FUNDAMENTALS OF METAL FORMING

1. Overview of Metal Forming
2. Material Behavior in Metal Forming
3. Temperature in Metal Forming
4. Strain Rate Sensitivity

Metal Forming

Large group of manufacturing processes in which plastic deformation is used to change the shape of metal workpieces

- The tool, usually called a *die*, applies stresses that exceed the yield strength of the metal
  - The metal takes a shape determined by the geometry of the die

Stresses in Metal Forming

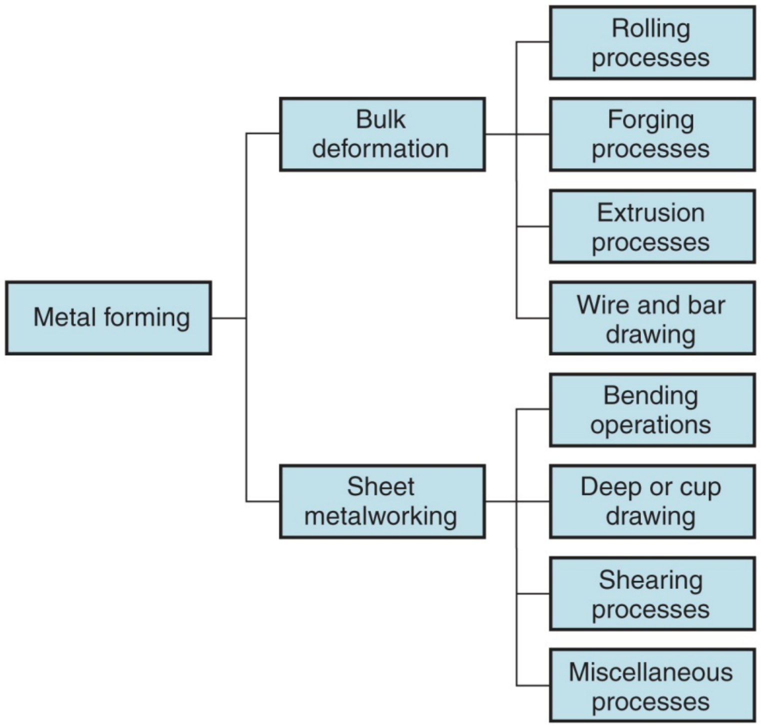
- Stresses to plastically deform the metal are usually compressive
  - Examples: rolling, forging, extrusion
- However, some forming processes
  - Stretch the metal (tensile stresses)
  - Others bend the metal (tensile and compressive)
  - Still others apply shear stresses

Material Properties in Metal Forming

- Desirable material properties:
  - Low yield strength
  - High ductility
- These properties are affected by temperature:
  - Ductility increases and yield strength decreases when work temperature is raised
- Other factors:
  - Strain rate and friction

Basic Types of Metal Forming Processes

1. Bulk deformation
   - Rolling processes
   - Forging processes
   - Extrusion processes
   - Wire and bar drawing
2. Sheet metalworking
   - Bending operations
   - Deep or cup drawing
   - Shearing processes

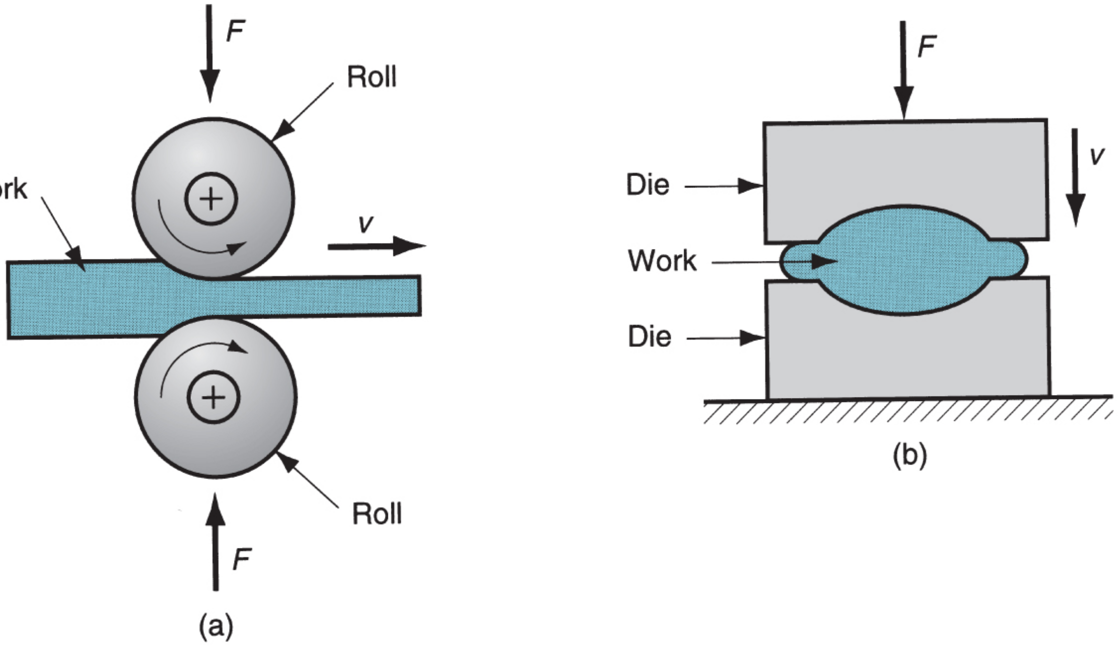


Bulk Deformation Processes

- Characterized by significant deformations and massive shape changes
- "Bulk" refers to workparts with relatively low surface area-to-volume ratios
- Starting work shapes are usually simple geometries
  - Examples:
    - Cylindrical billets
    - Rectangular bars

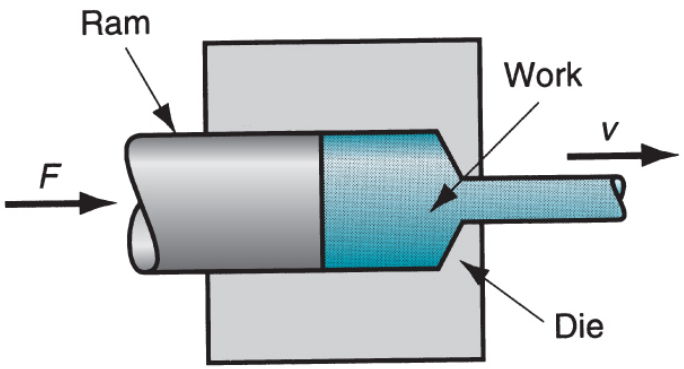
Bulk Deformation Processes

- (a) Rolling and (b) forging

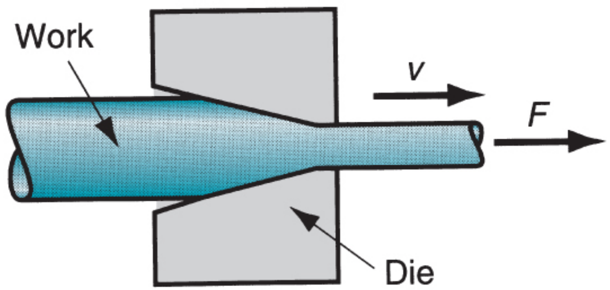


Bulk Deformation Processes

- (c) Extrusion and (d) wire and bar drawing



(c)



(d)

Material Behavior in Metal Forming

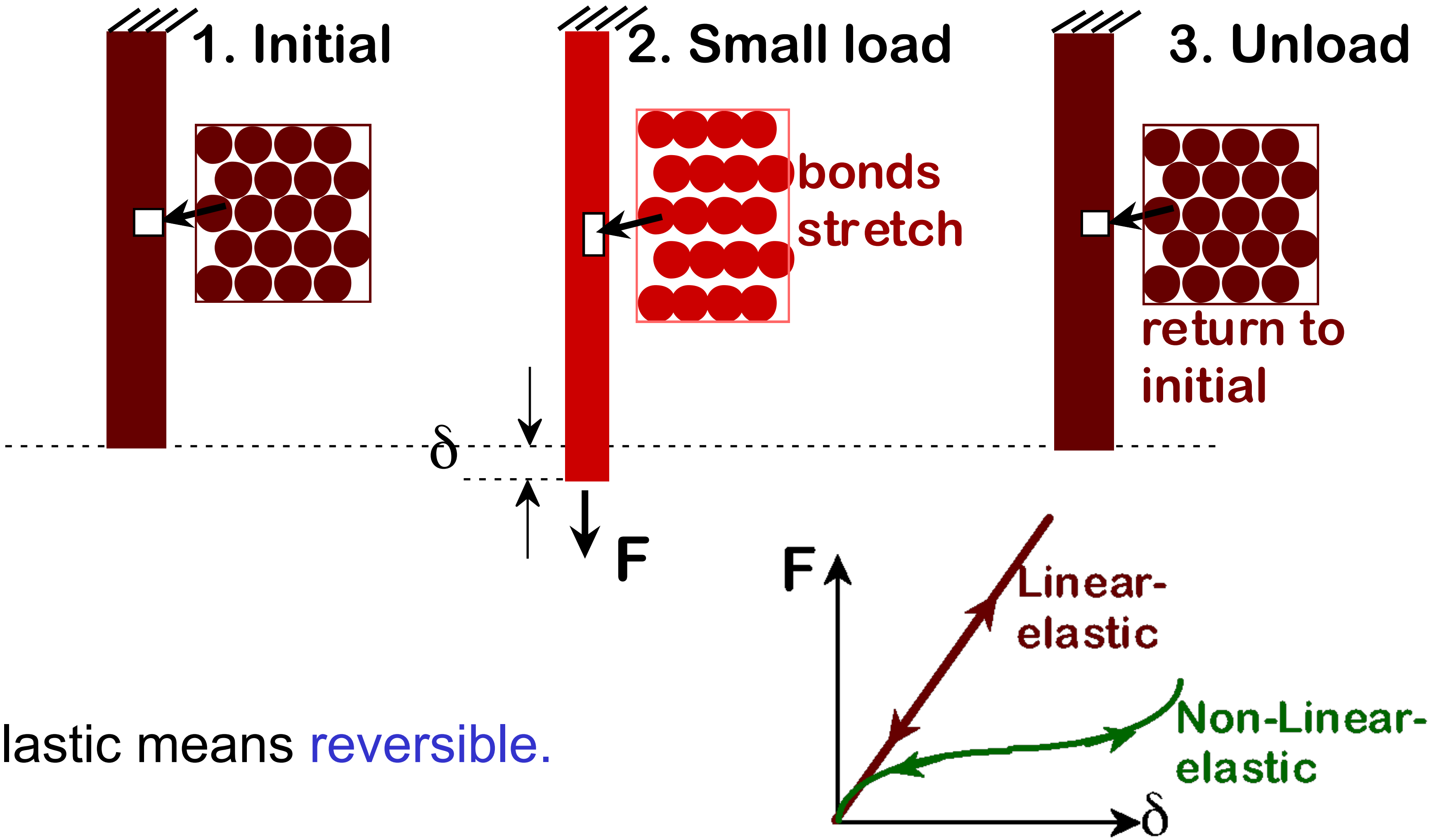
- Plastic region of stress-strain curve is primary interest because material is plastically deformed
- In plastic region, metal's behavior is expressed by the flow curve:

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

where K = strength coefficient; and n = strain hardening exponent

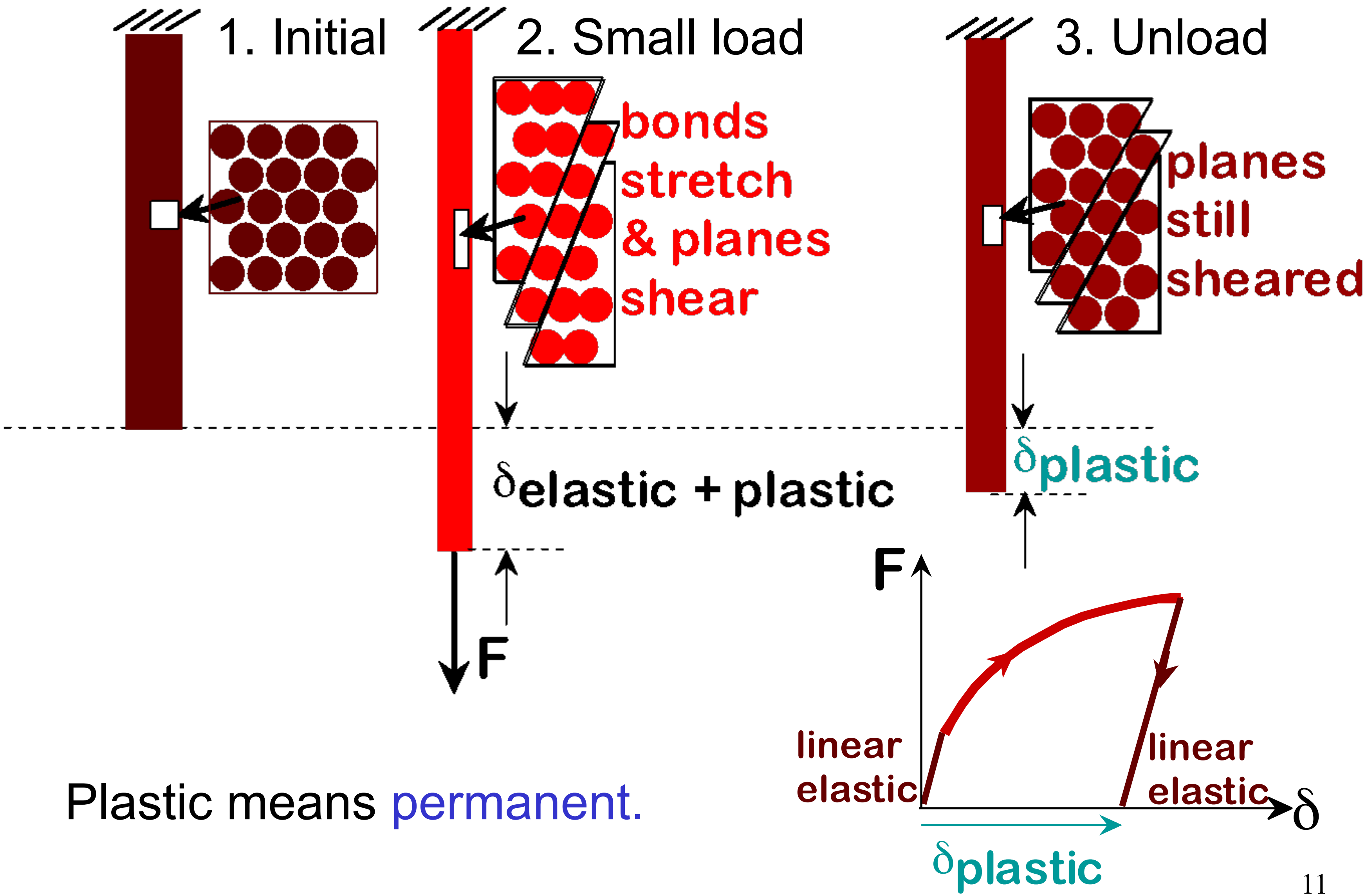
- Flow curve based on true stress and true strain

Elastic Deformation



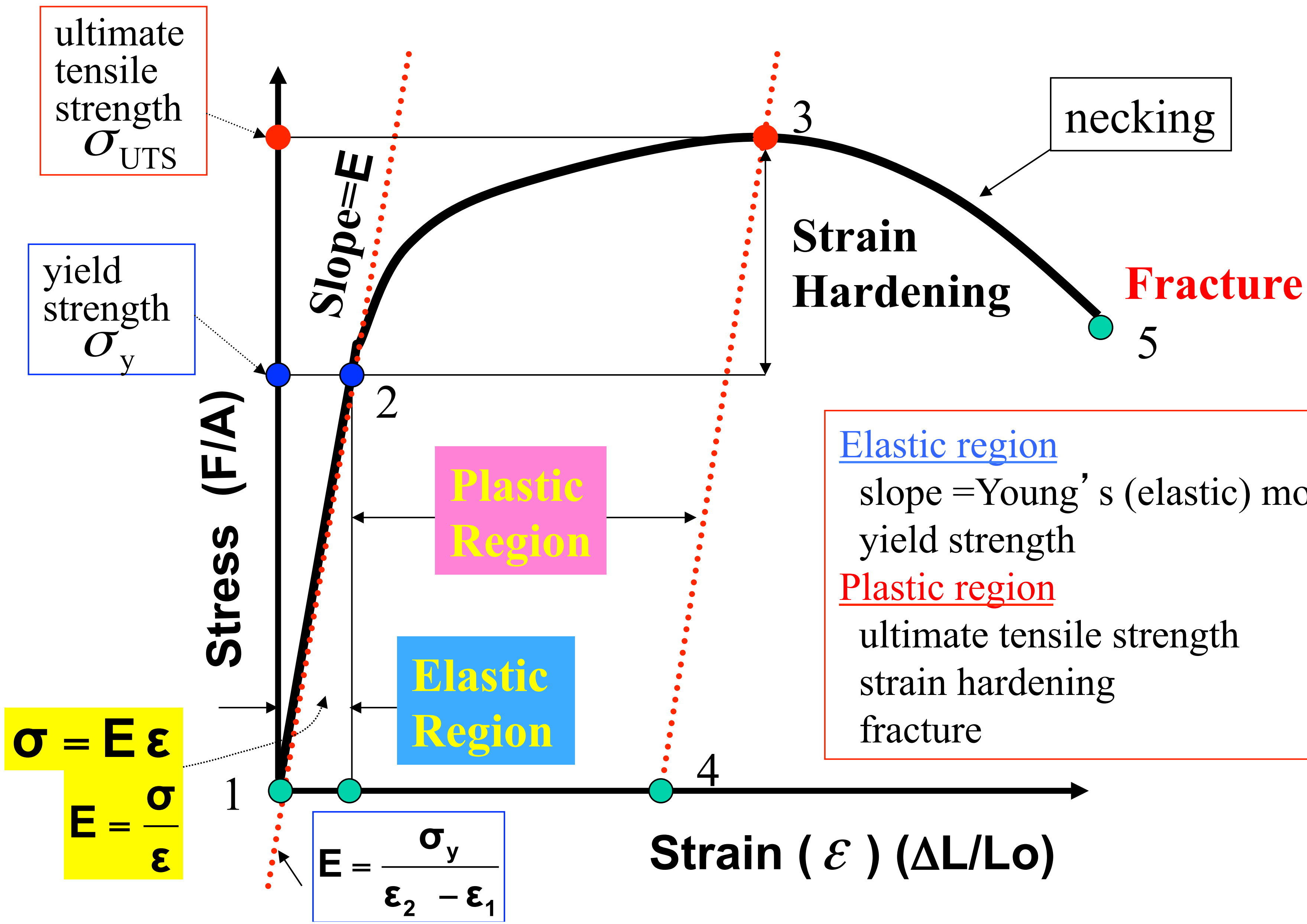
Elastic means reversible.

Plastic Deformation (Metals)



Plastic means permanent.

Stress-Strain Diagram

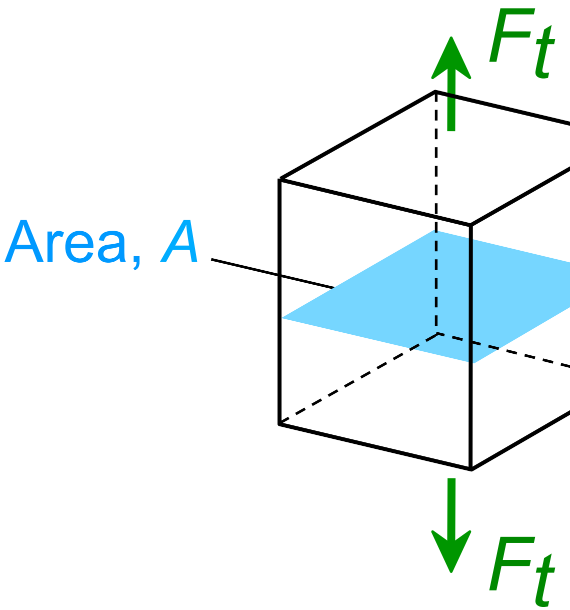


Elastic region
- slope =Young's (elastic) modulus
- yield strength

Plastic region
- ultimate tensile strength
- strain hardening
- fracture

Engineering Stress

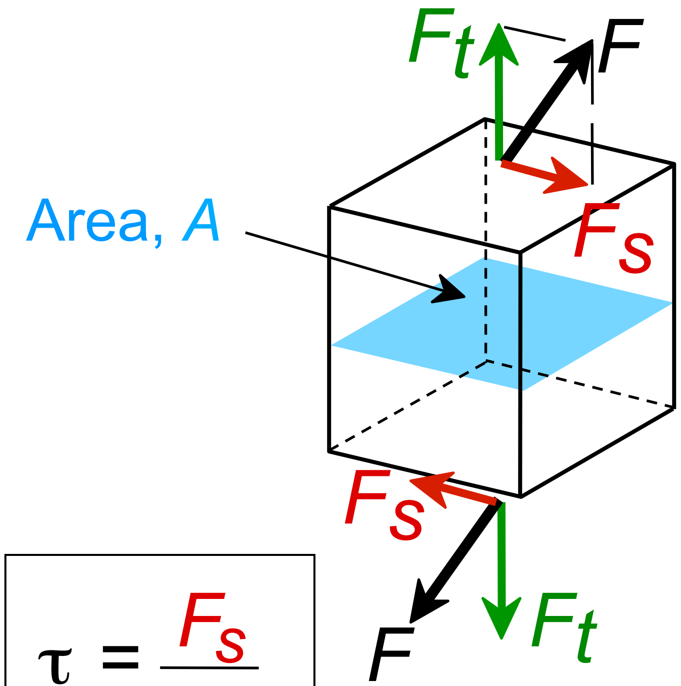
- Tensile stress, σ:



$$\sigma = \frac{F_t}{A_o} = \frac{\text{lb}_f}{\text{in}^2} \text{ or } \frac{\text{N}}{\text{m}^2}$$

original area
before loading

- Shear stress, τ:



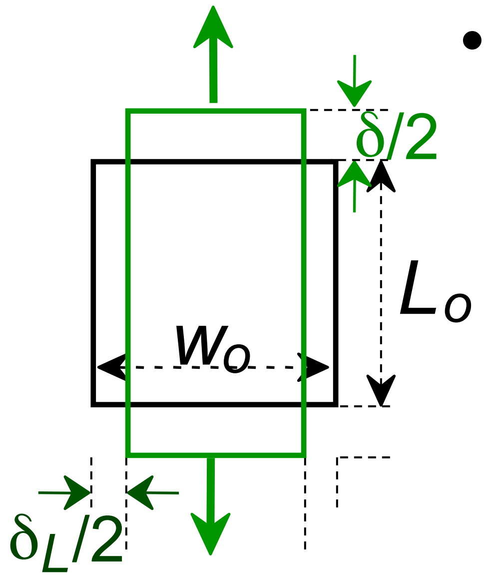
$$\tau = \frac{F_s}{A_o}$$

$\therefore$ Stress has units:
N/m^2 or lb_f/in^2

Engineering Strain

- **Tensile strain:**

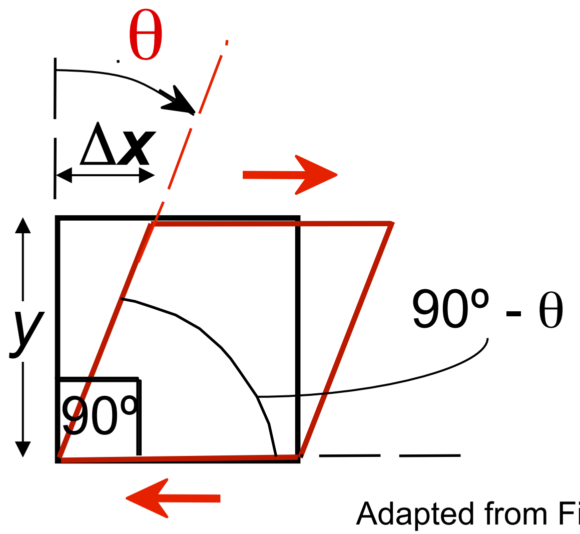
$$\varepsilon = \frac{\delta}{L_o}$$



- **Lateral strain:**

$$\varepsilon_L = \frac{-\delta_L}{w_o}$$

- **Shear strain:**



$$\gamma = \Delta x / y = \tan\theta$$

Strain is always dimensionless.

Adapted from Fig. 6.1 (a) and (c), *Callister 7e.*

Example 1

Tensile Testing of Aluminum Alloy

Convert the change in length data in the table to engineering stress and strain and plot a stress-strain curve.

The results of a tensile test of a 0.505-in. diameter aluminum alloy test bar, initial length (l_0) = 2 in.

Load (lb)	Measured Change in Length (Δl) (in.)	Calculated Stress (psi)	Calculated Strain (in./in.)
0	0.000	0	0
1000	0.001	5,000	0.0005
3000	0.003	15,000	0.0015
5000	0.005	25,000	0.0025
7000	0.007	35,000	0.0035
7500	0.030	37,500	0.0150
7900	0.080	39,500	0.0400
8000 (maximum load)	0.120	40,000	0.0600
7950	0.160	39,700	0.0800
7600 (fracture)	0.205	38,000	0.1025

Example 1 SOLUTION

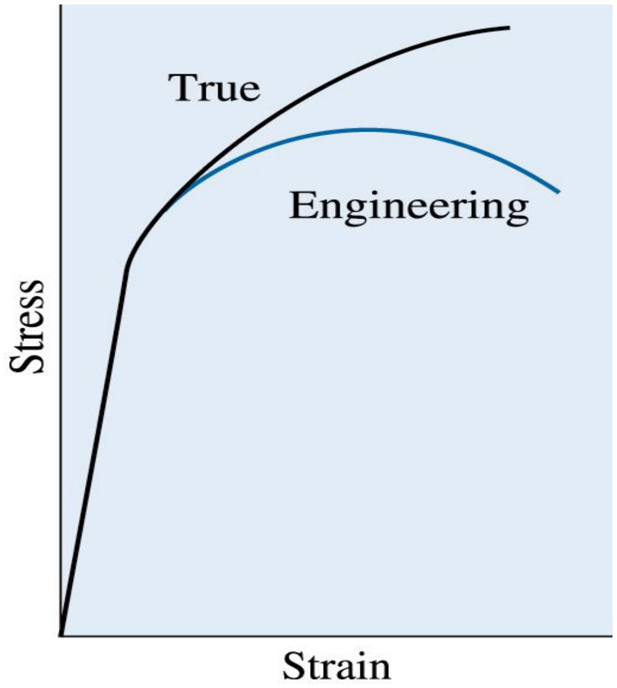
For the 1000-lb load:

$$\sigma = \frac{F}{A_0} = \frac{1000 \text{ lb}}{(\pi/4)(0.505 \text{ in.})^2} = \frac{1000 \text{ lb}}{0.2 \text{ in.}^2} = 5000 \text{ psi}$$

$$\varepsilon = \frac{\Delta l}{l_0} = \frac{0.001 \text{ in.}}{2.000 \text{ in.}} = 0.0005 \text{ in./in.}$$

True Stress and True Strain

- True stress The load divided by the actual cross-sectional area of the specimen at that load.
- True strain The strain calculated using actual and not original dimensions, given by ε_t ln(l/l_0).



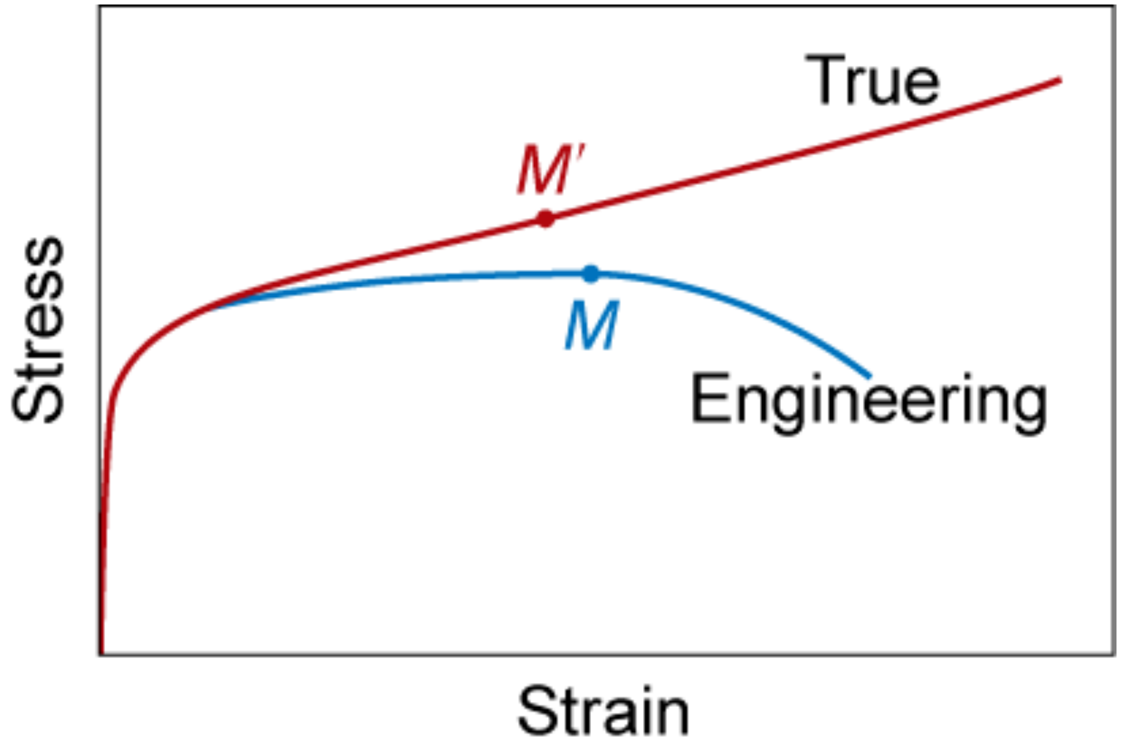
•The relation between the true stress-true strain diagram and engineering stress-engineering strain diagram.
•The curves are identical to the yield point.

True Stress & Strain

Note: S.A. changes when sample stretched

- True stress $\sigma_T = F/A_i$
- True Strain $\varepsilon_T = \ln(\ell_i/\ell_o)$

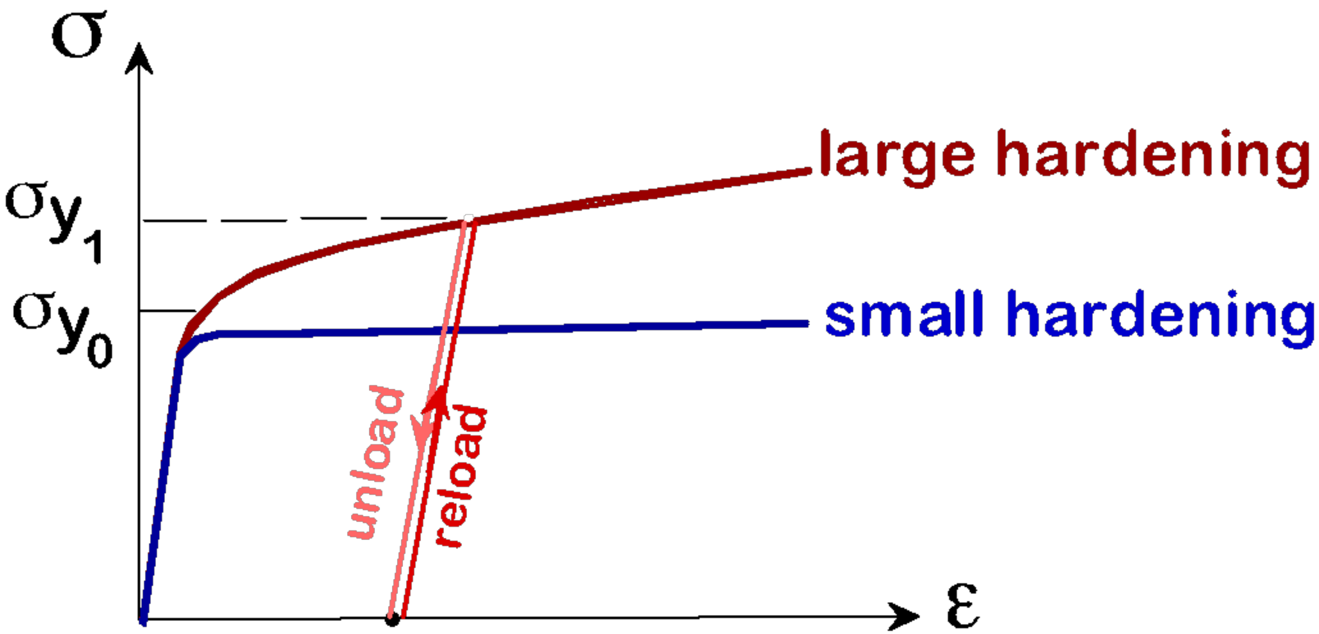
$$\boxed{\begin{aligned}\sigma_T &= \sigma(1+\varepsilon)\\ \varepsilon_T &= \ln(1+\varepsilon)\end{aligned}}$$



Adapted from Fig. 6.16, *Callister 7e.*

Hardening

HARDENING: **An increase in σ_y due to plastic deformation.**



- **Curve fit to the stress-strain response:**

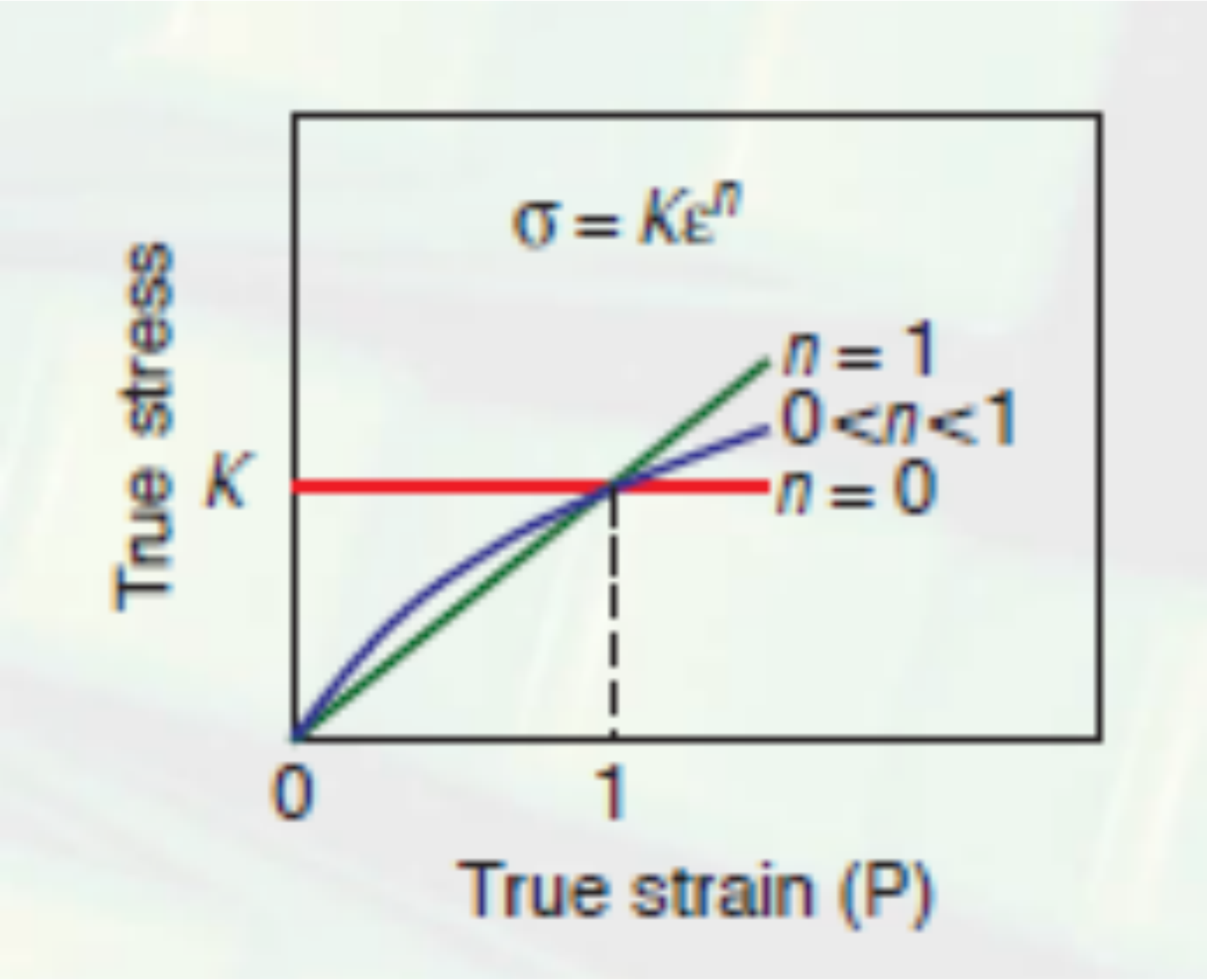
$$\sigma_T = K\varepsilon_T^n$$

n = hardening exponent
n = 0.15 (some steels)
n = 0.5 (some copper)

Table 7.4 Tabulation of *n* and *K* Values (Equation 7.19) for Several Alloys

		K	
Material	*n*	*MPa*	*psi*
Low-carbon steel (annealed)	0.21	600	87,000
4340 steel alloy (tempered @ 315°C)	0.12	2650	385,000
304 stainless steel (annealed)	0.44	1400	205,000
Copper (annealed)	0.44	530	76,500
Naval brass (annealed)	0.21	585	85,000
2024 aluminum alloy (heat treated—T3)	0.17	780	113,000
AZ-31B magnesium alloy (annealed)	0.16	450	66,000

Idealized stress strain curves



Flow Stress

- For most metals at room temperature, strength increases when deformed due to strain hardening
- *Flow stress* = instantaneous value of stress required to continue deforming the material

$$Y_f = K\varepsilon^n$$

where Y_f = flow stress, that is, the yield strength as a function of strain

Average Flow Stress

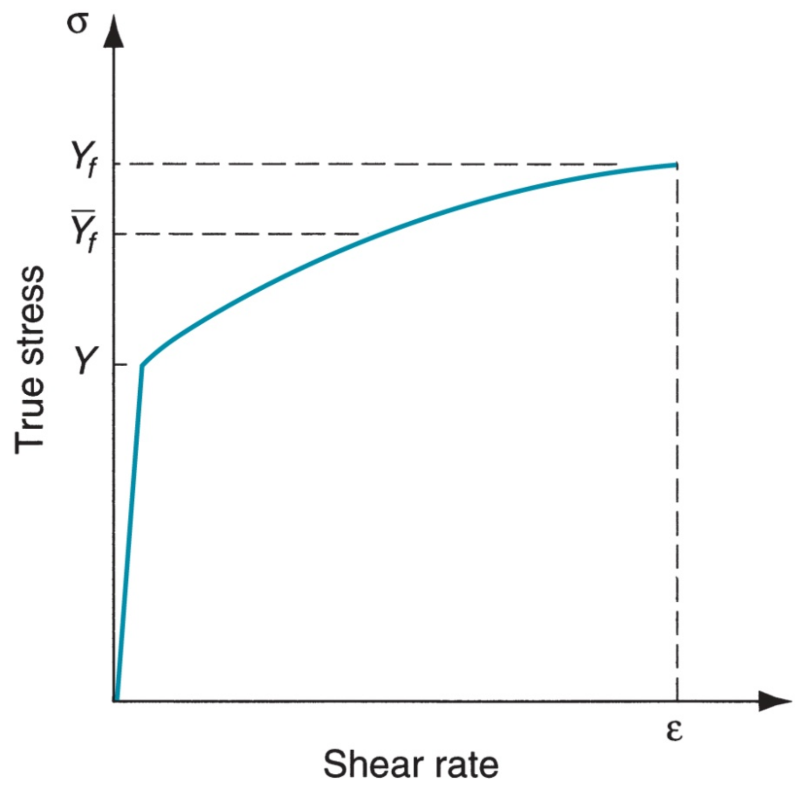
- Determined by integrating the flow curve equation between zero and the final strain value defining the range of interest

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

where $\bar{Y}_f$ = average flow stress; and ε = maximum strain during deformation process

Stress-Strain Relationship

- Average flow stress $\overline{Y}_f$ in relation to
  - Flow stress Y_f
  - Yield strength Y



Example 1

Question: The strength coefficient = 550 MPa and strain-hardening exponent = 0.22 for a certain metal. During a forming operation, the final true strain that the metal experiences = 0.85. Determine the flow stress at this strain and the average flow stress that the metal experienced during the operation.

Solution: Flow stress $Y_f = 550(0.85)_{0.22} =$ ***531 MPa.***
Average flow stress $\bar{Y}_f = 550(0.85)_{0.22}/1.22 =$ ***435 MPa***

Example 2

Question: Determine the value of the strain-hardening exponent for a metal that will cause the average flow stress to be 3/4 of the final flow stress after deformation

Solution: n = 0.333

Example 3

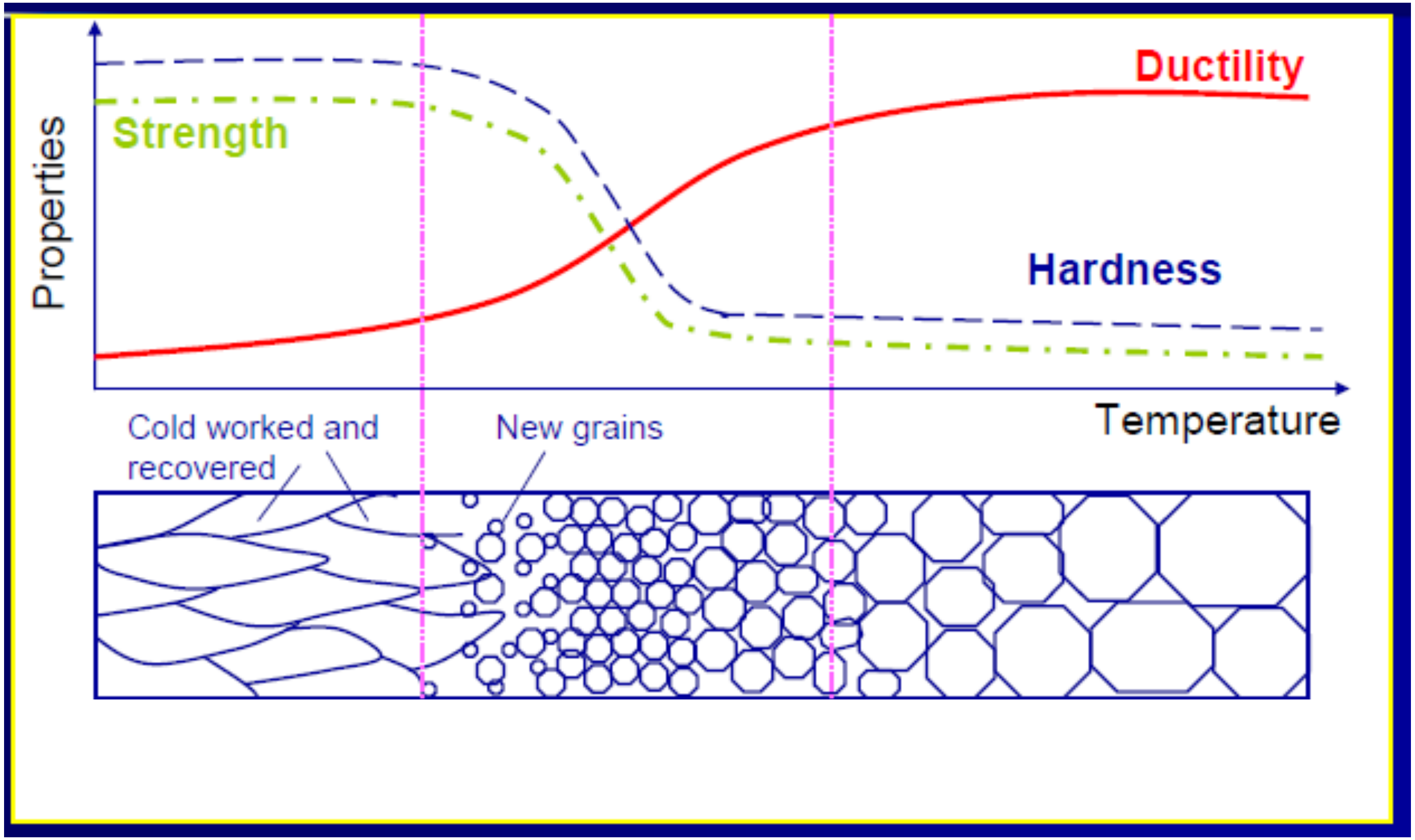
Question: In a tensile test, two pairs of values of stress and strain were measured for the specimen metal after it had yielded: (1) True stress = 217 MPa and true strain = 0.35, and (2) true stress = 259 MPa and true strain = 0.68. Based on these data points, determine the strength coefficient and strain-hardening exponent.

