Manufacturing Processes

Mechanical Properties of Materials

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.

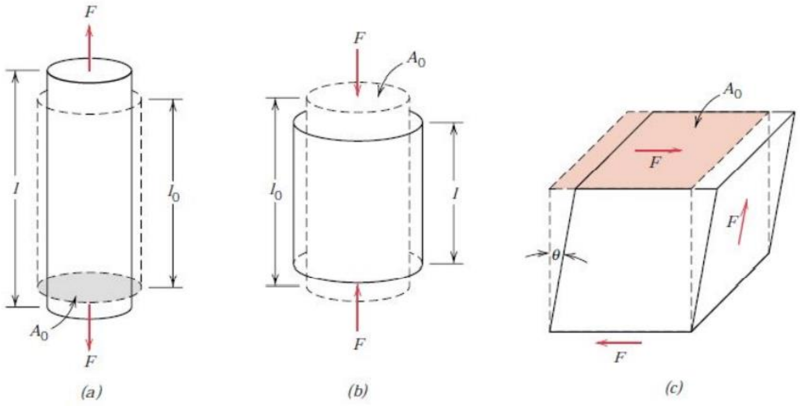


Fig. 3-1: Materials under static stresses; (a) Tensile, (b) compressive, and (c) shear (γ= tan θ). Dashed lines: shape before deformation

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.

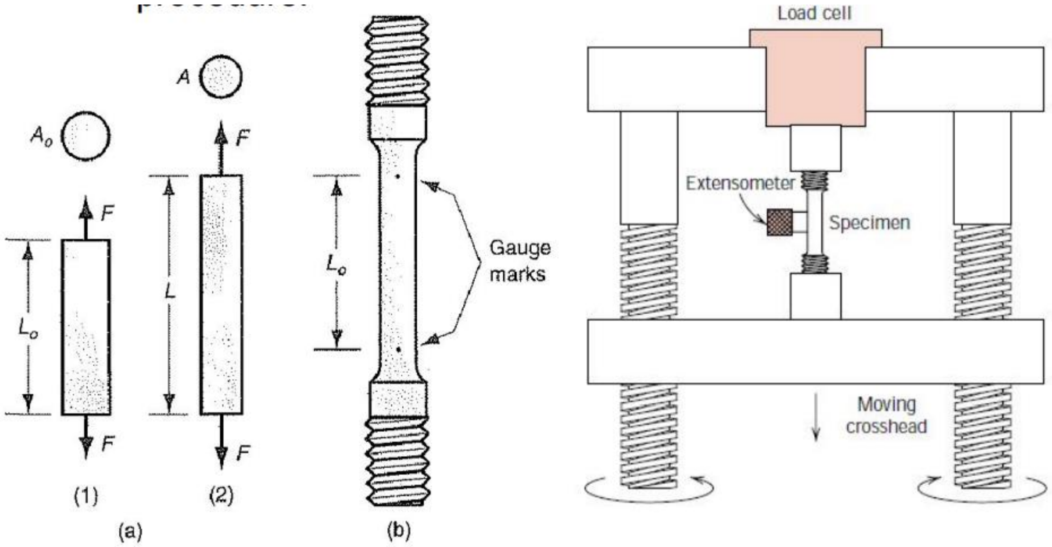


Fig. 3-2: Tensile specimen and setup of the tensile test. (A0 & L0 : cross sectional area and length before test, length is measured between the gauge marks (gauge length))

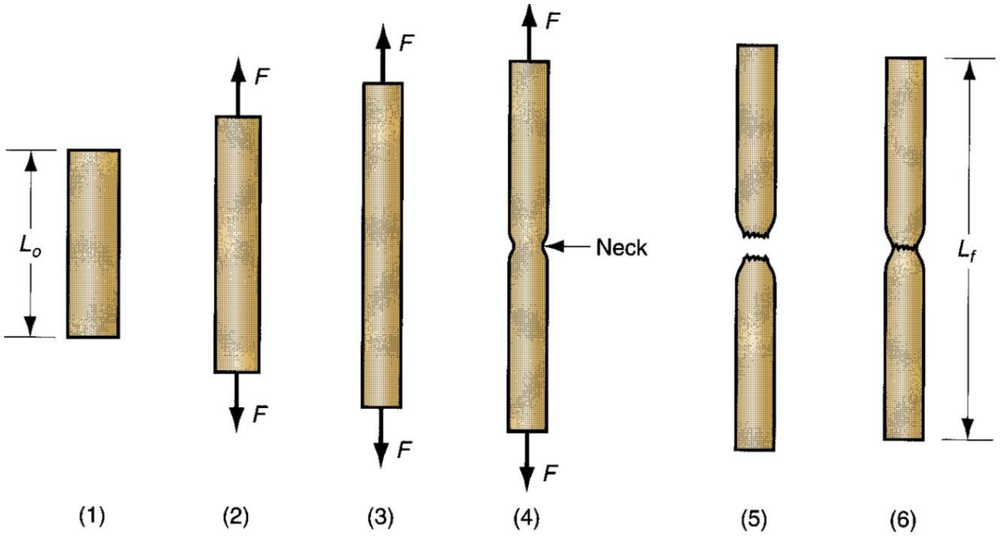


Fig. 3-3: Progress of a tensile test: (1) beginning of test, no load, (2) uniform elongation and reduction of A0 , (3) Continued elongation, max. load reached, (4) necking begins and load decreases, (5) fracture, and (6) final length can be measured if pieces are put back together.

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.

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:

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

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.

e can be thought of as elongation per unit length.

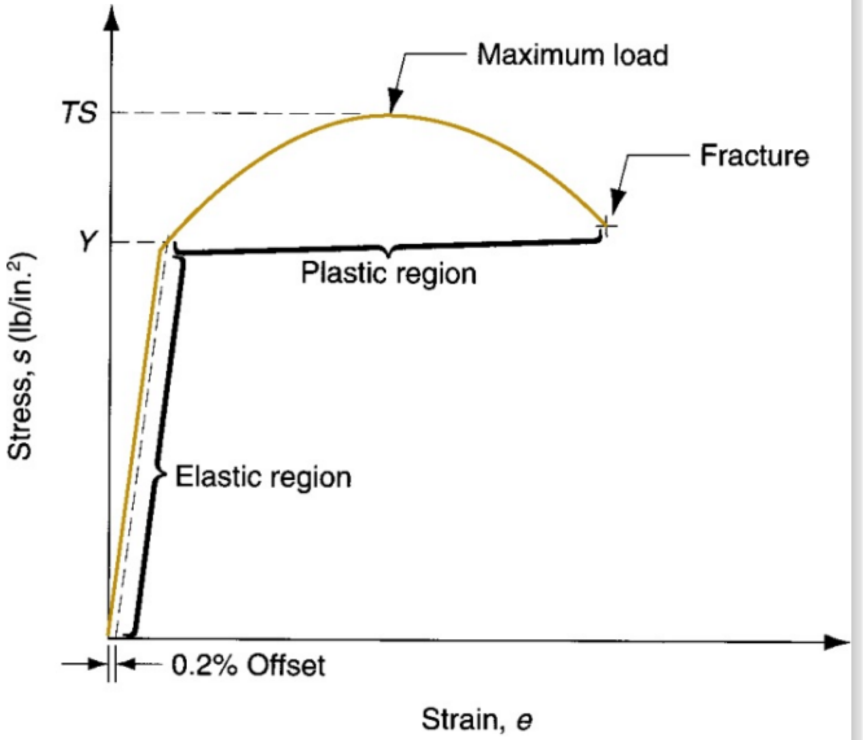


Fig. 3-4: a typical engineering stress-strain curve for a metallic specimen

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:

$$\sigma_e = Ee$$,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).

- 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 A0 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 = Fmax / A0 .

– 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

- ***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:

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

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:

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

where σ: true stress, MPa (n / mm2), F = applied force, N, and A is the instantaneous area resisting the load, mm2

- 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:

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

where L is the instantaneous length at any moment during deformation

- 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.

$$\boxed{\varepsilon = \ln(1+e)} \qquad \boxed{\sigma = \sigma_e(1+e)}$$

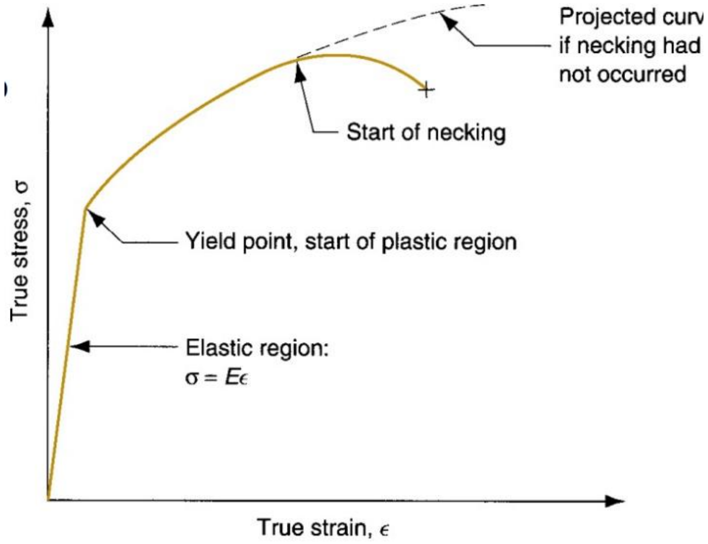


Fig. 3-5: a typical true stress-strain curve for a metallic specimen

- 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:

$$\sigma = K\varepsilon^n$$

K (strength coefficient) = σ if ε = 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

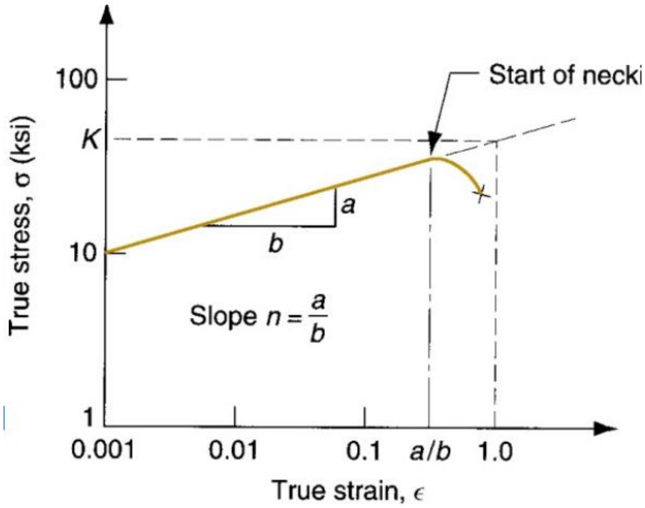


Fig. 3-6: true stress-strain curve plotted on a log-log scale.

Note: Necking is closely related to strain hardening.

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

- 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.

- 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:

