering, (b) edging, and (c) cogging.

Forging
Impression-Die Forging

- ***Impression-die forging*** (sometimes called ***closed-die forging***): performed with dies that contain the inverse of the desired shape of the part.
  - As the die closes to its final position, flash is formed by metal that flows beyond the die cavity and into the small gap between the die plates.
  - Although this flash must be finally cut away, it serves an important function during impression-die forging.
    - As the flash begins to form, friction resists continued flow of metal into the gap, thus constraining the bulk of the work material to remain in the die cavity.
    - In hot forging, metal flow is further restricted because the thin flash cools quickly against the die plates, thereby increasing its resistance to deformation.
    - Accordingly, compression pressure is increased, thus forcing the material to fill the whole cavity.

Forging
Impression-Die Forging

- Sequence in impression-die forging:

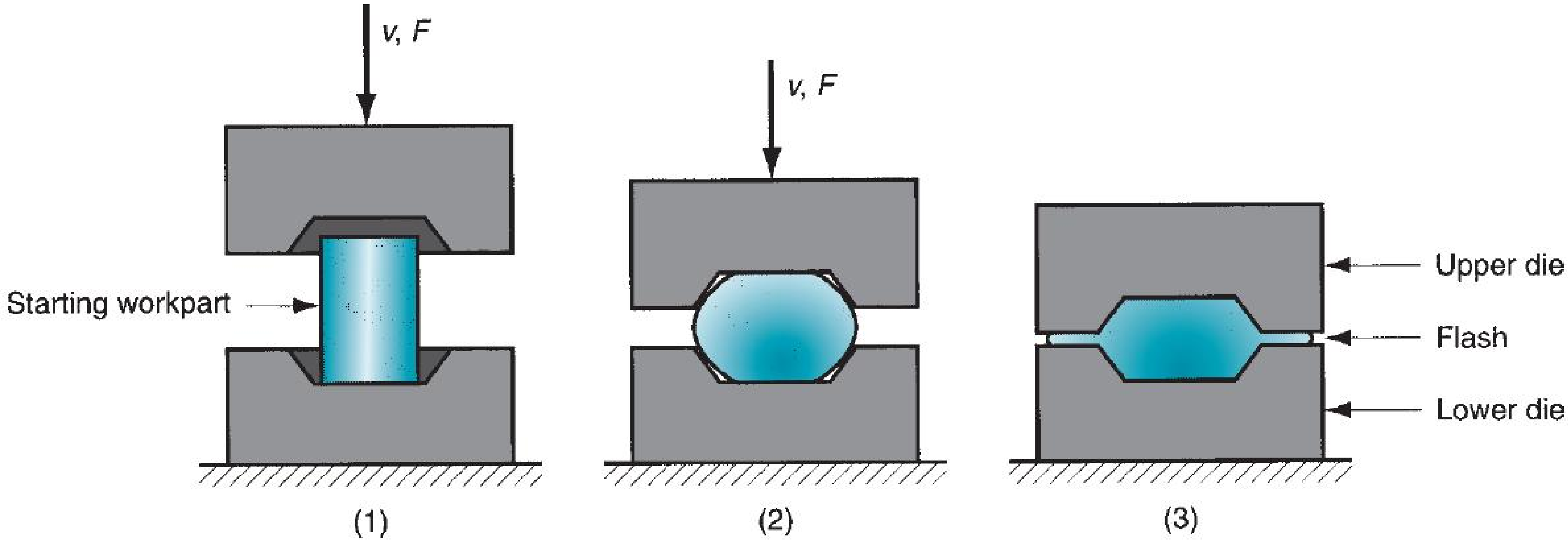


Figure 19.12 Sequence in impression-die forging: (1) just prior to initial contact with raw workpiece, (2) partial compression, and (3) final die closure, causing flash to form in gap between die plates.

Forging
Impression-Die Forging

- Advantages of impression-die forging compared to machining from solid stock include: higher production rates, less waste of metal, greater strength and favorable grain orientation in the metal.

- Limitations include: the incapability of close tolerances and machining is often required to achieve accuracies and features needed.

Forging
Flashless Forging

- ***Flashless Forging***: the raw workpiece is completely contained within the die cavity during compression, and no flash is formed.

- Several requirements:

  – The work volume must equal the space in the die cavity within a very close tolerance.

  – If the starting blank is too large, excessive pressures may cause damage to the die or press. If the blank is too small, the cavity will not be filled.

  – Simple geometries required.

  – Best for soft metals, such as aluminum and cupper and their alloys.

  – Sometimes classified as ***Precision Forging***.

Forging
Flashless Forging

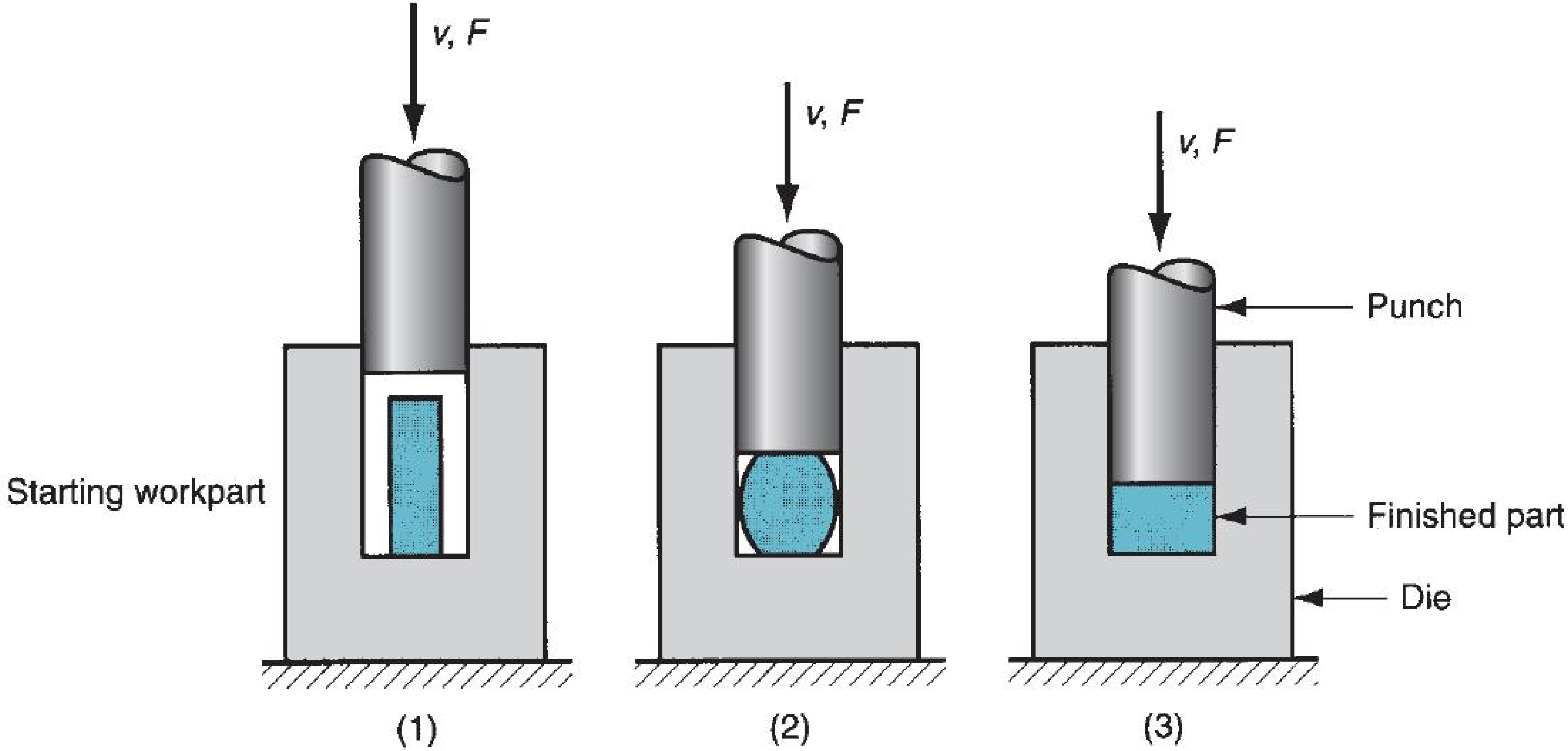


Figure 19.13 Flashless forging: (1) just before initial contact with workpiece, (2) partial compression, and (3) final punch and die closure.

Forging
Flashless Forging

- ***Coining***: is a type of flashless forging, in which fine details in the die are impressed into the top and bottom surfaces of the workpart. There is little flow of metal in coining.

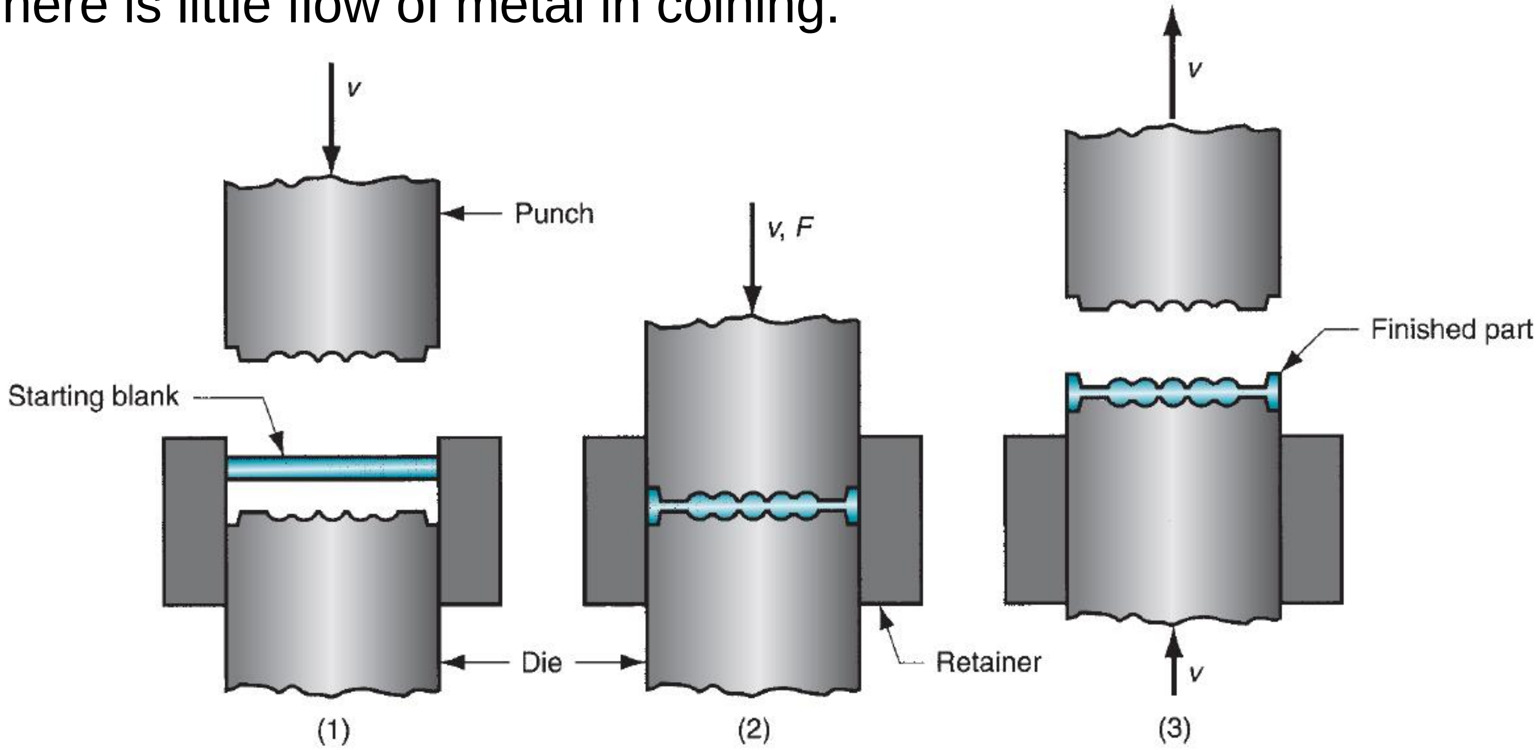


Figure 19.14 Coining operation: (1) start of cycle, (2) compression stroke, and (3) ejection of finished part.

Forging
Forging Hammers and Presses

- Equipment used in forging consists of forging machines, classified as hammers or presses, and forging dies.

- In addition, auxiliary equipment is needed, such as furnaces to heat the work, mechanical devices to load and unload the work, and trimming stations to cut away the flash in impression-die forging.

Forging
Forging Hammers and Presses

(1) ***Forging Hammers***: operate by applying an impact loading against the work. They deliver impact energy to the workpiece.

- Used for impression-die forging.
- The upper portion of the forging die is attached to the ram, and the lower portion is attached to the anvil.
- The work is placed on the lower die, and the ram is lifted and then dropped.
- When the upper die strikes the work, the impact energy causes the part to assume the form of the die cavity.
- Several blows of the hammer are often required to achieve the desired change in shape.

Forging
Forging Hammers and Presses

- Forging hammers are classified into:

(1) Gravity drop hammers: achieve their energy by the falling weight of a heavy ram, and the force of the blow is determined by the height of the drop and the weight of the ram.

(2) Power drop hammers: accelerate the ram by pressurized air or steam.

- Disadvantage: a large amount of the impact energy is transmitted through the anvil and into the floor of the building.

Forging
Forging Hammers and Presses

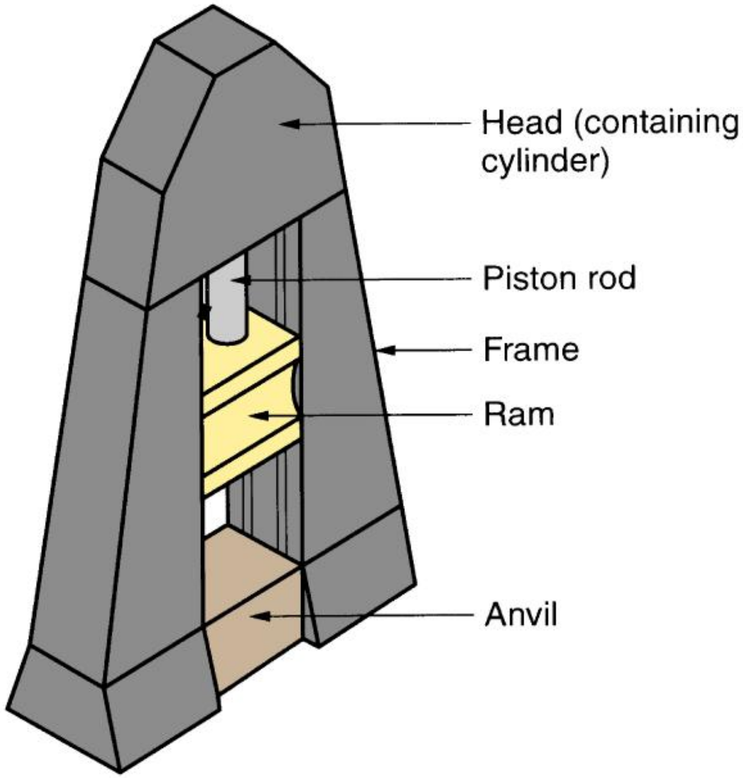


Figure 19.15 Diagram showing details of a drop hammer for impression−die forging.

Forging
Forging Hammers and Presses

(2) ***Forging Presses***: apply gradual pressure, rather than sudden impact, to accomplish the forging operation.

- Include mechanical presses, hydraulic presses, and screw presses.
- Mechanical presses convert the rotating motion of a drive motor into the translation motion of the ram.
- Hydraulic presses use a hydraulically driven piston to drive the ram.
- Screw presses apply force by a screw mechanism that drives the vertical ram.

Other Deformation Processes Related to Forging

- ***Upsetting*** and ***Heading***: a deformation operation in which a cylindrical workpart is increased in diameter and reduced in length.
- Used in the fastener industry to form heads on nails, bolts, etc (in these applications, it is referred to as heading).
- More parts produced by upsetting than any other forging operation.
- Performed cold, hot or warm on special upset forging machines, called headers or formers.
- Long wire is fed into the machines, the end of the stock is upset forged, and then the piece is cut to length to make the desired hardware item.

Other Deformation Processes Related to Forging

- ***Upsetting*** and ***Heading***: a deformation operation in which a cylindrical workpart is increased in diameter and reduced in length.

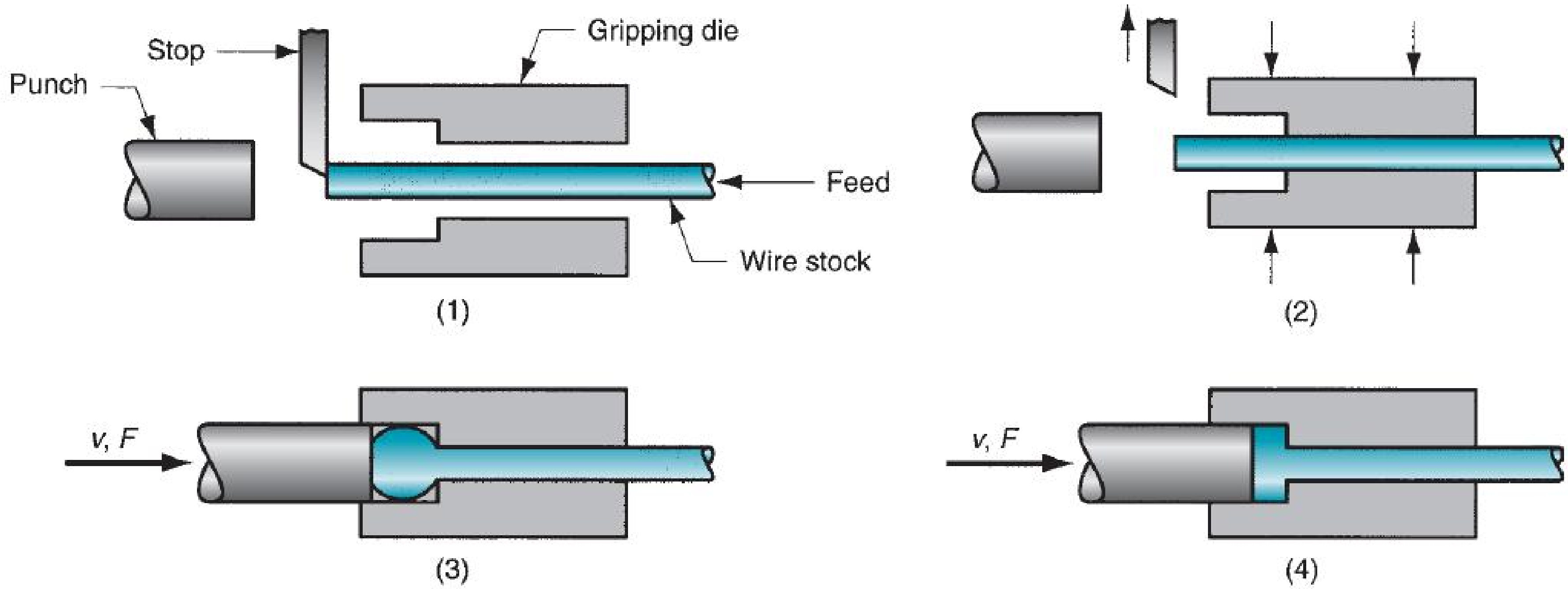


Figure 19.16 An upset forging operation to form a head on a bolt. (1) wire stock is fed to the stop; (2) gripping dies close on the stock and the stop is retracted; (3) punch moves forward; and (4) bottoms to form the head.

Other Deformation Processes Related to Forging

- ***Upsetting*** and ***Heading***: a deformation operation in which a cylindrical workpart is increased in diameter and reduced in length.

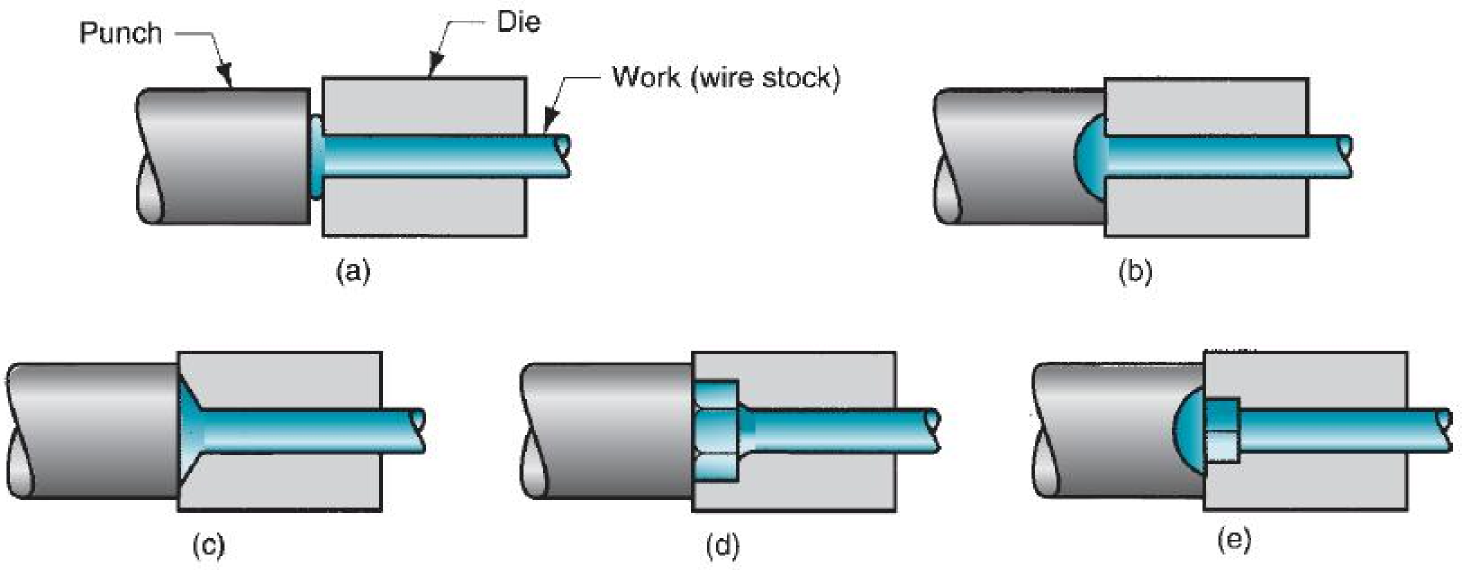


Figure 19.17 Examples of heading (upset forging) operations: (a) heading a nail using open dies, (b) round head formed by punch, (c) and (d) heads formed by die, and (e) carriage bolt head formed by punch and die.

Other Deformation Processes Related to Forging

- ***Swaging*** and ***Radial Forging***: forging processes used to reduce the diameter of a tube or solid rod.

- The ***swaging*** process is accomplished by means of rotating dies that hammer a workpiece radially inward to taper it as the piece is fed into the dies.

- ***Radial forging*** is similar to swaging in its action against the work and is used to create similar part shapes. The difference is that in radial forging the dies do not rotate around the workpiece; instead, the work is rotated as it feeds into the hammering dies.

Other Deformation Processes Related to Forging

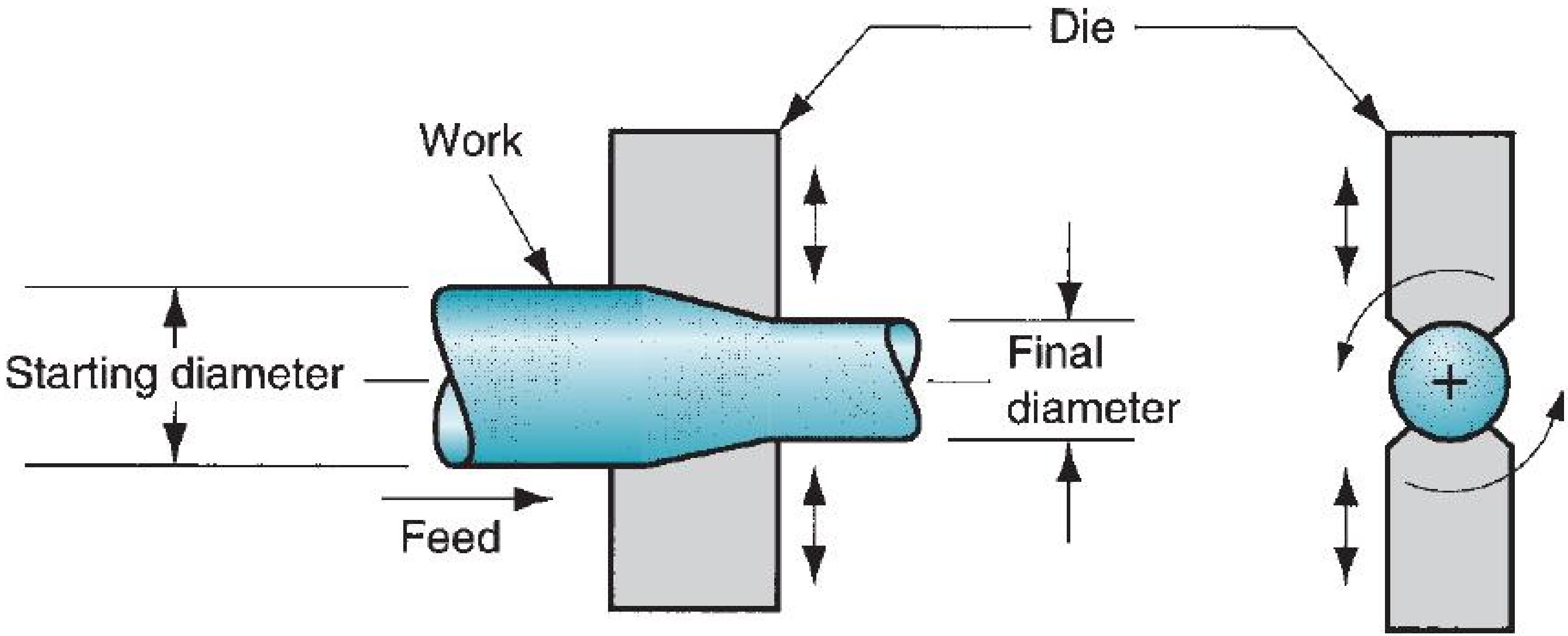


Figure 19.18 Swaging process to reduce solid rod stock; the dies rotate as they hammer the work. In radial forging, the workpiece rotates while the dies remain in a fixed orientation as they hammer the work.

Other Deformation Processes Related to Forging

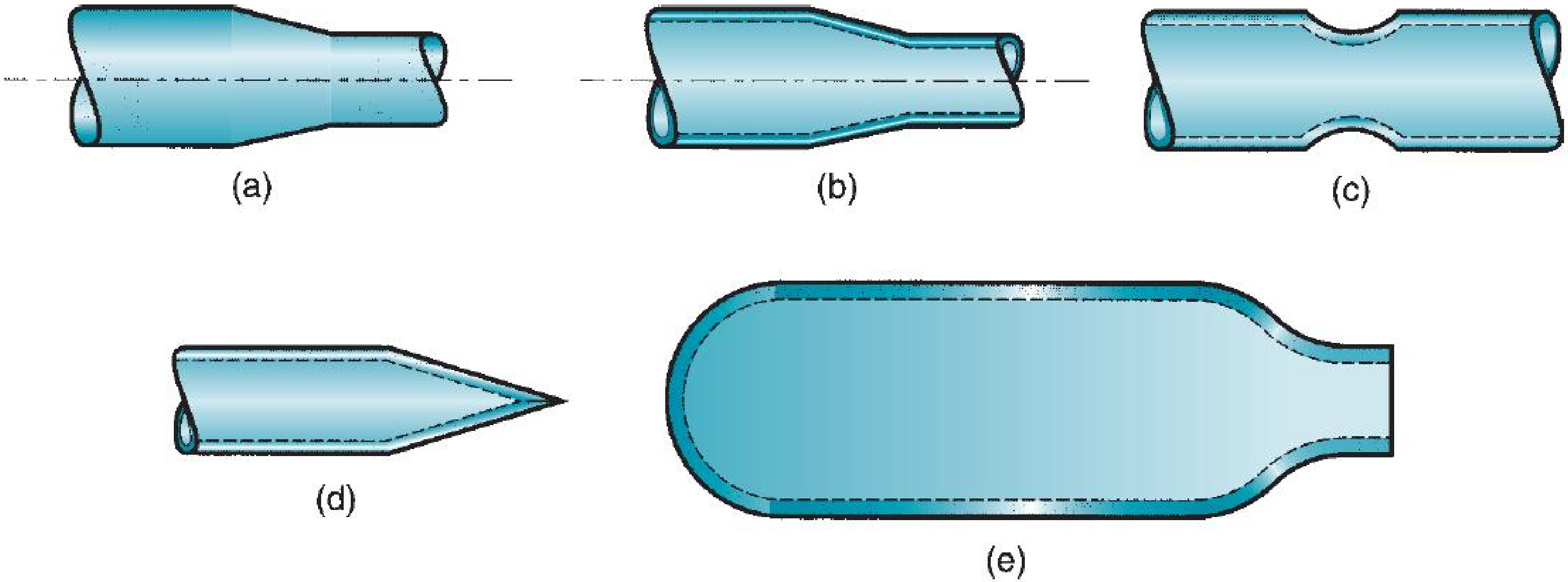


Figure 19.19 Examples of parts made by swaging: (a) reduction of solid stock, (b) tapering a tube, (c) swaging to form a groove on a tube, (d) pointing of a tube, and (e) swaging of neck on a gas cylinder.

Other Deformation Processes Related to Forging

- ***Trimming:*** an operation used to remove flash on the workpart in impression-die forging.
- In most cases, trimming is accomplished by shearing.
- Trimming is usually done while the work is still hot.
- In cases where the work might be damaged by the cutting process, trimming may be done by alternative methods, such as grinding or sawing.

Other Deformation Processes Related to Forging

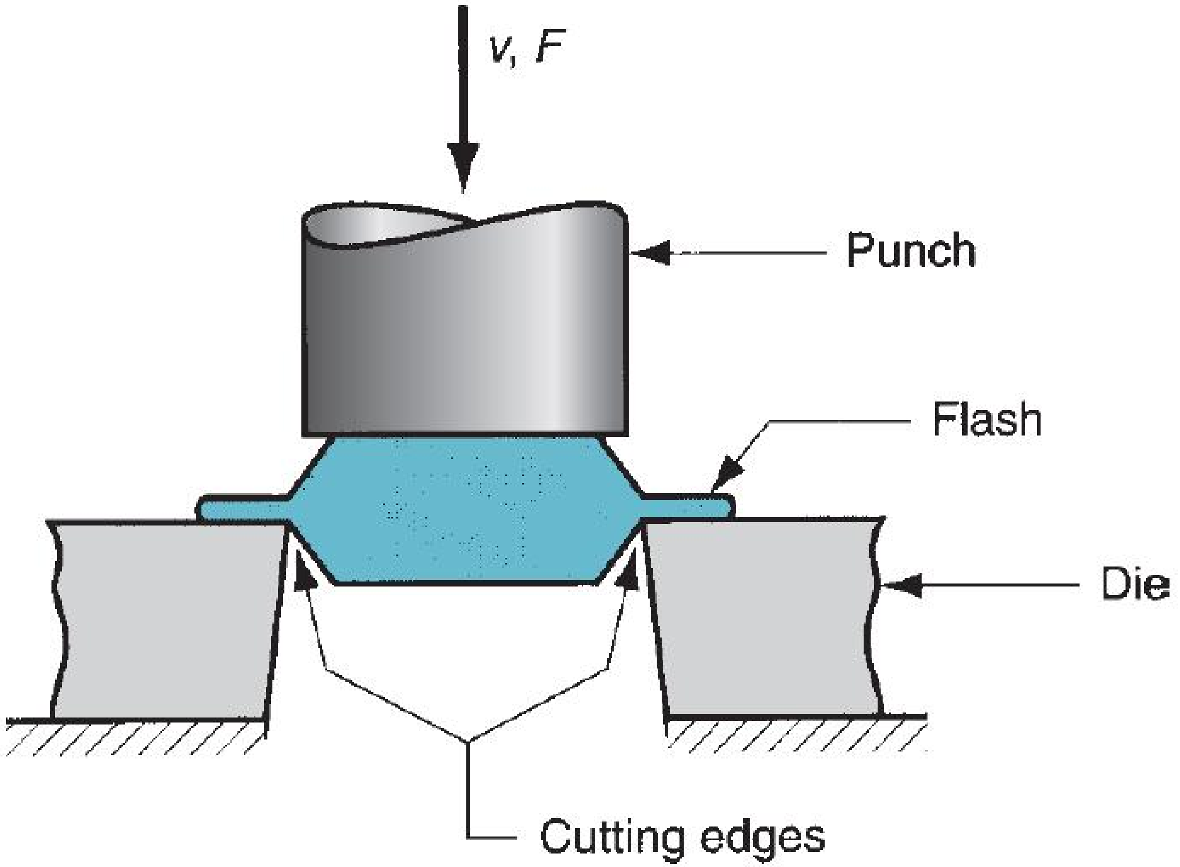


Figure 19.20 Trimming operation (shearing process) to remove the flash after impression-die forging.

Extrusion

- ***Extrusion:*** a compression process in which the work metal is forced to flow through a die opening to produce a desired cross-sectional shape.
- Imagine squeezing toothpaste out of toothpaste tube.
- Advantages include:
  - A variety of shapes are possible (especially in hot extrusion).
  - Microstructure and strength are enhanced in cold and warm extrusion.
  - Close tolerances are possible, especially in cold extrusion.
  - in some extrusion operations, little or no wasted material is created.

Extrusion
Types of Extrusion

- Extrusion can be classified in various ways:
  - By physical configuration: ***Direct Extrusion*** and ***Indirect Extrusion***.
  - By working temperature: ***Cold***, ***Warm***, or ***Hot Extrusion***.
  - Finally, it is performed as either a ***Continuous*** or ***Discrete process***.

Extrusion
Types of Extrusion

- ***Direct*** versus ***Indirect Extrusion***: (1) Direct extrusion (also called ***forward extrusion***) is illustrated in the Figure below.

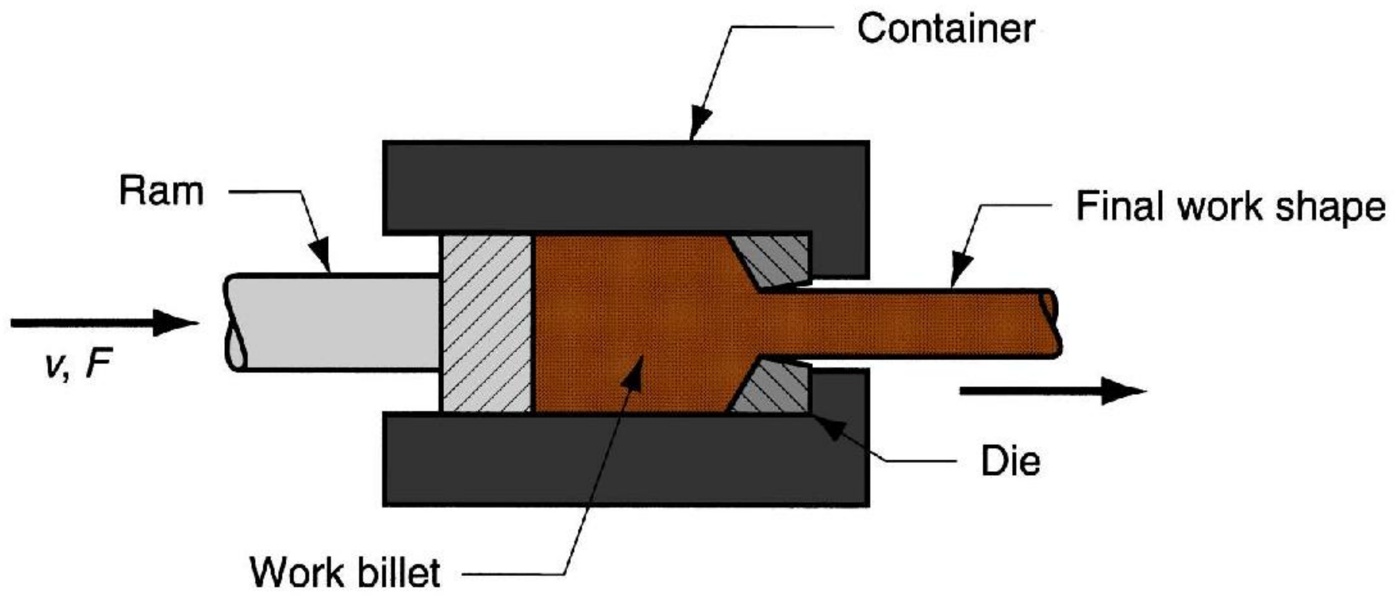


Figure 19.21 Direct extrusion.

Extrusion
Direct Extrusion

- 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.
- Friction between container's walls and workpiece is one big problem in extrusion (so higher forces are needed to accomplish the process).
- The problem is aggravated in hot extrusion due to formation of oxide layer.

Extrusion
Direct Extrusion

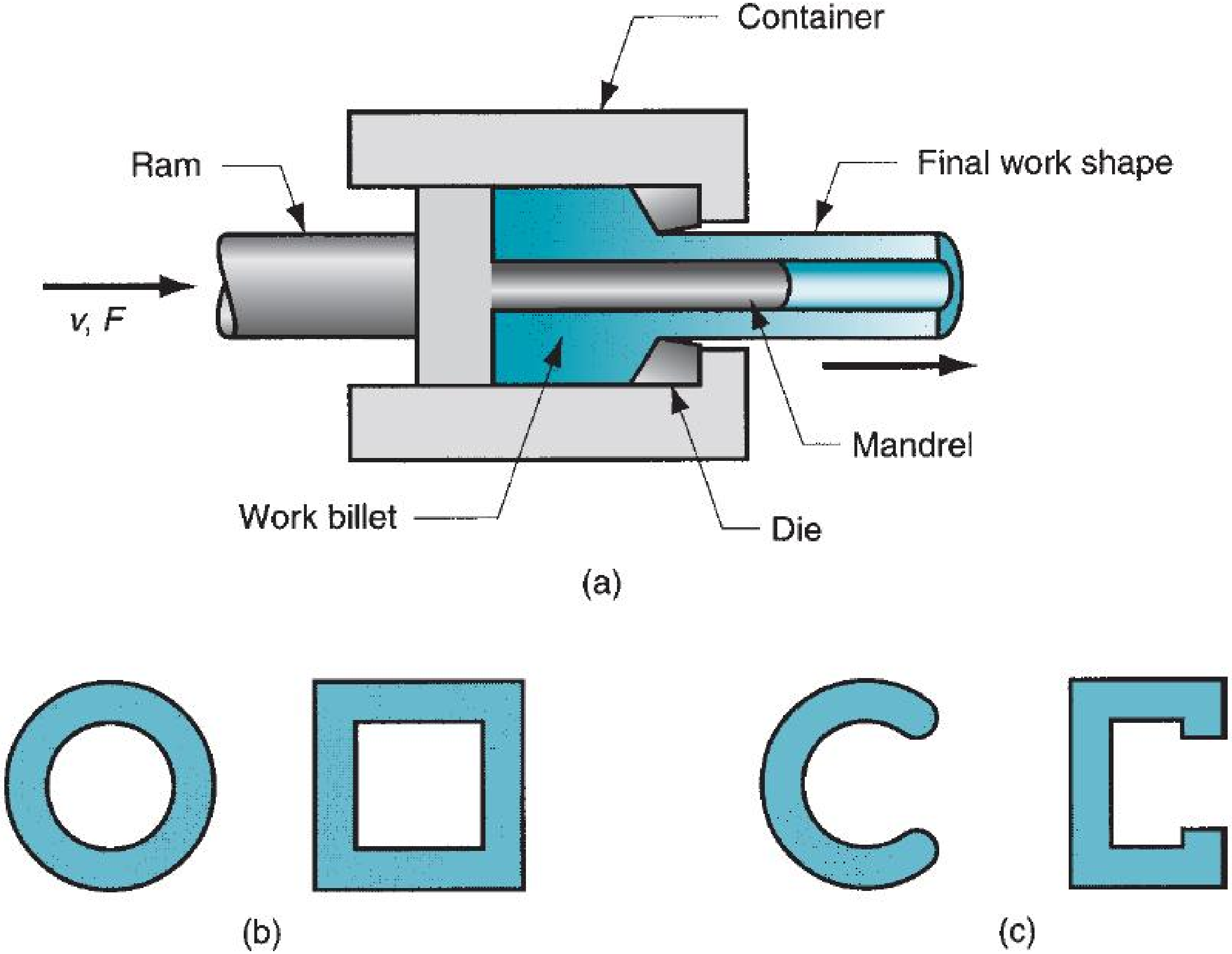


Figure 19.22 (a) Direct extrusion to produce a hollow or semi-hollow cross section; (b) hollow and (c) semi-hollow cross sections.

Extrusion
Types of Extrusion

- ***Direct*** versus ***Indirect Extrusion***: (2) Indirect extrusion (also called ***backward extrusion***) is illustrated in the Figure below.

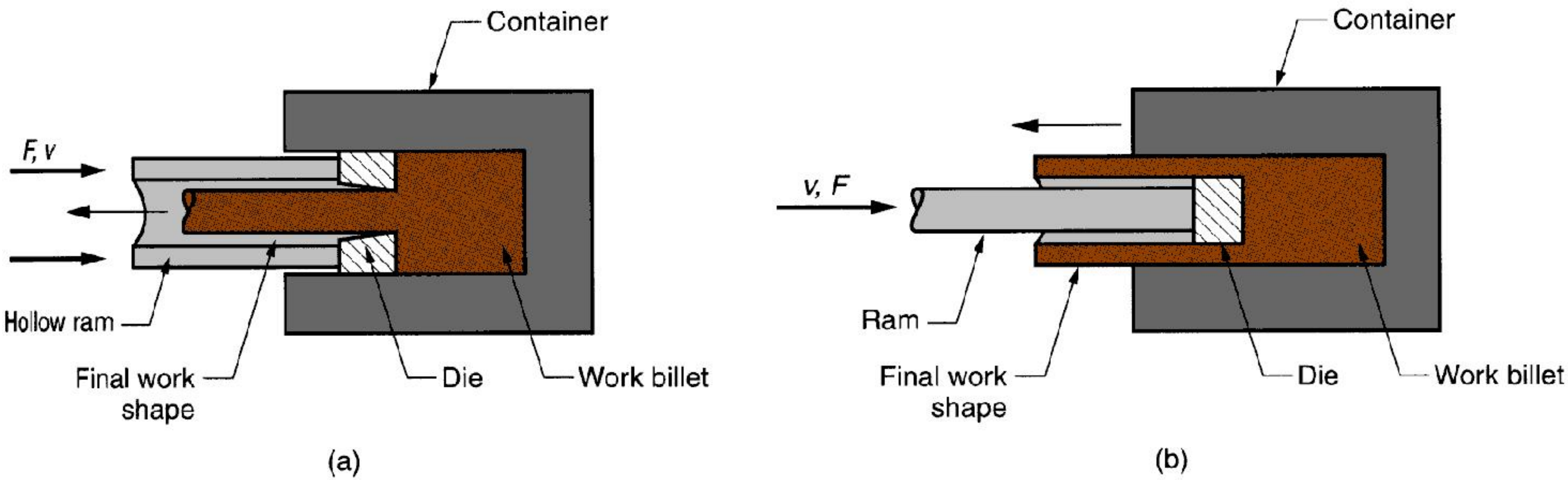


Figure 19.23 Indirect extrusion to produce (a) a solid cross section and (b) a hollow cross section.

Extrusion
Indirect Extrusion

- The die is mounted to the ram rather than at the opposite end of the container.
- As the ram penetrates into the work, 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.

Extrusion
Types of Extrusion

- ***Hot*** versus ***Cold Extrusion***:
  - Extrusion can be performed either hot or cold, depending on work metal and amount of strain to which it is subjected during deformation.
  - Hot extruded metals include: Al, Cu, Mg, Zn, Sn, and their alloys.
  - Steel alloys are usually extruded hot, although the softer, more ductile grades are sometimes cold extruded (e.g. low C-steels).
  - Al is probably the most ideal metal for extrusion (hot and cold).
  - Products include: doors and window frames.

Extrusion
Types of Extrusion

- ***Hot Extrusion***:
  - Involves prior heating of the billet to a temperature above its recrystallization temperature.
  - This reduces strength and increases ductility.
  - Additional advantages include reduction of ram force, and increased ram speed.

Extrusion
Types of Extrusion

- ***Cold Extrusion***:
  - Used to produce discrete parts, in finished (or near finished) form.
  - Impact Extrusion: indicates high-speed cold extrusion.
  - Advantages: increased strength due to strain hardening, close tolerances, improved surface finish, absence of oxide layers, and high production rates.

Extrusion
Types of Extrusion

- ***Continuous*** versus ***Discrete Extrusion***:

  – ***Continuous Extrusion***: producing very long sections in one cycle, but these operations are limited by the size of the starting billet that can be loaded into the extrusion container. In nearly all cases, the long section is cut into smaller lengths in a subsequent sawing or shearing operation.

  – ***Discrete Extrusion***: a single part is produced in each extrusion cycle. Impact extrusion is an example of the discrete processing case.

Extrusion
Analysis of Extrusion

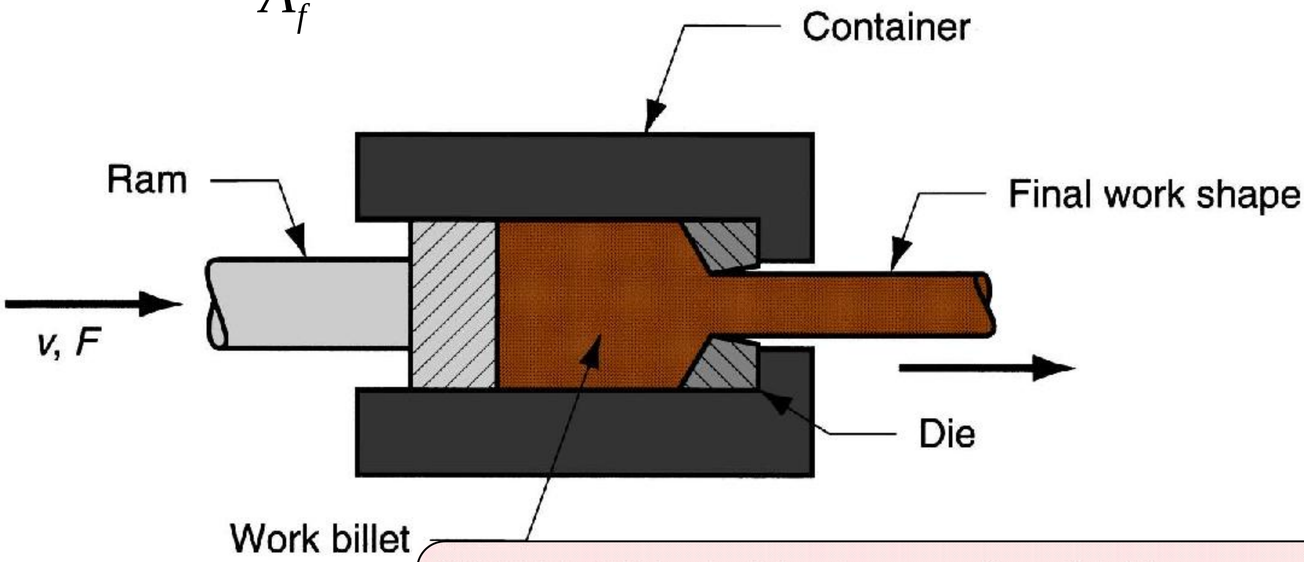
- Consider the figure below:

Extrusion ratio: $r_x = \frac{A_o}{A_f}$

True strain: $\text{£} = \ln \frac{A_o}{A_f}$

Idea (no friction) case, pressure p: $p = \overline{Y_f} \ln r_x$

Average flow stress (MPa): $\overline{Y_f} = \frac{K\text{£}^n}{1+n}$



NOTE: This is ideal case (no friction considered).

The workpiece has round cross section

Extrusion
Analysis of Extrusion

- If friction is considered:

Extrusion strain: $\pounds_x = a + b \ln r_x$ where a & b are constants for a given die angle: a = 0.8 & b = 1.2 to 1.5.

For indirect extrusion: $p = \overline{Y_f} \pounds_x$

For direct extrusion, friction is higher, so: $p = \overline{Y_f}\left(\pounds_x + \frac{2L}{D_o} \right)$

Ram forces in indirect or direct extrusion, F (N): $F = pA_o$

Power required P (J/s): $P = Fv$ v is velocity in m/s

NOTE: friction considered and cross section is round.

Extrusion
Extrusion Dies and Presses

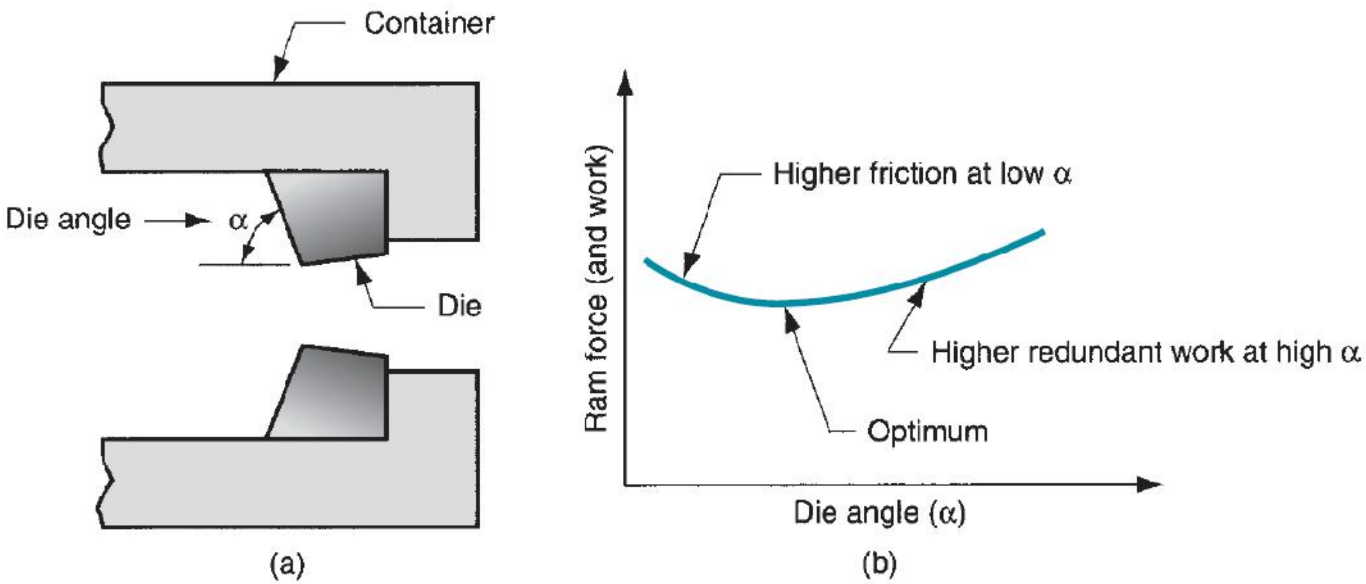


Figure 19.24 (a) Definition of die angle in direct extrusion; (b) effect of die angle on ram force.

Low die angles (α): high friction so high ram force.

High die angles (α): more turbulence, so increased ram force.

An optimum die angle exists.

Extrusion
Extrusion Dies and Presses

- The effect of the die orifice shape can be assessed by the die shape factor, can be expressed as follows:

$$K_x = 0.98 + 0.02\left(\frac{C_x}{C_c}\right)^{2.25}$$

where K_x = die shape factor in extrusion; C_x = perimeter of the extruded cross section, mm; and C_c = perimeter of a circle of the same area as the extruded shape, mm.

K_x for circular shape = 1

K_x for hollow, thin-walled sections is higher.

For indirect extrusion: $p = K_x \overline{Y_f} £_x$

For direct extrusion: $p = K_x \overline{Y_f}\left(£_x + \frac{2L}{D_o}\right)$

→ For shapes other than round.