Solution: n = 0.2664 and K = 287 MPa

Temperature in Metal Forming

- For any metal, *K* and *n* in the flow curve depend on temperature
  - Both strength (*K*) and strain hardening (*n*) are reduced at higher temperatures
  - In addition, ductility is increased at higher temperatures

Temperature in Metal Forming



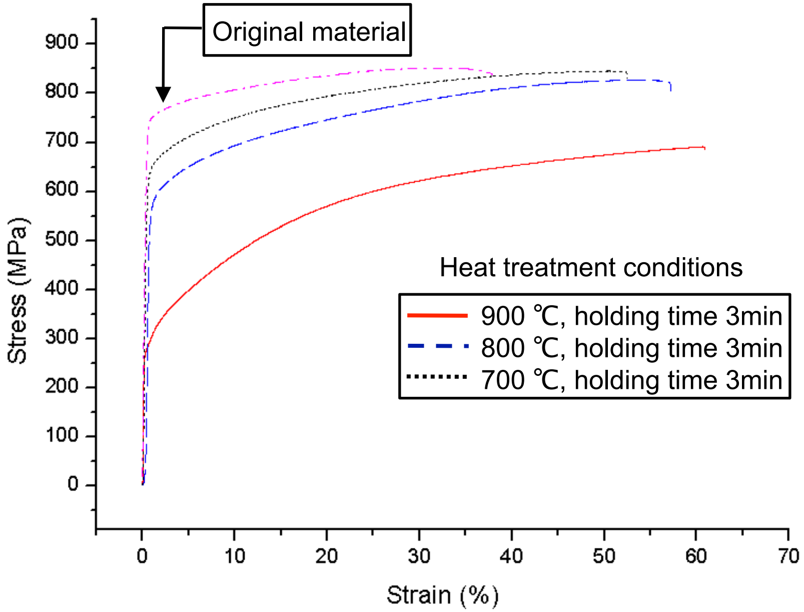
Temperature in Metal Forming

- Any deformation operation can be accomplished with lower forces and power at elevated temperature
- Three temperature ranges in metal forming:
  - Cold working
  - Warm working
  - Hot working

Hot Working

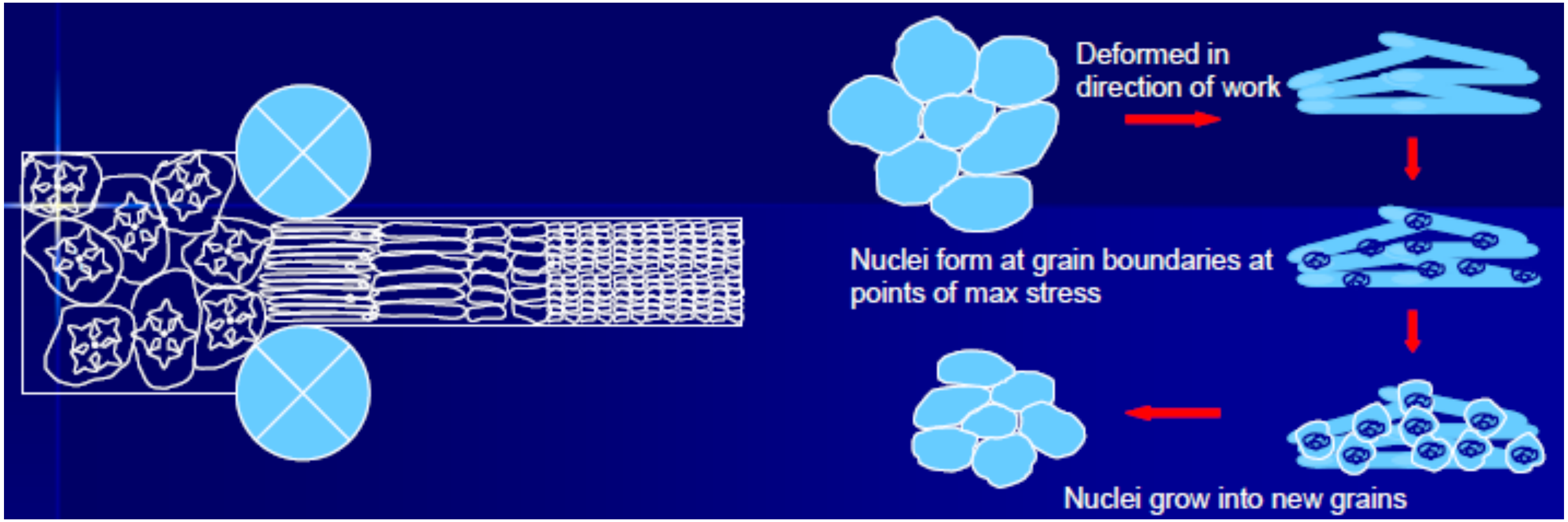
- Deformation at temperatures above the *recrystallization temperature*
  - Recrystallization temperature = about one-half of melting point on absolute scale
    - In practice, hot working usually performed somewhat above $0.5T_m$
    - Metal continues to soften as temperature increases above $0.5T_m$, enhancing advantage of hot working above this level

Effect of annealing
(In case of sheet metal)



Material		Y.S (MPa)	T.S (MPa)	El (%)	Hardness (Hv)
STS 304-1/2H	Original material	651.4	851.8	38.4	270.07
	700℃	618.5	845.7	52.5	258.76
	800℃	552.5	827.3	57.2	237.32
	900℃	272.1	691.3	60.9	155.08

Hot Working (Recrystallization)



Why Hot Working?

Capability for substantial plastic deformation - far more than is possible with cold working or warm working

- Why?
  - Strength coefficient (*K*) is substantially less than at room temperature
  - Strain hardening exponent (*n*) is zero (theoretically)
  - Ductility is significantly increased

Strain Rate Sensitivity

- Theoretically, a metal in hot working behaves like a perfectly plastic material, with strain hardening exponent *n* = 0
  - The metal should continue to flow at the same flow stress, once that stress is reached
  - However, an additional phenomenon occurs during deformation, especially at elevated temperatures:
    - Strain rate sensitivity

What is Strain Rate?

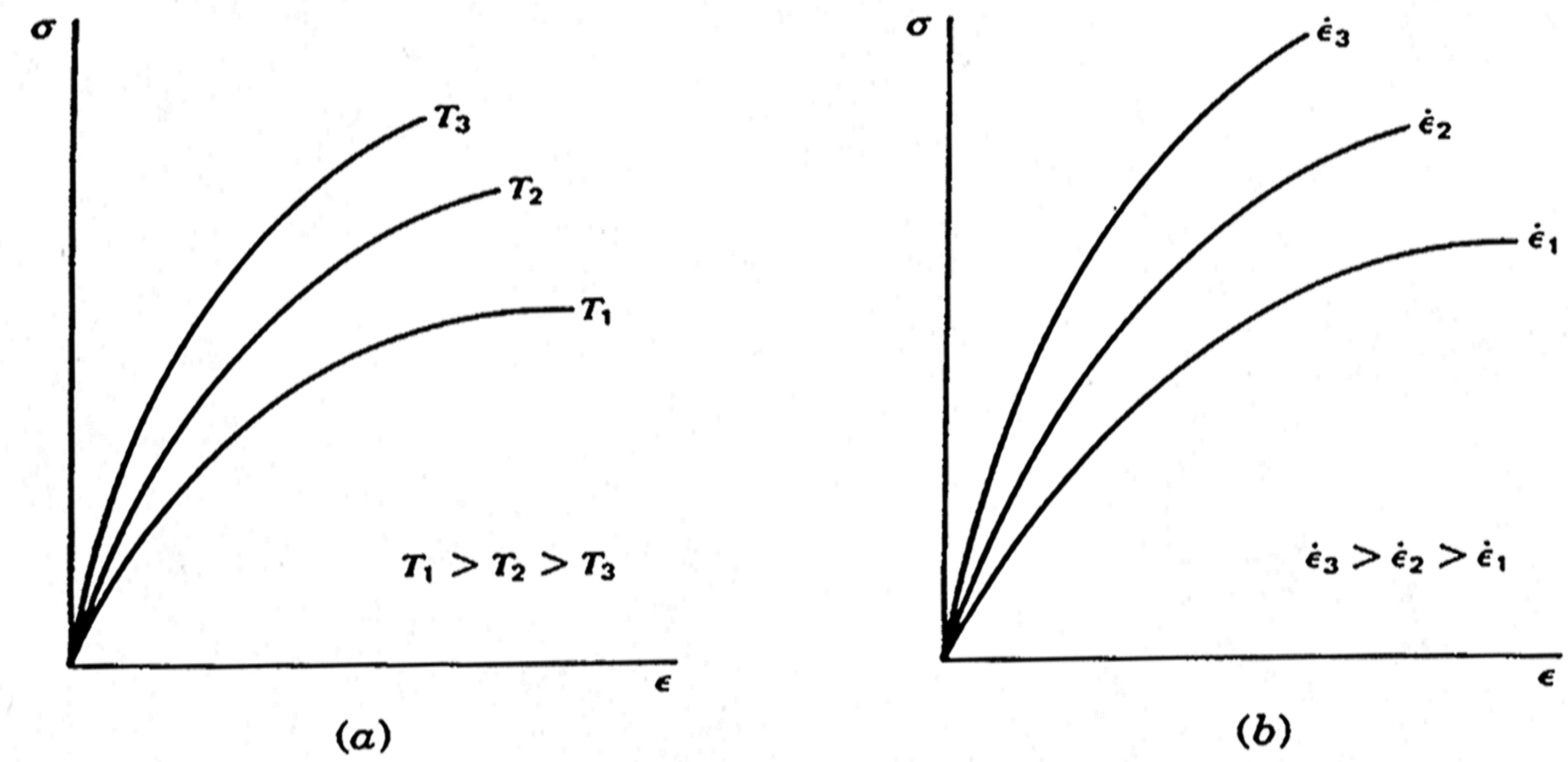
- Strain rate in forming is directly related to speed of deformation *v*
- Deformation speed *v* = velocity of the ram or other movement of the equipment
- *Strain rate* is defined:

$$\dot{\varepsilon} = \frac{v}{h}$$

where $\dot{\varepsilon}$ = true strain rate; and *h* = instantaneous height of workpiece being deformed

Effect of Strain Rate on Flow Stress

- Flow stress is a function of temperature
- At hot working temperatures, flow stress also depends on strain rate
  - As strain rate increases, resistance to deformation increases
  - This is the effect known as strain-rate sensitivity



Yield strength changes as a function of (a) temperature and (b) strain rate

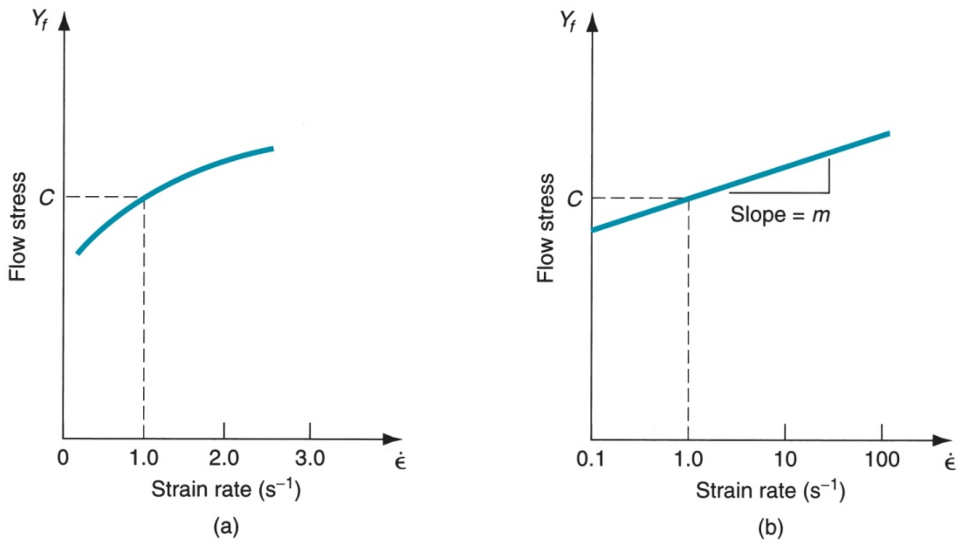
Strain Rate Sensitivity Equation

$$Y_f = C\dot{\varepsilon}^m$$

where *C* = strength constant (analogous but not equal to strength coefficient in flow curve equation), and *m* = strain-rate sensitivity exponent

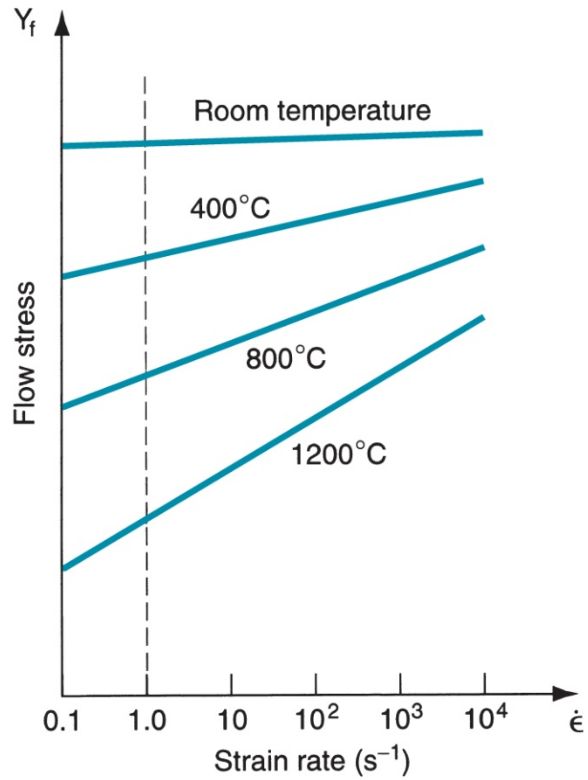
Strain Rate Sensitivity

- (a) Effect of strain rate on flow stress at an elevated work temperature
- (b) Same relationship plotted on log-log coordinates



Effect of Temperature on Flow Stress

- The constant *C*, indicated by the intersection of each plot with the vertical dashed line at strain rate = 1.0, decreases
- And *m* (slope of each plot) increases with increasing temperature



Observations about Strain Rate Sensitivity

- Increasing temperature decreases *C* and increases *m*
  - At room temperature, effect of strain rate is almost negligible
    - Flow curve alone is a good representation of material behavior
  - As temperature increases
    - Strain rate becomes increasingly important in determining flow stress

Friction in Metal Forming

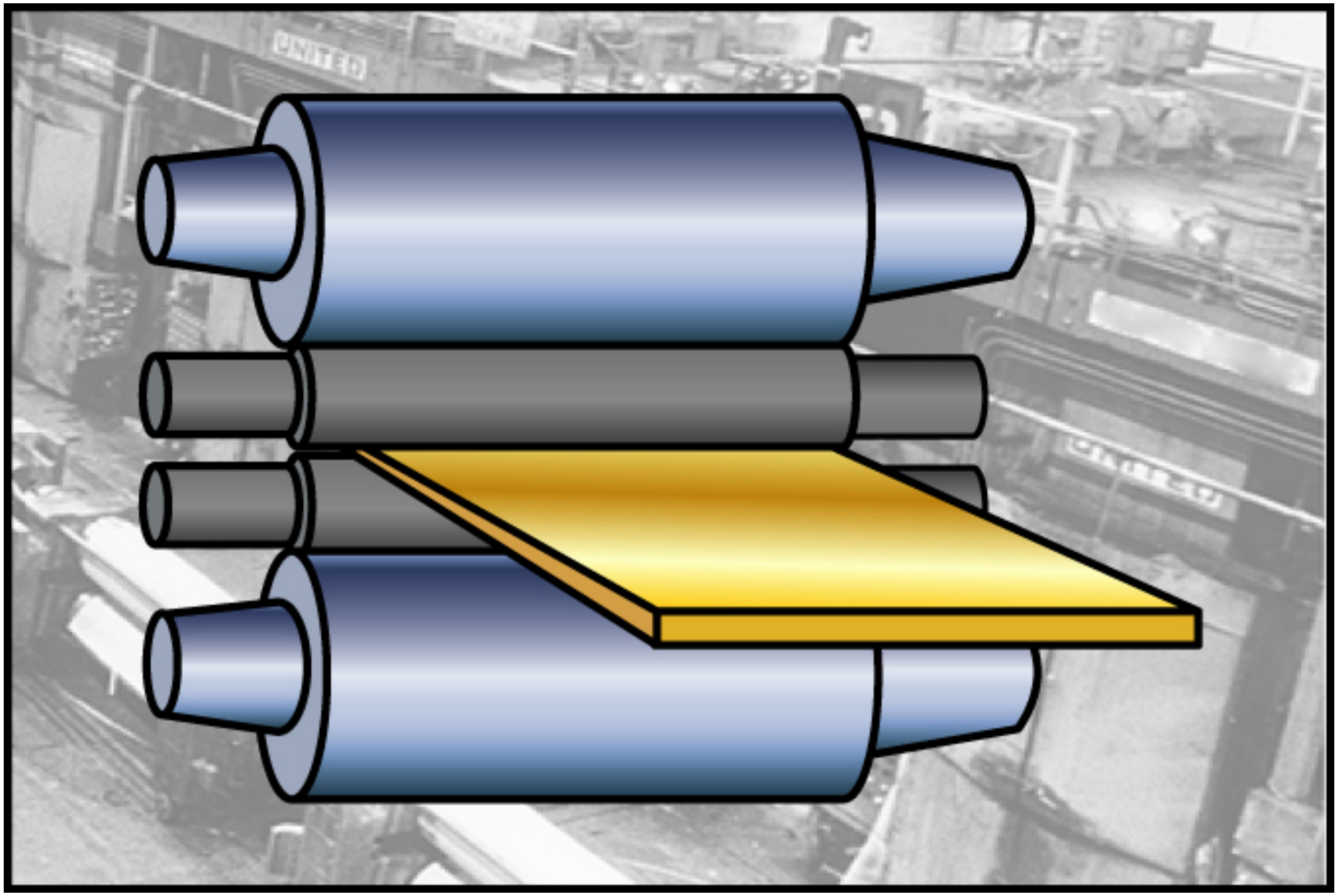
- In most metal forming processes, friction is undesirable:
  - Metal flow is reduced
  - Forces and power are increased
  - Tools wear faster
- Friction and tool wear are more severe in hot working

Friction in Metal Forming

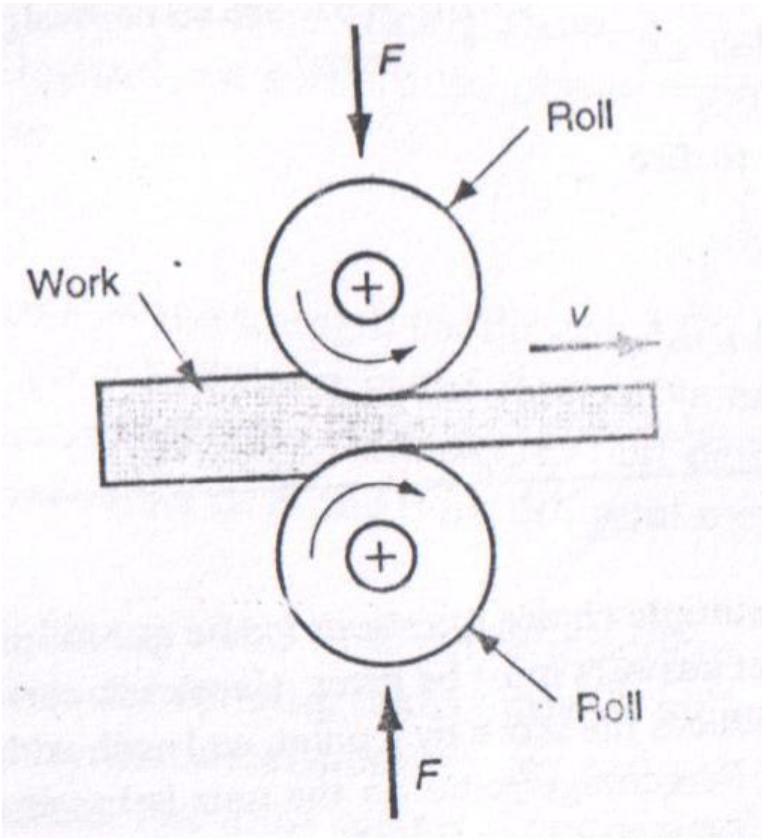
- Friction is undesirable:
  - retard metal flow causing residual stress
  - increase forces and power
  - rapid wear of tooling
- Lubrication is used to reduce friction at the

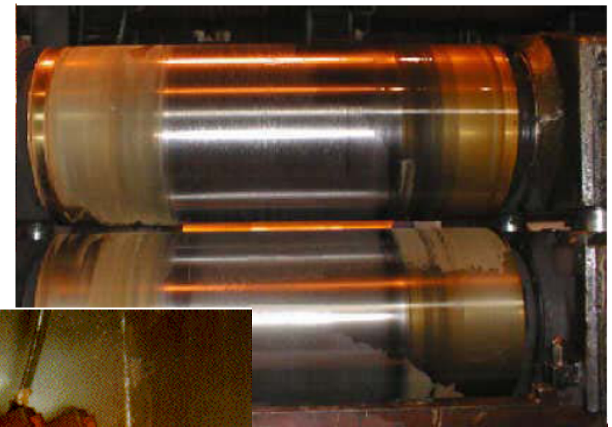
Category	Temperature range	Strain-rate sensitivity exponent	Coefficient of friction
Cold working	$\leq 0.3T_m$	$0 \leq m \leq 0.05$	0.1
Warm working	$0.3T_m - 0.5T_m$	$0.05 \leq m \leq 0.1$	0.2
Hot working	$0.5T_m - 0.75T_m$	$0.05 \leq m \leq 0.4$	0.4–0.5

Rolling Processes



Rolling





- About 75% of steel output is treated in rolling mill and about 25% is consumed for forging, extrusion etc.
- Both hot rolling & cold rolling

Introduction to Rolling

Rolling is a bulk 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 work between them.

- Developed in late 1500s
- Accounts for 75 to 90% of all metals produced by metal working processes
- Often carried out at elevated temperatures first (hot rolling) to change coarse-grained, brittle, and porous ingot structures to wrought structures with finer grain sizes and enhanced properties

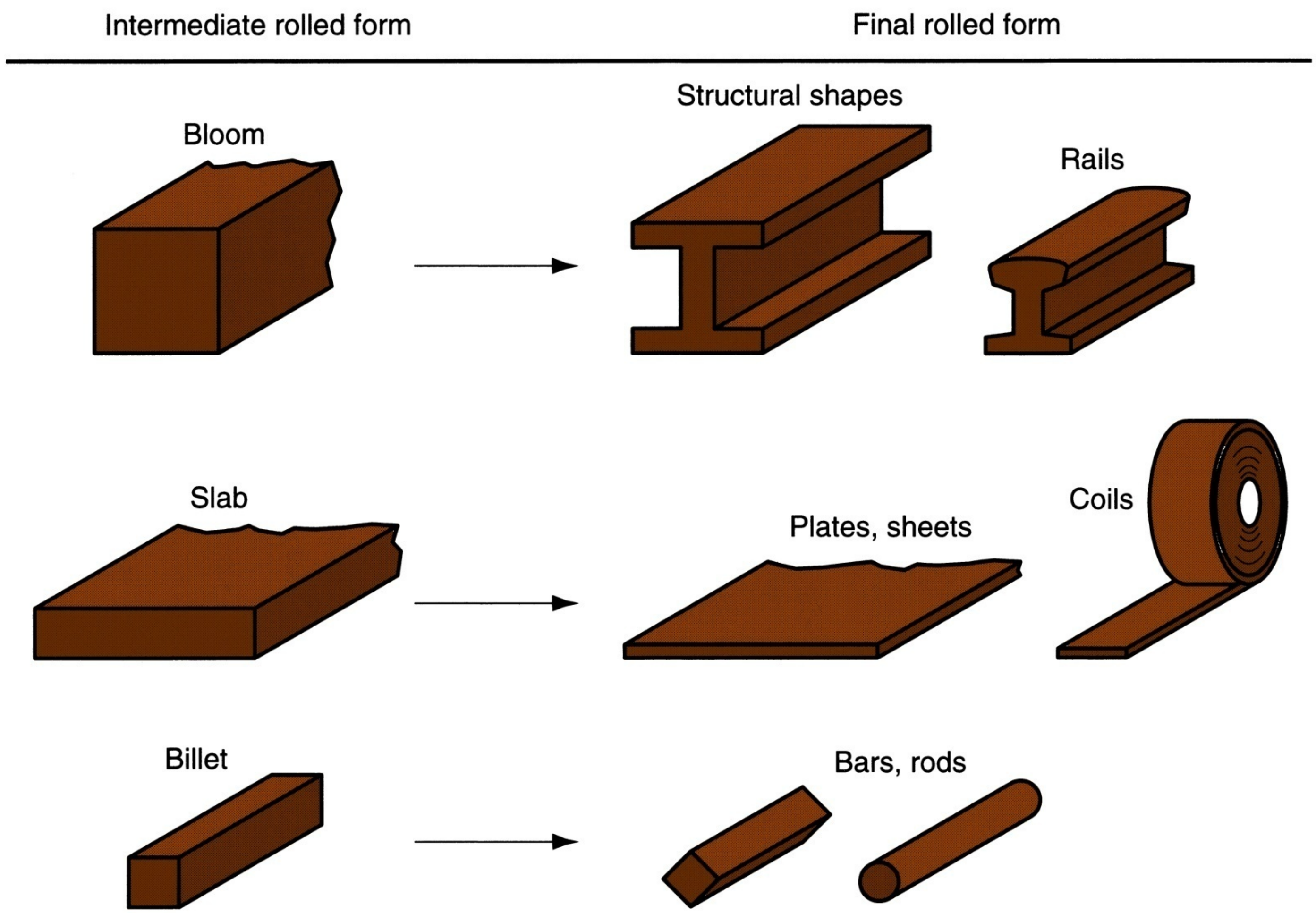
The Rolls

The rotating rolls perform two main functions:

- Pull the workpiece into the gap between them by friction between workpiece and rolls
- Simultaneously squeeze the workpiece to reduce cross section

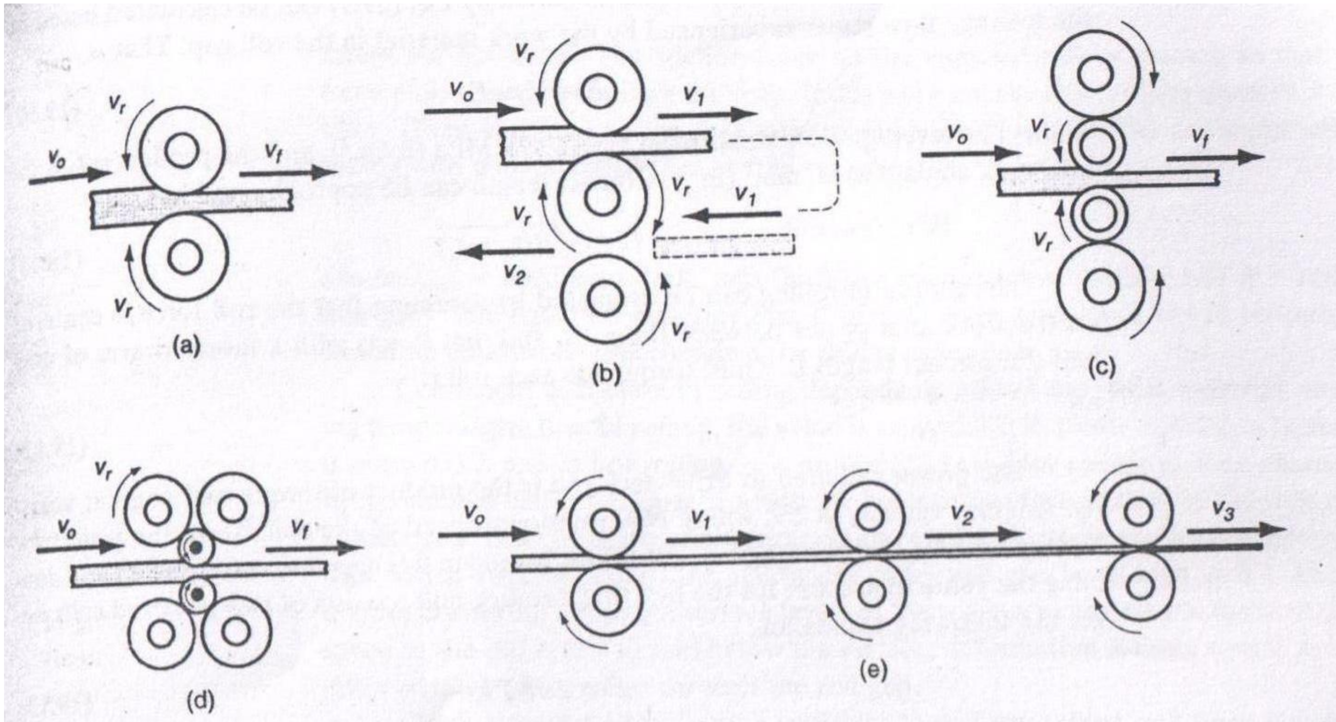
Types of Rolling

- By geometry of work:
  - *Flat rolling* - used to reduce thickness of a rectangular cross-section
  - *Shape rolling* - a square cross-section is formed into a shape such as an I-beam
- By temperature of work:
  - *Hot Rolling* – most common due to the large amount of deformation required
  - *Cold rolling* – produces finished sheet and plate stock



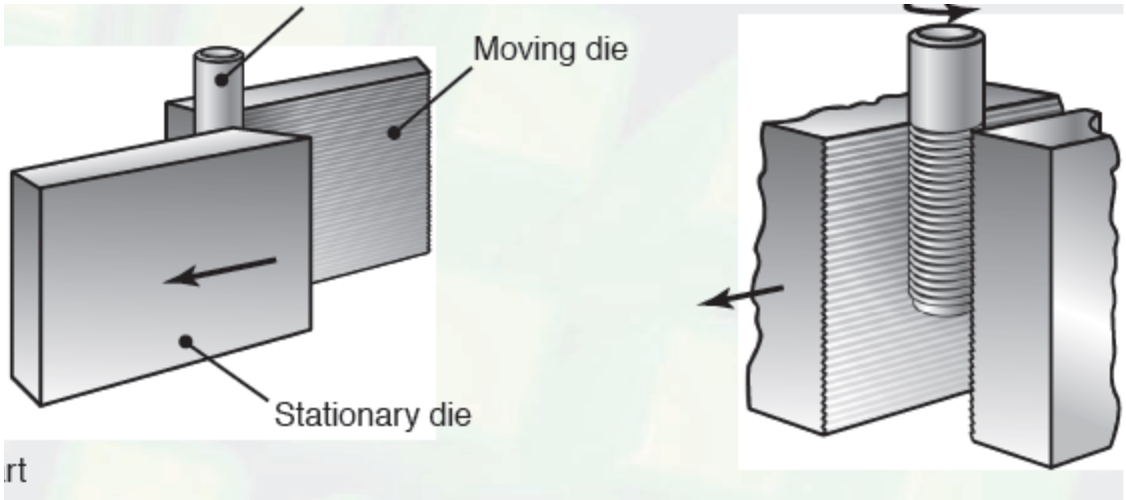
Some of the steel products made in a rolling mill

Rolling Mills

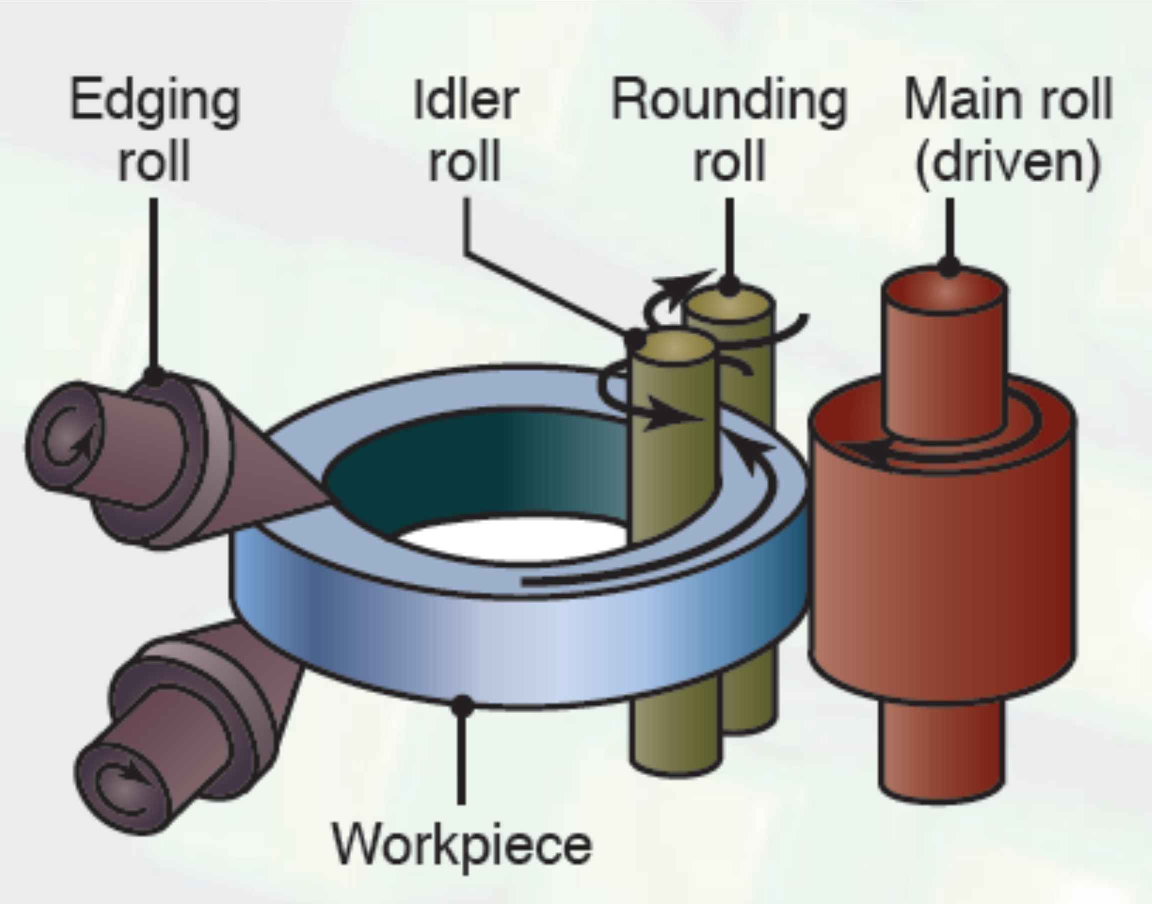


a. Two high mill
b. Three high mill
c. Four high mill
d. Cluster rolling mill
e. Tandem rolling mill

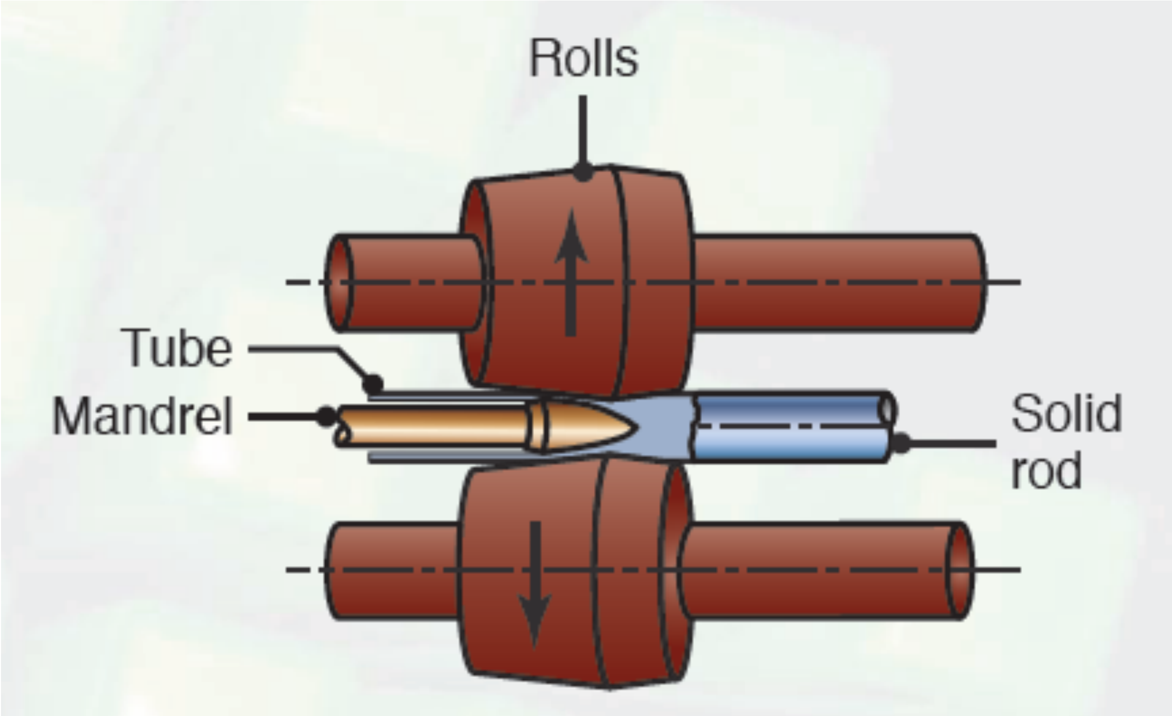
Thread rolling



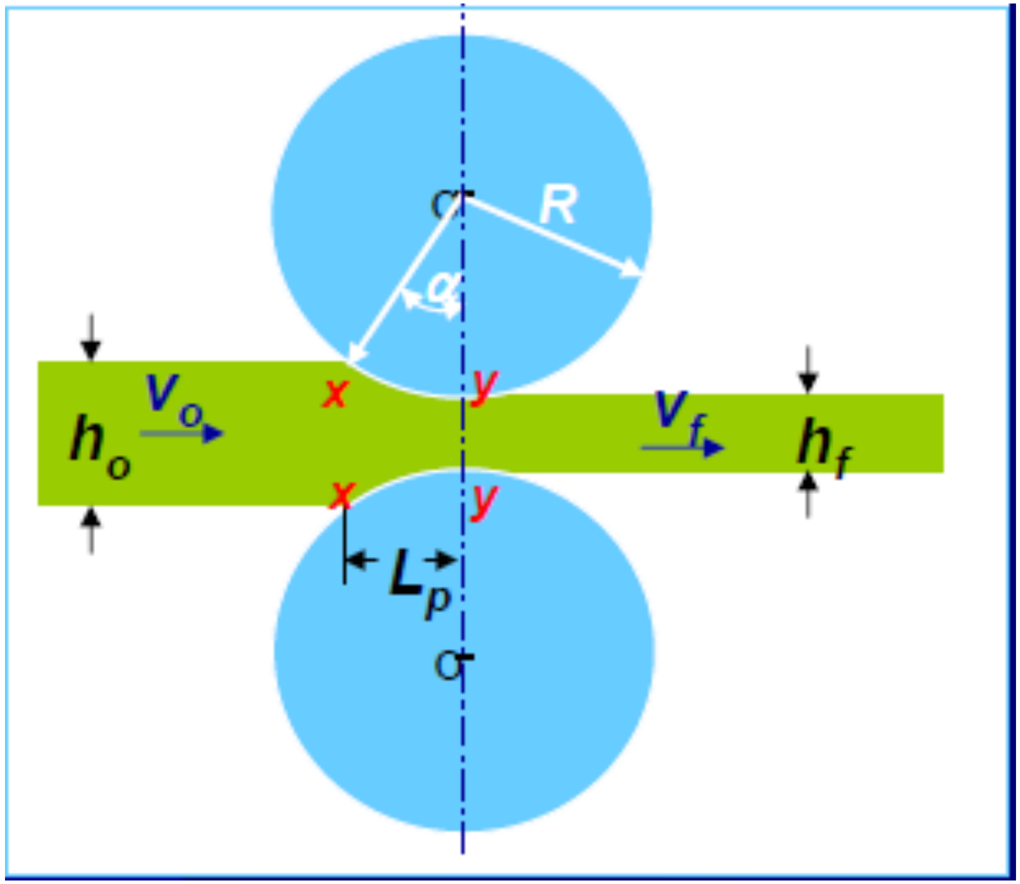
Ring rolling



Roll Piercing

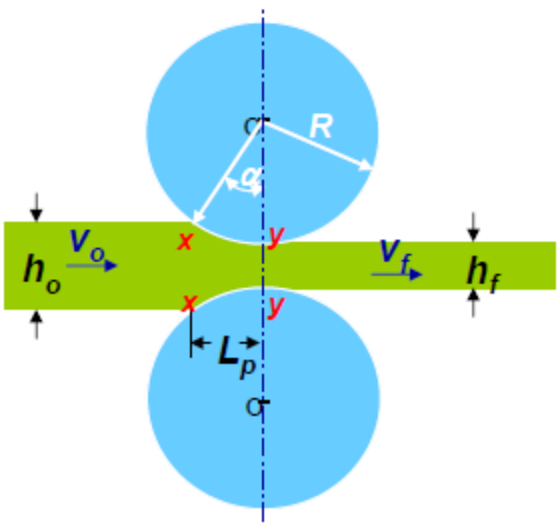


Mechanics of flat rolling



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

Fundamentals concepts of metal rolling



Assumptions

-Arc on contact is a part of circle

-Coefficient of friction, μ is constant

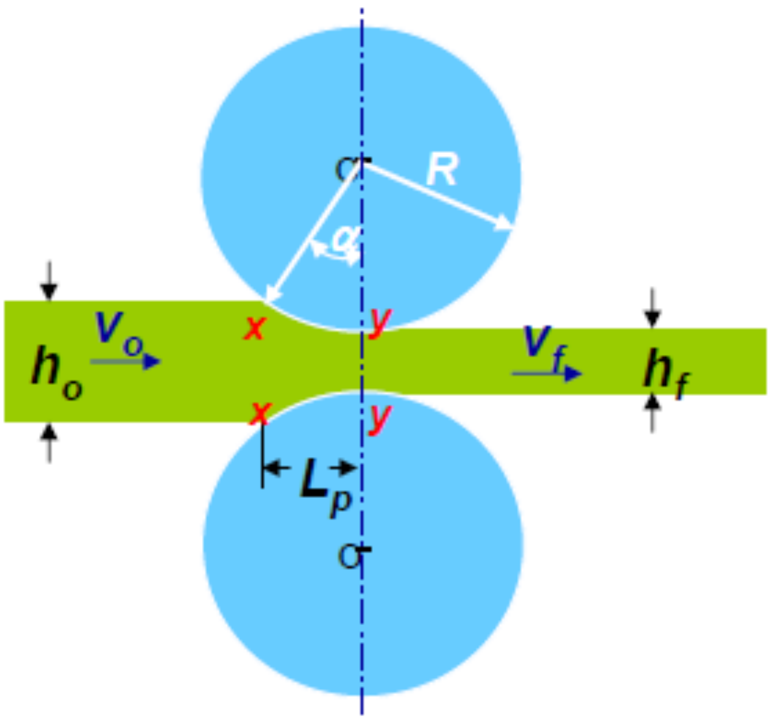
-Material deform plastically

-Volume of metal remains constant

-Velocity of rolls assumed to be constant

-No extension in the width

Fundamentals concepts of metal rolling

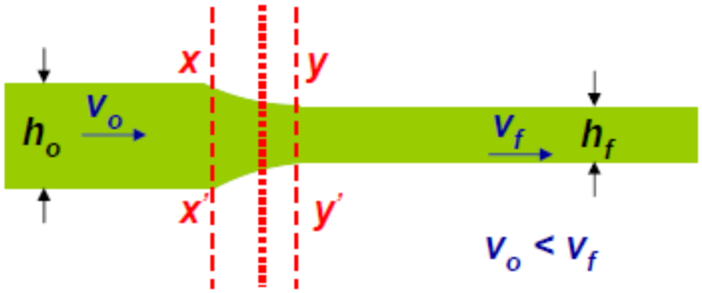


$$bh_o v_o = bhv = bh_f v_f$$

Where b is the width of the sheet

v is the velocity at any thickness h, intermediate between h_o and h_f

Fundamentals concepts of metal rolling



$$bh_o v_o = bh_f v_f$$

$$h_o v_o = h_f v_f$$

When $h_o > h_f$ then $v_o < v_f$

$$\frac{v_o}{v_f} = \frac{h_f}{h_o}$$

Fundamentals concepts of metal rolling

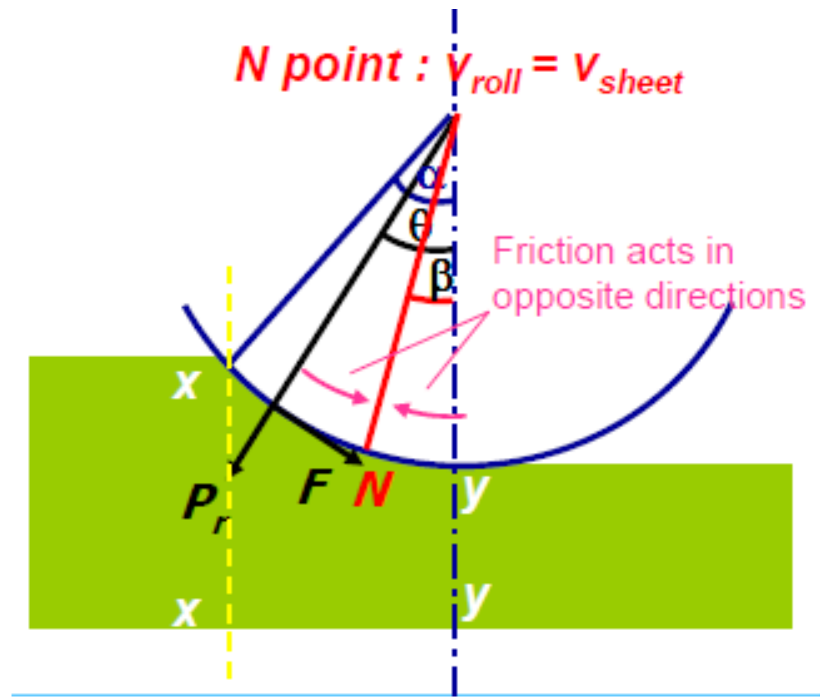
Radial force (P_r) and Tangential force (F)