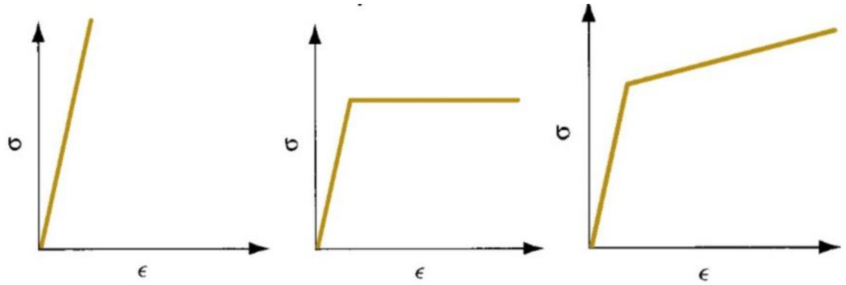
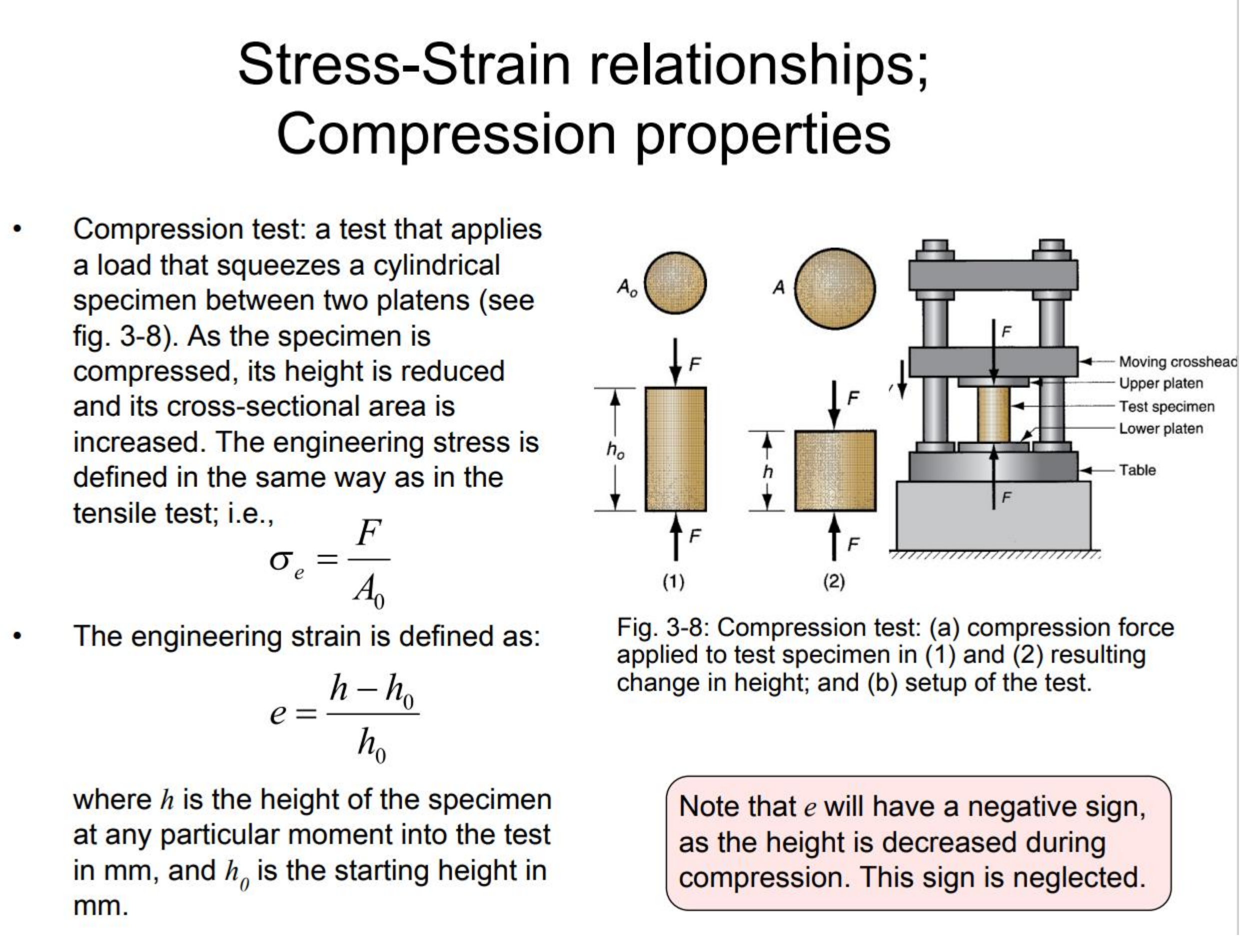


Fig. 3-7: Three categories of stress-strain relationships: (a) perfectly elastic, (b) elastic and perfectly plastic and (c) elastic and strain hardening.



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.,

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

- 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.

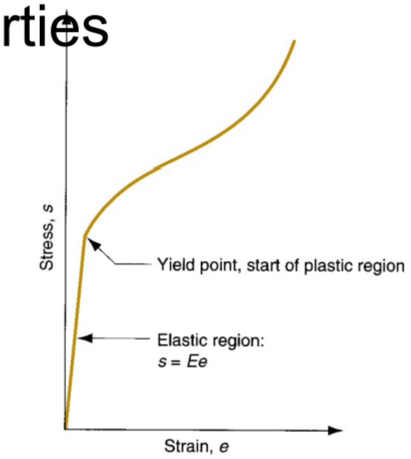


Fig. 3-9: Typical engineering stress-strain curve for a compres

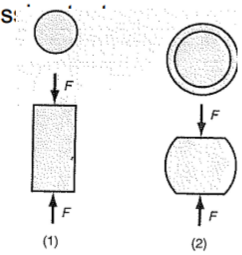


Fig. 3-10: Barreling effect. (1) before and (2) after compression.

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.

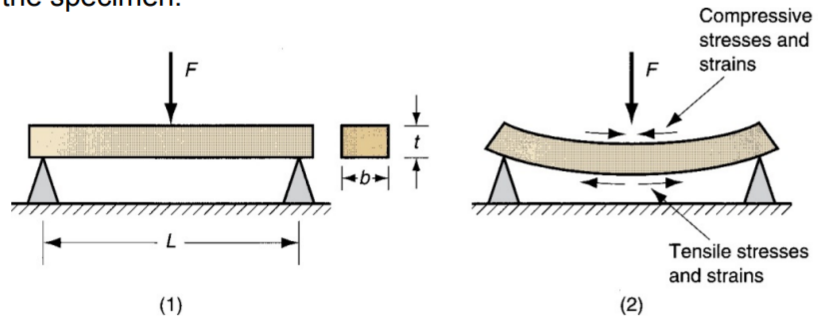


Fig. 3-11: Bending test setup and specimen: (1) initial loading, and (2) highly stressed and strained specimen

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:

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

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

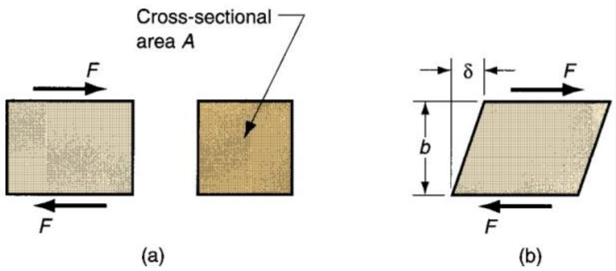


Fig. 3-12: Shear (a) stress and (b) strain.

- Shear strain can be defined as:

$$\gamma = \frac{\delta}{b}$$

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.

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).

$$\tau = \frac{T}{2\pi R^2 t}$$

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 :

$$\gamma = \frac{R\alpha}{L}$$

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

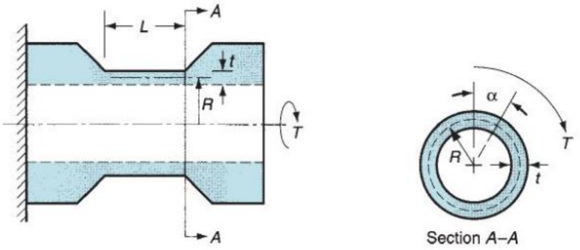


Fig. 3-13: Torsion test setup.

Stress-Strain relationships;
Shear properties

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

$$\tau = G\gamma$$

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*).

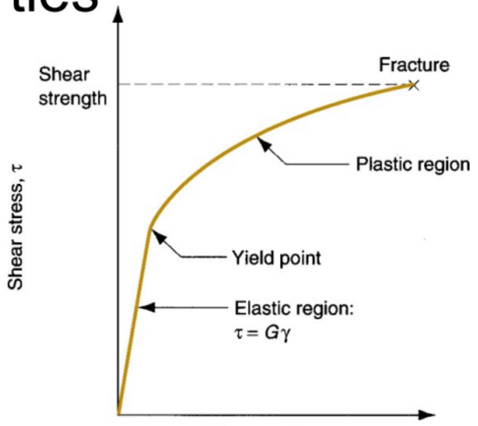


Fig. 3-14: A typical shear stress-strain curve from a torsion test.

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.
- There is a good correlation between the material’s hardness and its strength
- 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.

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.

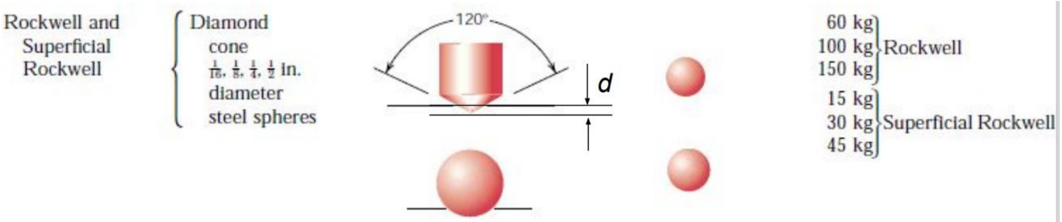


Fig. 3-15: Rockwell hardness testing technique.

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.

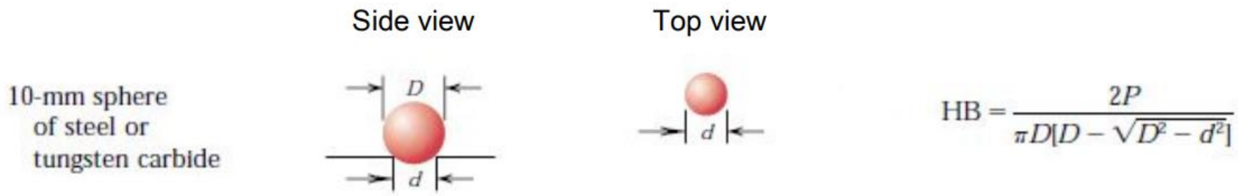


Fig. 3-15: Brinell hardness testing technique.

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.

Fig. 3-16: Vickers hardness testing technique

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.

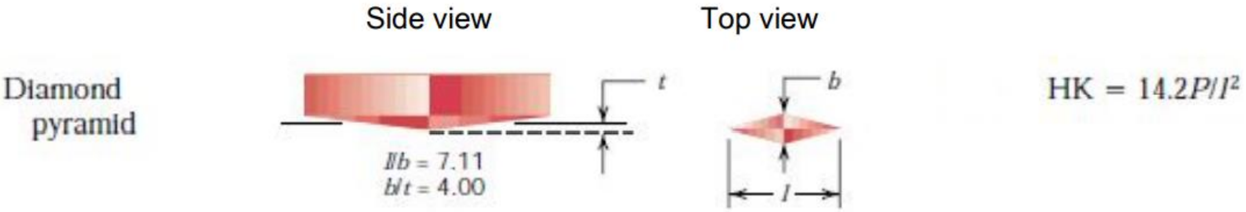
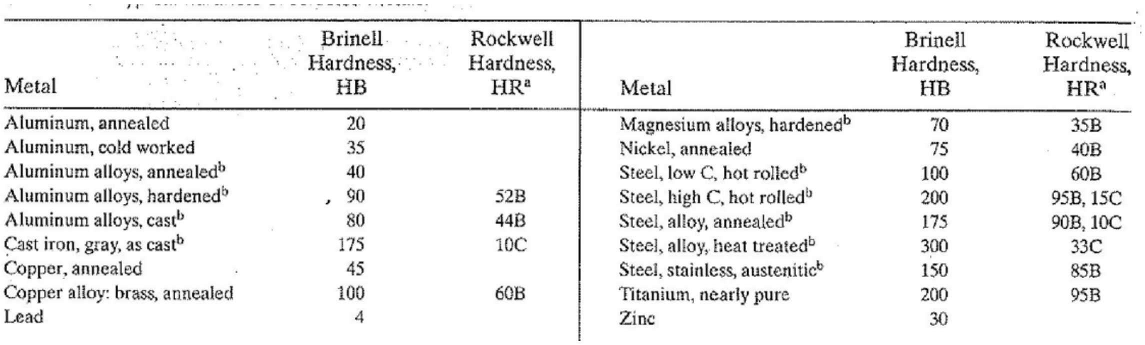


Fig. 3-17: Knoop hardness testing technique.

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:

$$TS = 3.45HB$$

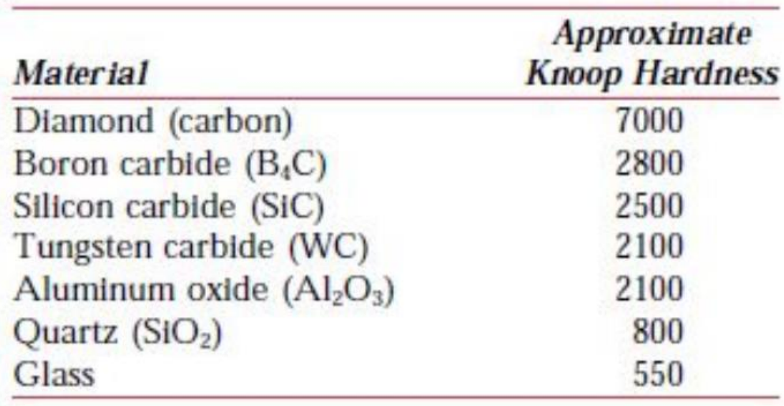


Metal	Brinell Hardness, HB	Rockwell Hardness, HR[a]	Metal	Brinell Hardness, HB	Rockwell Hardness, HR[a]
Aluminum, annealed	20		Magnesium alloys, hardened[b]	70	35B
Aluminum, cold worked	35		Nickel, annealed	75	40B
Aluminum alloys, annealed[b]	40		Steel, low C, hot rolled[b]	100	60B
Aluminum alloys, hardened[b]	90	52B	Steel, high C, hot rolled[b]	200	95B, 15C
Aluminum alloys, cast[b]	80	44B	Steel, alloy, annealed[b]	175	90B, 10C
Cast iron, gray, as cast[b]	175	10C	Steel, alloy, heat treated[b]	300	33C
Copper, annealed	45		Steel, stainless, austenitic[b]	150	85B
Copper alloy: brass, annealed	100	60B	Titanium, nearly pure	200	95B
Lead	4		Zinc	30	

Hardness of Various Materials

- <u>Ceramics</u>: 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.