Extrusion
Extrusion Dies and Presses

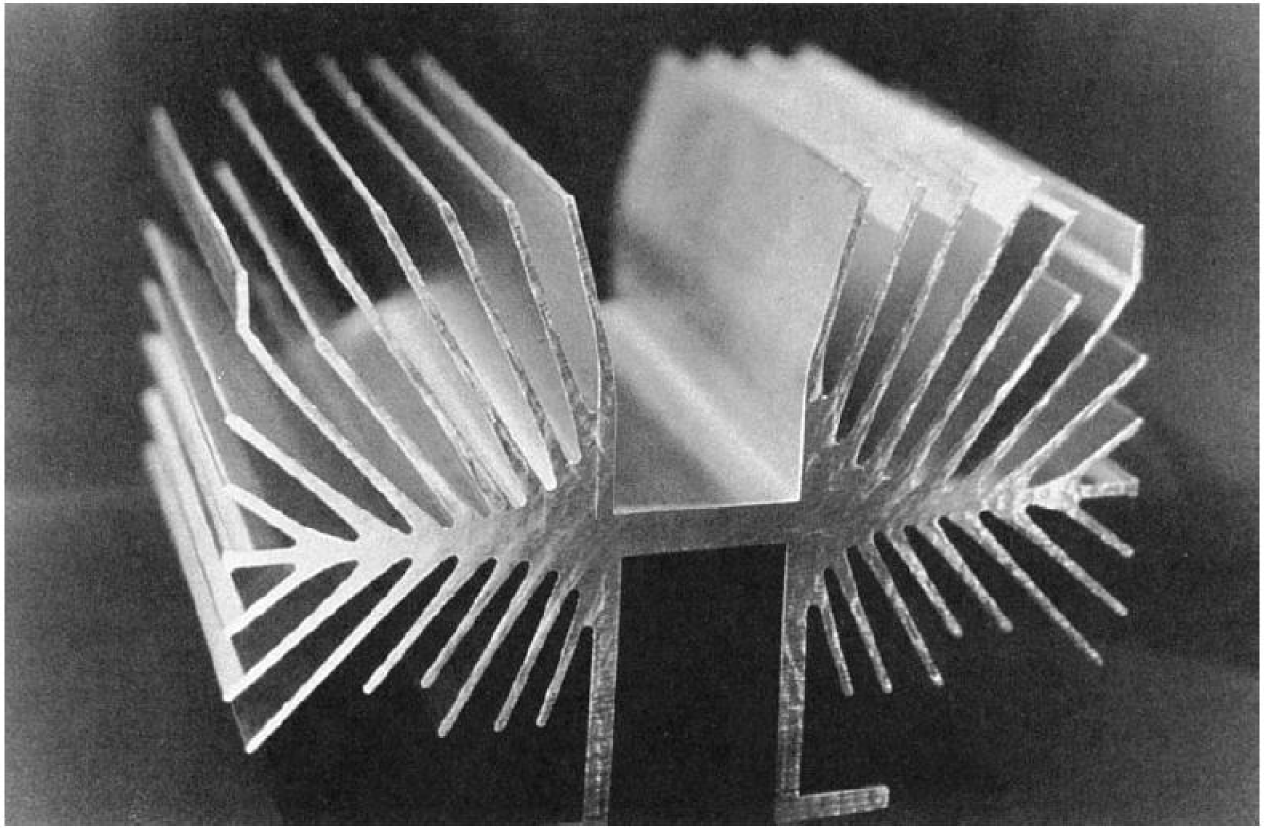


Figure 19.25 A complex extruded cross section for a heat sink. (Photo courtesy of Aluminum Company of America, Pittsburg, Pennsylvania).

Extrusion
Extrusion Dies and Presses

- ***Extrusion presses***: either horizontal or vertical, depending on orientation of the work axis.
- Usually hydraulically driven.
- This drive is especially suited to semi-continuous production of long sections, as in direct extrusion.
- Mechanical drives are often used for cold extrusion of individual parts, such as in impact extrusion.

Extrusion
Defects in Extrusion

- ***Centerburst***: an internal crack that develops as a result of tensile stresses along the centerline of the workpart during extrusion. Conditions that promote centerburst are high die angles, low extrusion ratios, and impurities.

- ***Piping***: a defect associated with direct extrusion. 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.

- ***Surface cracking***: 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.

Extrusion
Defects in Extrusion

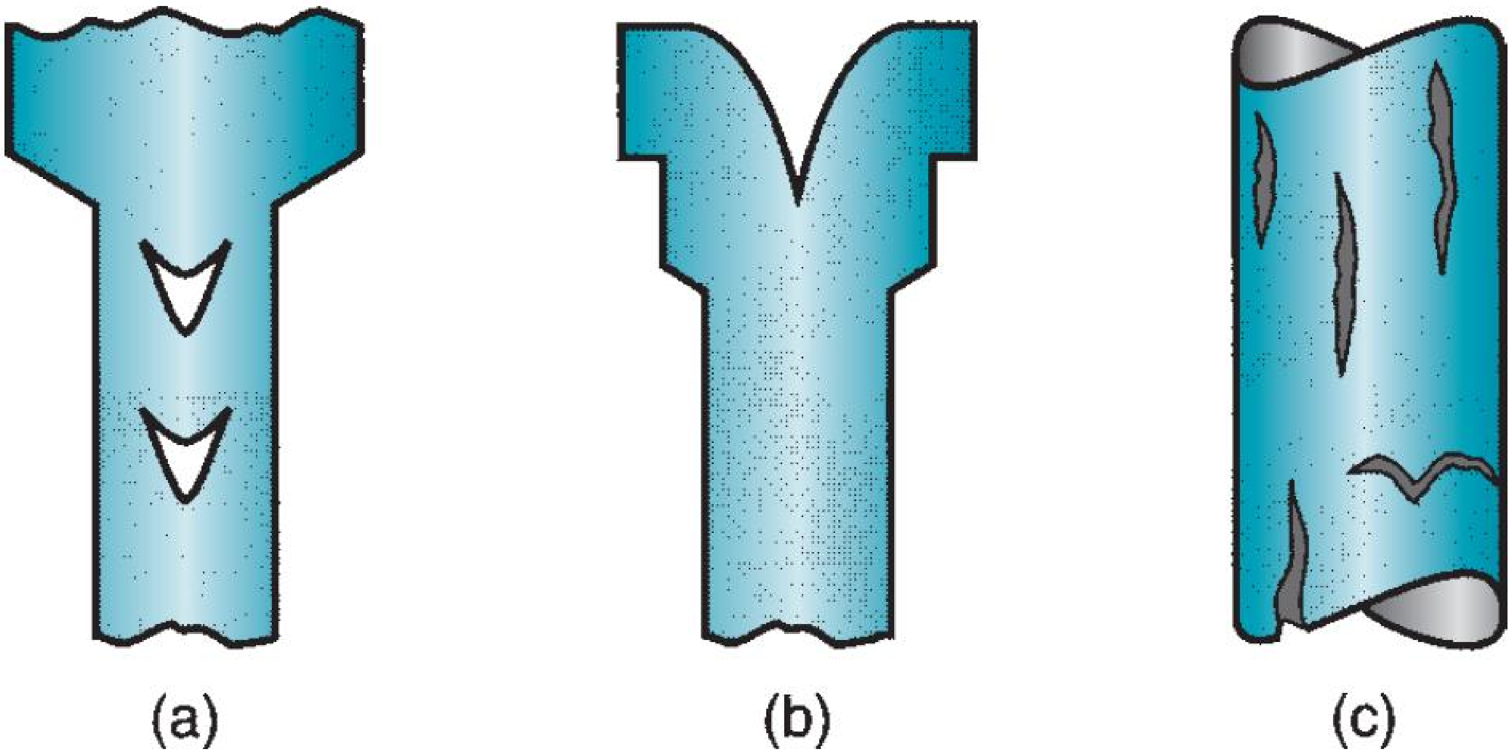


Figure 19.26 Some common defects in extrusion: (a) centerburst, (b) piping, and (c) surface cracking.

Wire and Bar Drawing

- ***Drawing***: is an operation in which the cross section of a bar, rod, or wire is reduced by pulling it through a die opening.

- The difference between drawing and extrusion: the work is pulled through the die in drawing, whereas it is pushed through the die in extrusion.

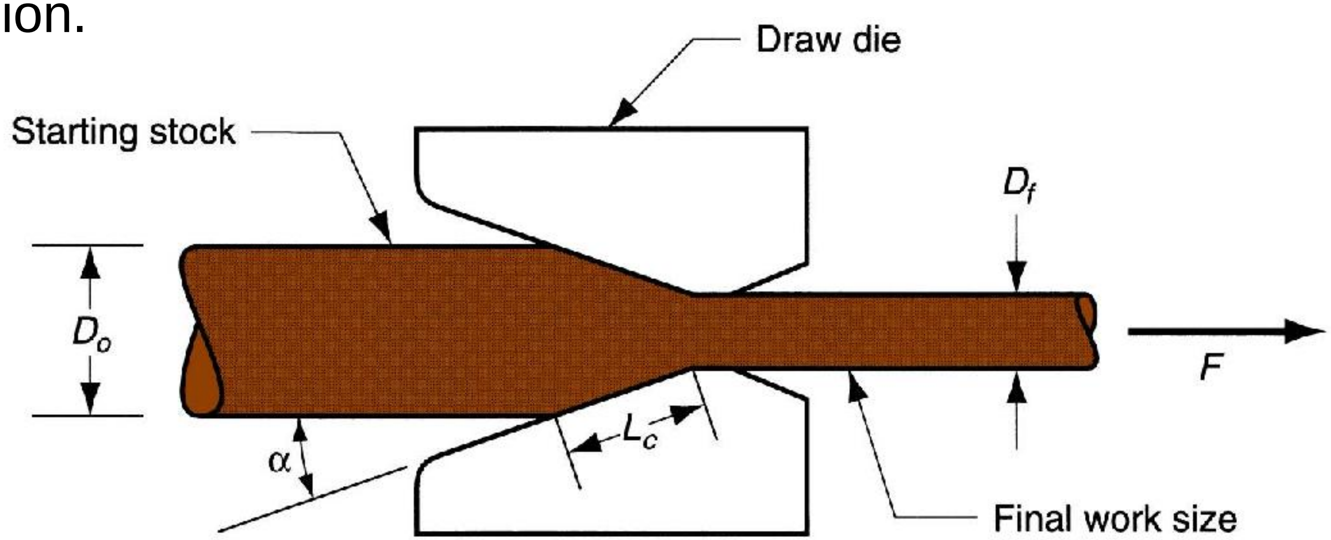


Figure 19.27 Drawing of bar, rod, or wire.

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Wire and Bar Drawing

- ***Bar drawing***: the term used for large diameter bars.
- ***Wire drawing***: applies to small diameter bars (wire sizes down to 0.03 mm are possible in wire drawing).
- Two stress components are present is drawing; ***tensile stresses*** due to the pulling action and ***compressive stresses*** because the metal is squeezed down as it passes through the die opening.
- Change in size of work (given by area reduction): $r = \frac{A_o - A_f}{A_o}$
- Draft: difference between original and final diameter: $d = D_o - D_f$

Note: A is in (mm^2) and D is in (mm).

Wire and Bar Drawing
Analysis of Drawing

- ***Mechanics of Drawing***: assume no friction.

True strain: $£ = \ln \frac{A_o}{A_f} = \ln \frac{1}{1-r}$

Stress: $\pm = \overline{Y_f}£ = \overline{Y_f} \ln \frac{A_o}{A_f}$ where $\overline{Y_f} = \frac{K£^n}{1+n}$

Wire and Bar Drawing
Analysis of Drawing

- ***Mechanics of Drawing***: assuming friction, consider Figure 19.27 .

$$\sigma_d = \overline{Y}_f \left(1 + \frac{\mu}{\tan\alpha}\right) \Phi \ln \frac{A_o}{A_f}$$

where σ_d = draw stress, MPa; μ = die-work coefficient of friction; α = die angle; and Φ is a factor that accounts for inhomogeneous deformation.

$$\Phi = 0.88 + 0.12 \frac{D}{L_c}$$

where D = average diameter of work during drawing, mm; and L_c = contact length of the work with the draw die.

$$D = \frac{D_o + D_f}{2} \quad \text{and} \quad L_c = \frac{D_o - D_f}{2\sin\alpha}$$

Accordingly, $F = A_f \sigma_d = A_f \overline{Y}_f \left(1 + \frac{\mu}{\tan\alpha}\right) \Phi \ln \frac{A_o}{A_f}$ where F = drawing force, N.

Wire and Bar Drawing
Analysis of Drawing

- ***Maximum Reduction per Pass***: why entire reduction is not taken in one pass?
  - As the reduction increases, draw stress increases.
  - If the reduction is large enough, draw stress will exceed the yield strength of the exiting metal.
  - When that happens, the drawn wire will simply elongate instead of new material being squeezed through the die opening.
  - For wire drawing to be successful, maximum draw stress must be less than the yield strength of the exiting metal.

Wire and Bar Drawing
Analysis of Drawing

- ***Maximum Reduction per Pass:*** assuming perfectly plastic material; then (n = 0 hence $\overline{Y}_f = Y$), and no friction:

$$\pm_d = \overline{Y_f} \ln \frac{A_o}{A_f} = Y \ln \frac{A_o}{A_f} = Y \ln \frac{1}{1-r} = Y$$

- This means that ln (A_o/A_f) = ln ($1/(1-r)$) = 1. Hence, $A_o/A_f = 1/(1 - r)$ must equal the natural logarithm base e. that is, the maximum possible strain is 1.0:

$$£_{\max} = 1.0$$

- The maximum possible reduction is: $\frac{A_o}{A_f} = e = 2.7183$

- The maximum possible reduction is: $r_{\max} = \frac{e-1}{e} = 0.632$

Wire and Bar Drawing
Drawing Practice

- Drawing is usually performed as a cold working operation.
- Most frequently used to produce round cross sections, but other shapes are also drawn.
- Drawn products include:
  - Electrical wire and cable; wire stock for fences, coat hangers, and shopping carts.
  - Rod stock to produce nails, screws, rivets, springs, and other hardware items.
  - Bar drawing is used to produce metal bars for machining, forging, and other processes.

Wire and Bar Drawing
Drawing Practice

- Advantages include:
  - Close dimensional control.
  - Good surface finish.
  - Improved mechanical properties such as strength and hardness.
  - Adaptability to mass production.

Wire and Bar Drawing
Drawing Practice

- ***Drawing Equipment***: (Bar Drawing)
  - Draw bench: consists of an entry table, die stand, carriage, and exit rack.
  - The carriage is used to pull the stock through the draw die.
  - Powered by hydraulic cylinders or motor-driven chains.

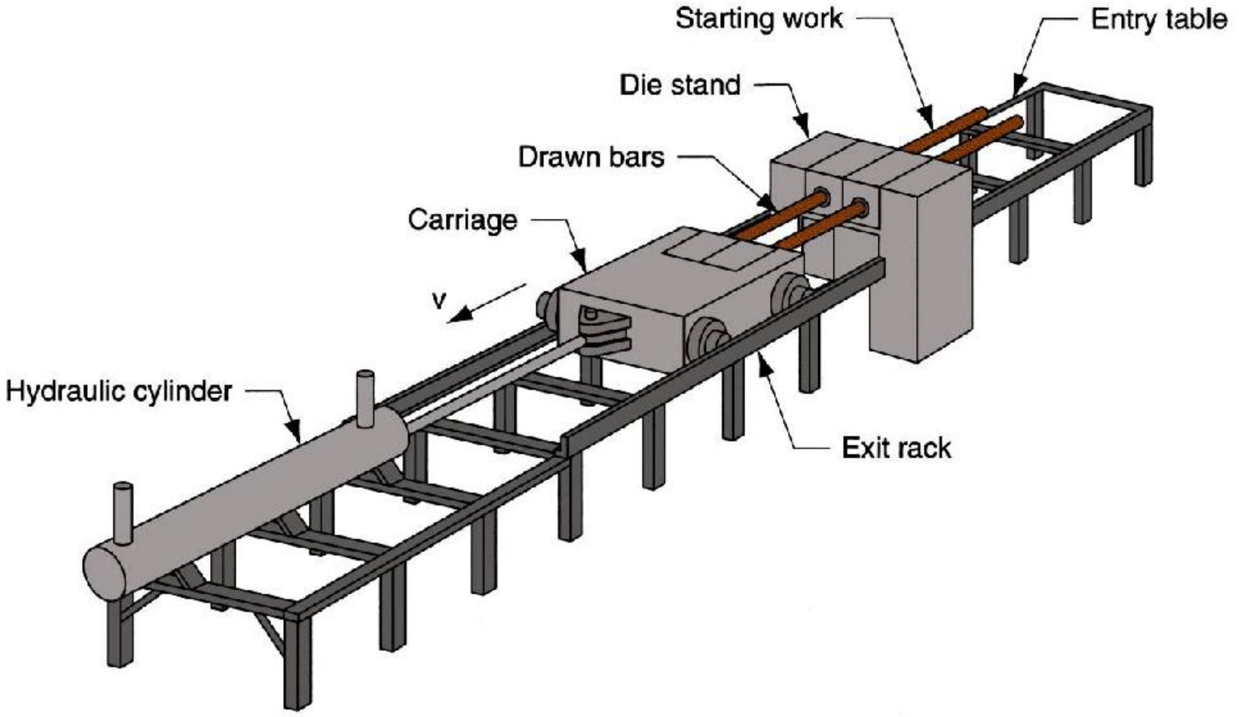


Figure 19.28 Hydraulically operated draw bench for drawing metal bars.

Wire and Bar Drawing
Drawing Practice

- ***Drawing Equipment***: (Wire Drawing)

  – Done on continuous drawing machines that consist of multiple draw dies, separated by accumulating drums between the dies.

  – 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.

Wire and Bar Drawing
Drawing Practice

- ***Drawing Equipment***: (Wire Drawing)

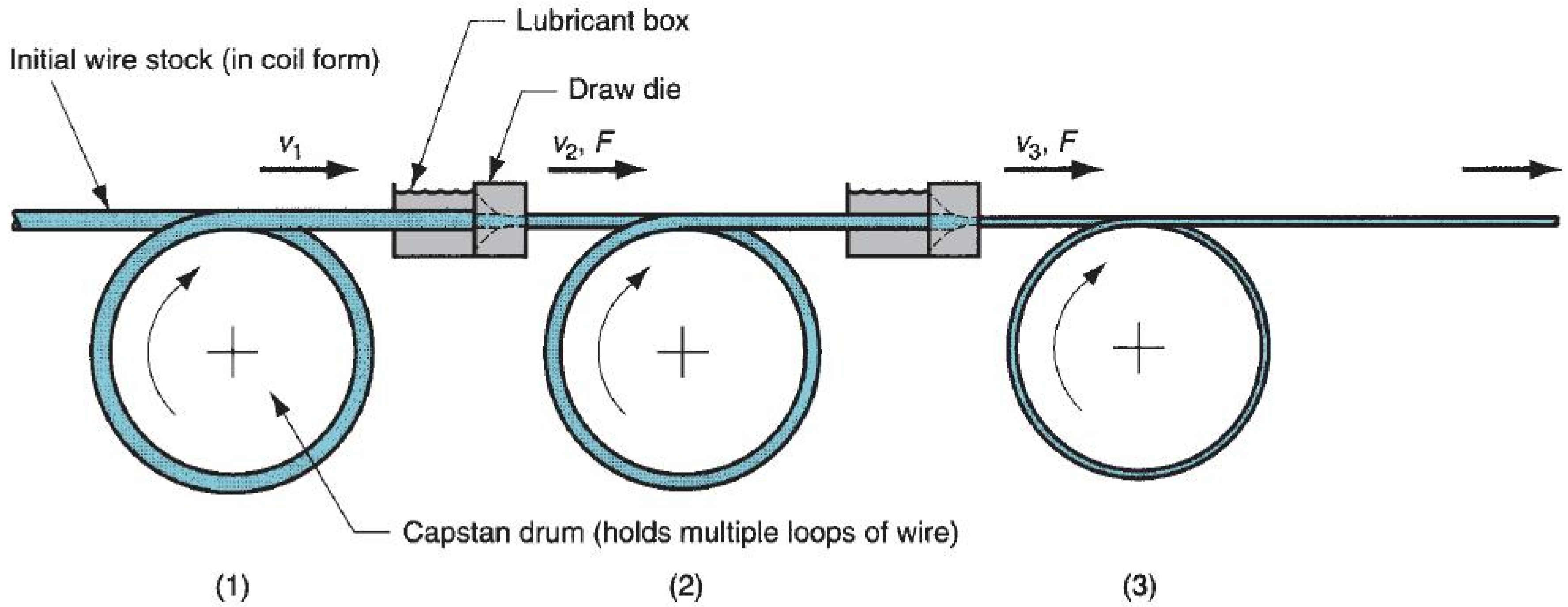


Figure 19.29 Continuous drawing of wire.

Wire and Bar Drawing
Drawing Practice

- ***Drawing Dies*** are made of tool steel, cemented carbides or diamond and they consist of 4 regions:

  (1) ***Entry Region***: 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.

  (2) The ***Approach Region***: is where the drawing process occurs. It is cone-shaped with an angle (half-angle) normally ranging from about 6 to 20º.

  (3) The ***Bearing Surface*** (***Land***): determines the size of the final drawn stock.

  (4) The ***Back Relief***: is the exit zone. It is provided with a back relief angle (half-angle) of about 30º.

Wire and Bar Drawing
Drawing Practice

- ***Drawing Dies***:

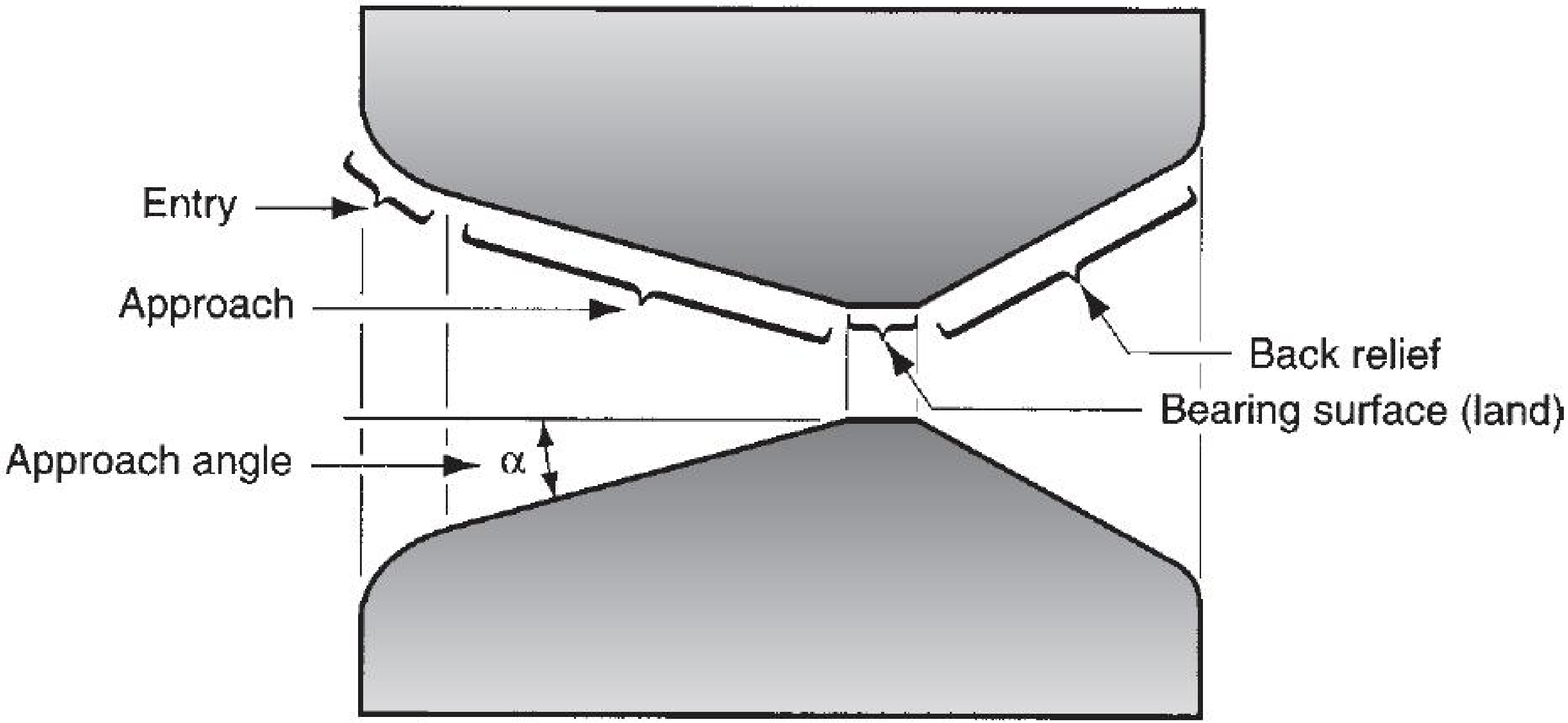


Figure 19.30 Draw die for drawing of round rod or wire.

Wire and Bar Drawing
Drawing Practice

- ***Preparation of work***: involves three steps: (1) annealing, (2) cleaning, and (3) pointing.

(1) ***Annealing***: done to increase the ductility of the stock.

(2) ***Cleaning***: required to prevent damage of the work surface and draw die.

(3) ***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.

Manufacturing Processes

Chapter Two:
Nature of Materials

Dr. Eng. Yazan Al-Zain
Department of Industrial Engineering

Introduction

- Some materials are hard and some are soft. Some are brittle while others are ductile. Some materials can withstand temperature while others cannot.

- The reason for these differences between various materials is strongly related to the <u>atomic structure</u>; the way the atoms are arranged within the materials. It is also related to the interactions that exist among the constituent atoms or molecules.

- The understanding of the atomic structure of materials allows us to <u>predict and evaluate</u> their properties.

Atomic Structure & The Elements

- The atom is the basic structural unit of matter. It is composed of a small nucleus composed of protons and neutrons, which is encircled by moving electrons.

- Both electrons and protons are electrically charged, the charge magnitude being 1.60×10^{-19} C, which is negative in sign for electrons and positive for protons; neutrons are electrically neutral.

- Protons and neutrons have approximately the same mass, 1.67×10^{-27} kg, which is significantly larger than that of an electron, 9.11×10^{-31} kg.

- The number of electrons (or protons) identifies the atomic number (*Z*) and the element of the atom. ($Z = 1$ & 90 for H and U, respectively).

Atomic Structure & The Elements

- The elements are grouped into families and relationships established between and within the families by means of the periodic table.

- Grouped into metals, nonmetals and intermediate (metalloids or semimetals).

Key: 29 — Atomic number; Cu — Symbol; 63.54 — Atomic weight

Metal / Nonmetal / Intermediate

IA	IIA	IIIB	IVB	VB	VIB	VIIB	VIII	VIII	VIII	IB	IIB	IIIA	IVA	VA	VIA	VIIA	0
1 H 1.0080																	2 He 4.0026
3 Li 6.939	4 Be 9.0122											5 B 10.811	6 C 12.011	7 N 14.007	8 O 15.999	9 F 18.998	10 Ne 20.183
11 Na 22.990	12 Mg 24.312											13 Al 26.982	14 Si 28.086	15 P 30.974	16 S 32.064	17 Cl 35.453	18 Ar 39.948
19 K 39.102	20 Ca 40.08	21 Sc 44.956	22 Ti 47.90	23 V 50.942	24 Cr 51.996	25 Mn 54.938	26 Fe 55.847	27 Co 58.933	28 Ni 58.71	29 Cu 63.54	30 Zn 65.37	31 Ga 69.72	32 Ge 72.59	33 As 74.922	34 Se 78.96	35 Br 79.91	36 Kr 83.80
37 Rb 85.47	38 Sr 87.62	39 Y 88.91	40 Zr 91.22	41 Nb 92.91	42 Mo 95.94	43 Tc (99)	44 Ru 101.07	45 Rh 102.91	46 Pd 106.4	47 Ag 107.87	48 Cd 112.40	49 In 114.82	50 Sn 118.69	51 Sb 121.75	52 Te 127.60	53 I 126.90	54 Xe 131.30
55 Cs 132.91	56 Ba 137.34	Rare earth series	72 Hf 178.49	73 Ta 180.95	74 W 183.85	75 Re 186.2	76 Os 190.2	77 Ir 192.2	78 Pt 195.09	79 Au 196.97	80 Hg 200.59	81 Tl 204.37	82 Pb 207.19	83 Bi 208.98	84 Po (210)	85 At (210)	86 Rn (222)
87 Fr (223)	88 Ra (226)	Acti-nide series															

Rare earth series	57 La 138.91	58 Ce 140.12	59 Pr 140.91	60 Nd 144.24	61 Pm (145)	62 Sm 150.35	63 Eu 151.96	64 Gd 157.25	65 Tb 158.92	66 Dy 162.50	67 Ho 164.93	68 Er 167.26	69 Tm 168.93	70 Yb 173.04	71 Lu 174.97
Actinide series	89 Ac (227)	90 Th 232.04	91 Pa (231)	92 U 238.03	93 Np (237)	94 Pu (242)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (249)	99 Es (254)	100 Fm (253)	101 Md (256)	102 No (254)	103 Lw (257)

- Depending on temp. & press. All these elements can exist as liquid, solid and gas; e.g. at room temp.:

Fe: Metal

Hg: Liquid.

N: gas.

Fig. 2-1: The periodic table.

Atomic Structure & The Elements

- In the periodic table, elements are arranged in such a way that similarities exist between elements in the same columns; for example:

- Noble gases: found in the extreme right column (He, Ne, Ar, Kr, Xe & Rn) are chemically stable and exhibit low reaction rates.

- The halogens: found in column VIIA (F, Cl, Br, I & At) share similar properties.

- The noble metals: found in column IB (Cu, Ag & Au) share similar properties.

Atomic Structure & The Elements

- Many of the similarities and differences between elements can be explained by their respective atomic structures.

- The planetary model (Bohr atom): the simplest atomic model showing the electrons of the atom orbiting around the nucleus at certain fixed distance, called shells.

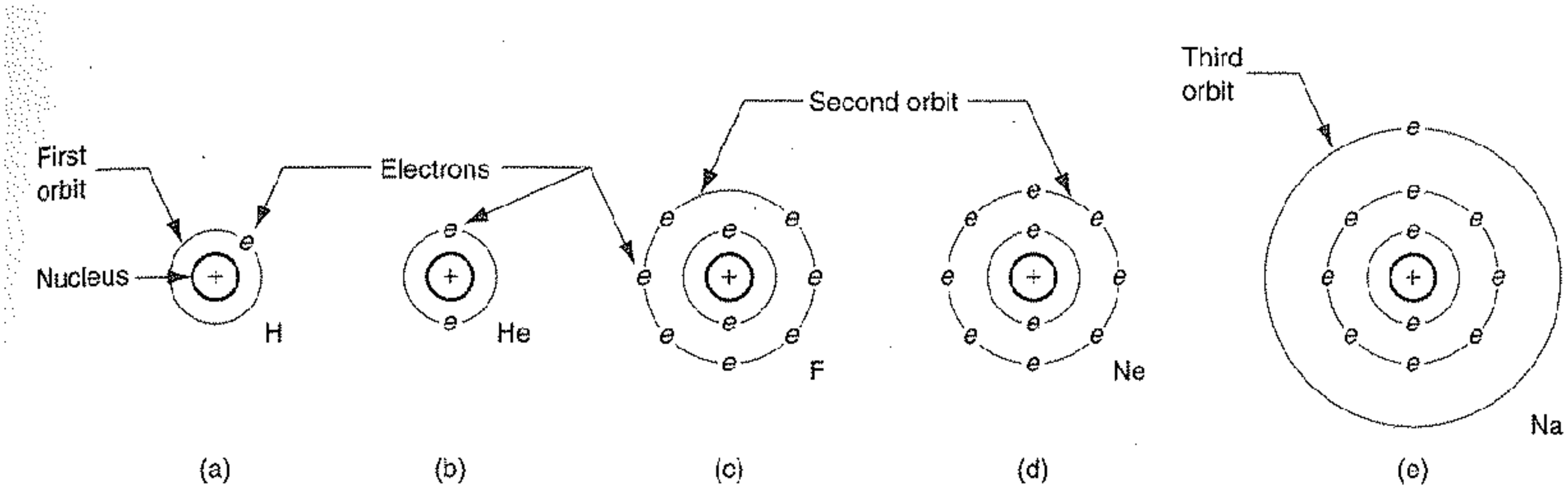


Fig. 2-2: Planetary (Bohr) atomic model.

Atomic Structure & The Elements

- The maximum numbers of atoms / orbit can be defined as:

  - Max. no. of electrons / orbit = $2n^2$; where n identifies the orbit.

- The electrons in the outmost shell are called valance electrons; the number of these atoms determine the atom's chemical affinity for other atoms.

- For example, Max. no. of electrons for the first orbit is 2. Hydrogen atom has one electron and hence needs another electron in its shell to become stable. That's why H reacts (bonds) readily with other atoms such as O to form H_2O or with another H atom to form H_2 molecule.

- On the other hand, the two electrons in the helium's atom only orbit are the maximum allowed, and so He is very stable.

Bonding Between Atoms & Molecules

- Atoms are bonded together to form molecules. Molecules on the other hand attract to each other to form other bonds, relatively weaker that the atom-atom bonds. Thus, we have two types of bonding; primary and secondary bonds.

  (1) <u>Primary bonds</u>: characterized by strong atom-to-atom attractions that involve the exchange of valence electrons. Primary bonds include the following forms:

  (a) *Ionic bonds*: in this form, the atoms of one element give up their outer electron(s), which are in turn attracted to atoms of some other element to increase their electron count in the outmost shell to 8.

- For example, the bond between fluorine and sodium.

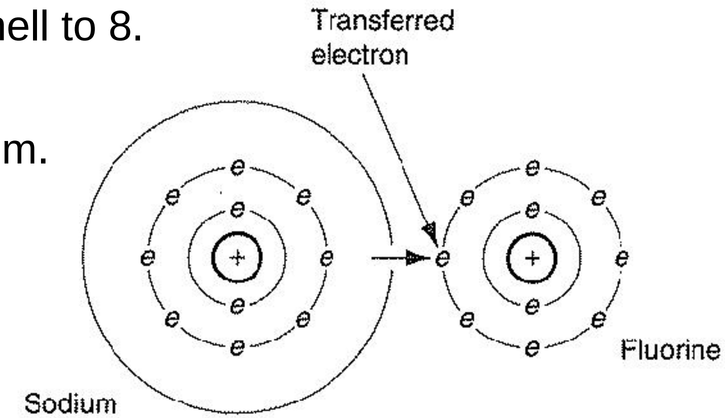


Fig. 2-3: Sodium fluoride molecule (ionic bond).

Note: properties of solid materials with ionic bonding include low electrical conductivity and poor ductility.

Bonding Between Atoms & Molecules

(1) Primary bonds: characterized by strong atom-to-atom attractions that involve the exchange of valence electrons. Primary bonds include the following forms:

(b) Covalent bonds: is one in which electrons are shared between atoms in their outmost shells to achieve a stable set of eight.

- For example, a fluorine atom bonds to another fluorine atom to form fluorine gas F_2. Also, one carbon atom (4 electrons in the outmost shell) bonds with four hydrogen atoms (only one electron in the only shell) to form methane gas.

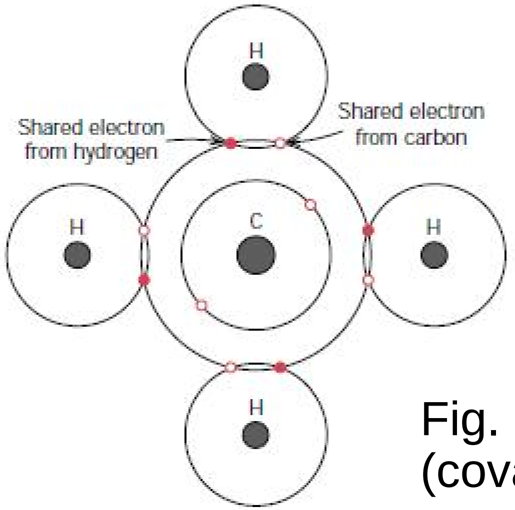


Fig. 2-4: Methane molecule (covalent bond).

Note: Ionic and covalent bonds are called *intra*molecular bonds because they involve attractive forces between atoms within the molecule.

Bonding Between Atoms & Molecules

(1) Primary bonds: characterized by strong atom-to-atom attractions that involve the exchange of valence electrons. Primary bonds include the following forms:

(c) Metallic bonds: involve the sharing of outer-shell electrons by all atoms to form a general electron cloud (sea of electrons) that permeates the entire block . This cloud provide the attractive forces to hold the atoms together and form a strong, rigid structure.

- For example, bonds in pure metals and metal alloys.

Note: Because of the general sharing of electrons, and their freedom to move within the metals, metallic bonding provides for good electrical conductivity. Materials with this type of bonding have good ductility, and good heat induction.

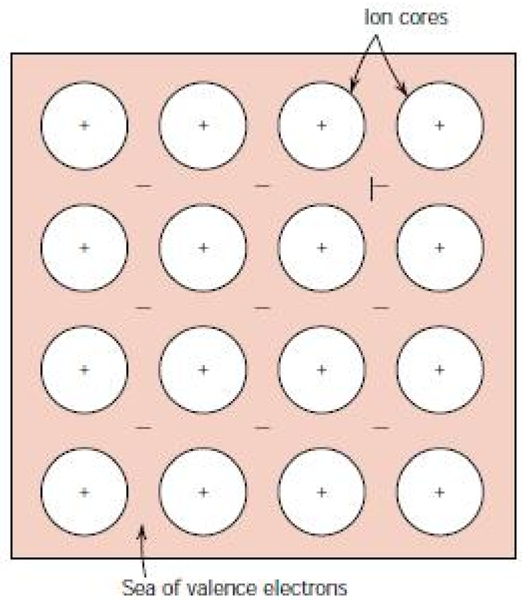


Fig. 2-5: metallic bonding.

Bonding Between Atoms & Molecules

(2) Secondary bonds: involve interaction forces between molecules, or intermolecular forces. There is no transfer or sharing of electrons in secondary bonding, and those bonds are therefore weaker than the primary bond. There are three forms of secondary bonds:

(a) Dipole forces: arise in a molecule comprising 2 atoms that have equal and opposite electrical charges. Each molecule therefore forms a dipole.

- For example, bonds between two HCl molecules.

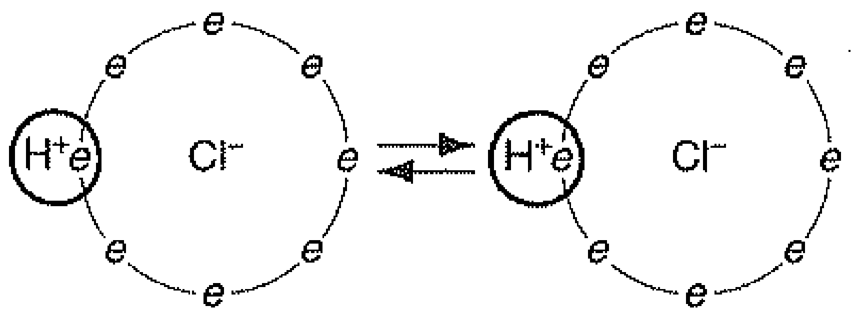


Fig. 2-6: dipole forces.

Bonding Between Atoms & Molecules

(2) Secondary bonds: involve interaction forces between molecules, or intermolecular forces. There is no transfer or sharing of electrons in secondary bonding, and those bonds are therefore weaker than the primary bond. There are three forms of secondary bonds:

(b) London forces: involve attractive forces between nonpolar molecules; that is, the atoms in the molecule do not form dipoles in the same sense as dipole forces. However, owing to the rapid motion of electrons in orbit around the molecule, temporary dipoles form when more electrons happen to be on one side of the molecule than the other.

Note: Dipole and London forces are often referred to as *van der Waals* forces.

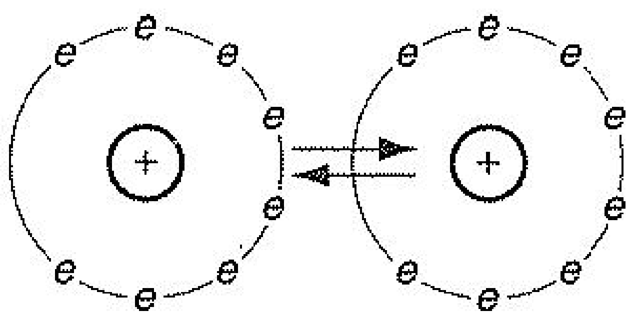


Fig. 2-7: London forces.

Bonding Between Atoms & Molecules

(2) Secondary bonds: involve interaction forces between molecules, or intermolecular forces. There is no transfer or sharing of electrons in secondary bonding, and those bonds are therefore weaker than the primary bond. There are three forms of secondary bonds:

(c) Hydrogen bonding: occurs in molecules containing H atoms that are covalently bonded to another atom (e.g. oxygen in H_2O). Since the electrons needed to complete the shell of the hydrogen atom are aligned on one side of its nucleolus, the opposite side has a net positive charge that attracts the electrons of atoms in neighboring molecules.

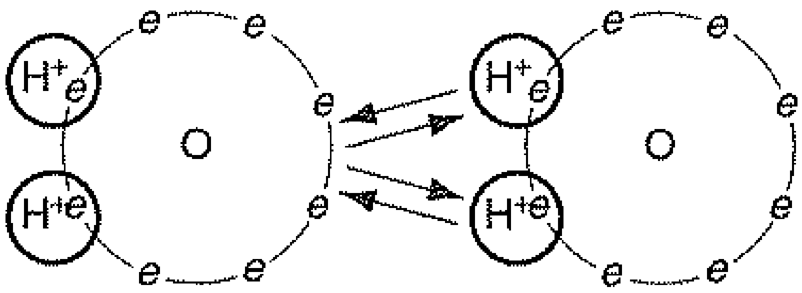


Fig. 2-8: Hydrogen bonding (water).

Note: hydrogen bonding is generally stronger than the other forms of secondary bonding (dipole and London forces), and it is important in the formation of many polymers.

Crystalline Structures

- A **crystalline** material is one in which the atoms are situated in a repeating or periodic array over large atomic distances; that is, long-range order exists, such that upon solidification, the atoms will position themselves in a repetitive three-dimensional pattern, in which each atom is bonded to its nearest-neighbor atoms (that includes all metals, many ceramics and many polymers).

- For those that do not crystallize, this long-range atomic order is absent; these are called **amorphous** materials.

- In metals, three lattice structures are common: (1) body-centered cubic, (2) face-centered cubic and (3) hexagonal close-packed.

Crystalline Structures

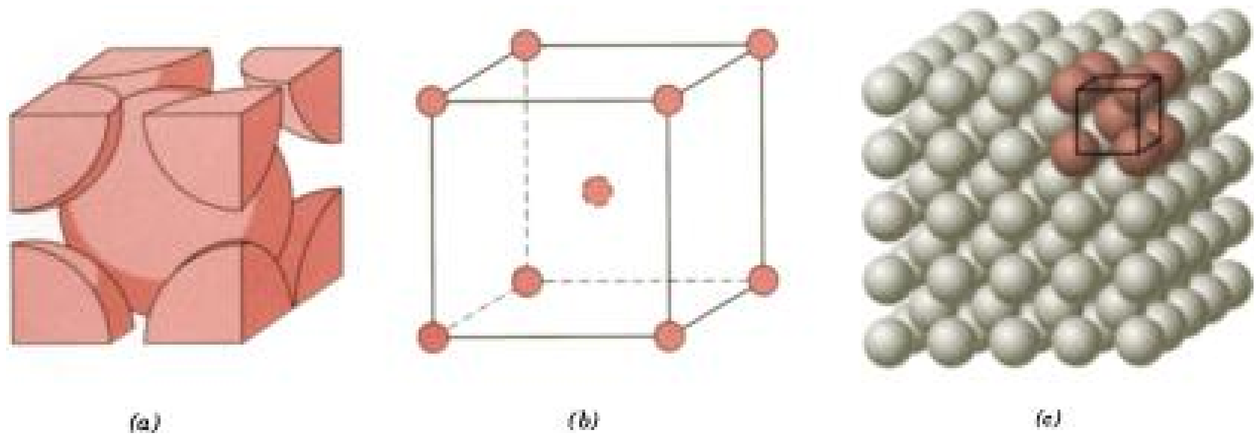


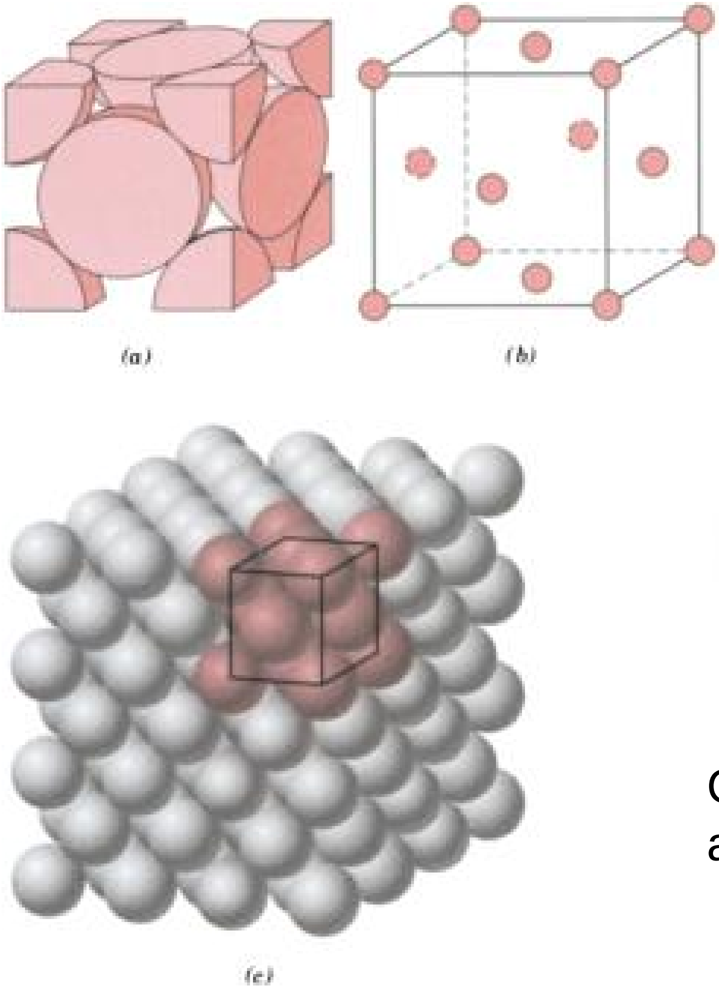
Fig. 2-9: BCC crystal structure.

(1) BCC: a crystal structure that has a cubic unit cell with atoms located at all eight corners and a single atom at the cube center (total of two atoms/unit cell).

Center and corner atoms touch one another along cube diagonals.

Coordination number and atomic packing factor for BCC are 8 and 0.68, respectively.

Crystalline Structures



(2) FCC: a crystal structure that has a cubic unit cell with atoms located at all eight corners and six atoms at the center of each face of the cube. (total of four atoms/unit cell).

Atoms touch one another across a face diagonal.

$a = 2r\sqrt{2}$; where a is the lattice constant and *r* is the atomic radius.

Coordination number and atomic packing factor for FCC are 12 and 0.74, respectively.

So, what do the Coordination number and atomic packing factor mean??

Fig. 2-10: FCC crystal structure.

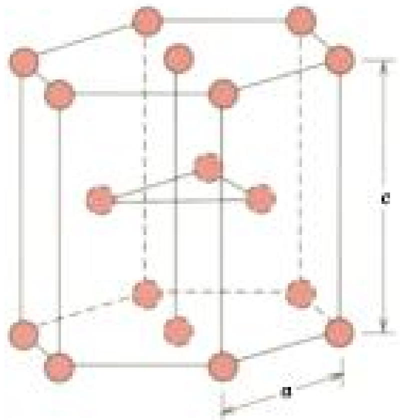
Crystalline Structures

- Coordination number: the number of nearest-neighbor atoms per atom.
- For FCC, the coordination number is 12; the front face atom has four corner nearest-neighbor atoms surrounding it, four face atoms that are in contact from behind, and four other equivalent face atoms residing in the next unit cell to the front.
- For the BCC, the coordination number is 8; each center atom has as nearest neighbors as its eight corner atoms.

Crystalline Structures

- Atomic packing factor (APF): is the fraction of solid sphere volume in a unit cell, assuming the atomic hard sphere model.
- APF = Volume of atoms in a unit cell / Volume if unit cell.
- Calculate the APF for FCC lattice.

Crystalline Structures



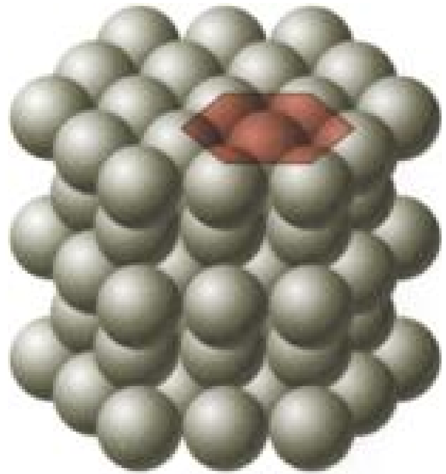


Fig. 2-11: HCP crystal structure.

(3) HCP: the top and bottom faces of the unit cell consist of six atoms that form regular hexagons and surround a single atom in the center. Another plane that provides three additional atoms to the unit cell is situated between the top and bottom planes. The equivalent of six atoms is contained in each unit cell; one-sixth of each of the 12 top and bottom face corner atoms, one-half of each of the 2 center face atoms, and all the 3 midplane interior atoms. If *a* and *c* represent, respectively, the short and long unit cell dimensions, the *c/a* ratio should be 1.633; however, for some HCP metals this ratio deviates from the ideal value.

Coordination number and atomic packing factor for HCP is similar to those of FCC (12 and 0.74, respectively).

Imperfections in Crystals

- Usually, crystal structures are not perfect. The imperfections (defects) arise due to the inability of the solidifying material to continue the replication of the unit cell indefinitely without interruption (grain boundaries are an example).
- In some other cases, these imperfections are introduced purposely during the manufacturing process; e.g. the addition of an alloying element in a metal to increase its strength (C in Fe).
- Hence, either term, imperfections or defects refers to the deviation in the regular pattern of the crystalline lattice structure. These can be catalogued as: (1) point defects, (2) line defects, and (3) surface defects.

Imperfections in Crystals

(1) <u>Point Defects</u>: there are four types of point defects:

(a) The simplest of the point defects is a **vacancy,** or vacant lattice site, one normally occupied from which an atom is missing.

(b) **Ion-pair vacancy** (or Schottky defect) involves a missing pair of ions of opposite charge in a compound that has an over all charge balance.

(c) **Interstitialcy**: a lattice distortion produced by the presence of an extra atom in the structure.

(d) **Displaced ion**: (Frenkel defect) occurs when an ion becomes removed from a regular position in the lattice structure and inserted into an interstitial position not normally occupied by such an ion.

Imperfections in Crystals

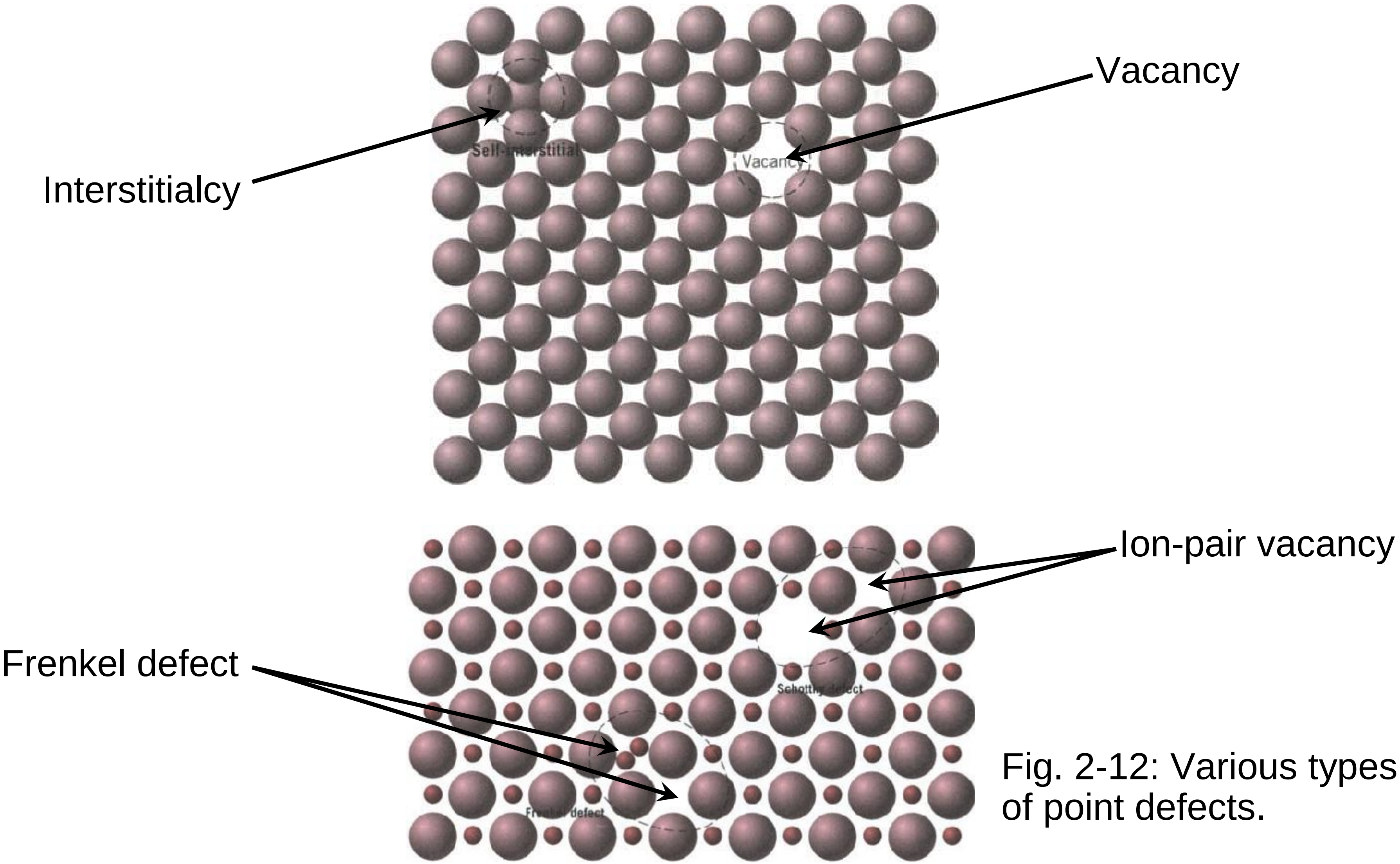


Fig. 2-12: Various types of point defects.