Neutral point/No slip point (N): $V_{roll} = V_{sheet}$

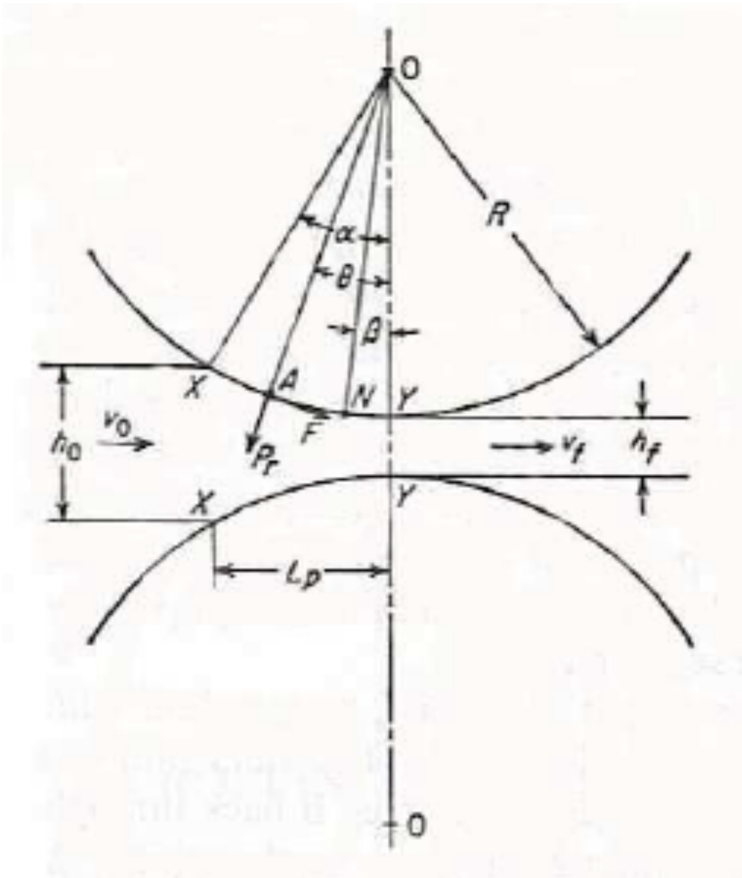
Tangential frictional force direction

Region 1: XX-N

Region 2: N-YY



Fundamentals concepts of metal rolling



Specific roll pressure

$$p = \frac{F}{bL_p}$$

p: Specific roll pressure

F: total force

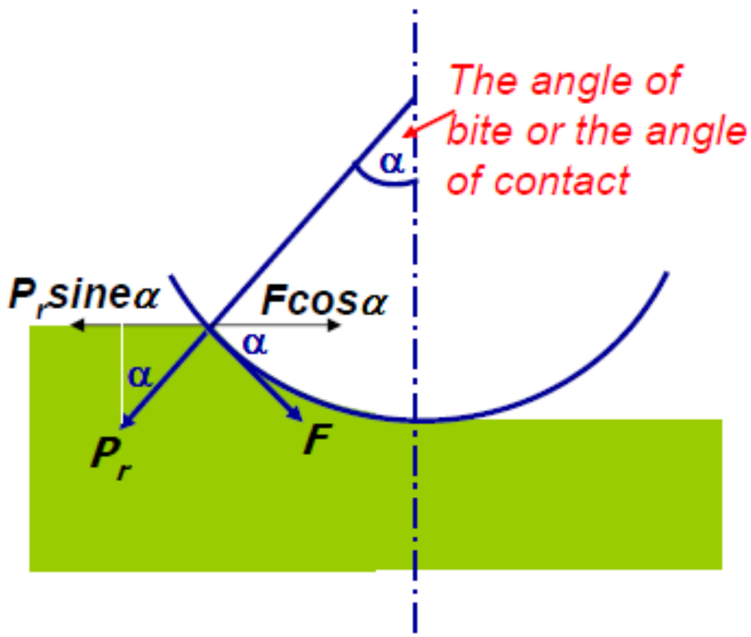
b: width

L_p: projected length of the arc of contact

$$Reduction(r) = \Delta h / h_o$$

Where, $L_p \approx \sqrt{R\Delta h}$

Roll bite condition



For the workpiece to enter inside the rolls

$$F\cos\alpha \geq P_R \sin\alpha$$

$$\frac{F}{P_R} \geq \frac{\sin\alpha}{\cos\alpha} \geq \tan\alpha$$

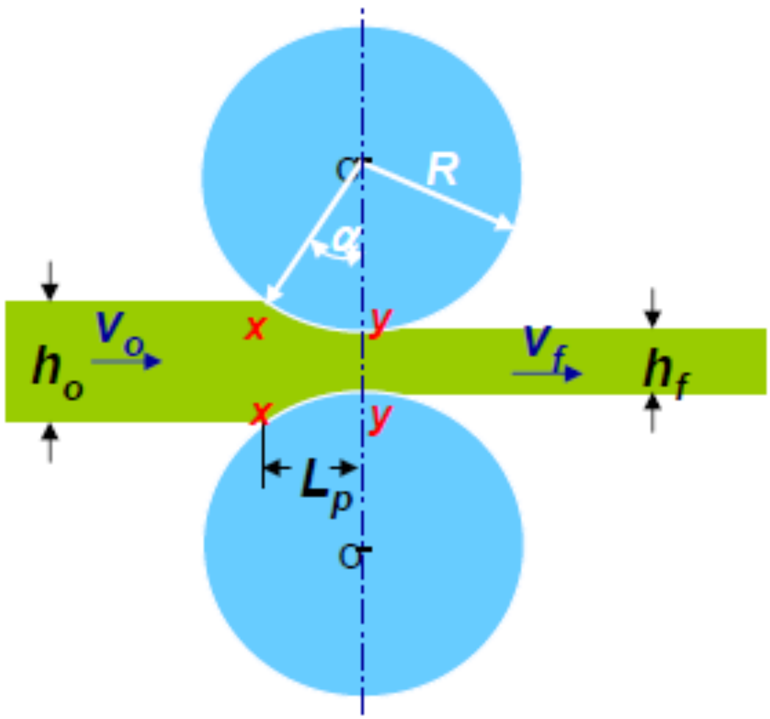
We know that $F = \mu P_R$

Therefore, $\mu = \tan\alpha$

If $\tan\alpha > \mu$, the workpiece cannot be drawn

If $\mu = 0$ rolling cannot occur

Maximum reduction



For the rolling to occur

$$F\cos\alpha \geq P_R \sin\alpha$$

$$\frac{F}{P_R} \geq \frac{\sin\alpha}{\cos\alpha} \geq \tan\alpha$$

$$\mu \geq \tan\alpha$$

$$(\Delta h)_{\max} = ?$$

$$(\Delta h)_{\max} = \mu^2 R$$

Example

Question: Determine the maximum possible reduction for cold rolling a 300 mm-thick slab when $\mu = 0.08$ and the roll diameter is 600 mm. What is the maximum reduction on the same mill for hot rolling when $\mu = 0.5$?

Answer:
Cold rolling = 1.92 mm
Hot rolling: 75 mm

Main variables in rolling

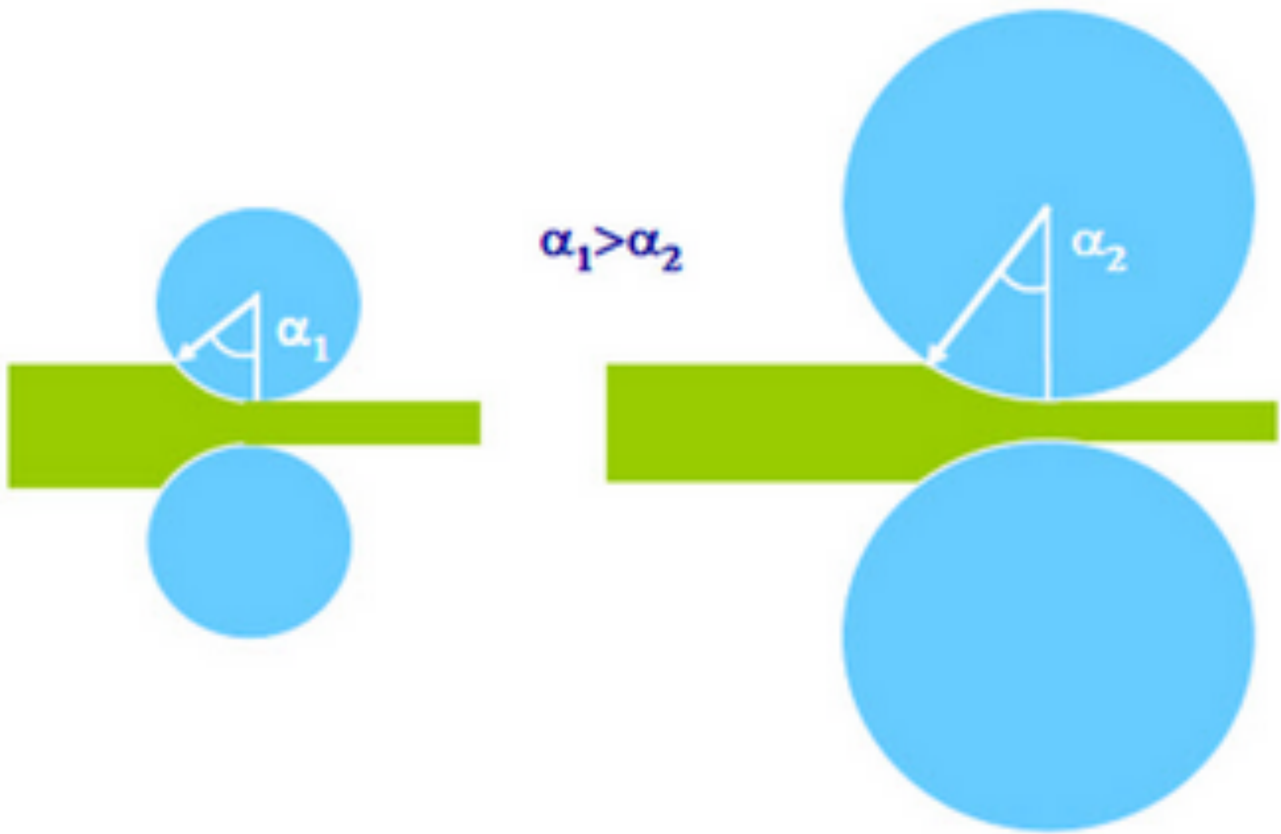
•The **roll diameter**.
Rolling load P increases with the roll radius

•The **reduction** (Δh) .
Rolling load also increases as the sheet entering the rolls gets thinner.

•The deformation resistance of the metal as influenced by the **metallurgy, temperature** and **strain rate**.

•The **friction** between the roll and work piece.

Main variables in rolling



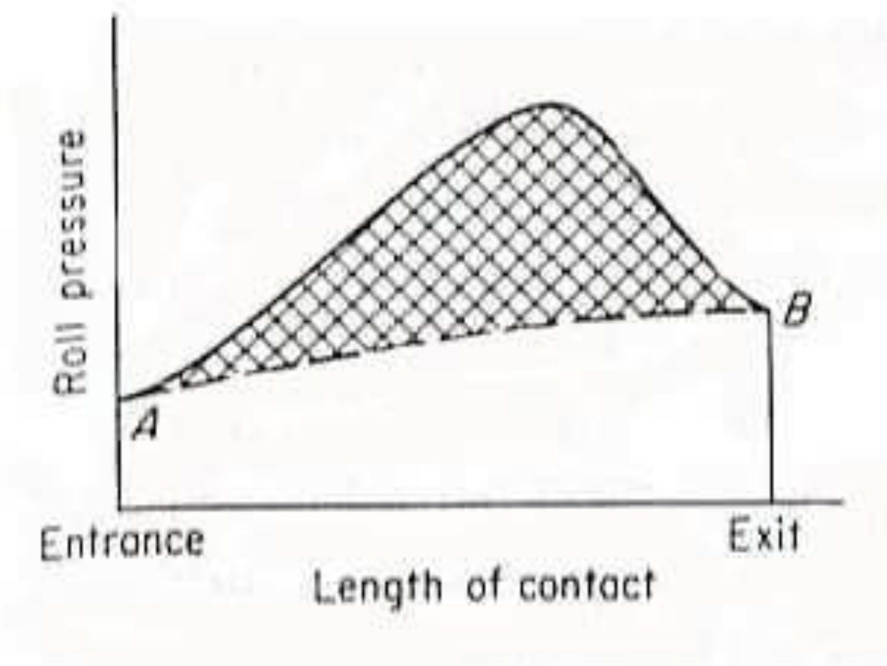
Main variables in rolling

Frictional force is needed to pull the metal into the rolls and responsible for a large portion of the rolling load.

High friction results in high rolling load, a steep friction hill and great tendency for edge cracking.

Cold rolling with lubricants, $\mu = 0.05\text{-}0.1$
Hot rolling with lubricants, $\mu = 0.4\text{-}0.7$ (sticking condition)
In sticking the hot wok surface adheres to roll and thus the central part of the strip undergoes with a severe deformation.

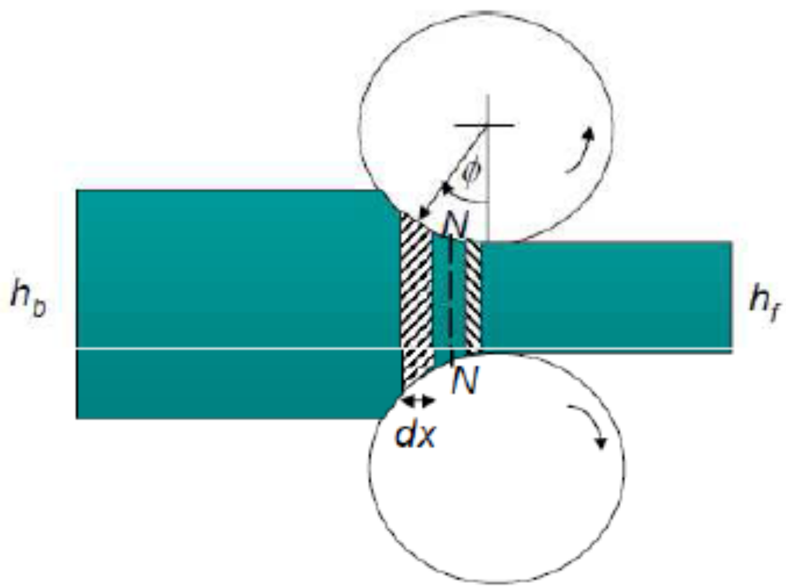
Main variables in rolling



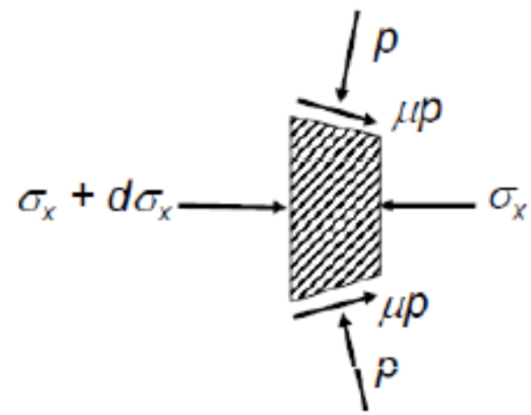
•The area in shade is the force required to overcome frictional forces.

•Area under the line AB represent force required for plastic deformation.

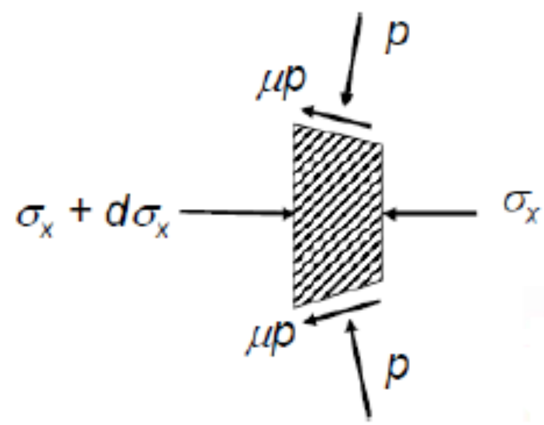
Flat rolling analysis



Stresses on slab in entry zone



Stresses on slab in exit zone



Flat rolling analysis

Simplifying and ignoring the HOTs

$$\frac{d(\sigma_x h)}{d\phi} = 2pR \cdot (\sin\phi \mp \mu\cos\phi)$$

Since $\alpha << 1$, then $\sin\phi = \phi$, $\cos\phi = 1$

$$\frac{d(\sigma_x h)}{d\phi} = 2pR \cdot (\phi \mp \mu)$$

Slab Method for Rolling

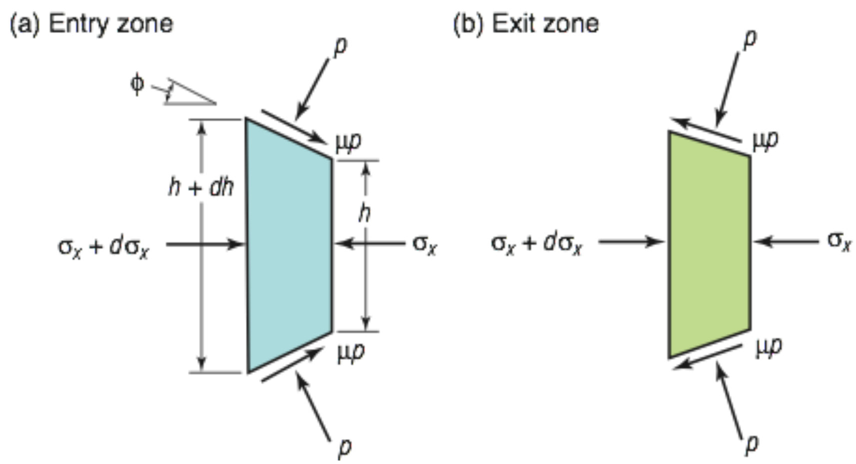


FIGURE 6.32 Stresses acting on an element in rolling: (a) entry zone and (b) exit zone.

Entry zone pressure:

$$p = Y_f' \frac{h}{h_0} e^{\mu(H_0 - H)}$$

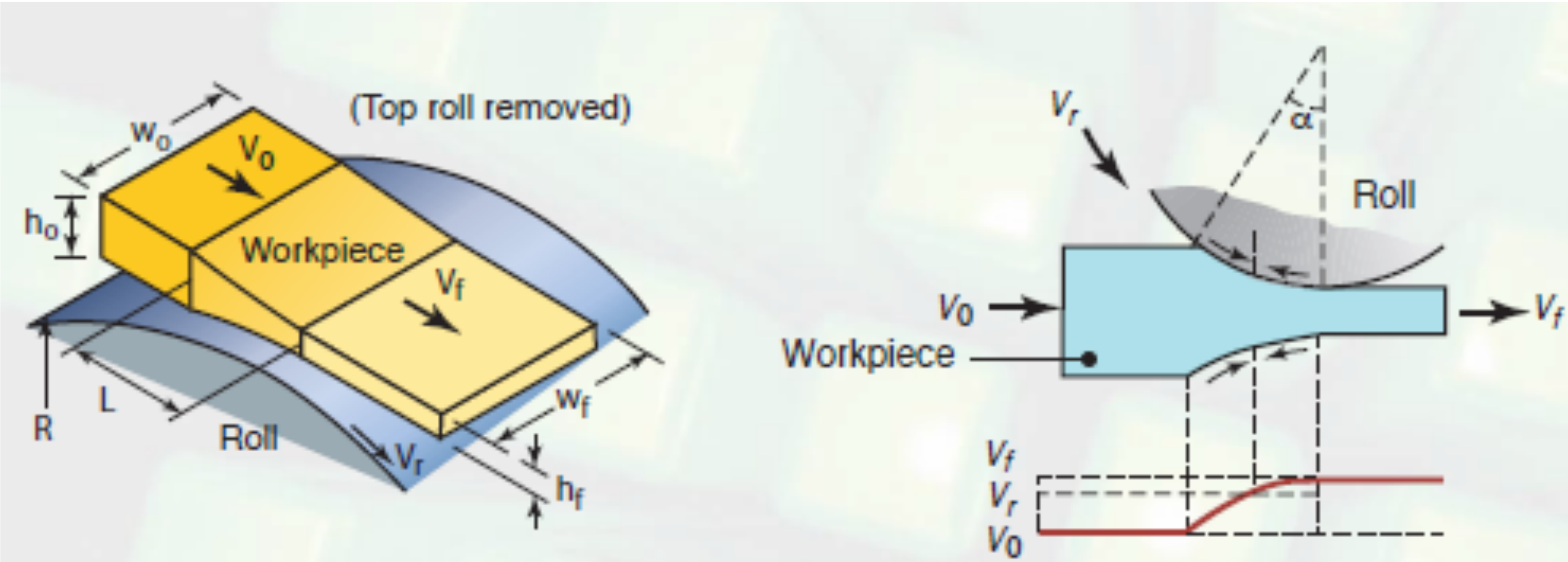
Exit zone pressure:

$$p = Y_f' \frac{h}{h_f} e^{\mu H}$$

where

$$H = 2\sqrt{\frac{R}{h_f}} \tan^{-1}\left(\sqrt{\frac{R}{h_f}}\phi\right)$$

Forward slip



Forward slip:

$$\text{Forward slip} = \frac{V_f - V_r}{V_r}$$

Pressure Distribution in Rolling

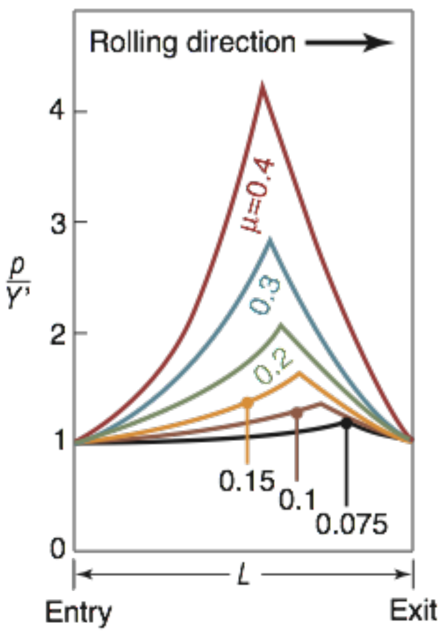


FIGURE 6.33 Pressure distribution in the roll gap as a function of the coefficient of friction. Note that as friction increases, the neutral point shifts toward the entry. Without friction, the rolls will slip, and the neutral point shifts completely to the exit. (See also Table 4.1.)

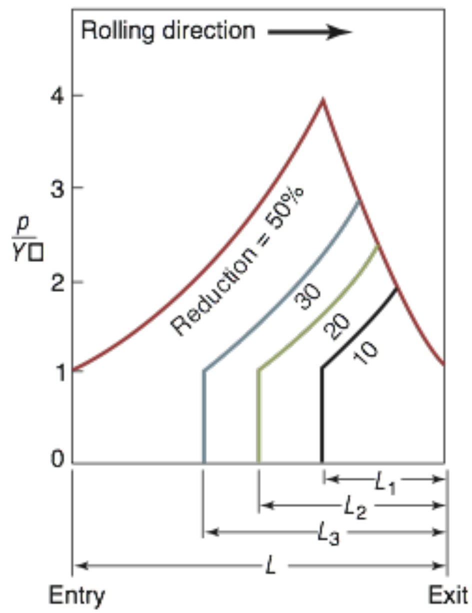


FIGURE 6.34 Pressure distribution in the roll gap as a function of reduction in thickness. Note the increase in the area under the curves with increasing reduction, thus increasing the roll force.

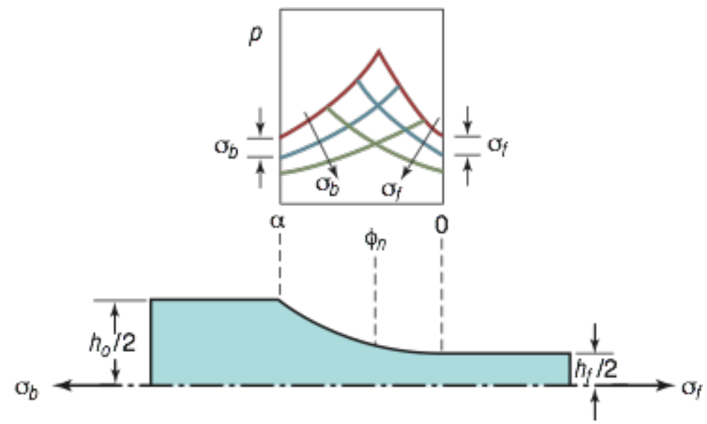


FIGURE 6.35 Pressure distribution as a function of front and back tension in rolling. Note the shifting of the neutral point and the reduction in the area under the curves (hence reduction in the roll force) as tensions increase.

Example

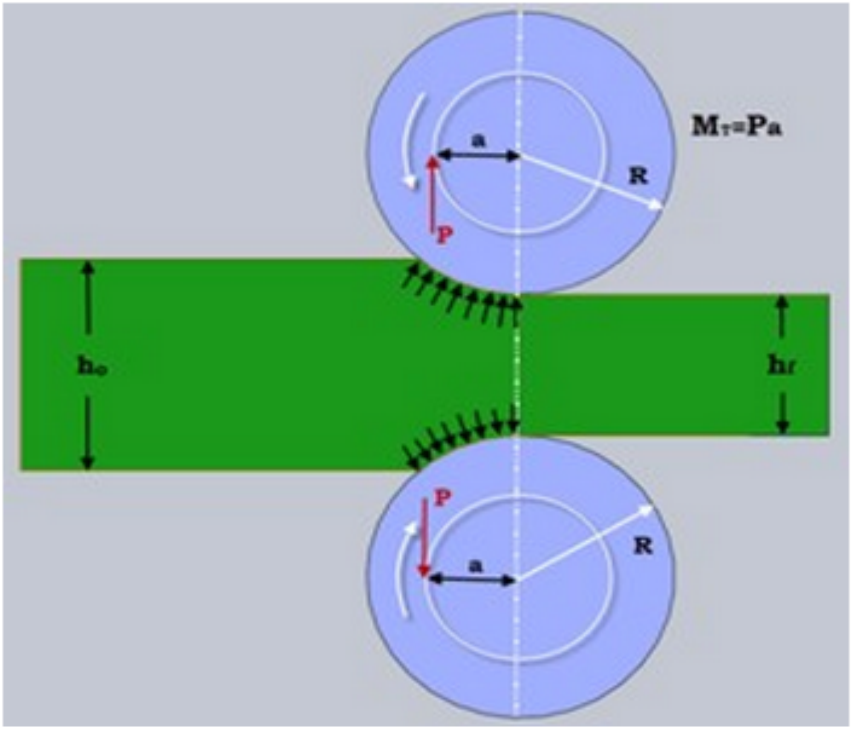
Question: Calculate the rolling load if steel sheet is hot rolled 30% from a 40 mm-thick slab using a 900 mm-diameter roll. The slab is 760 mm wide. Assume μ = 0.30. The plane-strain flow stress is 140 MPa at entrance and 200 MPa at the exit from the roll gap due to the increasing vel

$$P = \sigma_o^{'}\left[\frac{1}{Q}(e^{Q}-1)b\sqrt{R\Delta h}\right] \qquad Q = \frac{\mu L_p}{\bar{h}} \qquad \frac{\sigma'_{entrance} + \sigma'_{exit}}{2}$$

Answer:

Load = 13.4 MN

Roll torque and power



$$Torque/roller = r \cdot F_{roller} = \frac{L}{2} \cdot F_{roller} = \frac{F_{roller}L}{2}$$

Power / roller = $T\omega$ = $F_{roller}L\omega / 2$

Example

Question: A 250 mm wide annealed brass 70-30 strip is rolled from a thickness of 20 mm to 12 mm. For a roll radius of 300 mm and roll rpm of 100, estimate the total power required for this operation.
For brass K= 895 Mpa and n=0.49

Answer:
Load = 3111 kW

Problems and defects in rolled products

•Defects from cast ingots before rolling
-Porosity
-Cracks
-Blow holes
-Non metallic inclusions (Dross)

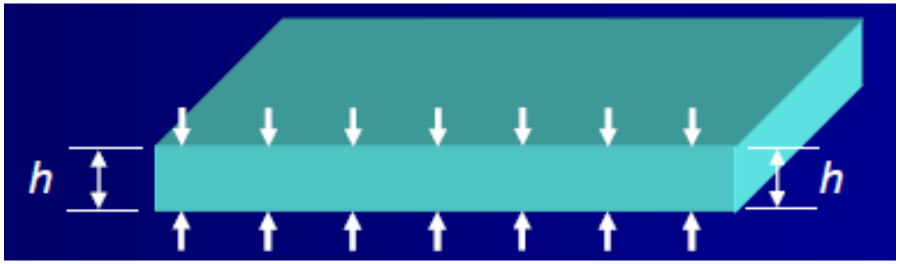
Drastically reduce the strength and ductility properties

Problems and defects in rolled products

•**Defects during rolling**

There are two aspects to the problem of a shape of a sheet

- **Uniform thickness: over the width and length**

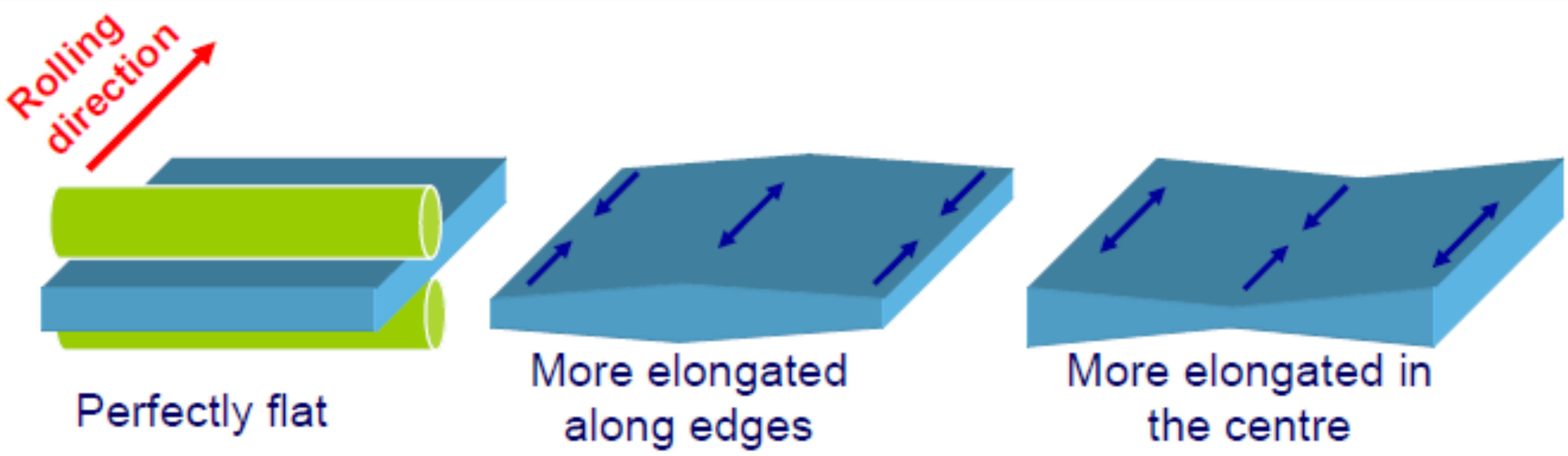


- **Flatness: difficult to measure accurately**

Flatness

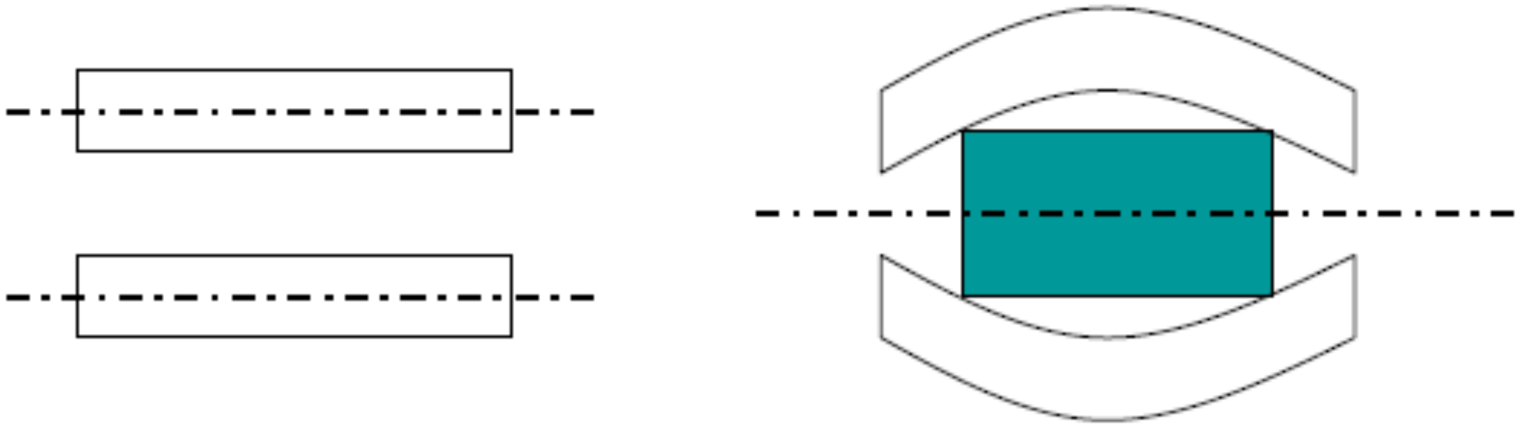
• The roll gap must be perfectly parallel to produce sheets/ plates with equal thickness at both ends.

• The rolling speed is very sensitive to flatness. A difference in elongation of one part in the sheet can cause waviness.

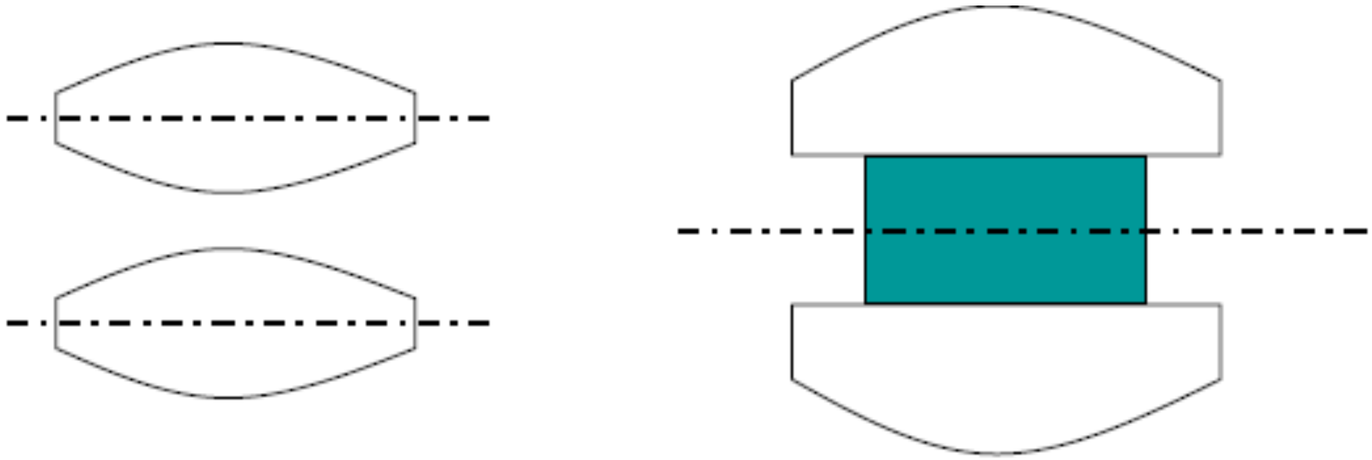


Solutions to flatness problem

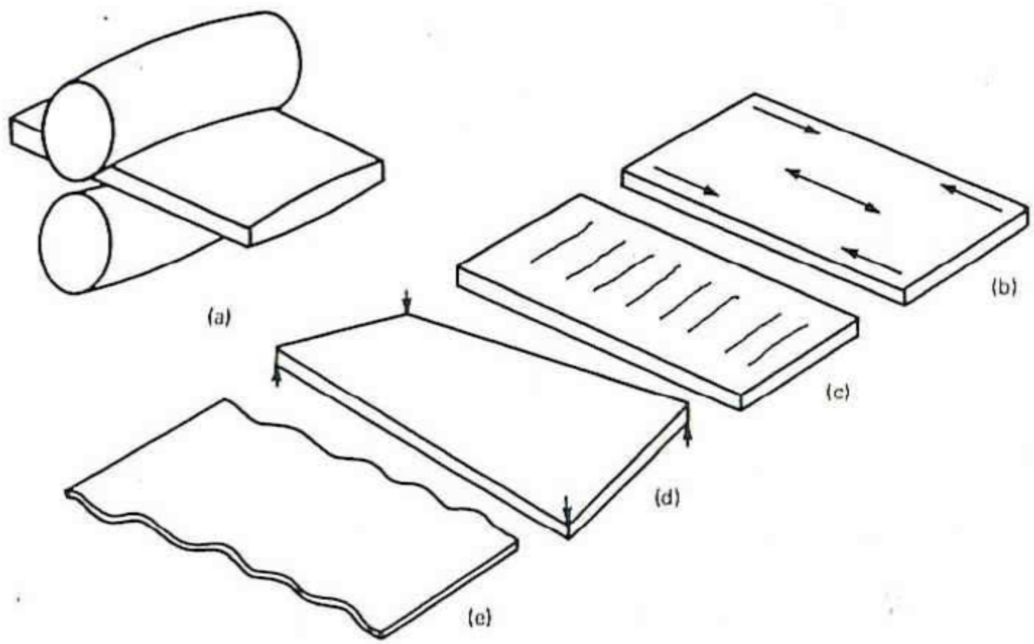
- Rolls can deflect under load



- Rolls can be crowned



Defects due to insufficient camber

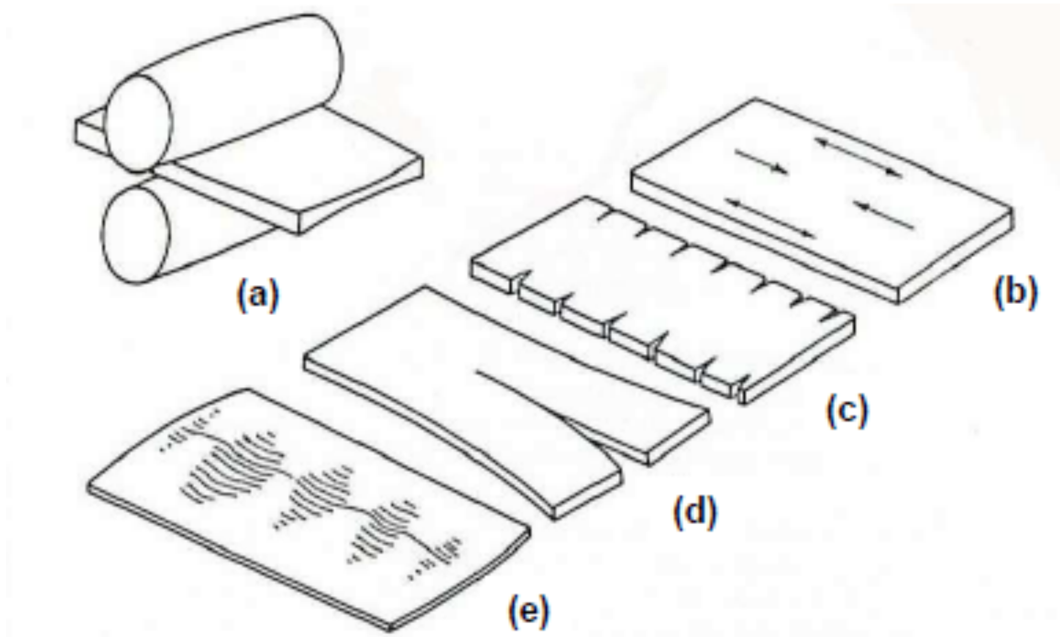


• Thicker centre means the edges would be plastically elongated more than the centre, normally called long edges.

• This induces the residual stress pattern of compression at the edges and tension along the centreline.

This can cause centreline cracking (c), warping (d) or edge wrinkling or crepe-paper effect or wavy edge (e).

Defects due to insufficient camber



• Thicker edges than the centre means the centre would be plastically elongated more than the edges, resulting in lateral spread.

•The residual stress pattern is now under compression in the centreline and tension at the edges.

• This may cause edge cracking (c), centre splitting (d), centreline wrinkling (e).