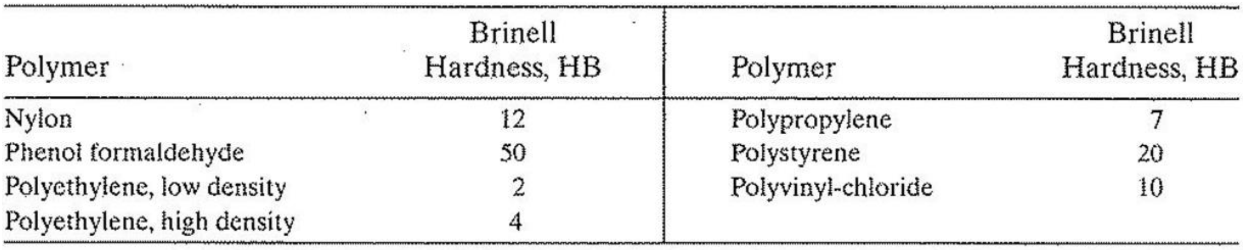


Material	*Approximate Knoop Hardness*
Diamond (carbon)	7000
Boron carbide (B_4C)	2800
Silicon carbide (SiC)	2500
Tungsten carbide (WC)	2100
Aluminum oxide (Al_2O_3)	2100
Quartz (SiO_2)	800
Glass	550

Approximate Knoop Hardness (100 g load) for Seven Ceramic Materials.

Hardness of Various Materials

- <u>Polymers</u>: 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
Nylon	12
Phenol formaldehyde	50
Polyethylene, low density	2
Polyethylene, high density	4
Polypropylene	7
Polystyrene	20
Polyvinyl-chloride	10

Effect of Temperature on Properties

- Temperature has a significant effect on nearly all properties of materials.
- **Important in design**: a designer need to know how the material properties at the operating temperatures during service.
- **Important in manufacturing**: 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).

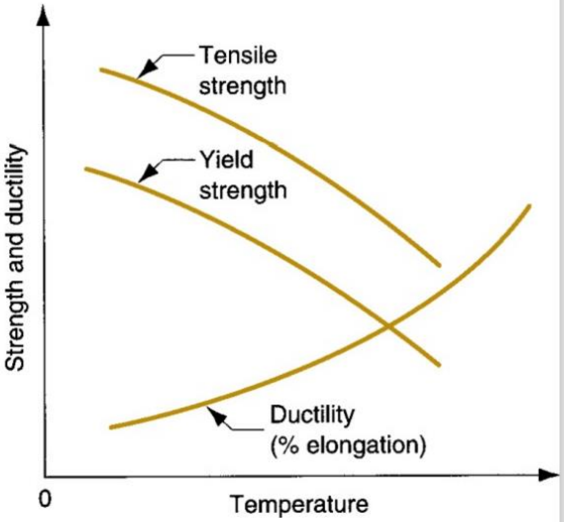


Fig. 3-18: Effect of temp. on strength & ductility

Effect of Temperature on Properties (Hot Hardness)

- **Hot hardness**: 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.

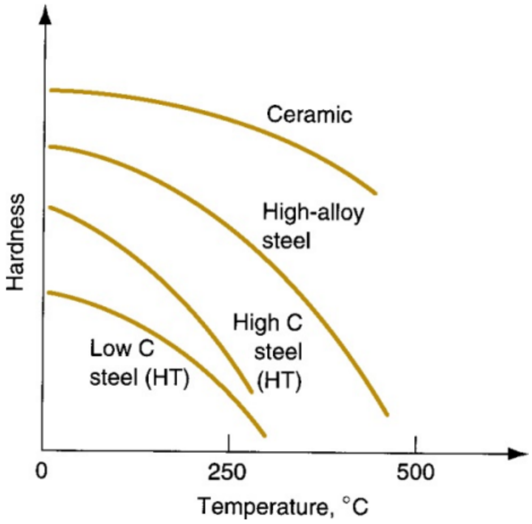


Fig. 3-19: Hardness vs. temperature for various materials.

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 v (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.

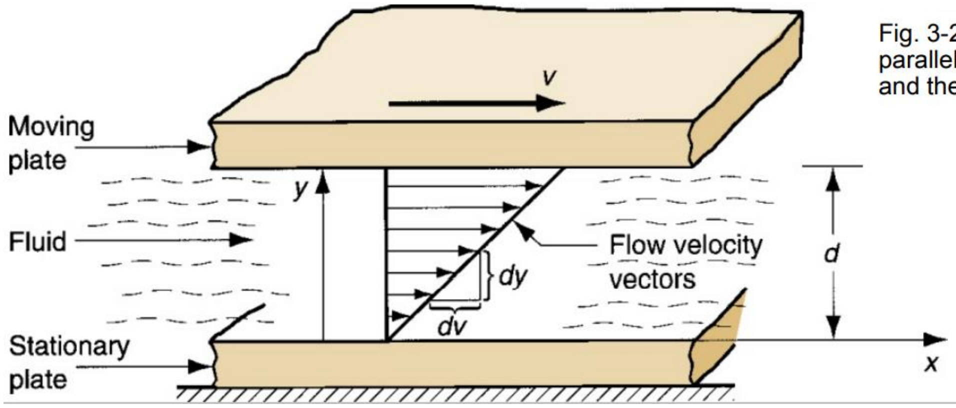


Fig. 3-20: Fluid flow between two parallel plates. One is stationary and the other is moving.

- 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).

Fluid Properties
Viscosity in Manufacturing Processes

- <u>In metals</u>: 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.

- <u>In glasses</u>: 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 ºC.

Manufacturing Processes

Bulk Deformation Processes in Metal Working

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.
- 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.
- 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.
- 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.

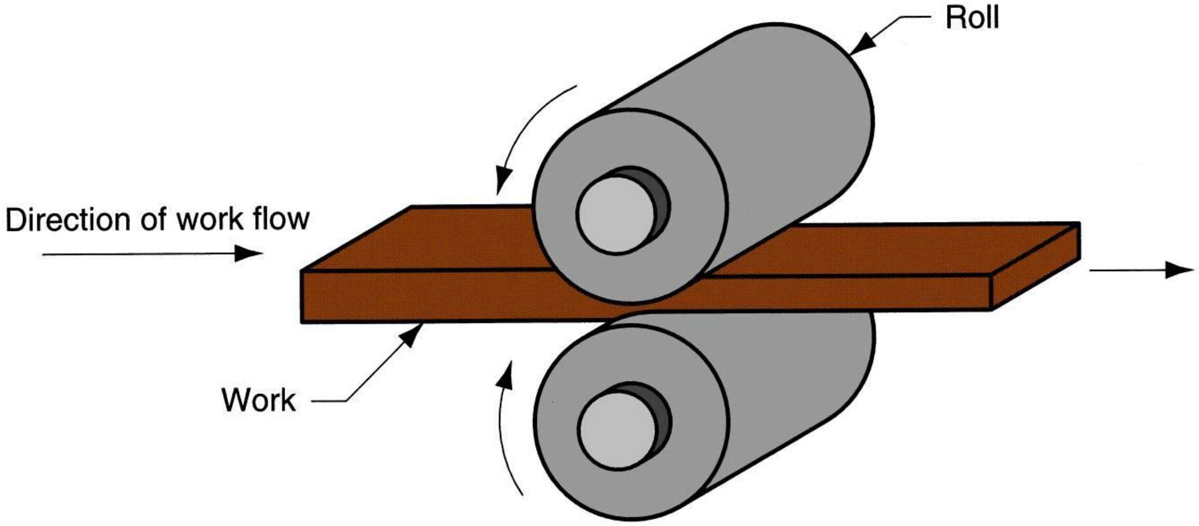


Figure 2.1 The rolling process (specifically, flat rolling).

- 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 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 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.

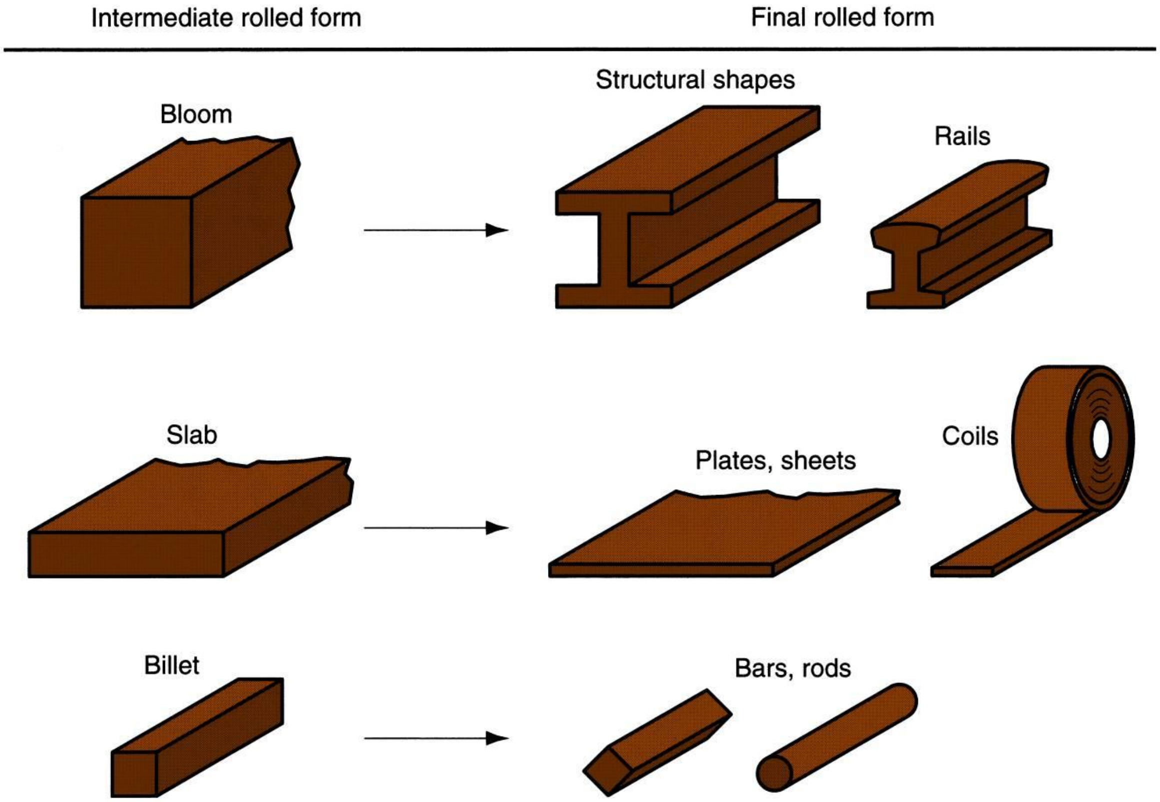


Figure 2.2 Some of the steel products made in a rolling mill.

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):

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

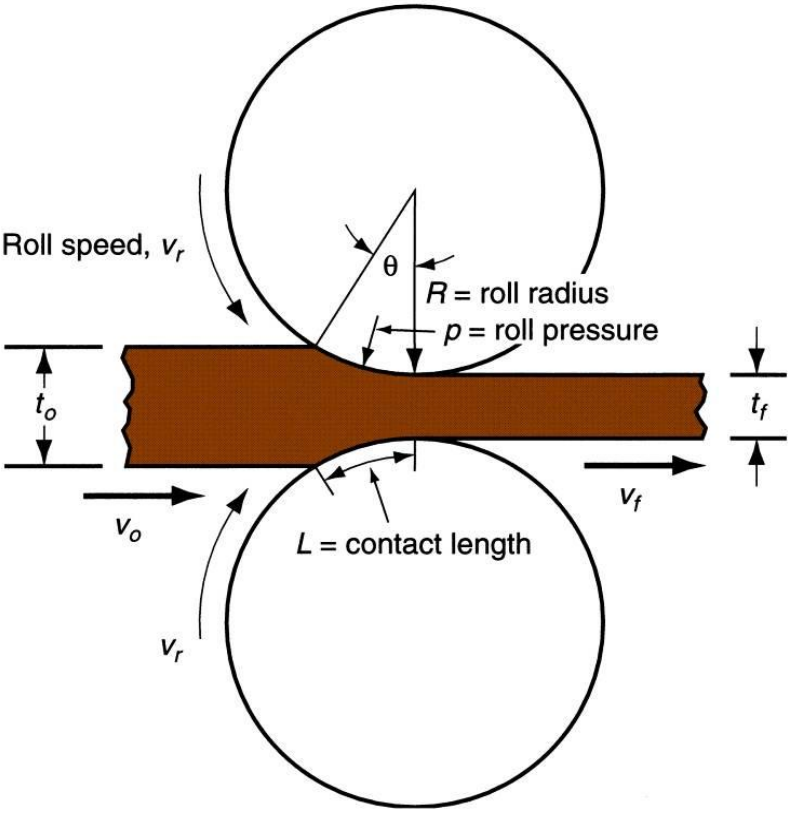


Figure 2.3 Side view of flat rolling, indicating before and after thicknesses, work velocities, angle of contact with rolls, and other features.