Imperfections in Crystals

(2) Line Defects: a line defect is a connected group of point defects that form a line in the lattice structure. The most important line defect is the *dislocation*, which can take two forms:

(a) Edge dislocation: an extra portion of a plane of atoms, or half-plane, the edge of which terminates within the crystal. it is a linear defect that centers around the line that is defined along the end of the extra half-plane of atoms. This is sometimes termed the **dislocation line,** which, for the edge dislocation in Figure 2-13, is perpendicular to the plane of the page.

Note: lattice distortion is maximum near the dislocation line.

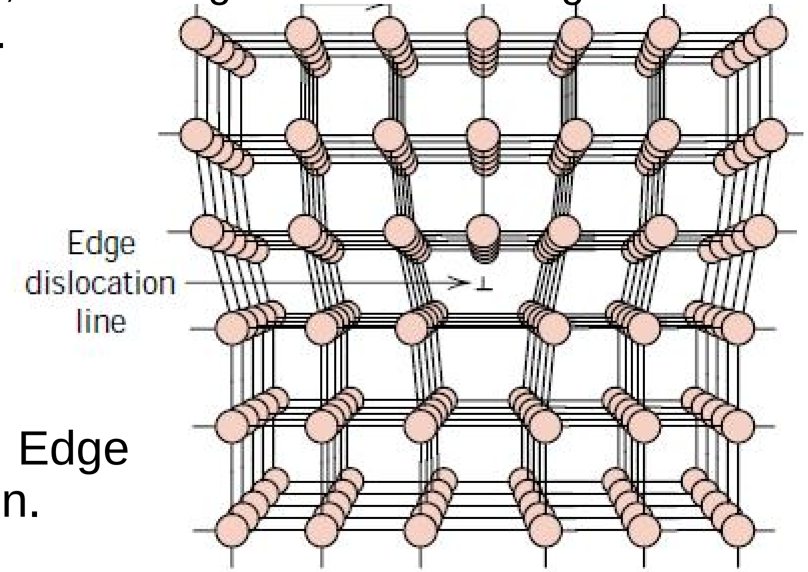


Fig. 2-13: Edge dislocation.

Imperfections in Crystals

(2) <u>Line Defects</u>: a line defect is a connected group of point defects that form a line in the lattice structure. The most important line defect is the *dislocation*, which can take two forms:

(b) Screw dislocation: which may be thought of as being formed by a shear stress that is applied to produce the distortion shown in Figure 2-14: the upper front region of the crystal is shifted one atomic distance to the right relative to the bottom portion.

Note: both types of dislocations are usually found in materials. They arise during solidification processes (casting) or during deformation processes (metal forming).

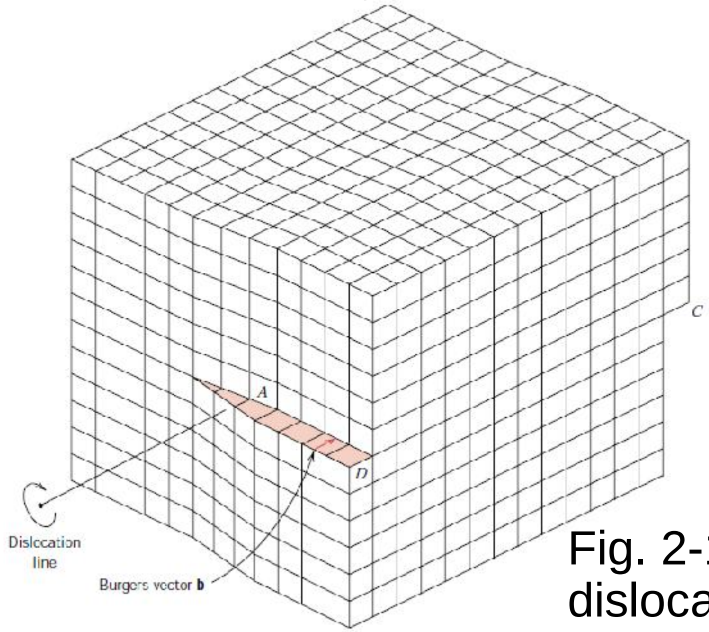


Fig. 2-14: Screw dislocation.

Imperfections in Crystals

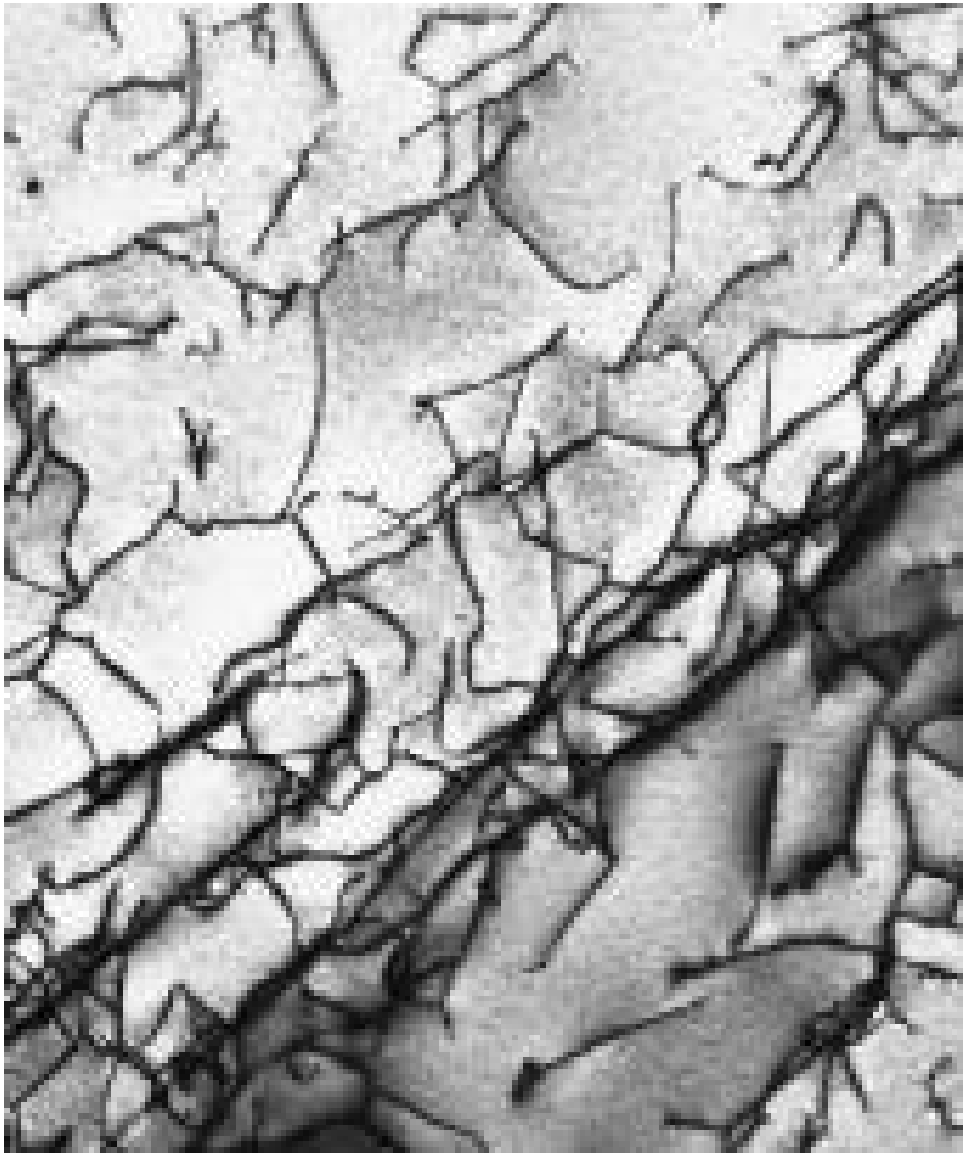


Fig 2-15: A transmission electron micrograph of a titanium alloy in which the dark lines are dislocations. 51,450×. (Courtesy of M. R. Plichta, Michigan Technological University.)

Imperfections in Crystals

(3) <u>Surface Defects</u>: imperfections that extend in two directions to form a boundary.

- The most obvious example is (a) the external surface of a crystalline object that defines its shape. The surface is an interruption in the lattice structure.

- Surface boundaries can also lie inside the material. Grain boundaries are the best example of these (b) internal surface interruptions.

Deformation in Metallic Crystals

- When a crystal is subjected to gradually increasing mechanical stress, its initial response it deform elastically **(elastic deformation)**. If the stress reaches a high value relative to the electrostatic forces holding the atoms in their lattice positions, a permanent shape change occurs, called **plastic deformation**.

(1) <u>Elastic deformation</u>: that type of deformation where the lattice structure is being tilted without any changes of position among the atoms in the lattice (Fig. 2-16 a and b). If the force is removed, the lattice structure (and therefore the crystal) returns to its original shape.

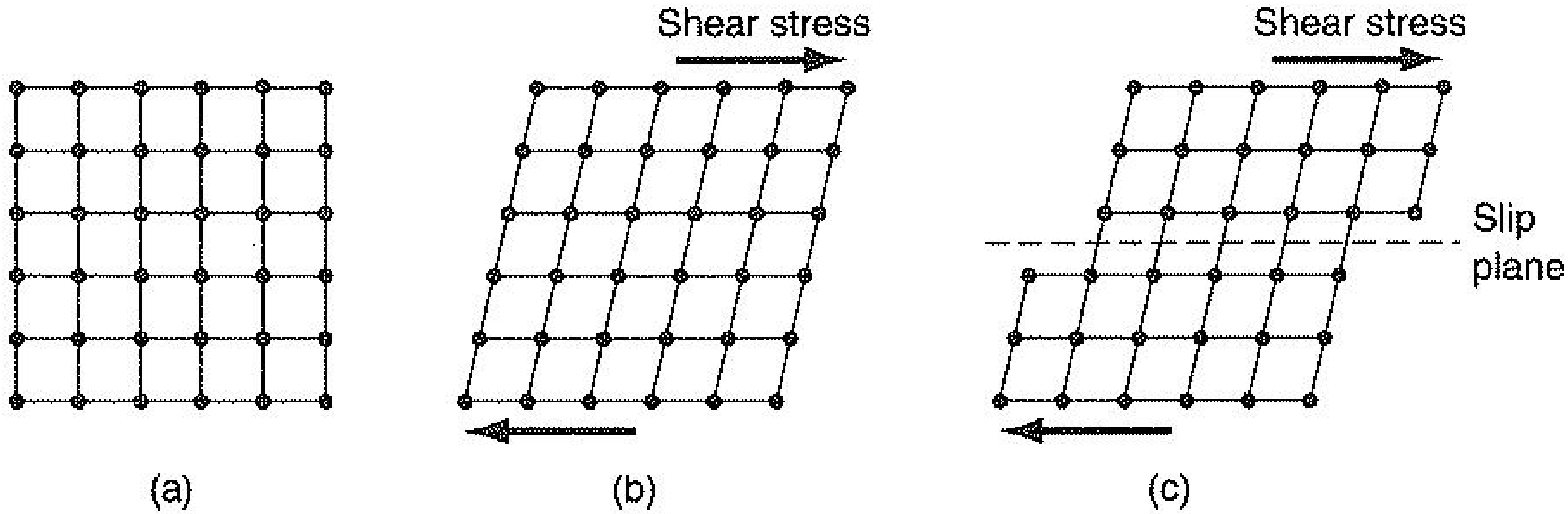


Fig. 2-16: (a) original crystal (b) elastic deformation (c) plastic deformation .

Deformation in Metallic Crystals

- When a crystal is subjected to gradually increasing mechanical stress, its initial response it deform elastically **(elastic deformation)**. If the stress reaches a high value relative to the electrostatic forces holding the atoms in their lattice positions, a permanent shape change occurs, called **plastic deformation**.

(2) Plastic deformation: that type of deformation where the atoms in the lattice have permanently moved from their previous locations, and a new equilibrium lattice has been formed (Fig. 2-16 c). If the force is removed, the lattice structure (and therefore the crystal) does not return to its original shape.

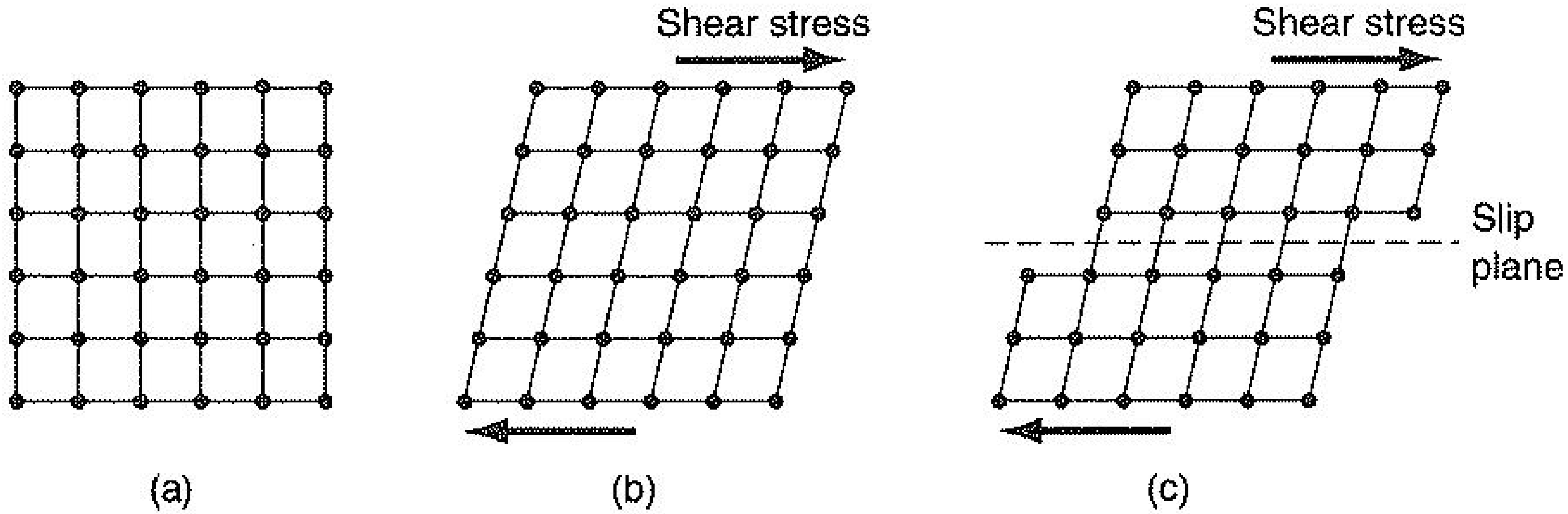


Fig. 2-16: (a) original crystal (b) elastic deformation (c) plastic deformation .

Deformation in Metallic Crystals

(2) Plastic deformation: the lattice deformation shown in (c) is one possible mechanism called slip, by which plastic deformation can occur in a crystalline structure. The other is called twinning.

- **Slip and slip systems**: slip involves the movement of atoms on the opposite sides of a plane in the lattice (preferred plane), and in that plane there are specific directions along which dislocation motion occurs. This plane is called the *slip plane;* it follows that the direction of movement is called the *slip direction.* This combination of the slip plane and the slip direction is termed the **slip system** (different crystal structures have different slip systems). The slip system depends on the crystal structure of the metal and is such that the atomic distortion that accompanies the motion of a dislocation is a minimum.

Materials with dislocations deform much more rapidly than in a perfect structure.

Dislocations move with stress.

Easier to move a dislocation than it is to deform the lattice itself! Why??

Deformation in Metallic Crystals

- The atoms at the edge dislocation require a smaller displacement within the distorted lattice structure in order to reach a new equilibrium position. Thus, a lower energy is needed to realign the atoms into the new positions than if the lattice were missing a dislocation.

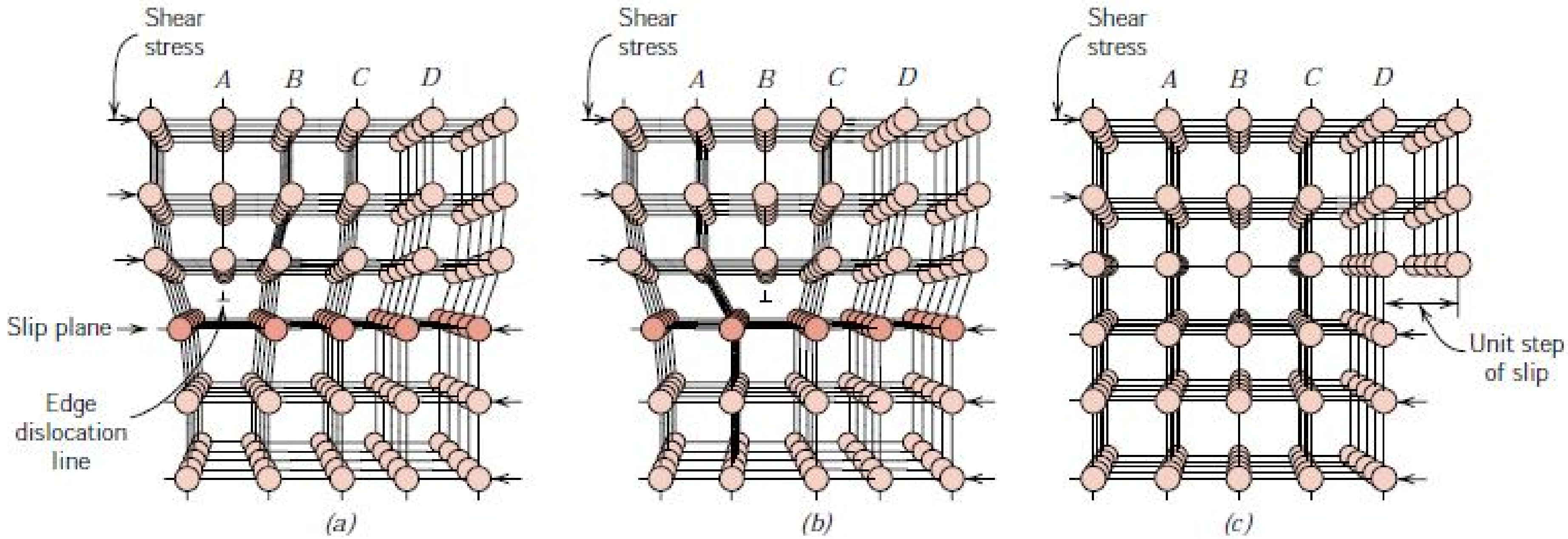


Fig. 2-17: Atomic rearrangements that accompany the motion of an edge dislocation as it moves in response to an applied shear stress. (*a*) The extra half-plane of atoms is labeled *A*. (*b*) The dislocation moves one atomic distance to the right as *A* links up to the lower portion of plane *B*; in the process, the upper portion of *B* becomes the extra half-plane. (*c*) A step forms on the surface of the crystal as the extra half-plane exits.

Deformation in Metallic Crystals; Slip Systems in FCC, BCC

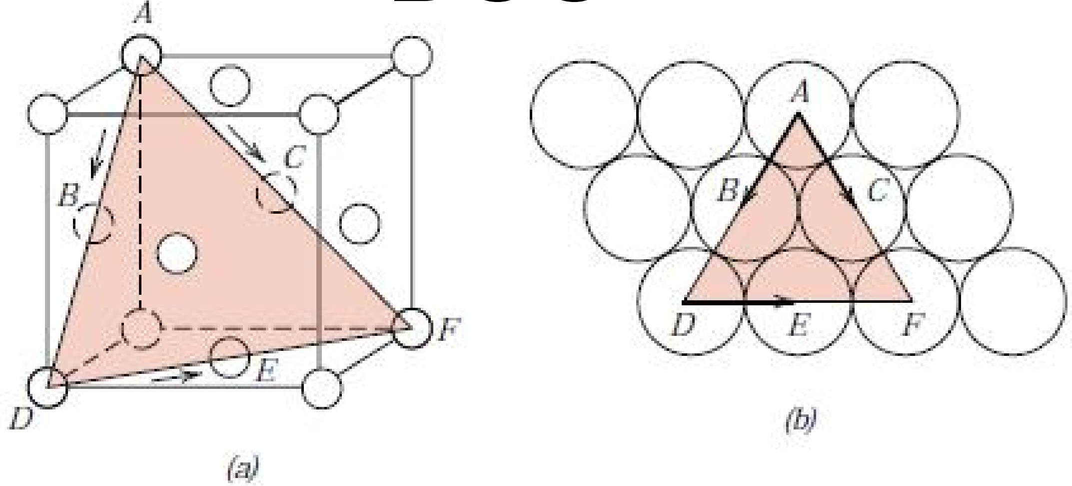


Fig. 2-18: (*a*) A {111} <110> slip system shown within an FCC unit cell. (*b*) The (111) plane from (*a*) and three <110> slip directions (as indicated by arrows) within that plane comprise possible slip systems.

There are 12 slip systems: four unique {111} planes and, within each plane, three independent <110> directions.

BCC crystal structure has more slip systems than FCC, an example is: {110} <111>.

Deformation in Metallic Crystals

(2) Plastic deformation: the lattice deformation shown in (c) is one possible mechanism called slip, by which plastic deformation can occur in a crystalline structure. The other is called twinning.

- **Twinning**: it is another way in which metal crystals plastically deform. Twinning is the mechanism of plastic deformation in which atoms of one side of a plane (twinning plane) are shifted to form a mirror image of the other side of the plane.

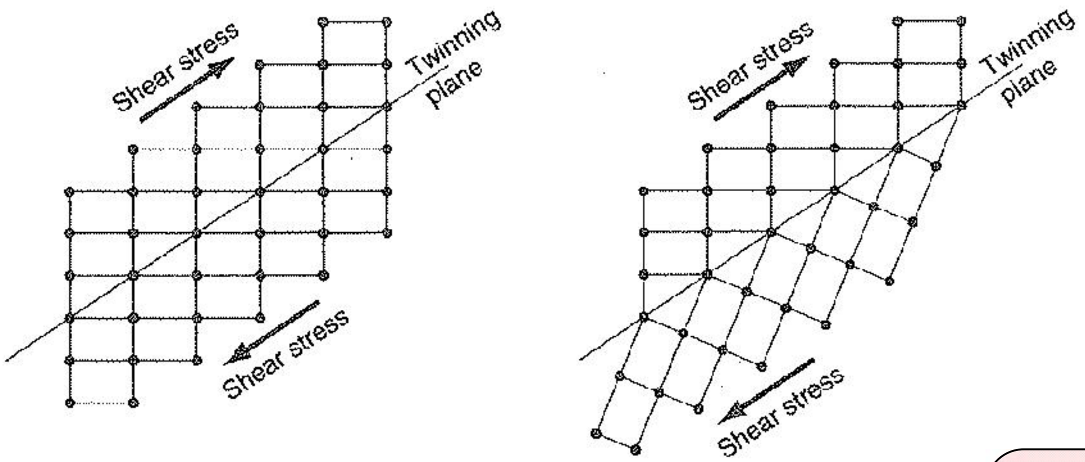


Fig. 2-19: Twinning involves the formation of an atomic mirror image (i.e., a "twin") on the opposite side of the twinning plane (a) before, and (b) after twinning.

Twinning is important for HCP metals as they do not slip readily.

Rate of deformation: slip needs time while twinning occurs instantaneously.

When subjected to high deformation rates, some metals would twin, while at moderate rates they deform by slip.

Grains and Grain Boundaries (GBs)

- Most crystalline solids are composed of a collection of many small crystals or **grains;** such materials are termed **polycrystalline.** Various stages in the solidification of a polycrystalline specimen are represented schematically in Fig. 2-20. Initially, small crystals or nuclei form at various positions. These have random crystallographic orientations, as indicated by the square grids. The small grains grow by the successive addition from the surrounding liquid of atoms to the structure of each. The extremities of adjacent grains impinge on one another as the solidification process approaches completion. As indicated in the figure, the crystallographic orientation varies from grain to grain. Also, there exists some atomic mismatch within the region where two grains meet; this area, called a **grain boundary**.

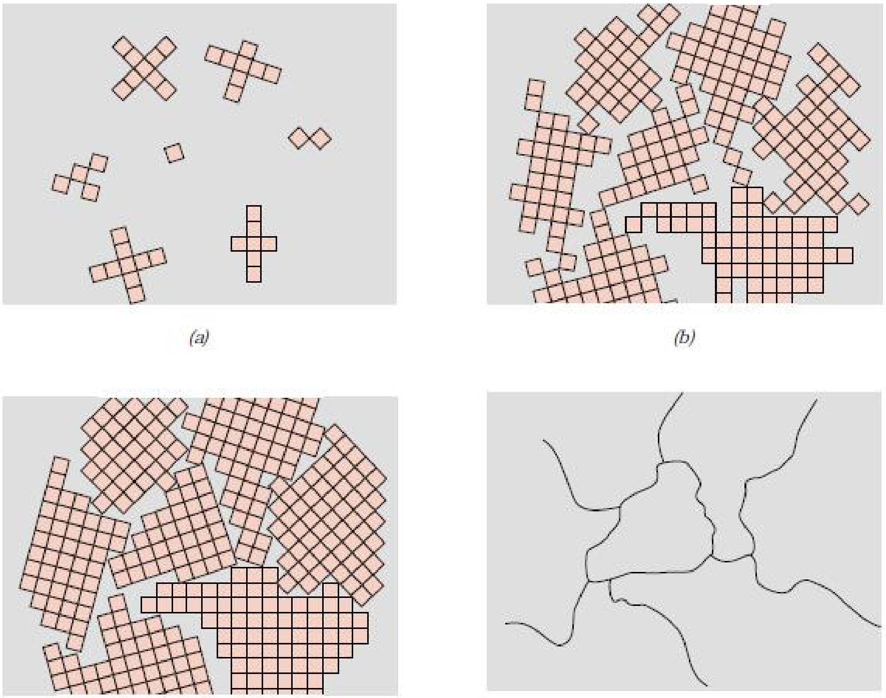


Fig. 2-20: Schematic diagrams of the various stages in the solidification of a polycrystalline material; the square grids depict unit cells. (*a*) Small crystallite nuclei. (*b*) Growth of the crystallites; the obstruction of some grains that are adjacent to one another is also shown. (*c*) Upon completion of solidification, grains having irregular shapes have formed. (*d*) The grain structure as it would appear under the microscope; dark lines are the grain boundaries.

Grains and Grain Boundaries (GBs)

Grain size is inversely related to cooling rate.

Grain size is important in metals; it affects the properties.

Materials with small grain sizes have higher strength and hardness (GBs hinder dislocation motion).

Noncrystalline (Amorphous) Structures

- **Noncrystalline** solids are those materials that lack a systematic and regular arrangement of atoms over relatively large atomic distances. Sometimes such materials are also called **amorphous** (meaning literally without form), or supercooled liquids, inasmuch as their atomic structure resembles that of a liquid; e.g. many glasses, and rubber.

- Amorphous structures can form if the cooling rate during the transformation from liquid to solid is high enough, so that little time is allowed for the ordering process.

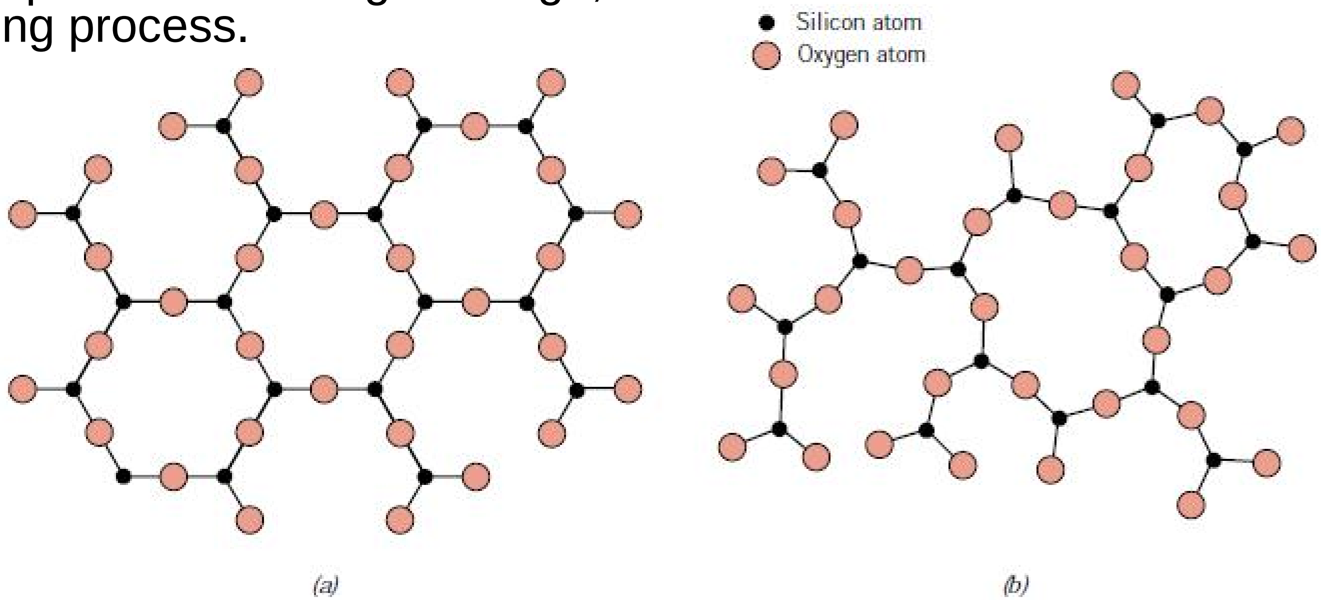


Fig 2-21: Two-dimensional schemes of the structure of (*a*) crystalline and (*b*) noncrystalline SiO_2.

Noncrystalline (Amorphous) Structures

- There are two main differences between crystalline and noncrystalline materials:

(a) Absence of a long-range order in the molecular structure of a noncrystalline material (as shown in the previous figure).

(b) Differences in melting and thermal expansion characteristics.

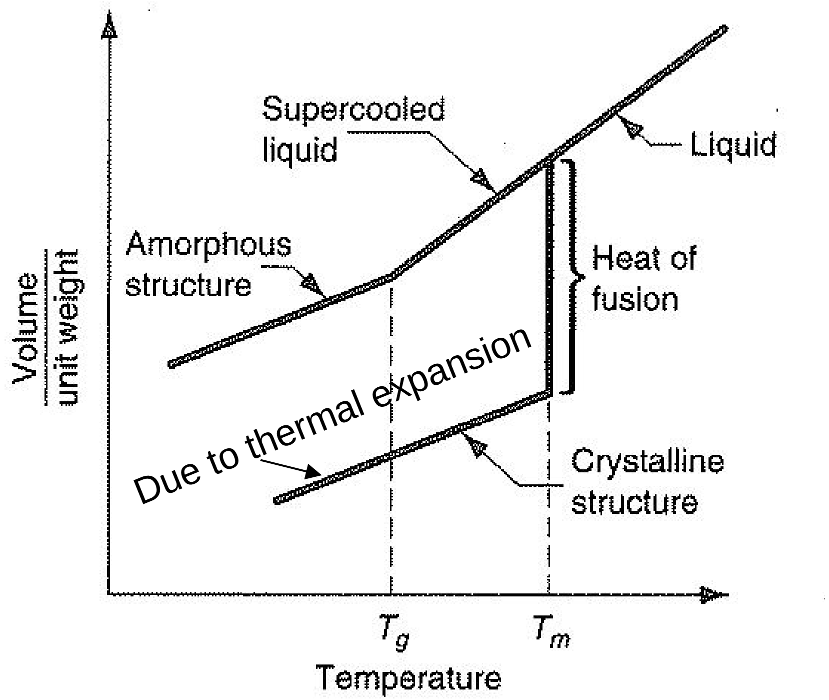


Fig 2-22: Change in volume for pure metal vs. glass.

T_g: temp. at which the supercooled liquid converts to solid. T_m: melting temp. of the metal.

Engineering Materials

(1) Metals: - Crystalline (BCC, FCC, HCP, etc). – Metallic bonding. Structure and bonding make metals strong, hard, ductile, high thermal and electrical conductivity, opaqueness and reflectivity.

(2) Ceramics: - Mostly crystalline. – Ionic or covalent bonding, or both. – High hardness and stiffness. – Brittleness. – Electrical and thermal insulating, and chemically inert.

(3) Polymers: A polymer molecule consists of many repeating *mers* to form very large molecules held together by covalent bonding. Secondary bonding (*van der Waals*) holds the molecules together. – Low density. – High electrical resistivity. – Low thermal conductivity. – Some polymers are hard and rigid while other exhibit great elasticity. - Amorphous or amorphous and crystalline. – Three types:

(a) Thermoplastic polymers.
(b) Thermosetting polymers, and
(c) Elastomers.

Manufacturing Processes

Chapter Twenty:

Sheet Metalworking

Dr. Eng. Yazan Al-Zain
Department of Industrial Engineering

Introduction

- ***Sheet Metalworking*** includes cutting and forming operations performed on relatively thin sheets of metal.
- Typical sheet-metal thicknesses are between 0.4 mm and 6 mm.
- For thickness more than 6 mm, the stock is usually referred to as plate rather than sheet.
- The sheet or plate stock used in sheet metalworking is produced by flat rolling.
- The most commonly used sheet metal is low carbon steel (0.06%–0.15% C). Its low cost and good formability, combined with sufficient strength for most product applications, make it ideal as a starting material.

Introduction

- Products that include sheet or plate metal parts: automobile and truck bodies, airplanes, railway cars, locomotives, farm and construction equipment, appliances, office furniture, and more.

- Accordingly, the commercial importance of sheet metalworking is significant.

- Sheet metal parts are generally characterized by high strength, good dimensional accuracy, good surface finish, and relatively low cost.

- Economical mass-production: designed to process the parts. Aluminum beverage cans are a prime example.

Introduction

- Sheet-metal processing is usually performed at room temperature (cold working).

- The exceptions are when the stock is thick, the metal is brittle, or the deformation is significant. These are usually cases of warm working rather than hot working.

- ***Stamping Presses***: machine tools on which most sheet-metal operations are performed.

- ***A Punch-and-Die*** (***Stamping Die***): the tooling that performs sheet metalwork.

- ***Stampings***: the sheet-metal products.

Cutting Operations

- Cutting of sheet metal is accomplished by a shearing action between two sharp cutting edges.

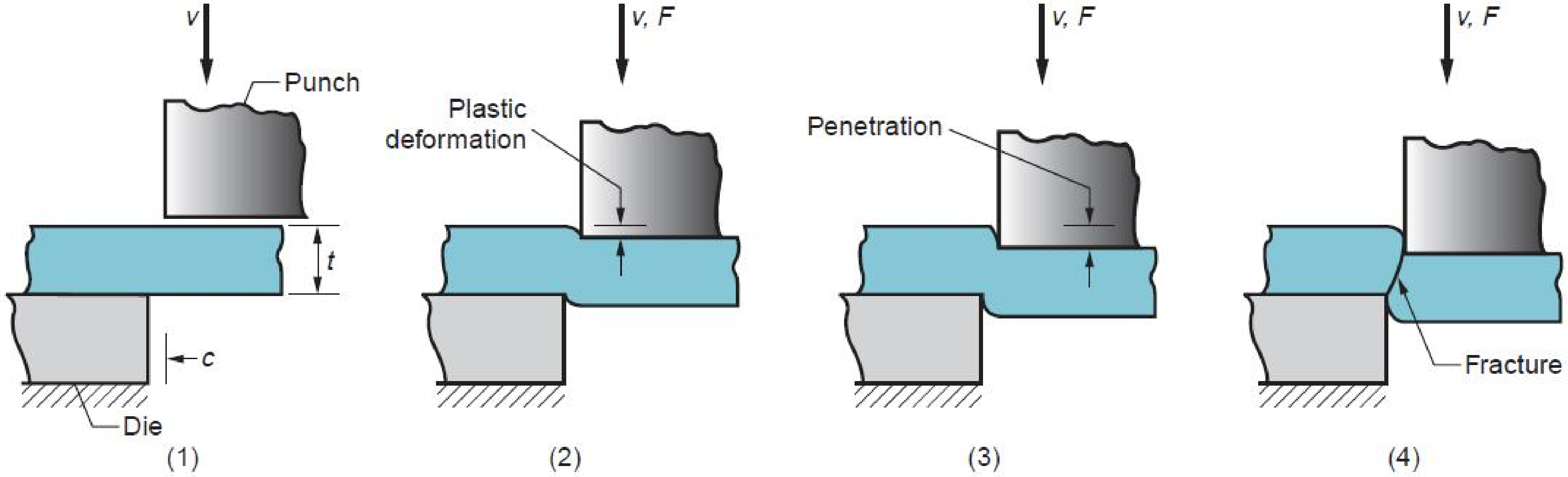


Figure 20.1 Shearing of sheet metal between two cutting edges: (1) just before the punch contacts work; (2) punch begins to push into work, causing plastic deformation; (3) punch compresses and penetrates into work causing a smooth cut surface; and (4) fracture is initiated at the opposing cutting edges that separate the sheet. Symbols *v* and *F* indicate motion and applied force, respectively, *t* = stock thickness, *c* = clearance.

Cutting Operations
Shearing, Blanking & Punching

- The three most important operations in pressworking that cut metal by the shearing mechanism: ***Shearing***, ***Blanking***, and ***Punching***.
  - ***Shearing***: a sheet-metal cutting operation along a straight line between two cutting edges.
  - Used to cut large sheets into smaller sections for subsequent pressworking operations.
  - Performed on a machine called ***a power shears***, or ***squaring shears***.
  - The upper blade of the power shears is often inclined to reduce the required cutting force.

Cutting Operations
Shearing, Blanking & Punching

– ***Shearing***:

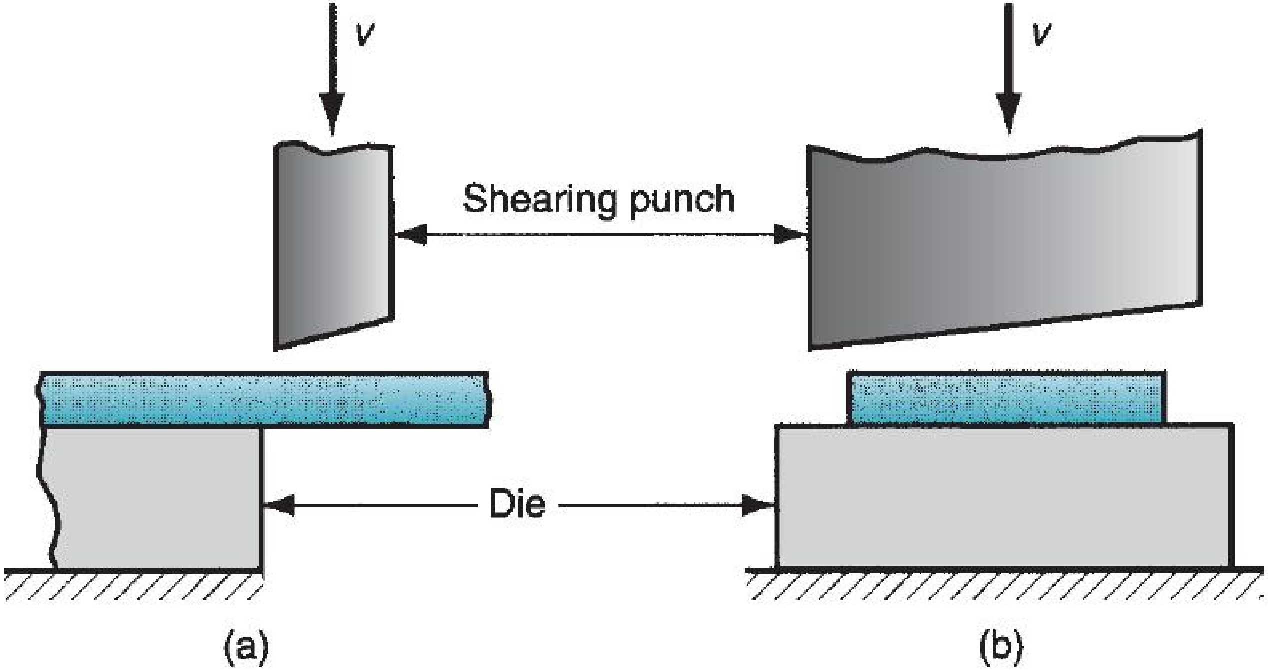


Figure 20.2 Shearing operation: (a) side view of the shearing operation; (b) front view of power shears equipped with inclined upper cutting blade.

Cutting Operations
Shearing, Blanking & Punching

- The three most important operations in pressworking that cut metal by the shearing mechanism: ***Shearing***, ***Blanking***, and ***Punching***.
  - ***Blanking***: involves cutting of the sheet metal along a closed outline in a single step to separate the piece from the surrounding stock.
  - The part that is cut out is the desired product in the operation and is called the ***blank***.
  - ***Punching***: similar to blanking except that it produces a hole, and the separated piece is scrap, called the ***slug***.
  - The remaining stock is the desired part.

Cutting Operations
Shearing, Blanking & Punching

– ***Blanking*** and ***Punching***:

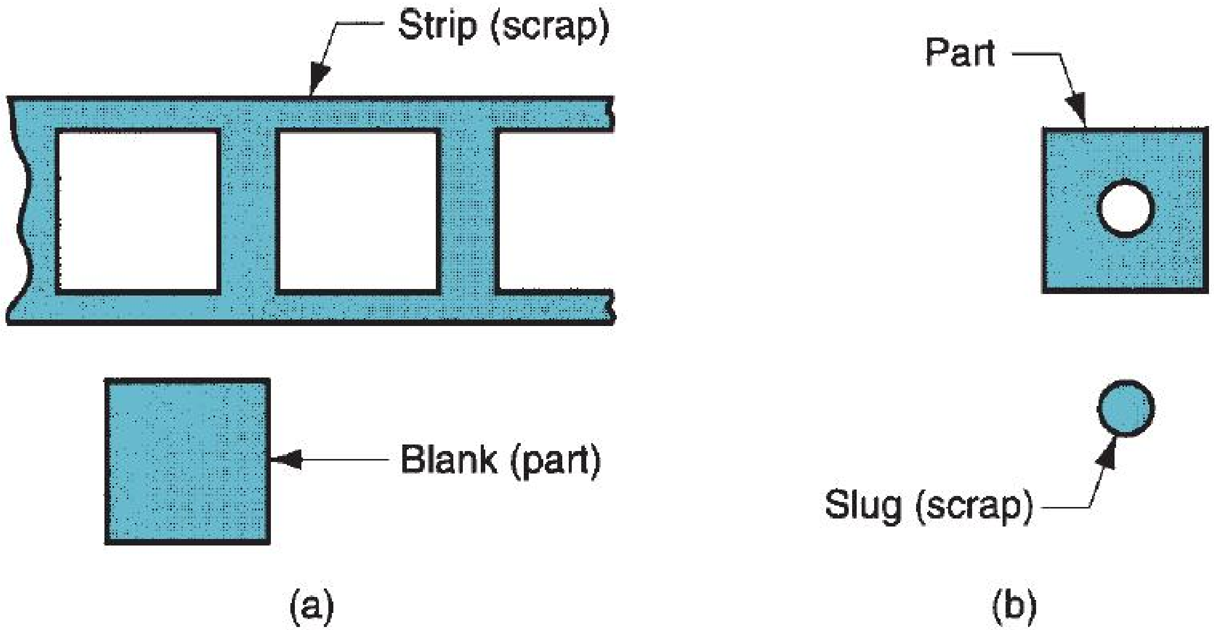


Figure 20.3 (a) Blanking and (b) punching.

Cutting Operations
Engineering Analysis of Sheet-Metal Cutting

- Process parameters in sheet-metal cutting are:
  - Clearance between punch and die.
  - Stock thickness.
  - Type of metal and its strength.
  - Length of the cut.

Cutting Operations
Engineering Analysis of Sheet-Metal Cutting

- ***Clearance***: The clearance *c* in a shearing operation is the distance between the punch and die, as shown in Figure 20.1(1).
  - Usually range between 4% and 8% of the sheet-metal thickness.
  - Improper clearance: see Figure below.

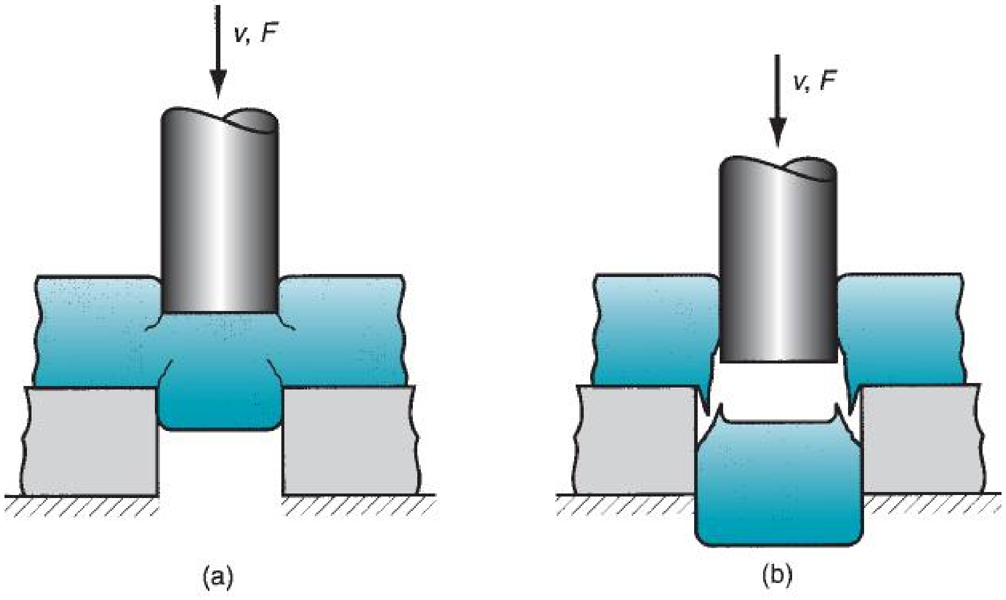


Figure 20.4 Effect of clearance: (a) clearance too small causes less than optimal fracture and excessive forces; and (b) clearance too large causes oversized burr (a sharp corner on the edge caused by elongation of the metal during final separation of the two pieces).

Cutting Operations
Engineering Analysis of Sheet-Metal Cutting

- ***Clearance***: correct value depends on sheet metal type and thickness.

$$c = at$$ where c = clearance, mm; a = allowance; and t = thickness, mm.

- Allowance depends on the sheet-metal type.

TABLE 20.1 Clearance allowance value for three sheet-metal groups.

Metal Group	A_c
1100S and 5052S aluminum alloys, all tempers	0.045
2024ST and 6061ST aluminum alloys; brass, all tempers; soft cold-rolled steel, soft stainless steel	0.060
Cold-rolled steel, half hard; stainless steel, half-hard and full-hard	0.075

- These calculated clearance values can be applied to conventional blanking and hole punching operations to determine the proper punch and die sizes.

Cutting Operations
Engineering Analysis of Sheet-Metal Cutting

- Whether to add the clearance value to the die size or subtract it from the punch size depends on whether the part being cut out is a blank or a slug, as illustrated below for a circular part.

Punch and dies sizes for a round blank of diameter D_b:

Blanking punch diameter = $D_b - 2c$

Blanking die diameter = D_b

Punch and dies sizes for a round hole of diameter D_h:

Hole punch diameter = D_h

Hole die diameter = $D_h + 2c$

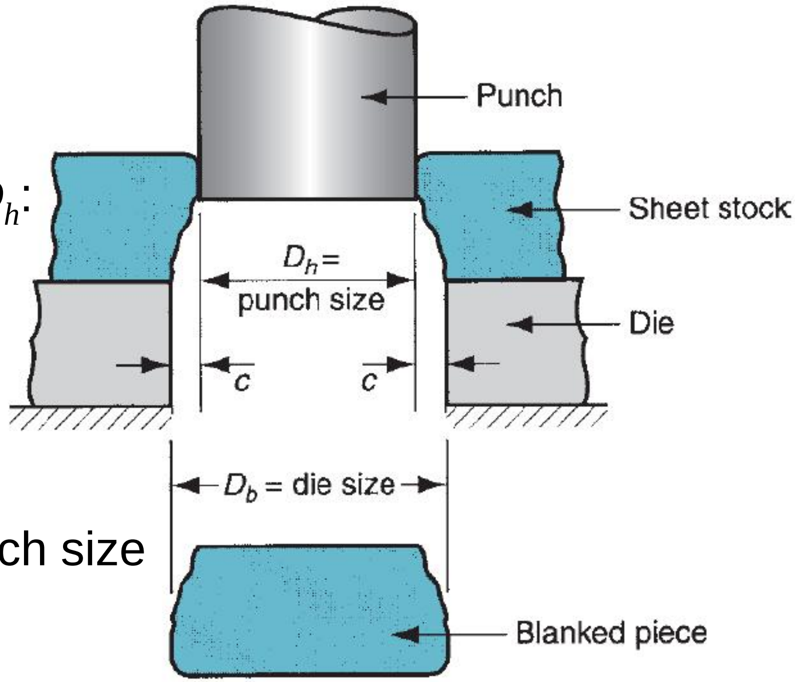


Figure 20.5 Die size determines blank size D_b; punch size determines hole size D_h.

Cutting Operations
Engineering Analysis of Sheet-Metal Cutting

- In order for the slug or blank to drop through the die, the die opening must have an angular clearance of 0.25º to 1.5º on each side.

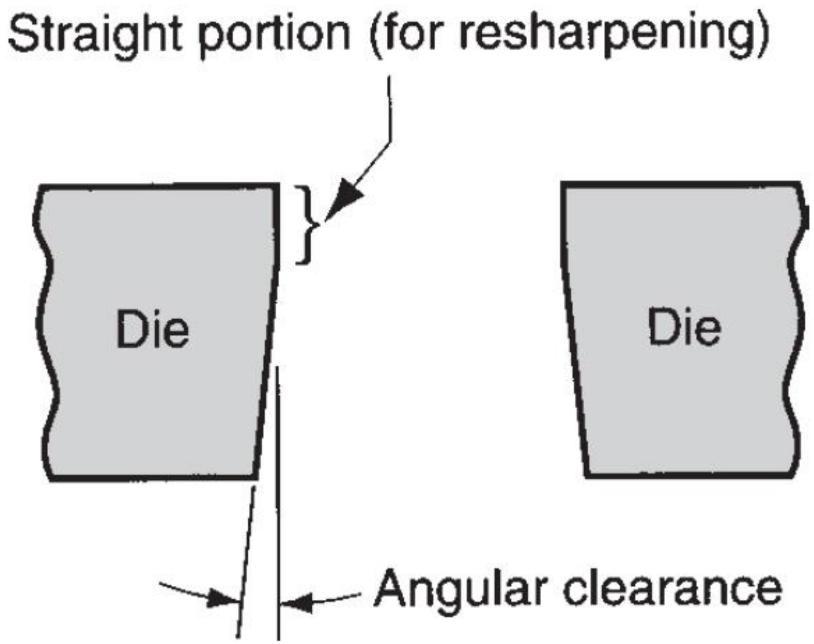


Figure 20.6 Angular clearance.

Cutting Operations
Engineering Analysis of Sheet-Metal Cutting

- ***Cutting Forces***: important as they determine the size of the press needed.

$$F = StL$$

where F = cutting force (N); S = shear strength of the metal (MPa); t = stock thickness (mm); and L = length of the cut edge (mm).

- In case the shear strength was unknown, then:

$$F = 0.7TStL$$

where TS = ultimate tensile strength (MPa).

- Example 20.1:

Cutting Operations
Other Sheet-Metal-Cutting Operations

- In addition to shearing, blanking, and punching, there are several other cutting operations in pressworking.

  - ***Cutoff*** and ***Parting***.
  - ***Slotting***, ***Perforating***, and ***Notching***.
  - ***Trimming***, ***Shaving***, and ***Fine Blanking***.

Cutting Operations
Other Sheet-Metal-Cutting Operations

- ***Cutoff*** and ***Parting***.