ME2300: Manufacturing Processes
Jan-May 2020

Forging

Part deformation by pressing between the dies

-Dies are hard metal shapes

Temperature

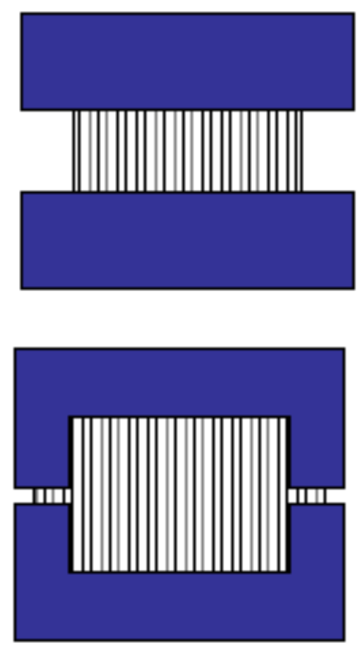
-Hot

-Cold

Processes

-Open-die forging

-Closed-die forging



Open-die forging/Upsetting

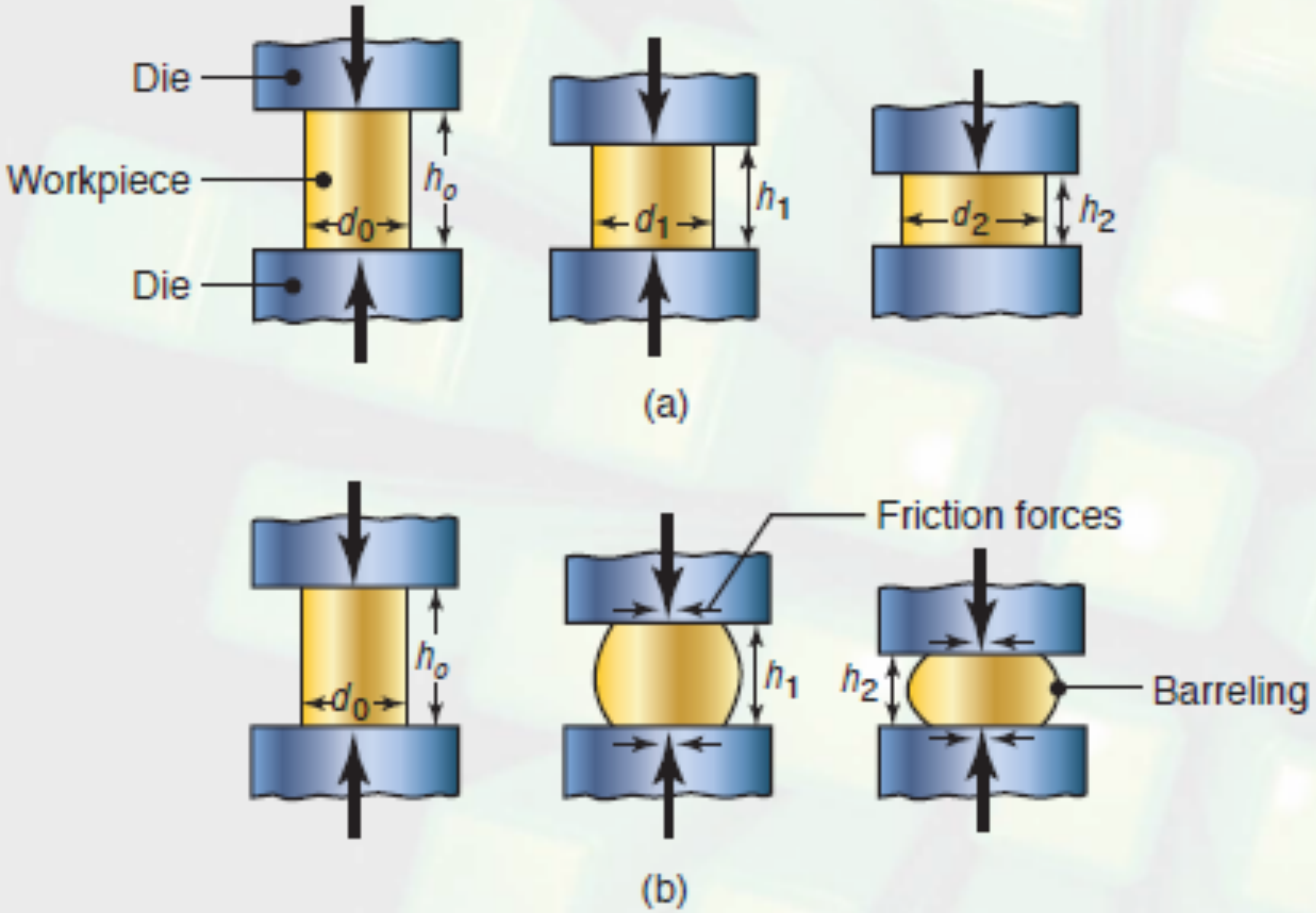
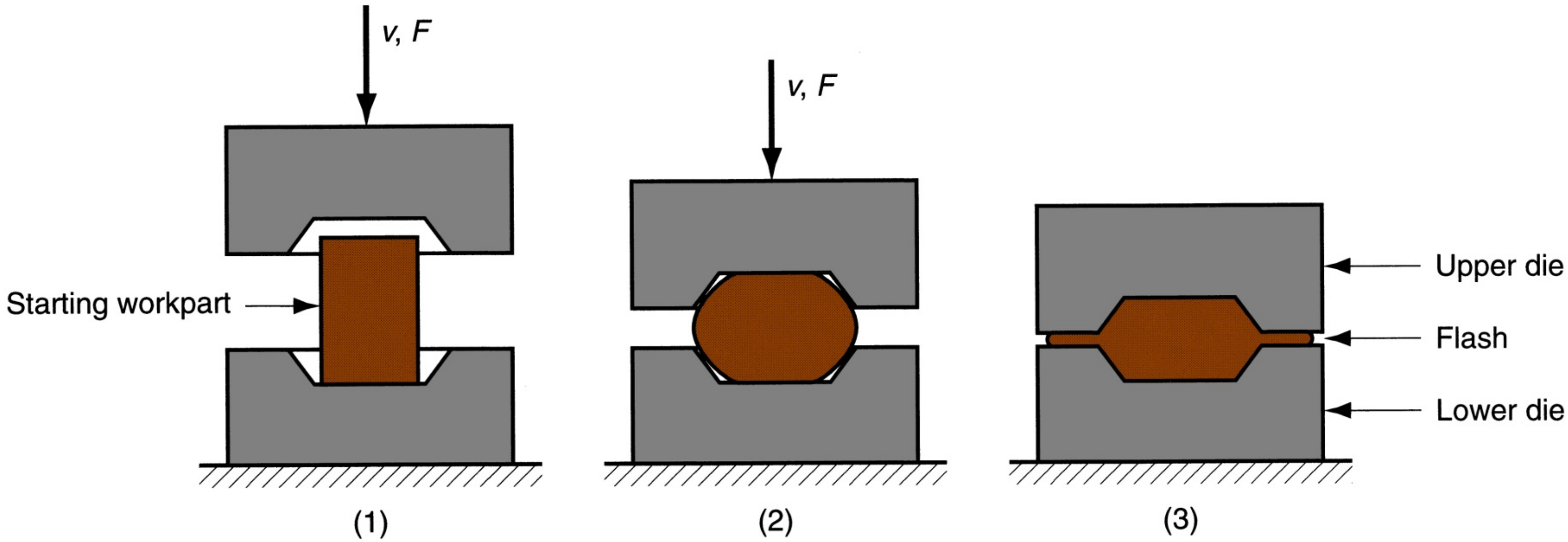


FIGURE 6.1 (a) Ideal deformation of a solid cylindrical specimen compressed between flat frictionless dies (platens), an operation known as upsetting. (b) Deformation in upsetting with friction at the die-workpiece interfaces. Note barrelling of the billet caused by friction.

Closed-die/Impression-die forging



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

Grain flow

FIGURE 6.2 Grain flow lines in upsetting a solid, steel cylindrical specimen at elevated temperatures between two flat cool dies. Note the highly inhomogeneous deformation and barreling, and the difference in shape of the bottom and top sections of the specimen. The latter results from the hot specimen resting on the lower die before deformation proceeds. The lower portion of the specimen began to cool, thus exhibiting higher strength and hence deforming less than the top surface. *Source:* After J.A. Schey.

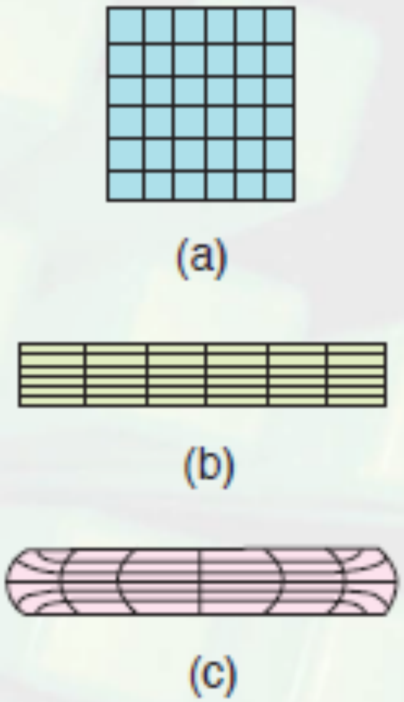
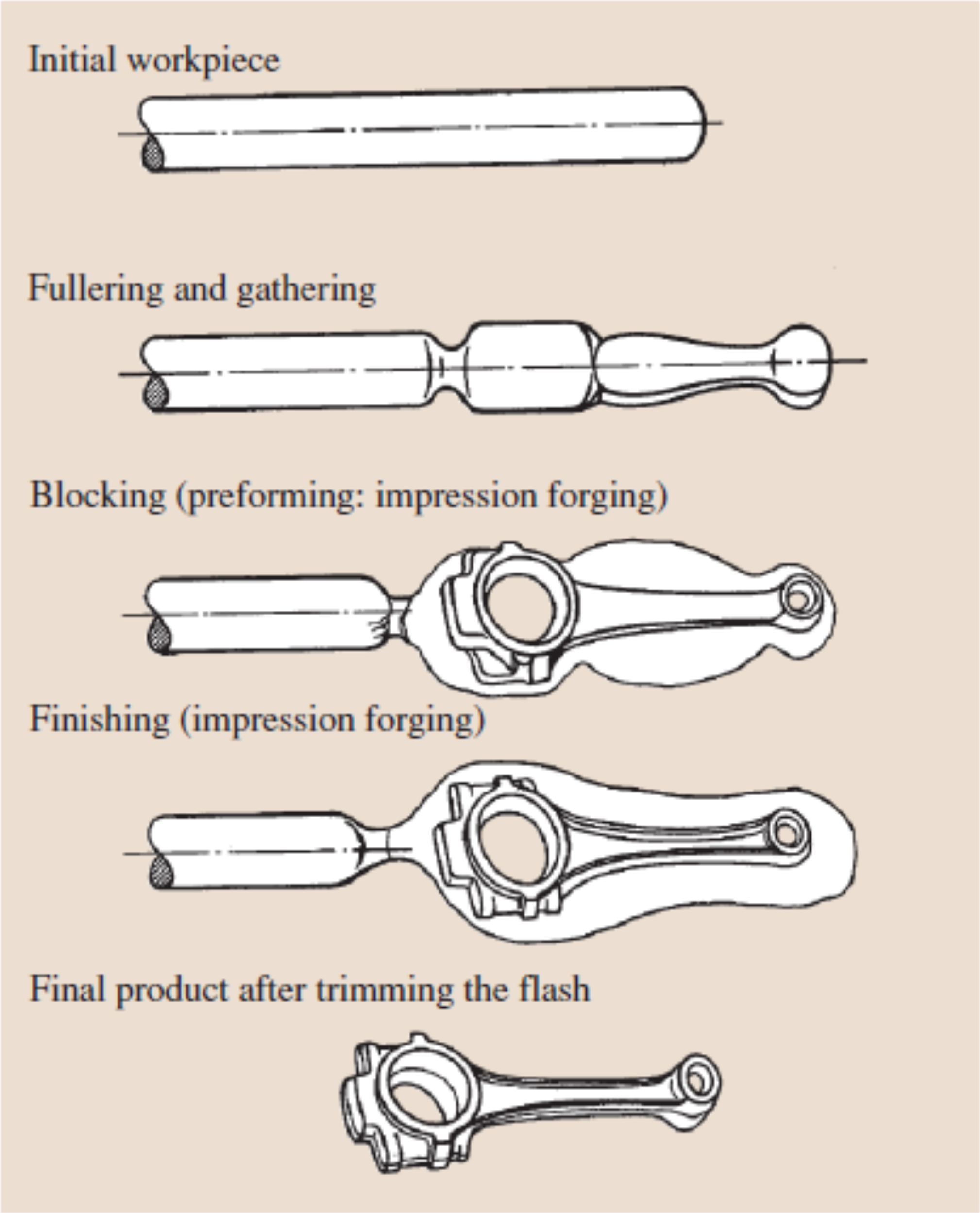


FIGURE 6.3 Schematic illustration of grid deformation in upsetting: (a) original grid pattern; (b) after deformation, without friction; (c) after deformation, with friction. Such deformation patterns can be used to calculate the strains within a deforming body.

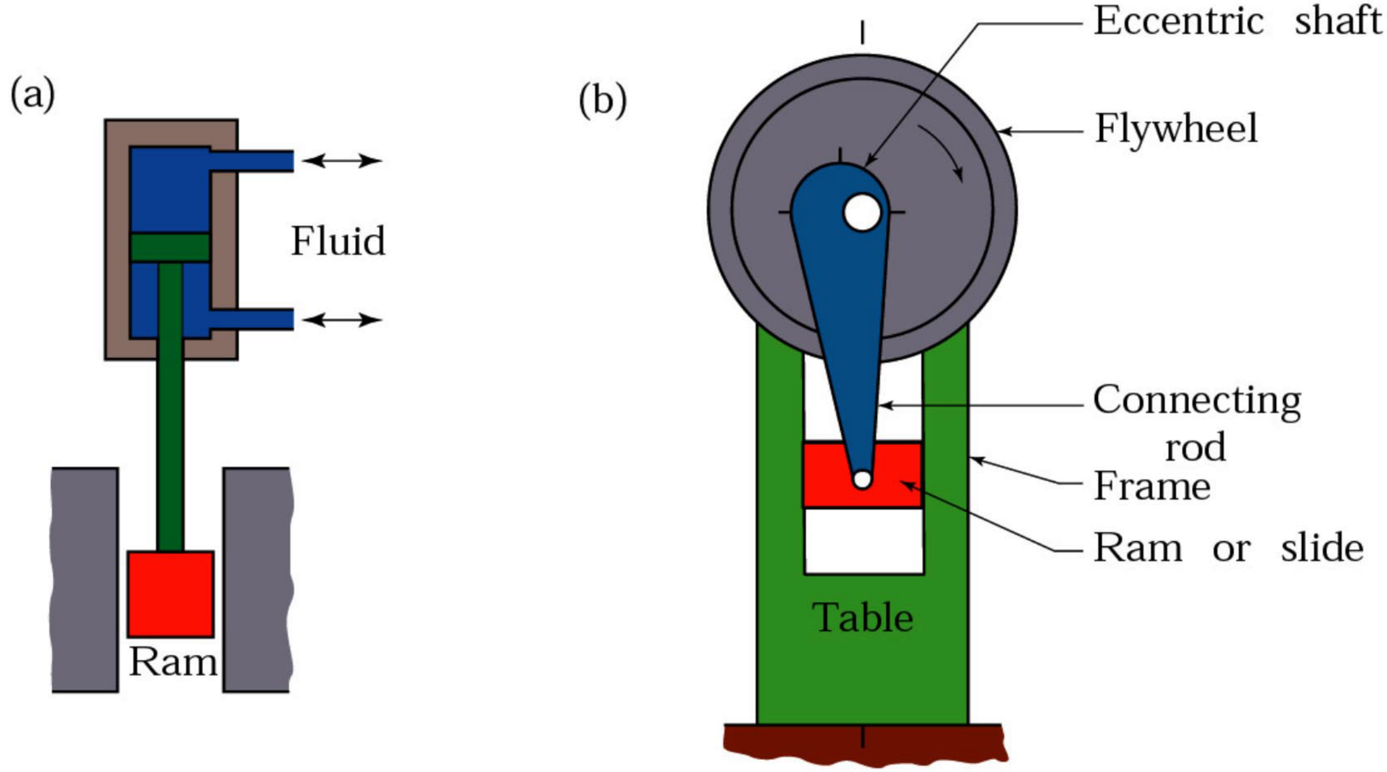
Applications

- Coins
- Gears
- Crank shaft
- Connecting rod
- Turbine shaft

Forging a connecting rod

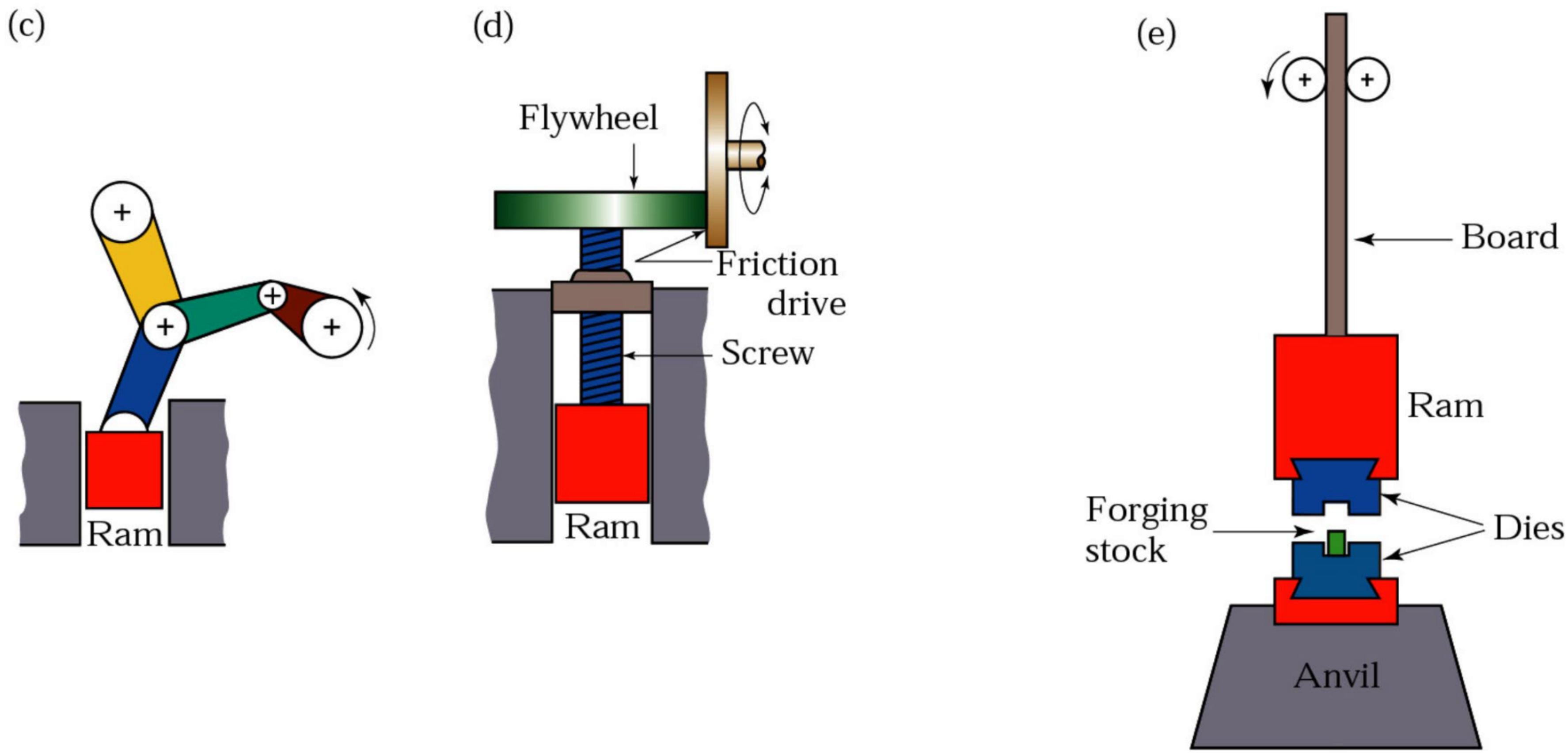


Principles of various forging machines



Schematic illustration of the principles of various forging machines. (a) Hydraulic press. (b) Mechanical press with an eccentric drive; the eccentric shaft can be replaced by a crankshaft to give the up-and-down motion to the ram. (continued)

Principles of various forging machines



(continued) Schematic illustration of the principles of various forging machines. (c) Knuckle-joint press. (d) Screw press. (e) Gravity drop hammer.

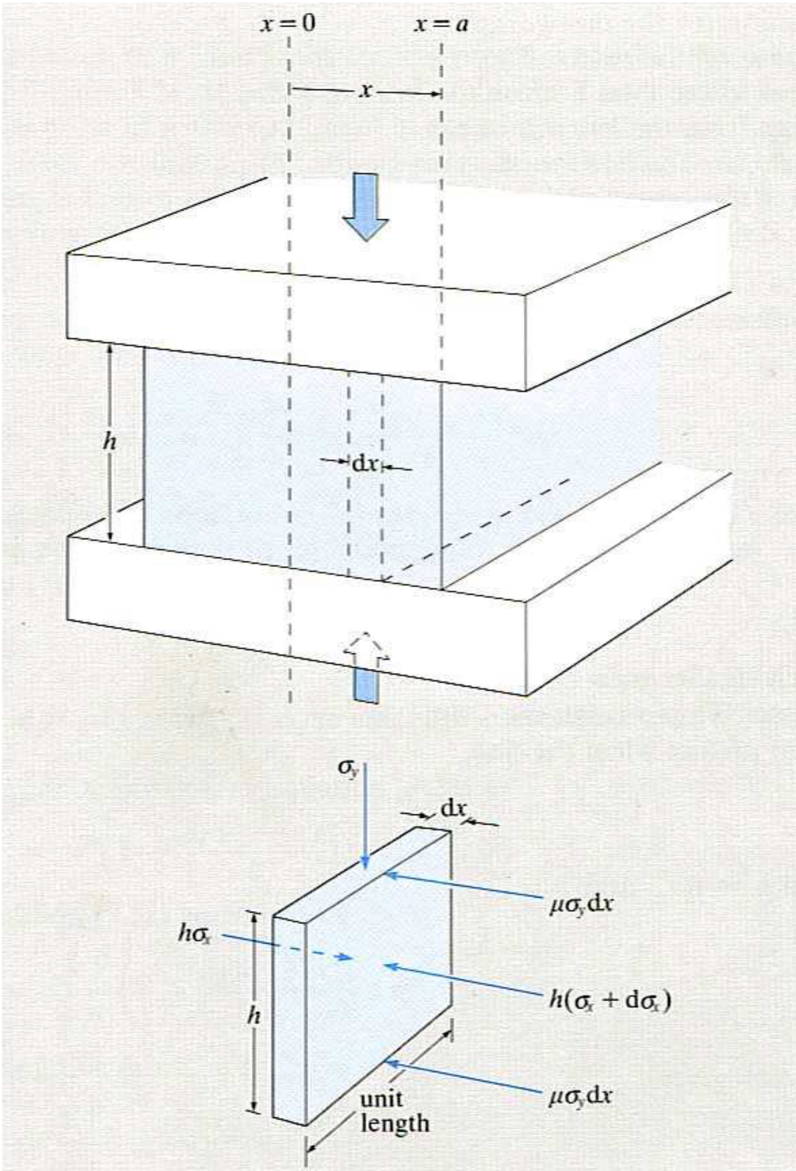
Forging temperature

Metal	°C	°F
Aluminum alloys	400-450	750-850
Copper alloys	625-950	1150-1750
Nickel alloys	870-1230	1600-2250
Alloy steels	925-1260	1700-2300
Titanium alloys	750-795	1400-1800
Refractory alloys	975-1650	1800-3000

Forging analysis (assumptions)

- Entire forging is plastic
- Material is perfectly plastic
- Friction coefficient (μ) is constant
- In any thin slab, stresses are uniform

Forging analysis (rectangular slab)



$$h(\sigma_x + d\sigma_x) + 2\mu\sigma_y dx = h\sigma_x \quad (1)$$

$$2\mu\sigma_y dx = -hd\sigma_x \quad (2)$$

$$\frac{d\sigma_x}{\sigma_y} = -\frac{2\mu}{h}dx \quad (3)$$

Forging analysis (rectangular slab)

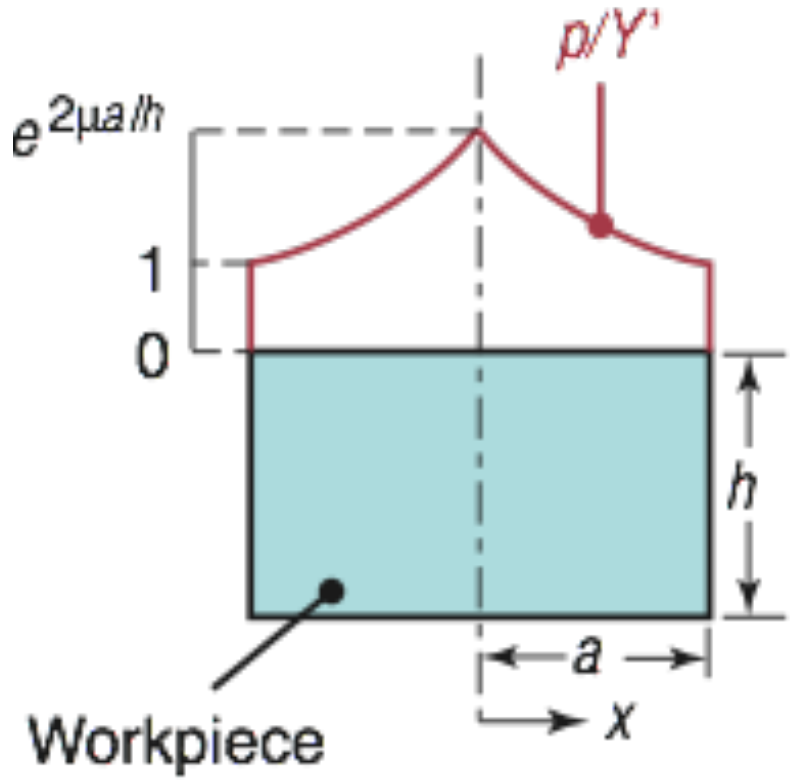
Yield criterion during deformation

$$\sigma_y - \sigma_x = \frac{2}{\sqrt{3}}\sigma_o = \sigma_o^{'}$$

$$d\sigma_y = d\sigma_x$$

$$\frac{d\sigma_y}{\sigma_y} = -\frac{2\mu}{h}dx \quad \Rightarrow \quad \sigma_y = C\exp\left(-\frac{2\mu x}{h}\right)$$

Die Pressure



Distribution of die pressure, in dimensionless form of *p*/*Y'*, in plane-strain compression with sliding friction. Note that the pressure at the left and right boundaries is equal to the yield stress of the material in plane strain, *Y'*. Sliding friction means that the frictional stress is directly proportional to the normal stress.

Flow Stress and Work of Deformation

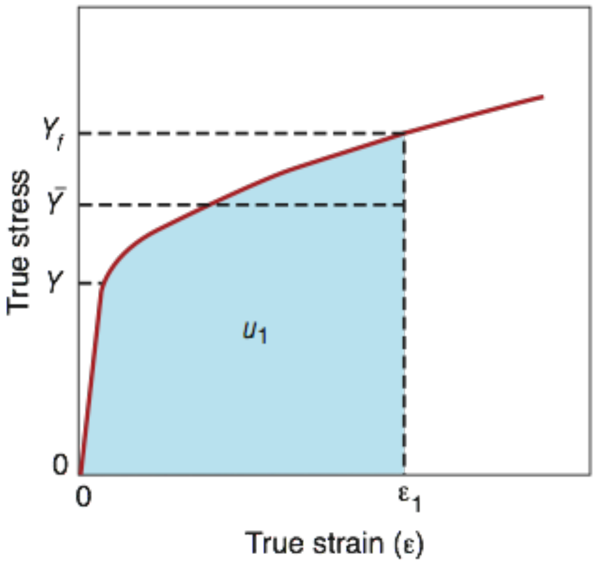


FIGURE Schematic illustration of true stress-true strain curve showing yield stress Y, average flow stress, specific energy u_1 and flow stress Y_f.

Flow stress:

$$\bar{Y} = \frac{K\varepsilon_1^n}{n+1}$$

Specific energy

$$u = \int_0^{\varepsilon} \bar{\sigma}\, d\bar{\varepsilon}$$

Ideal & Redundant Work

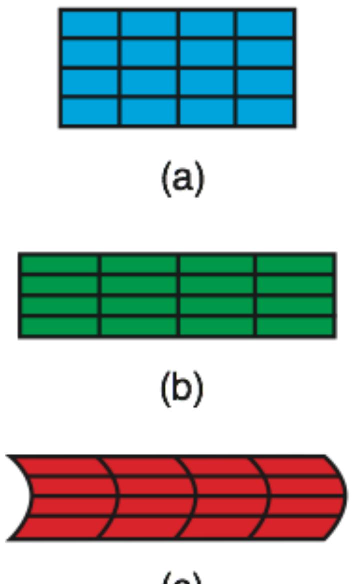


FIGURE 2.38 Deformation of grid patterns in a workpiece: (a) original pattern; (b) after ideal deformation; (c) after inhomogeneous deformation, requiring redundant work of deformation. Note that (c) is basically (b) with additional shearing, especially at the outer layers. Thus (c) requires greater work of deformation than (b). See also Figs. 6.3 and 6.49.

Total specific energy:

$$u_{total} = u_{ideal} + u_{friction} + u_{redundant}$$

Efficiency:

$$\eta = \frac{u_{ideal}}{u_{total}}$$

Average pressure and forging force (slab)

$$\bar{p} = \sigma_0'\left(1 + \frac{\mu a}{h}\right)$$

Force = (Average pressure)*(2a)*(width)

h is instantaneous height

Cylindrical workpiece

$$\bar{p} = \sigma_0'\left(1 + \frac{2\mu r}{3h}\right)$$

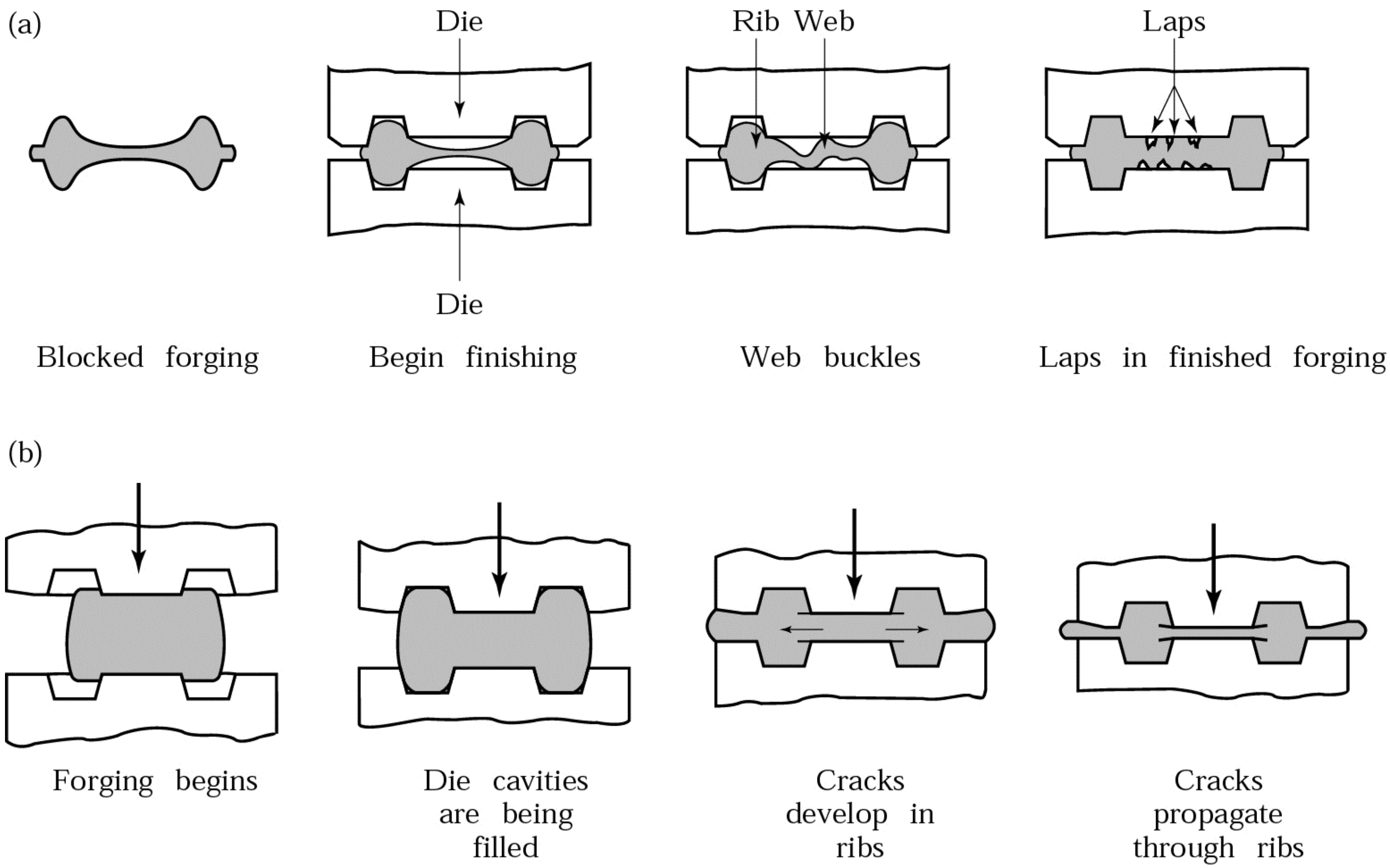
Force = (Average pressure)* πr^2

Example

Q: A cylindrical specimen made of steel has a diameter of 200 mm and is 125 mm high. It is forged at room temperature, by open die forging with flat dies to a height of 50 mm. Assuming that the coefficient of friction is 0.2, calculate the forging force required at the end of the stroke.
Strength constant, K = 760 MPa
Strain hardening exponent, n = 0.19

Answer: 8.32*10^7 N

Forging defects



Examples of defects in forged parts. (a) Laps formed by web buckling during forging; web thickness should be increased to avoid this problem. (b) Internal defects caused by oversized billet; die cavities are filled prematurely, and the material at the centre flows past the filled regions as the dies close.

Extrusion

Compression forming process in which the work metal is forced to flow through a die opening to produce a desired cross-sectional shape

- Process is similar to squeezing toothpaste out of a toothpaste tube
- In general, extrusion is used to produce long parts of uniform cross-sections
- Two basic types of extrusion:
  – Direct extrusion
  – Indirect extrusion

Extruded products

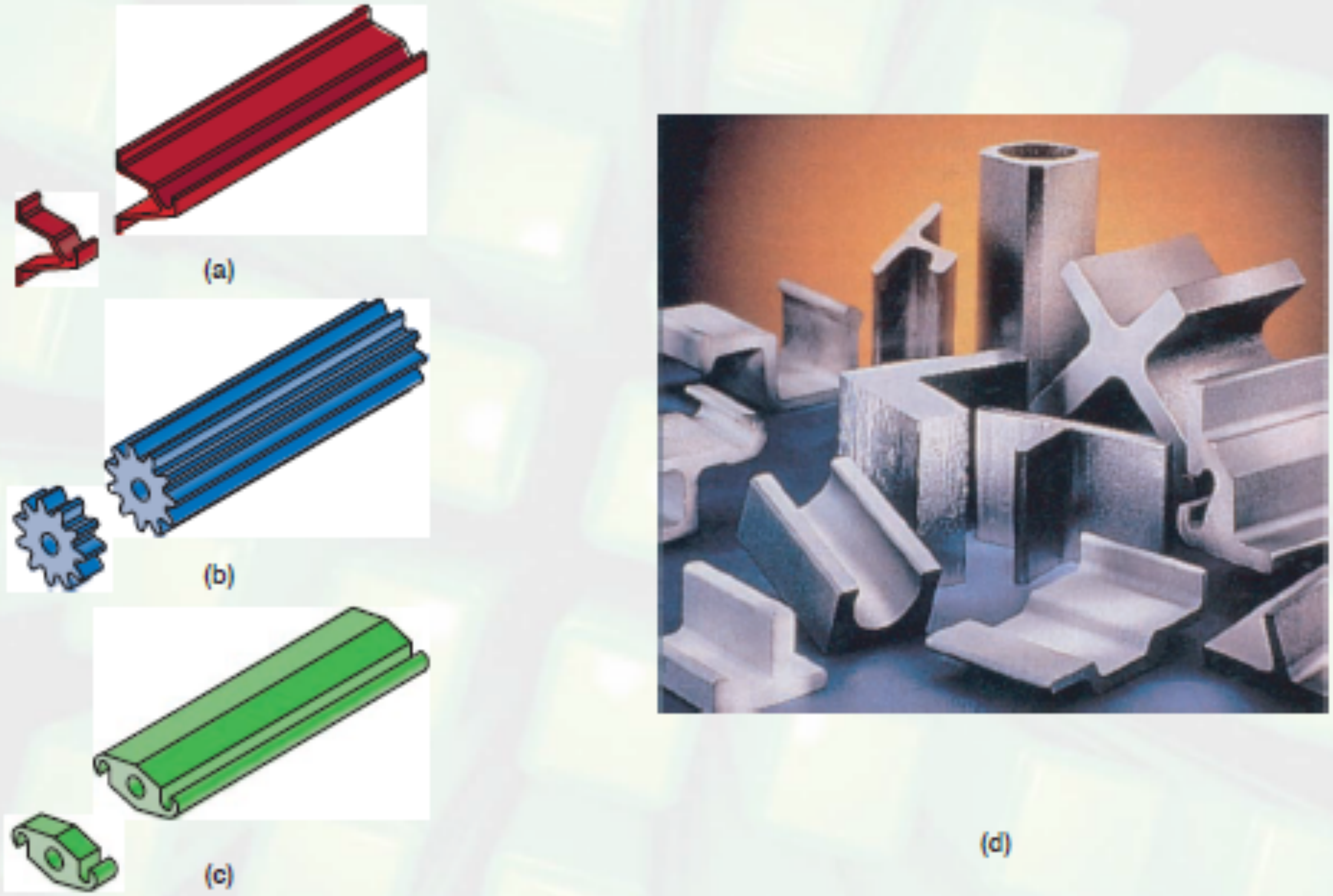
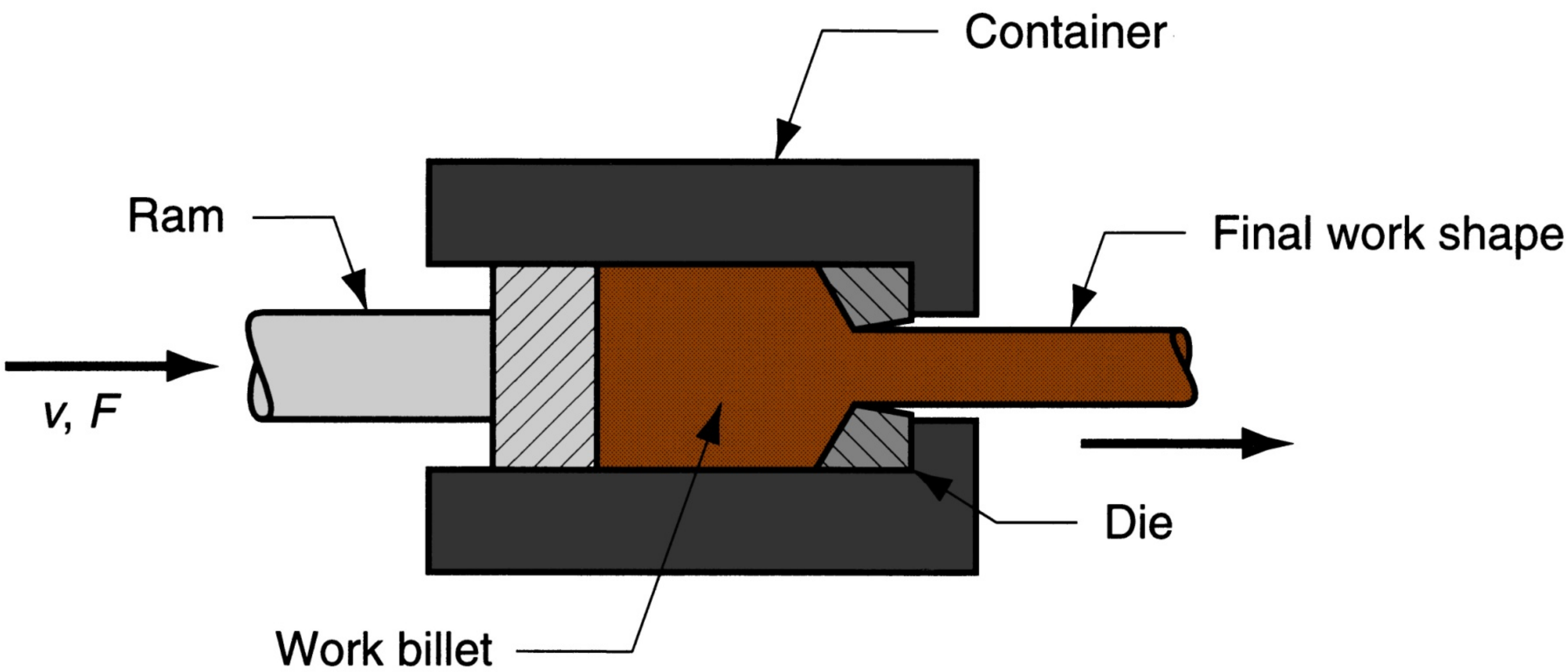


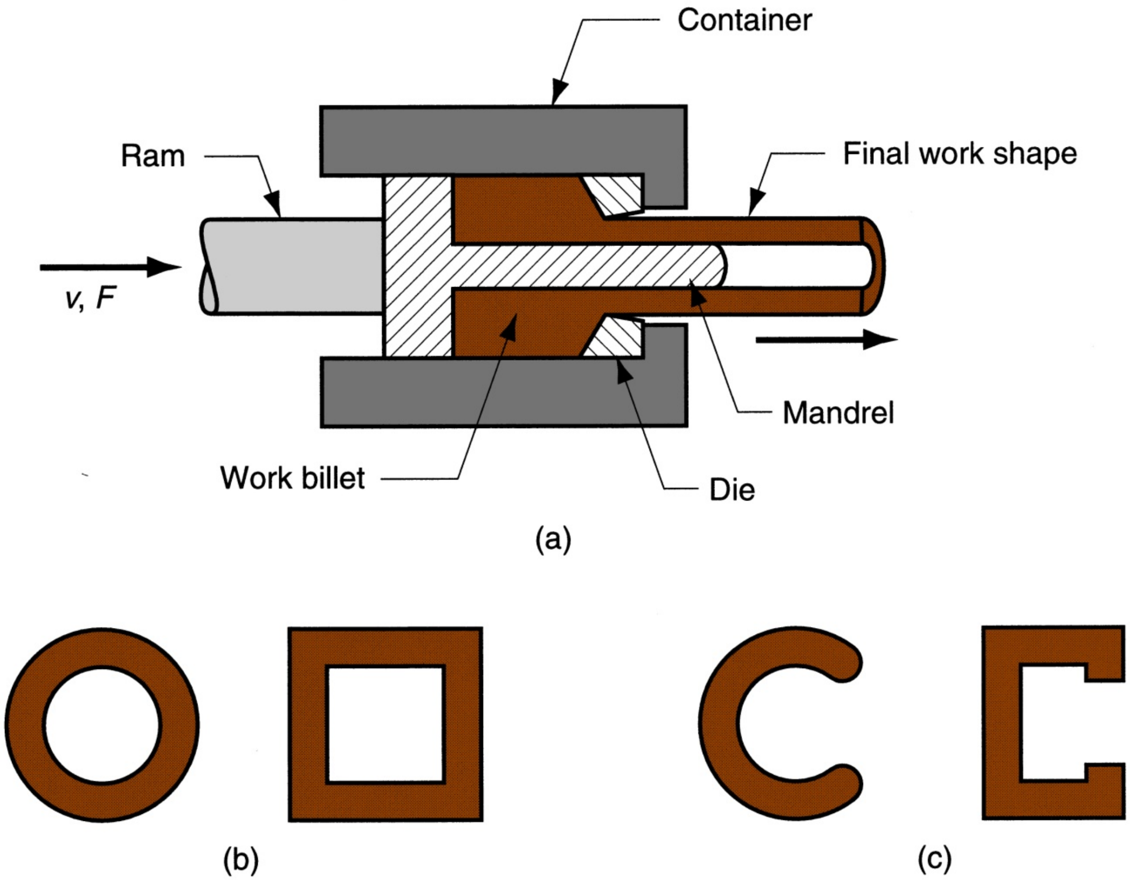
FIGURE 6.48 (a)-(c) Examples of extrusions and products made by sectioning them. *Source:* Kaiser Aluminum. (d) Examples of extruded cross-sections. *Source:* (d) Courtesy of Plymouth Extruded Shapes.