- ***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.

- True strain is expressed by:

$$\varepsilon = \ln \frac{t_o}{t_f}$$

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

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

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

- 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.

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 Mills

- Rolling mill configurations:

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

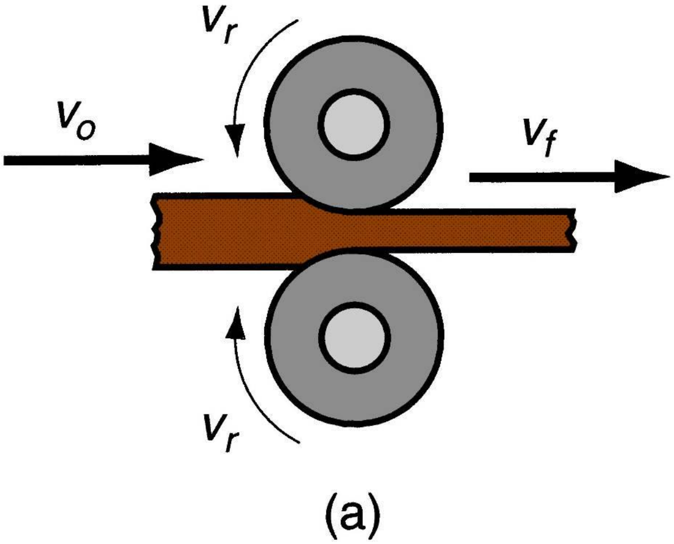


Figure 2.4 Various configurations of rolling mills: (a) two-high rolling mill.

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

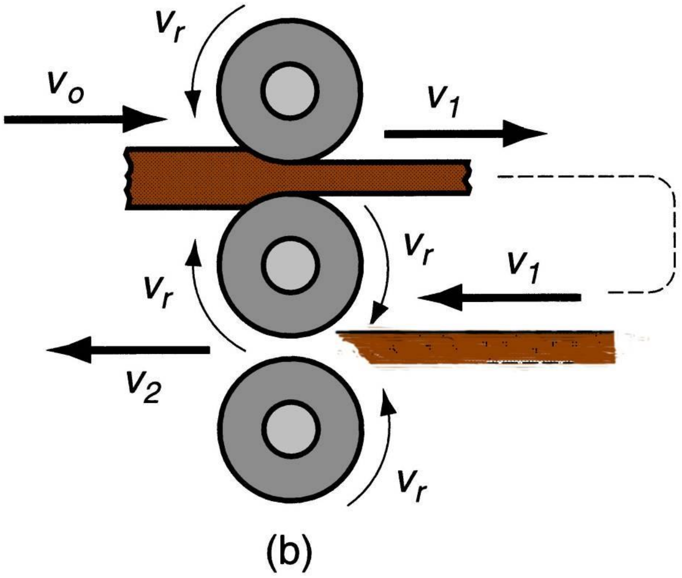


Figure 2.4 Various configurations of rolling mills: (b) three-high rolling mill.

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

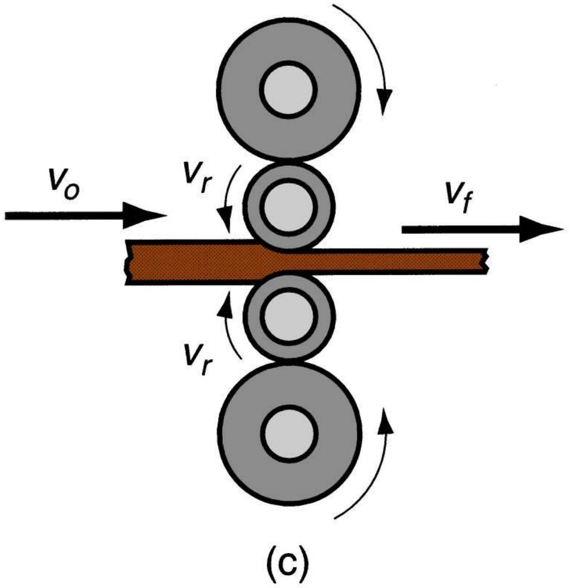


Figure 2.4 Various configurations of rolling mills: (c) four-high rolling mill.

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

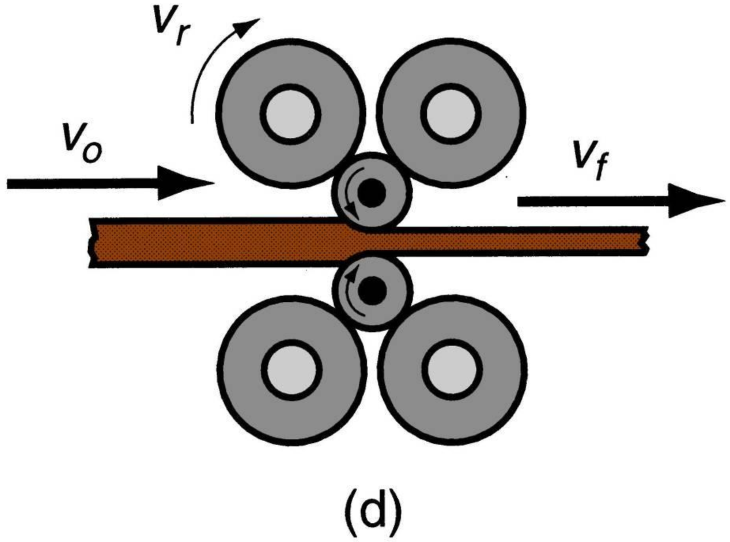


Figure 2.4 Various configurations of rolling mills: (d) cluster mill.

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

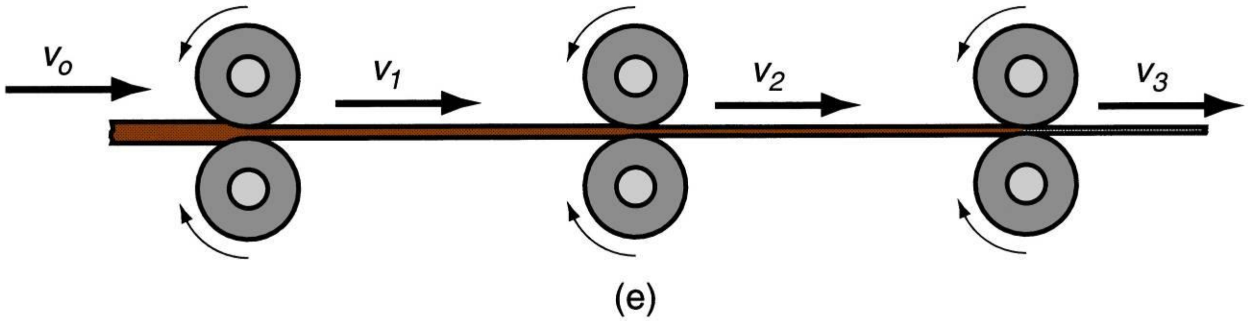


Figure 2.4 Various configurations of rolling mills: (e) tandem rolling mill.

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.

- ***Thread Rolling***:

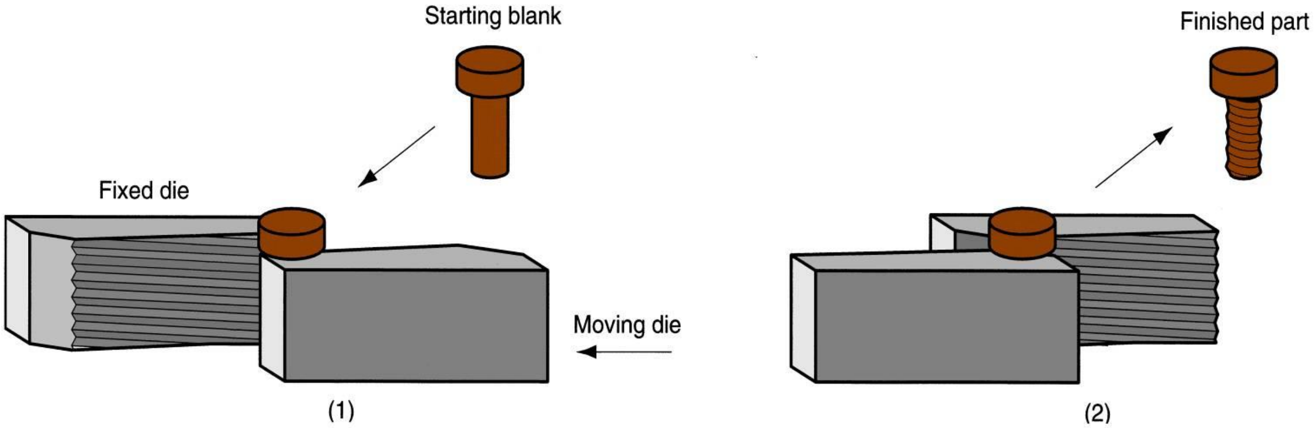


Figure 2.5 Thread rolling with flat dies: (1) start, and (2) end of cycle.

- ***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.

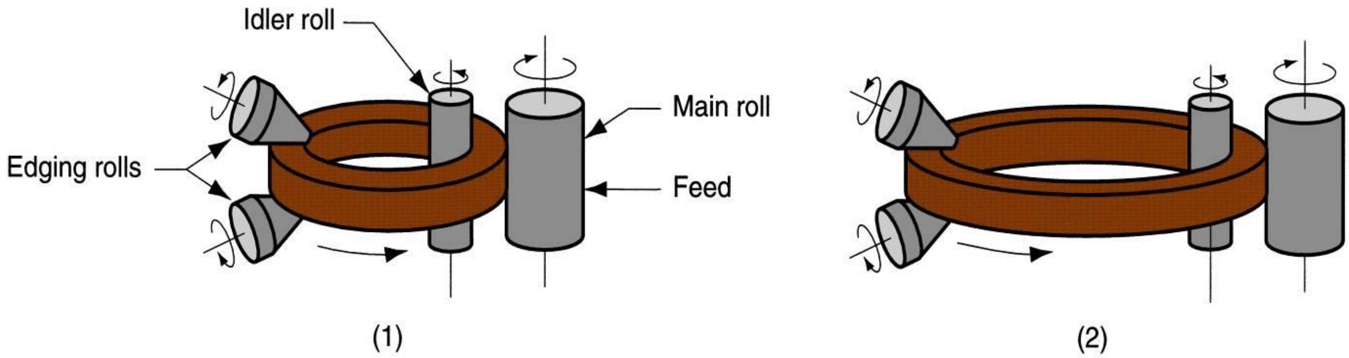


Figure 2.6 Ring rolling used to reduce the wall thickness and increase the diameter of a ring: (1) start, and (2) completion of process.

- ***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.

- ***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.

- ***Roll Piercing***:

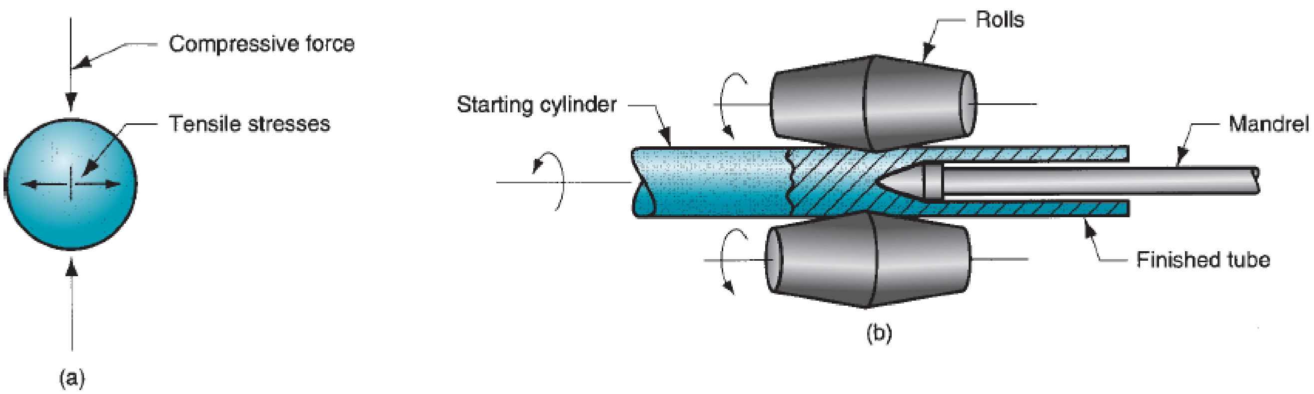


Figure 2.7 Roll piercing: (a) formation of internal stresses and cavity by compression of cylindrical part; and (b) setup of Mannesmann roll mill for producing seamless tubing.