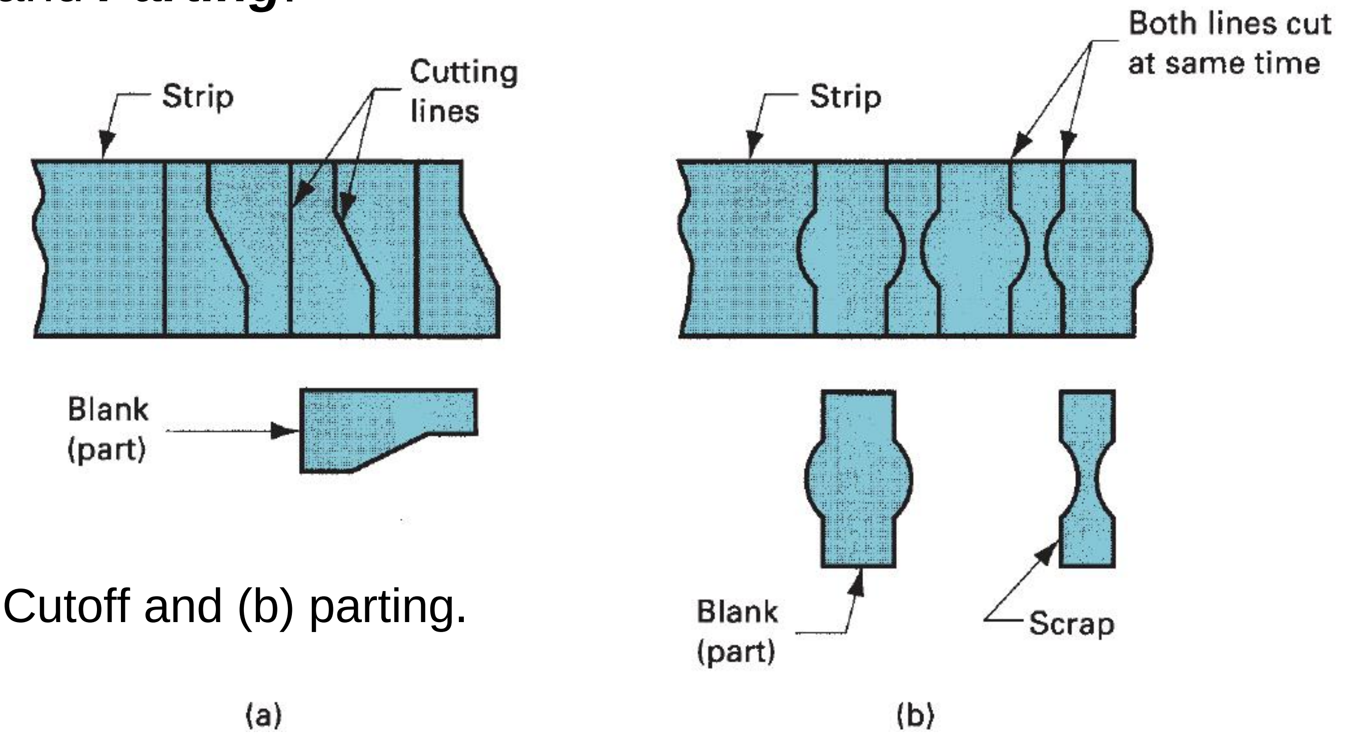


Figure 20.7 (a) Cutoff and (b) parting.

No scrap

Scrap forms

Cutting Operations
Other Sheet-Metal-Cutting Operations

- ***Slotting***, ***Perforating***, and ***Notching***..

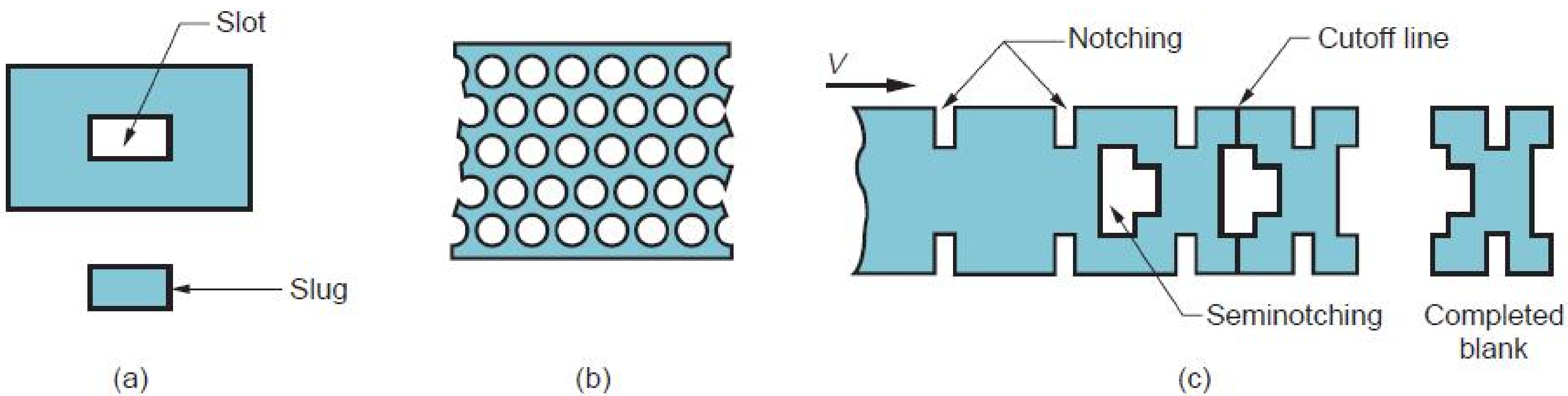


Figure 20.8 (a) Slotting (cutting out elongated or rectangular hole), (b) perforating (simultaneous punching of a pattern of holes), (c) notching (cutting out a portion of metal from the side of the sheet) and seminotching (removes a portion of metal from the interior of the sheet).

Cutting Operations
Other Sheet-Metal-Cutting Operations

- ***Trimming***, ***Shaving***, and ***Fine Blanking***.

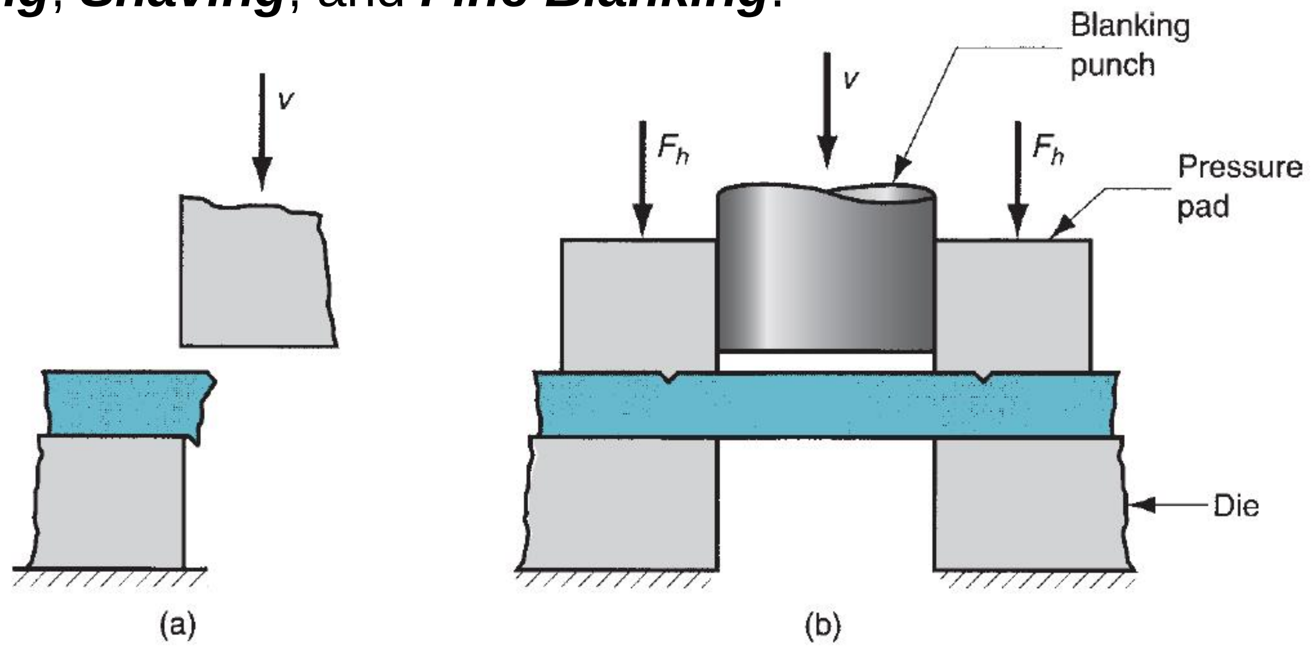


Figure 20.9 (a) Shaving (to cut unsmooth edges and get accurate dimensions) and (b) fine blanking (gives close tolerance and smooth, straight edges).

Bending Operations

- ***Bending*** in sheet-metalwork: the straining of the metal around a straight axis.

- During the bending: the metal on the inside of the neutral plane is compressed, while the metal on the outside is stretched.

- The metal is plastically deformed so that the bend takes a permanent set upon removal of the stresses that caused it.

- Bending produces little or no change in the thickness of the sheet metal.

Bending Operations

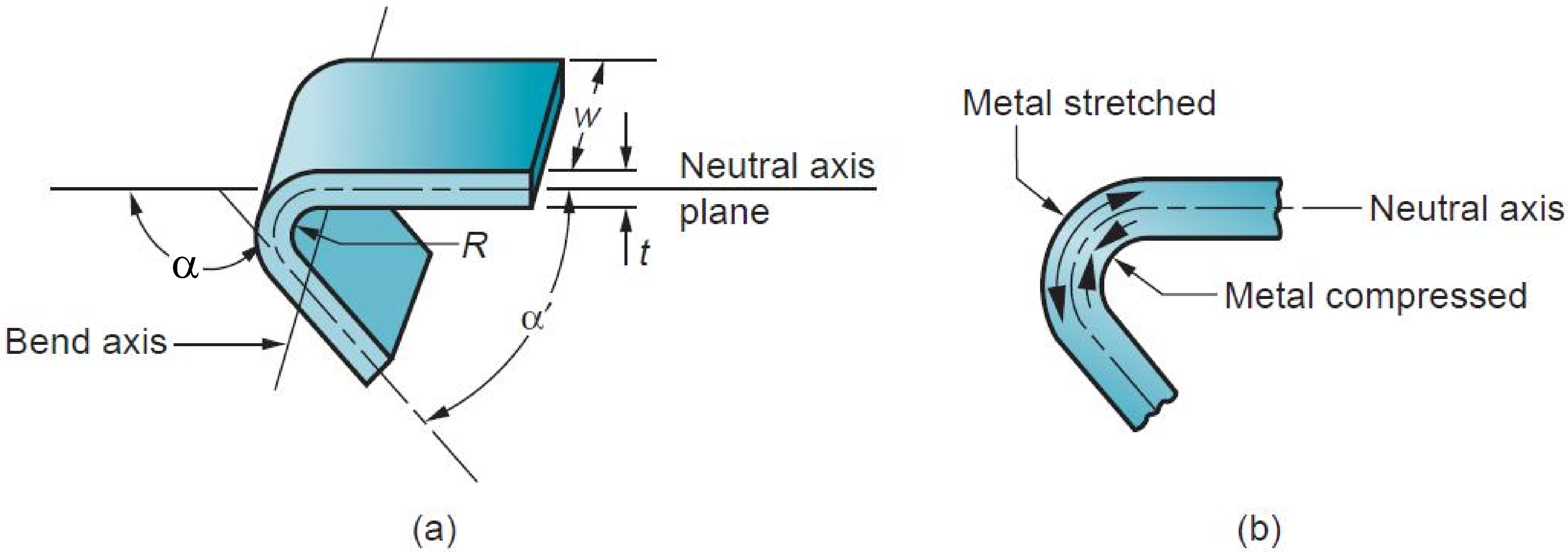


Figure 20.10 (a) Bending of sheet metal; (b) both compression and tensile elongation of the metal occur in bending.

Bending Operations
V-Bending & Edge-Bending

- 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.

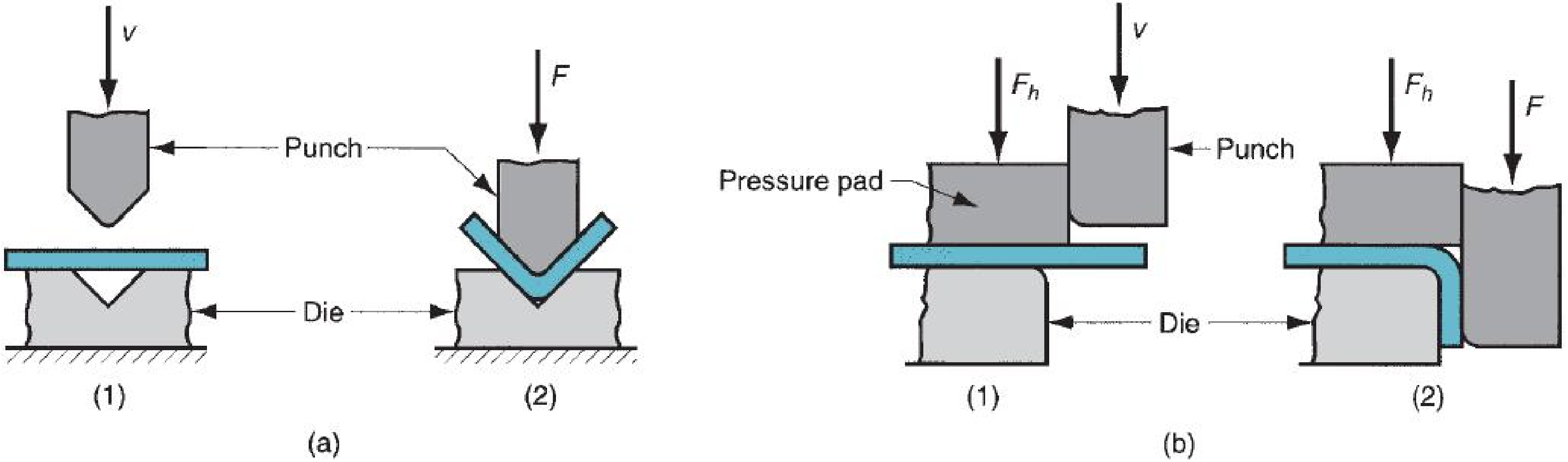


Figure 20.11 Two common bending methods: (a) V-bending and (b) edge-bending; (1) before and (2) after bending. v = motion, F = applied bending force, F_h = blank.

Bending Operations
V-Bending & Edge-Bending

- ***V-Bending***: the sheet metal is bent between a V-shaped punch and die.
  - Angles ranging from very obtuse to very acute can be made with V-dies.
  - Generally used for low-production operations.
  - 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 F_h 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.
  - Because of the pressure pad, wiping dies are more complicated and costly than V-dies and are generally used for high-production work.

Bending Operations
Engineering Analysis of Bending

[1] Metal of thickness *t* is bent through an angle called the bend angle α.

[2] Result: a sheet-metal part with an included angle α', where $\alpha + \alpha' = 180^o$.

[3] Bend radius (*R*): specified on the inside of the part, and is determined by the radius on the tooling used to perform the operation.

[4] The bend is made over the width of the workpiece *w*.

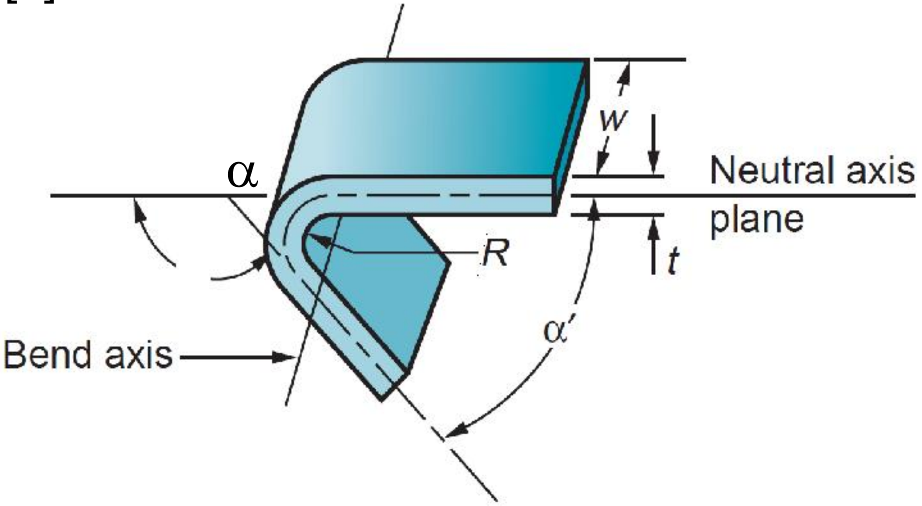


Figure 20.12 (a) Bending of sheet metal.

Bending Operations
Engineering Analysis of Bending

- ***Bend Allowance***: If the bend radius is small relative to stock thickness, the metal tends to stretch during bending.
  - It is important to be able to estimate the amount of stretching, so that the final part length will match the specified dimension.
  - The problem is to determine the length of the neutral axis before bending to account for stretching of the final bent section.
  - This length is called the ***bend allowance***.

$$A_b = 2\pi \frac{\alpha}{360}(R + K_{ba}t)$$

where A_b = Bend allowance, mm; α = bend angle, degrees; R = bend radius, mm; t = stock thickness, mm; and K_{ba} is factor to estimate stretching.

values recommended for K_{ba}: if $R < 2t$, K_{ba} = 0.33; and if $R \geq 2t$, K_{ba} = 0.50. The values of K_{ba} predict that stretching occurs only if bend radius is small relative to sheet thickness.

Bending Operations
Engineering Analysis of Bending

- ***Spring Back***: 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***.
  - It is the increase in included angle of the bent part relative to the included angle of the forming tool after the tool is removed.

$$SB = \frac{\alpha' - \alpha'_t}{\alpha'_t}$$

where SB = springback; α' = included angle of the sheet-metal part, degrees; and α'_t = included angle of the bending tool, degrees.

Although not as obvious, an increase in the bend radius also occurs due to elastic recovery. The amount of springback increases with modulus of elasticity E and yield strength Y of the work metal.

Bending Operations
Engineering Analysis of Bending

- Amount of springback can be compensated by:
  - ***Overbending***: the punch angle and radius are fabricated slightly smaller than the specified angle on the final part so that the sheet metal springs back to the desired value.
  - ***Bottoming***: squeezing the part at the end of the stroke, thus plastically deforming it in the bend region.

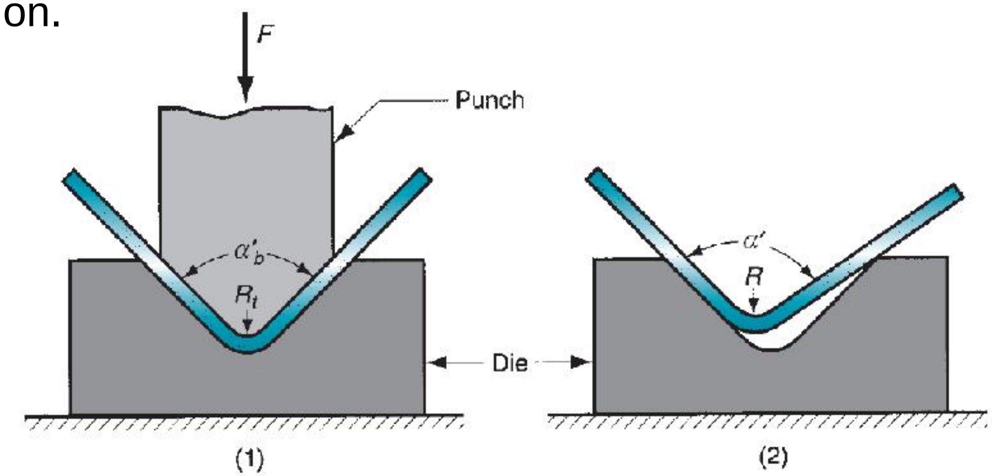


Figure 20.13 Springback in bending shows itself as a decrease in bend angle and an increase in bend radius: (1) during the operation, the work is forced to take the radius R_t and included angle α'_t is determined by the bending tool (punch in V-bending); (2) after the punch is removed, the work springs back to radius R and included angle α'.

Bending Operations
Engineering Analysis of Bending

- ***Bending Force***: force required to perform bending depends on geometry of the punch-and-die and strength, thickness, and length of the sheet metal.

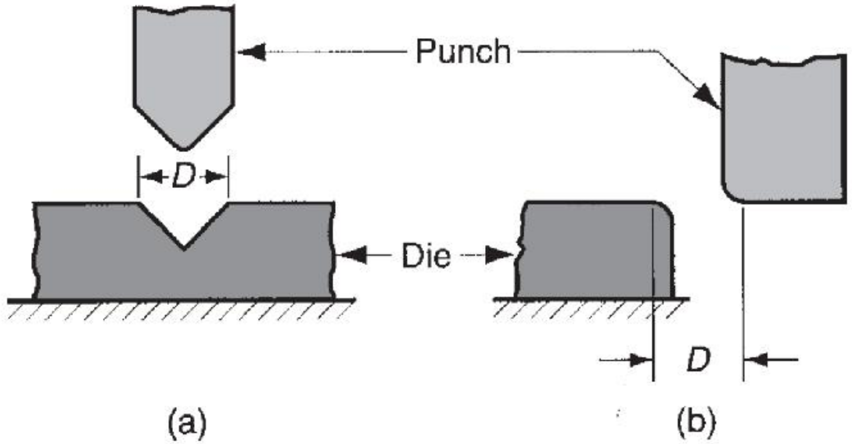


Figure 20.14 Die opening dimension *D*: (a) V-die, (b) wiping die.

$$F = \frac{K_{bf}(TS)wt^2}{D}$$

where F = bending force, N; (TS) = tensile strength of the sheet metal, MPa; w = width of part in the direction of the bend axis, mm; t = stock thickness, mm; and D = die opening dimension as defined in Figure 20.12, mm.

This equation is based on bending of a simple beam in mechanics, and K_{bf} is a constant that accounts for differences encountered in an actual bending process. Its value depends on type of bending: for V-bending, K_{bf} = 1.33; and for edge bending, K_{bf} = 0.33.

Bending Operations
Other Bending & Forming Operations

- ***Flanging***: a bending operation in which the edge of a sheet-metal part is bent at a 90º angle (usually) to form a rim or flange.
  - Often used to strengthen or stiffen sheet metal.
  - The flange can be formed over a straight bend axis.
  - It may also involve some stretching or shrinking of the metal.
- ***Hemming***: involves cantilever loading of the sheet metal.
  - Bending edge of the sheet over on itself, in more than one bending step.
  - Often done to eliminate the sharp edge on the piece, to increase stiffness, and to improve appearance.

Bending Operations
Other Bending & Forming Operations

- ***Seaming***: a related operation in which two sheet-metal edges are assembled.

- ***Curling*** (***beading***): forms the edges of the part into a roll or curl.
  - Done for purposes of safety, strength, and aesthetics.
  - Applications include hinges, pots and pans.

Bending Operations
Other Bending & Forming Operations

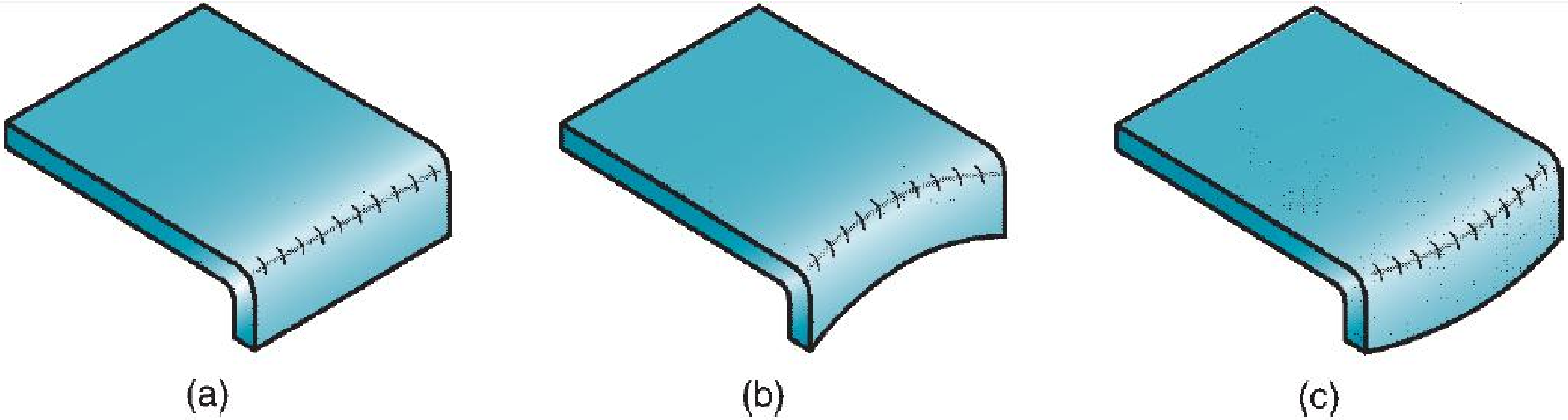


Figure 20.15 Flanging: (a) straight flanging, (b) stretch flanging, and (c) shrink flanging.

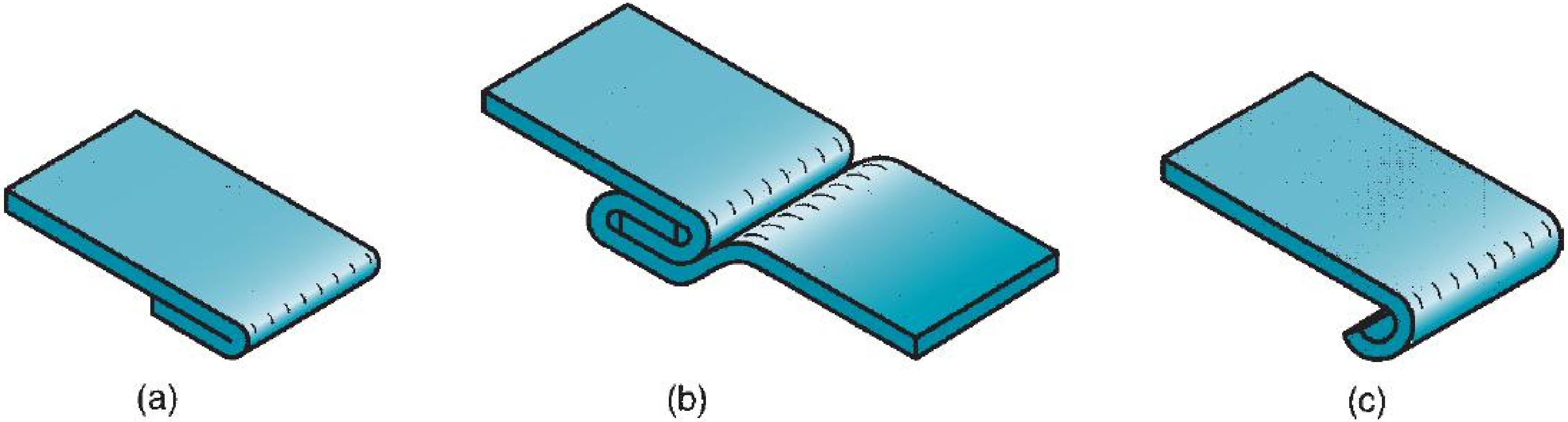


Figure 20.16 (a) Hemming, (b) seaming, and (c) curling.

Drawing

- ***Drawing***: a sheet metal forming to make cup−shaped, box−shaped, or other complex−curved, hollow−shaped parts .
  - Performed by placing a piece of sheet metal over a die cavity and then pushing the metal into the opening with a punch.
  - The blank must usually be held down flat against the die by a blankholder.
  - Examples on parts made by drawing: beverage cans, cooking pots, and automobile body panels.

Drawing

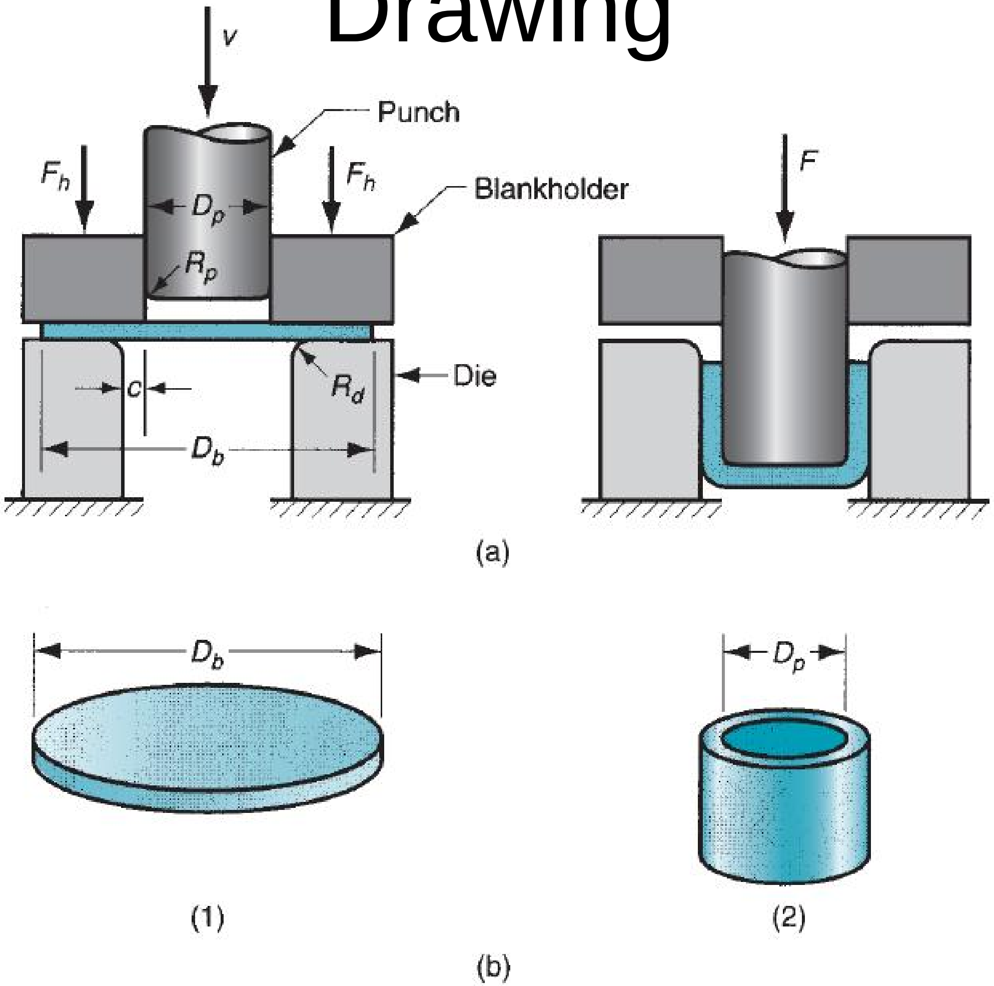


Figure 20.17 (a) Drawing of a cupshaped part: (1) start of operation before punch contacts work, and (2) near end of stroke; and (b) corresponding workpart: (1) starting blank, and (2) drawn part. Symbols: c = clearance, D_b = Blank diameter, D_p = Punch diameter, R_d = die corner radius, R_p = punch corner radius, F = drawing force, F_h = holding force.

Drawing
Mechanics of Drawing

- 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 and R_d.

- If the punch and die were to have sharp corners (R_p and $R_d = 0$), a hole-punching operation 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:

$$c = 1.1t$$

- 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.

Drawing
Mechanics of Drawing

- As the punch proceeds downward toward its final bottom position, the work experiences a complex sequence of stresses and strains as it is gradually formed into the shape defined by the punch and die cavity, as shown below:

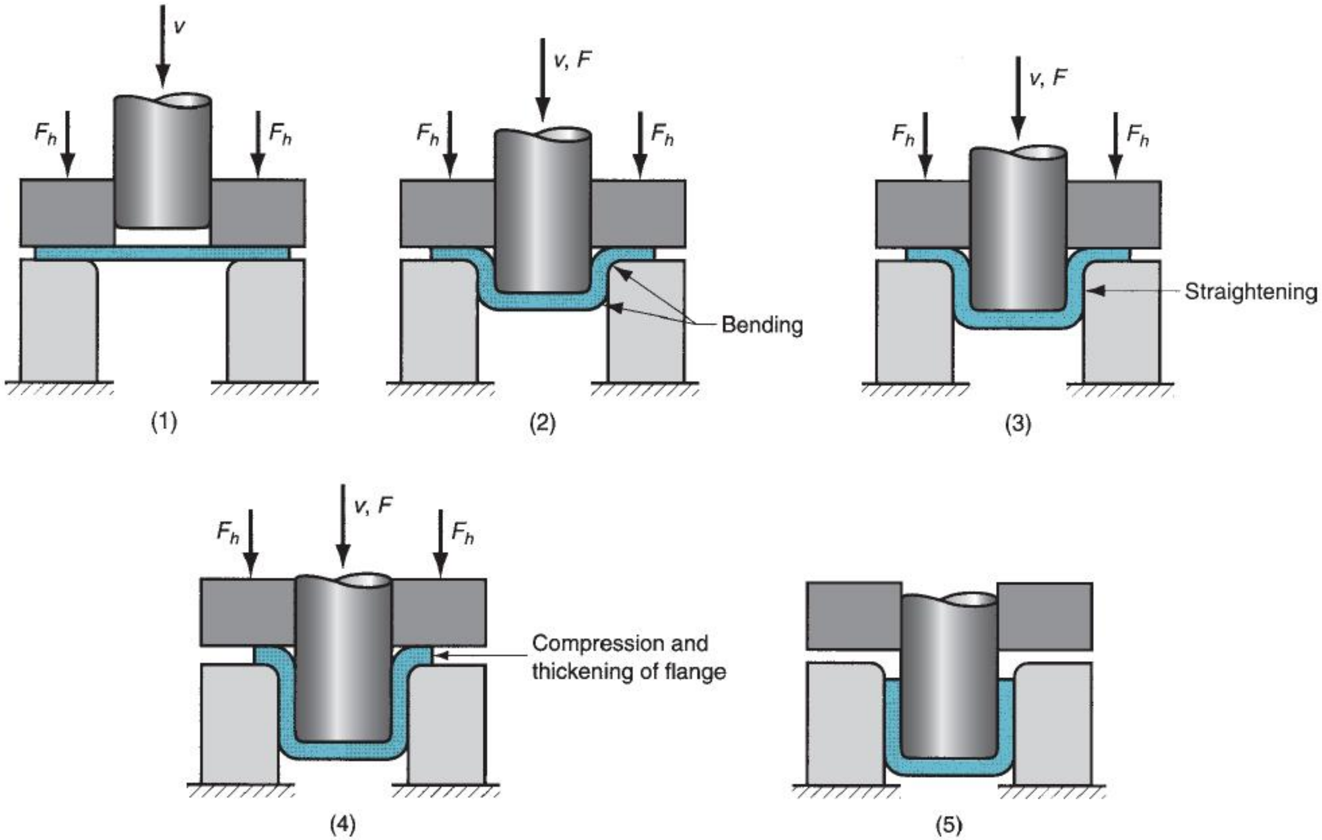


Figure 20.18 Stages in deformation of the work in deep drawing: (1) punch makes initial contact with work, (2) bending, (3) straightening, (4) friction and compression, and (5) final cup shape showing effects of thinning in the cup walls.

Drawing
Mechanics of Drawing

1. As the punch first begins to push into the work, the metal is subjected to a ***bending*** operation. The sheet is simply bent over the corner of the punch and the corner of the die. The outside perimeter of the blank moves in toward the center in this first stage, but only slightly.

2. As the punch moves further down, a ***straightening*** action occurs in the metal that was previously bent over the die radius. The metal at the bottom of the cup, as well as along the punch radius, has been moved downward with the punch, but the metal that was bent over the die radius must now be straightened in order to be pulled into the clearance to form the wall of the cylinder. At the same time, more metal must be added to replace that being used in the cylinder wall. This new metal comes from the outside edge of the blank. <u>This type of metal flow through a constricted space gives the drawing process its name.</u>

Drawing
Mechanics of Drawing

3. During this stage of the process, ***friction*** and compression play important roles in the flange of the blank. In order for the material in the flange to move toward the die opening, friction between the sheet metal and the surfaces of the blankholder and the die must be overcome. (use of lubricants to reduce friction)

4. In addition to friction, ***compression*** is also occurring in the outer edge of the blank. As the metal in this portion of the blank is drawn toward the center, the outer perimeter becomes smaller. Because the volume of metal remains constant, the metal is squeezed and becomes thicker as the perimeter is reduced.

This often results in wrinkling of the remaining flange of the blank, especially when thin sheet metal is drawn, or when the blankholder force is too low.

If the blankholder force is too large, it will prevent the flow resulting in possible tearing of the metal.

Drawing
Engineering Analysis of Drawing

- ***Measure of Drawing***:
  - Drawing can be characterized in 3 different ways; ***Drawing Ratio*** ($DR=D_b/D_p$), ***Reduction*** ($r=(D_b-D_p)/D_b$), and ***Thickness-to-Diameter Ratio*** (t/D_b).
  - DR should be equal to or less than 2, while r should be less than 0.5.
  - The greater the ratio, the more severe the drawing.
  - The t/D_b is desirable to be greater than 1% (to avoid wrinkling).

Drawing
Engineering Analysis of Drawing

- ***Force***: the ***drawing force*** required to perform a given operation can be estimated roughly by:

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

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

- ***Holding force***, expressed by:

$$F_h = 0.015Y\circledR\{D_b{}^2 - (D_p + 2.2t + 2R_d)^2\}$$

where F = holding force, N; Y = yield strength of the sheet metal, MPa; t = starting stock thickness, mm; R_d = die corner radius, mm.

The holding force is usually about 1/3 of the drawing force.

Drawing
Engineering Analysis of Drawing

- ***Blank Size Determination***: for the final dimensions to be achieved on the cylindrical drawn shape, the correct starting blank diameter is needed.

  – Must be large enough to supply sufficient metal to complete the cup.

  – Yet if there is too much material, unnecessary waste will result.

  – The blank diameter can be calculated by setting the initial blank volume equal to the final volume of the product and solving for diameter D_b.

Drawing
Other Drawing Operations

- ***Redrawing***: drawing done in more than a step, in case shape change is too severe. The second drawing step, and any further drawing steps if needed, are referred to as redrawing.

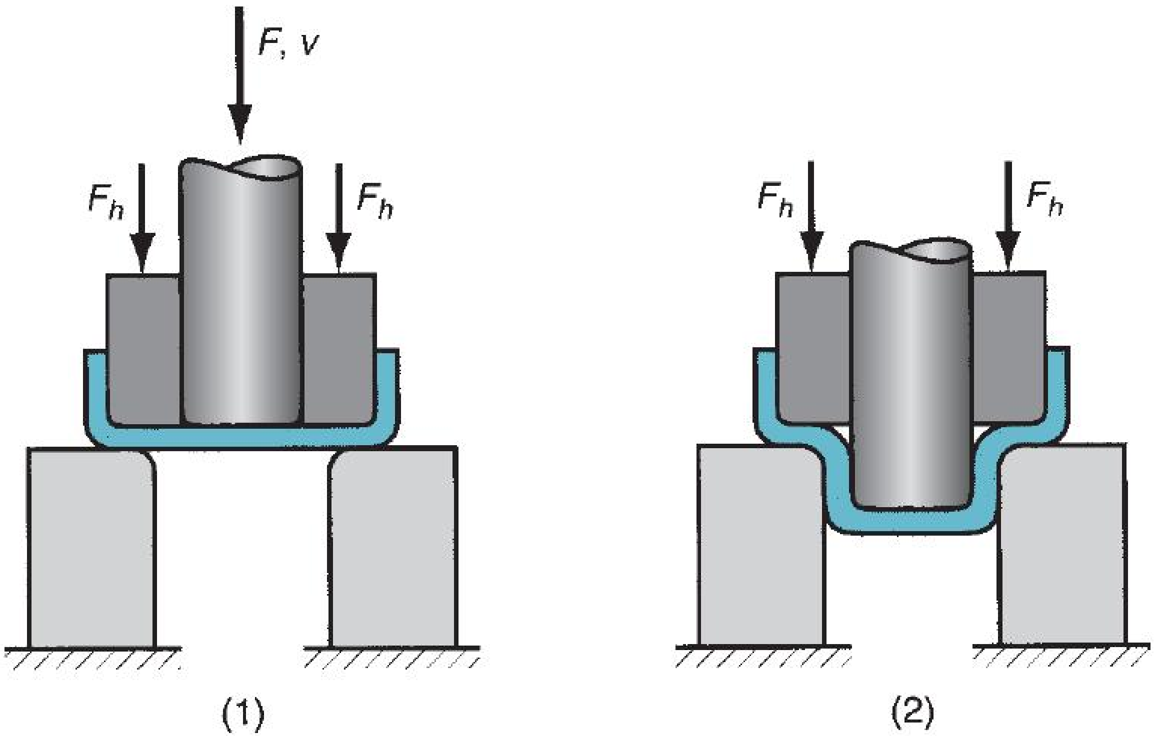


Figure 20.19 Redrawing of a cup: (1) start of redraw, and (2)endof stroke.

Drawing
Other Drawing Operations

- ***Redrawing***: drawing done in more than a step, in case shape change is too severe. The second drawing step, and any further drawing steps if needed, are referred to as redrawing.

- First draw: max. reduction 40 to 45%. Second: 30%. Third: 16%.

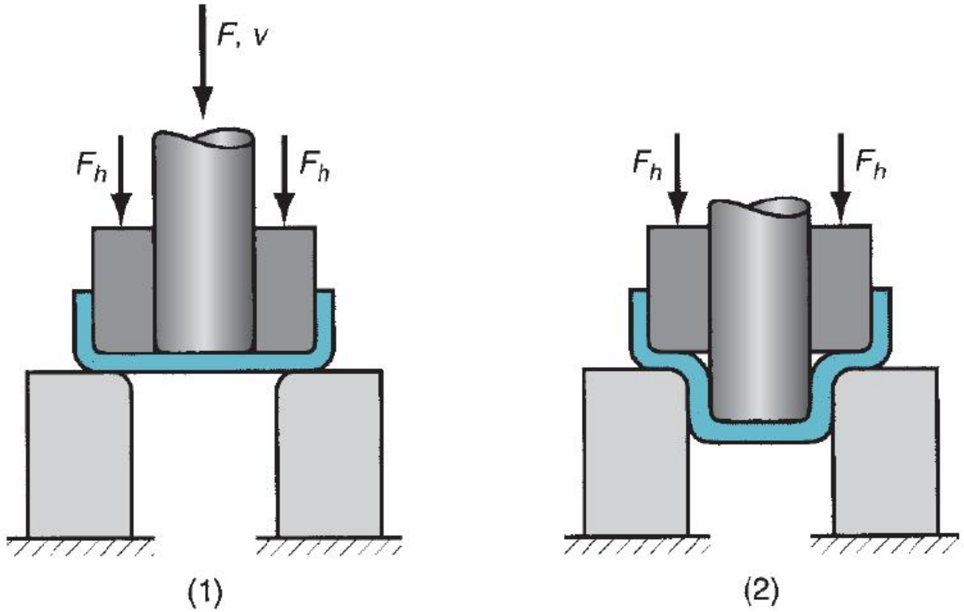


Figure 20.20 Redrawing of a cup: (1) start of redraw, and (2) end of stroke.

Drawing
Other Drawing Operations

- ***Drawing of Shapes Other Than Cylindrical Cups***: square or rectangular boxes (as in sinks), cups with spherical rather than flat bases, and irregular curved forms (as in automobile body panels).

- ***Drawing Without a Blankholder***: one of the primary functions of a blankholder is to prevent wrinkling. If the t/D_b ratio is large enough, drawing can be accomplished without a blankholder.

- The limiting condition of this process being: $D_b - D_p < 5t$.

- The draw die must have the shape of the funnel or cone.

- Advantages: lower cost tooling and a simpler press.

Drawing
Other Drawing Operations

- ***Drawing Without a Blankholder***:

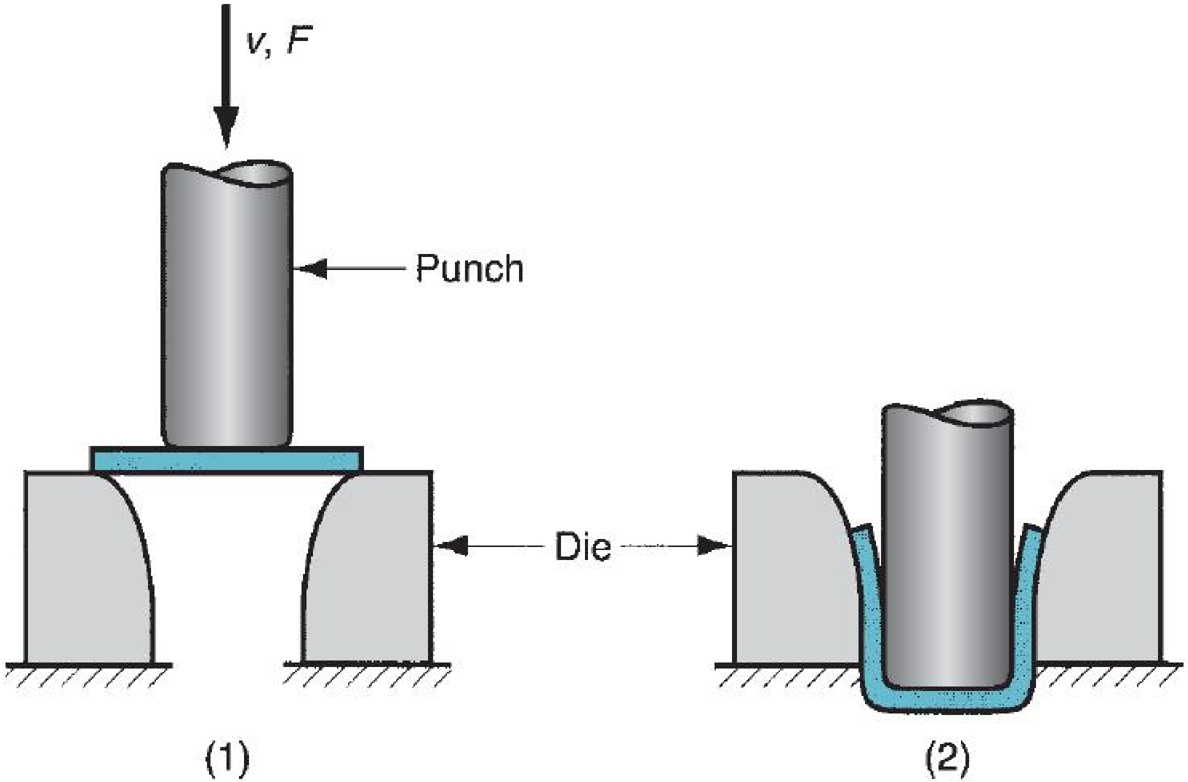


Figure 20.21 Drawing without a blankholder: (1) start of process, (2) end of stroke.

Drawing
Defects in Drawing

- ***Wrinkling*** in the flange: consists of a series of ridges that form radially in the undrawn flange of the workpart due to compressive buckling.

- ***Wrinkling*** in the wall: If and when the wrinkled flange is drawn into the cup, these ridges appear in the vertical wall.

- ***Tearing***: 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.

- ***Earing***: the formation of irregularities (called ears) in the upper edge of a deep drawn cup, caused by anisotropy in the sheet metal.

- ***Surface scratches***: occur on the drawn part if the punch and die are not smooth or if lubrication is insufficient.

Drawing
Defects in Drawing

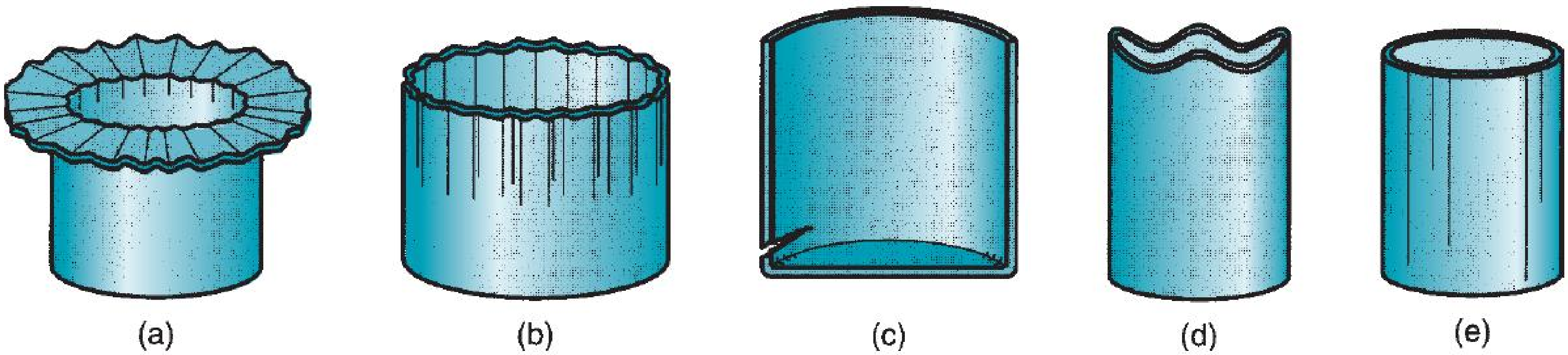


Figure 20.22 Common defects in drawn parts: (a) wrinkling can occur either in the flange or (b) in the wall, (c) tearing, (d) earing, and (e) surface scratches.

Other Sheet-Metal-Forming Operations

- ***Ironing***: done to correct the higher thickness at the edge of the blank (refer to point 4 in drawing mechanics).

- Ironing makes the cylindrical cup more uniform in wall thickness.

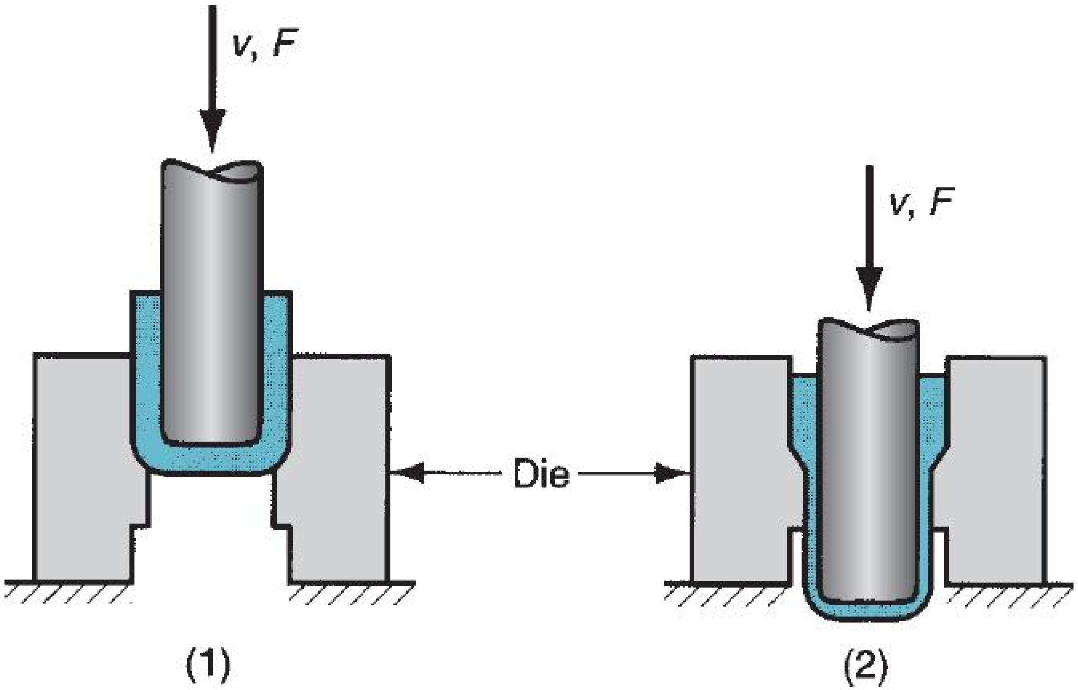


Figure 20.23 Ironing to achieve a more uniform wall thickness in a drawn cup: (1) start of process; (2) during process.

Other Sheet-Metal-Forming Operations

- ***Coining***: frequently used in sheet-metal work to form indentations and raised sections in the part (it is also a bulk deformation process as discussed in chapter 19).

- ***Embossing***: similar to coining, however, embossing dies possess matching cavity contours, the punch containing the positive contour and the die containing the negative; whereas coining dies may have quite different cavities in the two die halves

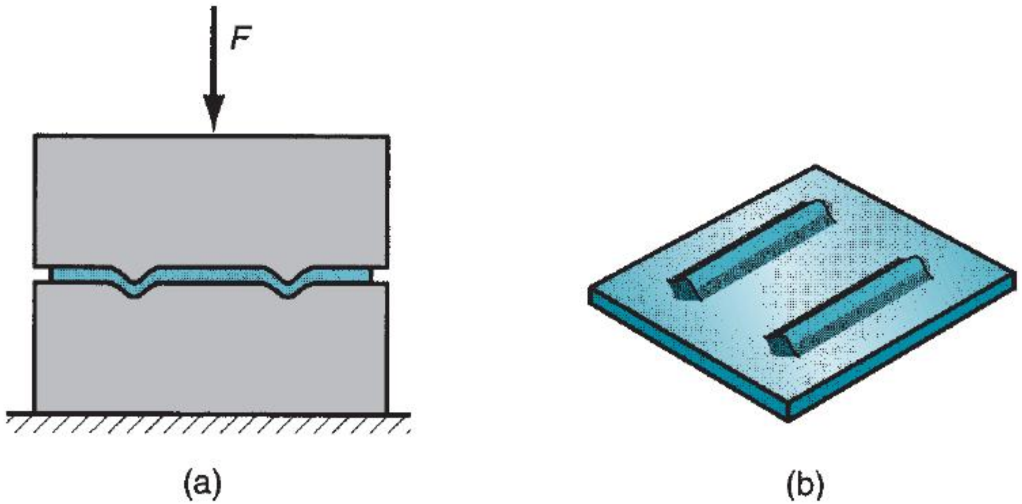
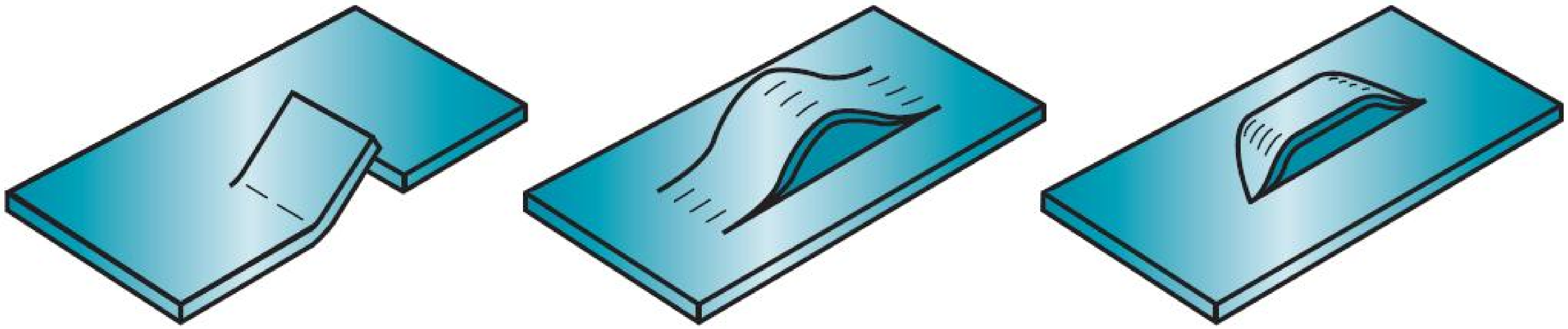


Figure 20.24 Embossing: (a) cross section of punch and die configuration during pressing; (b) finished part with embossed ribs.