Direct extrusion



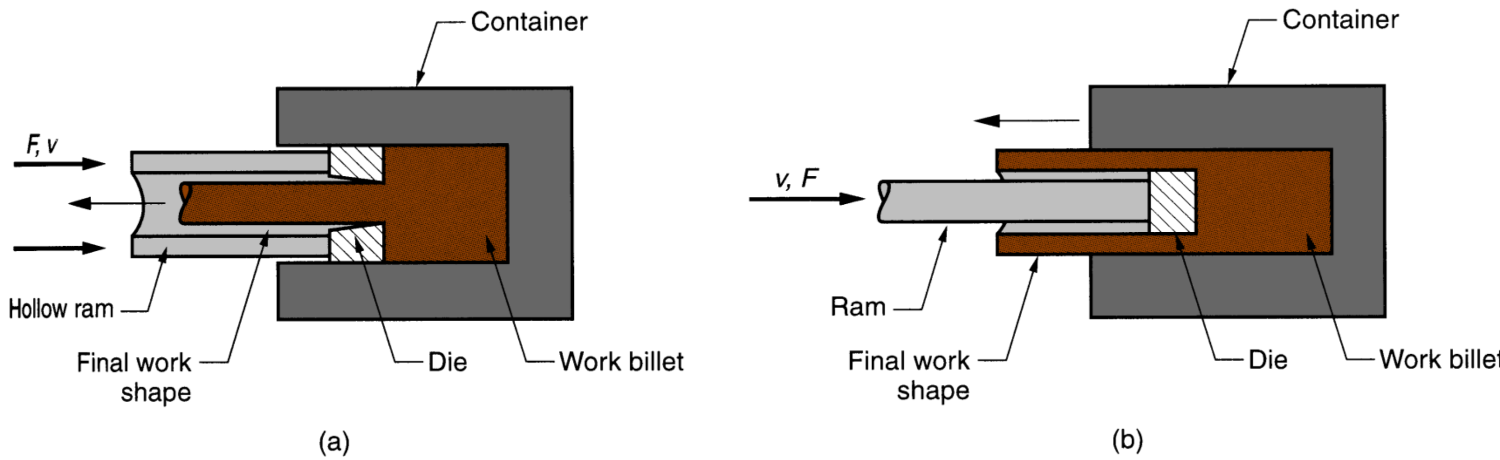
Direct extrusion

Direct extrusion



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

Indirect extrusion



Indirect extrusion to produce

(a) a solid cross-section and (b) a hollow cross-section

Extrusion ratio

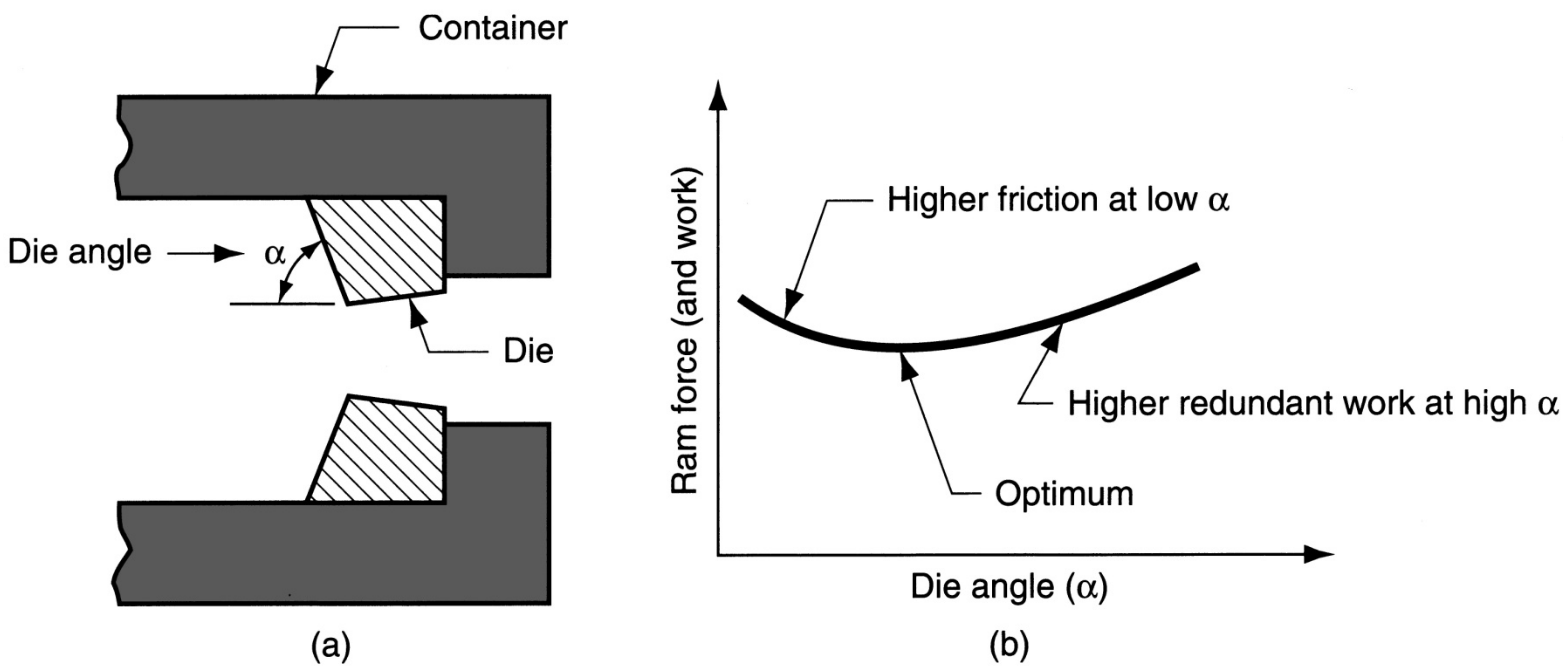
Also called the *extrusion ratio*, it is defined as

$$R = \frac{A_o}{A_f}$$

Where R = extrusion ratio; A_o = cross-sectional area of the starting billet; and A_f = final cross-sectional area of the extruded section

- Applies to both direct and indirect extrusion

Process variables in direct extrusion

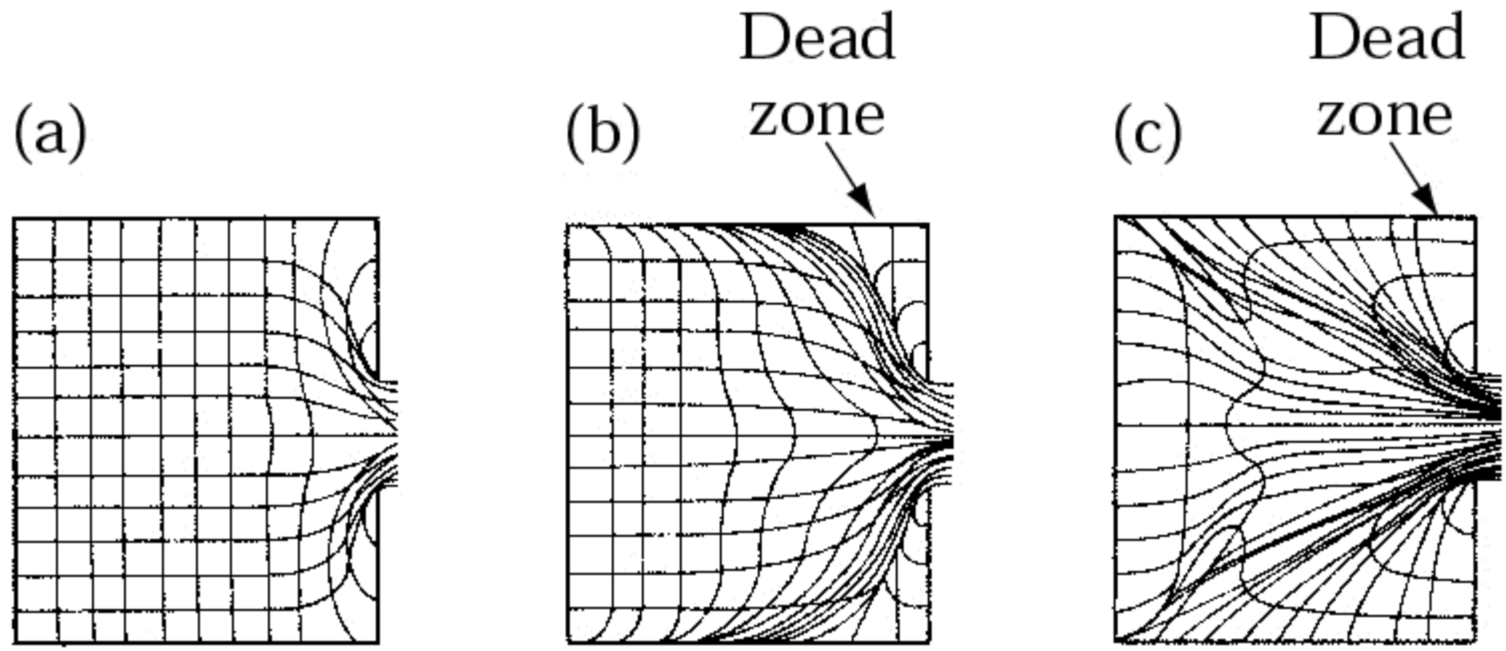


(a) Definition of die angle in direct extrusion;

(b) effect of die angle on ram force

The die angle, reduction in cross-section, extrusion speed, billet temperature, and lubrication all affect the extrusion pressure.

Metal flow in extrusion



Types of metal flow in extruding with square dies. (a) Flow pattern obtained at low friction, or in indirect extrusion. (b) Pattern obtained with high friction at the billet-chamber interfaces. (c) Pattern obtained at high friction, or with cooling of the outer regions of the billet in the chamber. This type of pattern, observed in metals whose strength increases rapidly with decreasing temperature, leads to a defect known as pipe, or extrusion defect.

Mechanics of extrusion

1. Ideal force, no friction

$$\varepsilon = \ln(\frac{A_o}{A_f}) = \ln(\frac{L_f}{L_o}) = \ln R$$

Assumption: perfectly plastic material, u=Yε

For a perfectly plastic material with a yield stress, Y the energy dissipated in plastic deformation per unit volume, u is, **u=Yε**

Work $=uA_oL_o = FL_0 = pA_oL_o$ (p: extrusion pressure)

$$p = u = Y\ln(\frac{A_o}{A_f}) = Y\ln(\frac{L_f}{L_o}) = Y\ln R$$

Mechanics of extrusion

1. Ideal force, no friction

$$\varepsilon = \ln(\frac{A_o}{A_f}) = \ln(\frac{L_f}{L_o}) = \ln R$$

Assumption: strain hardening material, u=?

Work $= uA_oL_o = FL_0 = pA_oL_o$ (p: extrusion pressure)

$$p = u = \bar{Y}\ln(\frac{A_o}{A_f}) = \bar{Y}\ln(\frac{L_f}{L_o}) = \bar{Y}\ln R$$

Mechanics of extrusion

2. Ideal force, with friction

$$p = Y\left(1 + \frac{\tan\alpha}{\mu}\right)\left[R^{\mu\cot\alpha} - 1\right]$$

3. Actual forces

$$p = Y(a + b\ln R)$$

Coefficient of friction, flow stress (temperature & strain rate and work during deformation)

Extrusion constant

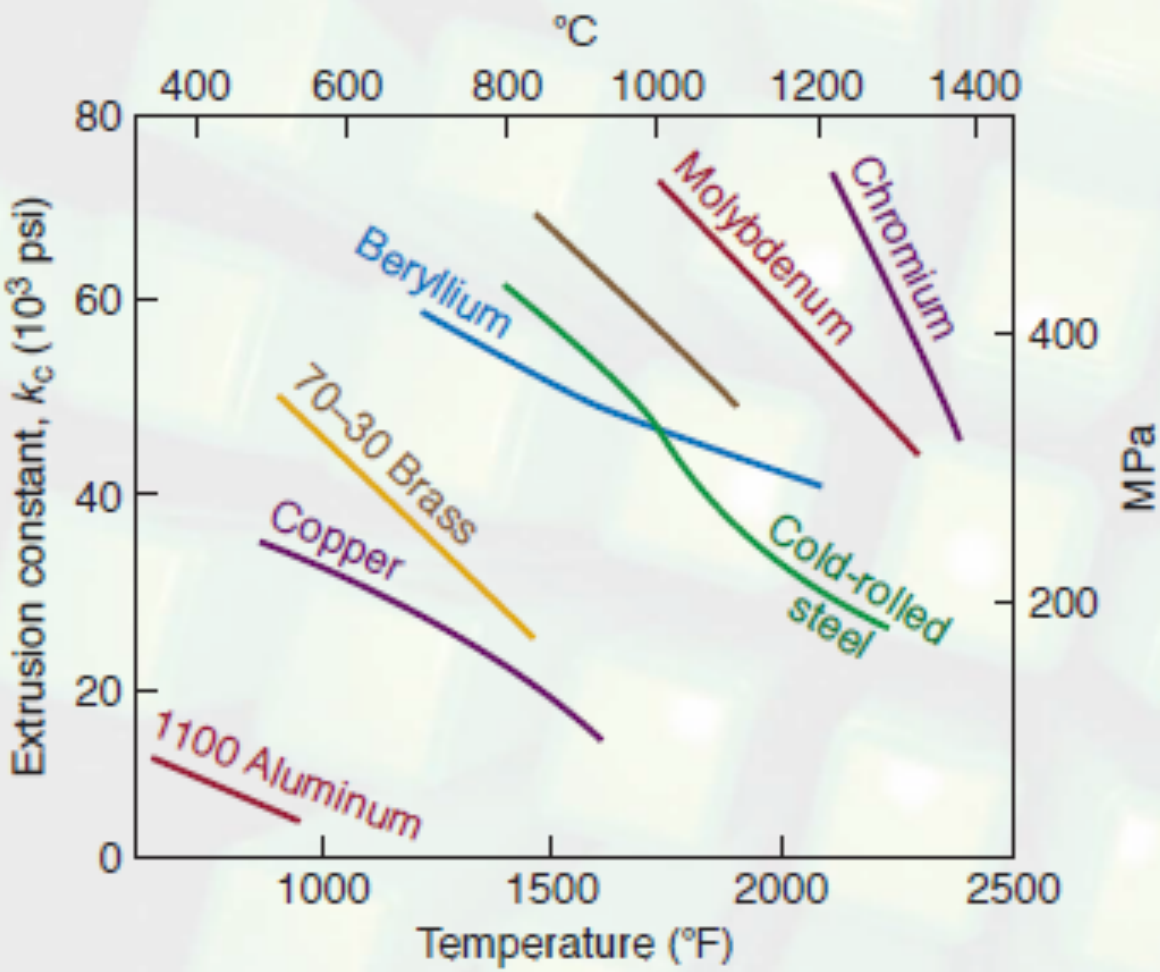


FIGURE 6.51 Extrusion constant, K_e, for various materials as a function of temperature. *Source:* After P. Loewenstein.

$$p = K_e \ln R$$

Extrusion force and pressure

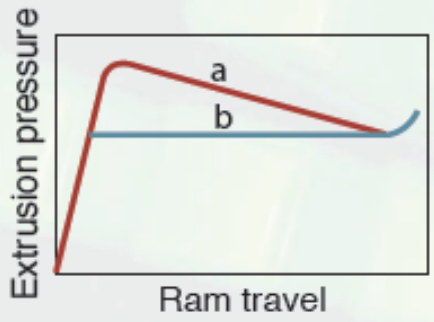


FIGURE 6.50 Schematic illustration of typical extrusion pressure as a function of ram travel: (a) direct extrusion and (b) indirect extrusion. The pressure in direct extrusion is higher because of frictional resistance at the container-billet interfaces, which decreases as the billet length decreases in the container.

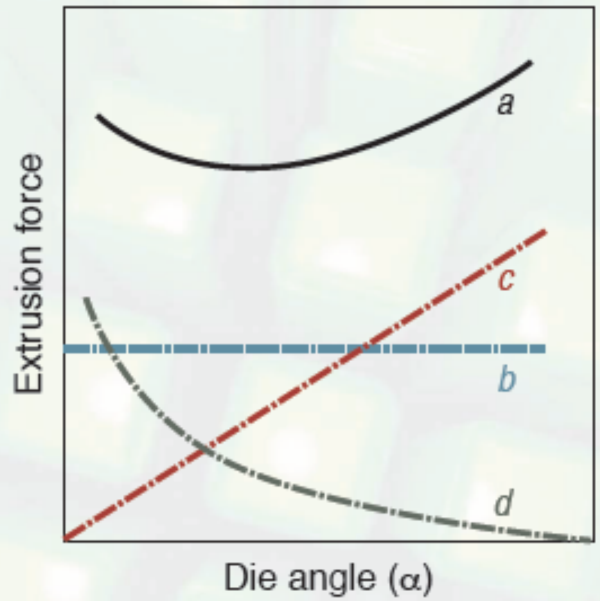


FIGURE 6.51 Schematic illustration of extrusion force as a function of die angle: (a) total force; (b) ideal force; (c) force required for redundant deformation; (d) force required to overcome friction. Note that there is a die angle where the total extrusion force is a minimum (optimum die angle).

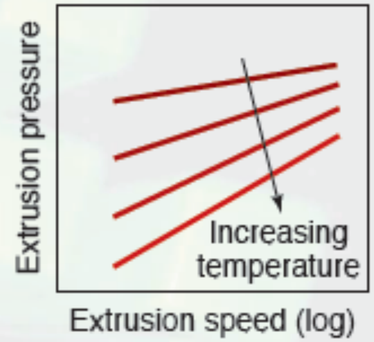
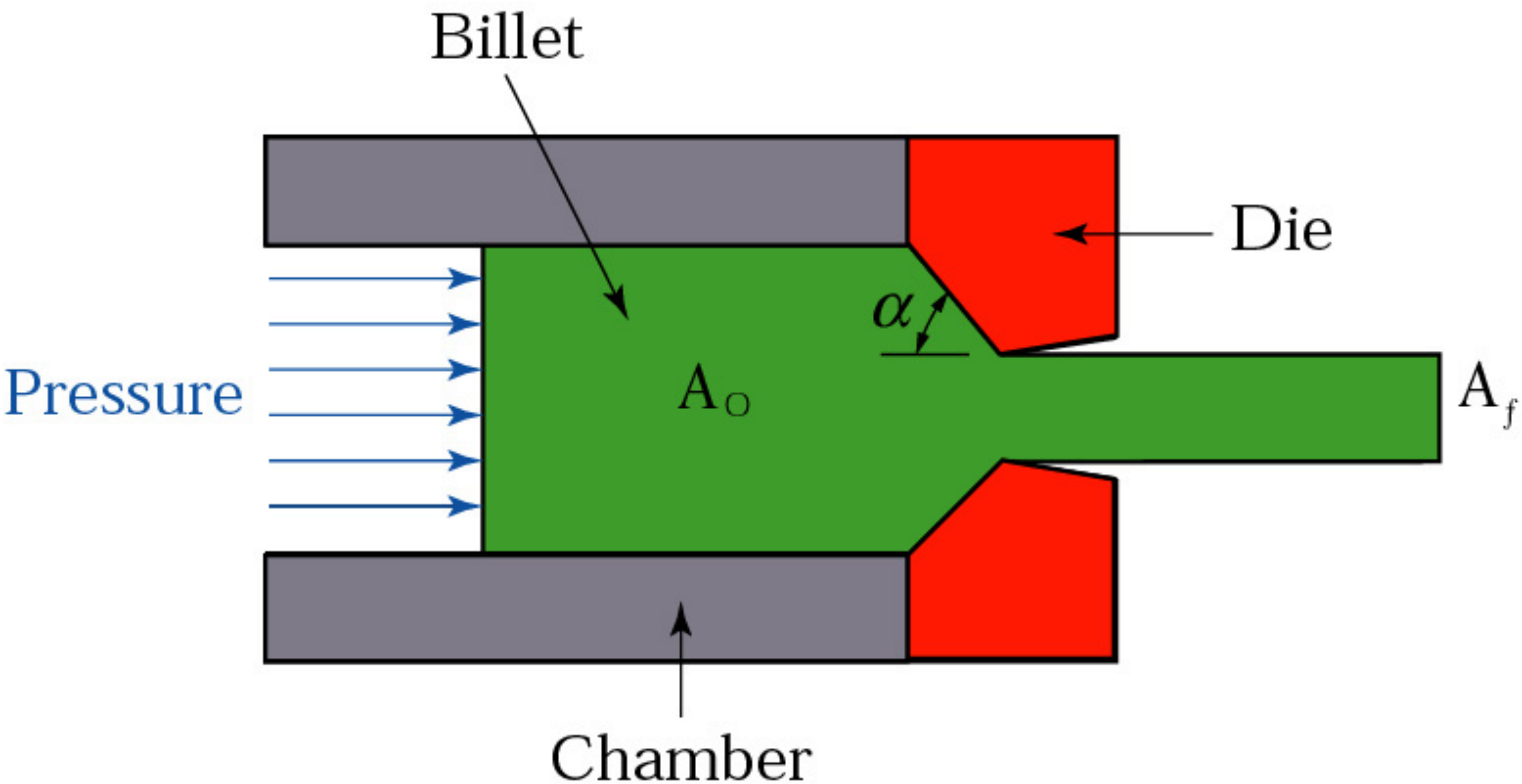


FIGURE 6.52 Schematic illustration of the effect of temperature and ram speed on extrusion pressure. Note the similarity of this figure with Fig. 2.10.

Example

Q: Determine the true strain rate in extruding a round billet of radius r_o as a function of distance x from the entry of a conical die.



Example

Q: A copper billet 150 mm in diameter and 300 mm long is extruded at 1123 K at a speed of 0.3 m/s. Using square dies and assuming poor lubrication, estimate the force required in this operation if the extruded diameter is 75 mm (C = 240 MPa, m = 0.06, a=0.8 & b=1.5).

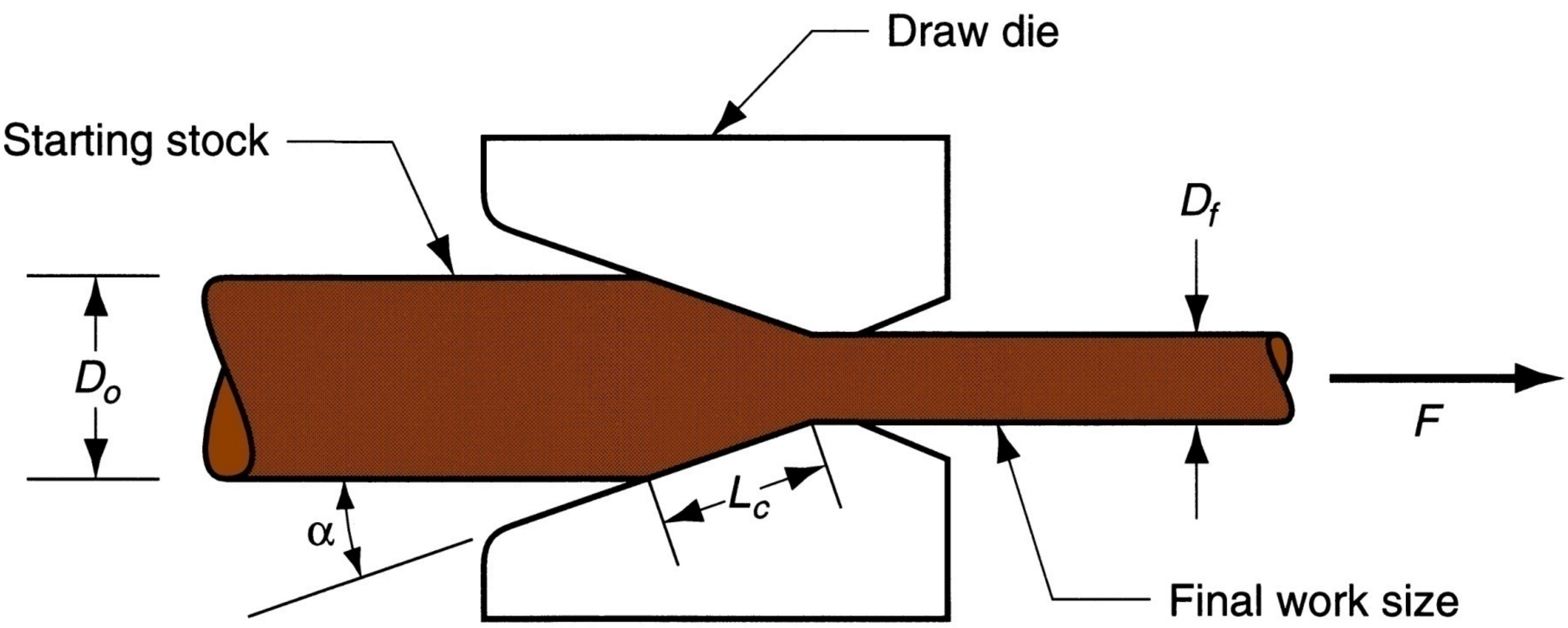
$$\bar{\dot{\varepsilon}} = \frac{6V_o}{D_o} \ln R$$

$$p = Y(a + b \ln R)$$

Wire and bar drawing

- Drawing operations involve pulling metal through a die by means of a tensile force applied to the exit side of the die.
- The plastic flow is caused by compression force, arising from the reaction of the metal with the die.
- Starting materials: hot rolled stock (ferrous) and extruded (nonferrous).
- Materials should have high ductility and good tensile strength
- Wire and bar drawing are usually carried out at room temperature
- The metal usually has a circular symmetry (but not always, depending on requirements).

Wire and bar drawing



Drawing of bar, rod, or wire

Area reduction in drawing

Change in size of work is usually given by area reduction:

$$r = \frac{A_o - A_f}{A_o}$$

where r = area reduction in drawing; A_o = original area of work; and A_r = final work

Wire drawing vs. bar drawing

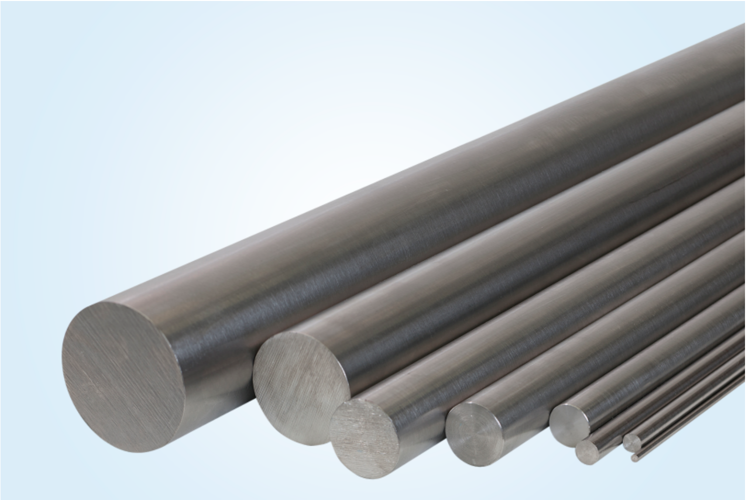
- Difference between bar drawing and wire drawing is stock size
  - *Bar drawing* - large diameter bar and rod stock
  - *Wire drawing* - small diameter stock - wire sizes down to 0.03 mm (0.001 in.) are possible
- Although the mechanics are the same, the methods, equipment, and even terminology are different

Drawing practice and products

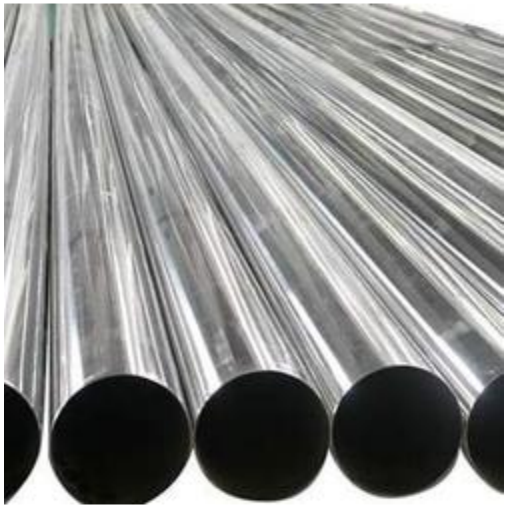
- Drawing practice:
  - Usually performed as cold working
  - Most frequently used for round cross-sections
- Products:
  - *Wire*: electrical wire; wire stock for fences, coat hangers, and shopping carts
  - *Rod stock* for nails, screws, rivets, and springs
  - *Bar stock*: metal bars for machining, forging, and other processes

Drawing practice and products

Metal wires

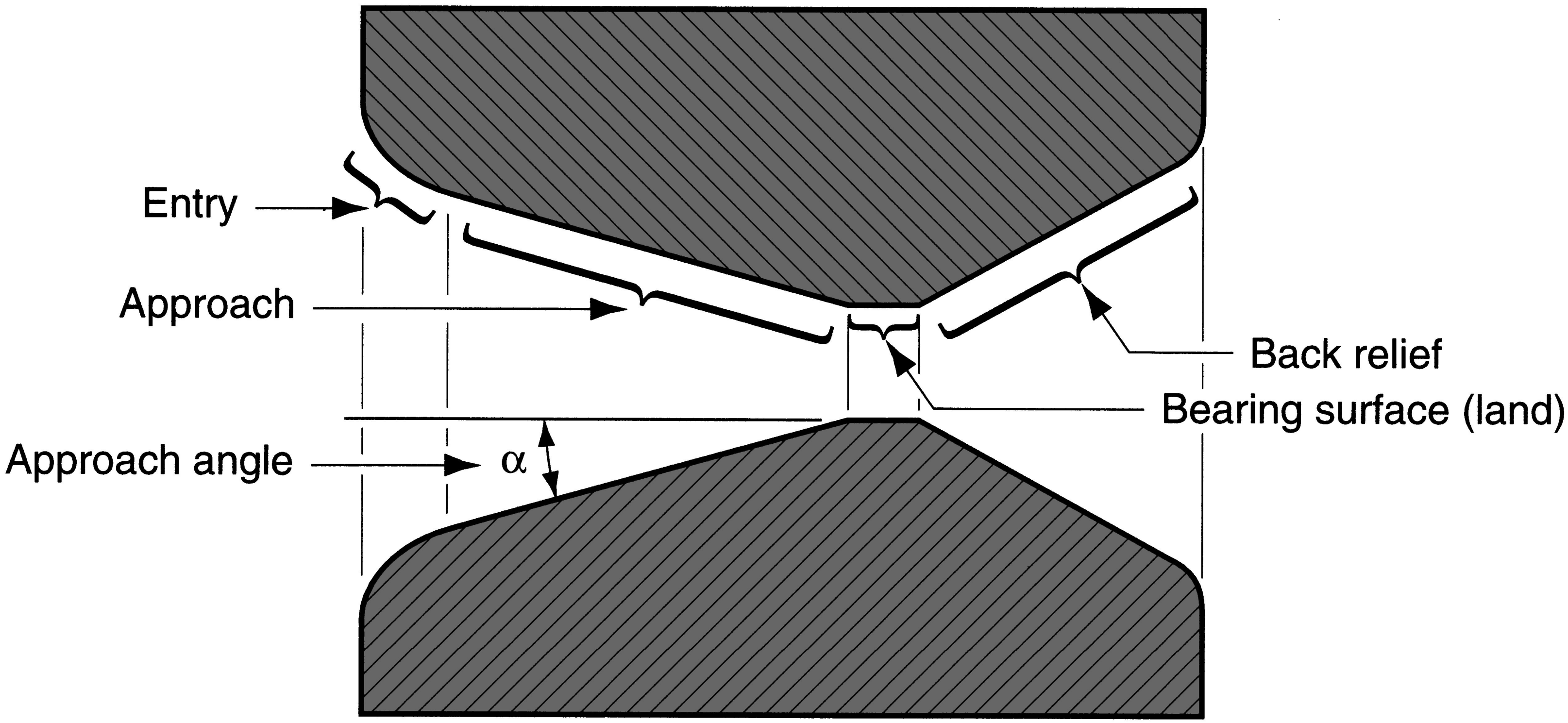


Metal rods



Pipes

Features of draw die



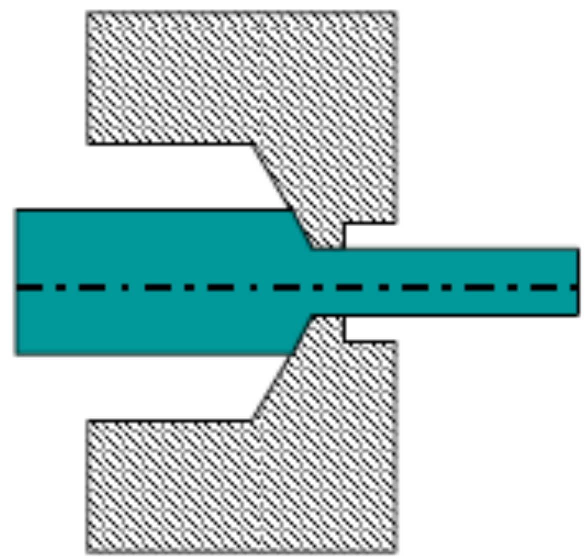
Draw die for drawing of round rod or wire

Die materials

- Large diameter
  – high carbon steel
  – high speed steel

- Moderate diameter
  – tungsten carbide (WC)

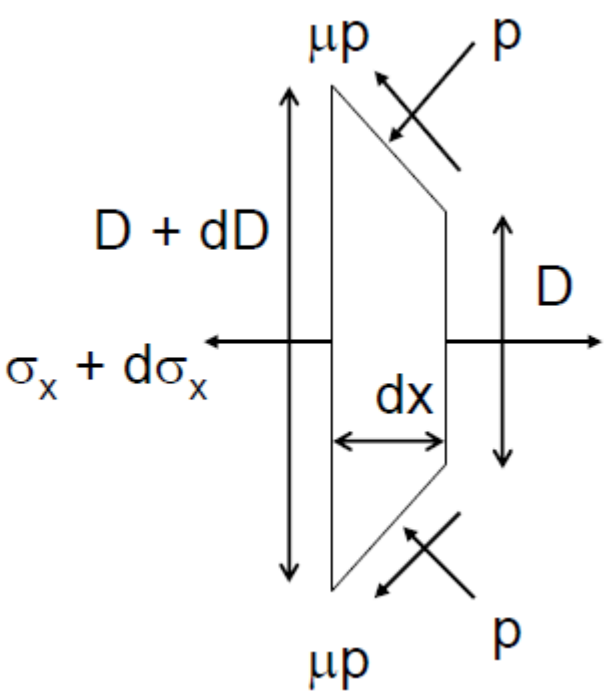
- Small diameter
  – diamond inserts

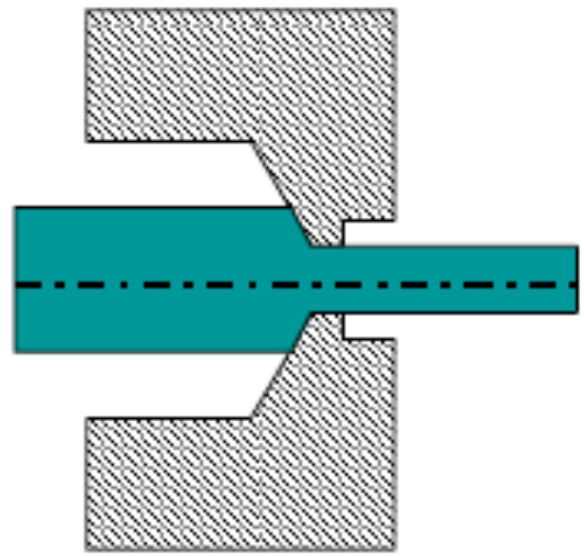


Workpiece preparation

- *Annealing* – to increase ductility of stock
- *Cleaning* - to prevent damage to work surface and draw die
- *Pointing* – to reduce diameter of starting end to allow insertion through draw die

Mechanics of wire and bar drawing





Assume p, σ_x are uniform

$$(\sigma_x + d\sigma_x)\frac{\pi}{4}(D + dD)^2 - \sigma_x \frac{\pi}{4} D^2$$

$$+ p\frac{\pi D \cdot dx}{\cos\alpha}\sin\alpha + \mu p\frac{\pi D \cdot dx}{\cos\alpha}\cos\alpha = 0$$

Mechanics of wire and bar drawing

Case 1: Ideal deformation, no friction

External work = work done during plastic deformation

$$\sigma_d (A_f l) = u(A_f l)$$

$$\sigma_d = u = \int_0^{\varepsilon_t} \sigma_t d\varepsilon_t$$

$$\boxed{\sigma_d = \frac{K\varepsilon_t^n}{n+1}\varepsilon_t = \bar{Y}_f \varepsilon_t = \bar{Y}_f \ln\left(\frac{A_0}{A_f}\right)}$$

Drawing force, $F_d = \sigma_d A_f$

Drawing power, $P_d = F_d V_f$

Maximum reduction per pass

Perfectly plastic material

Drawing stress = yield stress of the material

$$\sigma_d = Y \ln\left(\frac{A_o}{A_f}\right) = Y$$

r = 0.63

Maximum reduction per pass

Strain hardening material

Drawing stress = yield stress of the material

$$\sigma_d = \bar{Y} \ln\left(\frac{A_o}{A_f}\right) = \bar{Y}\varepsilon$$

$$r = 1 - e^{-(n+1)}$$

Mechanics of wire and bar drawing

Case 2: Ideal deformation, with friction

$$\sigma_d = Y\left(1+\frac{\tan\alpha}{\mu}\right)\left[1-\left(\frac{A_f}{A_o}\right)^{\mu\cot\alpha}\right]$$

Residual stresses in drawing

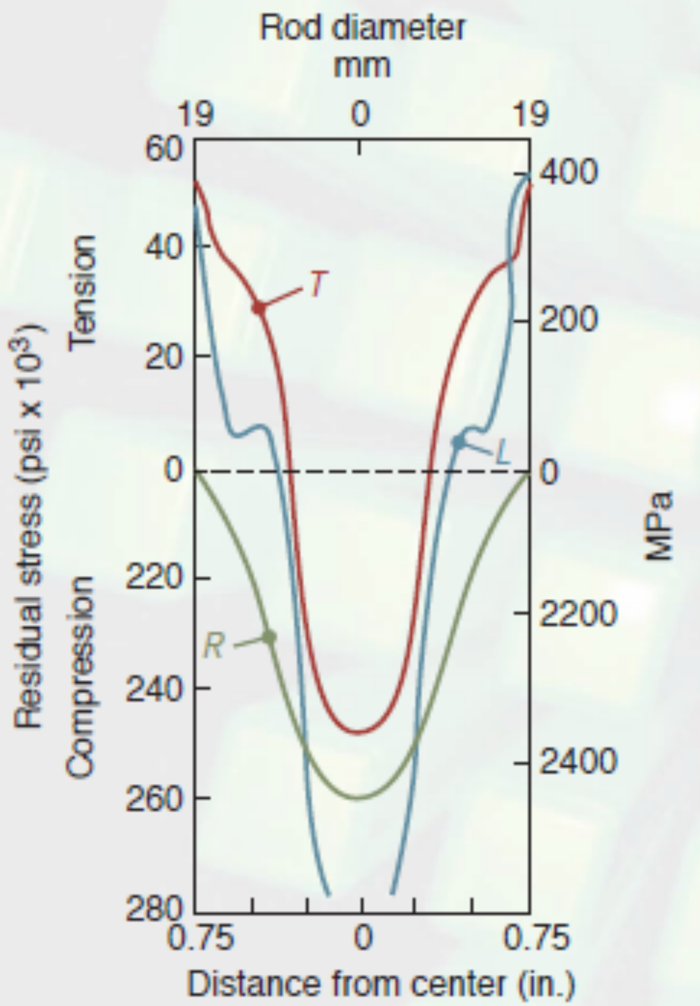


FIGURE 6.65 Residual stresses in cold-drawn 1045 carbon steel round rod: *T* = transverse direction, *L* = longitudinal direction and *R* = radial direction. *Source:* After E.S. Nachtman.

Drawing stresses

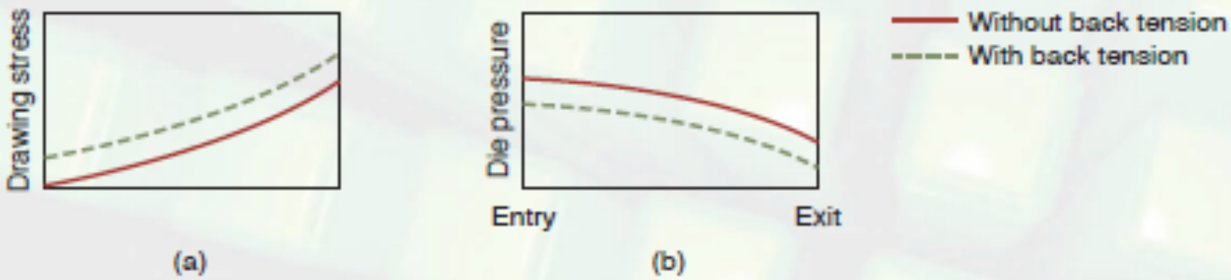


FIGURE 6.62 Variation in the (a) drawing stress and (b) die contact pressure along the deformation zone. Note that as the drawing stress increases, the die pressure decreases (see also yield criteria, described in Section 2.11). Note the effect of back tension on the stress and pressure.

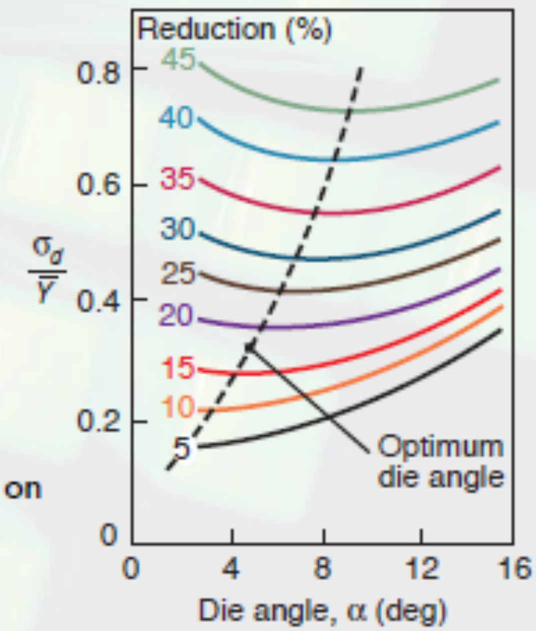


FIGURE 6.63 The effect of reduction in cross-sectional area on the optimum die angle in drawing. *Source:* After J.G.Wistreich.

$$p = Y_f - \sigma_d$$

Example

Q: Assuming zero redundant work and frictional work to be 20% of the ideal work, derive an expression for the maximum reduction in area per pass for a wire drawing operation for a material with a true-stress strain curve of $\sigma = K\varepsilon^n$

$$r = 1 - e^{-(n+1)/1.2}$$

Example

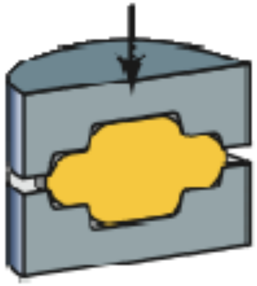
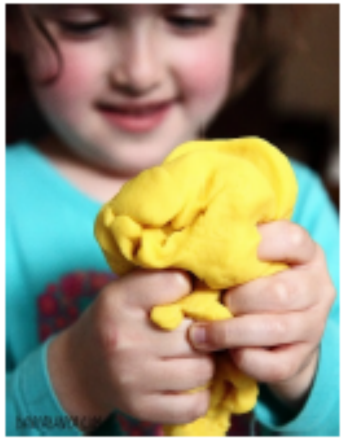
Q: A round rod of annealed brass 70-30 is being drawn from a diameter of 6 mm to 3 mm at a speed of 0.6 m/s. Assume that the frictional and redundant work together constitute 35% of the ideal work of deformation. (a) Calculate power required and die pressure at the exit of die.