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 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 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.

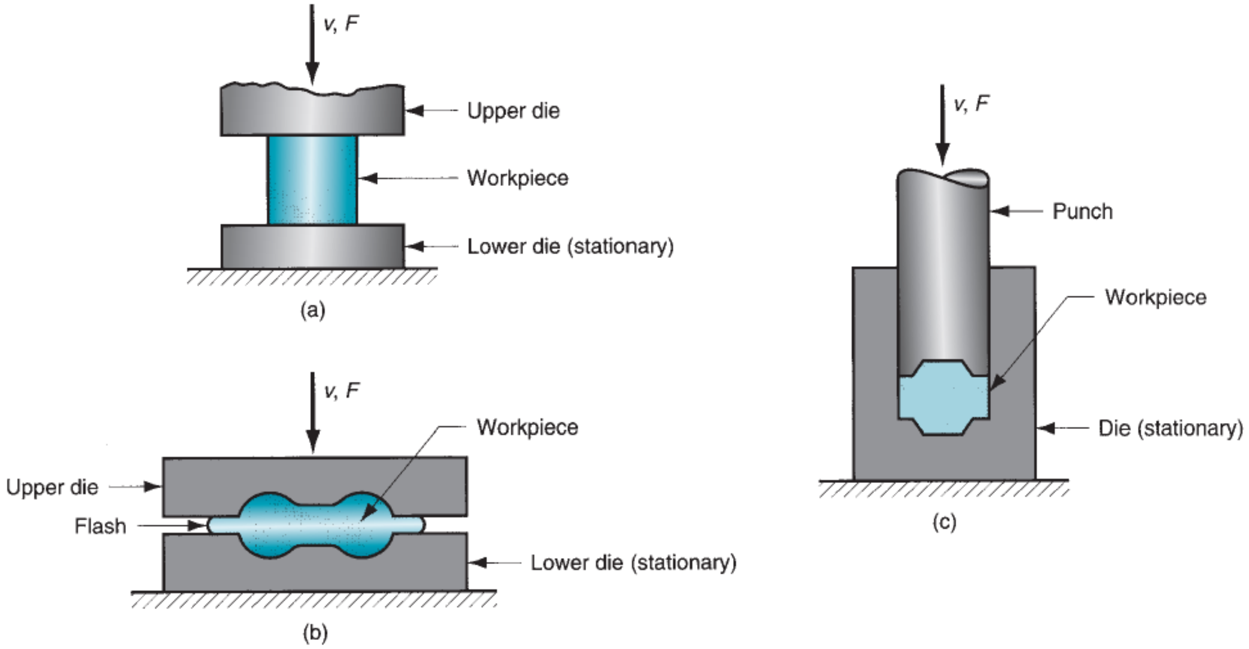


Figure 2.8 Three types of forging operation: (a) open-die forging, (b) impression-die forging, and (c) flashless forging.

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.
- 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.

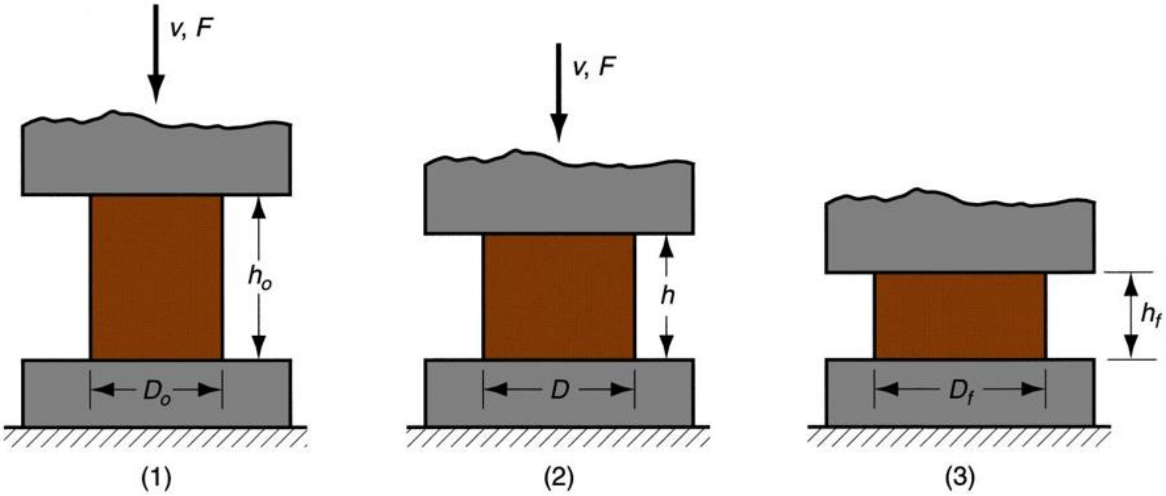


Figure 2.9 Homogeneous deformation of a cylindrical workpart under ideal conditions in an open-die forging operation: (1) start of process with workpiece at its original length and diameter, (2) partial compression, and (3) final size.

- Analysis of Open-Die Forging:

– Under these ideal conditions, the true strain experienced by the work during the process can be determined by:

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

– 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.

- 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.

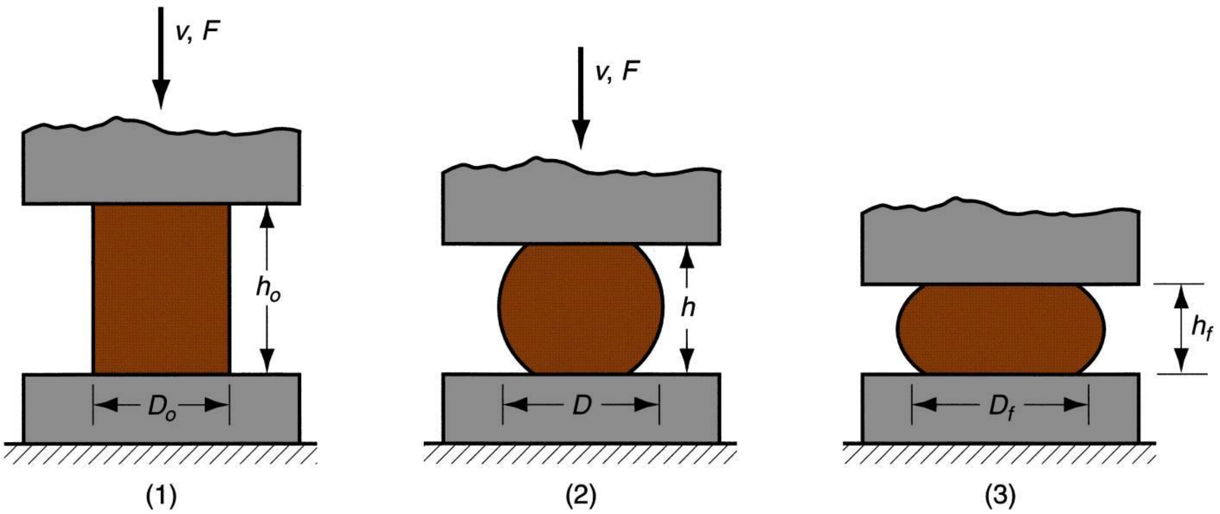


Figure 2.10 Actual deformation of a cylindrical workpart in open-die forging, showing pronounced barreling: (1) start of process, (2) partial deformation, and (3) final shape.

- 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:

$$K_f = 1 + \frac{0.4\mu D}{h}$$

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

- 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:

$$K_f = 1 + \frac{0.4 \mu D}{h}$$

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

- 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.

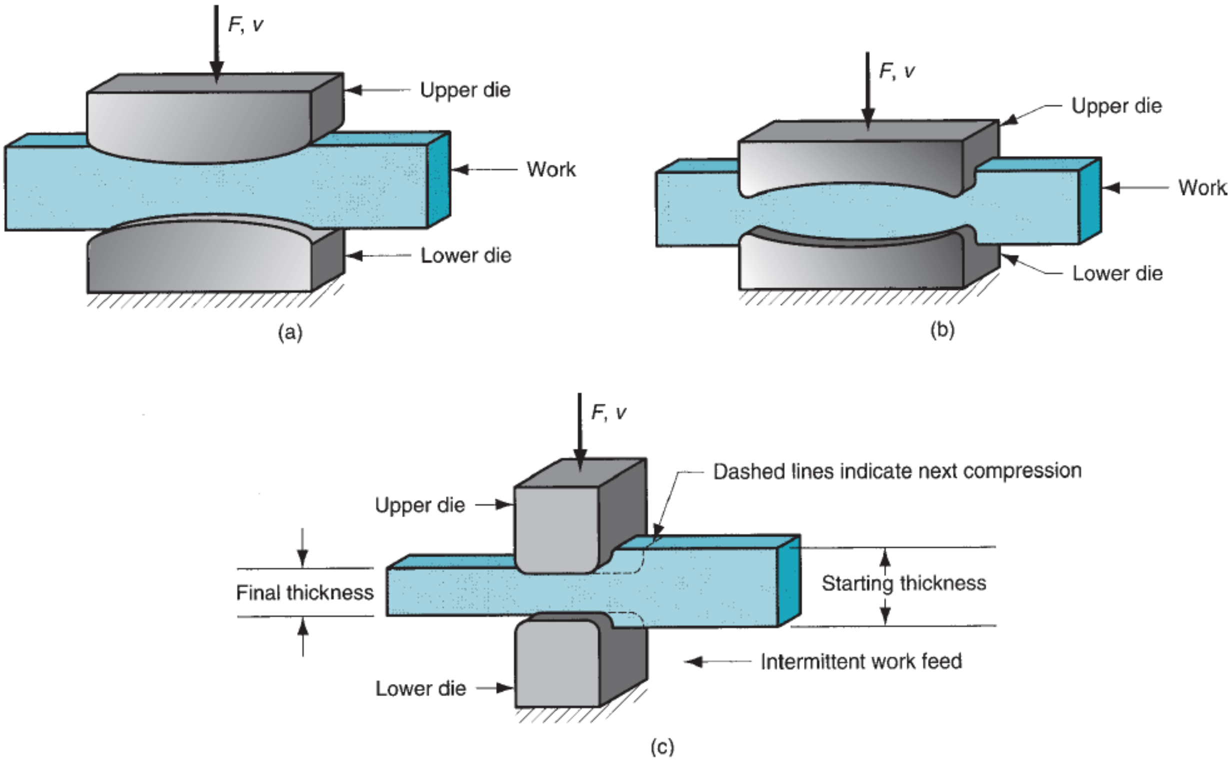


Figure 19.11 Several open-die forging operations: (a) fullering, (b) edging, and (c) cogging.

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.
- Sequence in impression-die forging:

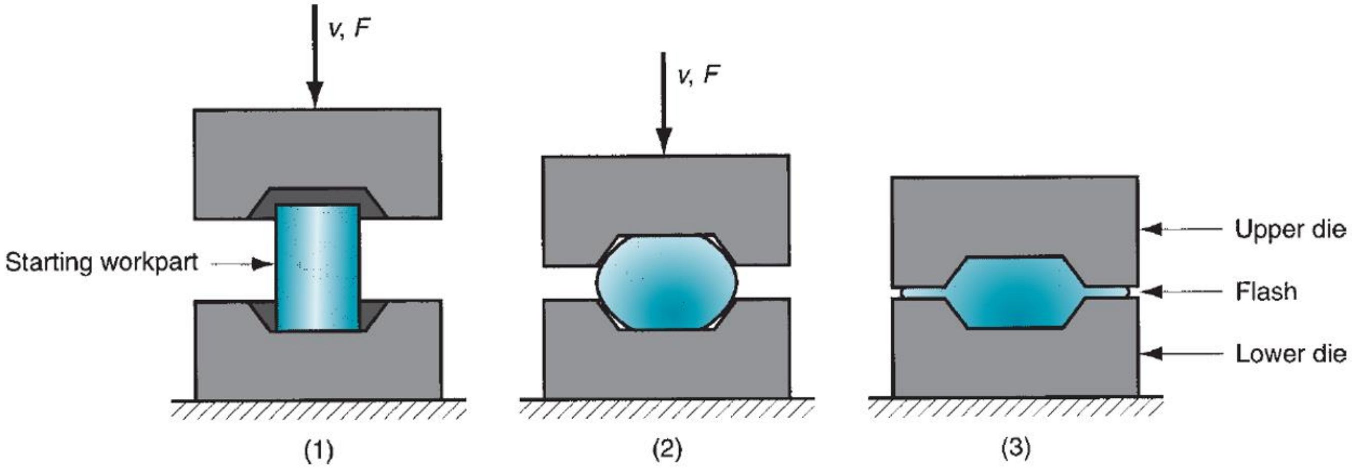


Figure 19.12 Sequence in impression-die forging: (1) just prior to initial contact with raw workpiece, (2) partial compression, and (3) final die closure, causing flash to form in gap between die plates.