Other Sheet-Metal-Forming Operations

- ***Lancing***: a combined cutting and bending or cutting and forming operation performed in one step to partially separate the metal from the sheet.
  - Example: used to make louvers in sheet metal air vents for heating and air conditioning systems in buildings.



(a) (b) (c)

Figure 20.25 Lancing in several forms: (a) cutting and bending; (b) and (c) two types of cutting and forming.

Dies and Presses for Sheet Metal Processes
Dies

Punch & die are the working components.

Bushing & Guide pins ensure proper alignment between punch & die.

Stripper prevents sheet metal from sticking to the punch after operation.

Stop: prevents sheet metal from advancing through the die between cycles. (e.g. In case of coils).

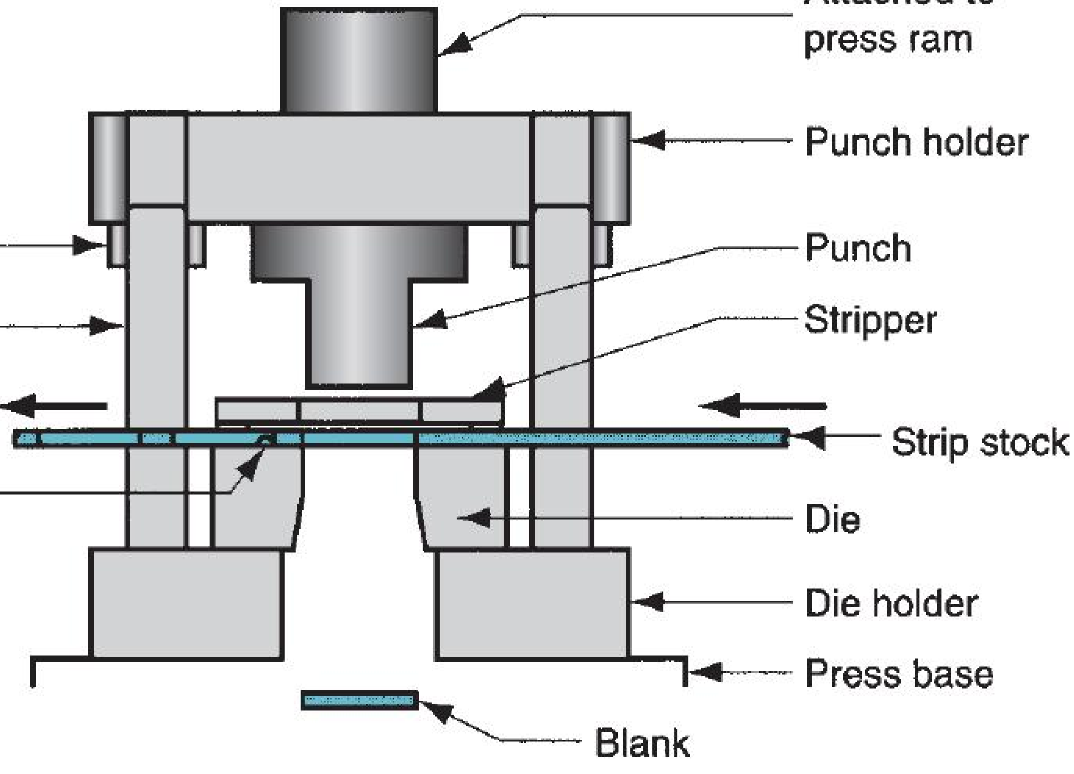


Figure 20.26 Components of a punch and die for a blanking operation.

Dies and Presses for Sheet Metal Processes
Presses

- ***Press***: a machine tool with a stationary ***bed*** and a powered ***ram*** that can be driven toward and away from the bed to perform various cutting and forming operations.
  - ***The Frame***: establishes the relative positions of the bed and ram.
  - Punch holder is attached to the ***ram*** and the die holder is attached to a ***bolster plate***.
  - ***Type of frame***: the physical construction of the press.
- Two types of frames:
  - ***Gap Frame Presses.***
  - ***Straight-sided frame presses.***

Dies and Presses for Sheet Metal Processes
Presses

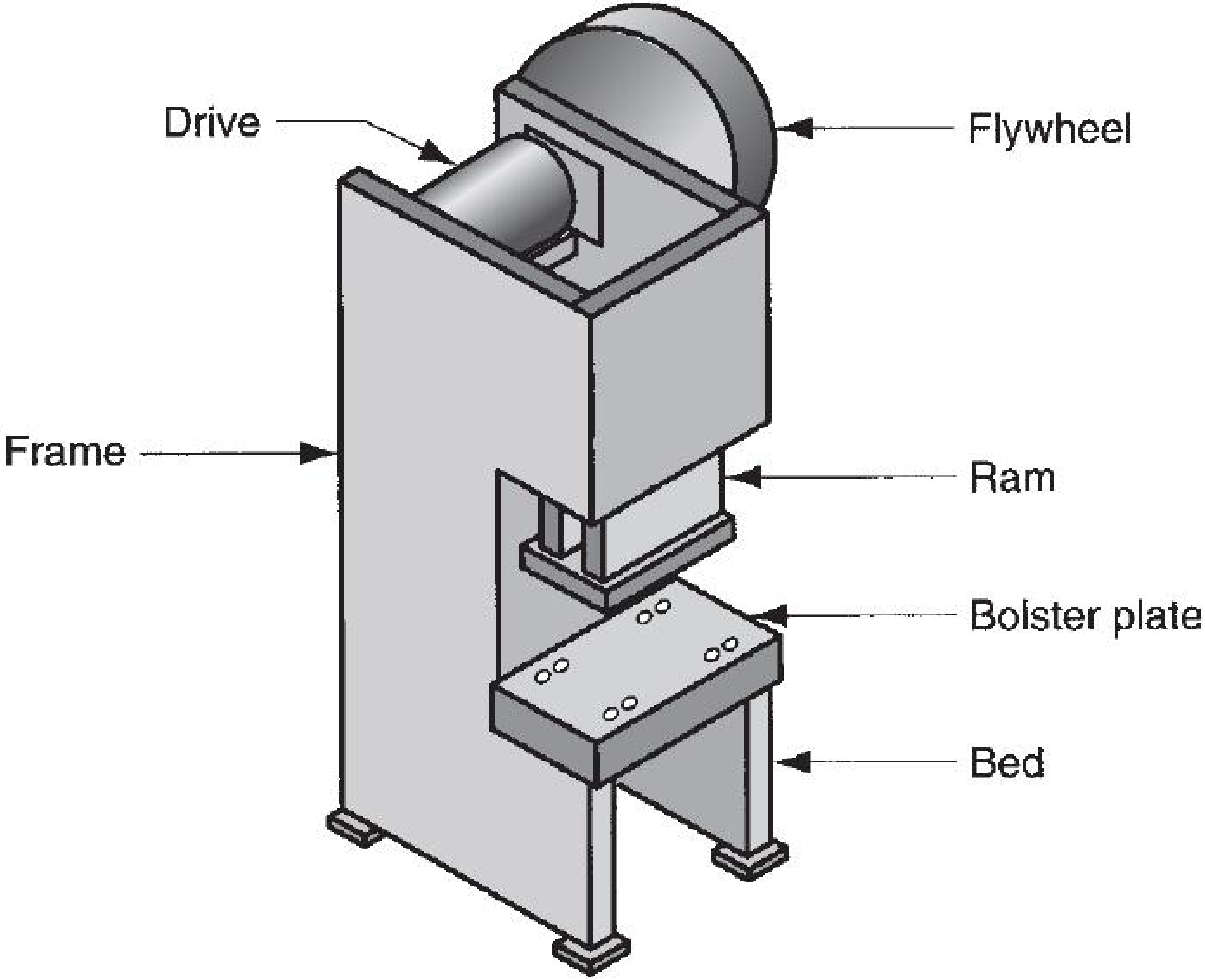


Figure 20.27 Components of a typical (mechanical drive) stamping press.

Dies and Presses for Sheet Metal Processes
Presses

- Two types of frames:
  - ***Gap Frame Presses***: has the general configuration of the letter C and is often referred to as a C-frame.
    - Provide good access to the die.
    - Usually open in the back to permit convenient ejection of stampings or scrap.
    - Available in a range of sizes, with capacities up to around 1000 tons.
  - ***Straight-sided frame presses***: posses greater structural rigidity for high tonnage.
    - Have full sides (box-like appearance).
    - Capacities up to 4000 tons are available.

Dies and Presses for Sheet Metal Processes
Presses

Figure 20.28 Gap-Frame Press.

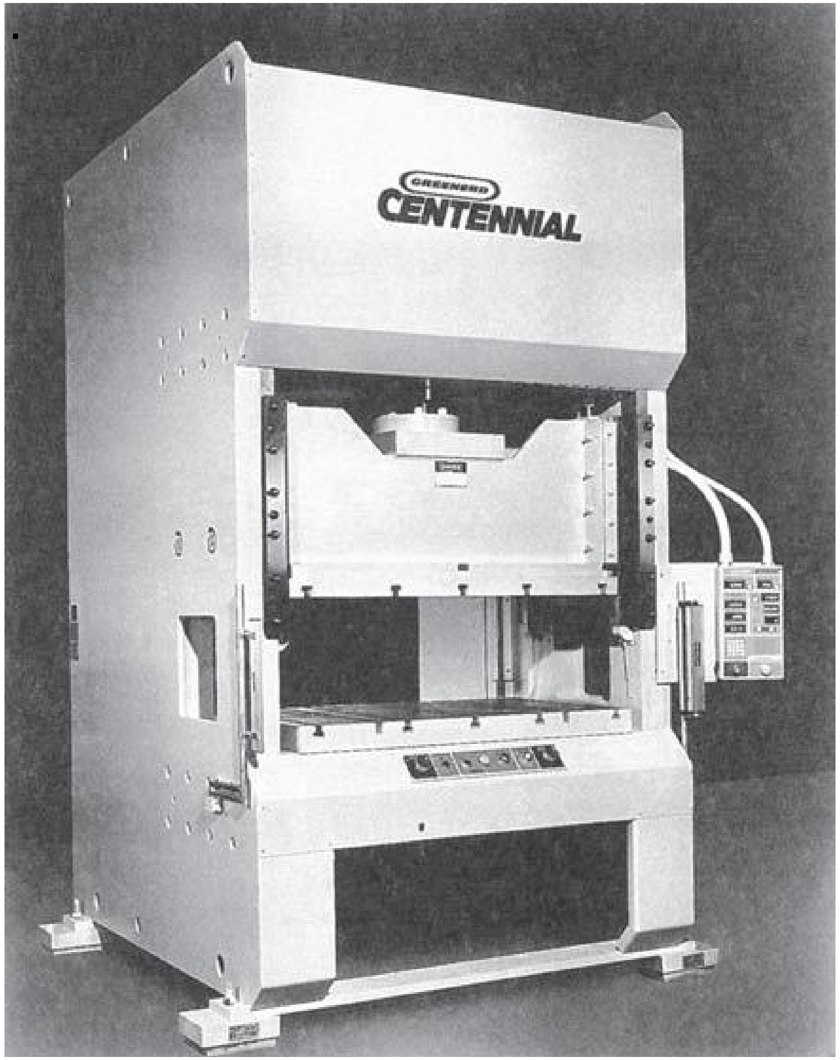


Figure 20.29 Straight-Sided Frame Press.

Sheet-Metal Operations Not Performed on Presses

- There are a number of sheet-metal operations not performed on conventional stamping presses. These include:

  - ***Stretch Forming.***
  - ***Roll Bending and Forming.***
  - ***Spinning.***
  - ***High-Energy-Rate Forming Processes.***

Sheet-Metal Operations Not Performed on Presses

- ***Stretch Forming***: a sheet-metal deformation process in which the sheet metal is intentionally stretched and simultaneously bent in order to achieve shape change.

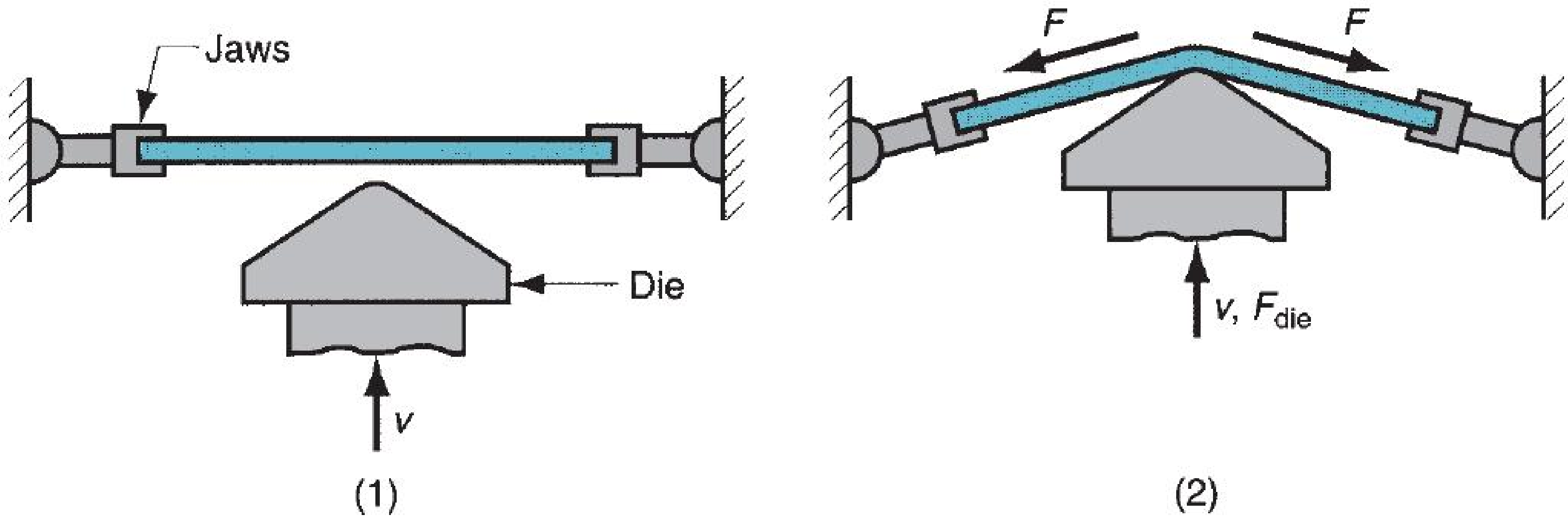


Figure 20.30 Stretch forming: (1) start of process; (2) form die is pressed into the work with force F_{die}, causing it to be stretched and bent over the form. F = stretching force.

Sheet-Metal Operations Not Performed on Presses

- ***Stretch Forming***:
  - Workpart is gripped by one or more jaws on each end and then stretched and bent over a positive die containing the desired form.
  - Tension level: above yield point, and force required to stretch forming:

$$F = LtY_f$$

where F = stretching force, N; Y_f = flow strength of the sheet metal, MPa; t = instantaneous stock thickness, mm; L = length of the sheet in a direction perpendicular to stretching, mm.

  - Die force F_{die} can be determined by balancing vertical force components.
  - Suitable for low-quantity large-size production; e.g. sheet-metal used in aircraft bodies.

Sheet-Metal Operations Not Performed on Presses

- ***Roll Bending***: an operation in which (usually) large sheet-metal or plate-metal parts are formed into curved sections by means of rolls.
  - Applications: Components for large storage tanks and pressure vessels and railroad rails.
  - ***Roll Straightening***: a related operation in which non-flat sheets are straightened by passing them between a series of rolls.

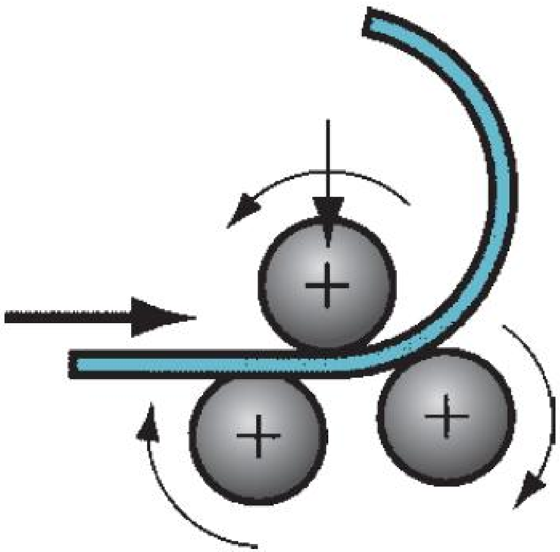


Figure 20.31 Roll bending: as the sheet passes between the rolls, the rolls are brought toward each other to a configuration that achieves the desired radius of curvature on the work.

Sheet-Metal Operations Not Performed on Presses

- ***Roll Forming***: a continuous bending process in which opposing rolls are used to produce long sections of formed shapes from coil or strip stock.
  - Several pairs of rolls are usually required to progressively accomplish the bending of the stock into the desired shape.
  - Products: include channels, pipes and tubing with seams.

Sheet-Metal Operations Not Performed on Presses

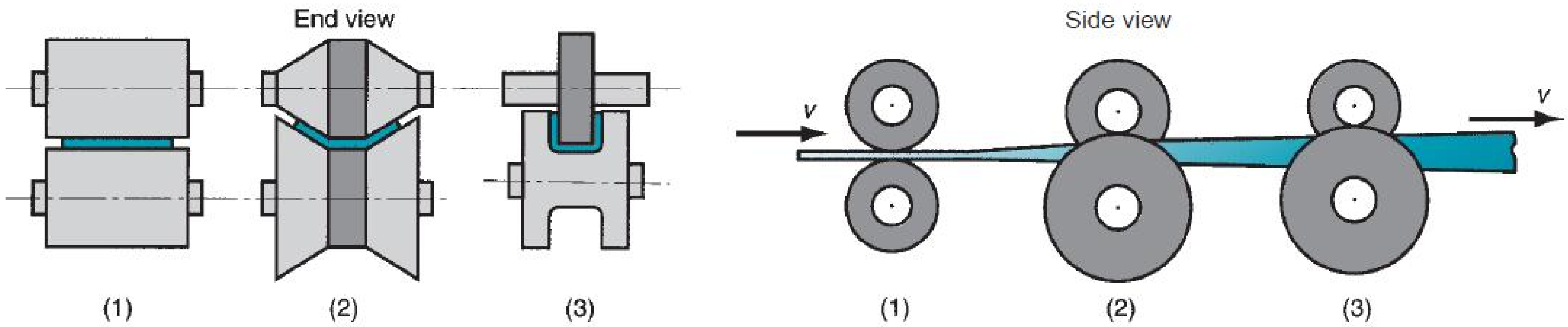


Figure 20.32 Roll forming of a continuous channel section: (1) straight rolls, (2) partial form, and (3) final form.

Although roll forming has the general appearance of a rolling operation (and the tooling certainly looks similar), the difference is that roll forming involves bending rather than compressing the work.

Sheet-Metal Operations Not Performed on Presses

- ***Spinning***: a metal-forming process in which an axially symmetric part is gradually shaped over a mandrel or form by means of a rounded tool or roller. Three types of spinning:
  - ***Conventional Spinning.***
  - ***Shear Spinning.***
  - ***Tube Spinning.***

Sheet-Metal Operations Not Performed on Presses

- ***Conventional Spinning***: a sheet-metal disk is held against the end of a rotating mandrel of the desired inside shape of the final part, while the tool or roller deforms the metal against the mandrel.

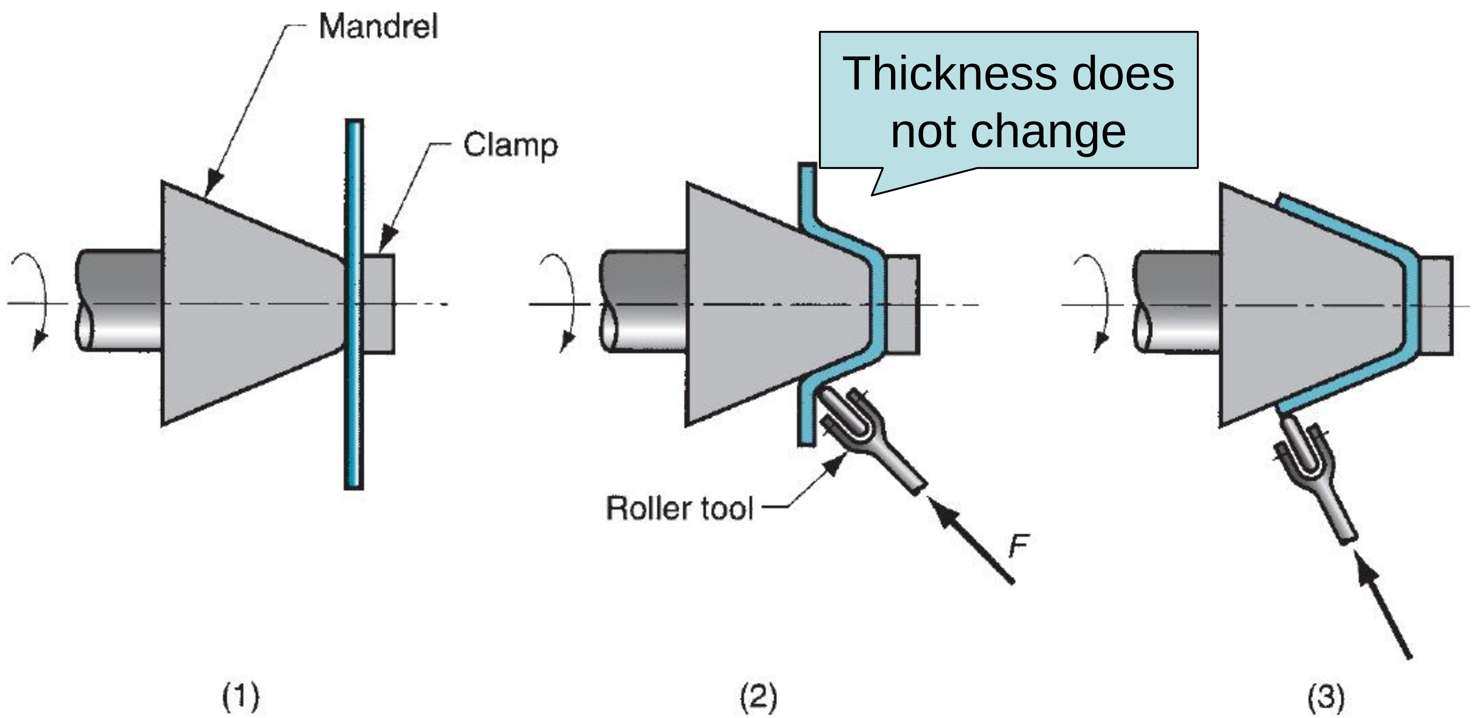


Figure 20.33 Conventional spinning: (1) setup at start of process; (2) during spinning; and (3) completion of process.

Sheet-Metal Operations Not Performed on Presses

– ***Conventional Spinning***.

- It ***bends*** the metal around a moving circular axis to conform to the outside surface of the axisymmetric mandrel.
- Applications include: production of conical and curved shapes in low quantities.
- Very large diameter parts up to 5 m or more can be made by spinning.
- Alternative sheet-metal processes would require excessively high die costs.
- The form mandrel in spinning can be made of wood or other soft materials that are easy to shape.
- It is therefore a low-cost tool compared to the punch and die required for deep drawing, which might be a substitute process for some parts.

Sheet-Metal Operations Not Performed on Presses

– ***Shear Spinning***: the part is formed over the mandrel by a ***shear*** deformation process (not bending) in which the outside diameter remains constant and the wall thickness is therefore reduced.

- Applied to aerospace industry to form large parts such as rocket nose cones.

- Thickness of the spun nose:

$$t_f = t \sin \sim$$

where t_f = the final thickness of the wall after spinning, t = the starting thickness of the disk, and α = the mandrel half angle.

- Spinning reduction (***r***):

$$r = \frac{t - t_f}{t}$$

Sheet-Metal Operations Not Performed on Presses

– ***Shear Spinning***:

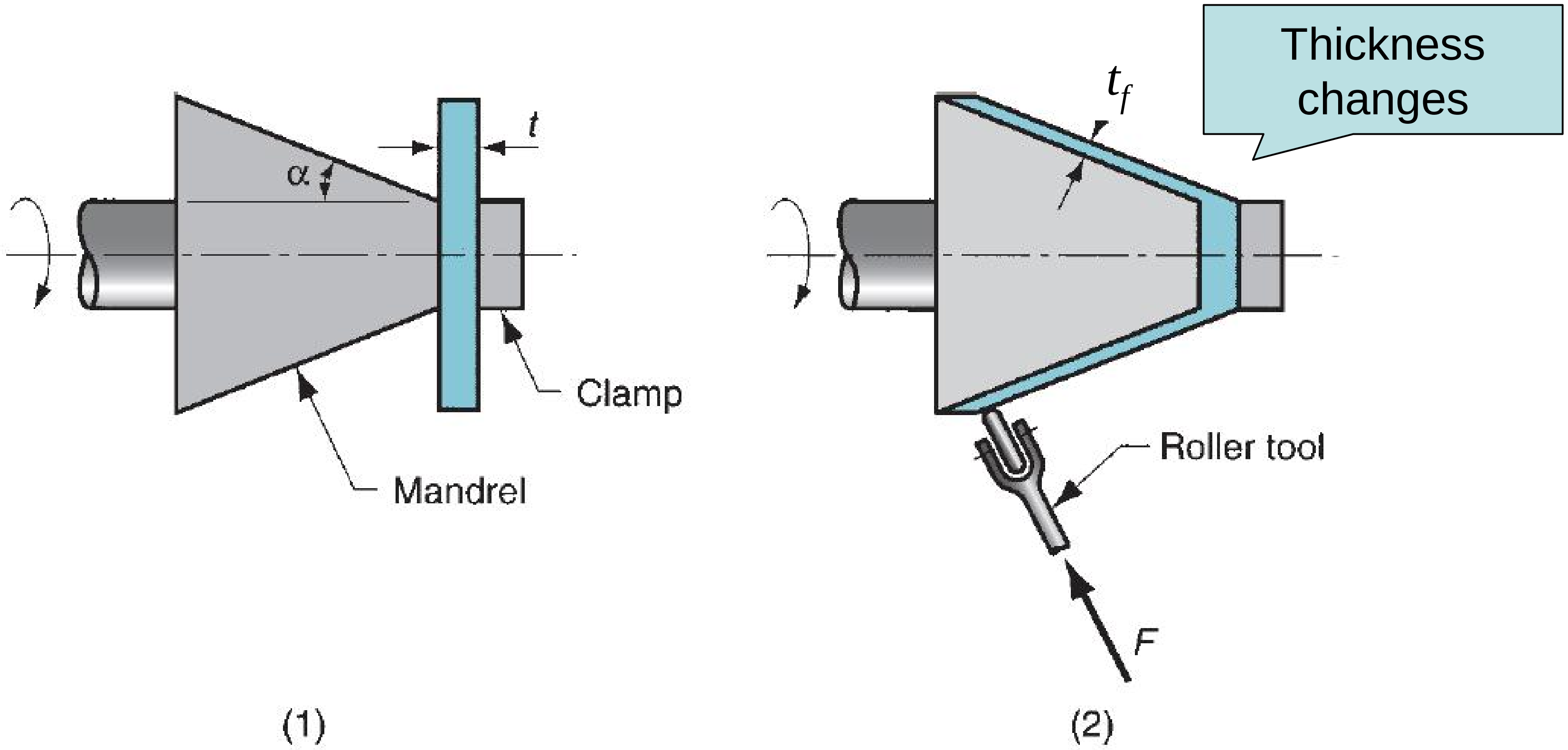


Figure 20.34 Shear spinning: (1) setup at start of process; and (2) completion of process.

Sheet-Metal Operations Not Performed on Presses

- ***High-Energy-Rate Forming*** (HERF): processes developed to form metals using large amounts of energy applied in a very short time, include:

  - ***Explosive Forming.***
  - ***Electrohydraulic Forming.***
  - ***Magnetic Forming.***

Sheet-Metal Operations Not Performed on Presses

– ***Explosive Forming:*** involves the use of an explosive charge to form sheet (or plate) metal into a die cavity.

- The workpart is clamped and sealed over the die, and a vacuum is created in the cavity beneath.
- The apparatus is then placed in a large vessel of water. An explosive charge is placed in the water at a certain distance above the work.
- Detonation of the charge results in a shock wave whose energy is transmitted by the water to cause rapid forming of the part into the cavity.

Sheet-Metal Operations Not Performed on Presses

– ***Explosive Forming:***

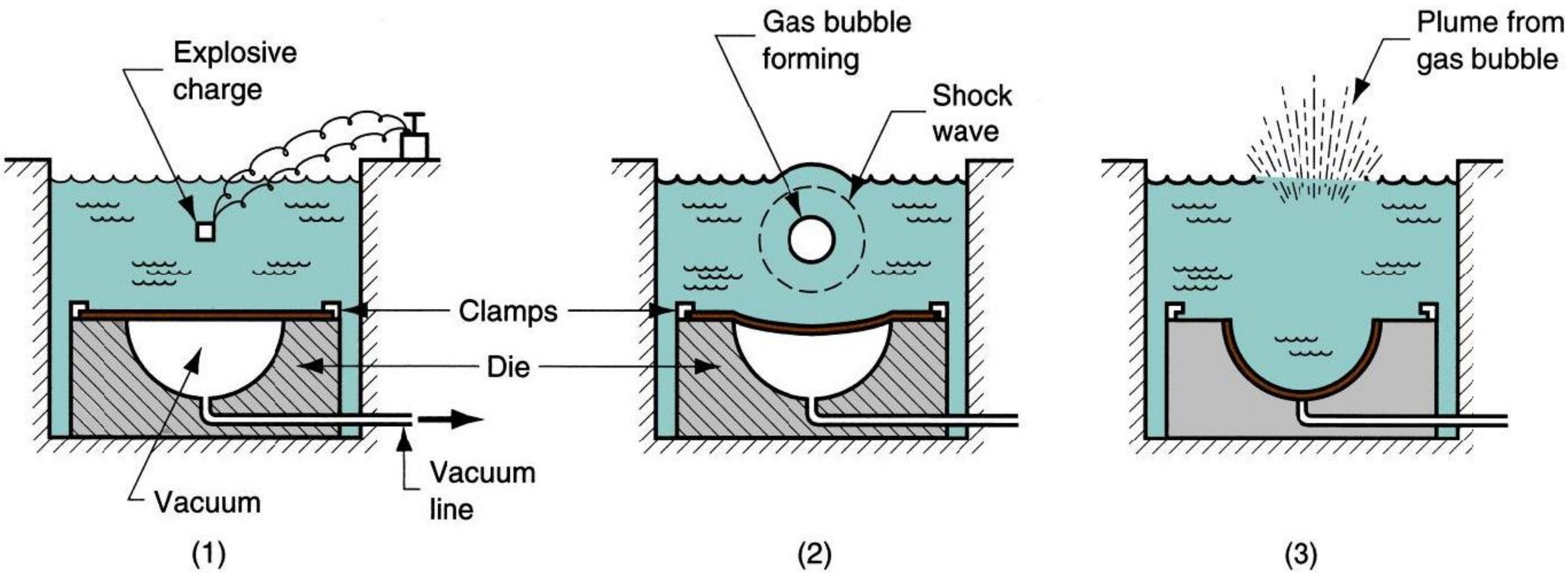


Figure 20.35 Explosive forming: (1) setup, (2) explosive is detonated, and (3) shock wave forms part and plume escapes water surface.

Sheet-Metal Operations Not Performed on Presses

– ***Electrohydraulic Forming:*** a HERF process in which a shock wave to deform the work into a die cavity is generated by the discharge of electrical energy between two electrodes submerged in a transmission fluid (water).

- Electrical energy is accumulated in large capacitors and then released to the electrodes.

- Electrohydraulic forming is similar to explosive forming. The difference is in the method of generating the energy and the smaller amounts of energy that are released.

- This limits electrohydraulic forming to much smaller part sizes.

Sheet-Metal Operations Not Performed on Presses

– ***Electrohydraulic Forming:***

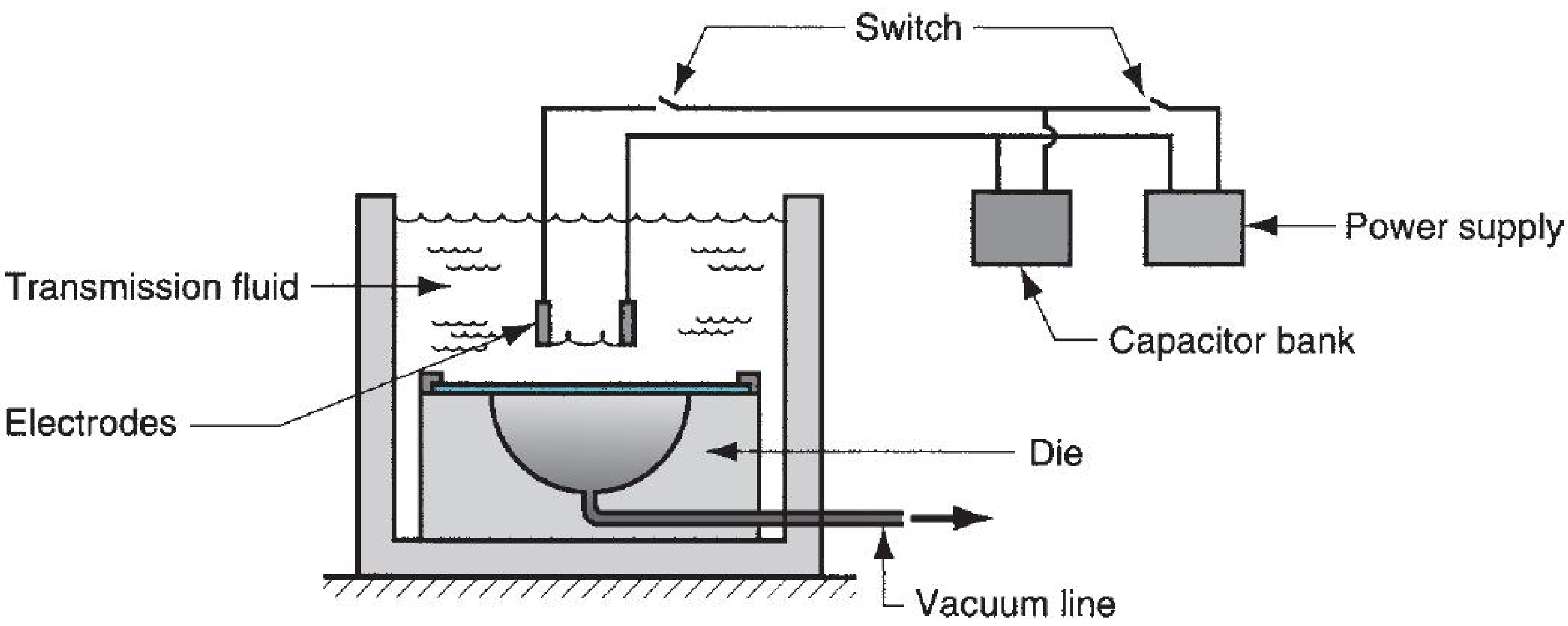


Figure 20.36 Electrohydraulic forming setup.

Bending of Tube Stock

- ***Bending of tube stock*** is more difficult than sheet stock because a tube tends to collapse and fold when attempts are made to bend it.
- Special flexible mandrels are usually inserted into the tube prior to bending to support the walls during the operation.

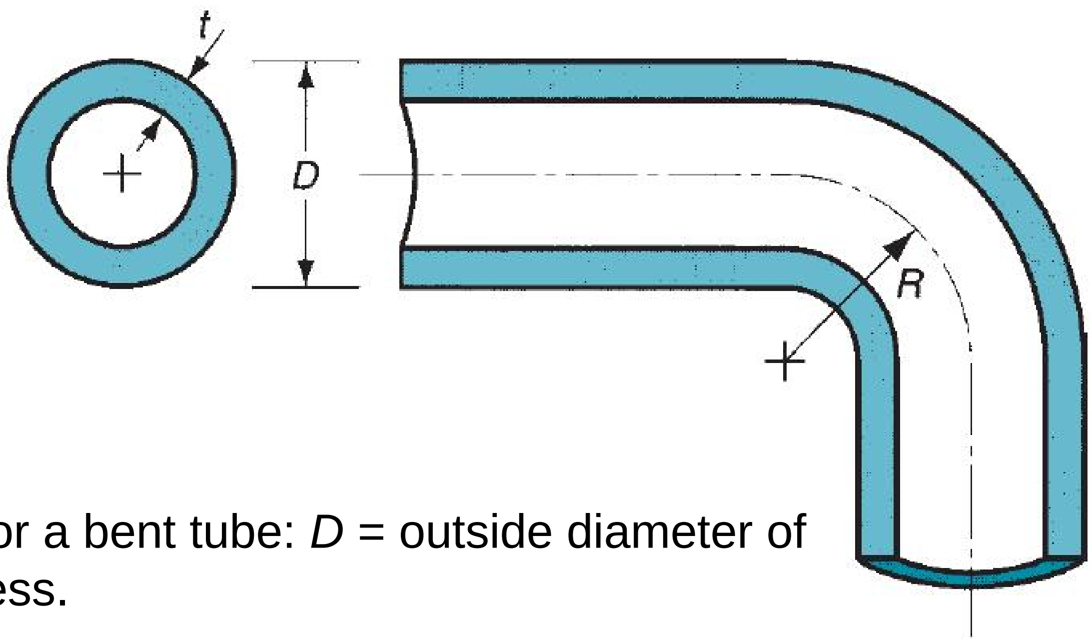


Figure 20.37 Dimensions and terms for a bent tube: *D* = outside diameter of tube, *R* = Bend radius, *t* = wall thickness.

Bending of Tube Stock

- The radius of the bend *R* is defined with respect to the centerline of the tube.
- When the tube is bent, the wall on the inside of the bend is in compression, and the wall at the outside is in tension.
- These stress conditions cause thinning and elongation of the outer wall and thickening and shortening of the inner wall.
- As a result, there is a tendency for the inner and outer walls to be forced toward each other to cause the cross section of the tube to flatten.
- Because of this flattening tendency, the minimum bend radius *R* that the tube can be bent is about 1.5 times the diameter *D* when a mandrel is used and 3.0 times *D* when no mandrel is used.
- The exact value depends on the wall factor *WF*, which is the diameter *D* divided by wall thickness *t*.
- Higher values of WF increase the minimum bend radius; that is, tube bending is more difficult for thin walls. ***Ductility*** is also a factor.

Bending of Tube Stock

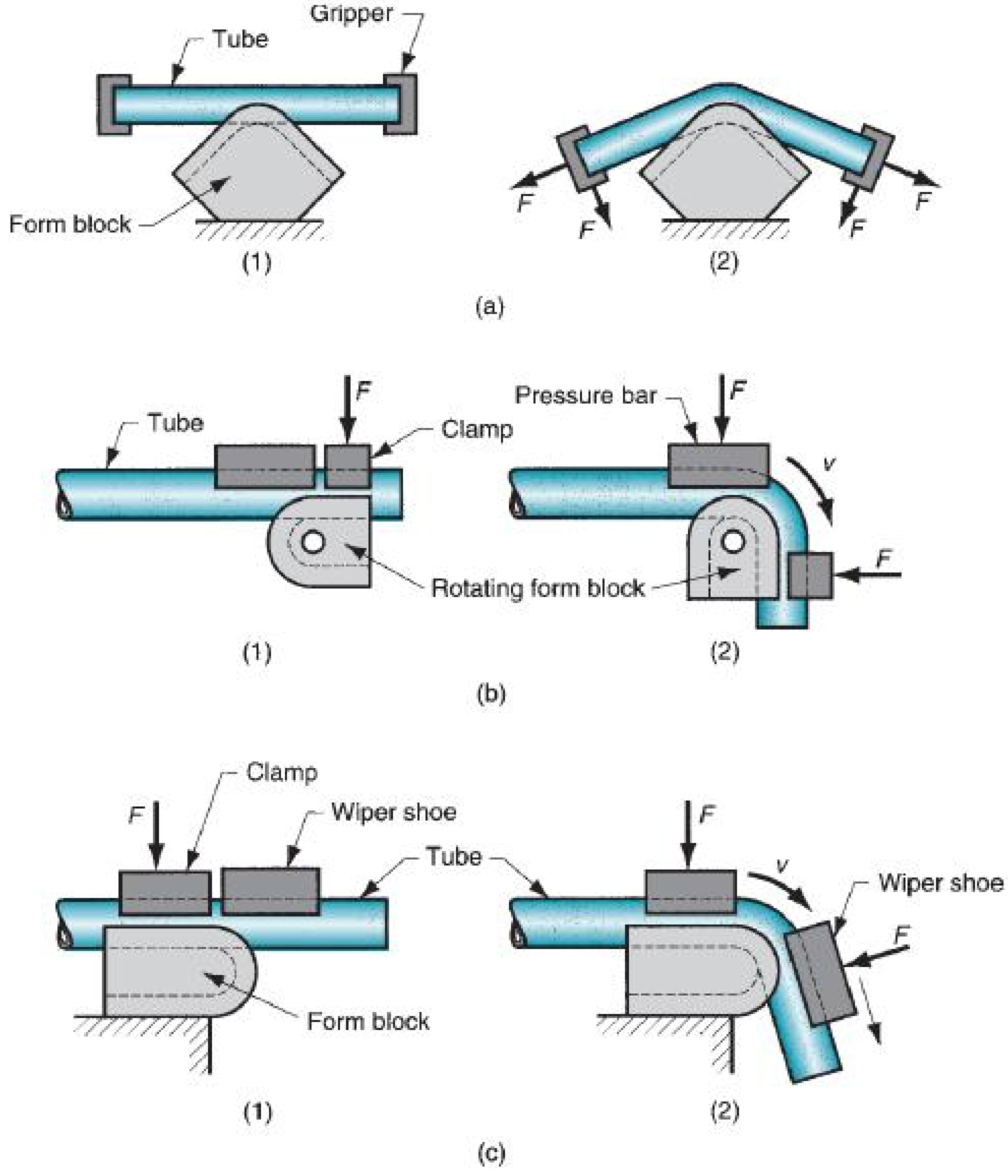


Figure 20.38 Tube bending methods: (a) stretch bending, (b) draw bending, and (c) compression bending. For each method: (1) start of process, and (2) during bending. Symbols *v* and *F* indicate motion and applied force, respectively.

Manufacturing Processes

Chapter Three:

Mechanical Properties Of Materials

Dr. Eng. Yazan Al-Zain
Department of Industrial Engineering

Introduction

- Mechanical properties of a material determine its behavior when subjected to mechanical stress (examples on materials under stress are aluminum alloy from which an airplane wing is constructed and the steel in an automobile axle).

- Mechanical properties include: elastic modulus, ductility, hardness, etc.

- Two opposite objectives for the product in design and manufacturing:
  - In design: the objective for the product is to withstand stresses without significant change in geometry (dependent on elastic modulus and yield stress).
  - In manufacturing: the objective is to alter the geometry by applying stresses that exceed the yield strength of the material.

Note: it is helpful for the manufacturing engineer to appreciate the design objective and for the designer to be aware of the manufacturing objective.

Stress-Strain relationships

- There are 3 static stresses to which materials can be subjected
  - Tensile stresses: tend to stretch the material
  - Compressive stresses: tend to squeeze the material.
  - Shear stresses: tend to cause adjacent portions of the material to slide against one another.

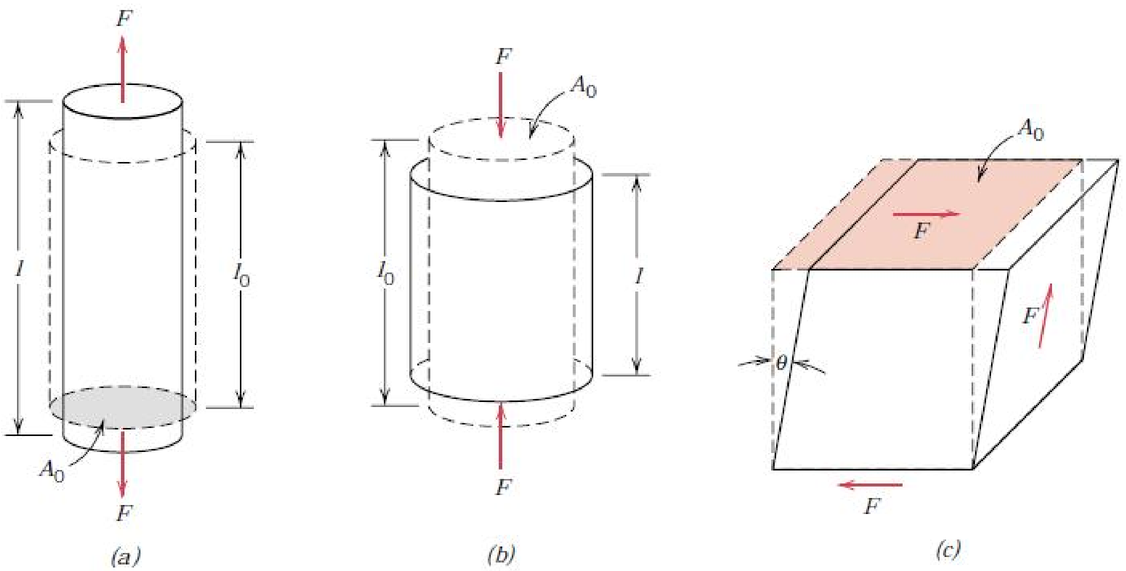
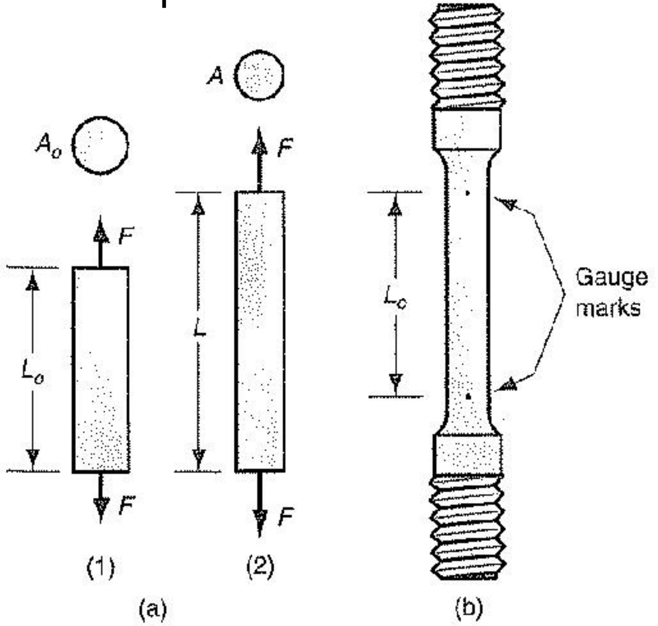


Fig. 3-1: Materials under static stresses; (a) Tensile, (b) compressive, and (c) shear ($\gamma = \tan\ \theta$). Dashed lines: shape before deformation.

Stress-Strain relationships; Tensile properties

- Tensile test: most common procedure for studying stress-strain relationships, particularly for metals.
- In the test, force is applied that pulls the material, tending to elongate it and reduce its diameter.
- Standards by ASTM specify the preparation of the test specimen and the test procedure.



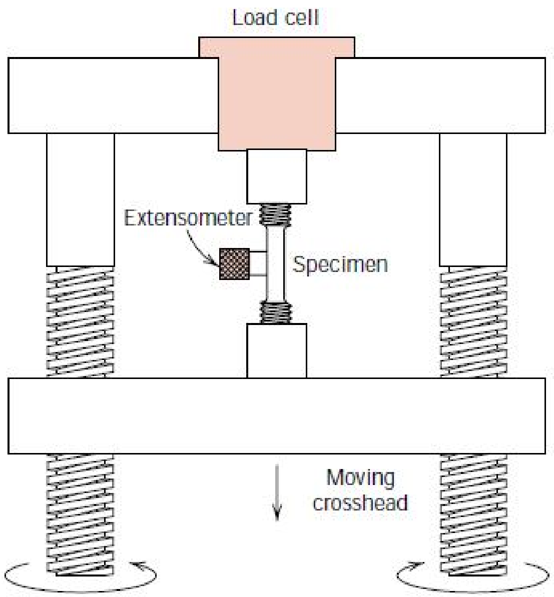


Fig. 3-2: Tensile specimen and setup of the tensile test. (A_0 & L_0: cross sectional area and length before test, length is measured between the gauge marks (gauge length)).

Stress-Strain relationships; Tensile properties

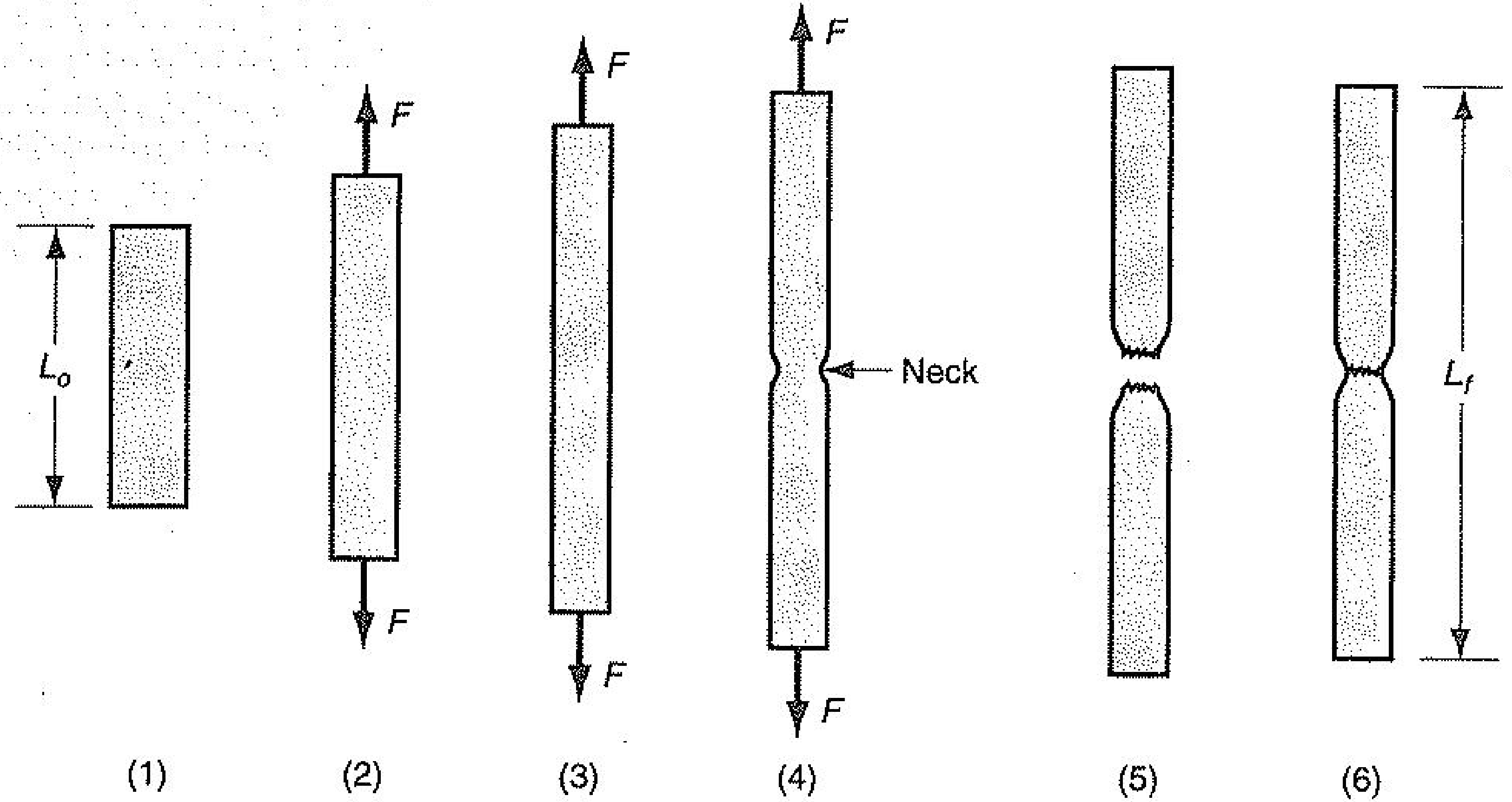


Fig. 3-3: Progress of a tensile test: (1) beginning of test, no load, (2) uniform elongation and reduction of A_0, (3) Continued elongation, max. load reached, (4) necking begins and load decreases, (5) fracture, and (6) final length can be measured if pieces are put back together.