K = 895 MPa and n = 0.49

Power = 1.992 kW

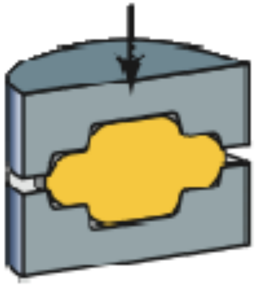
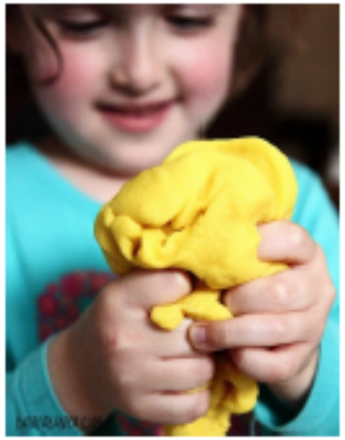
ME2300: Manufacturing Processes
Jan-May 2020

Bulk vs. Sheet

 :  ::  : 

Starting material: sheets made by deformation of bulk material

Bulk vs. Sheet

 :  ::  : 

Sheet forming unlike bulk deformation processes, involves workpieces with a high ratio of surface area to thickness

Sheet metalworking

1. Cutting Operations
2. Bending Operations
3. Drawing
4. Sheet Metal Operations Not Performed on Presses

Sheet metalworking

Cutting and forming operations performed on relatively thin sheets of metal

- Thickness of sheet metal = 0.4 mm (1/64 in) to 6 mm (1/4 in)
- Thickness of plate stock > 6 mm
- Operations usually performed as cold working

Sheet and plate metal products

- Sheet and plate metal parts for consumer and industrial products such as
  - Automobiles and trucks
  - Airplanes
  - Railway cars and locomotives
  - Farm and construction equipment
  - Small and large appliances
  - Office furniture
  - Computers and office equipment

Advantage of sheet metal parts

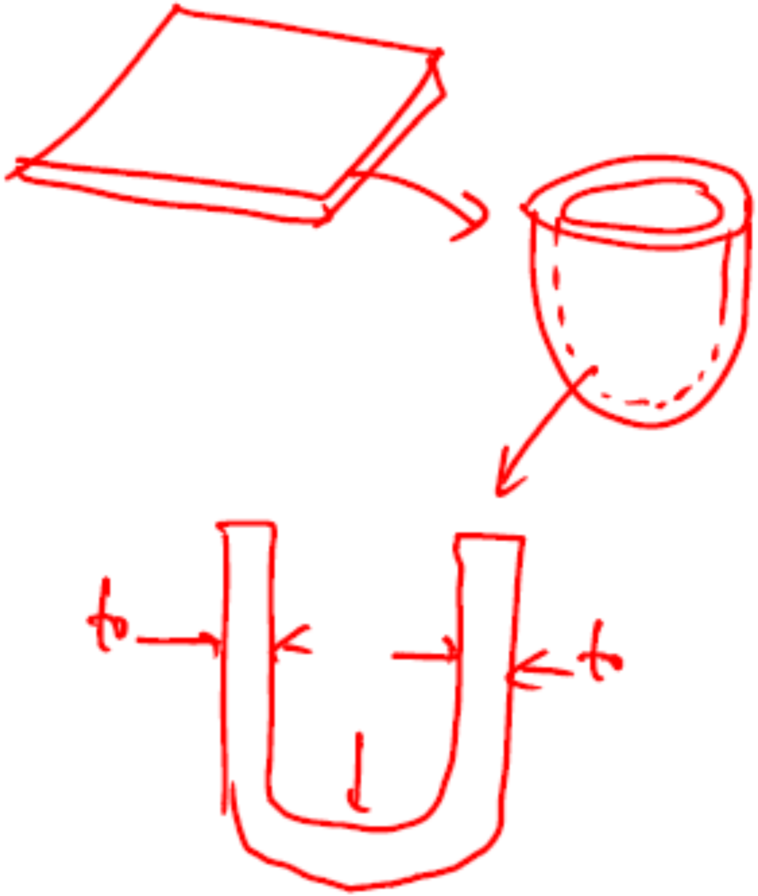
- High strength
- Good dimensional accuracy
- Good surface finish
- Relatively low cost
- For large quantities, economical mass production operations are available

Different ways to deform sheets

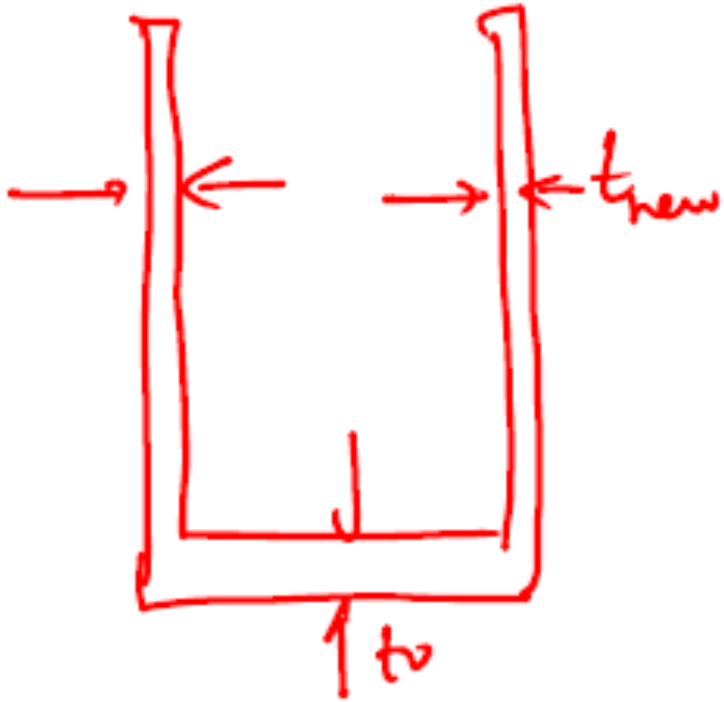
1. Shearing
2. Blanking
3. Rotary shearing
4. Shaving
5. Bending
6. Deep drawing
7. Roll forming

Different ways to deform sheet metals

Without change in thickness



With change in thickness



Bulk vs. Sheet deformation

There are several ways in which sheet metal works differs from bulk deformation:

-Type of deformation: compression vs. tension

-Amount of plastic strain and closeness to elastic region

-Grain size effects

-Anisotropy (directionally dependent property)

We will explore all these concepts in the next few slides

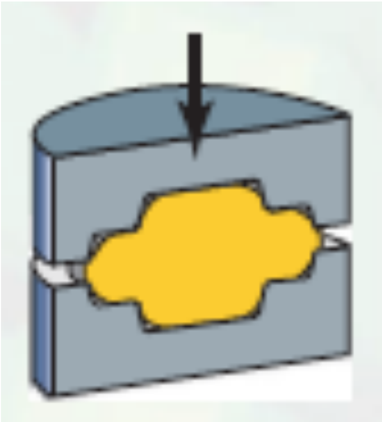
Bulk vs. Sheet: Compression vs. tension

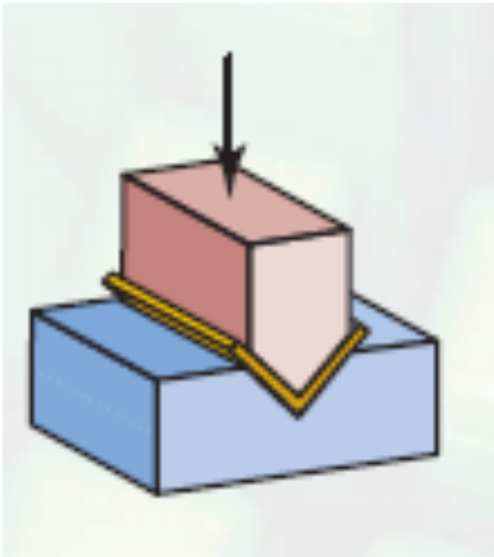
• Bulk deformation predominantly involves compressive stresses

-Some tensile stress regions will be there

• Sheet deformation predominantly involve stretching the sheet in tension

-Some areas will go into compression





Sheets are not good under compression

Sheets will buckle-wrinkle

Tensile test

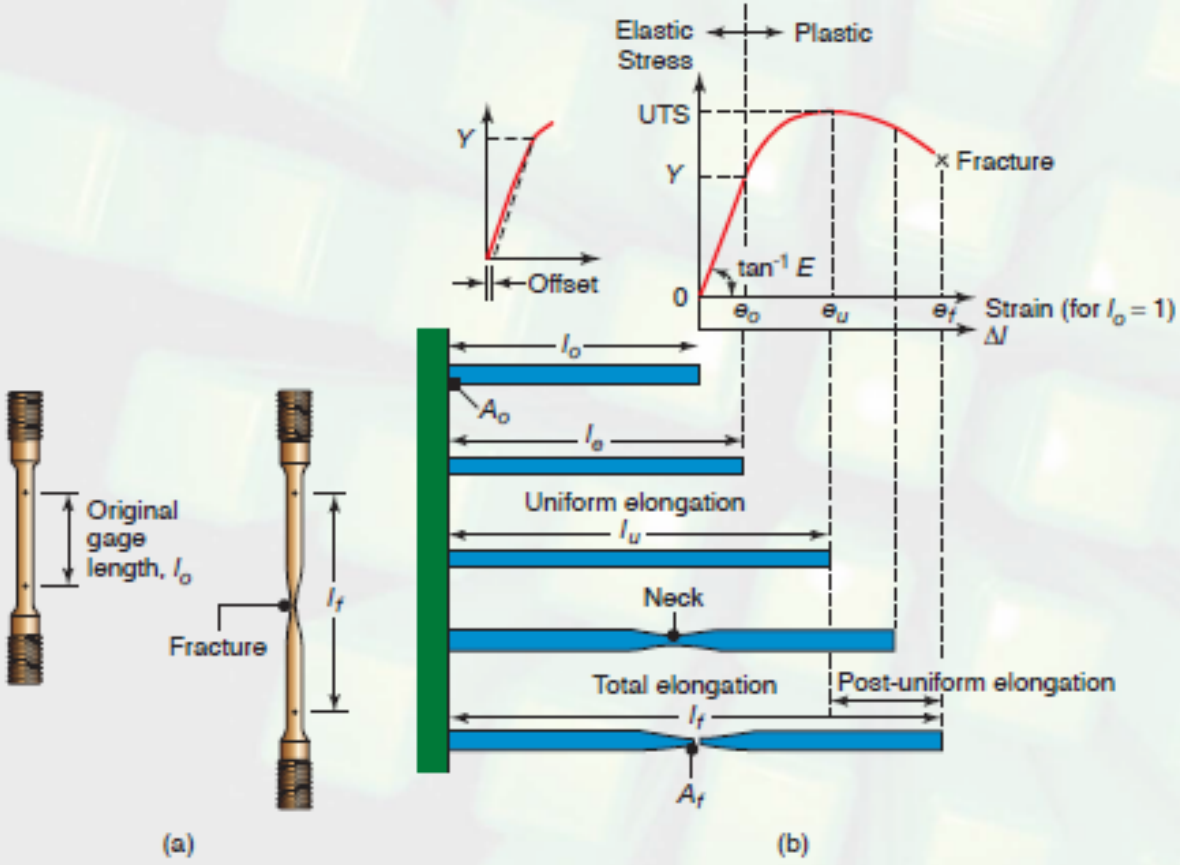
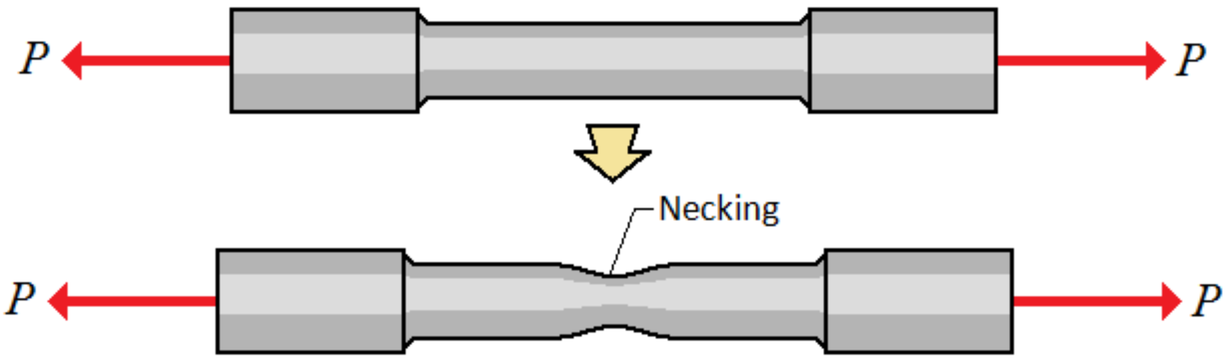


FIGURE 2.2 (a) Original and final shape of a standard tensile-test specimen. (b) Outline of a tensile-test sequence showing different stages in the elongation of the specimen.

Bulk vs. Sheet: Necking is important in sheet (tension effect)

When does necking occurs in tension?

Strain at which necking occurs?



Rate of decrease in cross sectional area is greater than the rate of increase in strength

Example

Q: A material has true stress-strain curve given by $\sigma=K\varepsilon^n$ where K= 690 kPa and n=0.5). Calculate the ultimate tensile strength and the engineering UTS of this material.

Bulk vs. Sheet: Necking is important in sheet (tension effect)

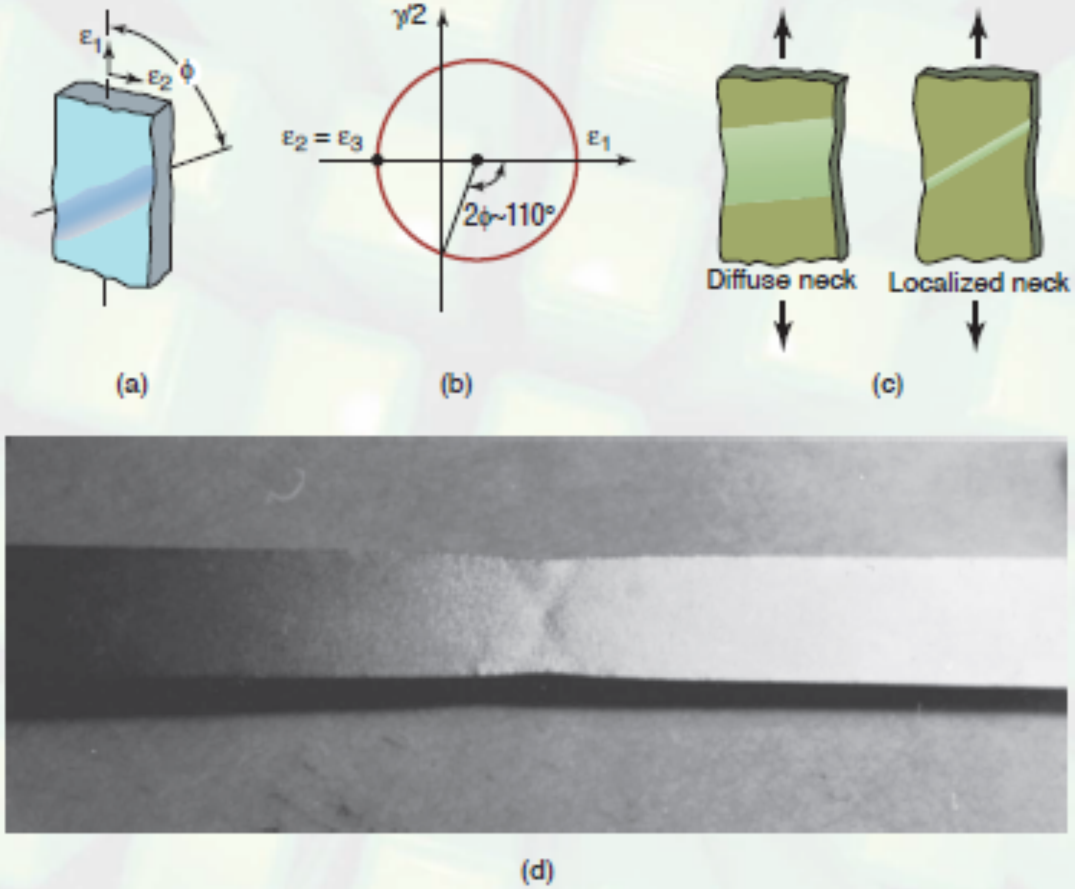


FIGURE 7.1 (a) Localized necking in a sheet-metal specimen under tension. (b) Determination of the angle of neck from the Mohr's circle for strain. (c) Schematic illustrations for diffuse and localized necking, respectively. (d) Localized necking in an aluminum strip in tension; note the double neck. *Source:* S. Kalpakjian.

Necking dependence on strain rate sensitivity

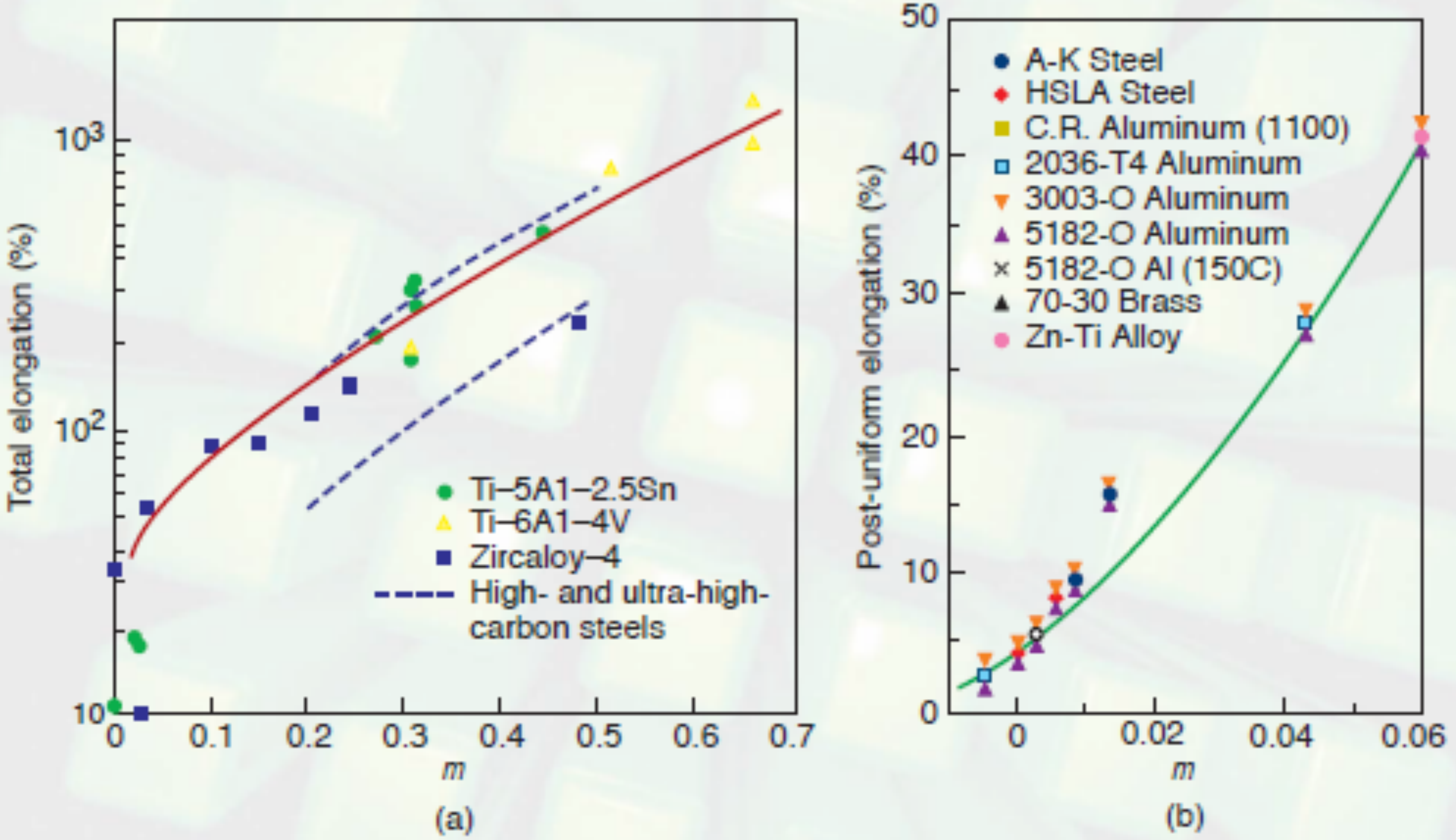


FIGURE 2.12 (a) The effect of strain-rate sensitivity exponent *m* on the total elongation for various metals. Note that elongation at high values of *m* approaches 1000%. *Source:* After D. Lee and W.A. Backofen. (b) The effect of strain-rate sensitivity exponent *m* on the post uniform (after necking) elongation for various metals. *Source:* After A.K. Ghosh.

Bauschinger effect

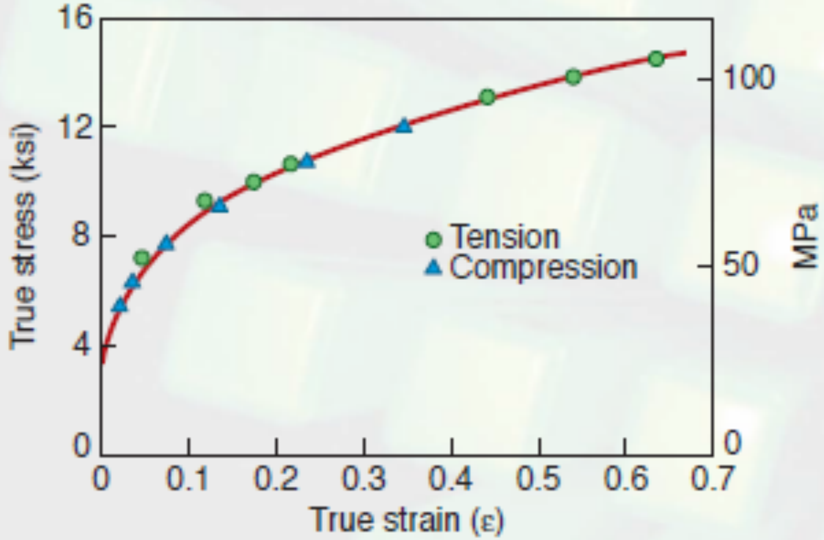


FIGURE 2.16 True stress-true strain curve in tension and compression for aluminum. For ductile metals, the curves for tension and compression are identical. *Source:* After A.H. Cottrell.

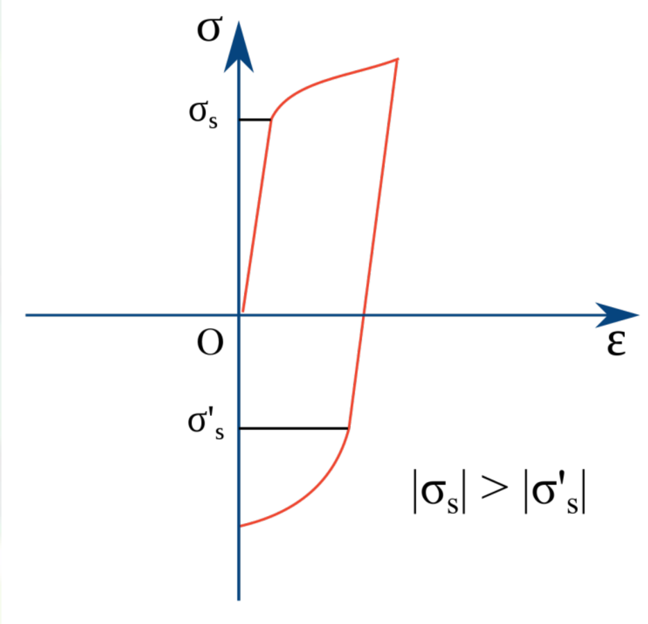
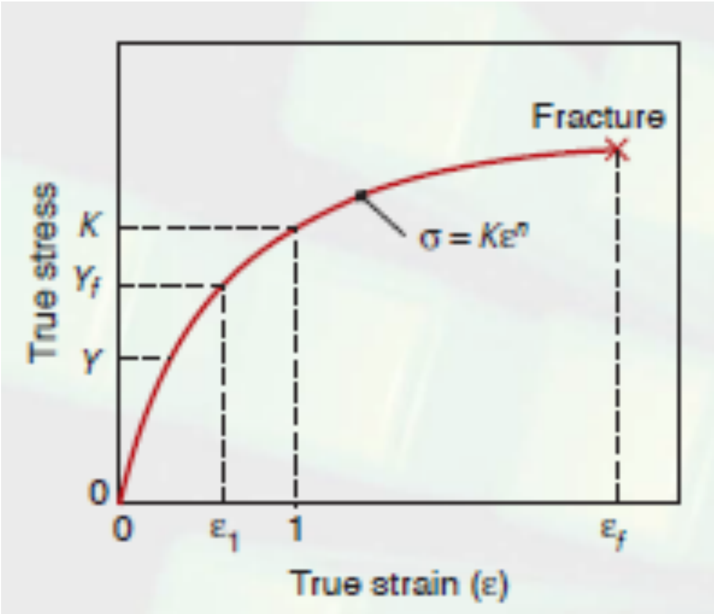


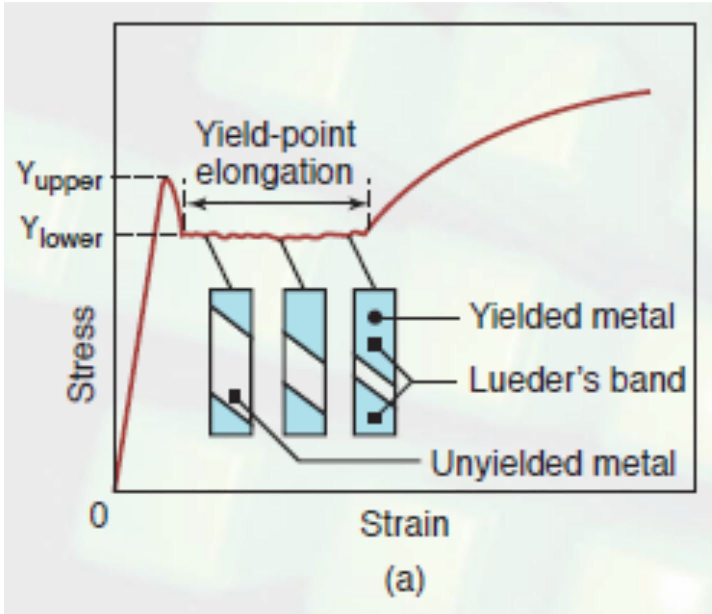
FIGURE 2.17 Schematic illustration of the Bauschinger effect. Arrows show loading and unloading paths. Note the decrease in the yield stress in compression after the specimen has been subjected to tension. The same result is obtained if compression is applied first, followed by tension, whereby the yield stress in tension decreases.

Bulk vs. Sheet: amount of plastic strain

- Bulk deformation involves large plastic strains – far away from the elastic region
- Sheet deformation involves lower plastic strains – closer to the elastic region

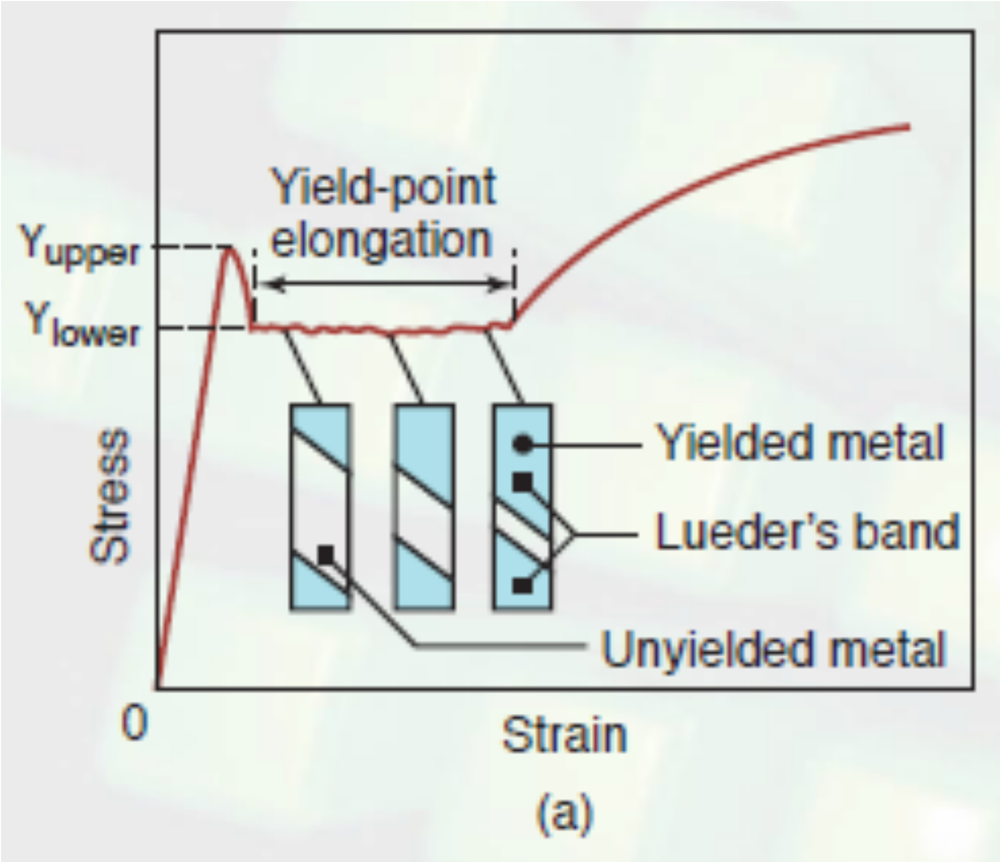


Bulk deformation elastic region is ignored



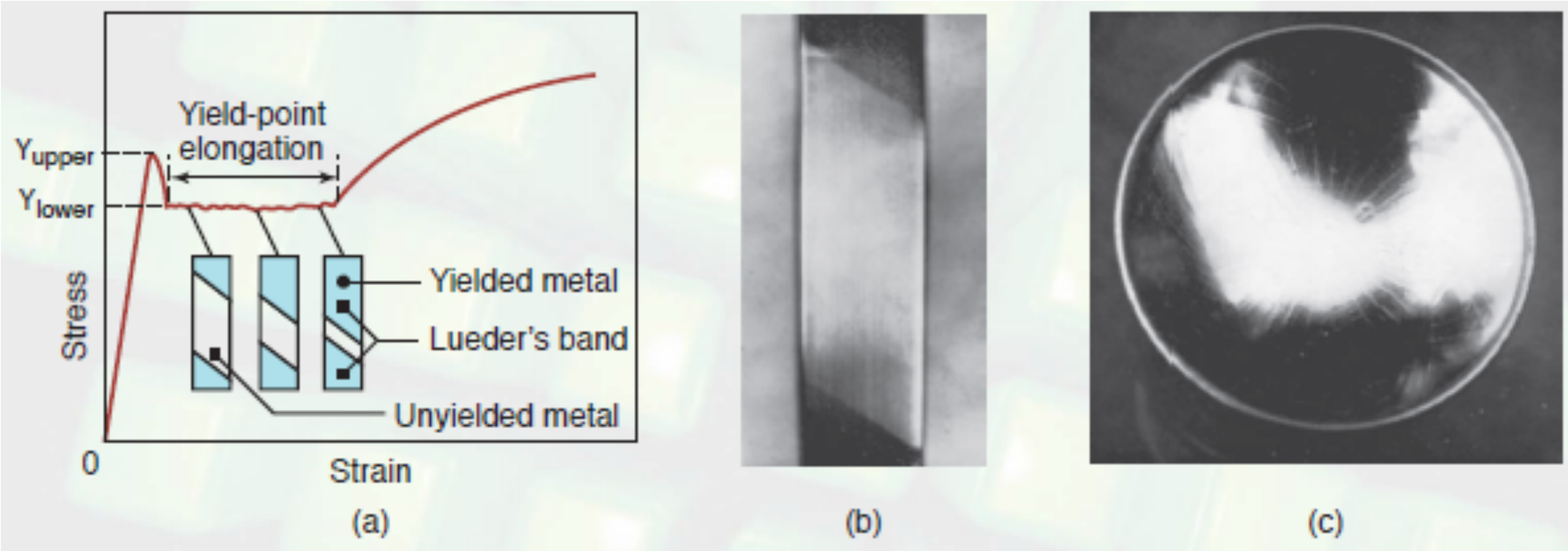
Sheet deformation: region near elastic region is an important consideration

Yield point elongation: low carbon steel



Strain rate (↑) and grain size (↓) of the sheet metal

Effect of being near elastic region: yield point elongation/Lueders bands



To avoid this problem, temper rolling is carried out – where sheet thickness is reduced (0.5-1.5%) by cold rolling

Sheet metal working terminology

1. "Punch-and-die"
   – Tooling to perform cutting, bending, and drawing
2. "Stamping press"
   – Machine tool that performs most sheet metal operations
3. "Stampings"
   – Sheet metal products

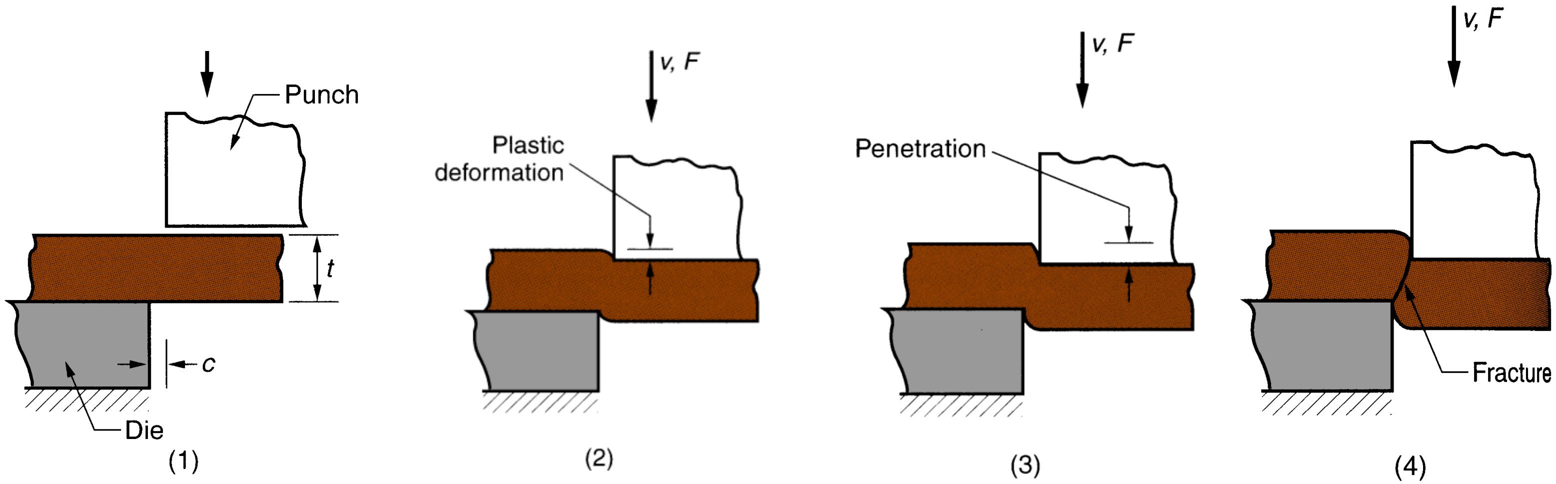
Major categories of sheet metal processes

1. Cutting
   - Shearing to separate large sheets; or cut part perimeters or make holes in sheets

2. Bending
   - Straining sheet around a straight axis

3. Drawing
   - Forming of sheet into convex or concave shapes

Cutting



Shearing between two sharp cutting edges

Shearing, Blanking and Punching

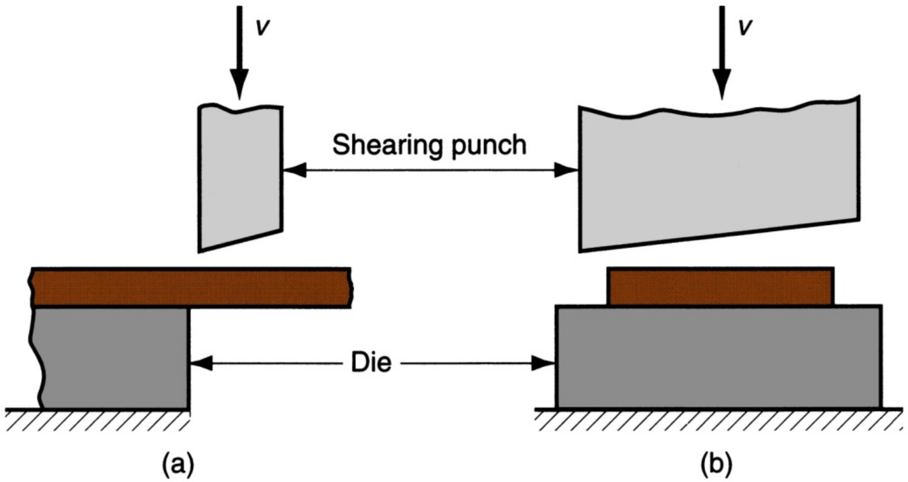
Three principal operations in pressworking that cut sheet metal:

- Shearing
- Blanking
- Punching

Shearing

Sheet metal cutting operation along a straight line between two cutting edges

- Typically used to cut large sheets into smaller sections for subsequent operations



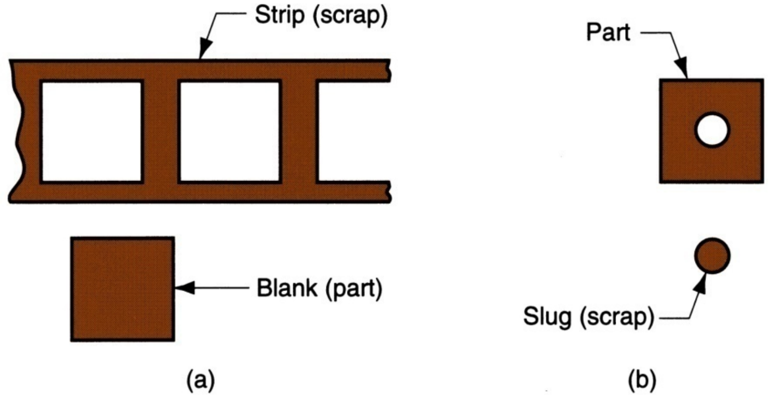
Blanking and punching

Blanking - sheet metal cutting to separate piece from surrounding stock

- Cut piece is the desired part, called a *blank*

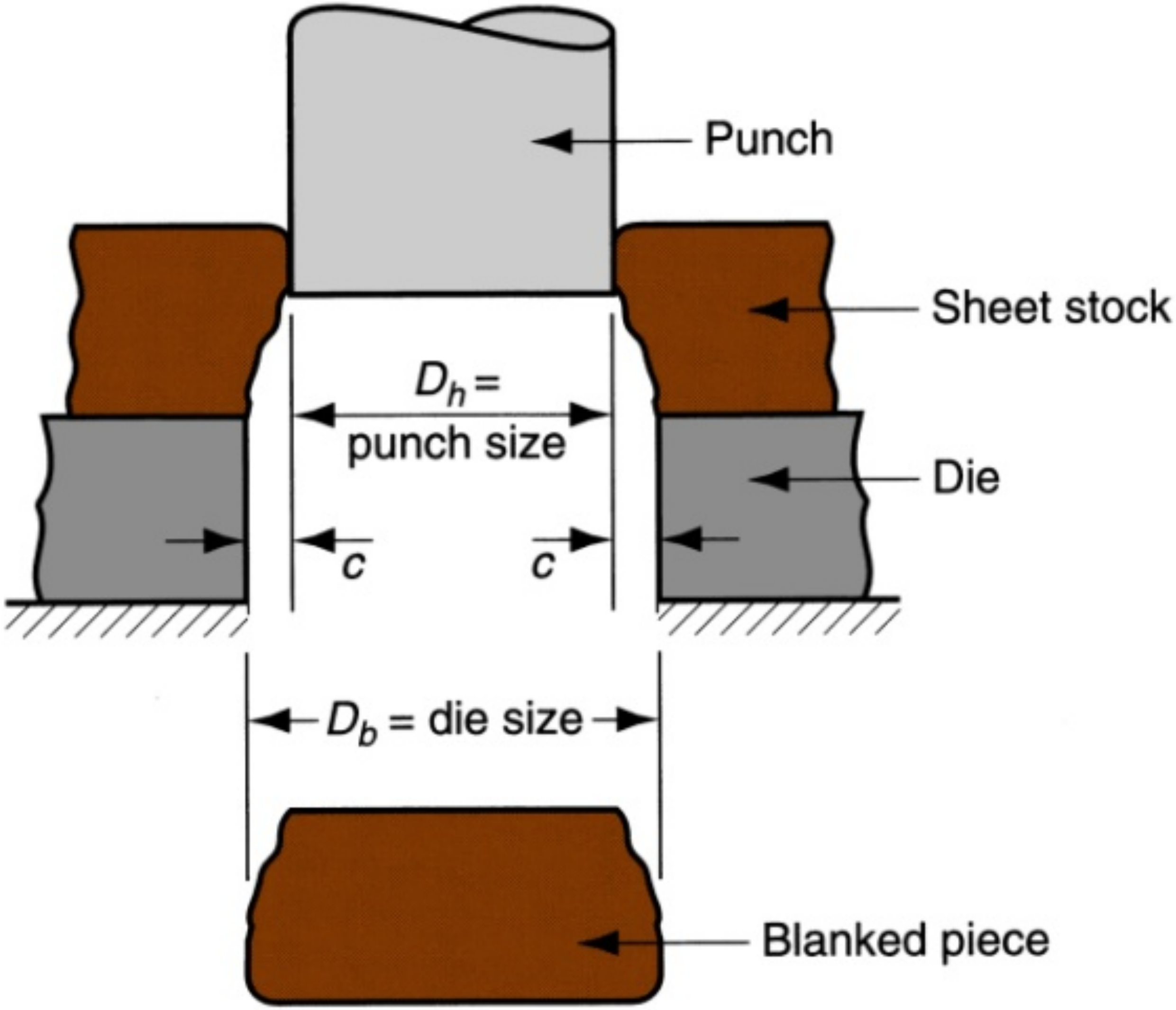
Punching - sheet metal cutting similar to blanking except cut piece is scrap, called a *slug*

- Remaining stock is the desired part



(a) Blanking and (b) punching

Clearance in sheet metal cutting



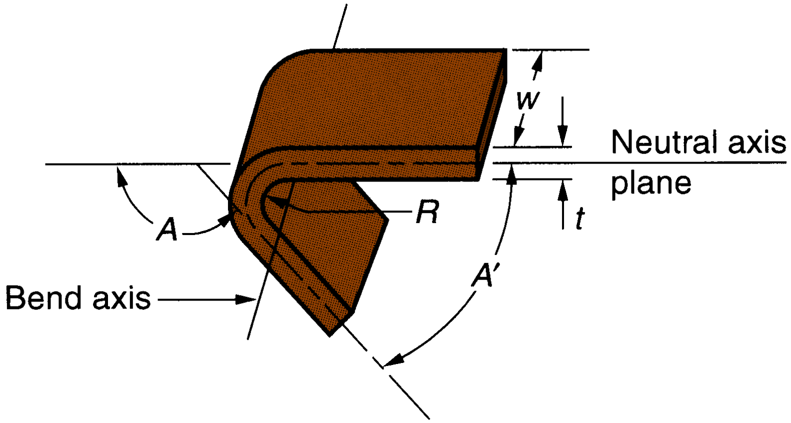
Clearance in sheet metal cutting

Distance between the punch and die

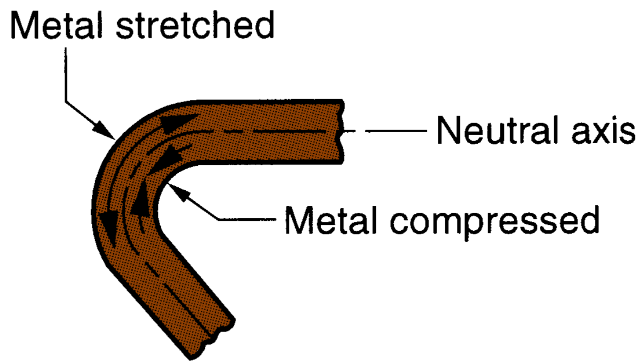
- Typical values range between 4% and 8% of stock thickness
  - If too small, fracture lines pass each other, causing double burnishing and larger force
  - If too large, metal is pinched between cutting edges and excessive burr results

Bending

Straining sheet metal around a straight axis to take a permanent bend



(a)