- 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.

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***.

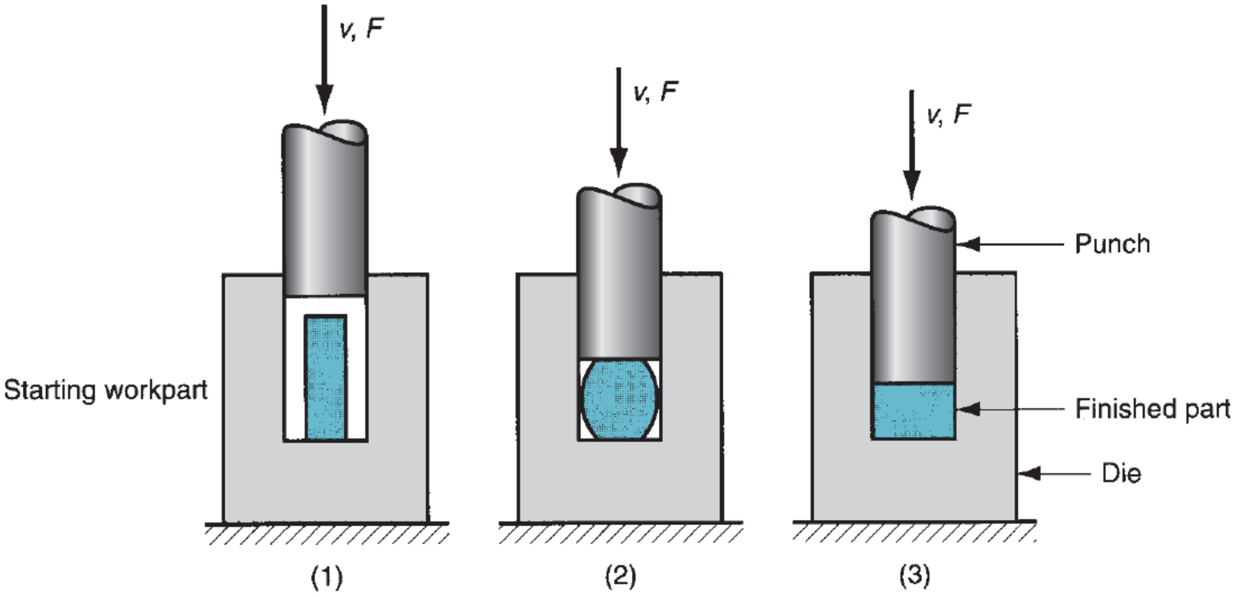


Figure 2.13 Flashless forging: (1) just before initial contact with workpiece, (2) partial compression, and (3) final punch and die closure.

- ***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.

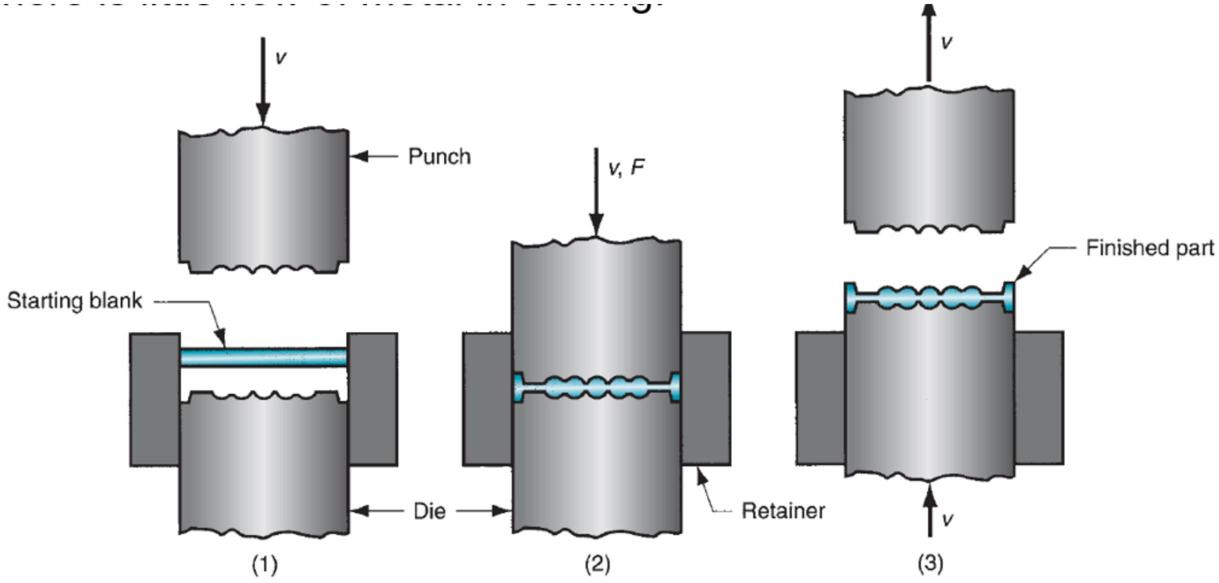


Figure 2.14 Coining operation: (1) start of cycle, (2) compression stroke, and (3) ejection of finished part.

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.

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 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.

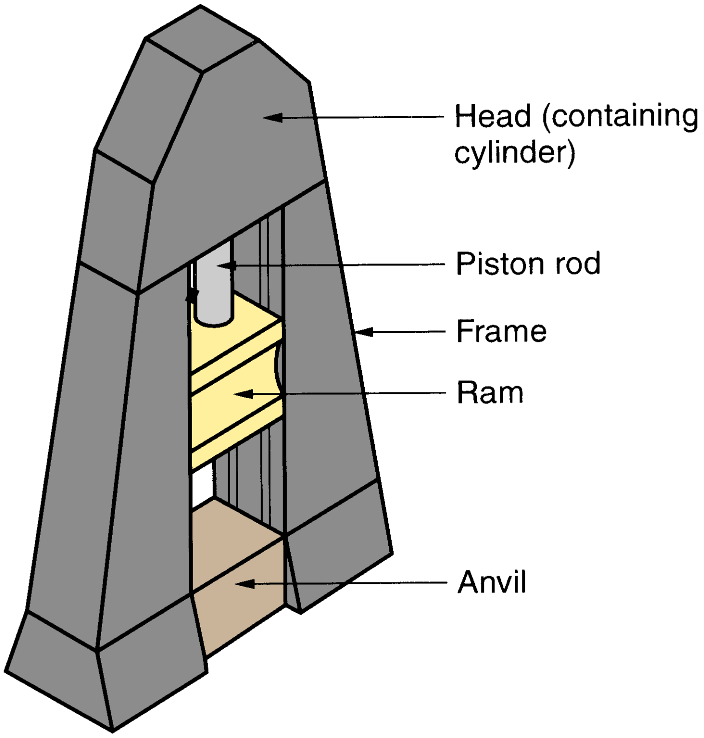


Figure 19.15 Diagram showing details of a drop hammer for impression-die forging.

(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.

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

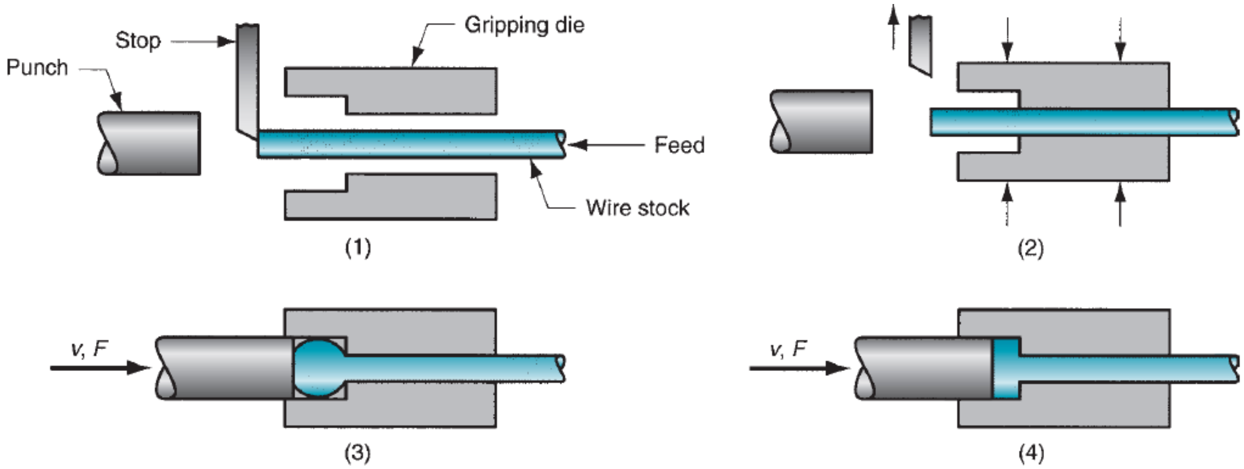


Figure 2.16 An upset forging operation to form a head on a bolt. (1) wire stock is fed to the stop; (2) gripping dies close on the stock and the stop is retracted; (3) punch moves forward; and (4) bottoms to form the head.

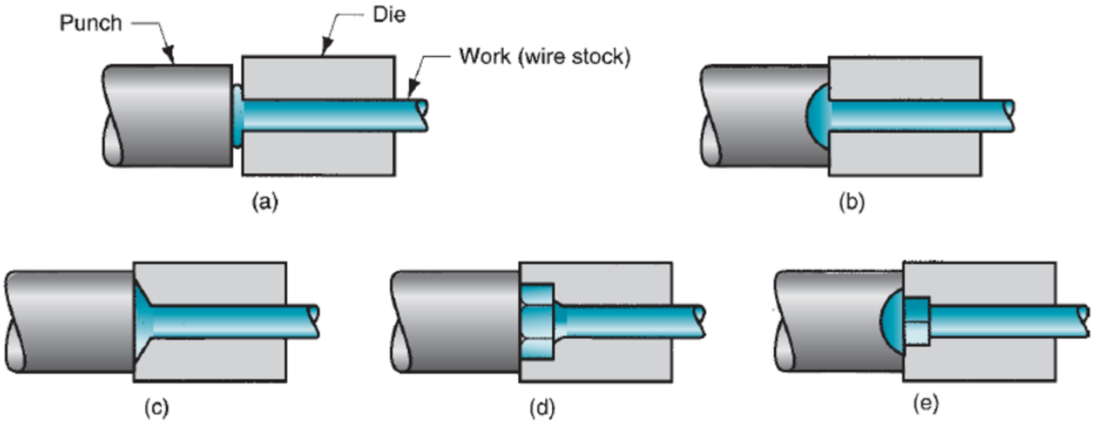


Figure 2.17 Examples of heading (upset forging) operations: (a) heading a nail using open dies, (b) round head formed by punch, (c) and (d) heads formed by die, and (e) carriage bolt head formed by punch and die.

- ***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.