Stress-Strain relationships; Tensile properties

- There are two different types of stress-strain curves: (1) Engineering stress-strain and (2) True stress-strain. The first is more important in design and the second is more important in manufacturing.

  (1) Engineering Stress-Strain: stress and strain defined relative to the original area and length of the specimen.

  – Important in design as the designer assumes that the strains experienced by any component will NOT significantly change its shape. The components are designed to withstand the anticipated stresses encountered in service.

Stress-Strain relationships; Tensile properties

- Fig. 3-4 shows an engineering stress-strain curve for a metallic specimen.

- The engineering stress at any point on the curve is defined as the force divided by the original area:

$$\pm_e = \frac{F}{A_0}$$

where σ_e: engineering stress, MPa (n / mm^2), F = applied force, N, and A_0 is the original area of the specimen, mm^2.

- The engineering strain at any point in the test is given by:

$$e = \frac{L - L_0}{L_0}$$

where e is engineering strain, mm / mm, L = length during the elongation at any point, mm, and L_0 is the gauge length, mm.

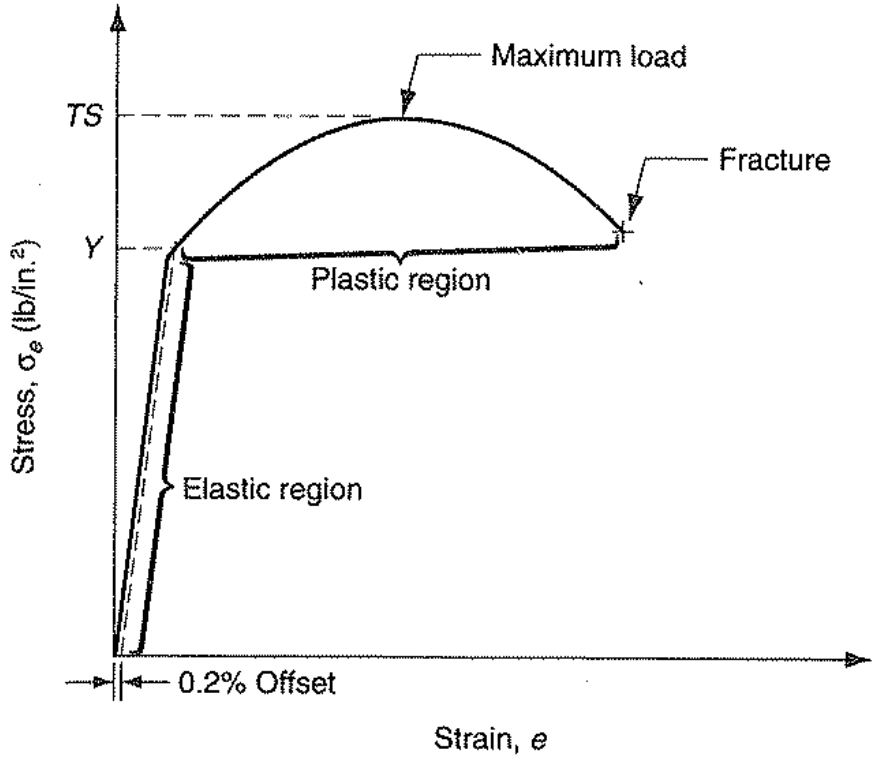


Fig. 3-4: a typical engineering stress-strain curve for a metallic specimen.

e can be thought of as elongation per unit length.

Stress-Strain relationships; Tensile properties

- The stress-strain relationship in the figure has two regions, elastic and plastic regions:

  (1) In the elastic region: the relationship is linear and the material exhibits elastic behavior by returning to its original length when the load is released. The relationship is defined by ***Hooke's law***:

$$\pm_e = Ee$$

,where E is modulus of elasticity (MPa)

  – As stress continues to increase, a point ***Y*** is reached, this is the point where material begins to yield and called the ***yield point*** *or* ***yield strength*** (end of elastic region and transition to plastic region). Y is defined as the stress at 0.2% strain offset (***Y*** is not always clear on the figure).

Stress-Strain relationships; Tensile properties

- The stress-strain relationship in the figure has two regions, elastic and plastic regions:

  (2) In the plastic region: the relationship is no more linear and is no longer guided by Hooke's law. Further stressing will lead to further elongation in the specimen but with faster rate, leading to a dramatic change in the slope.

  - Elongation is accompanied by a uniform reduction in A_0 so as to maintain a constant volume.

  - Finally, the applied load reaches a max. value. The engineering stress calculated at this point is called the *tensile (or ultimate) tensile strength (TS or UTS), where* $TS = F_{max} / A_0$.

  - After crossing the *TS* point, stress starts to decline where ***necking*** occurs; the specimen during necking starts exhibiting localized elongation. The area at the necking narrows down significantly until failure occurs. The stress calculated just before the failure is called ***fracture stress***.

Stress-Strain relationships; Tensile properties

- ***Ductility***: the ability of a material to plastically strain without fracture. Ductility is important in both design and manufacturing. This measure can be taken as either elongation or reduction in area:

(1) Elongation and defined as:

$$EL = \frac{L_f - L_0}{L_0}$$

(2) Area reduction and defined as:

$$AR = \frac{A_0 - A_f}{A_0}$$

Stress-Strain relationships; Tensile properties

- There are two different types of stress-strain curves: (1) Engineering stress-strain and (2) True stress-strain. The first is more important in design and the second is more important in manufacturing.

  (2) True Stress-Strain: stress and strain defined relative to the instantaneous (actual) area that becomes increasingly smaller as the test proceeds.

- The true stress at any point on the curve is defined as the force divided by the instantaneous area:

$$\pm = \frac{F}{A}$$

where σ : true stress, MPa (n / mm^2), F = applied force, N, and A is the instantaneous area resisting the load, mm^2.

Stress-Strain relationships; Tensile properties

- Similarly, the ***true strain*** is a more realistic assessment of the instantaneous elongation per unit length of the test specimen. This is done by dividing the total elongation into small increments, calculating the engineering strain for each increment of its starting length, and then adding up the strain values:

$$£ = \int_{L_0}^{L} \frac{dL}{L} = \ln \frac{L}{L_0}$$

where *L* is the instantaneous length at any moment during deformation

Stress-Strain relationships; Tensile properties

- The elastic region in the true stress-strain curve is almost similar to that of the engineering stress-strain curve (can you guess why). Hence, the elastic region in the true curve obeys Hooke's Law.

- The progressive reduction in area in the true stress-strain curve is considered in the plastic region. Hence, the stress in this region is higher as compared to that of the engineering stress-strain curve.

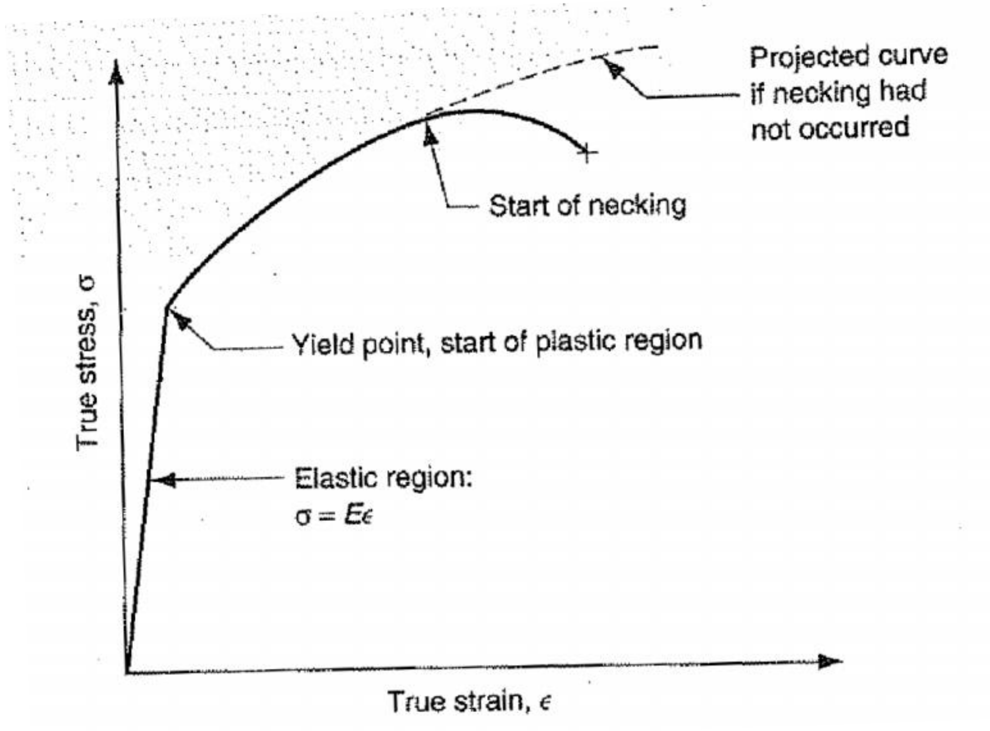


Fig. 3-5: a typical true stress-strain curve for a metallic specimen.

$$\varepsilon = \ln(1+e)$$

$$\pm = \pm_e(1+e)$$

Stress-Strain relationships; Tensile properties

- Strain (work) hardening: a property that most metals exhibits during deformation. It means that the metal is getting stronger as strain increases (see true stress-strain curve).

- Strain hardening is important in manufacturing, especially in metal forming processes.

- With plotting the true stress and true strain of the plastic region on a log-log scale, the result would be a linear relationship as in fig. 3-6, and the relation between true stress and true strain would then be:

  $$\pm = K£^{n}$$

  K (strength coefficient) = σ if $\varepsilon = 1$.

  n (strain hardening exponent) (slope), and related to a metal's tendency to work harden.

- Flow curve equation. It captures a good approximation of the behavior of metals in the plastic region, including their capacity for strain hardening

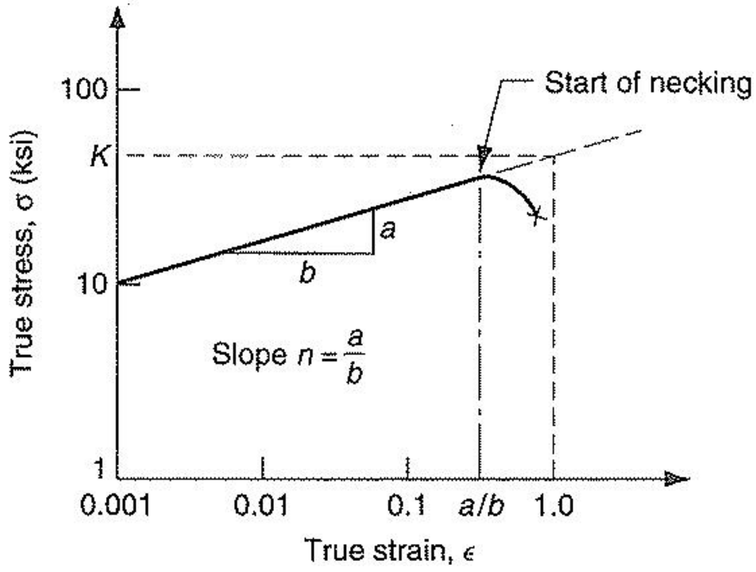


Fig. 3-6: true stress-strain curve plotted on a log-log scale.

Note: Necking is closely related to strain hardening.

Necking begins when $\varepsilon = n$. A higher n means the metal can be strained further before necking begins

Stress-Strain relationships; Tensile properties

- Much information about elastic-plastic behavior is provided by the true stress-strain diagram; as Hooke's law governs the metal's behavior in the elastic region and the flow curve equation determines the behavior in the plastic region. Three basic forms of stress-strain relationship describe the behavior of nearly all metals:

(a) Perfectly elastic: the material is defined completely by its stiffness indicated by modulus of elasticity. It fractures before yielding or plastic flow; example of these materials are ceramics and thermosetting polymers. These materials are bad for forming.

(b) Elastic and perfectly plastic: as yield stress is reached, the material deforms plastically at the same stress level. Flow curve in this case $K = Y$ and $n = 0$. Happens to metals heated during straining that recrystallization occurs rather than strain hardening. For Pb, this is the situation at RT as the recrystallization temperature for Pb is below RT.

(c) Elastic and strain hardening: obeys Hooke's Law in the elastic region, and starts to flow when Y is reached. Continued deformation requires an ever-increasing stress, given by flow curve whose K is > Y and n is > 0. Most ductile materials behave this way when cold-worked.

Stress-Strain relationships; Tensile properties

- Much information about elastic-plastic behavior is provided by the true stress-strain diagram; as Hooke's law governs the metal's behavior in the elastic region and the flow curve equation determines the behavior in the plastic region. Three basic forms of stress-strain relationship describe the behavior of nearly all metals:

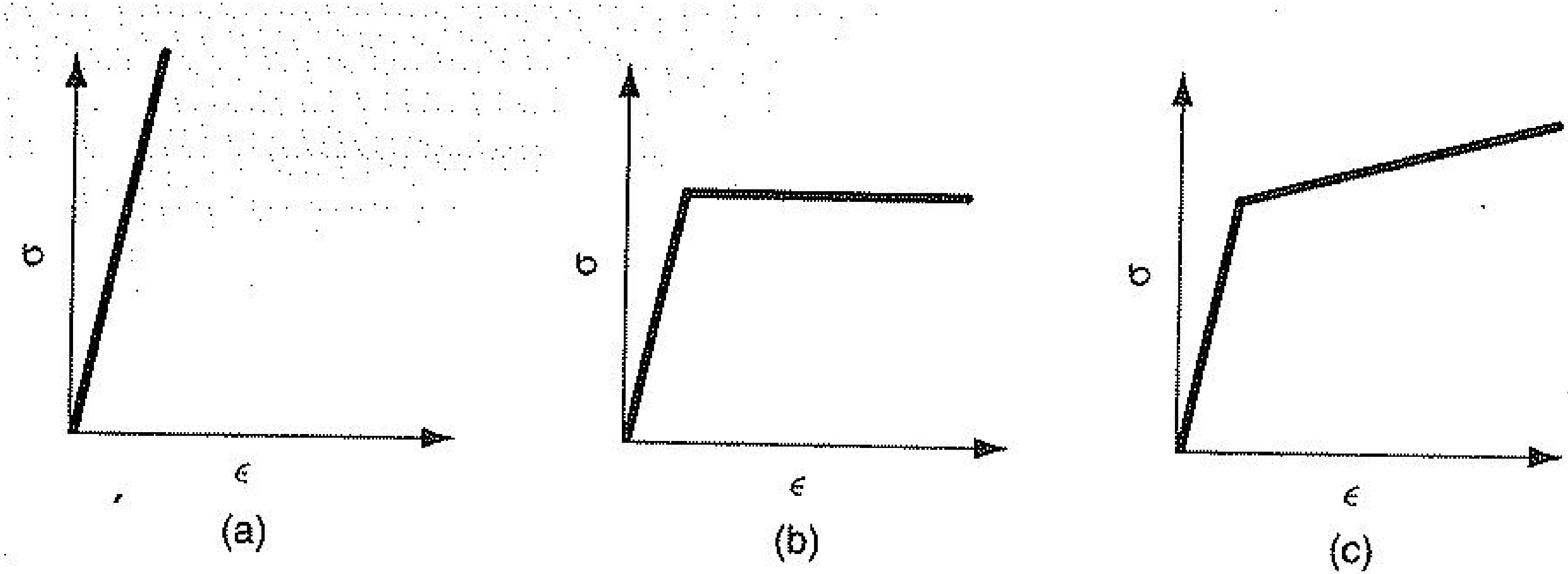


Fig. 3-7: Three categories of stress-strain relationships: (a) perfectly elastic, (b) elastic and perfectly plastic and (c) elastic and strain hardening.

Stress-Strain relationships; Compression properties

- Compression test: a test that applies a load that squeezes a cylindrical specimen between two platens (see fig. 3-8). As the specimen is compressed, its height is reduced and its cross-sectional area is increased. The engineering stress is defined in the same way as in the tensile test; i.e.,

$$\pm_e = \frac{F}{A_0}$$

- The engineering strain is defined as:

$$e = \frac{h - h_0}{h_0}$$

where h is the height of the specimen at any particular moment into the test in mm, and h_0 is the starting height in mm.

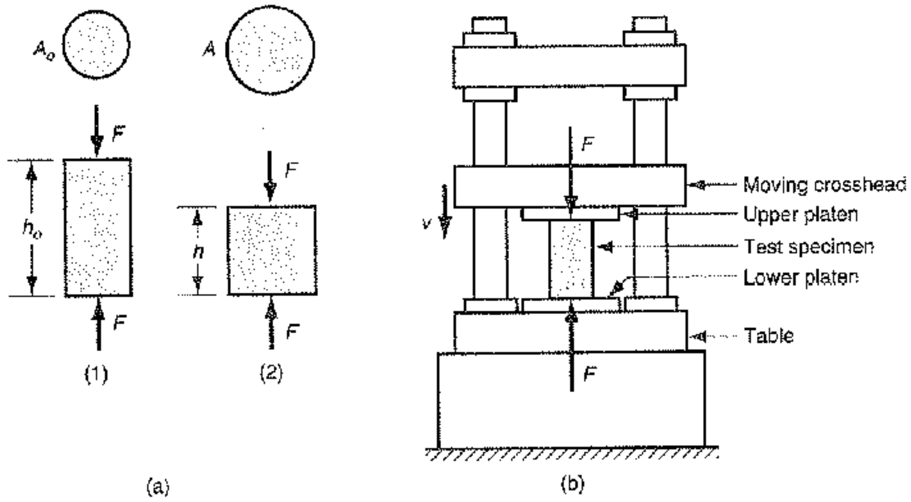


Fig. 3-8: Compression test: (a) compression force applied to test specimen in (1) and (2) resulting change in height; and (b) setup of the test.

Note that e will have a negative sign, as the height is decreased during compression. This sign is neglected.

Stress-Strain relationships; Compression properties

- Fig. 3-9 shows an engineering stress-strain curve. The curve has elastic and plastic regions as before, but the shape of the plastic region is different from its tensile test complement. Reasons:

  – Compression causes A to increase, the load increases more rapidly.

  – As the cylindrical specimen is compressed, friction at the surfaces in contact with the platens prevent the cylinder from spreading. Additional energy is consumed by friction during the test, resulting in a higher applied force.

  – This will result in ***barreling*** of the specimen; the middle of the specimen is permitted to increase in A much more than at the ends.

  – Important compression processes include forging, rolling and extrusion.

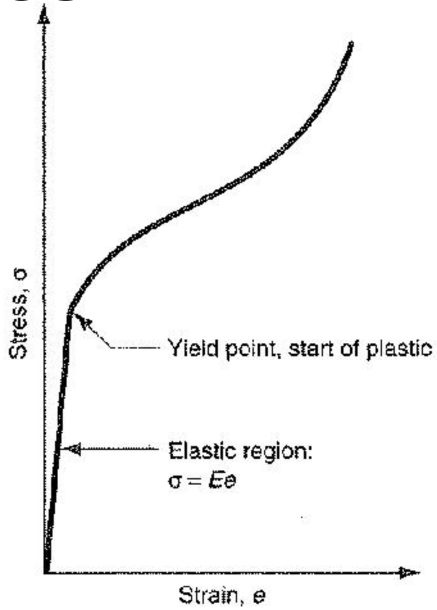


Fig. 3-9: Typical engineering stress-strain curve for a compression test.

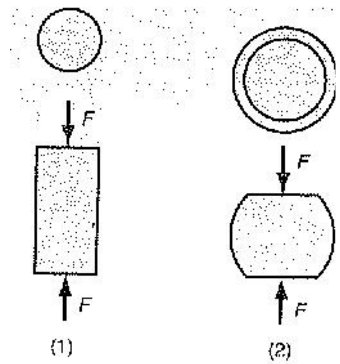


Fig. 3-10: Barreling effect. (1) before and (2) after compression.

Stress-Strain relationships; Bending & Testing of Brittle Materials

- Bending operations: used to form metal plates and sheets (Fig. 3-11; showing the setup of the bending test). Bending results in two stress (and strain) components; tensile in the outer half of the bent section and compressive in the inner half.

- ***Bending test*** (also known as ***flexure test***) suits brittle materials that possess elasticity the best; e.g. ceramics.

- These materials do not respond well to traditional tensile testing because of the difficulty in preparing the test specimens and possible misalignment of the press jaws that hold the specimen.

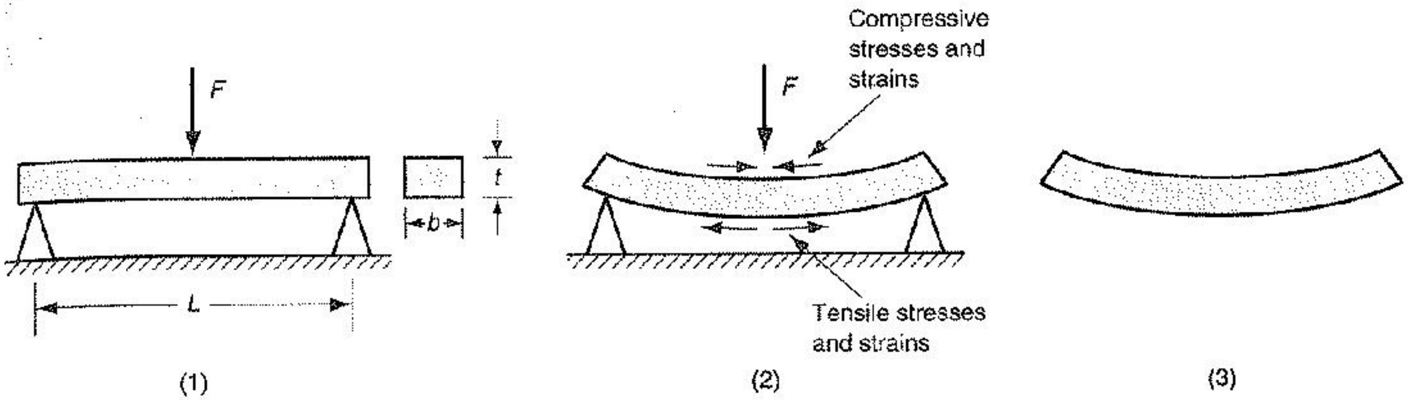


Fig. 3-11: Bending test setup and specimen: (1) initial loading, (2) highly stressed and strained specimen, and (3) bent part.

Stress-Strain relationships; Bending & Testing of Brittle Materials

- Specimen's cross-section is rectangular, positioned between supports and load is applied at its center (three-point bending test).
- The specimen bends elastically during the test until immediately before fracture (no plastic region).
- Strength value derived from this test is called ***Transverse Rupture Strength*** (*TRS*):

$$TRS = \frac{1.5FL}{bt^2}$$

where TRS is in MPa, F: the applied load at fracture in N, L: the length between supports and b and t are dimensions of the cross-section in mm (Fig. 3-11)

- Flexure test can be utilized for nonbrittle materials such as thermoplastic polymers. These materials deform rather fracture, so TRS cannot be determined. Instead, either of the two measures are used: (1) the load recorded at a given level of deflection, or (2) the deflection observed at a given load.

Stress-Strain relationships; Shear properties

- Shear: involves the application of stresses on opposite directions on either side of an element to deflect it.

- Shear stress is defined as:

$$2 = \frac{F}{A}$$

where τ : shear stress, MPa (n / mm^2), F = applied force, N, and A is the area over which force is applied, mm^2.

- Shear strain can be defined as:

$$¥ = \frac{¢}{b}$$

where γ is shear strain, mm / mm, δ = the deflection of the element, mm, and L_0 is the orthogonal distance over which the deflection occurs, mm.

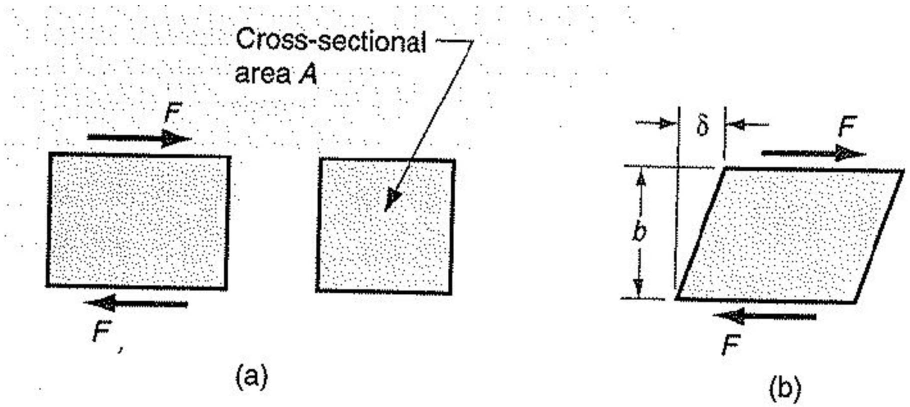


Fig. 3-12: Shear (a) stress and (b) strain.

Stress-Strain relationships; Shear properties

- Shear stresses and strains are commonly tested in a ***torsion test***.

- In torsion test: a thin-walled tubular specimen is subjected to a torque. As torque is increased, a tube deflects by twisting (shear strain for this geometry).

$$2 = \frac{T}{2®R^2 t}$$

where *T*: is the applied torque (N-mm), *R* = radius of the tube measured to the neutral axis of the wall (mm), and t = wall thickness (mm).

- Shear strain :

$$¥ = \frac{R\sim}{L}$$

where ~ is the angular deflection, radians, and *L* is the gauge length in mm.

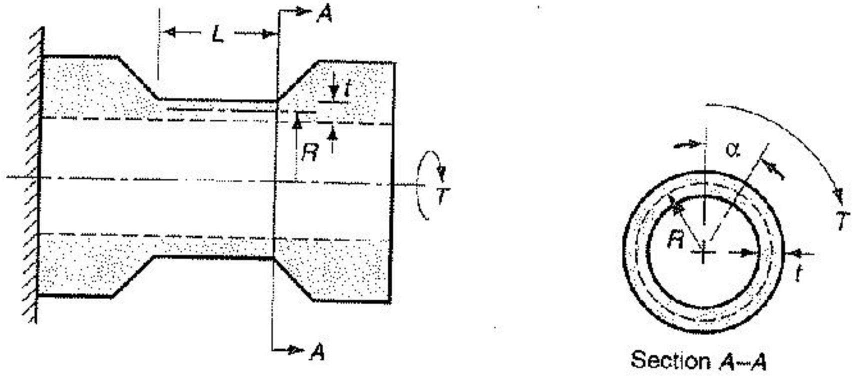


Fig. 3-13: Torsion test setup.

Stress-Strain relationships; Shear properties

- A typical shear stress-strain curve is shown in Fig. 3-14.
- In the elastic region:

$$^2 = G¥$$

where G: is the ***Shear modulus*** or ***shear modulus of elasticity*** (MPa)

- *G* is related to *E* by the equation:

$$G = 0.4E$$

where *E* is the conventional elastic modulus.

- In the plastic region:

The material strain hardens to cause the applied torque to continue to increase until fracture.

Shear strength is the stress at fracture (*S*).

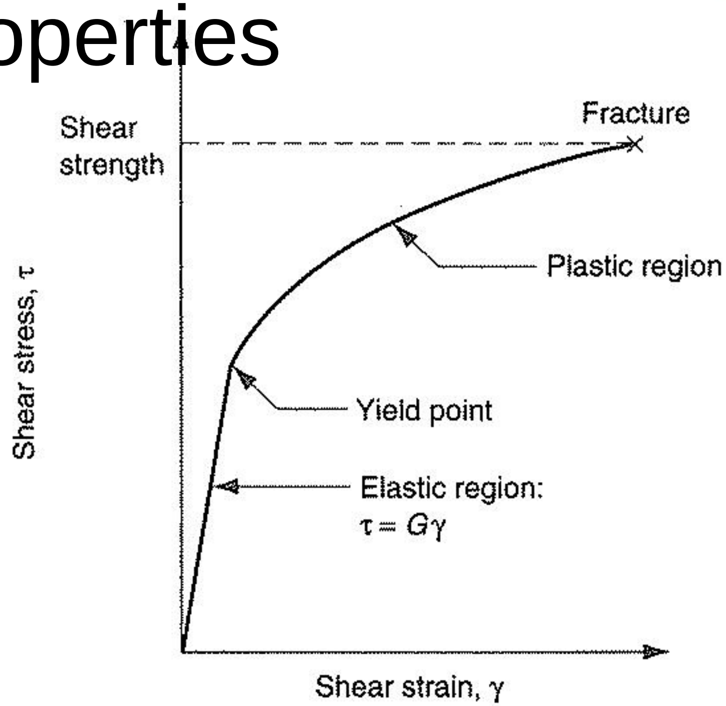


Fig. 3-14: A typical shear stress-strain curve from a torsion test.

S can be estimated from tensile test data

$$S = 0.7(TS)$$

Engineering and true stress-strain curves for shear are similar. Guess why?

Shear examples in industry: blanking, punching & machining

Hardness

- ***Hardness***: is a measure of a material's resistance to localized plastic deformation (permanent indentation).

- High hardness: material is resistant to scratching and wear.

- Mohs scale (qualitative): ranges from 1 on the soft end for talc to 10 for diamond.

- There is a good correlation between the material's hardness and its strength.

Hardness

- Hardness tests are performed more frequently than any other mechanical test for several reasons:
  - They are simple and inexpensive—ordinarily no special specimen need to be prepared, and the testing apparatus is relatively inexpensive.
  - The test is nondestructive—the specimen is neither fractured nor excessively deformed; a small indentation is the only deformation.
  - Other mechanical properties often may be estimated from hardness data, such as tensile strength

Hardness
Rockwell Hardness Tests

- The most common method used to measure hardness because they are so simple to perform and require no special skills.
- Several indenters (steel ball, conical diamond), several loads can be utilized. Thus, suitable for almost all metal alloys, including polymers.
- Indenter (1.6 or 3.2 mm in diameter) is pressed into the specimen. Load starts at 10 kg to seat the indenter in the material, and then increased up to 150 kg. The indenter penetrates into the material. The distance penetrated (*d*) is converted to Rockwell hardness by the testing machine.

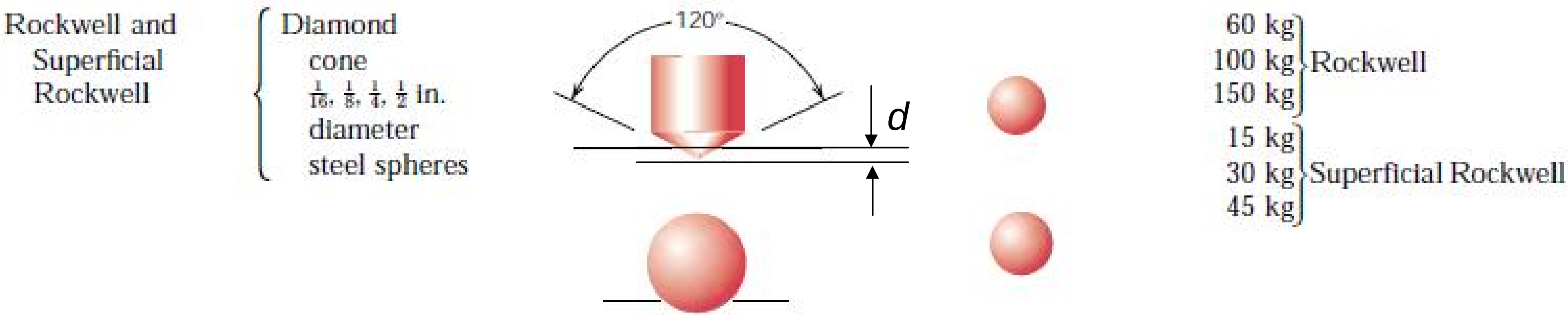


Fig. 3-15: Rockwell hardness testing technique.

Hardness
Brinell Hardness Tests

- In Brinell tests, as in Rockwell measurements, a hard, spherical indenter (10 mm in diameter) is forced into the surface of the metal to be tested.
- Standard loads range between 500 and 3000 kg.
- The load is then divided into the indentation area to get Brinell Hardness number.

Brinell

10-mm sphere of steel or tungsten carbide

$$HB = \frac{2P}{\pi D[D - \sqrt{D^2 - d^2}]}$$

Fig. 3-15: Brinell hardness testing technique.

Hardness
Vickers Hardness Test

- Uses a pyramid-shaped diamond indenter (10 mm in diameter).
- Impressions made by this indenter are geometrically similar regardless of load.
- Value of load applied depends on the material's hardness.
- Applied loads are much smaller than for Rockwell and Brinell, ranging between 1 and 1000 g.

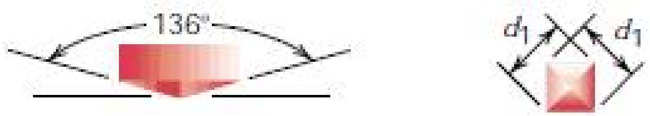
Test	Indenter	Side view	Top view	Formula
Vickers microhardness	Diamond pyramid			$HV = 1.854P/d_1^2$

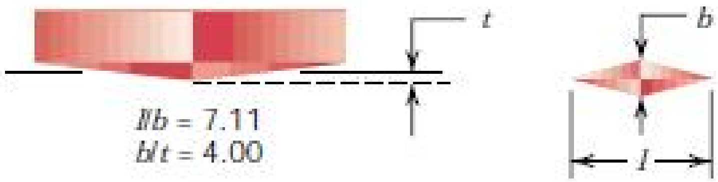
Fig. 3-16: Vickers hardness testing technique.

Hardness
Knoop Hardness Test

- Uses a pyramid-shaped diamond indenter with length to width ratio of 7:1.
- Applied loads are the smallest comparing to Rockwell, Brinell and Vickers hardness.

Side view Top view

Knoop microhardness | Diamond pyramid



$HK = 14.2P/l^2$

Fig. 3-17: Vickers hardness testing technique.

Hardness of Various Materials

- **Metals**: For most metals, hardness is closely related to strength.
- Hardness is a form of compression, so one would expect a good correlation between hardness and strength properties determined in a compression test.
- Compression and tensile tests are nearly the same, so the correlation with tensile properties would also be acceptable.
- Brinell hardness exhibits a close correlation with *TS* (MPa) for steels, and the formula is:

$$TS = 3.45HB$$

Metal	Brinell Hardness, HB	Rockwell Hardness, HR[a]
Aluminum, annealed	20	
Aluminum, cold worked	35	
Aluminum alloys, annealed[b]	40	
Aluminum alloys, hardened[b]	90	52B
Aluminum alloys, cast[b]	80	44B
Cast iron, gray, as cast[b]	175	10C
Copper, annealed	45	
Copper alloy: brass, annealed	100	60B
Lead	4	
Magnesium alloys, hardened[b]	70	35B
Nickel, annealed	75	40B
Steel, low C, hot rolled[b]	100	60B
Steel, high C, hot rolled[b]	200	95B, 15C
Steel, alloy, annealed[b]	175	90B, 10C
Steel, alloy, heat treated[b]	300	33C
Steel, stainless, austenitic[b]	150	85B
Titanium, nearly pure	200	95B
Zinc	30	

Hardness of Various Materials

- Ceramics: Brinell hardness is not appropriate for ceramics as they are usually harder than the Brinell hardness indenter.
- Instead, Vickers and Koop hardness tests are used to test ceramics.

Material	*Approximate Knoop Hardness*
Diamond (carbon)	7000
Boron carbide (B_4C)	2800
Silicon carbide (SiC)	2500
Tungsten carbide (WC)	2100
Aluminum oxide (Al_2O_3)	2100
Quartz (SiO_2)	800
Glass	550

Approximate Knoop Hardness (100 g load) for Seven Ceramic Materials.

Hardness of Various Materials

- Polymers: Softer than metals and ceramics, and most hardness tests are conducted by penetration techniques similar to those described for metals. Rockwell and Brinell tests are frequently used for polymers.

Polymer	Brinell Hardness, HB	Polymer	Brinell Hardness, HB
Nylon	12	Polypropylene	7
Phenol formaldehyde	50	Polystyrene	20
Polyethylene, low density	2	Polyvinyl-chloride	10
Polyethylene, high density	4		

Effect of Temperature on Properties

- Temperature has a significant effect on nearly all properties of materials.

- **<u>Important in design</u>**: a designer need to know how the material properties at the operating temperatures during service.

- **<u>Important in manufacturing</u>**: a manufacturer need to know how the properties are affected by temperature during manufacturing.

- Generally speaking, the higher the temperature the higher the ductility and the lower the strength (better formability at high temperatures).

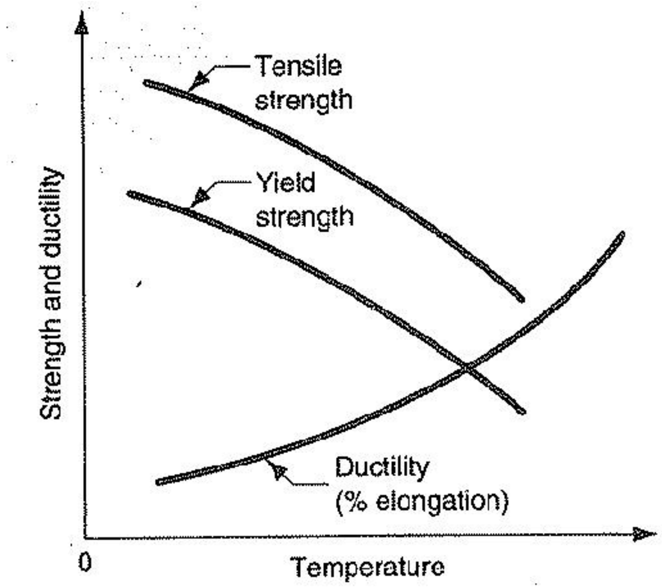


Fig. 3-18: Effect of temp. on strength & ductility

Effect of Temperature on Properties (Hot Hardness)

- **<u>Hot hardness</u>**: is a property often used to characterize strength and hardness at elevated temperatures. It is simply the ability of a material to retain hardness (or resist softening) at elevated temperatures.
- Usually presented as a plot of hardness versus temperature.
- In steel: alloying would enhance the hot hardness.
- Ceramics: they show superior properties at elevated temperatures (that is why they are used as refractory material).
- Good hot hardness is desirable in tooling materials used in manufacturing operations.

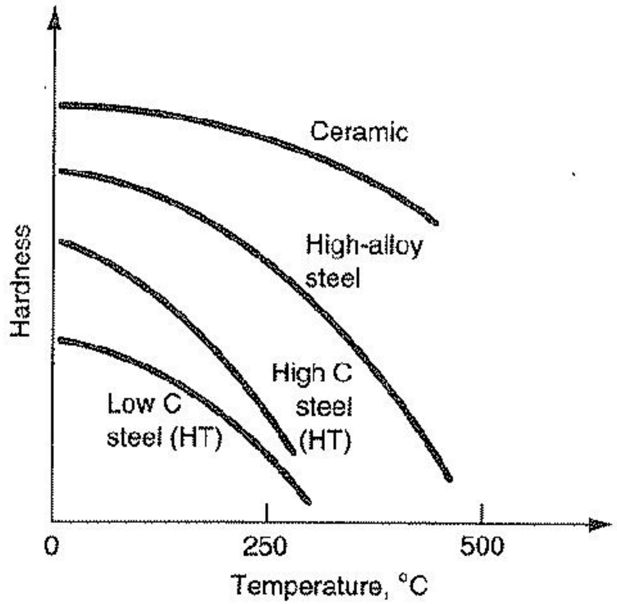


Fig. 3-19: Hardness vs. temperature for various materials.

Effect of Temperature on Properties (Recrystallization Temp.)

- **Recrystallization**: is the process in which new strain-free grains are formed. The temperature at which this process happens is called the ***Recrystallization Temperature*** (~ one half the melting temperature (0.5 $T_{melting}$)).

- If metals were deformed at room temperature, they would behave in accordance with the flow curve equation.

- If metals where deformed at high temperatures, say recrystallization temperature, then they would have an elastic and superplastic behavior (no strain hardening).

- This is due to the formation of new strain-free grains at elevated temperatures.

- Higher strain can be endured at recrystallization temperature. Power spent to carry out deformation is significantly reduced.

- Metal forming at recrystallization temperature is called ***Hot Working***.

Fluid Properties

- Unlike solids, fluids flow; they take the shape of the container that holds them.
- Fluids include liquids and gases.
- Many manufacturing processes are done by converting the materials from the solid state to the liquid state.
- Examples are: metal casting, glass blowing and polymer molding.

Fluid Properties
Viscosity

- All fluids can flow. However, the tendency to flow differs for different fluids.

- **Viscosity**: is the resistance to flow, that is characteristic of a fluid. It is the property that determines fluid flow, and a measure of the internal friction that arises when velocity gradients are present in the fluid.

- In other words, the more viscous the fluid is, the higher the internal friction and the greater the resistance to flow.

- **Fluidity**: is the reciprocal of viscosity; the ease with which a fluid flows.

Fluid Properties
Viscosity

- Considering Fig. 3-20, viscosity can be defined more precisely.

- Two plates, one is stationary and the other is moving at velocity ν (oriented to the *x*-axis). Plates are separated by a distance *d* (oriented to the *y*-axis). The space between the plates is occupied by a fluid.

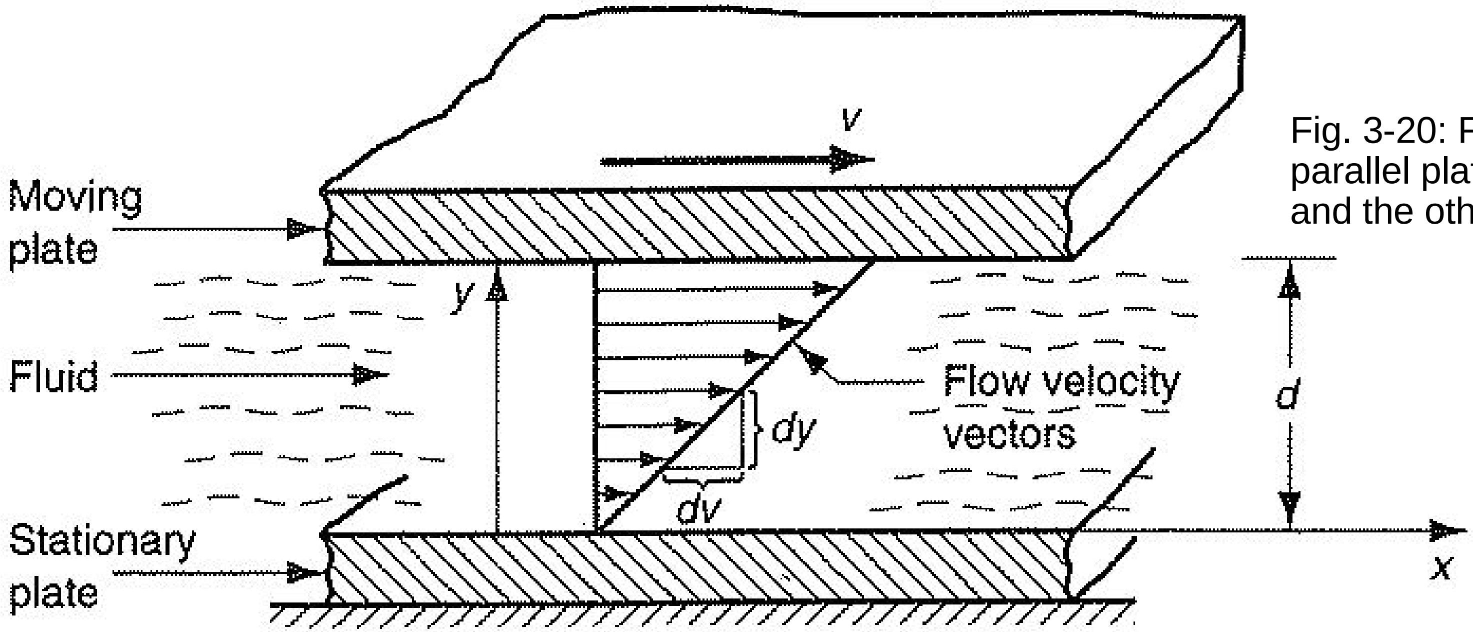


Fig. 3-20: Fluid flow between two parallel plates. One is stationary and the other is moving.

Fluid Properties
Viscosity

- The motion of the upper plate is resisted by force F that results from shear viscous action. This force can be described as shear stress:

$$\tau = \frac{F}{A}$$

Where τ is the shear stress in Pa (N/m^2).

- Shear stress is related to the rate of shear, which is defined as the change in velocity $d\nu$ relative to the dy:

$$\gamma = \frac{d\nu}{dy}$$

Where γ is the shear rate in 1/s; $d\nu$ is the incremental change in velocity in m/s; and dy is the incremental change in distance y in m.

Fluid Properties
Viscosity

- The shear viscosity is the fluid property that defines the relationship between F/A and *dv/dy*:

$$\frac{F}{A} = \eta \frac{dv}{dy} \quad \text{or} \quad \tau = \eta \gamma$$

where η is the coefficient of viscosity (Pa-s).

- Rearranging, we get:

$$\eta = \frac{\tau}{\gamma}$$

- Thus, viscosity of a fluid can be defined as the ratio between shear stress to shear rate during flow; where shear stress is the frictional force exerted by a fluid per unit area , and shear rate is the velocity gradient perpendicular to the flow direction.

- Newton observed that viscosity is a constant property of a given fluid. Such a fluid is called ***Newtonian fluid***.

Fluid Properties
Viscosity in Manufacturing Processes

- In metals: many manufacturing processes require melting the metal; e.g. welding and casting.

- Success in these operations require low viscosity so that the molten metal fills the mold cavity or weld seam before solidifying.

- In forming processes, lubricants and coolants are used, and again the success of these fluids depends to some extent on their viscosity.

- In glasses: they exhibit gradual transition from solid to liquid. They become less and less viscous with the increase in temperature, until they can be finally shaped by blowing or molding at around 1100 ^{o}C.

Fluid Properties
Viscosity in Manufacturing Processes

- <u>In thermoelastic polymers</u>; e.g. polyethylene, it is solid at RT, they change into a rubbery material on heating. With further increase in temp., it transforms into a thick fluid. Viscosity decreases gradually on heating until it is suitable for molding processes.

- For polymers however, the viscosity is not a constant; it changes with the flow rate. A polymer melt does not behave in a Newtonian fashion.

- A polymer that exhibits decreasing viscosity with increasing shear rate is called ***pseudoplastic***. This behavior complicates the analysis of polymer shaping.

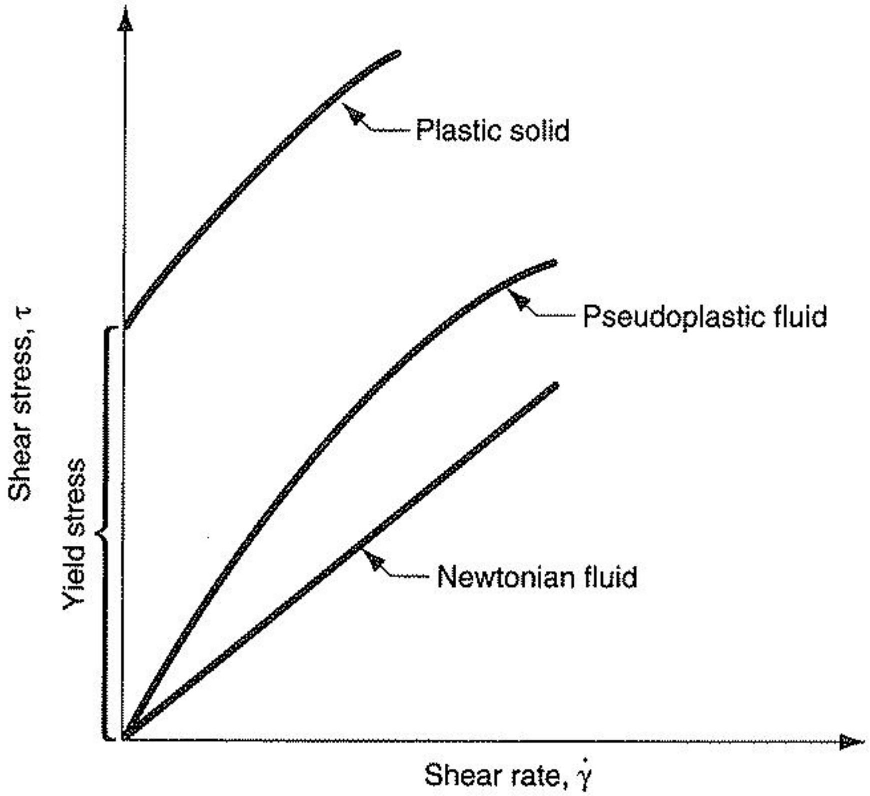


Fig. 3-21: Viscous behavior of different fluids.

Viscoelastic Behavior of Polymers

- <u>Viscoelasticity</u>: the property of the material that determines the strain it experiences when subjected to combinations of stress and time over temperature.

(a) Perfect elastic behavior; the material returns to its original shape when load is removed.

(b) Viscoelastic behavior; the strain gradually increases over time under the applied stress. The material does not return immediately to its original shape upon load removal; instead, the strain decays gradually.

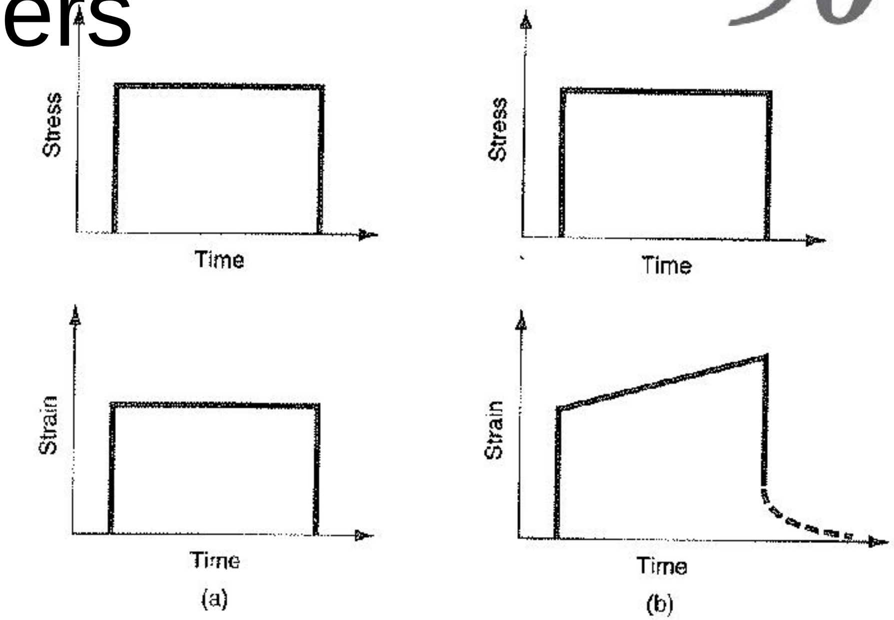


Fig. 3-22: Comparison of elastic and viscoelastic properties.

If stress had been applied & then immediately removed, the material would have returned immediately to its original shape (time dependent property).

Accordingly, the time-dependent stress-strain relationship can be expressed as:

$\pm (t) = f(t)$£ where $f(t)$ is the time function.

Viscoelastic Behavior of Polymers

Temperature effect:

- For relatively small deformations, the mechanical behavior at low temperatures may be elastic; that is, in conformity to Hooke's law.
- At the highest temperatures, viscous or liquid-like behavior prevails.
- For intermediate temperatures is found a rubbery solid that exhibits the combined mechanical characteristics of these two extremes

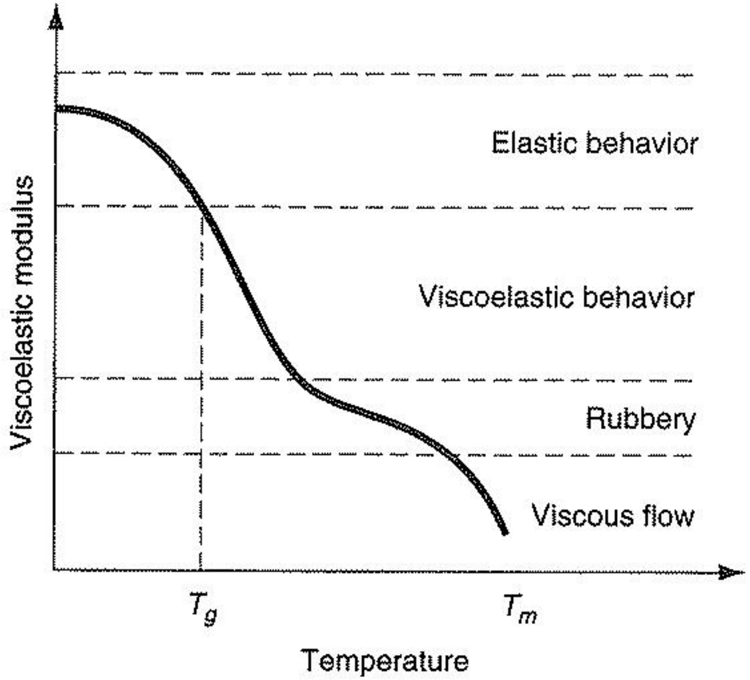


Fig. 3-23: Effect of temperature on viscoelasticity.