(b)

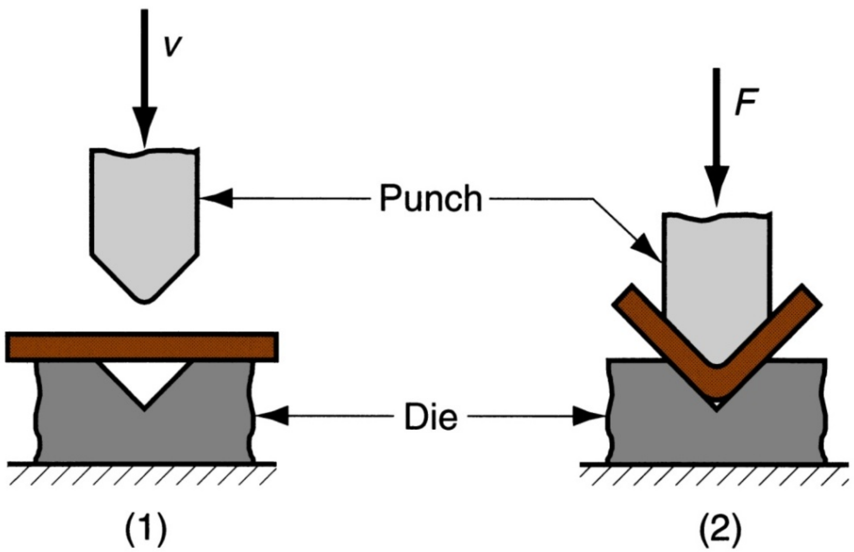
(a) Bending of sheet metal

(b) both compression and tensile elongation of the metal occur in bending

V-bending

V-bending: Performed with a V-shaped die

- For low production
- Performed on a *press brake*
- V-dies are simple and inexpensive

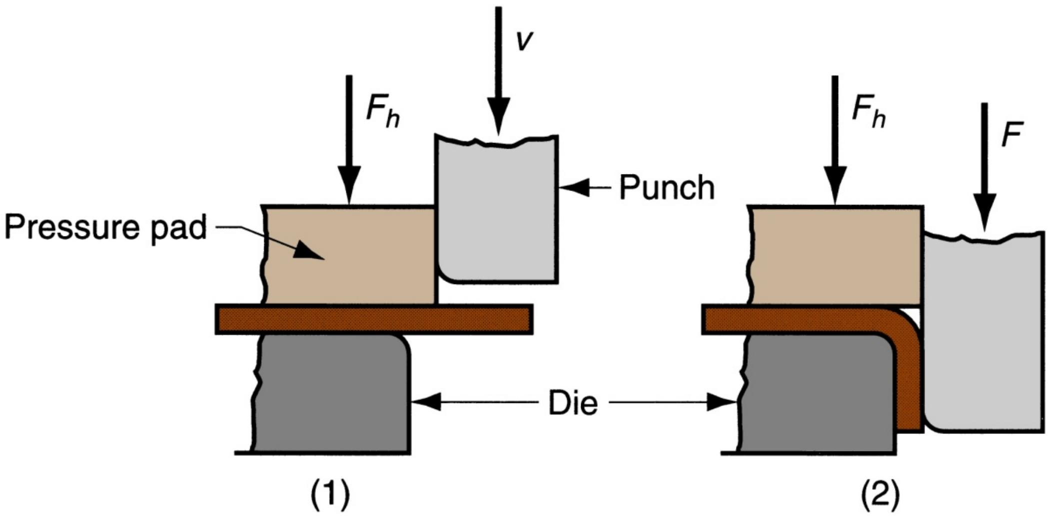


(a)

Edge bending

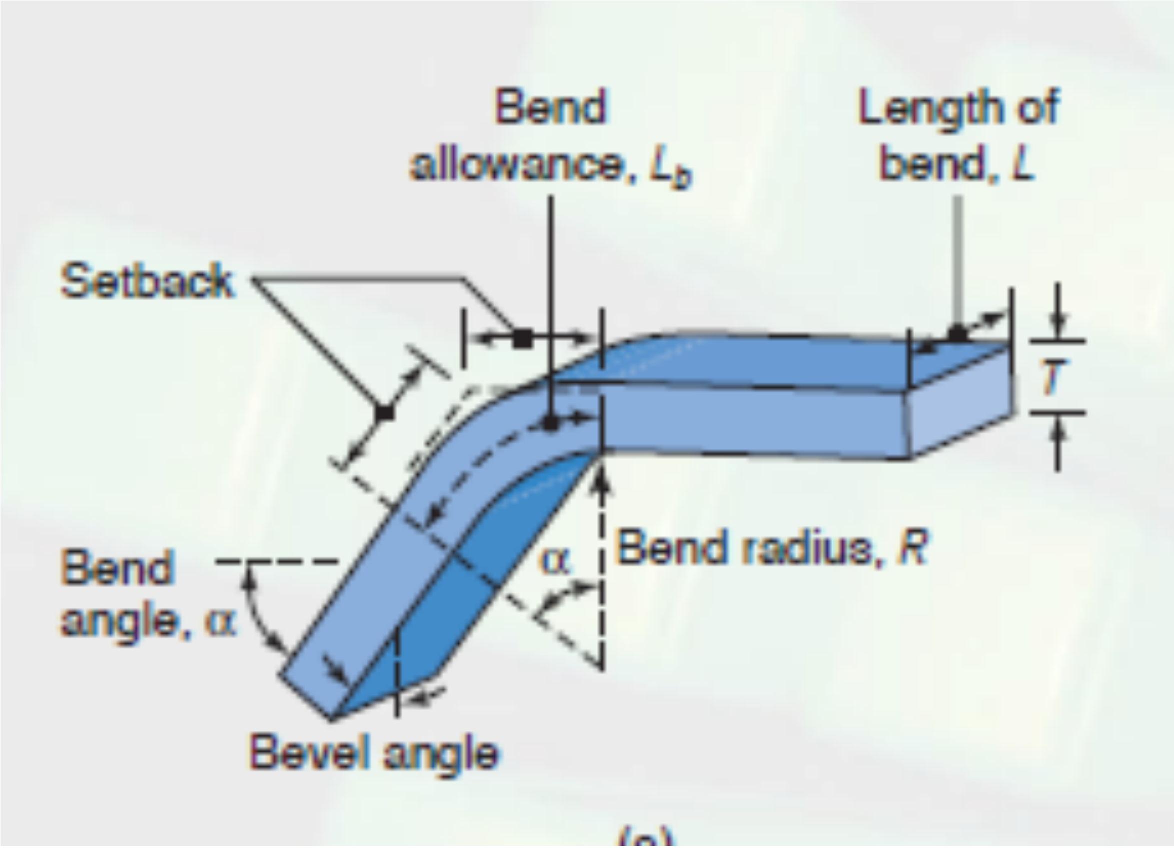
Edge-bending: Performed with a wiping die

- For high production
- Pressure pad required
- Dies are more complicated and costly



(b)

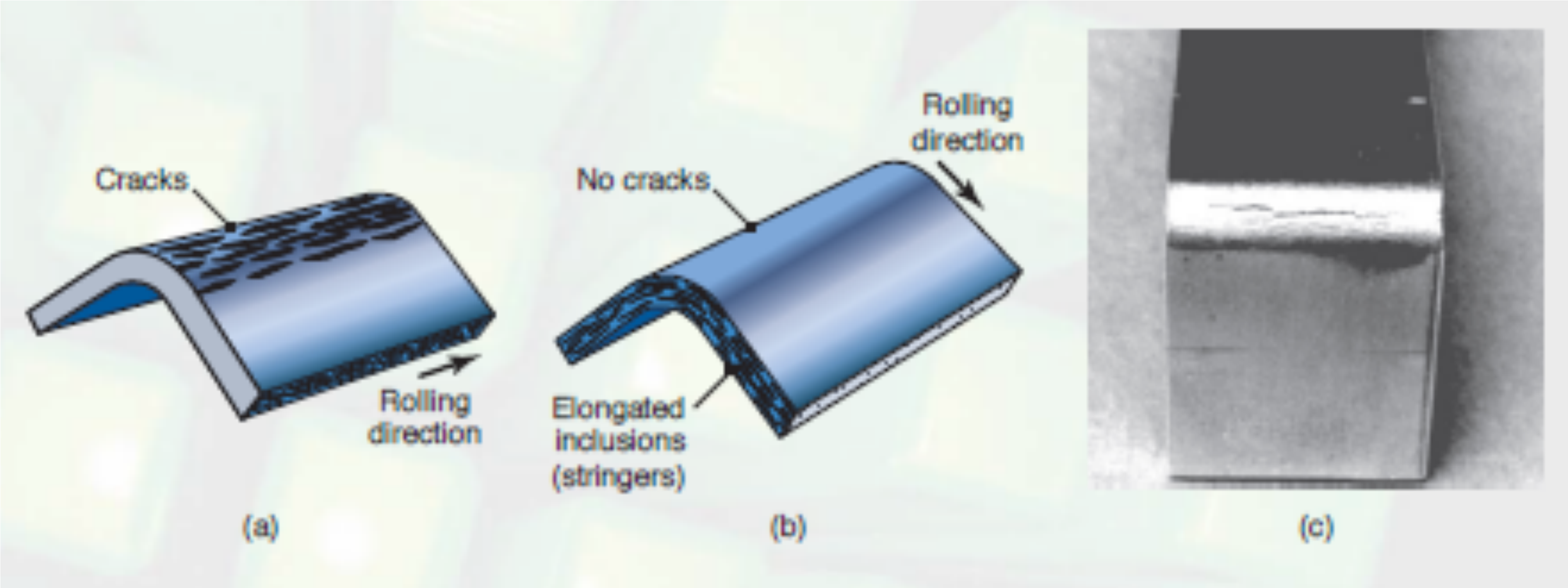
Calculation of length: Bending



$$L_b = \alpha(R + kt)$$

k = 0.33 for R<2t
k = 0.5 for R>2t

Minimum bending radius



The radius R at which cracks appear at the outer surface of the bend is called minimum bending radius

Strain while bending?

$$e = \frac{1}{(2R/t+1)}$$

Minimum bending radius

$$\frac{R}{t} = \frac{50}{r} - 1$$

Minimum bending radius

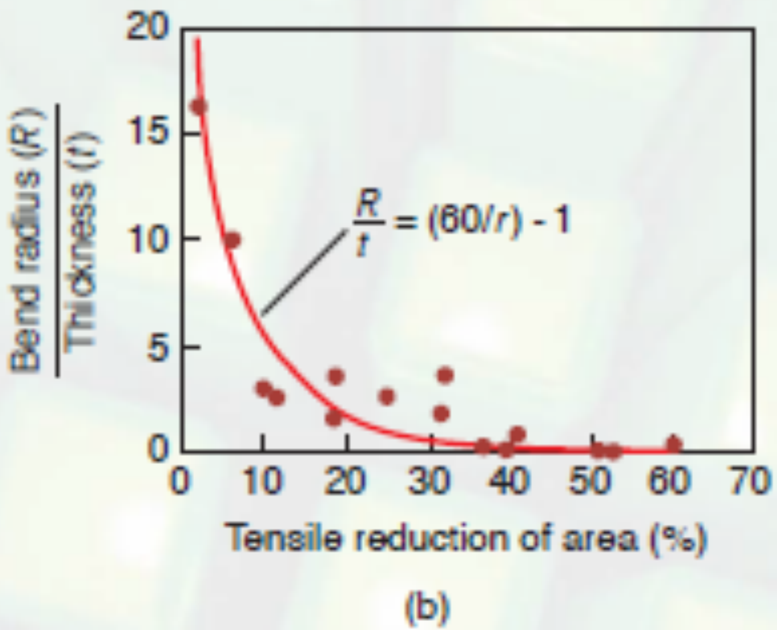
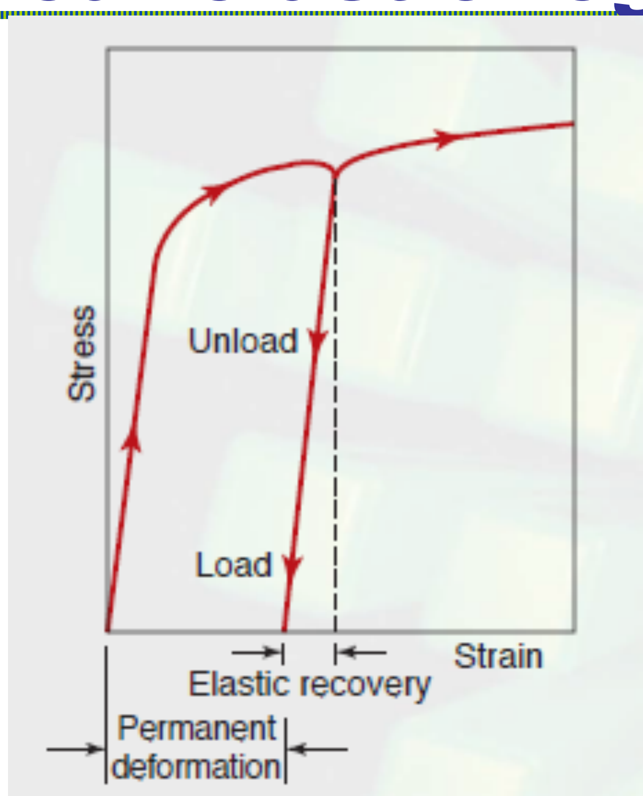


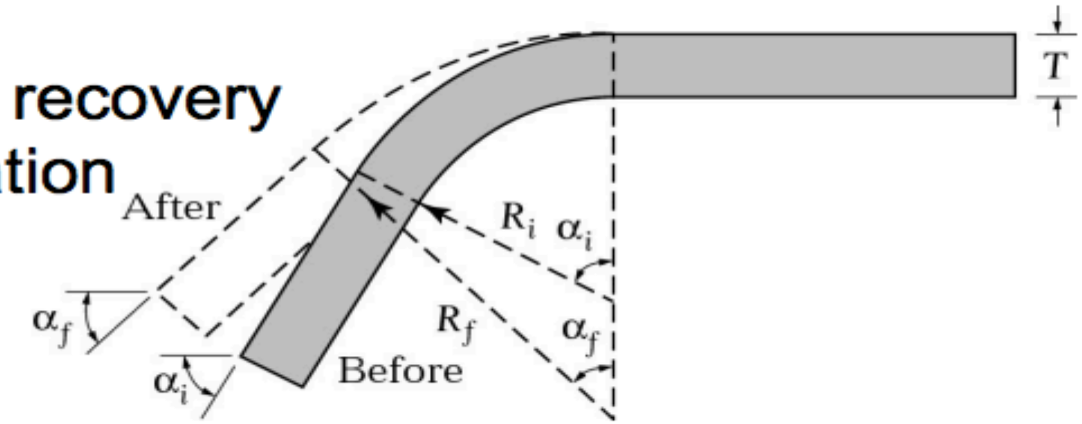
FIGURE 7.5 (a) Bending terminology. Note that the bend radius is measured to the inner surface of the bend, and that the length of the bend is the width of the sheet. (b) Relationship between the ratio of bend-radius to sheet-thickness and tensile reduction of area for a variety of materials. Note that sheet metal with a reduction of area of about 50% can be bent and flattened over itself without cracking, similar to folding paper. *Source:* After J. Datsko and C.T. Yang.

Effect of being near elastic region: Springback



- Springback is the elastic recovery following plastic deformation during bending

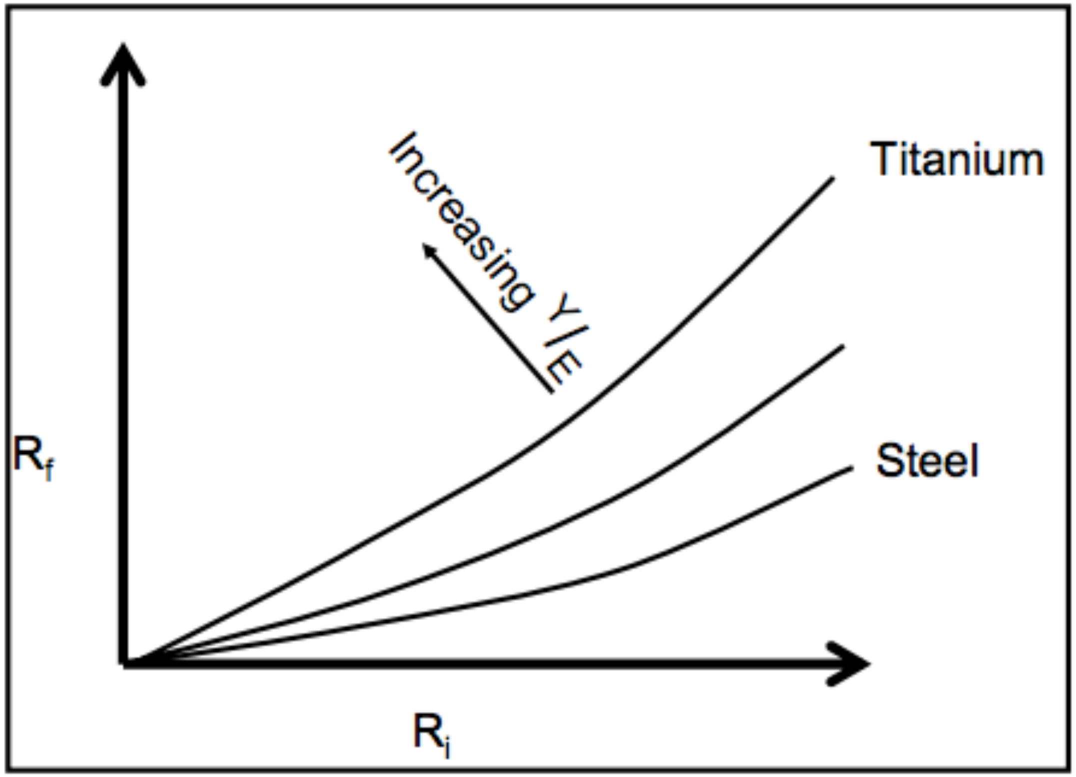
$$\frac{R_i}{R_f} = 4\left(\frac{R_i Y}{ET}\right)^3 - 3\left(\frac{R_i Y}{ET}\right) + 1$$



Springback

Elastic recovery of material leads to spring back

- Y = Yield stress E = Young's Modulus t = thickness
- $$\frac{R_i}{R_f} = 4\cdot\left(\frac{R_i}{t}\cdot\frac{Y}{E}\right)^3 - 3\cdot\left(\frac{R_i}{t}\cdot\frac{Y}{E}\right) + 1 \longrightarrow \frac{1}{R_i} - \frac{1}{R_f} = \frac{3}{t}\cdot\left(\frac{Y}{E}\right) - \frac{4R_i^2}{t^3}\cdot\left(\frac{Y}{E}\right)^3$$
- With increase in R_i / t or Y OR decrease in E spring back increases



Springback

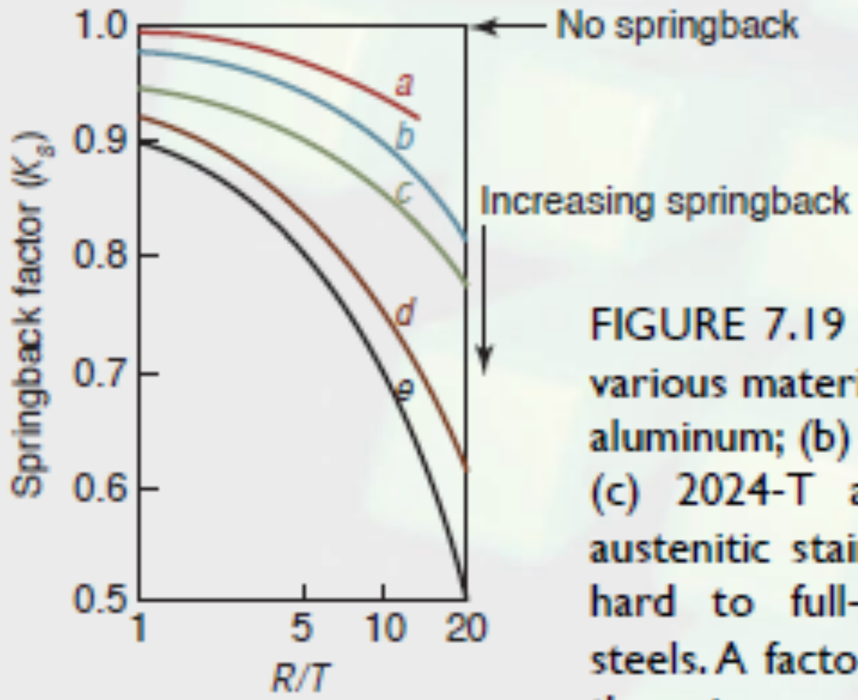


FIGURE 7.19 Springback factor, K_s, for various materials: (a) 2024-0 and 7075-0 aluminum; (b) austenitic stainless steels; (c) 2024-T aluminum; (d) 1/4-hard austenitic stainless steels; and (e) 1/2-hard to full-hard austenitic stainless steels. A factor of $K_s = 1$ indicates that there is no springback. *Source:* After G. Sachs.

Springback factor:

$$K_s = \frac{\alpha_f}{\alpha_i} = \frac{(2R_i/t)+1}{(2R_f/t)+1}$$

Sheet metal: Anisotropy effect

Directionality

Rolling

Sheet metal working

Anisotropy

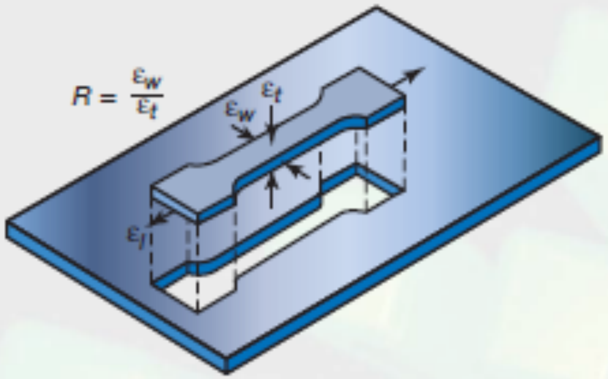


FIGURE 7.54 Definition of the normal anisotropy, R, in terms of width and thickness strains in a tensile-test specimen cut from a rolled sheet. Note that the specimen can be cut in different directions with respect to the length, or rolling direction, of the sheet.

Material	R
Zinc alloys	0.4-0.6
Hot-rolled steel	0.8-1.0
Cold-rolled rimmed steel	1.0-1.4
Cold-rolled aluminum-killed steel	1.4-1.8
Aluminum alloys	0.6-0.8
Copper and brass	0.6-0.9
Titanium alloys (α)	3.0-5.0
Stainless steels	0.9-1.2
High-strength low-alloy steels	0.9-1.2

TABLE 7.3 Typical range of the average normal anisotropy ratio, $\overline{R}$, for various sheet metals.

Normal anisotropy:

$$R = \frac{\varepsilon_w}{\varepsilon_t} = \frac{\ln\left(\frac{w_o}{w_f}\right)}{\ln\left(\frac{t_o}{t_f}\right)}$$

Average anisotropy:

$$\bar{R} = \frac{R_0 + 2R_{45} + R_{90}}{4}$$

Planar anisotropy:

$$\Delta R = \frac{R_0 - 2R_{45} + R_{90}}{2}$$

Sheet metal: Anisotropy effect

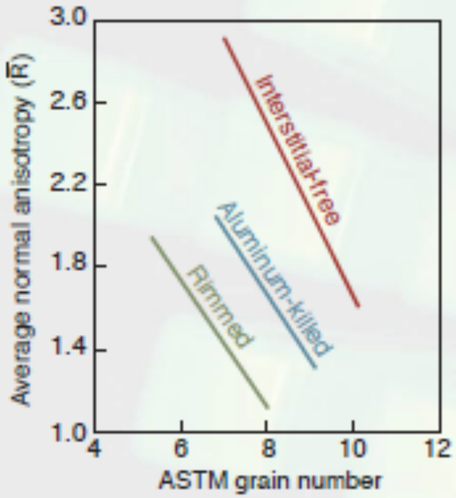


FIGURE 7.55 Effect of grain size on the average normal anisotropy for various low-carbon steels. *Source:* After D.J. Blickwede.

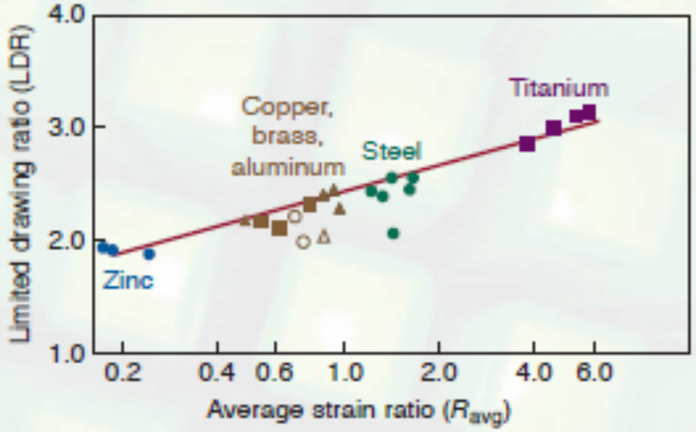


FIGURE 7.56 Effect of average normal anisotropy, $\bar{R}$ on limiting drawing ratio (LDR) for a variety of sheet metals. *Source:* After M. Atkinson.

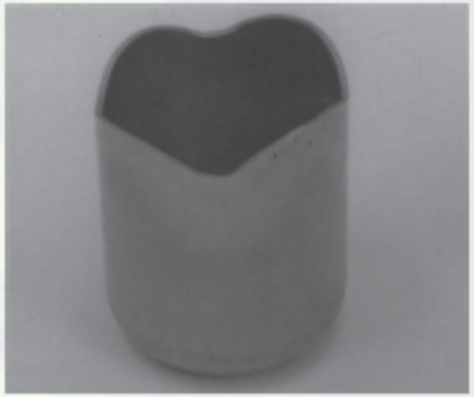


FIGURE 7.57 Typical earing in a drawn steel cup, caused by the planar anisotropy of the sheet metal.

Negative springback

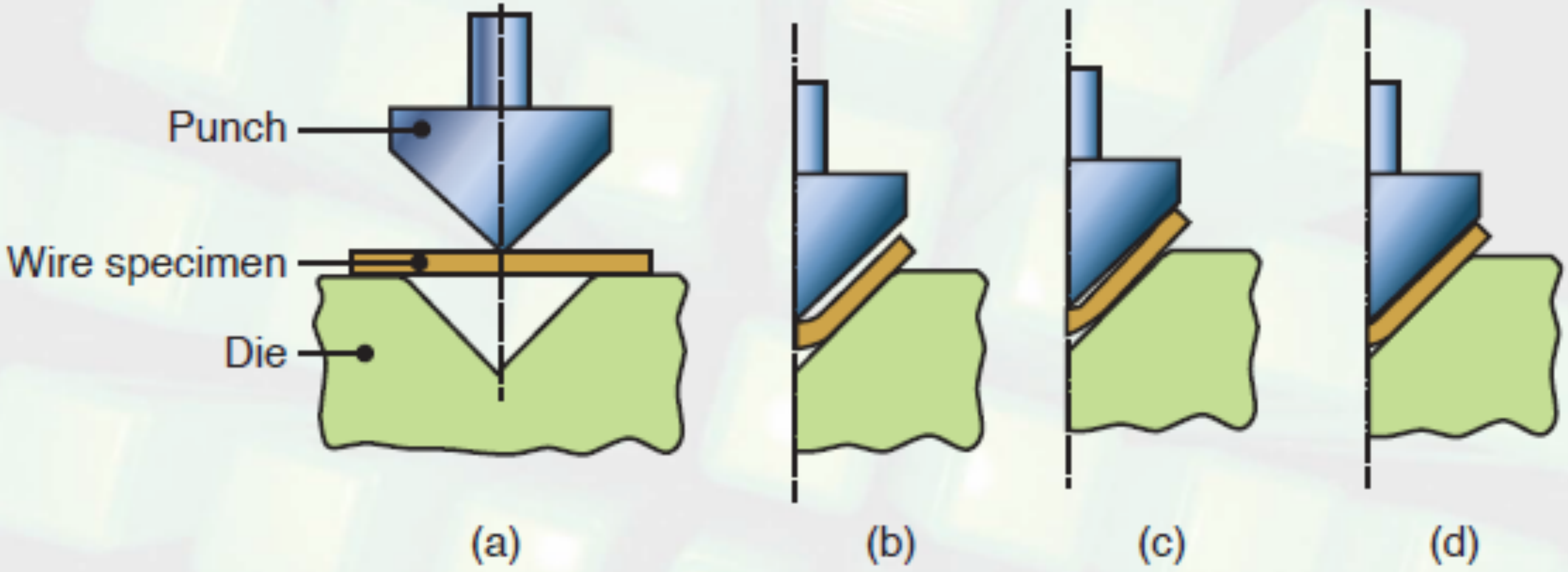


FIGURE 7.20 Schematic illustration of the stages in bending round wire in a V-die. This type of bending can lead to negative springback, which does not occur in air bending (shown in Fig. 7.24a). *Source:* After K.S. Turke and S. Kalpakjian.

Die bending operation

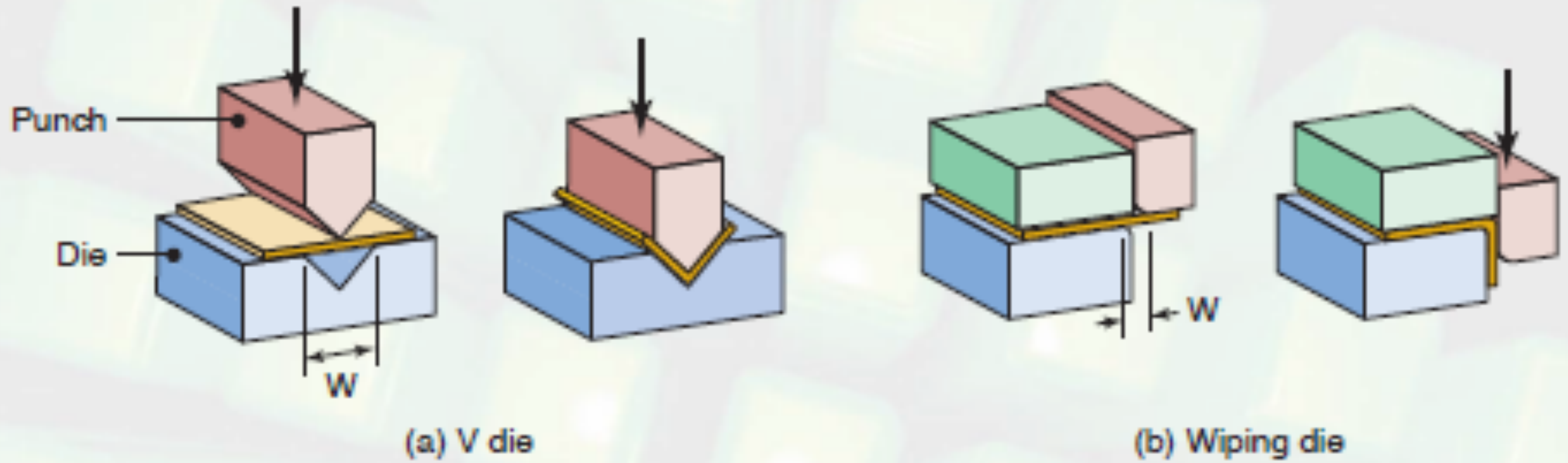


FIGURE 7.22 Common die-bending operations, showing the die-opening dimension W, used in calculating bending forces, as shown in Eq. (7.11).

Bending force:

$$F_{max} = k\frac{(\mathrm{UTS})Lt^2}{W}$$

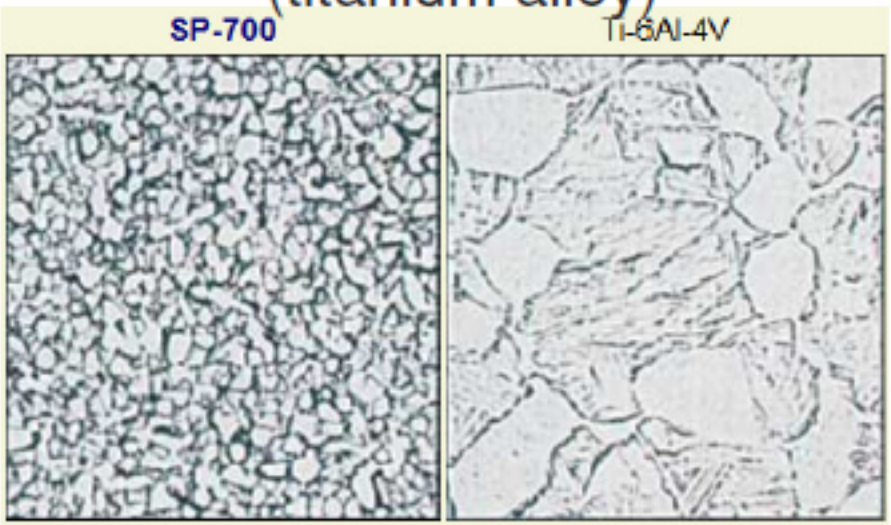
How to apply the force?

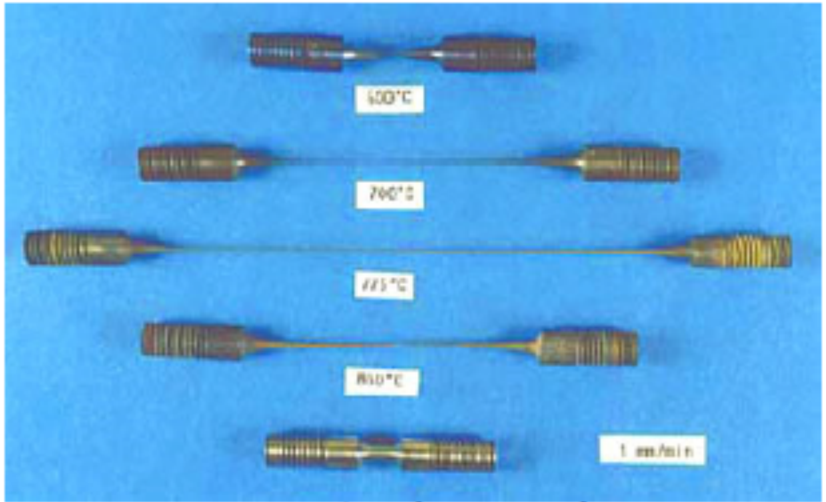
• Mechanically – push by making mechanical contact
– Using a shaped die
– Using a localized tool traversed incrementally (without mold/die)
• Using fluid pressure (with a mold/die)
• Using explosive detonated pressure waves in fluids (with a mold/die)
• Using electro-hydraulic forces (using a mold/die)
• Using magnetic pulses (using a mold/die)
• Internal forces - by inducing compressive stresses on one side of the part

Super plasticity

- Under some conditions (temp, low strain-rates, microstructure) – some materials can stretch to very long lengths without necking
- Ti alloys: 1173 K, Al-alloys: 773 K
- Strain-rates: 10^{-4} to 10^{-2} s^{-1}

(titanium alloy)

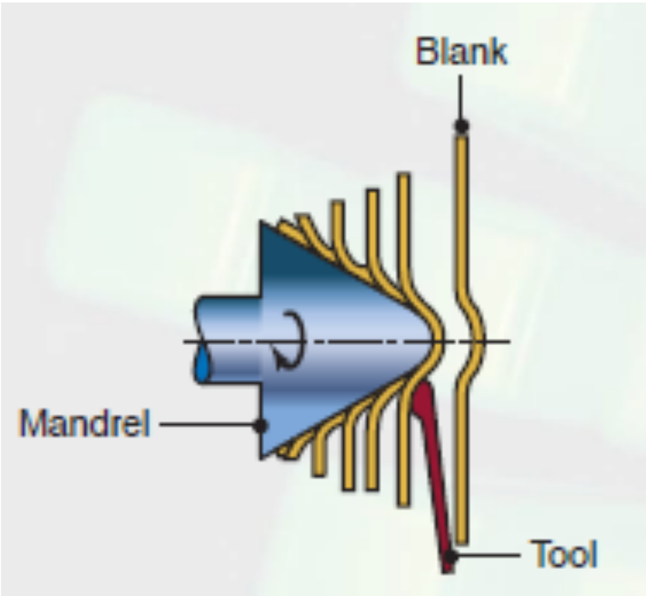




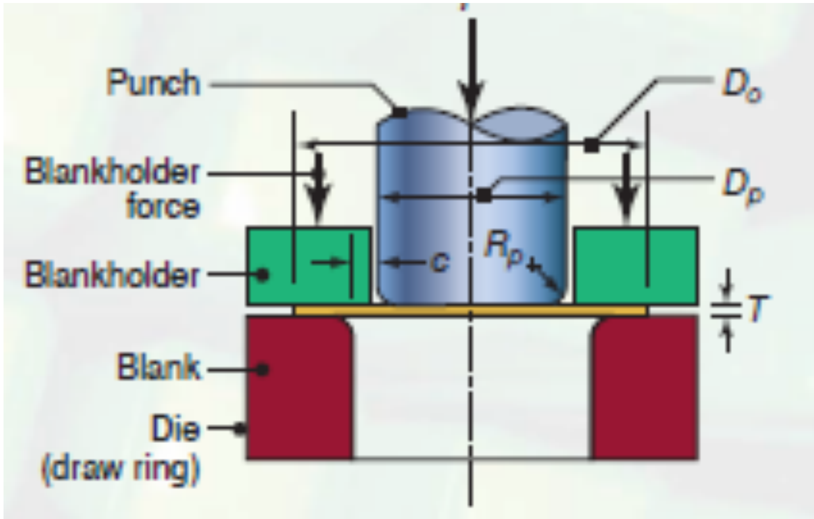
2000% elongation

Spinning and deep drawing

Spinning



Deep drawing



Spinning: Folding over a die constant t

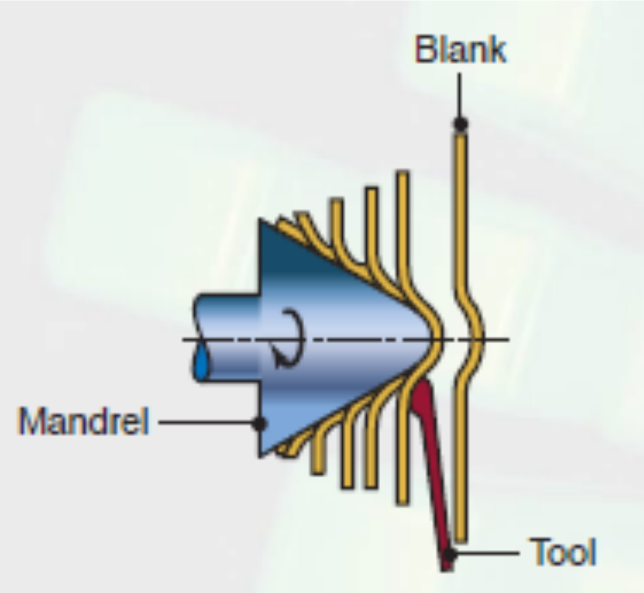
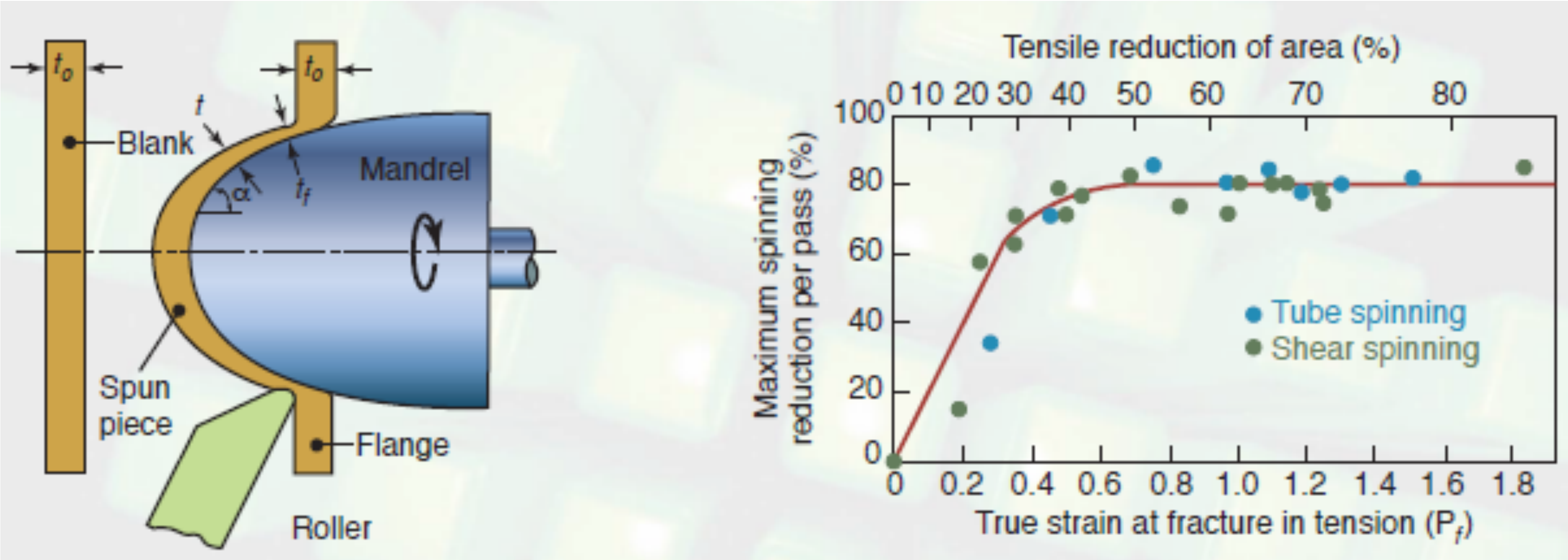


FIGURE 7.37 Typical shapes produced by the conventional spinning process. Circular marks on the external surfaces of components usually indicate that the parts have been made by spinning, such as aluminum kitchen utensils and light reflectors.

Spinnability test



Maximum spinning reduction per pass $\dfrac{t_o - t_f}{t_o} \times 100\%$

Deep drawing

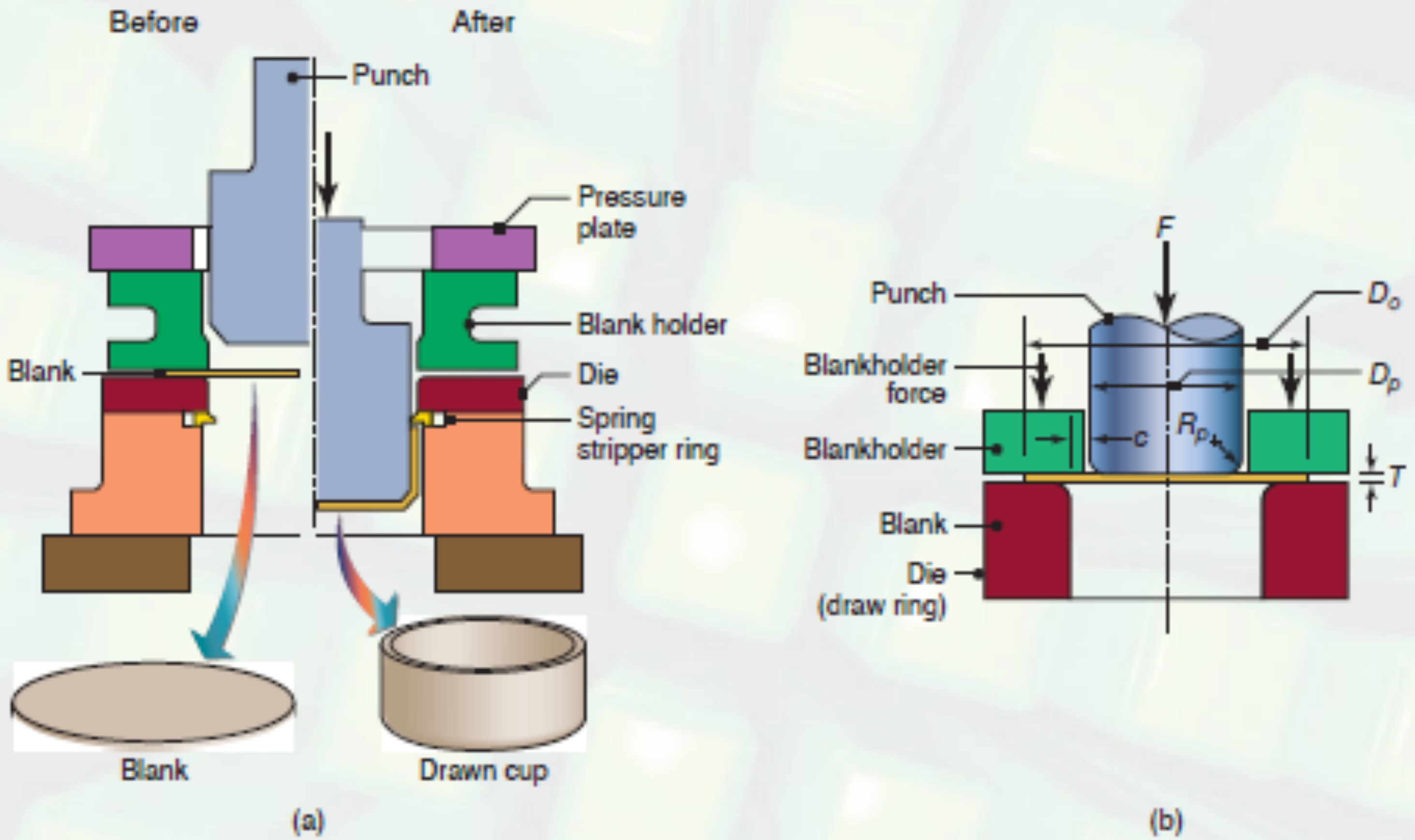


FIGURE 7.49 (a) Schematic illustration of the deep drawing process on a circular sheet-metal blank. The stripper ring facilitates the removal of the formed cup from the punch. (b) Variables in deep drawing of a cylindrical cup. Note that only the punch force in this illustration is a dependent variable; all others are independent variables, including the blankholder force.