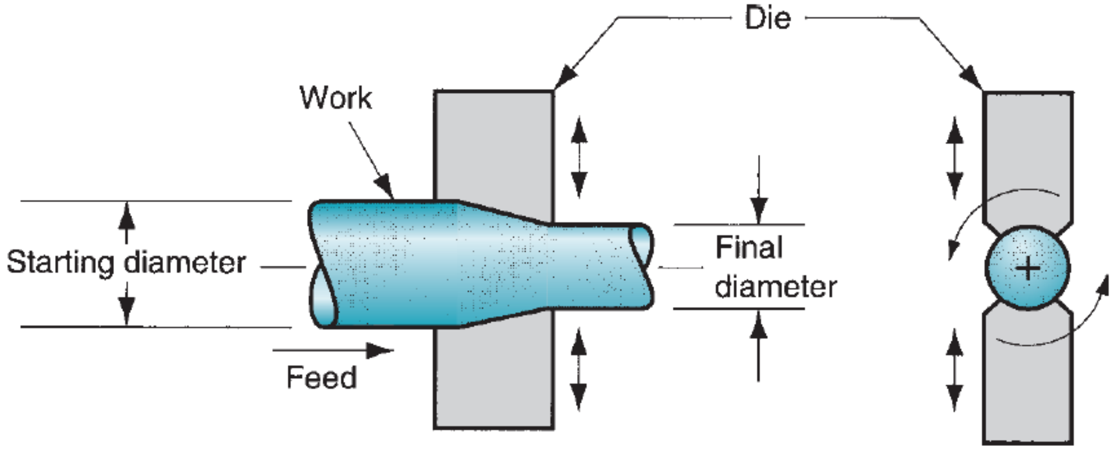


Figure 2.18 Swaging process to reduce solid rod stock; the dies rotate as they hammer the work. In radial forging, the workpiece rotates while the dies remain in a fixed orientation as they hammer the work

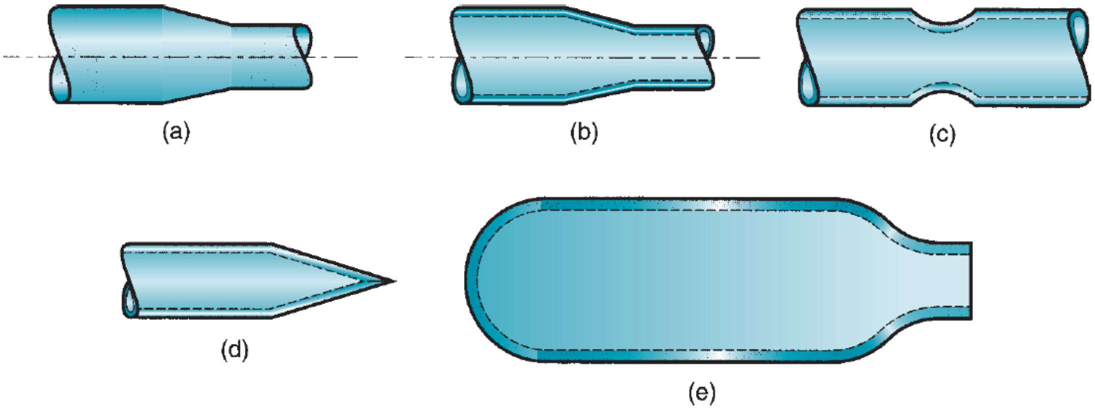


Figure 2.19 Examples of parts made by swaging: (a) reduction of solid stock, (b) tapering a tube, (c) swaging to form a groove on a tube, (d) pointing of a tube, and (e) swaging of neck on a gas cylinder.

- ***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.

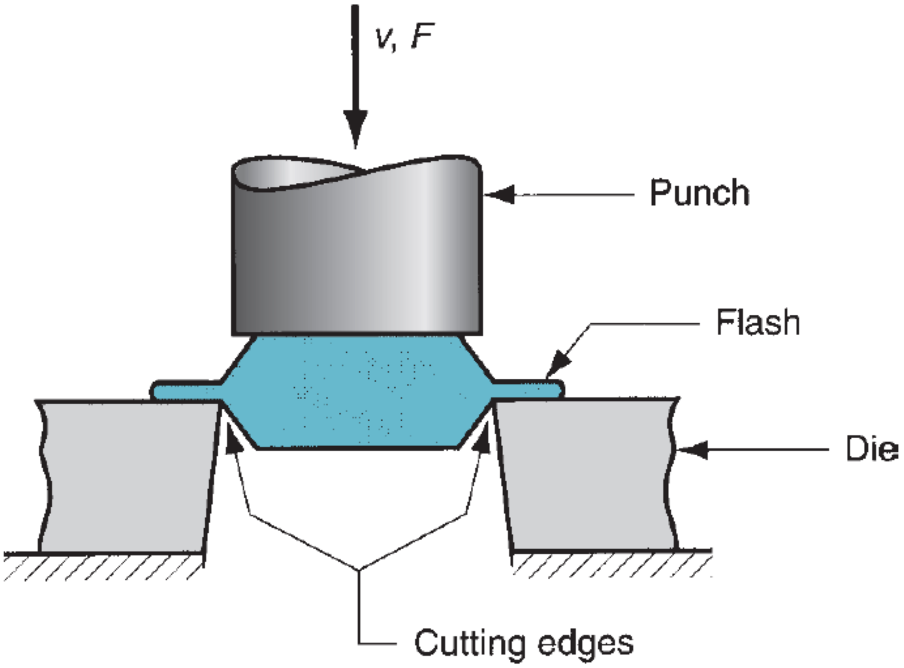


Figure 2.20 Trimming operation (shearing process) to remove the flash after impression-die forging.

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.

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***.

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

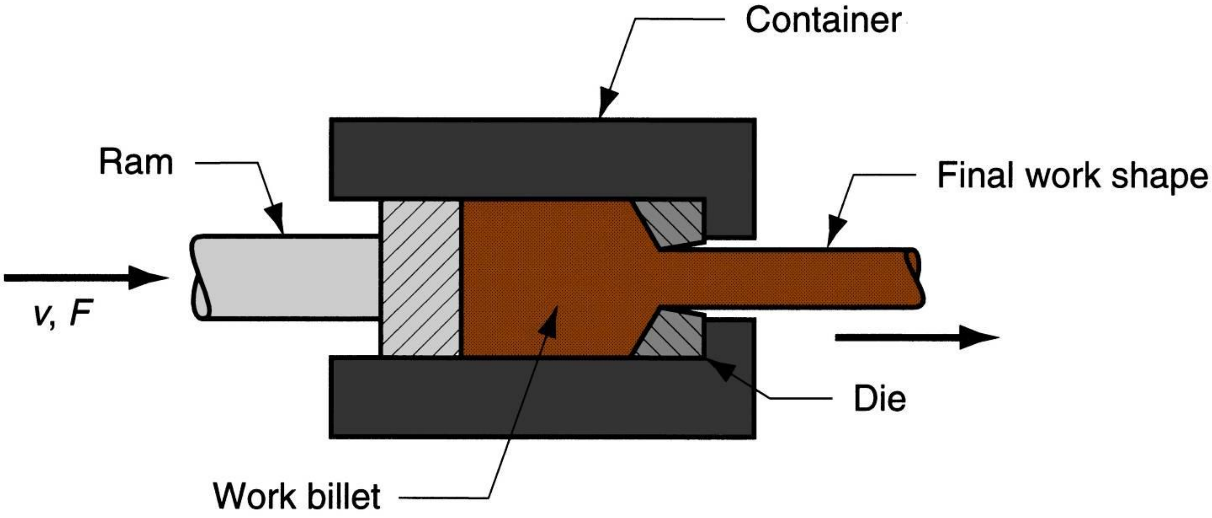


Figure 2.21 Direct extrusion.

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.

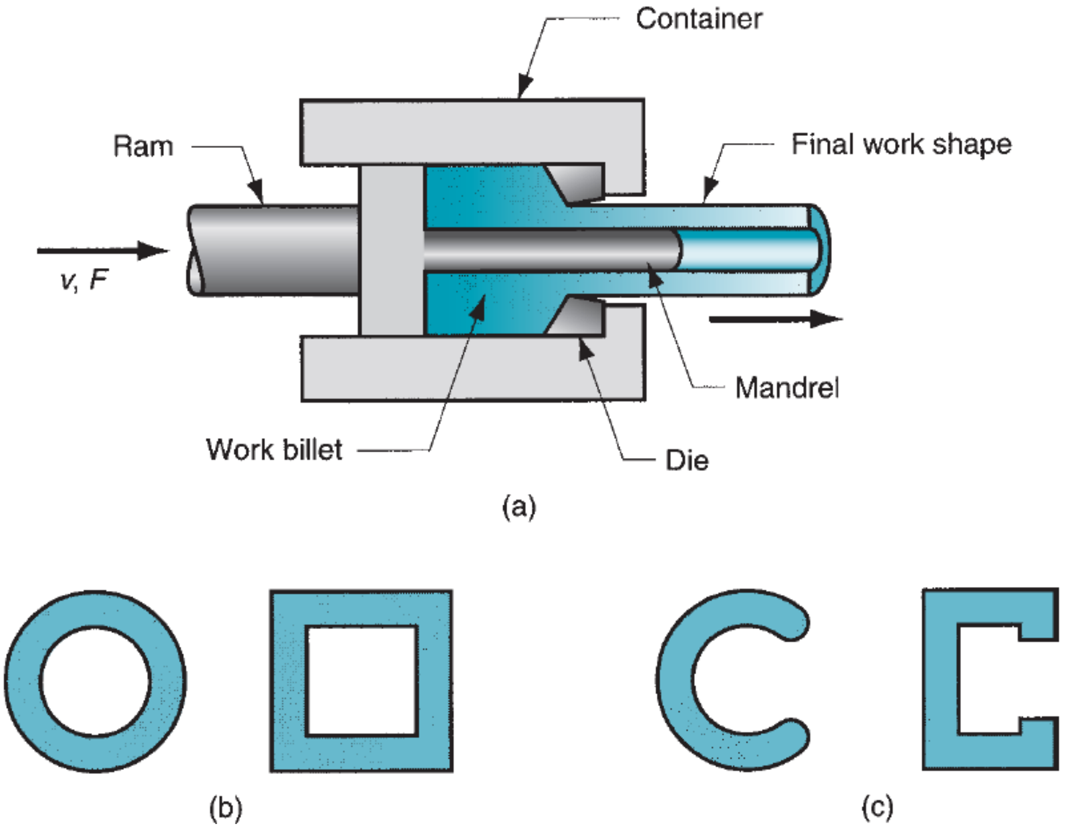


Figure 2.22 (a) Direct extrusion to produce a hollow or semi-hollow cross section; (b) hollow and (c) semi-hollow cross sections.

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

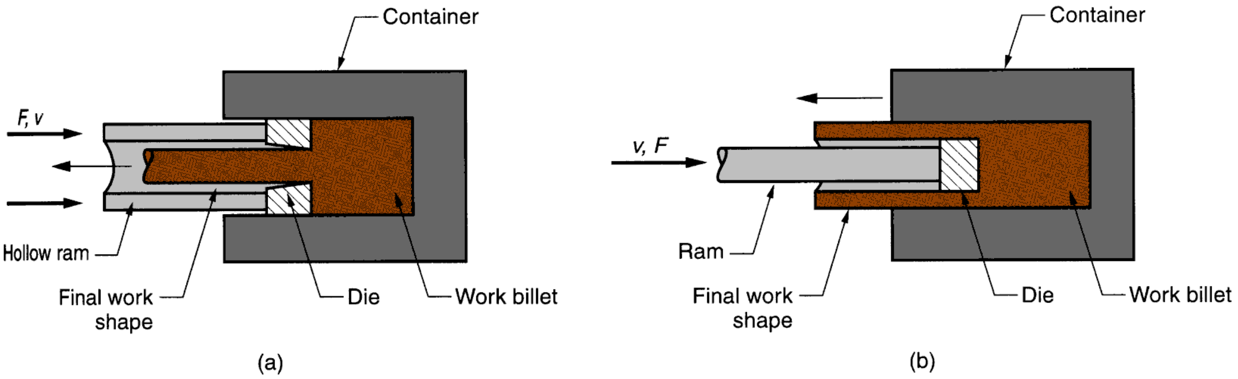


Figure 2.23 Indirect extrusion to produce (a) a solid cross section and (b) a hollow cross section.

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.
- ***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 (sometimes extruded cold as well).
    - 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.
- ***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.
- ***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.

- ***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.

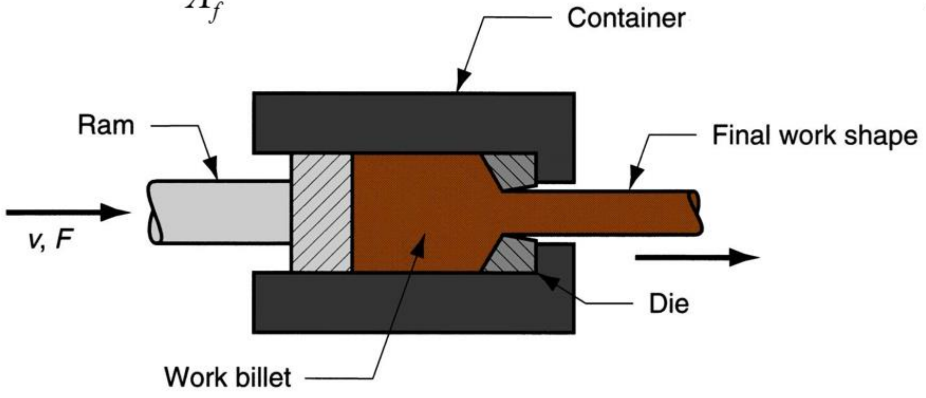
- Consider the figure below:

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

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

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

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



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

The workpiece has round cross section

- If friction is considered:

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

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

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

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 Dies and Presses

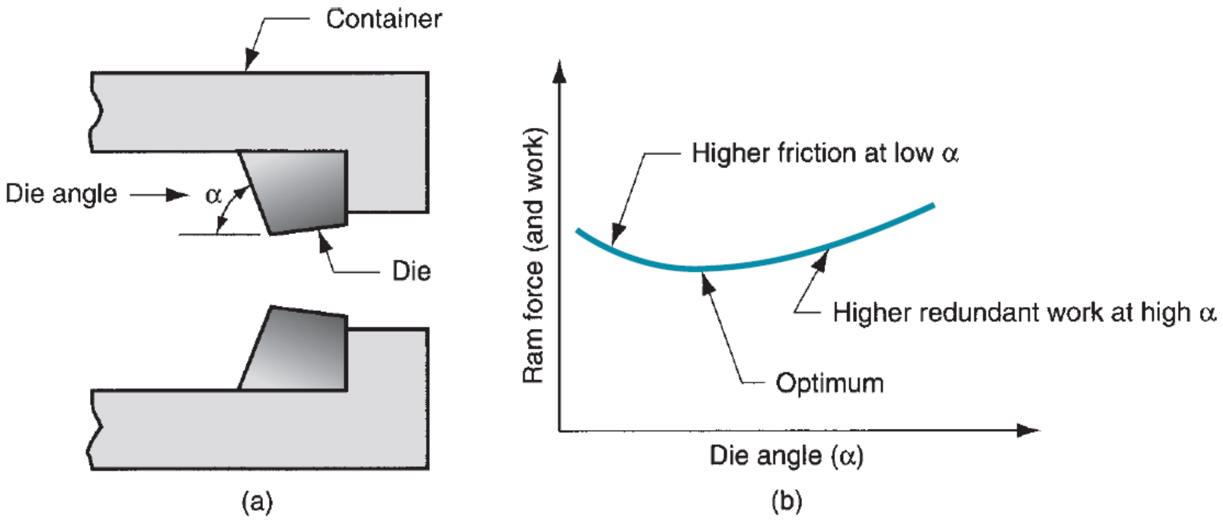


Figure 2.24 (a) Definition of die angle in direct extrusion; (b) effect of die angle on ram force.