Viscoelastic Behavior of Polymers

- Deformation rate effect:
  - At low strain rate, the material exhibits significant viscous flow.
  - At high strain rate, it behaves in a much more brittle fashion.

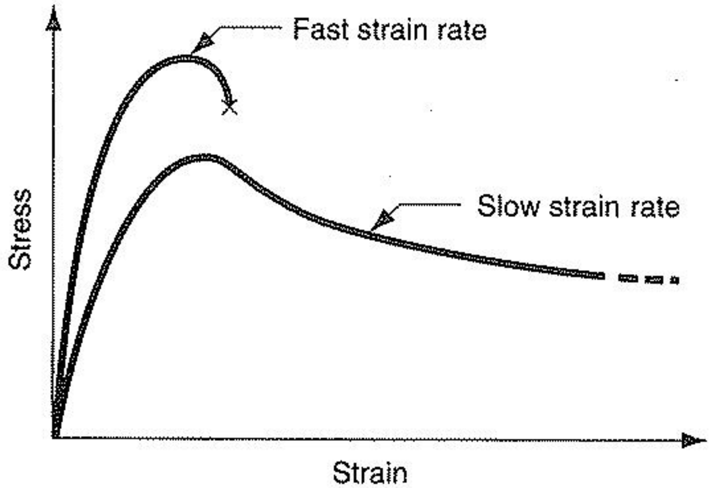
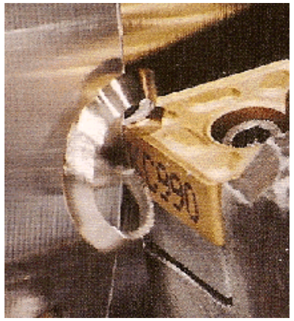


Fig. 3-24: Strain rate effect on viscoelasticity.



MACHINING OPERATIONS AND MACHINE TOOLS

1. Turning and Related Operations
2. Drilling and Related Operations
3. Milling
4. Machining Centers and Turning Centers
5. Other Machining Operations
6. Machining Operations for Special Geometries
7. High Speed Machining

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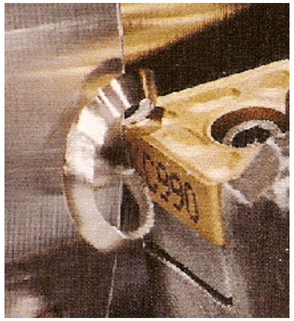

Machining

Material removal process in which a sharp cutting tool is used to mechanically cut away material so that the desired part geometry remains

- Most common application: metal parts
- Most versatile of all manufacturing processes in its capability to produce a diversity of part shapes and geometric features with high precision and accuracy
  - Casting can also produce a variety of shapes, but it lacks the precision and accuracy of machining

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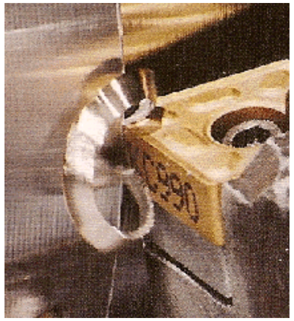
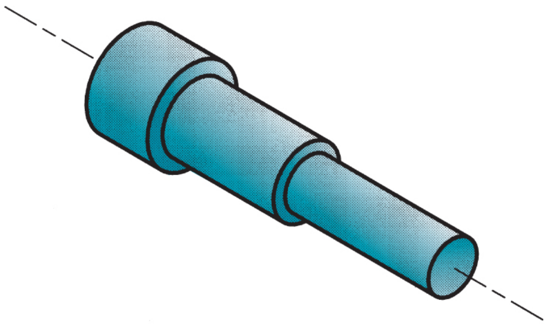
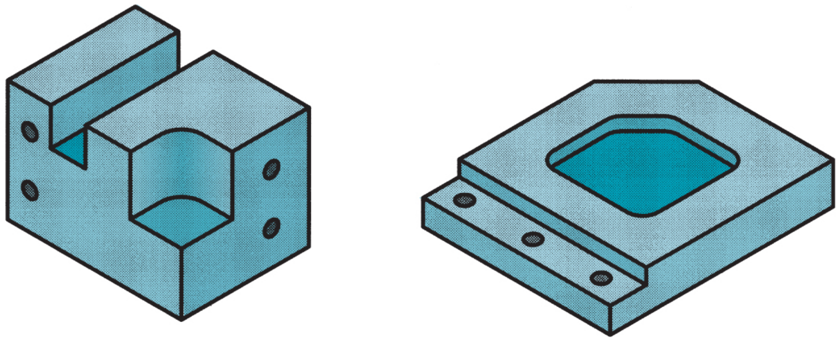


Classification of Machined Parts

- Rotational - (a) cylindrical or disk-like shape
- Nonrotational - (b) block-like or plate-like



(a)



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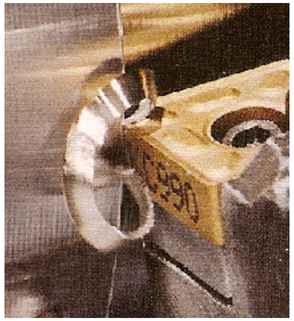

Machining Operations and Part Geometry

Each machining operation produces a characteristic part geometry due to two factors:

1. Relative motions between tool and workpart
   - *Generating* – part geometry determined by feed trajectory of cutting tool
2. Shape of the cutting tool
   - *Forming* – part geometry is created by the shape of the cutting tool

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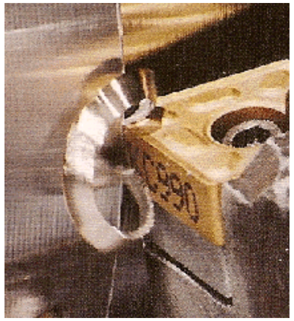
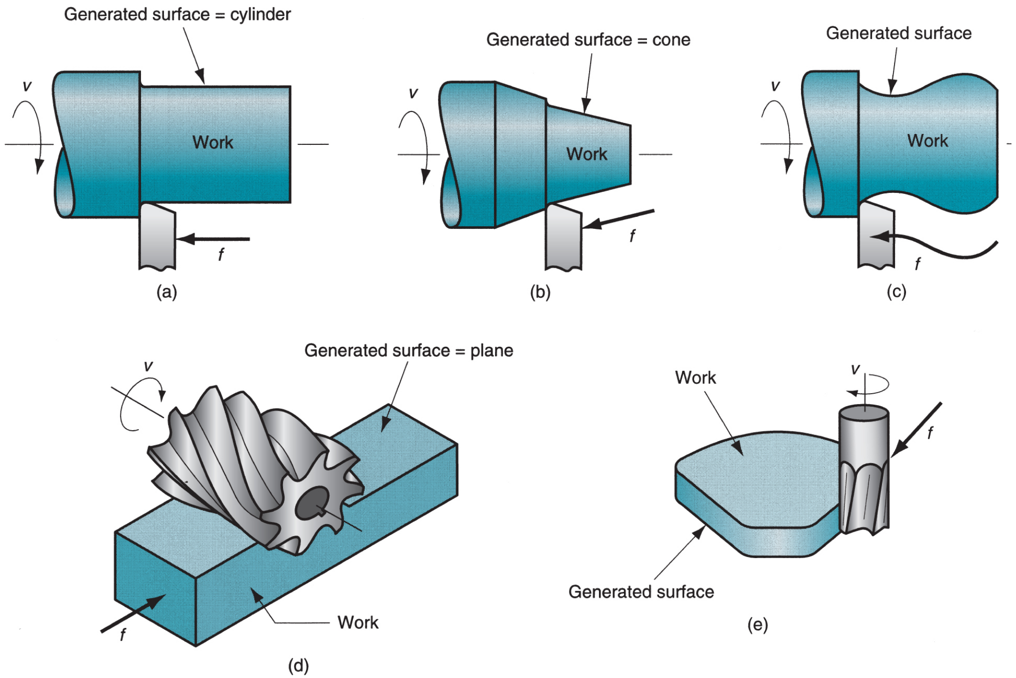


Generating Shape

- Generating shape: (a) straight turning, (b) taper turning, (c) contour turning, (d) plain milling, (e) profile milling



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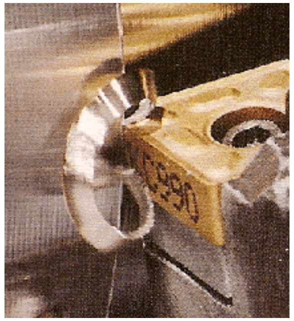
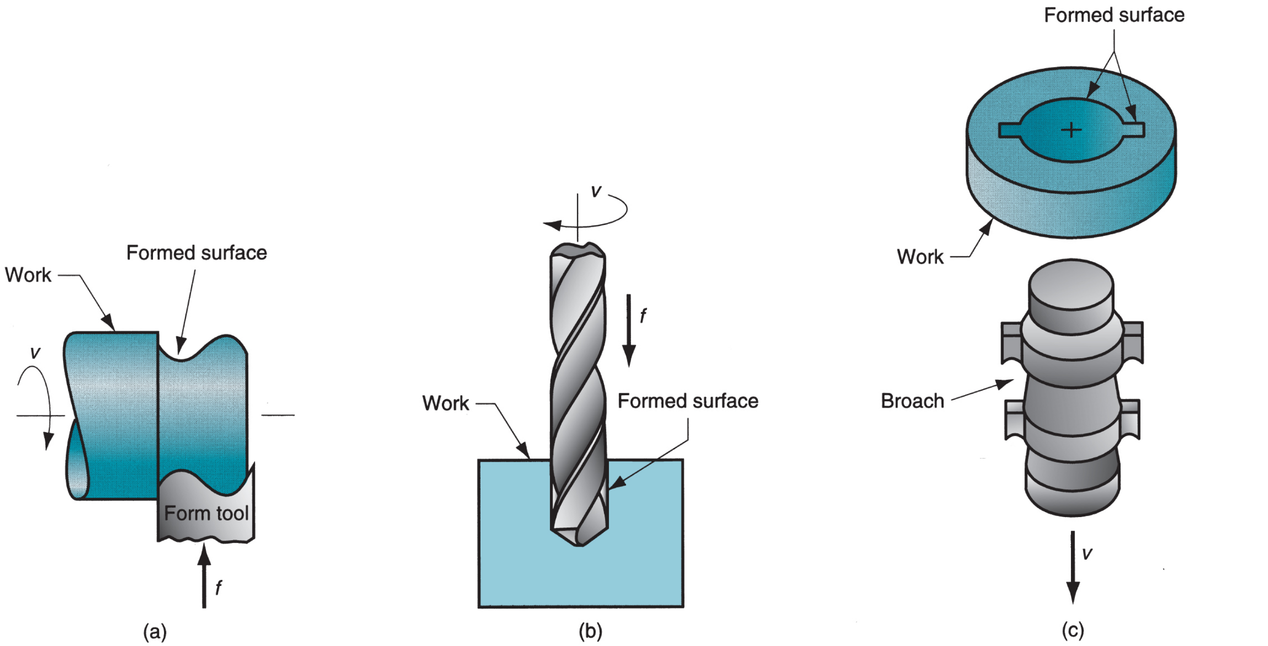


Forming to Create Shape

- Forming to create shape: (a) form turning, (b) drilling, and (c) broaching



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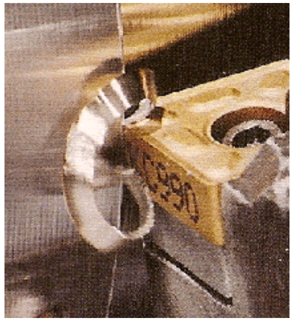
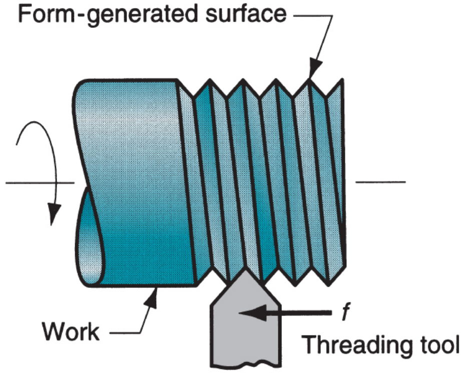
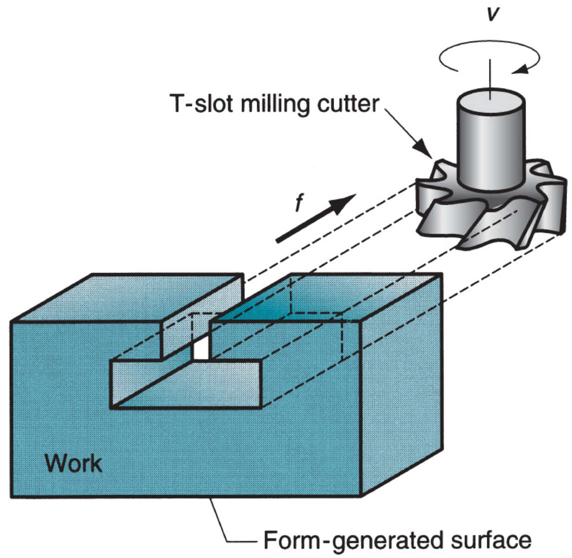


Forming and Generating

- Combination of forming and generating to create shape: (a) thread cutting on a lathe, and (b) slot milling



(a)



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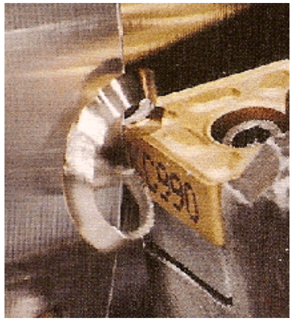

Turning

Single point cutting tool removes material from a rotating workpiece to generate a cylindrical shape

- Performed on a machine tool called a *lathe*
- Variations of turning performed on a lathe
  - Facing
  - Contour turning
  - Chamfering
  - Cutoff
  - Threading

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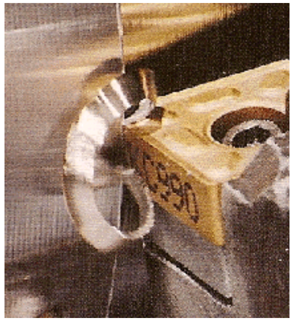
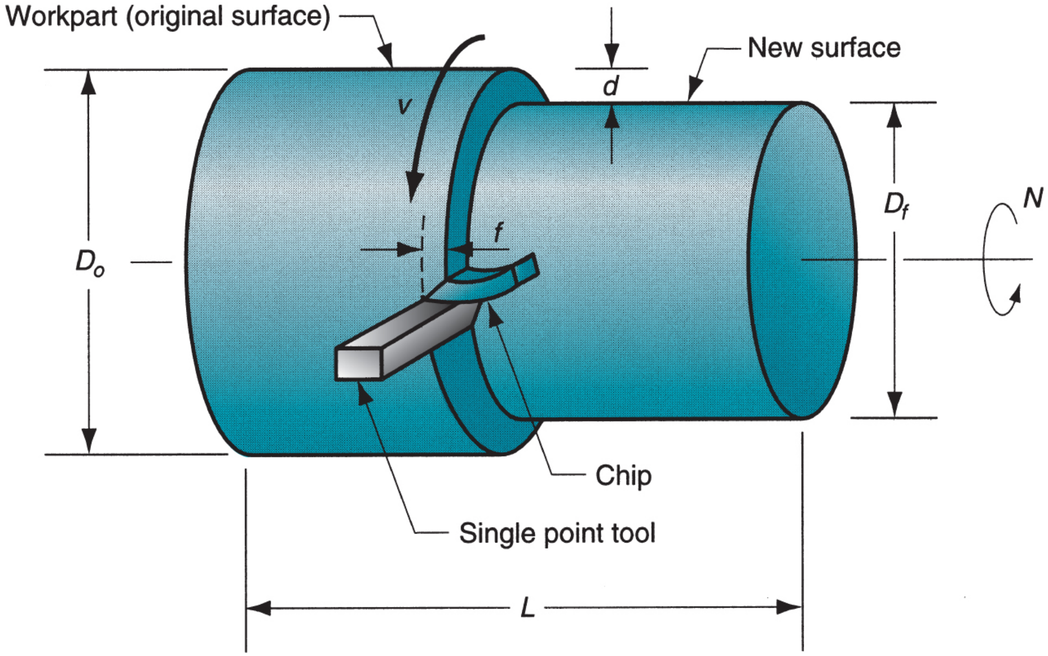


Turning Operation



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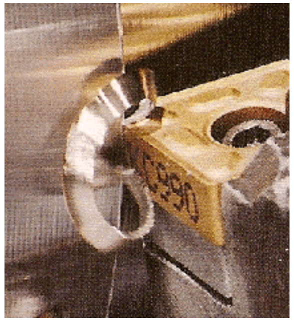
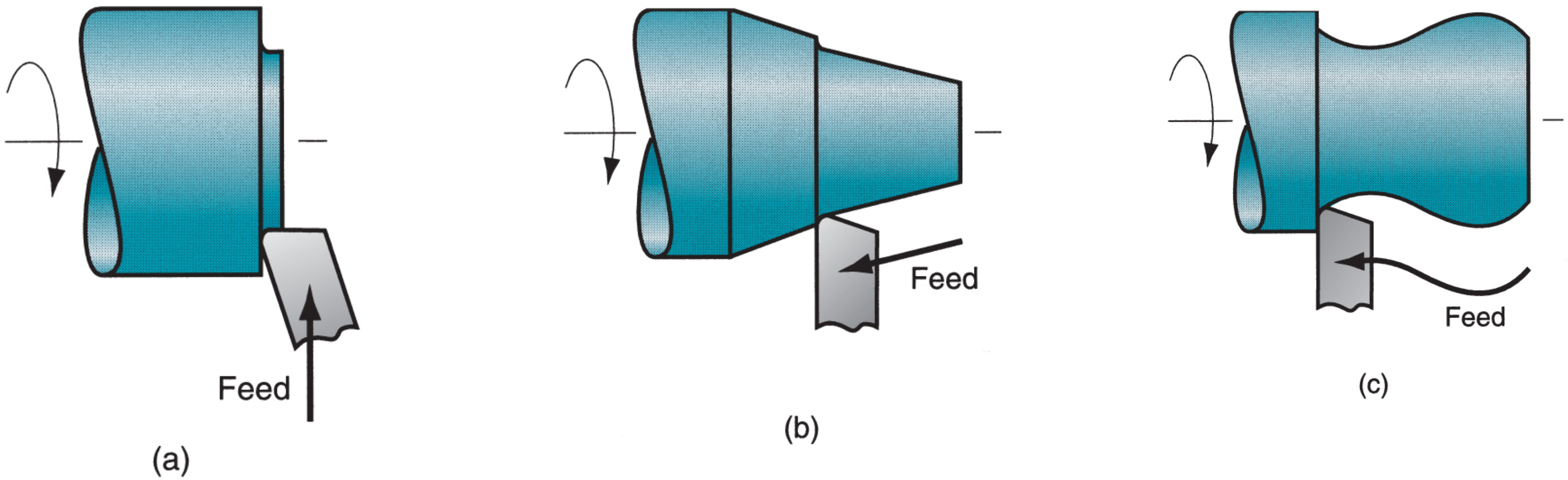


Operations Related to Turning

- (a) Facing, (b) taper turning, (c) contour turning



Produces flat surface

Feeding at an angle, producing a taper.

Tool follows a contour, producing a contoured form.

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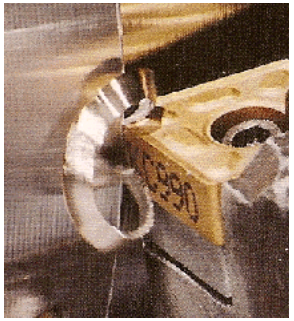
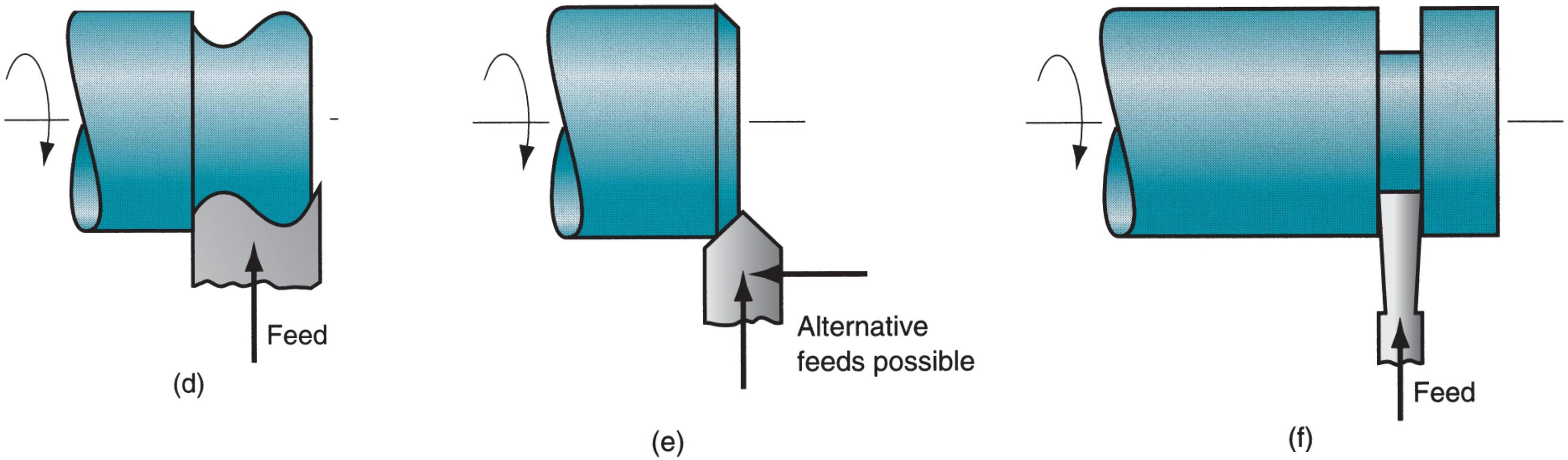


More Operations Related to Turning

- (d) Form turning, (e) chamfering, (f) cutoff



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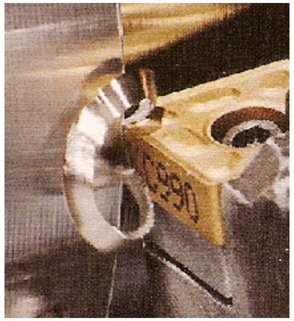
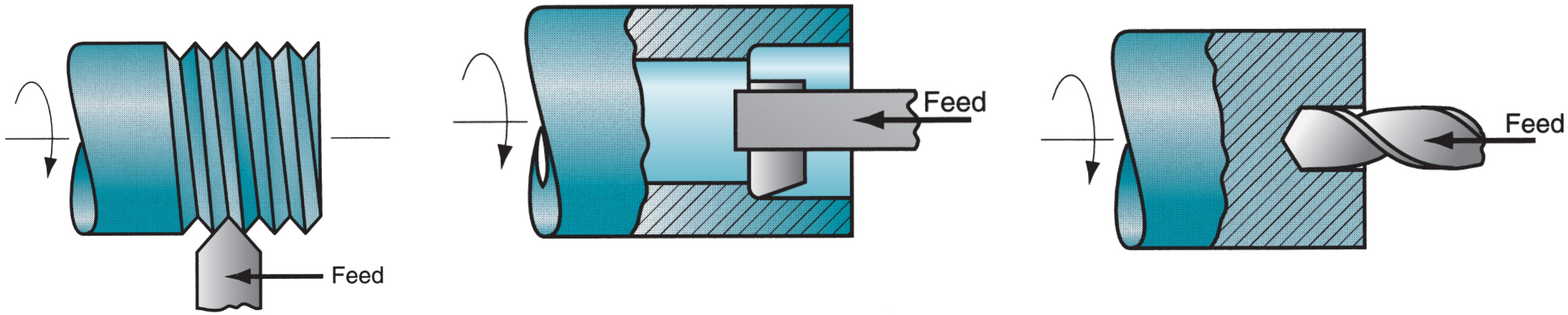


More Operations Related to Turning

- (g) Threading, (h) boring, (i) drilling



(g) (h) (i)

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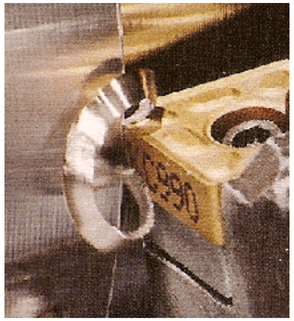
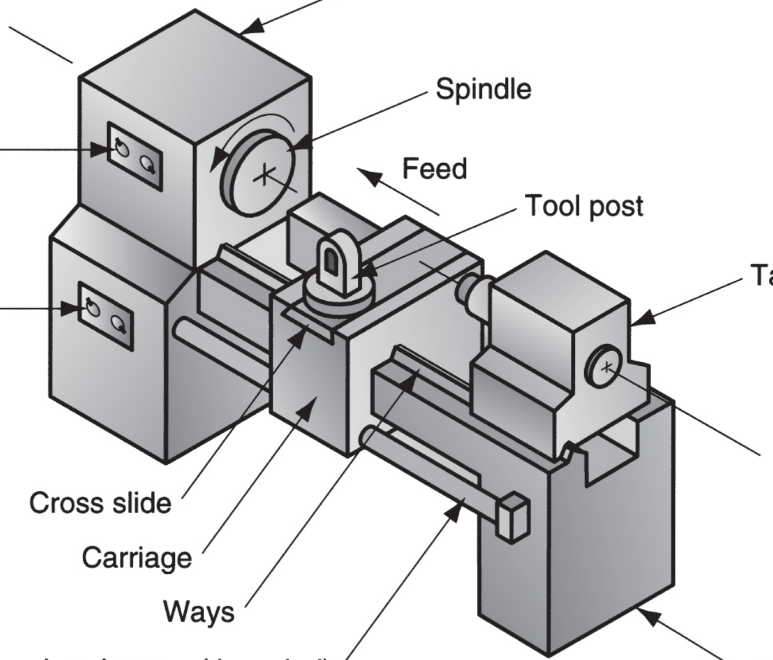


Engine Lathe

- Diagram of an engine lathe showing its principal components and motions



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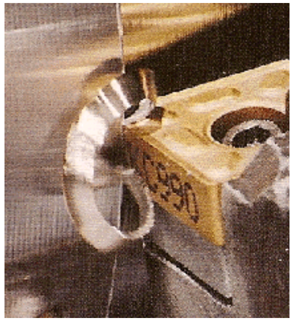
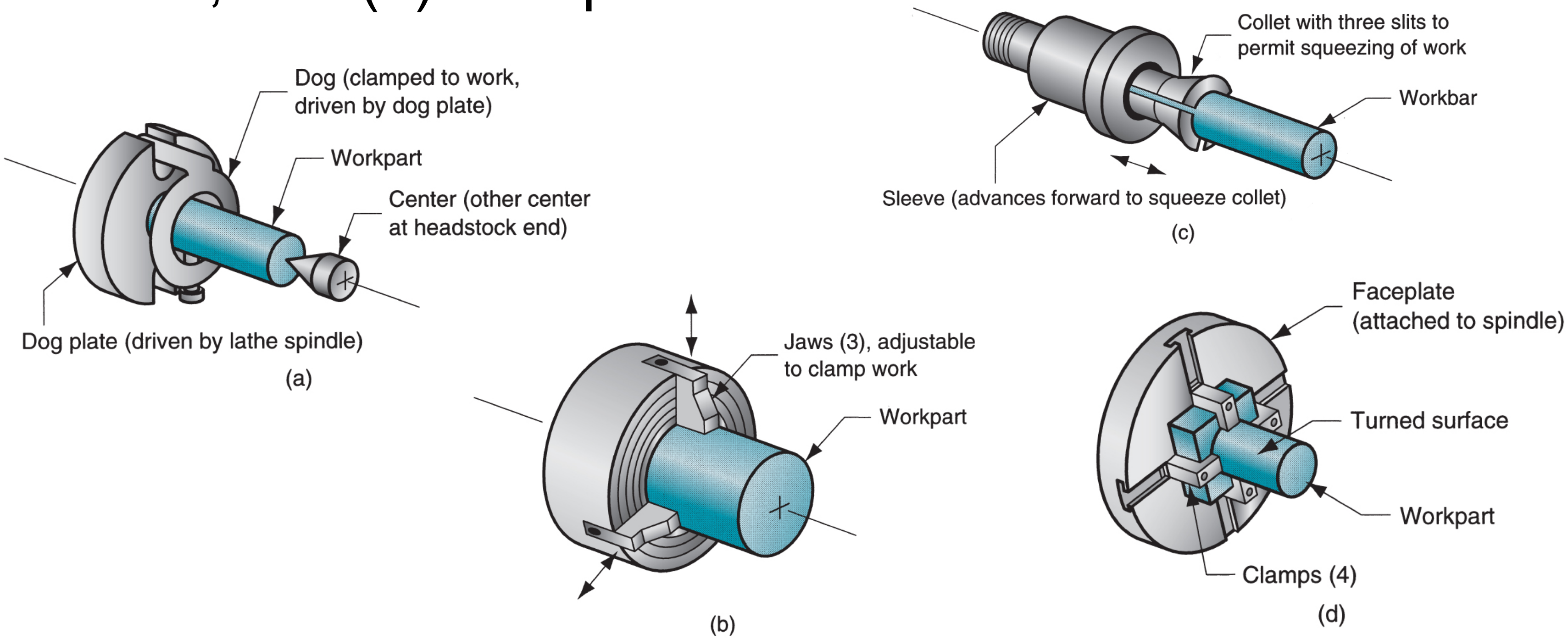


Methods of Holding Workpiece in a Lathe

- (a) Holding the work between centers, (b) chuck, (c) collet, and (d) face plate



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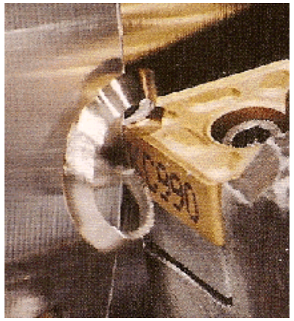
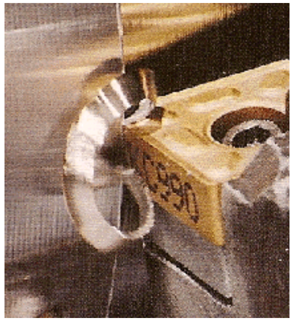


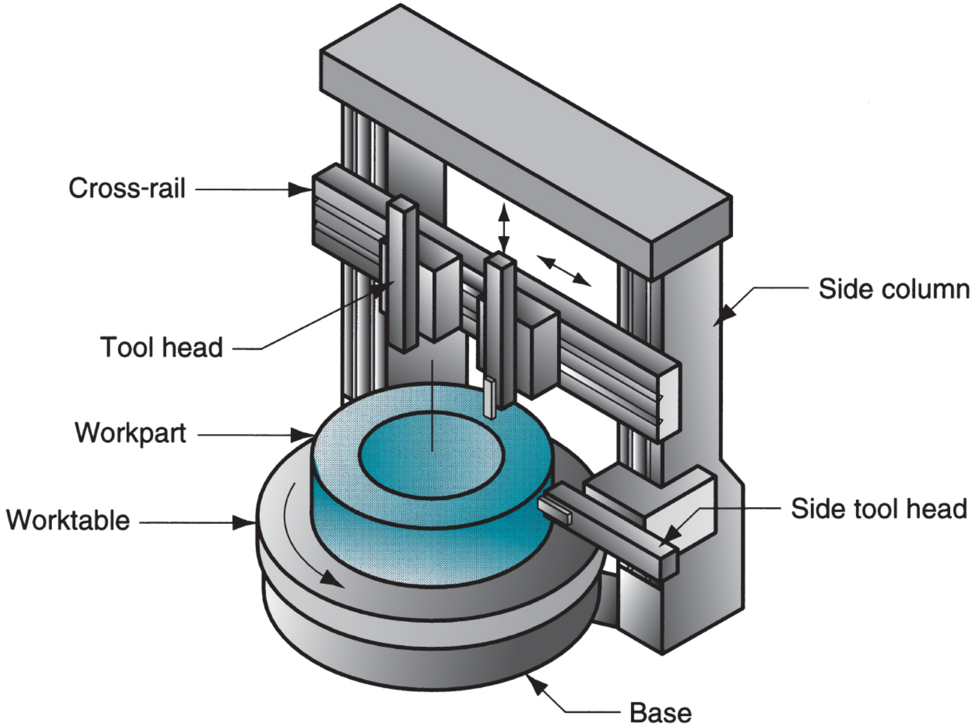
Boring

- Difference between boring and turning:
  - Boring is performed on the inside diameter of an existing hole
  - Turning is performed on the outside diameter of an existing cylinder
    - In effect, boring is internal turning operation
- Boring machines
  - Horizontal or vertical - refers to the orientation of the axis of rotation of machine spindle



Vertical Boring Mill

- Applications – large, heavy workparts that have low L/D ratio



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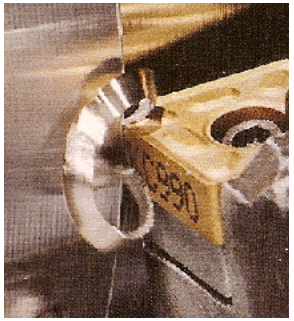
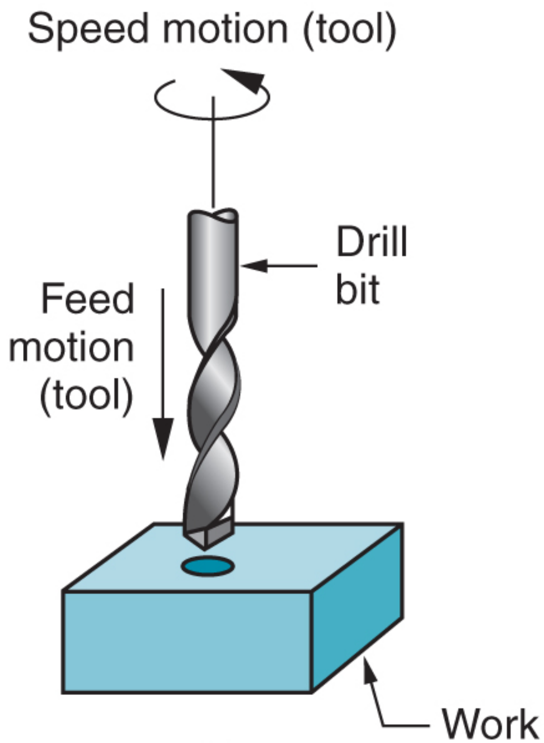
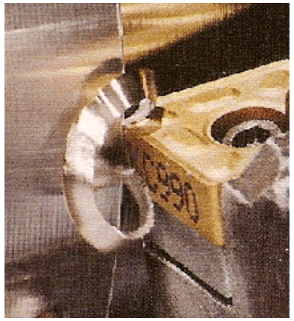


Drilling

- Creates a round hole in a workpart
- Compare to boring which can only enlarge an existing hole
- Cutting tool called a *drill* or *drill bit*
- Machine tool: *drill press*

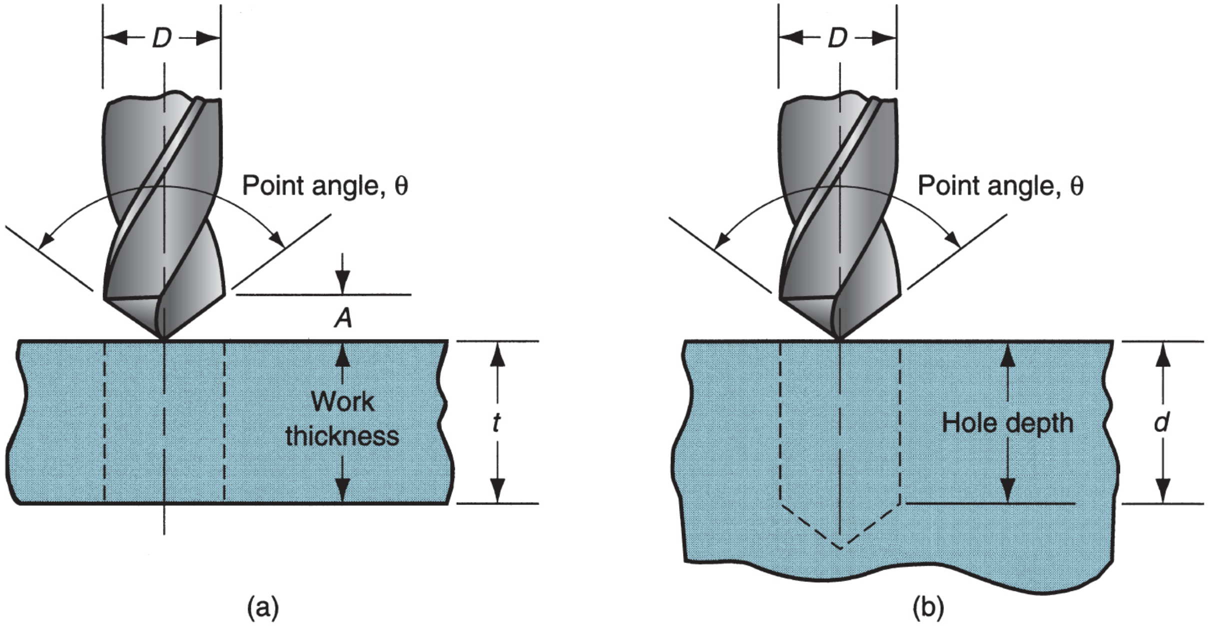


(b)



Through Hole vs. Blind Hole

- (a) Through hole - drill exits opposite side of work and (b) blind hole – drill does not exit opposite side



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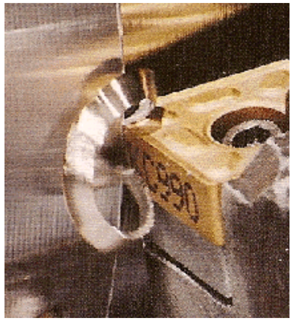
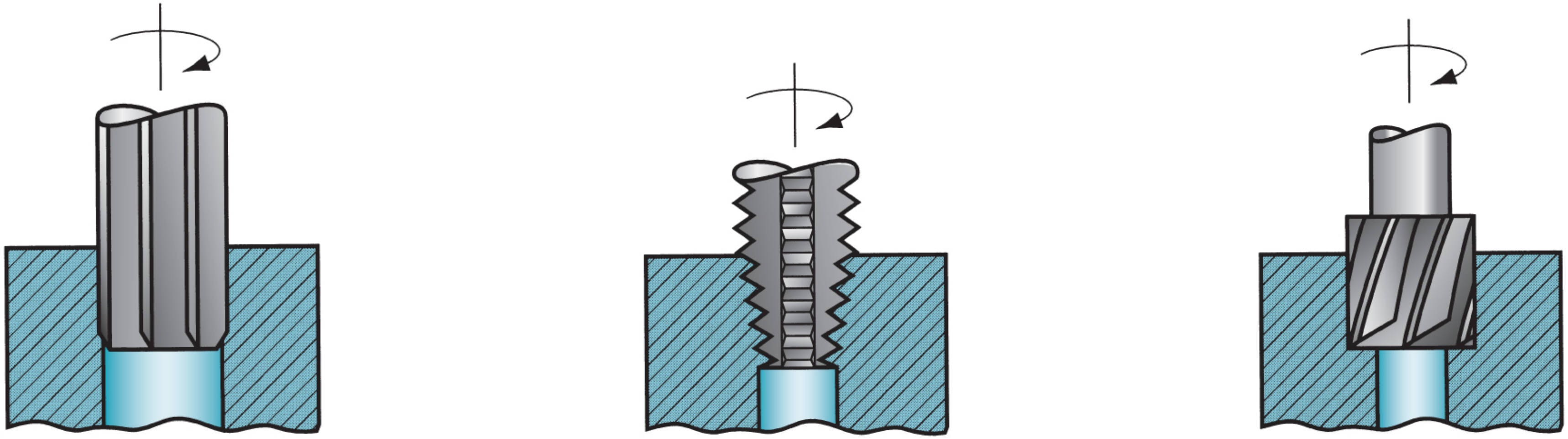


Operations Related to Drilling

- (a) Reaming, (b) tapping, (c) counterboring



(a) (b) (c)

Slightly enlarge a hole
Improve surface finish
Provide a better tolerance.

Provide internal screw threads on an existing hole.

Stepped hole, to seat bolt heads into a hole. (No heads above the surface).

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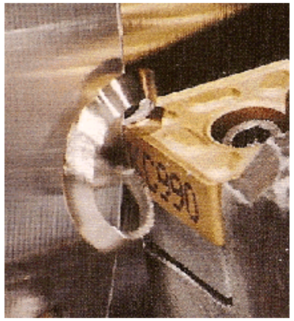
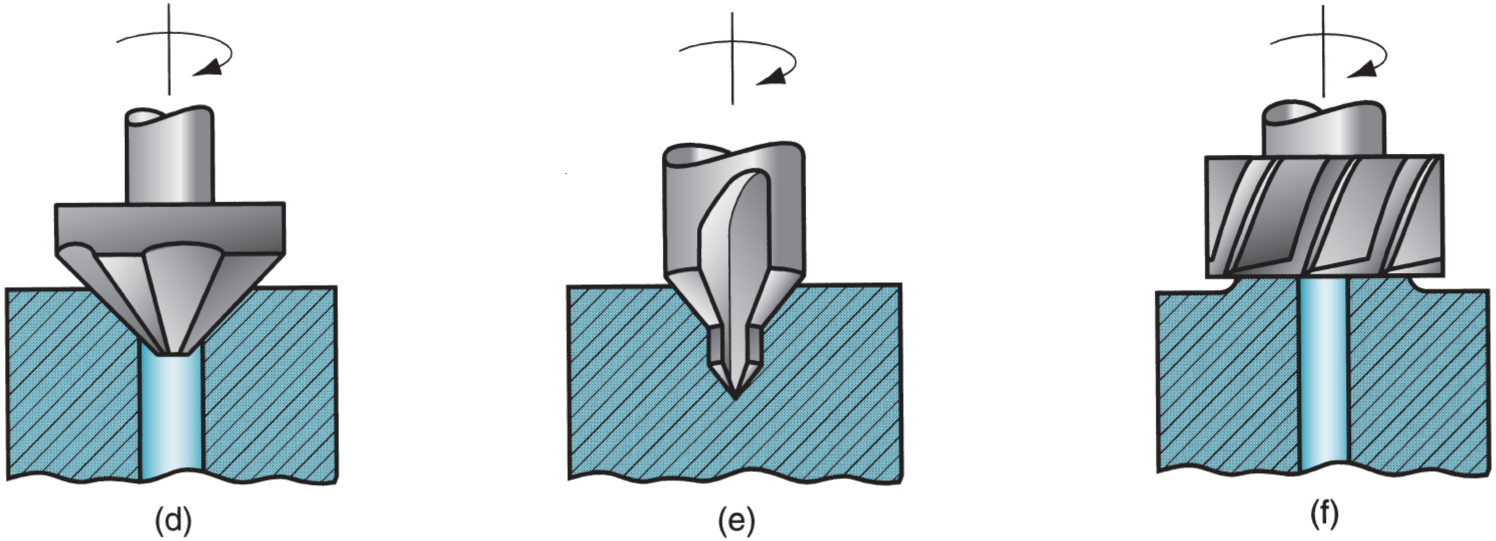


More Operations Related to Drilling

- (d) Countersinking, (e) centerdrilling, (f) spot facing



Similar to counterboring except that step is cone-shaped.

Drill a starting hole to accurately establish location for subsequent drilling.

Similar to milling. Flat surface on a localized area

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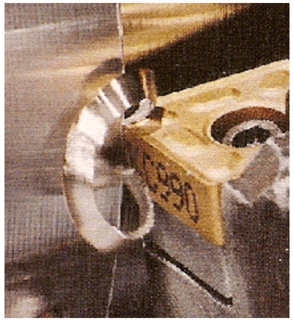
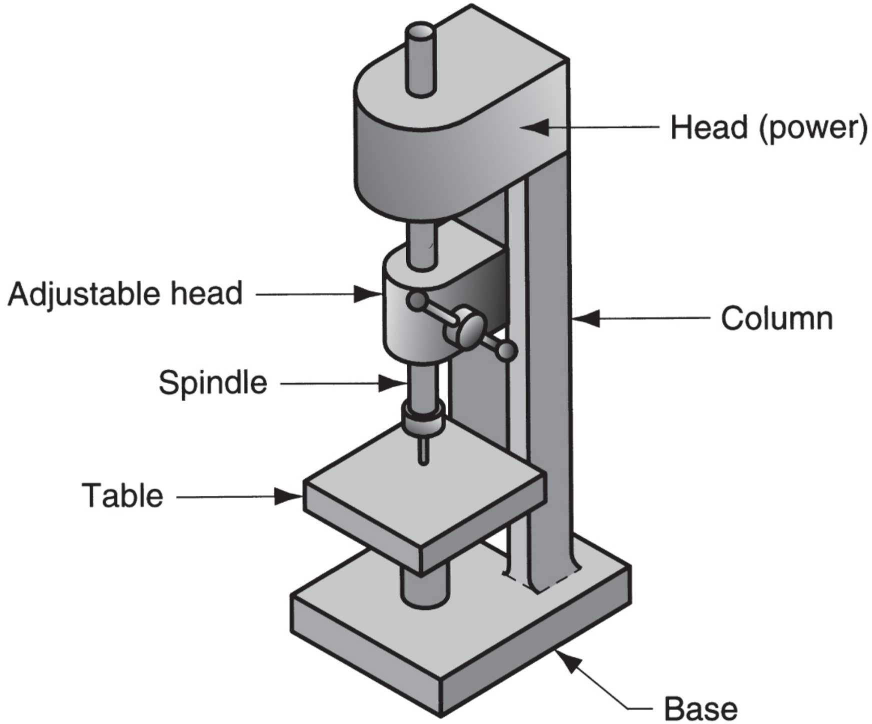


Drill Press

- Upright drill press stands on the floor
- Bench drill similar but smaller and mounted on a table or bench



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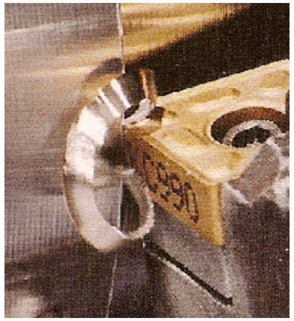
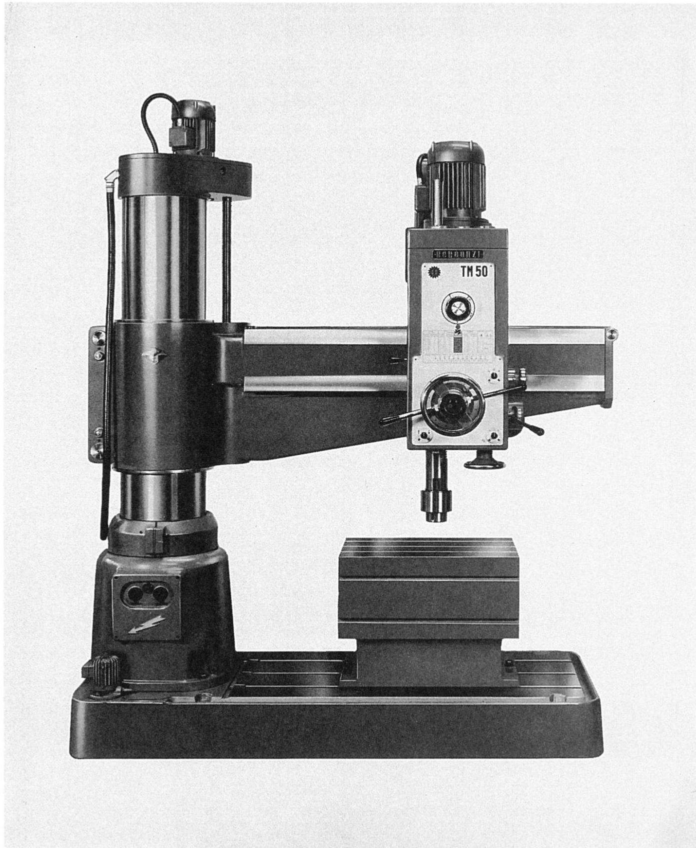


Radial Drill Press

- Large drill press designed for large parts (photo courtesy of Willis Machinery and Tools)



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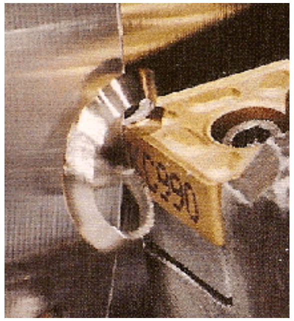
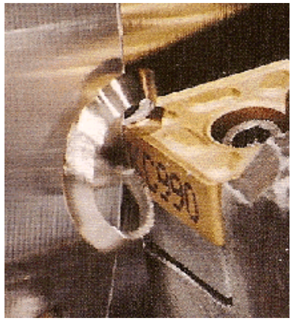


Work Holding for Drill Presses

- Workpart in drilling can be clamped in any of the following workholders:
  - *Vise* - general purpose workholder with two jaws
  - *Fixture* - workholding device that is usually custom-designed for the particular workpart
  - *Drill jig* – similar to fixture but also provides a means of guiding the tool during drilling



Milling

Machining operation in which work is fed past a rotating tool with multiple cutting edges

- Axis of tool rotation is perpendicular to feed
- Cutting tool called a milling cutter
  - Cutting edges called teeth
- Machine tool called a milling machine
- Interrupted cutting operation
- Basic milling operation creates a planar surface
  - Other geometries possible

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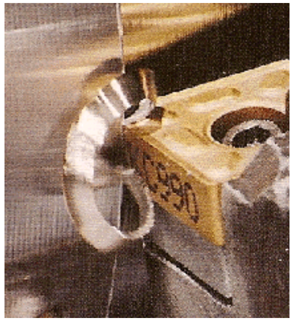
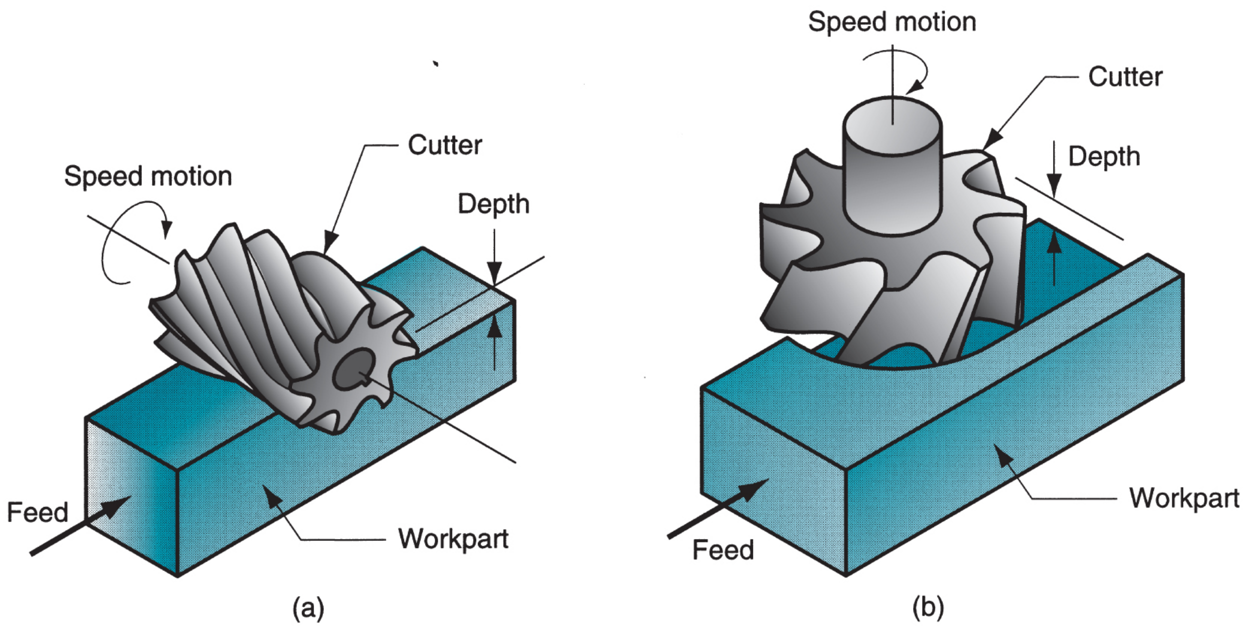


Two Forms of Milling

- (a) Peripheral milling and (b) face milling



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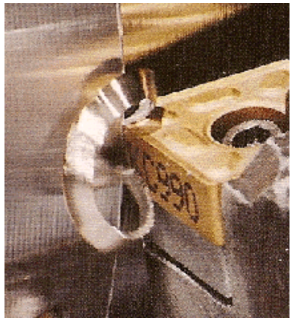