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.

- 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: $p = K_x \overline{Y_f} \varepsilon_x$

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

→ For shapes other than round.

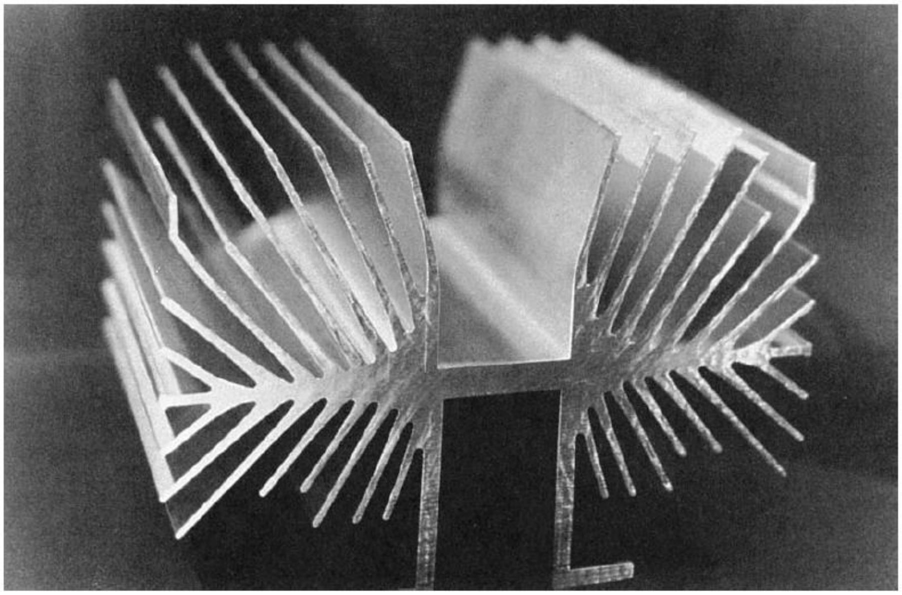


Figure 2.25 A complex extruded cross section for a heat sink. (Photo courtesy of Aluminum Company of America, Pittsburg, Pennsylvania).

- ***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.

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.

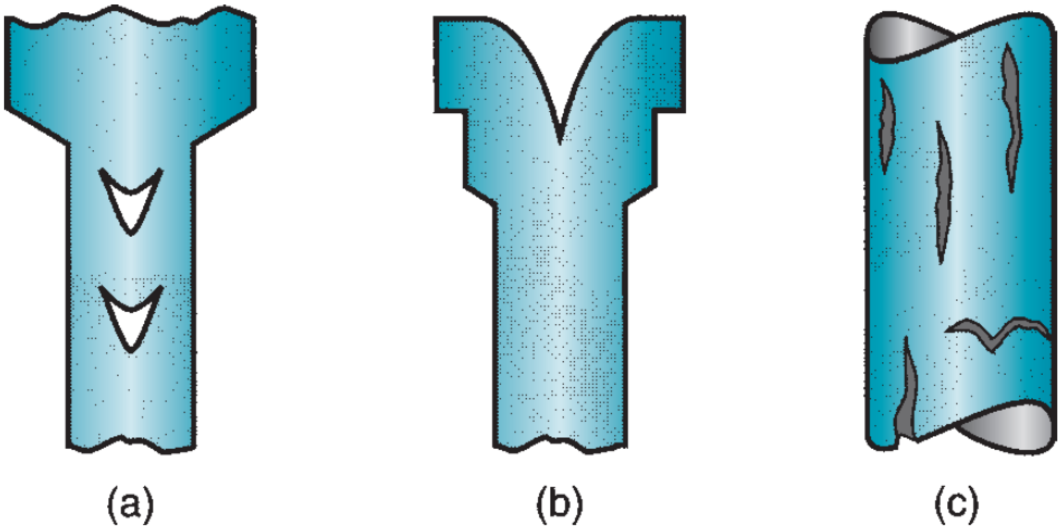


Figure 2.26 Some common defects in extrusion: (a) centerburst, (b) piping, and (c) surface cracking.

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.

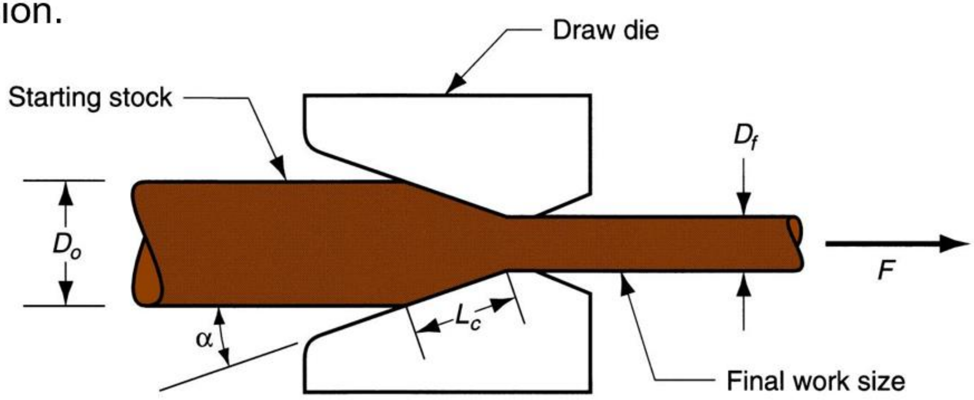


Figure 2.27 Drawing of bar, rod, or wire.

- ***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): $r = \dfrac{A_o - A_f}{A_o}$

- Draft: difference between original and final diameter: $d = D_o - D_f$

Note: A is in (mm²) and D is in (mm).

Analysis of Drawing

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

True strain: $\varepsilon = \ln \dfrac{A_o}{A_f} = \ln \dfrac{1}{1-r}$

Stress: $\sigma = \overline{Y_f}\varepsilon = \overline{Y_f} \ln \dfrac{A_o}{A_f}$ where $\overline{Y_f} = \dfrac{K\varepsilon^n}{1+n}$

Mechanics of Drawing: assuming friction, consider Figure 2.27

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

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.

- ***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.

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

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

- 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:

$$\varepsilon_{\max} = 1.0$$

- The maximum possible area ratio is: $\dfrac{A_o}{A_f} = e = 2.7183$
- The maximum possible reduction is: $r_{\max} = \dfrac{e-1}{e} = 0.632$

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

- Adaptability to mass production.

- ***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.

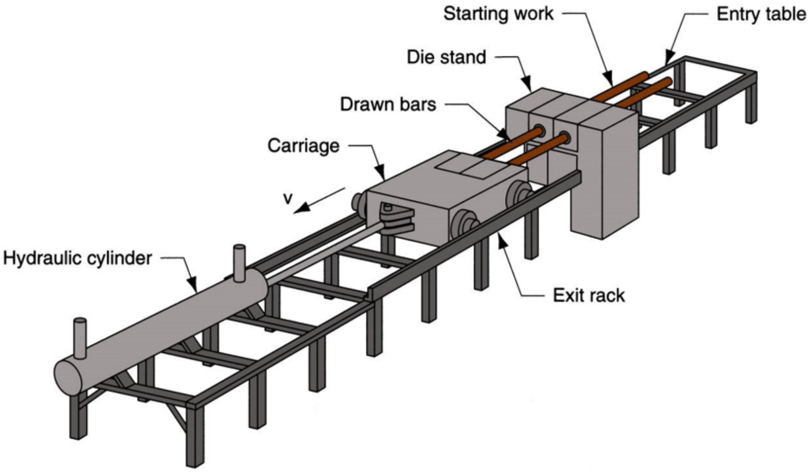


Figure 2.28 Hydraulically operated draw bench for drawing metal bars.

- ***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.

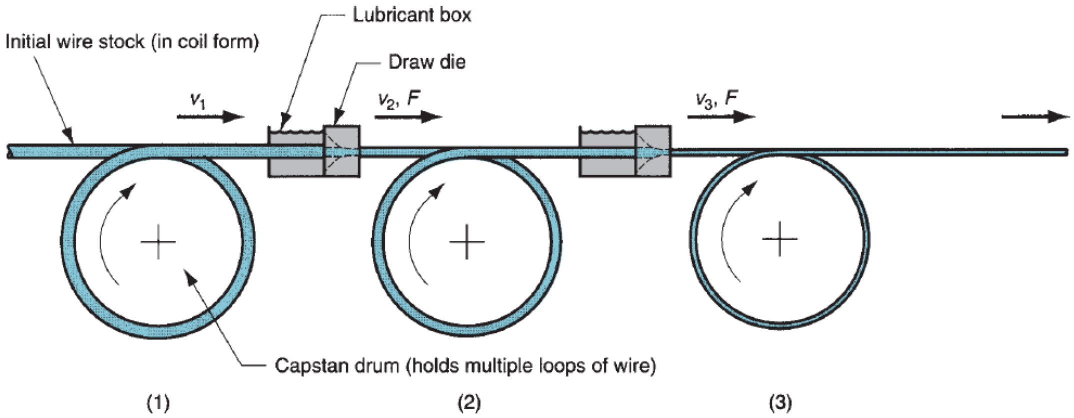


Figure 2.29 Continuous drawing of wire.

- ***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.

- ***Drawing Dies***:

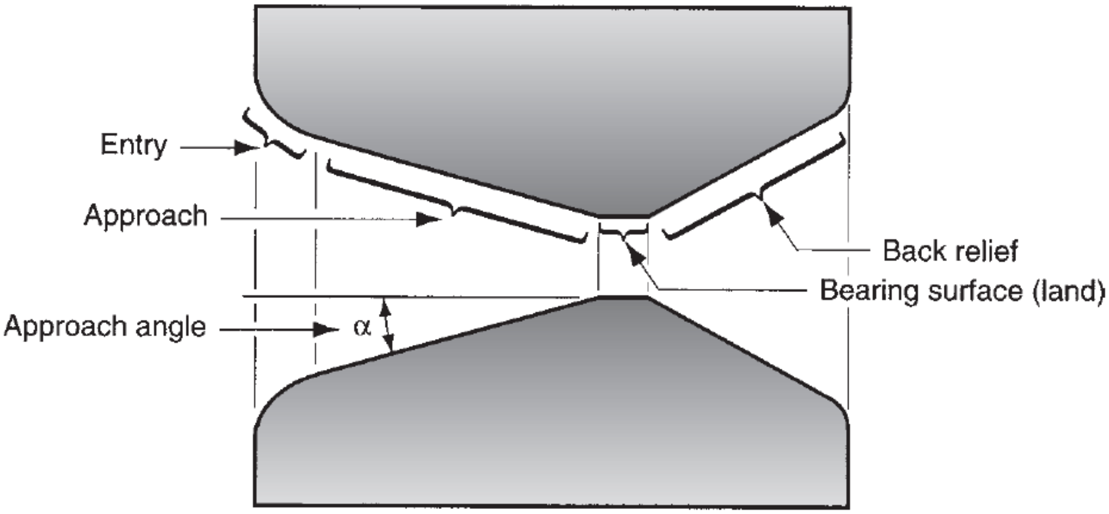


Figure 2.30 Draw die for drawing of round rod or wire.

- ***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.