Peripheral Milling vs. Face Milling

- Peripheral milling
  - Cutter axis parallel to surface being machined
  - Cutting edges on outside periphery of cutter
- Face milling
  - Cutter axis perpendicular to surface being milled
  - Cutting edges on both the end and outside periphery of the cutter

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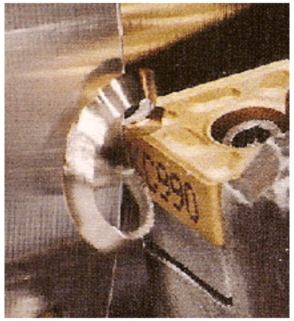
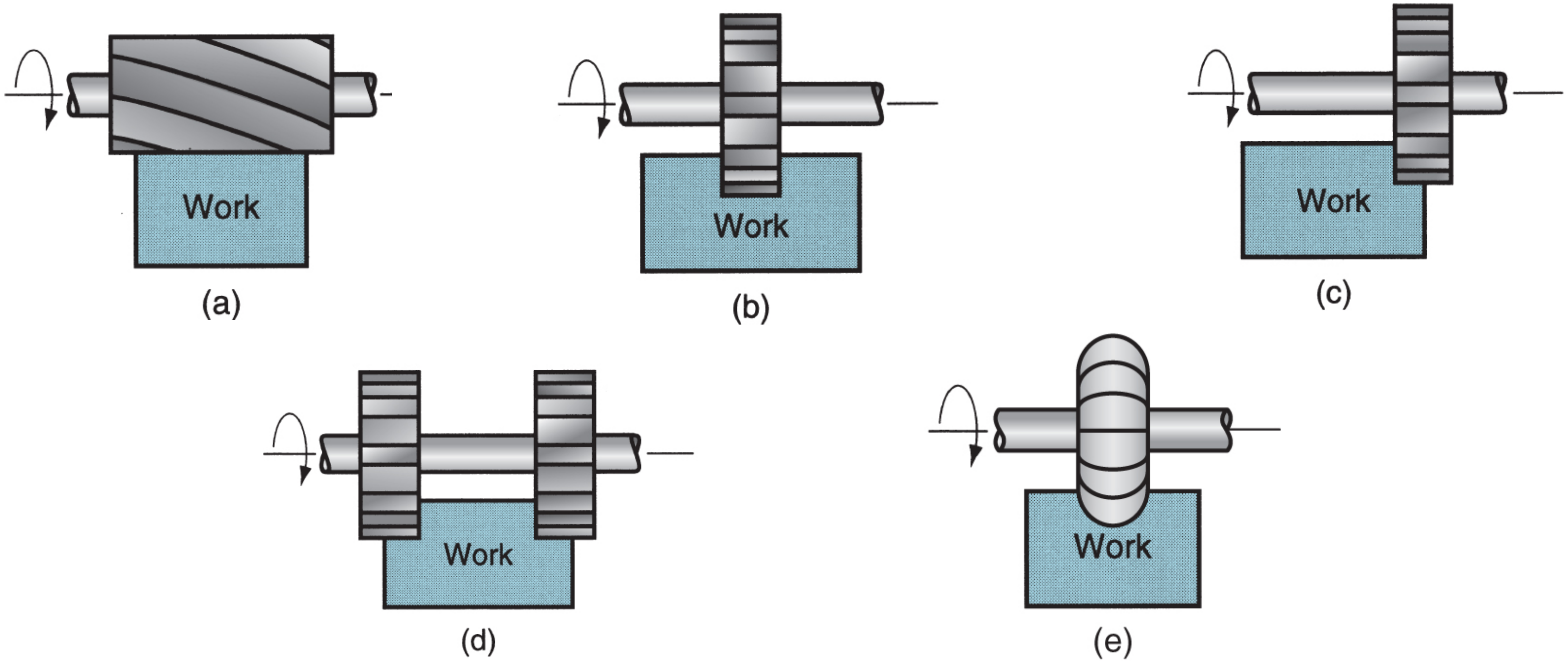
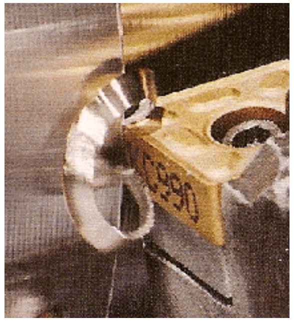


Types of Peripheral Milling

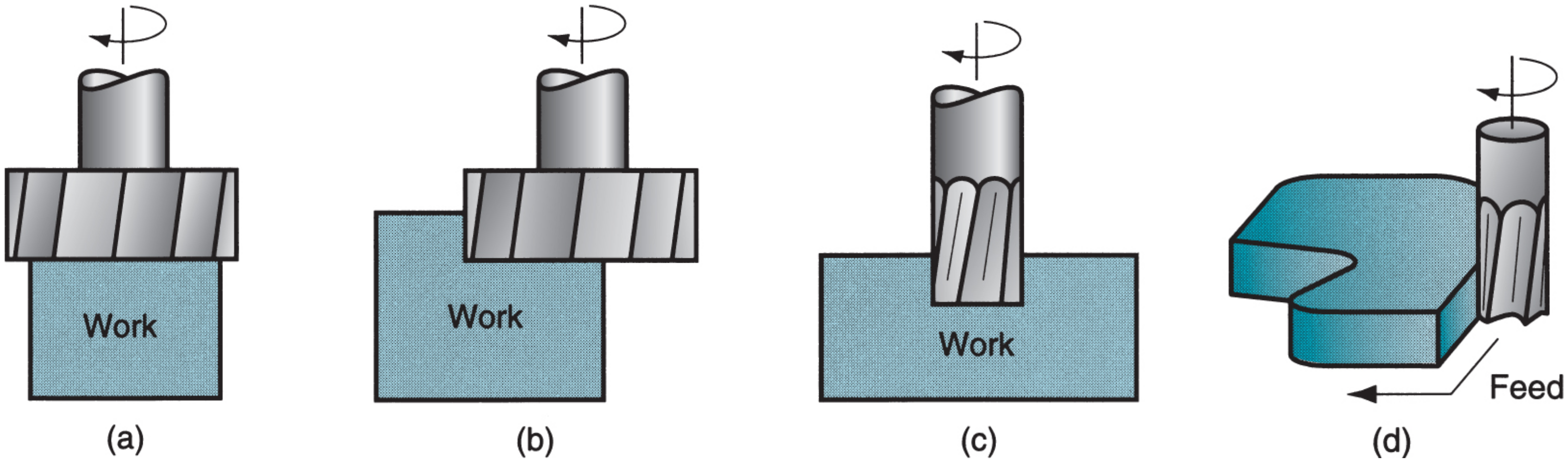
- (a) Slab milling, (b) slotting, (c) side milling, (e) straddle milling, and (e) form milling





Types of Face Milling

- (a) Conventional face milling, (b) partial face milling, (c) end milling, and (d) profile milling using an end mill



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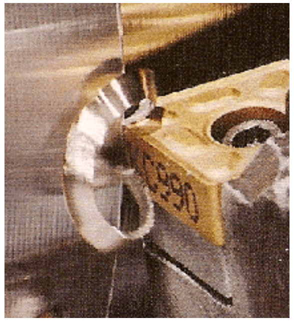
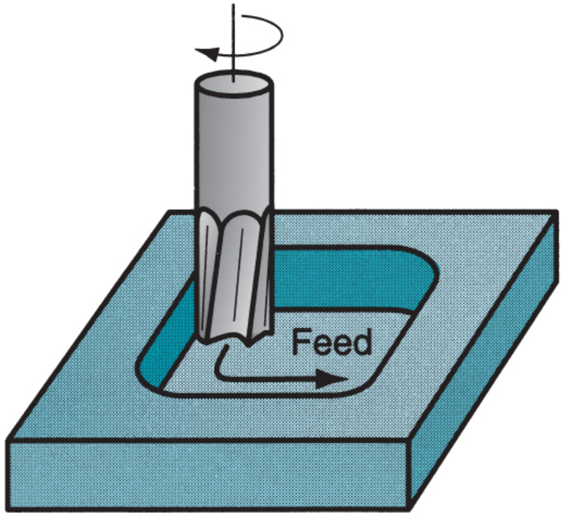
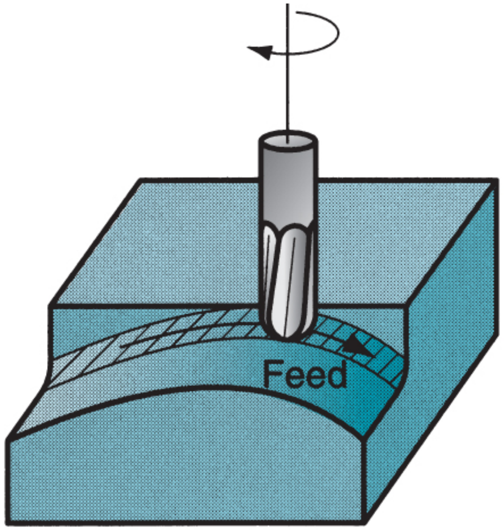


Types of Face Milling

- (e) Pocket milling and (f) contour milling





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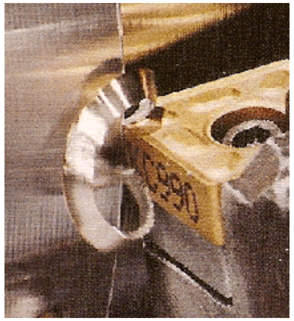
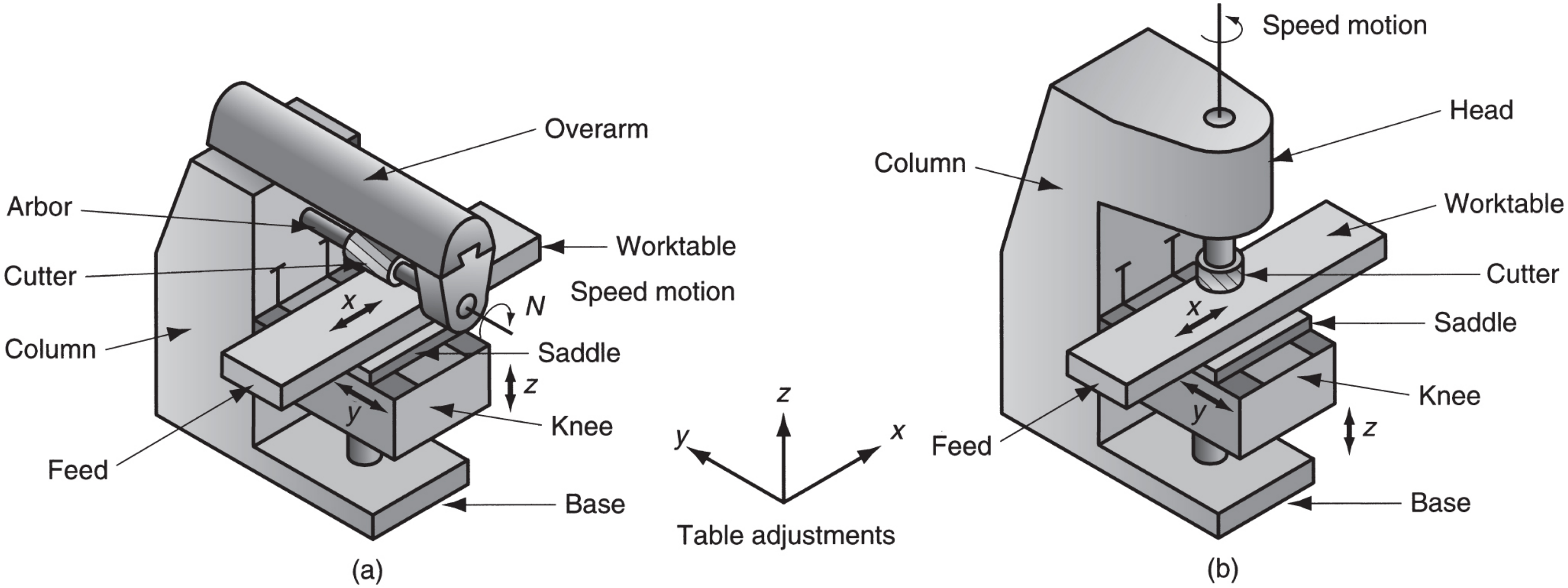


Knee-And-Column Milling Machines

- (a) Horizontal and (b) vertical knee-and-column milling machines



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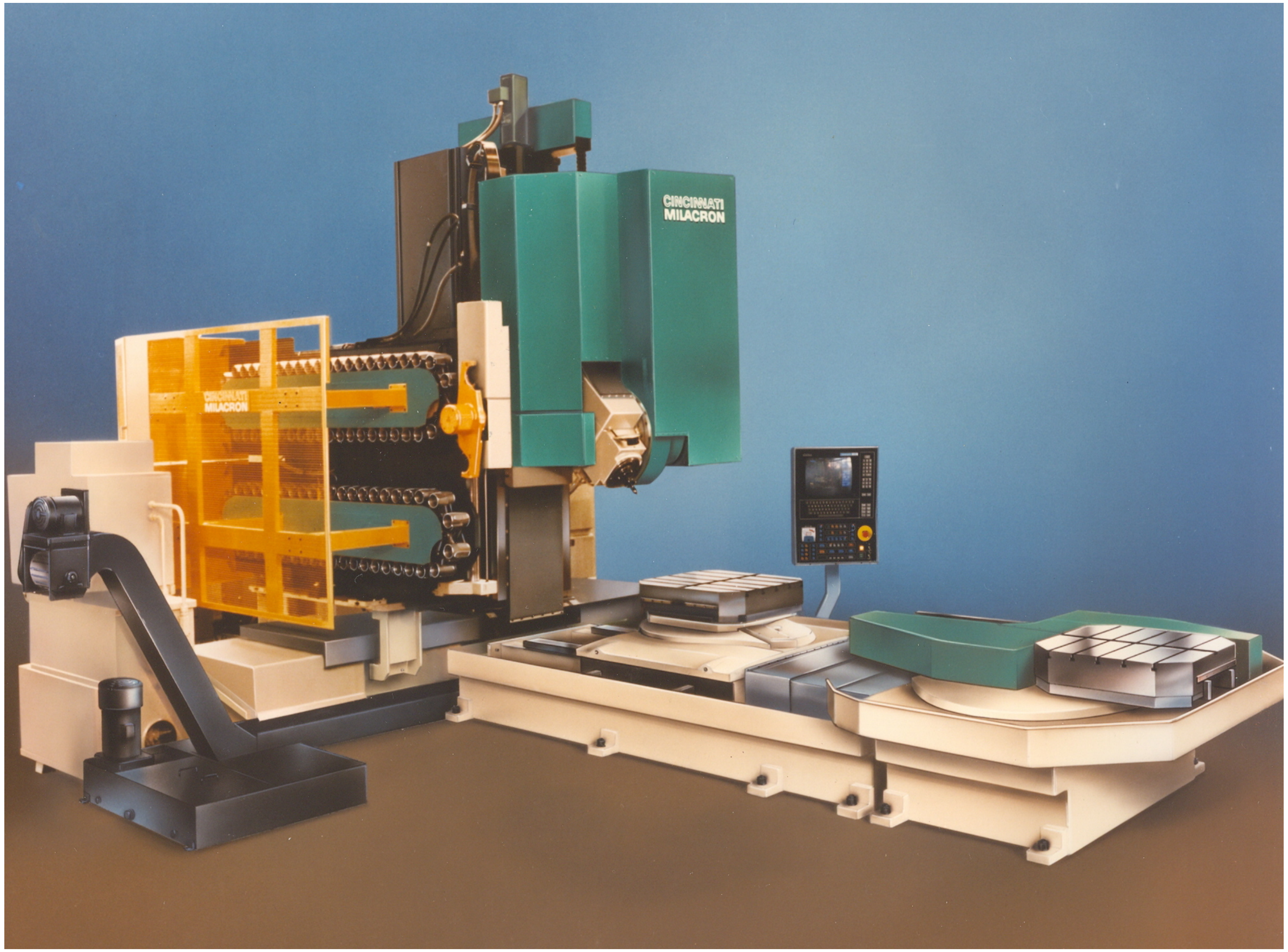
Machining Center

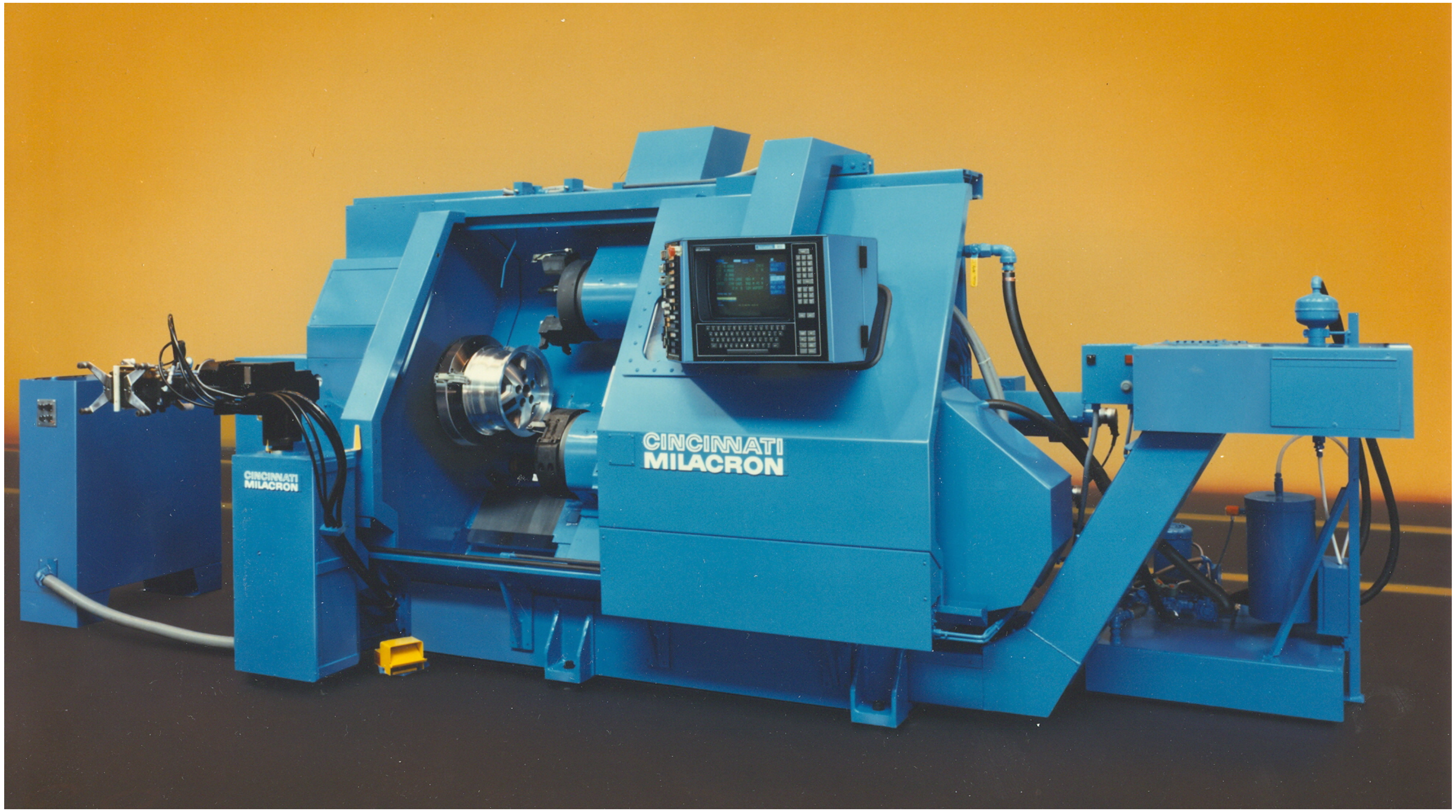
Highly automated machine tool that can perform multiple machining operations under CNC control in one setup with minimal human attention

- Typical operations are milling and drilling
- Three, four, or five axes
- Other features:
  - Automatic tool-changing
  - Pallet shuttles
  - Automatic workpart positioning

CNC Machining Center



CNC Turning Center - Industrial Robot to Load and Unload Parts



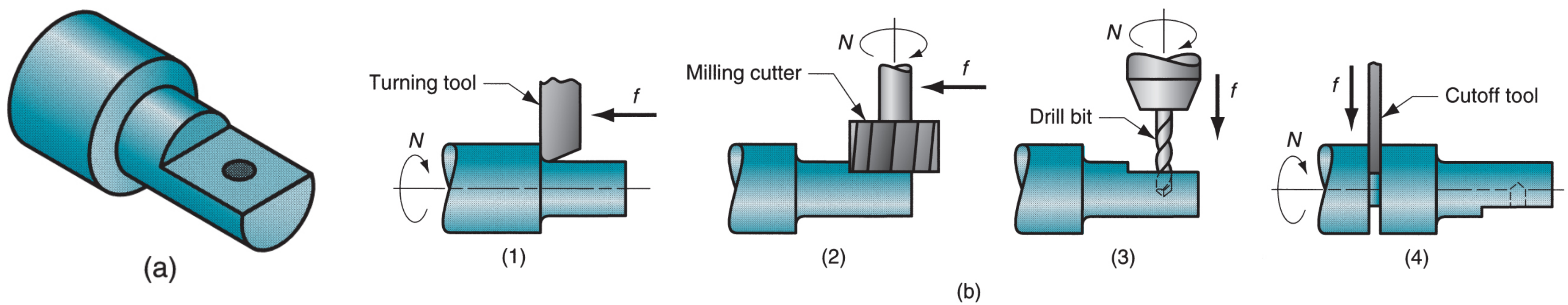
Mill-Turn Centers

Highly automated machine tool that can perform turning, milling, and drilling operations in one setup

- General configuration of a turning center
- Can position a cylindrical workpart at a specified angle so a rotating cutting tool (e.g., milling cutter) can machine features into outside surface of part
  - Conventional turning center cannot stop workpart at a defined angular position and does not include rotating tool spindles

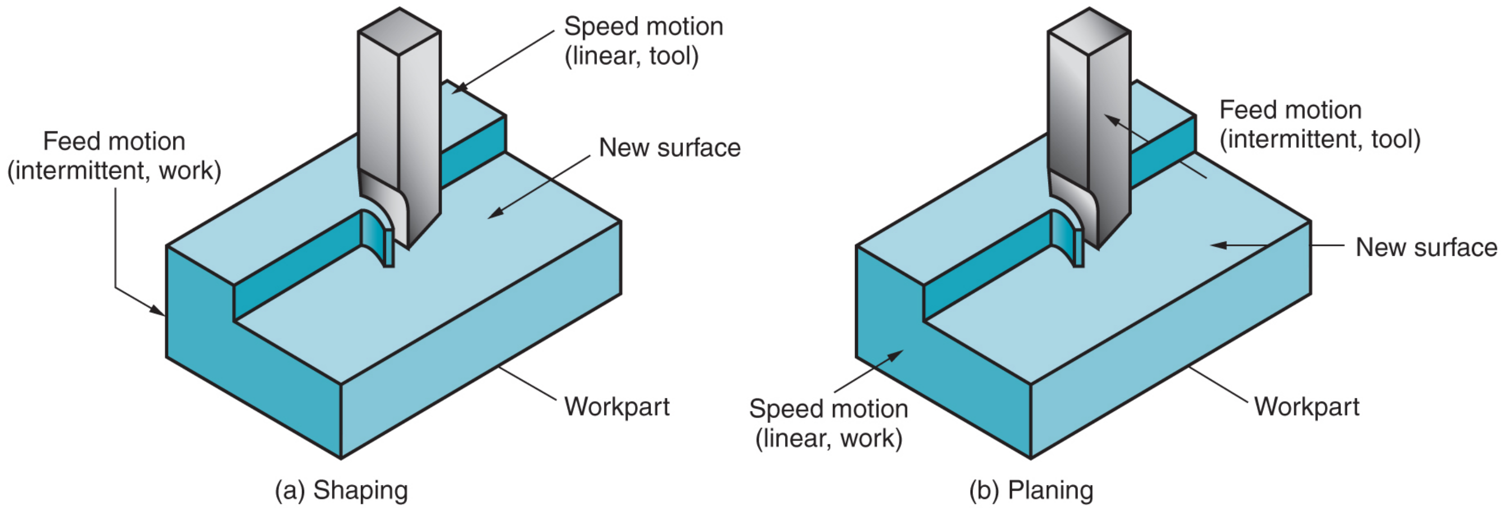
Operation of Mill-Turn Center

- (a) Part with turned, milled, and drilled surfaces; and (b) sequence of operations : (1) turn second diameter, (2) mill flat, (3) drill hole, and (4) cutoff



Shaping and Planing

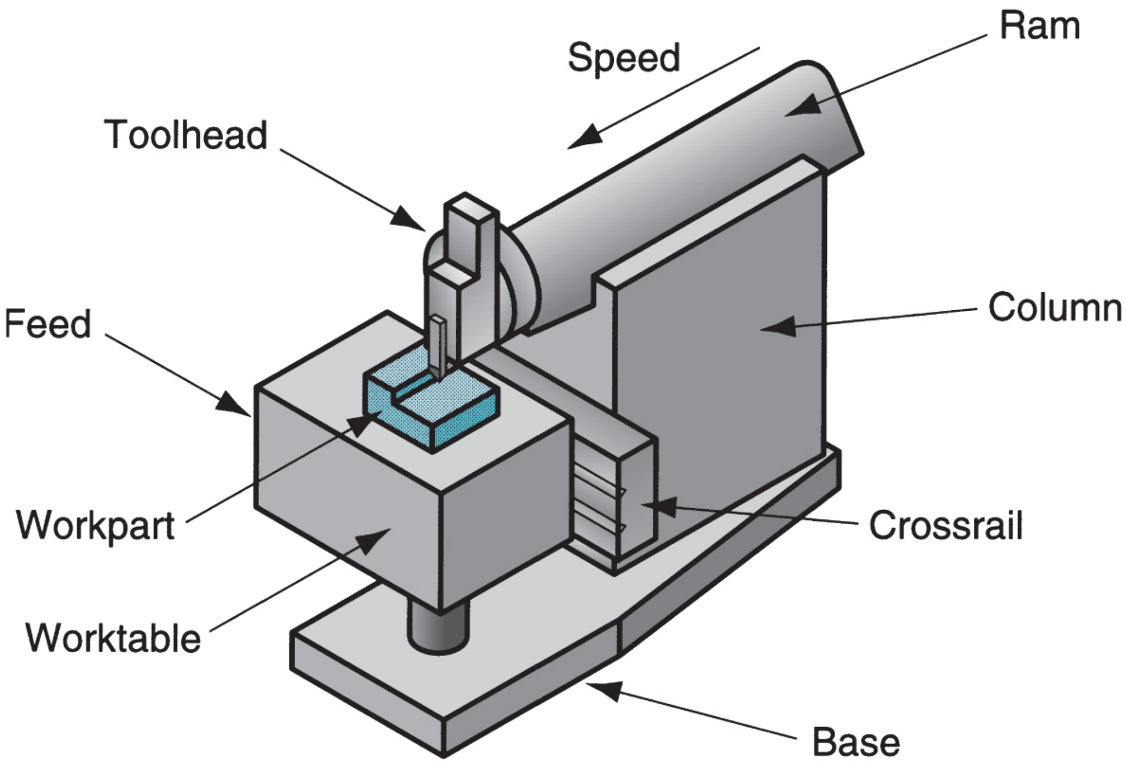
- Similar operations, both use a single point cutting tool moved linearly



Shaping and Planing

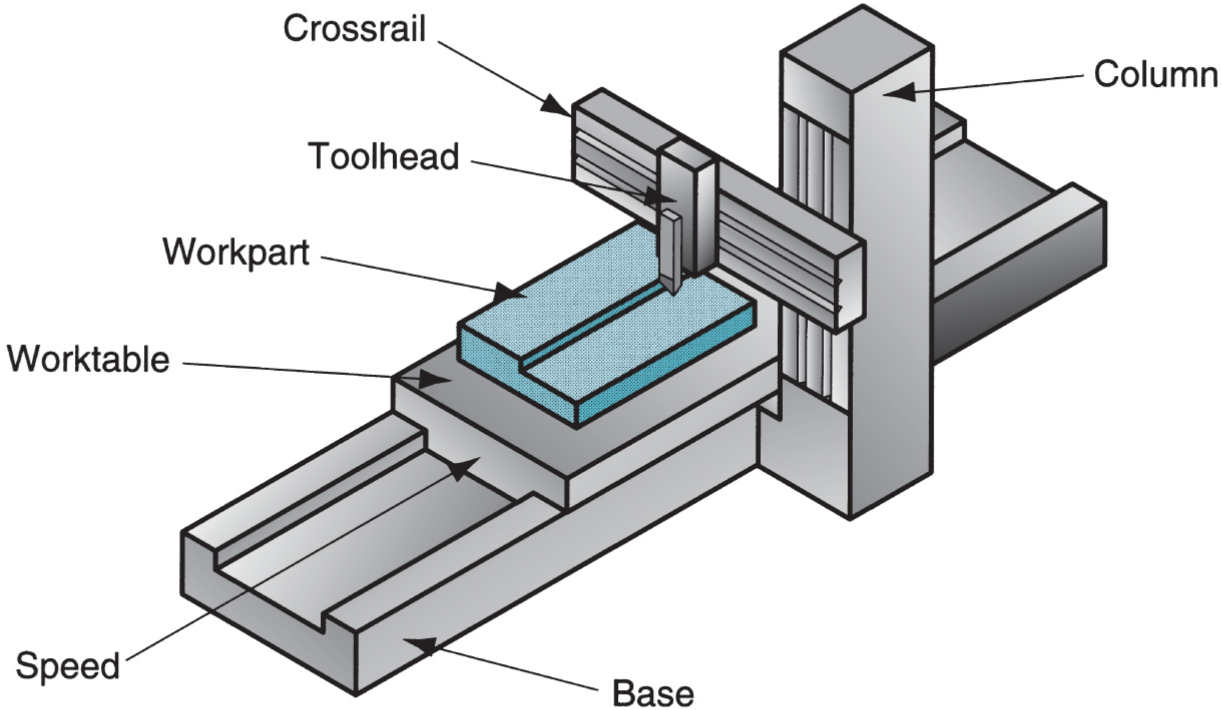
- A straight, flat surface is created in both operations
- Interrupted cutting operation
  - Subjects tool to impact loading when entering work
    - Typical tooling: single point high speed steel tools
  - Low cutting speeds due to start-and-stop motion

Shaper



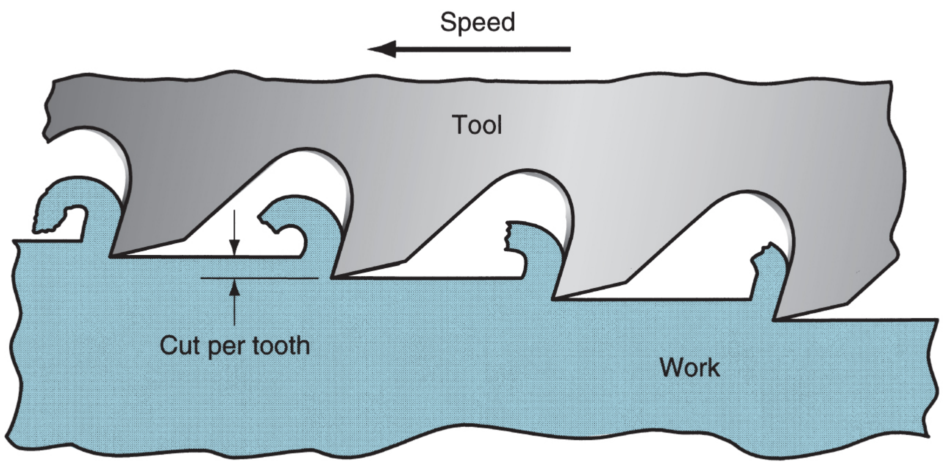
Speed
Ram
Toolhead
Column
Feed
Workpart
Crossrail
Worktable
Base

Planer



Broaching

- A multiple tooth cutting tool is moved linearly relative to work in direction of tool axis (to produce cross-sectional shapes)



Broaching

Advantages:

- Good surface finish
- Close tolerances
- Variety of work shapes possible

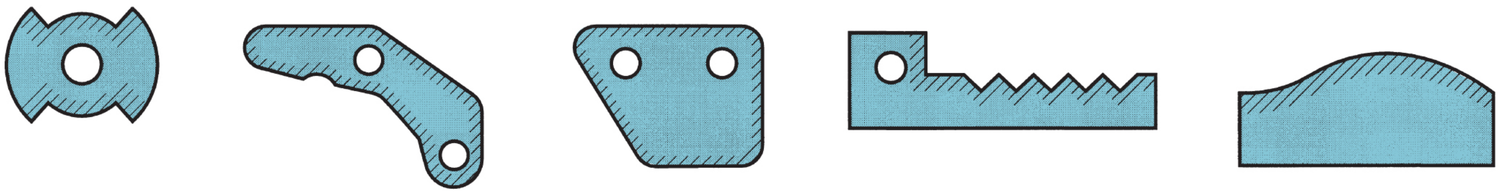
Cutting tool called a *broach*

- Owing to complicated and often custom-shaped geometry, tooling is expensive

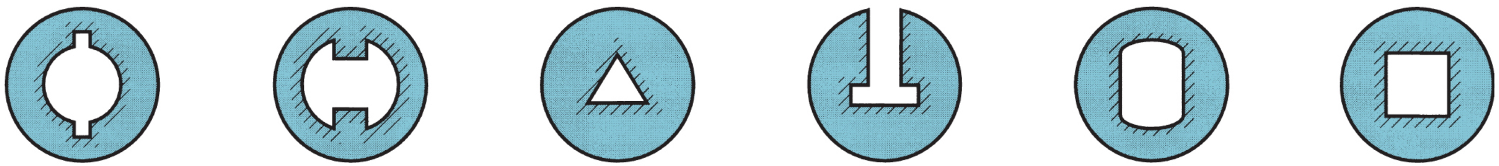
Broaching

- (a) External and (b) internal broaching (cross-hatching indicates surface broached)

Performed on the outside surface of the work.



(a)



(b)

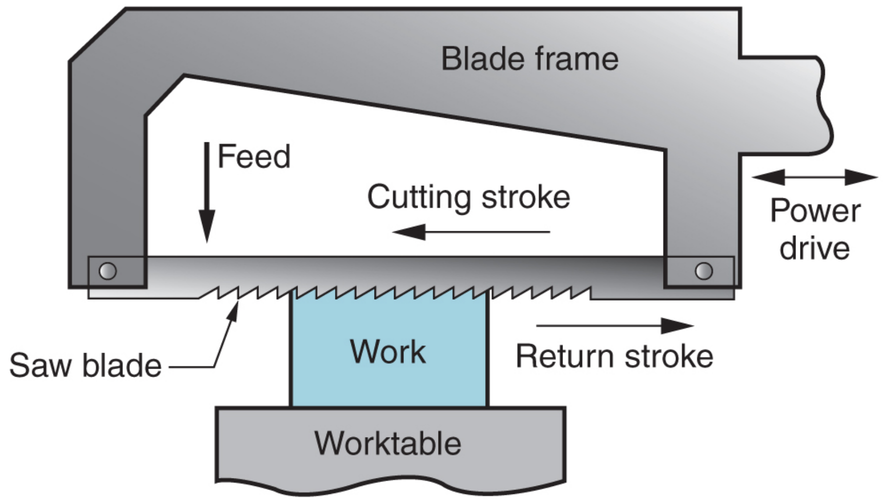
Performed on an internal surface of a hole.

Sawing

- Cuts narrow slit in work by a tool consisting of a series of narrowly spaced teeth
- Tool called a *saw blade*
- Typical functions:
  - Separate a workpart into two pieces
  - Cut off unwanted portions of part
  - Cut outline of flat part

Power Hacksaw

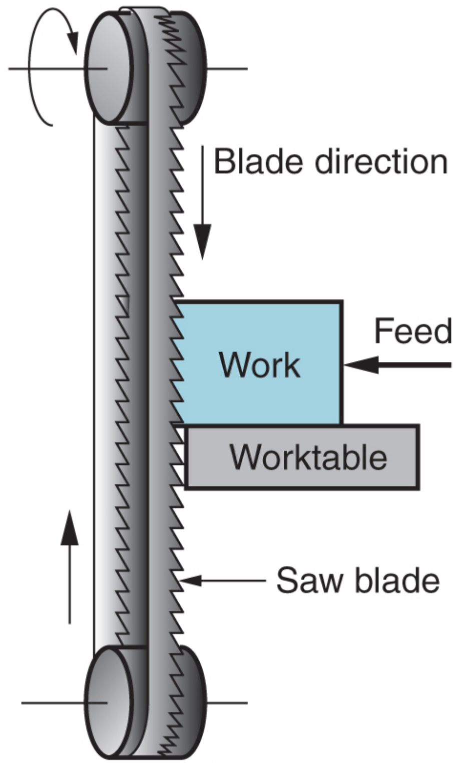
- Linear reciprocating motion of hacksaw blade against work



(a)

Band Saw

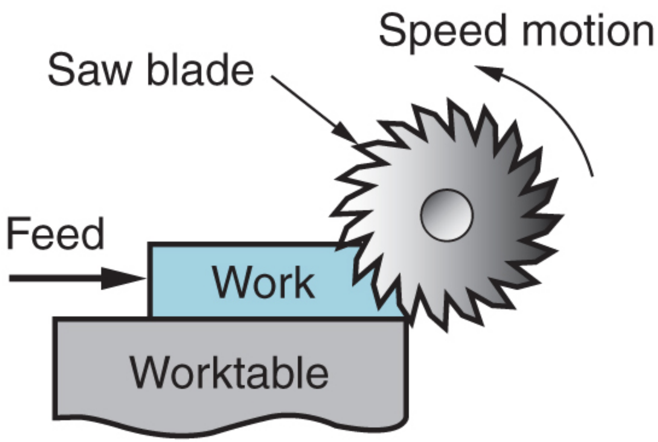
- Linear continuous motion of bandsaw blade, which is in the form of an endless flexible loop with teeth on one edge



(b)

Circular Saw

- Rotating saw blade provides continuous motion of tool past workpart



(c)

Machining Operations for Special Geometries

- Screw threads
- Gear teeth

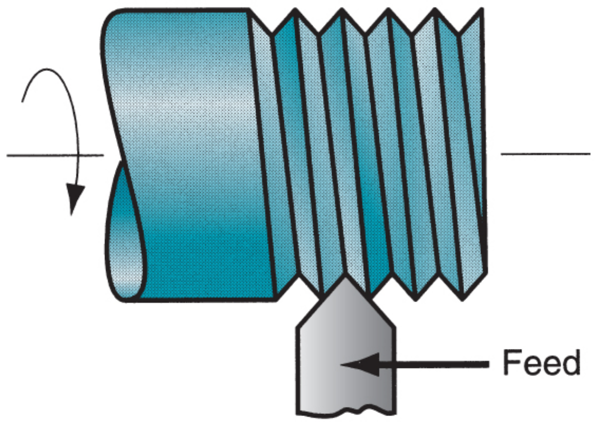
Cutting Screw Threads

- Methods for producing external threads
  - Single-point threading
  - Threading die
  - Thread chasing - using self-opening threading dies
  - Thread milling

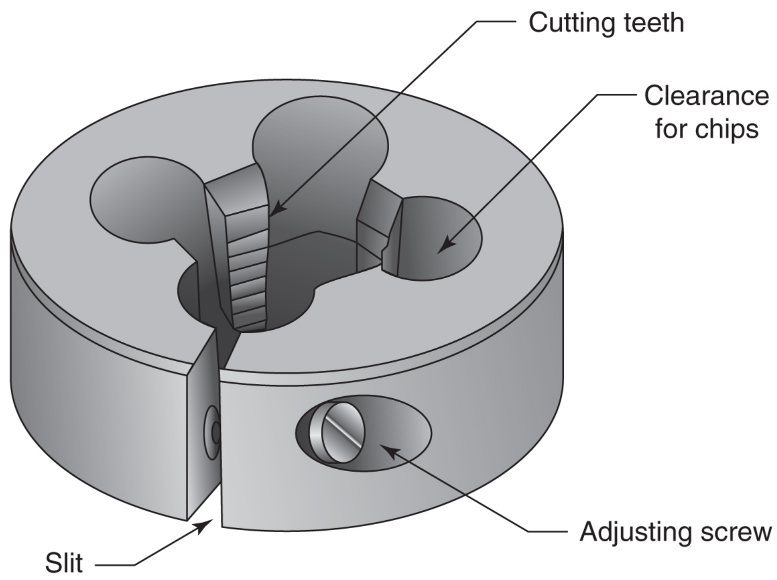
- Methods for producing internal threads
  - Tapping - using a solid tap
  - Collapsible taps - cutting teeth retract for quick removal from hole

Cutting External Screw Threads

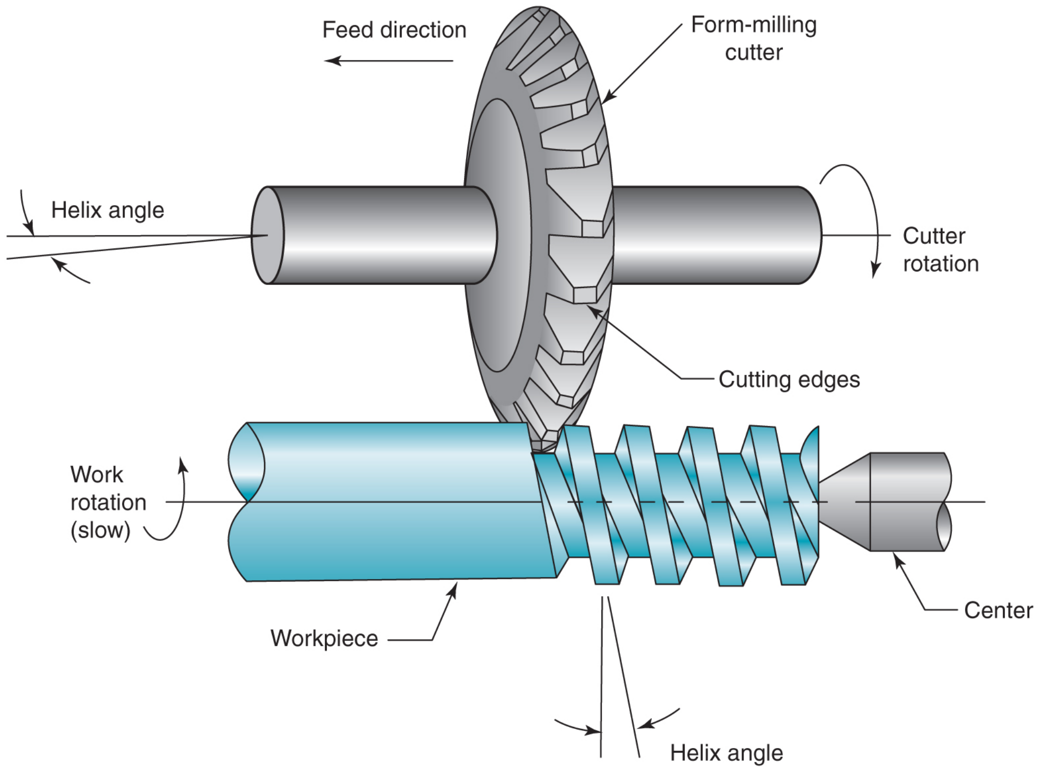
- (left) Single-point thread cutting and (right) threading die



(g)



Thread Milling Using a Form-Milling Cutter

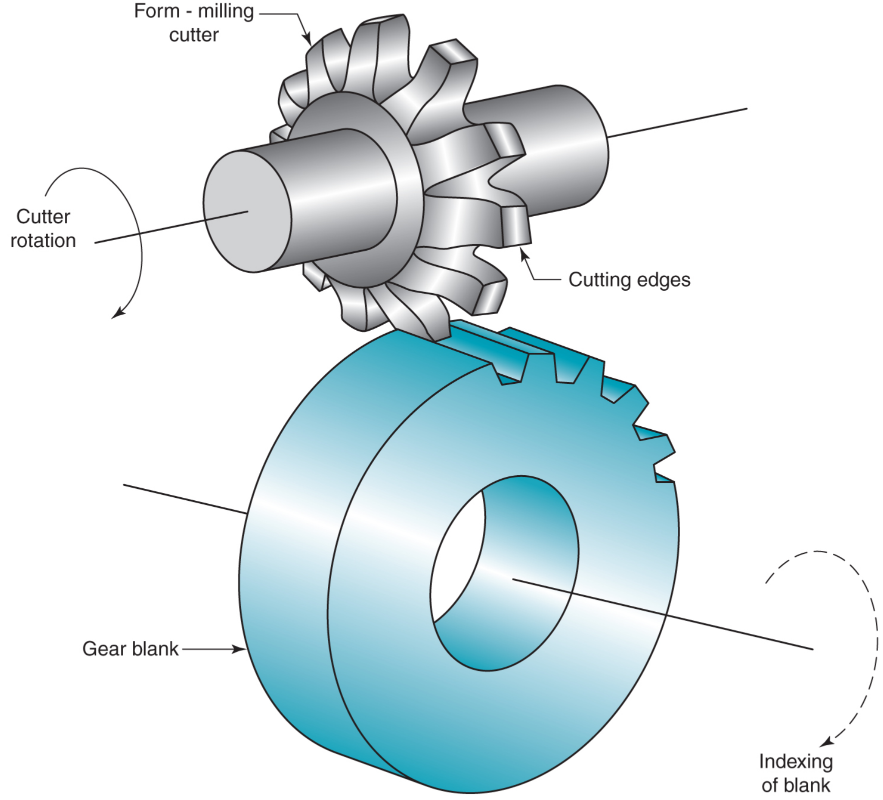


Principal Operations for Machining Gear Teeth

- Form milling - use of a form milling cutter
- Gear hobbing - also milling but using a special cutter called a *hob*
- Gear shaping - two forms
  - Single point tool to gradually shape each gear tooth spacing
  - Cutter has general shape of the gear but with cutting teeth on one side
- Gear broaching - for internal and external gears

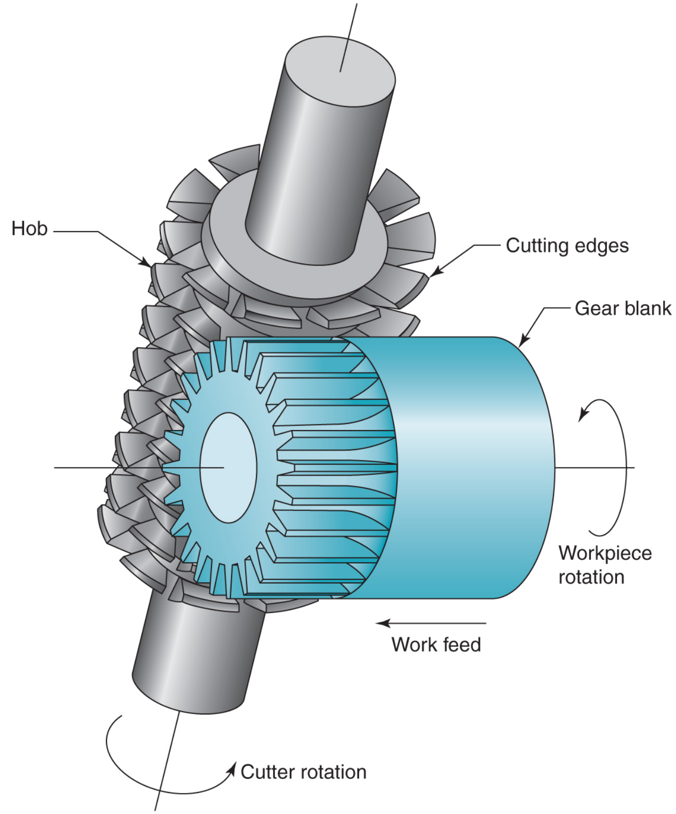
Form Milling of Gear Teeth

- The form milling cutter has teeth with the shape of the spaces between teeth on the gear
- Gear blank is indexed between each pass to establish correct size of the gear tooth



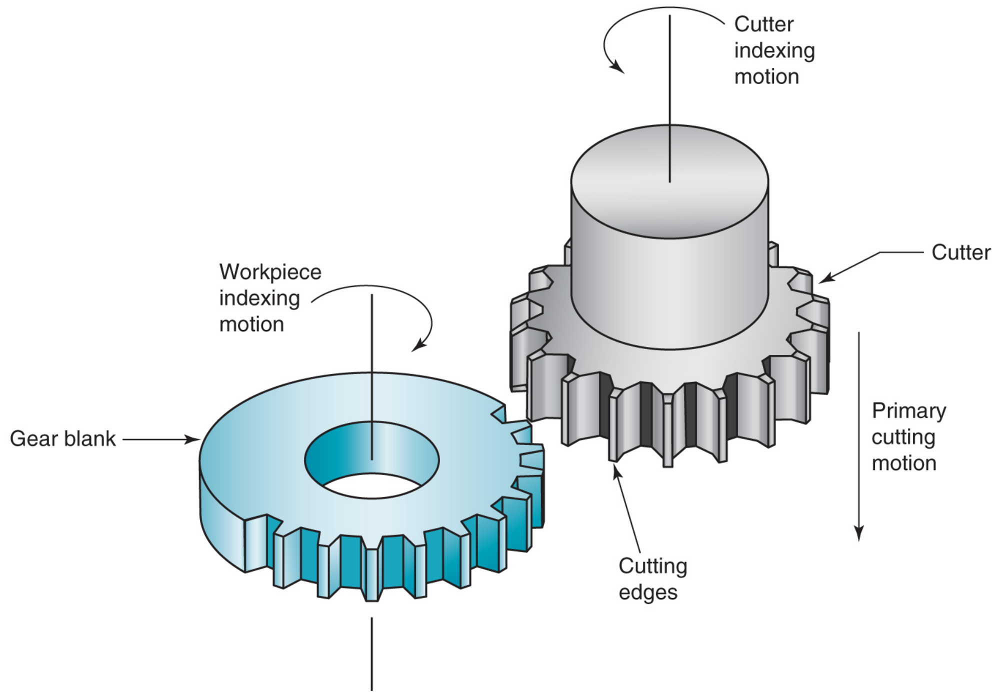
Gear Hobbing

- Hob has a slight helix and its rotation must be coordinated with much slower rotation of the gear blank
- Performed on special milling machines (called *hobbing machines*) that accomplish the relative speed and feed motions between cutter and gear blank



Gear Shaping

- To start the process, cutter is gradually fed into gear blank
- Then, cutter and blank are slowly rotated after each stroke to maintain tooth spacing
- Performed on special machines called *gear shapers*



Gear Broaching

- Applicable for both external gears and internal gears (teeth on inside of gear)
- Cost of tooling (broach) is high due to its complex geometry
- For internal gears, broach consists of a series of gear-shaped cutting teeth of increasing size to form the gear teeth in successive steps as broach is drawn through starting hole
- For external gears, broach is tubular with inward-facing cutting teeth

High Speed Machining (HSM)

Cutting at speeds significantly higher than those used in conventional machining operations

- Persistent trend throughout history of machining is higher and higher cutting speeds
- At present there is a renewed interest in HSM due to potential for faster production rates, shorter lead times, and reduced costs

High Speed Machining

Work material	Conventional speed (Indexable tools (face mills))		High speed	
	m/min	ft/min	m/min	ft/min
Aluminum	600+	2000+	3600+	12,000+
Cast iron, soft	360	1200	1200	4000
Cast iron, ductile	250	800	900	3000
Steel, alloy	210	700	360	1200

Source: Kennametal Inc.

Other HSM Definitions: DN Ratio

DN ratio = bearing bore diameter (mm) multiplied by maximum spindle speed (rev/min)

- For high speed machining, typical DN ratio is between 500,000 and 1,000,000
- Allows larger diameter bearings to fall within HSM range, even though they operate at lower rotational speeds than smaller bearings

Other HSM Definitions: HP/RPM Ratio

hp/rpm ratio = ratio of horsepower to maximum spindle speed

- Conventional machine tools usually have a higher hp/rpm ratio than those equipped for HSM
- Dividing line between conventional machining and HSM is around 0.005 hp/rpm (50/10000)
- Thus, HSM includes 15 hp spindles that can rotate at 30,000 rpm (0.0005 hp/rpm)

Other HSM Definitions

- Emphasis on:
  - Higher production rates
  - Shorter lead times
  - Rather than functions of spindle speed

- Important non-cutting factors:
  - Rapid traverse speeds
  - Automatic tool changes

Requirements for High Speed Machining

- Special bearings designed for high rpm
- High feed rate capability (e.g., 50 m/min)
- CNC motion controls with “look-ahead” features to avoid “undershooting” or “overshooting” tool path
- Balanced cutting tools, toolholders, and spindles (to minimize vibration)
- Coolant delivery that provides higher pressures
- Chip control and removal systems to cope with much larger metal removal rates

High Speed Machining Applications

- Aircraft industry, machining of large airframe components from large aluminum blocks
  - Much metal removal, mostly by milling
- Multiple machining operations on aluminum to produce automotive, computer, and medical parts
  - Quick tool changes and tool path control important
- Die and mold industry
  - Fabricating complex geometries from hard materials