Deformation in Flange and Wall

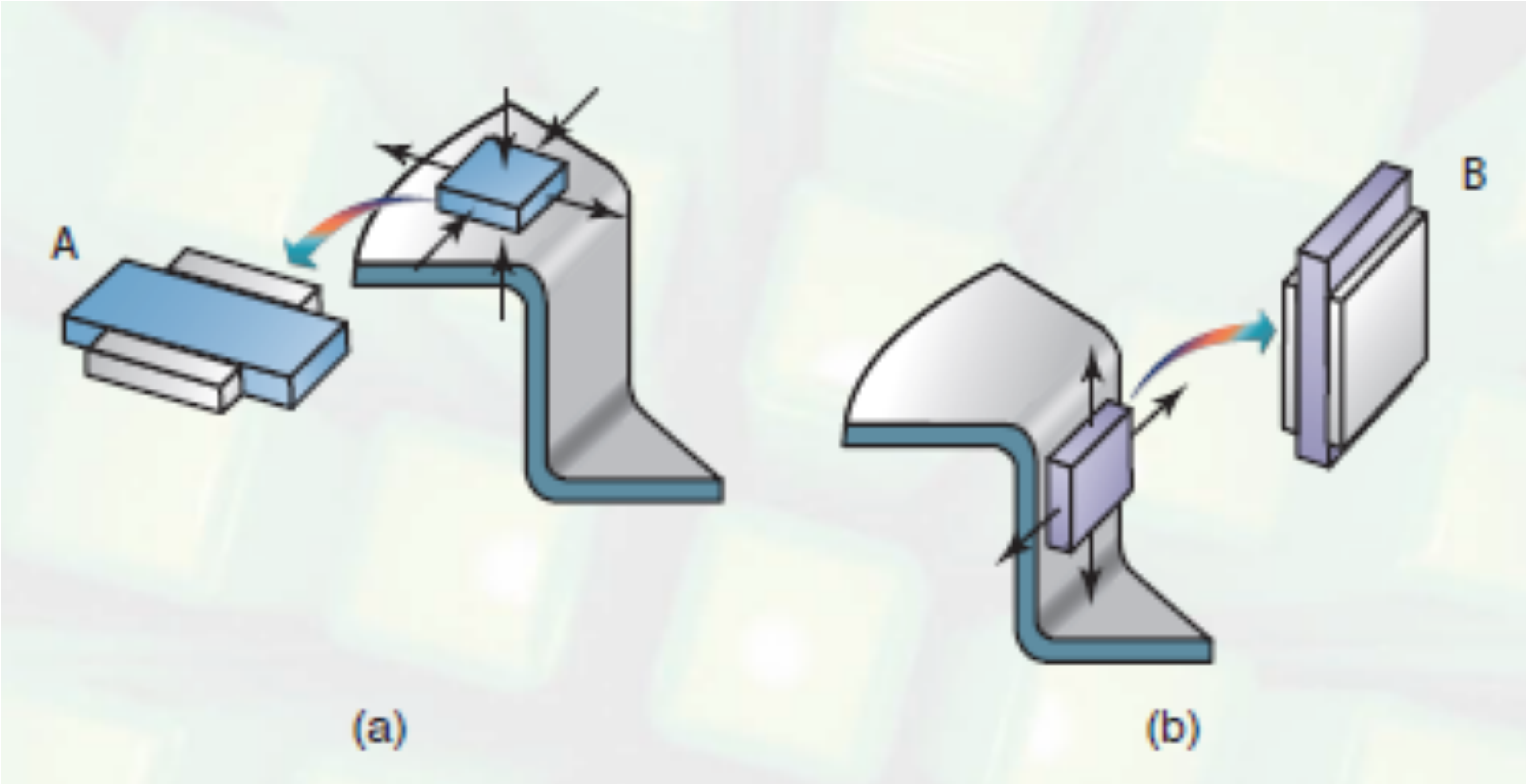


FIGURE: Deformation of elements in (a) the flange and (b) the cup wall in deep drawing of a cylindrical cup.

Pure drawing vs. pure stretching

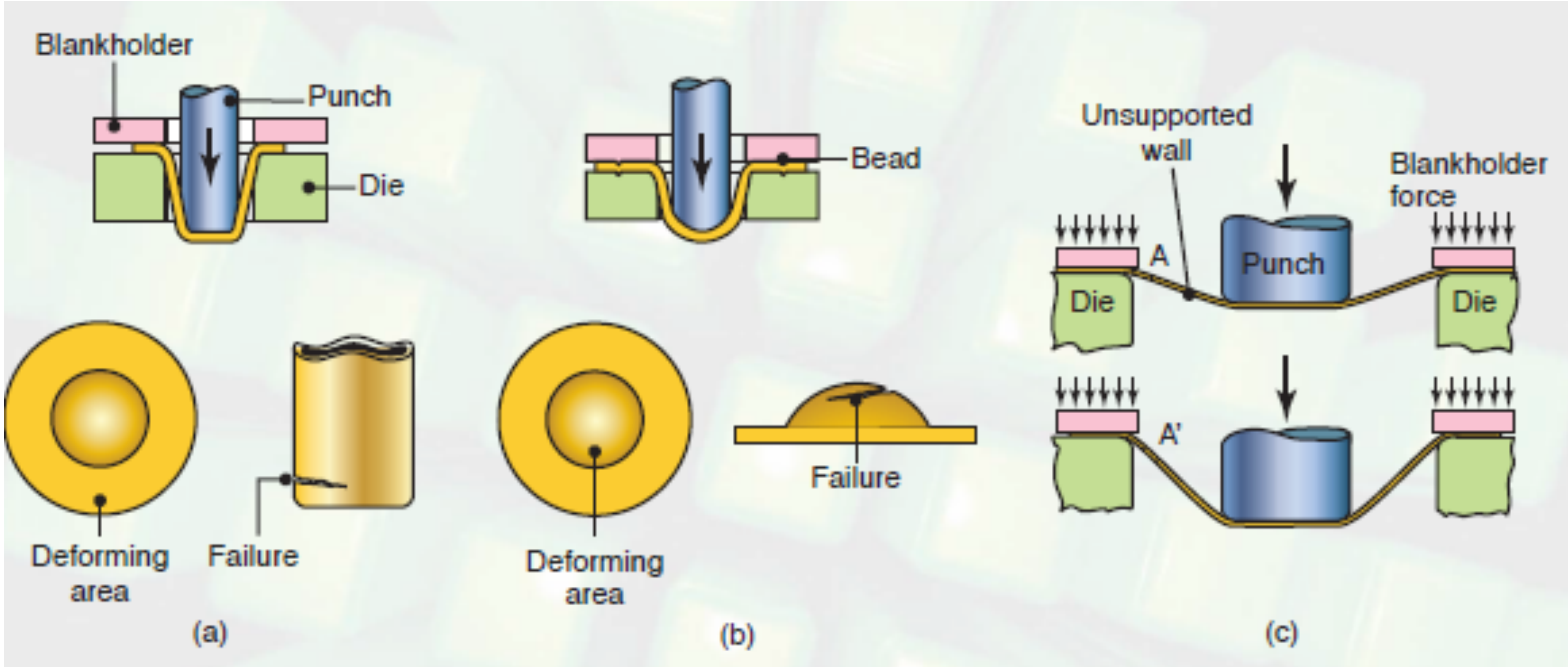


FIGURE 7.51 Examples of (a) pure drawing and (b) pure stretching; the bead prevents the sheet metal from flowing freely into the die cavity. (c) Unsupported wall and possibility of wrinkling of a sheet in drawing. Source: After W.F. Hosford and R.M. Caddell.

Draw Beads & Metal Flow

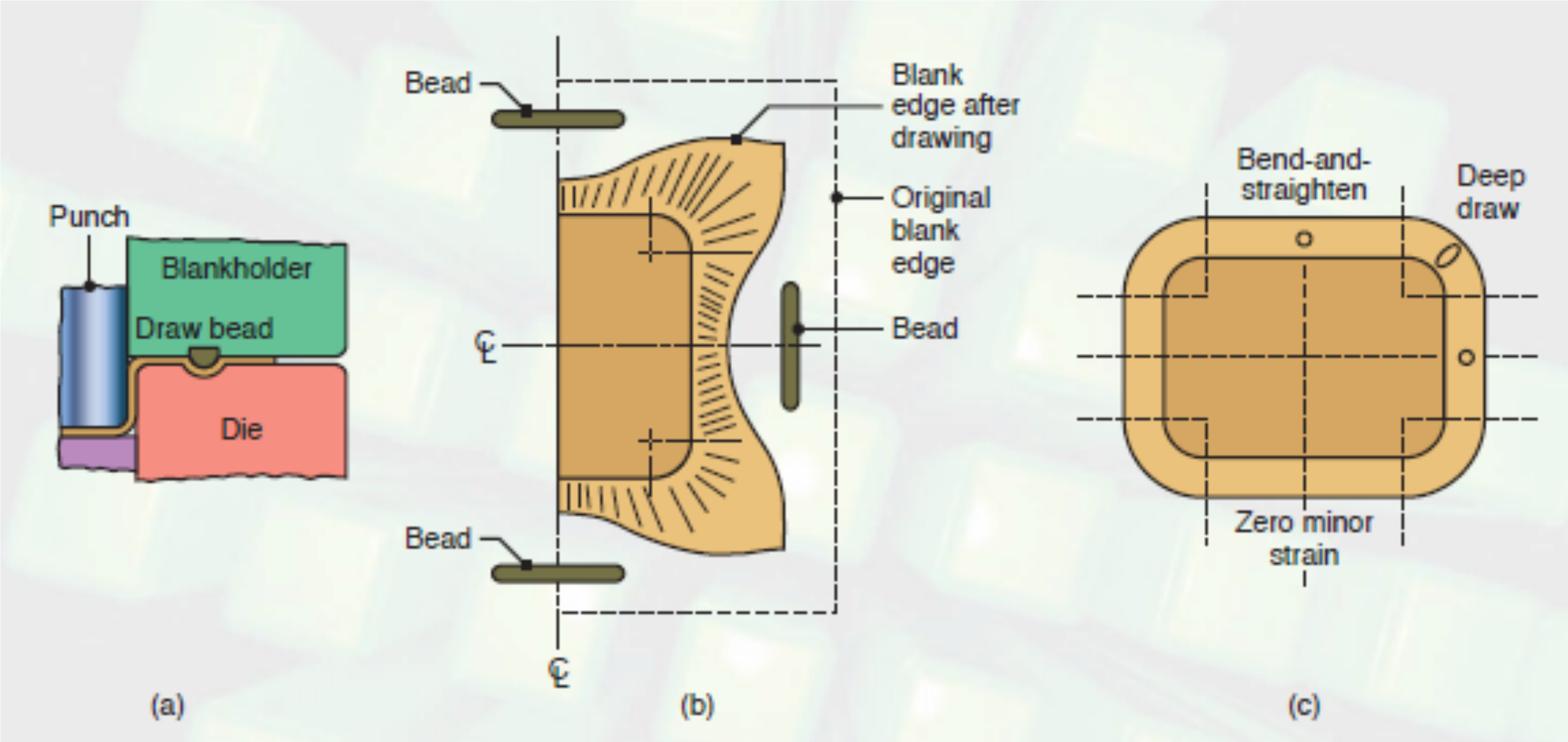


FIGURE: (a) Schematic illustration of a draw bead. (b) Metal flow during drawing of a box-shaped part, using beads to control the movement of the material. (c) Deformation of circular grids in drawing. (See Section 7.7.)

Ironing

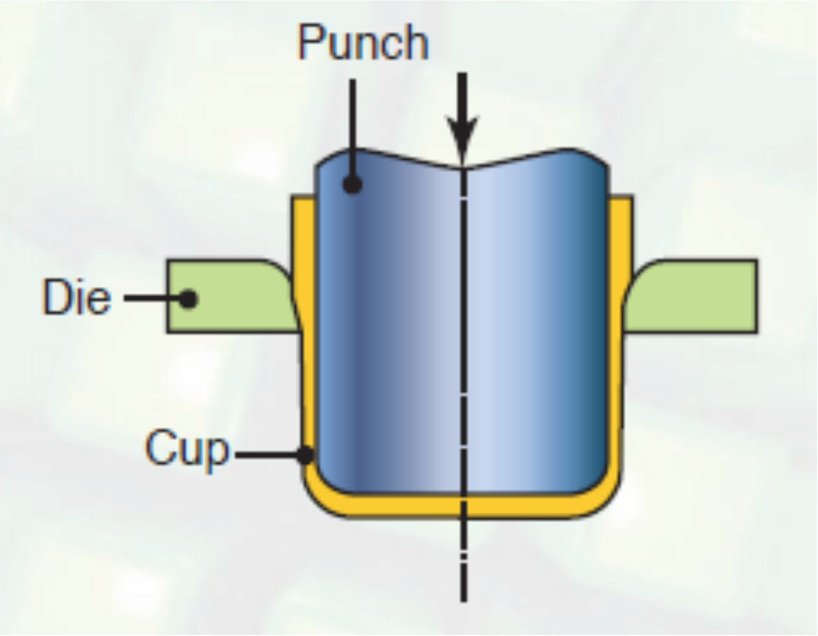
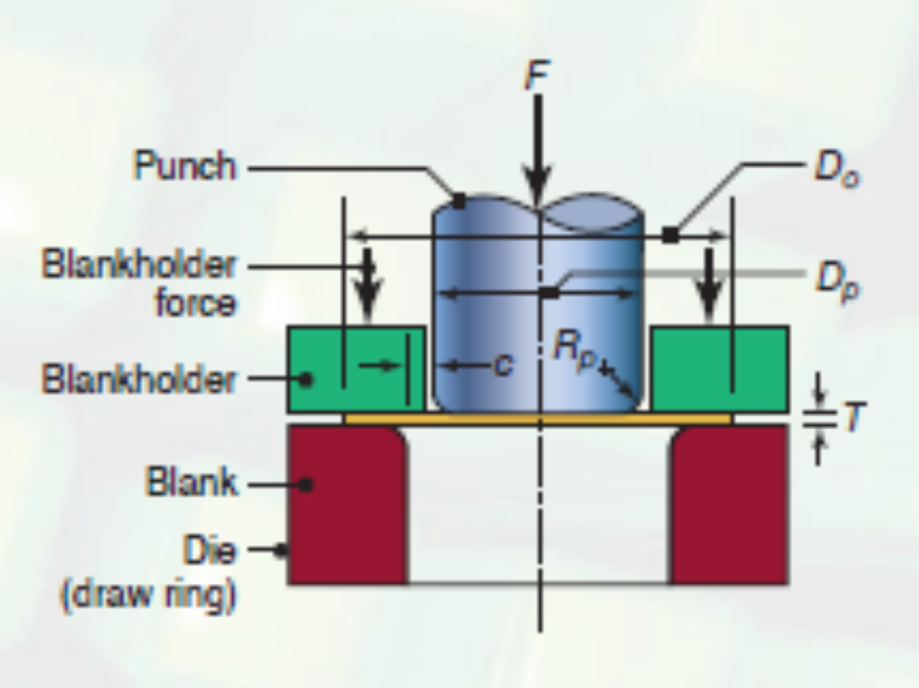


FIGURE 7.53 Schematic illustration of the ironing process. Note that the cup wall is thinner than its bottom. All beverage cans without seams (known as two-piece cans) are ironed, generally in three steps, after being deep drawn into a cup. Cans with separate tops and bottoms are known as three-piece cans.

Limiting drawing ratio



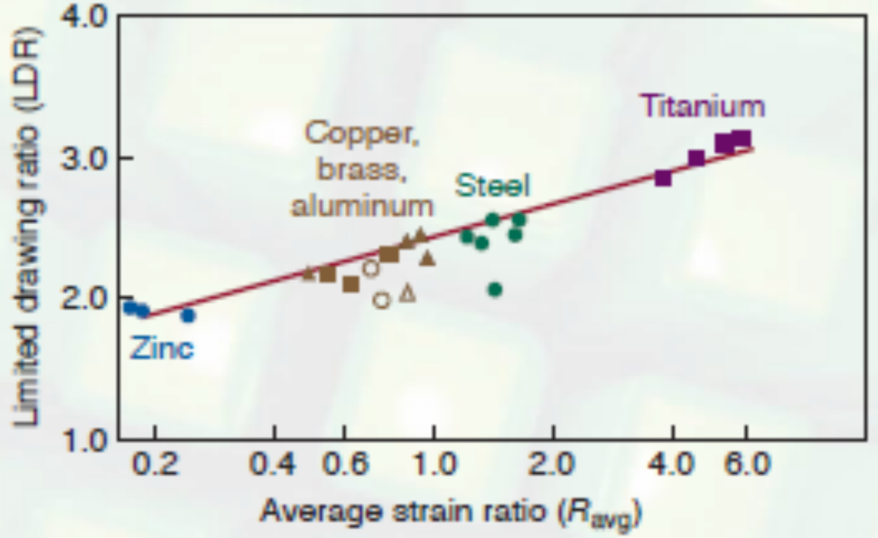


FIGURE 7.56 Effect of average normal anisotropy, $\bar{R}$ on limiting drawing ratio (LDR) for a variety of sheet metals. *Source*: After M.Atkinson.

$$LDR = \frac{D_o}{D_p}$$

Example

Estimate the limiting drawing ratio (LDR) that you would expect from a sheet metal that, when stretched by 23% in length, decreases in thickness by 10%.

Max punch force in drawing

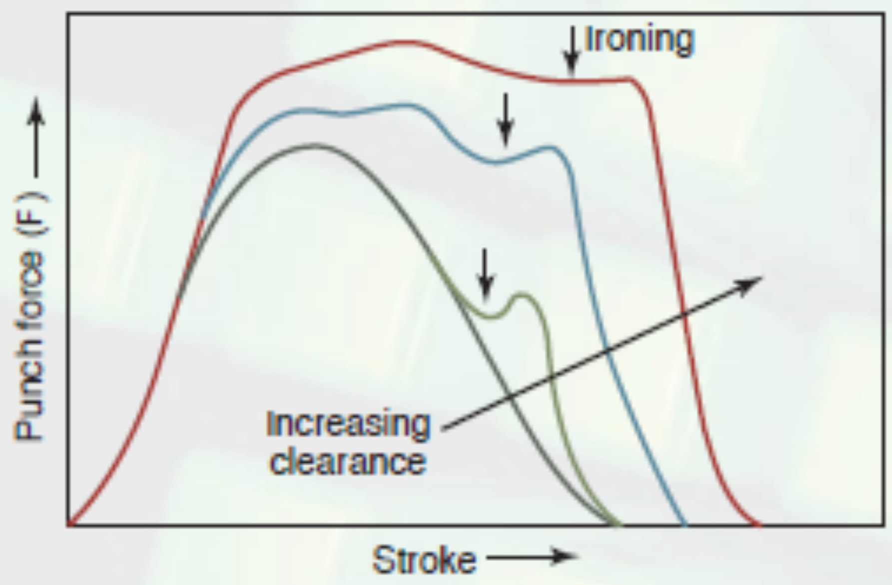


FIGURE 7.58 Schematic illustration of the variation of punch force with stroke in deep drawing. Arrows indicate the initiation of ironing. Note that ironing does not begin until after the punch has traveled a certain distance and the cup is partially formed.

Maximum punch force:

$$F_{max} = \pi D_p t_o (\mathrm{UTS}) \left(\frac{D_o}{D_p} - 0.7 \right)$$

Effect of clearance, die/punch corner radii

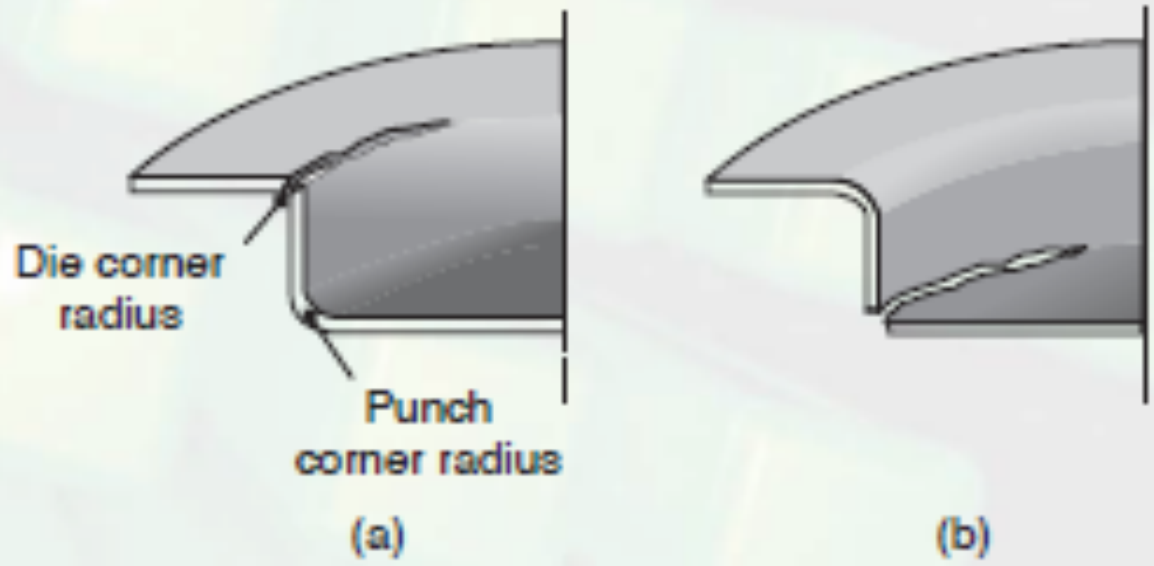


FIGURE 7.59 Effect of die and punch corner radii on fracture in deep drawing of a cylindrical cup. (a) Die corner radius too small; typically, it should be 5 to 10 times the sheet thickness. (b) Punch corner radius too small. Because friction between the cup and the punch aids in the drawing operation, excessive lubrication of the punch is detrimental to drawability.

Redrawing

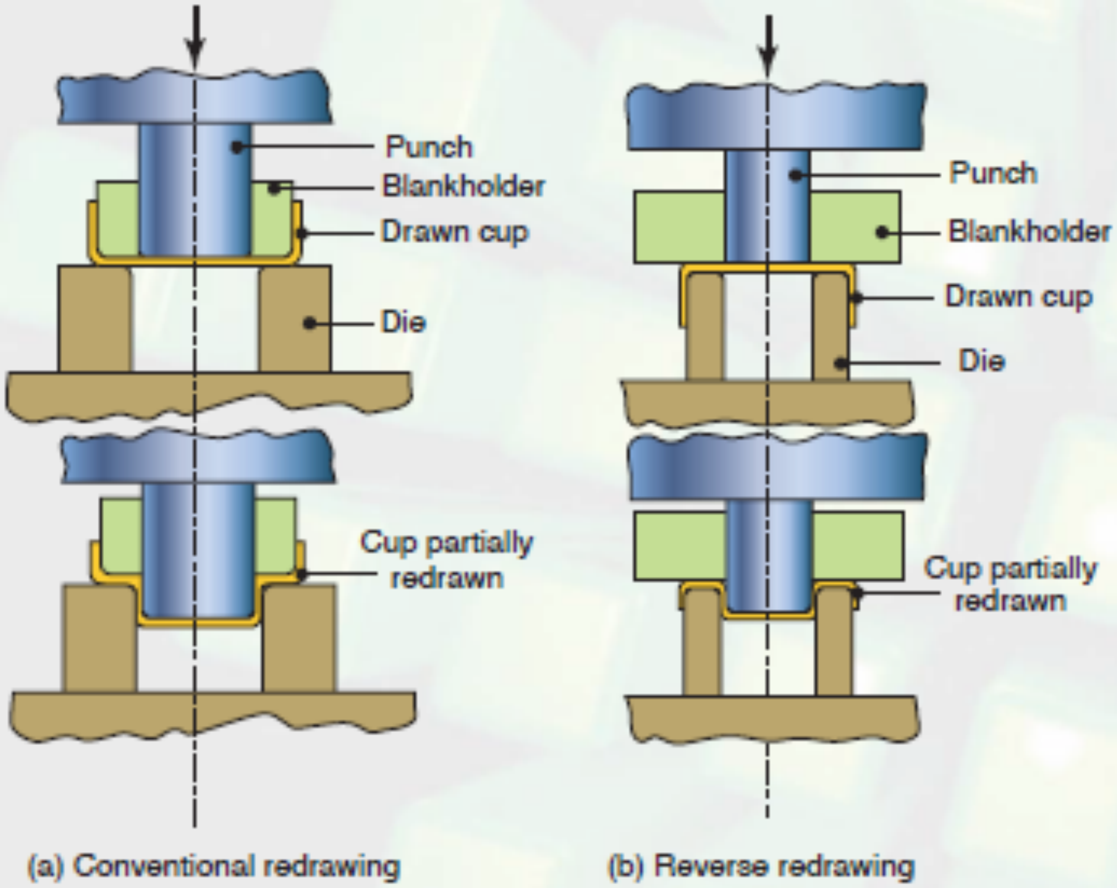


FIGURE 7.60 Reducing the diameter of drawn cups by redrawing operations: (a) conventional redrawing, and (b) reverse redrawing. Small-diameter deep containers may undergo several redrawing operations.

Drawing without a blank holder

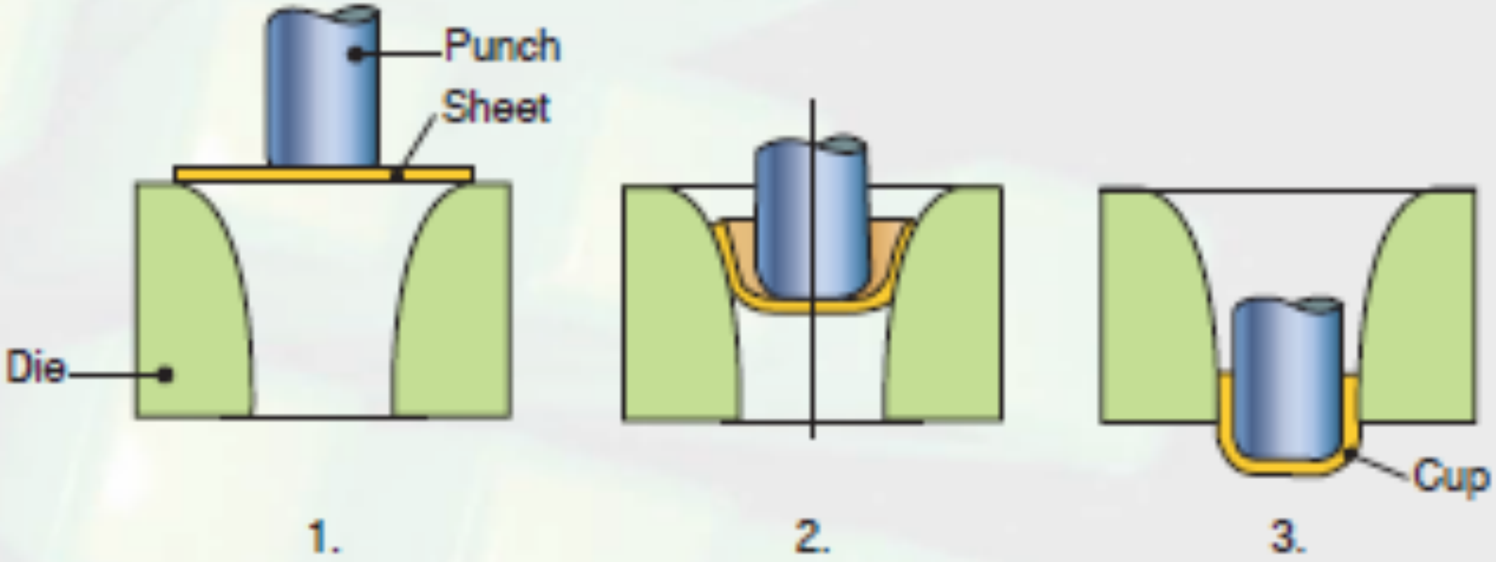
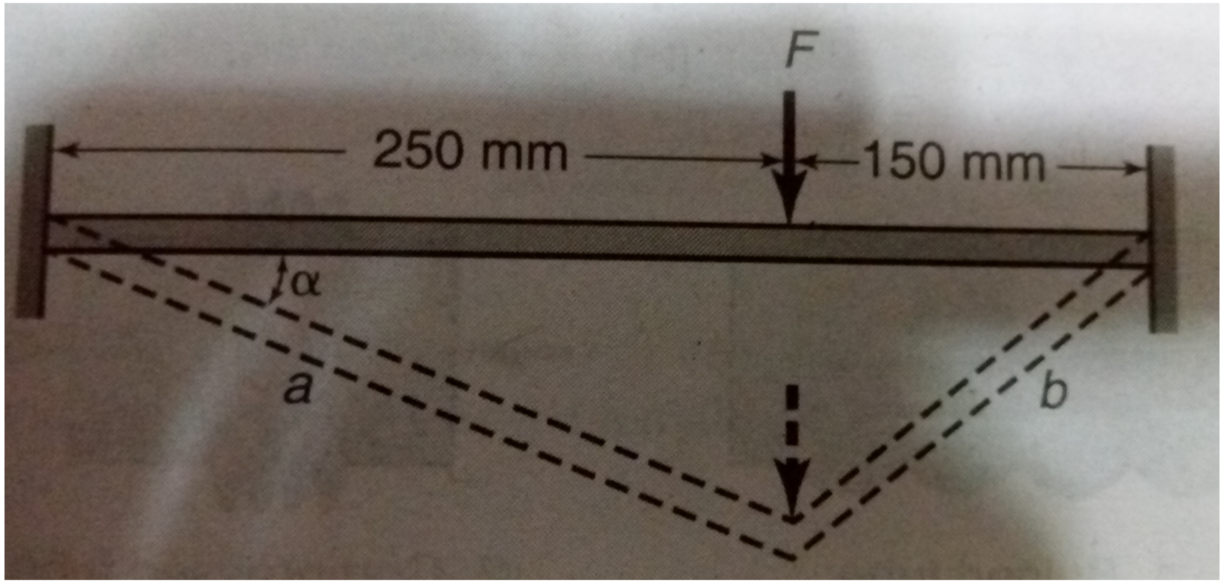


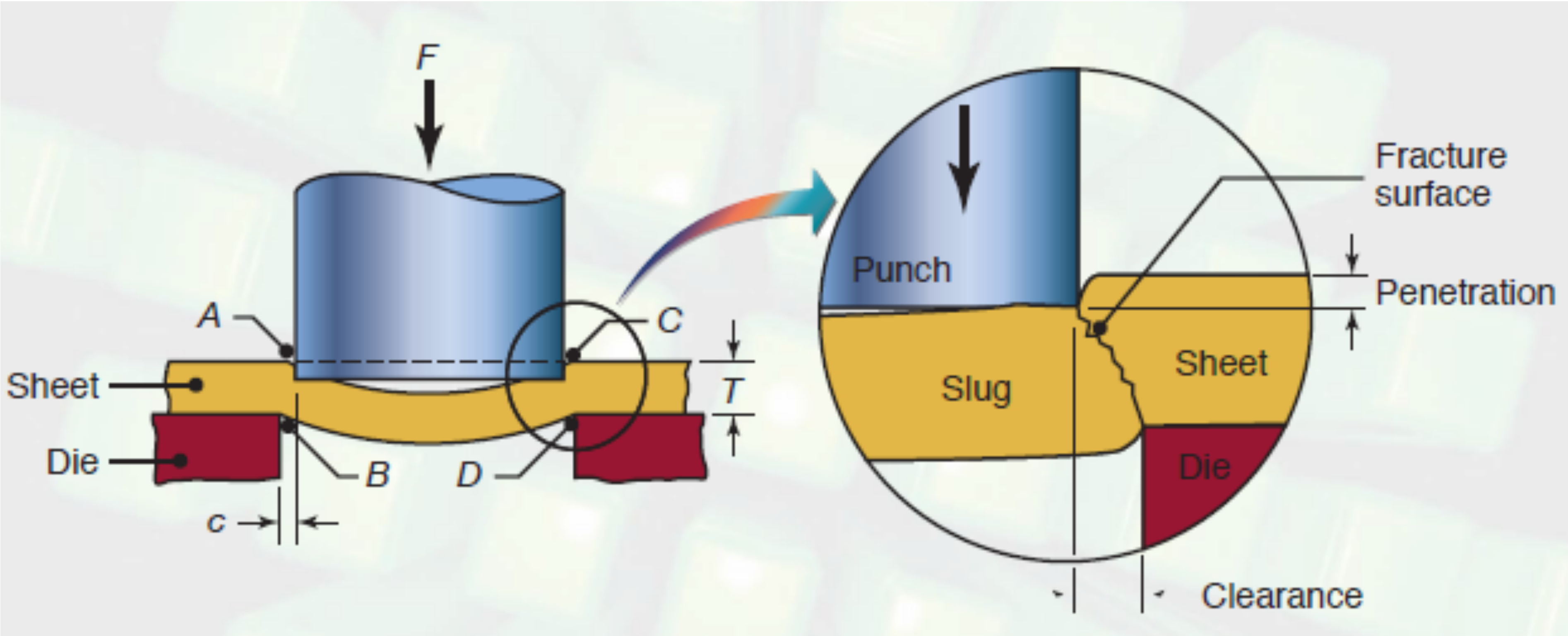
FIGURE 7.61 Stages in deep drawing without a blankholder, using a *tractrix* die profile. The tractrix is a special curve, the construction for which can be found in texts on analytical geometry or in handbooks.

Example

A 400 mm long sheet with a cross sectional area of 300 mm^2 is stretched with a force F, until α = 20 degree. The material has a strength constant of 700 MPa and strain hardening exponent of 0.3. (a) Find the total work done ignoring end effects and bending. (b) What is α_{max} before necking begins?



Deforming sheets enough to cause fracture and break



Its almost exactly like punching a hole
in a paper using a paper-punch

Hole and slug

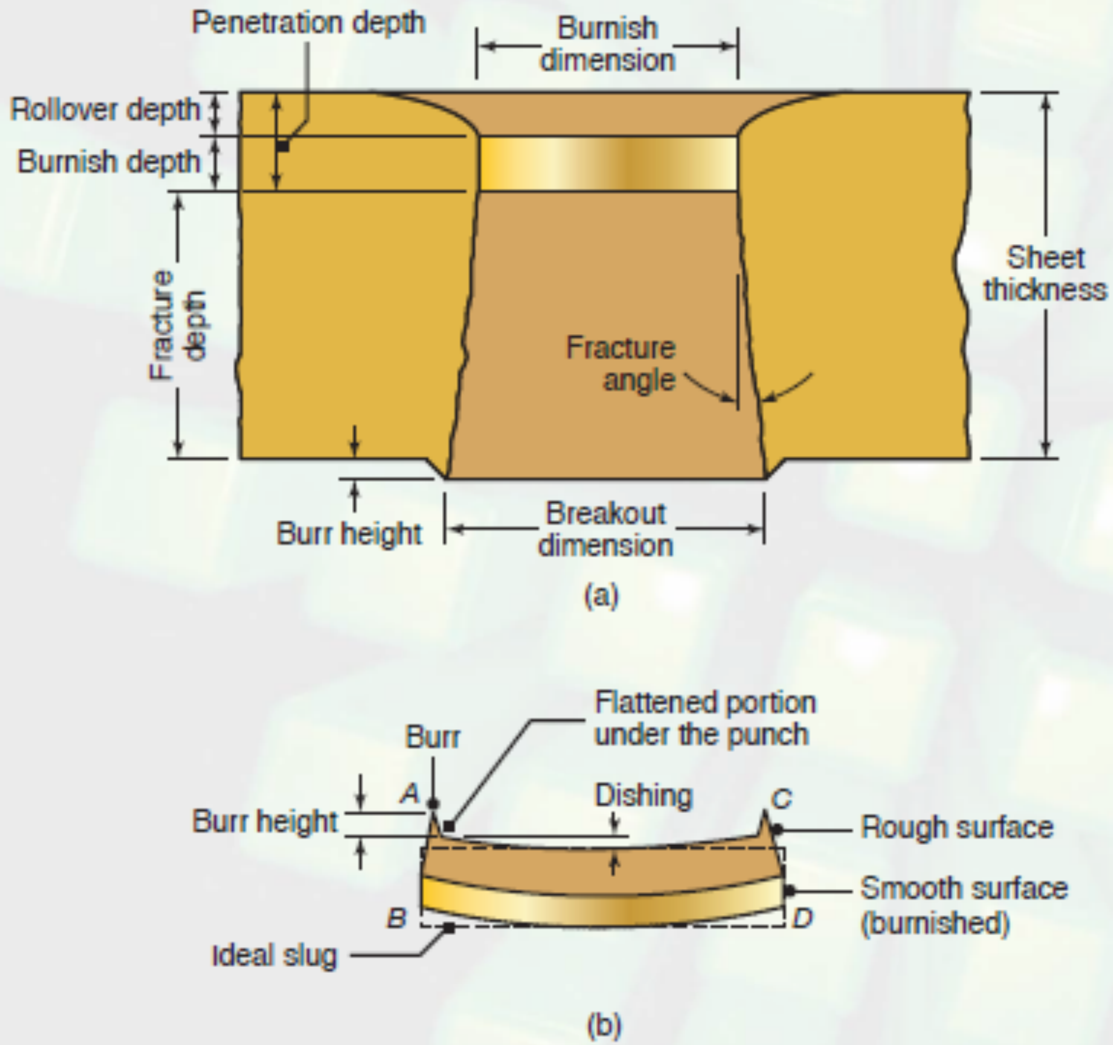


FIGURE 7.5 Characteristic features of (a) a punched hole and (b) the punched slug. Note that the slug has a different scale than the hole.

Shearing mechanics

FIGURE 7.6 a) Effect of clearance, c, on the deformation zone in shearing. Note that, as clearance increases, the material tends to be pulled into the die, rather than being sheared. (b) Microhardness (HV) contours for a 6.4-mm (0.25-in.) thick AISI 1020 hot-rolled steel in the sheared region. *Source:* After H.P. Weaver and K.J. Weinmann.

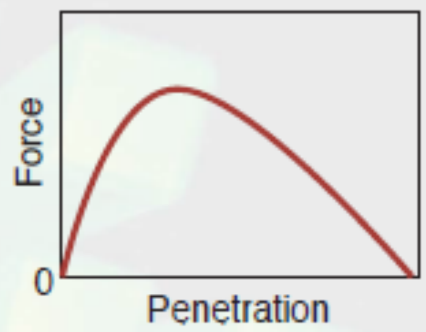


FIGURE 7.7 Typical punch force vs. penetration curve in shearing. The area under the curve is the work done in shearing. The shape of the curve depends on processing parameters and material properties.

ME2300: Manufacturing Processes
Jan-May 2020

Shaping by mass change (removal: machining-introduction)

Introduction

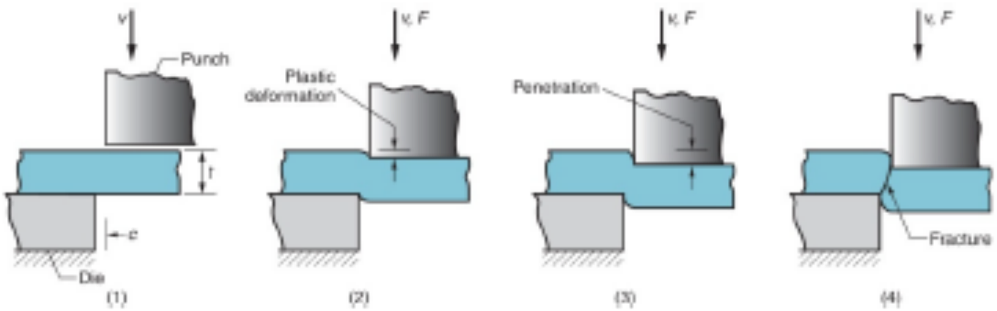
Five methods to achieve shape/properties

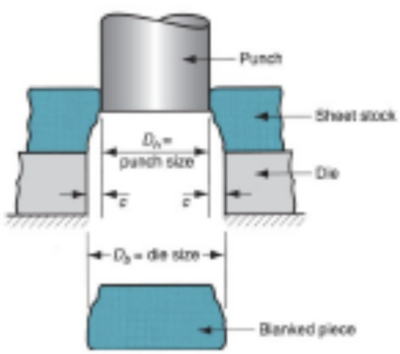
- Phase change: change raw material from solid to liquid (liquid-like) and back to solid
- Mass change: remove or add mass to raw material
- Joining: group together various raw material shapes
- Deformation: change shape in solid state by permanently distorting raw material
- Properties change: impart needed properties by changing structure of raw material

Introduction

Can we always shear, punch, blank to remove material?

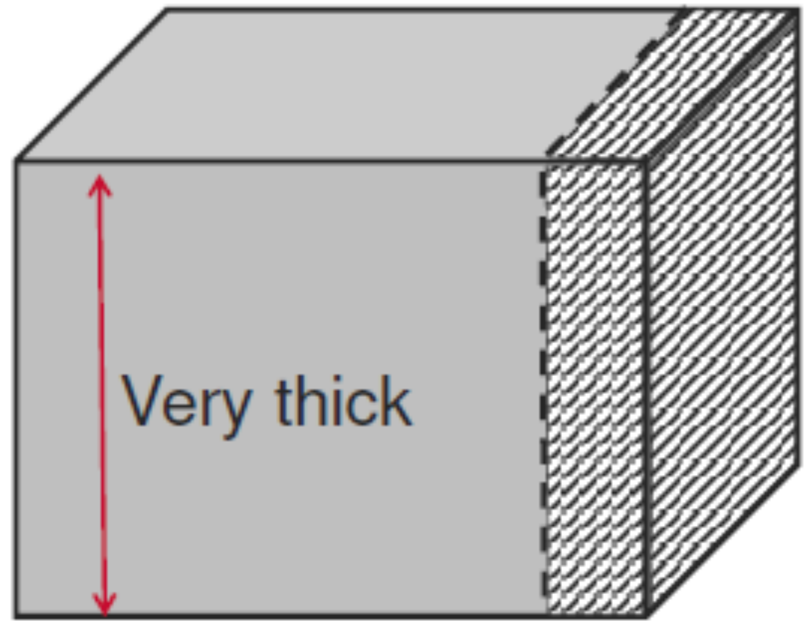
You have already seen some material removal before in this course





What was the thickness 't' of this material?

Can this same technique be used for this starting raw material?



How can we cut this out?

Mass removal – how to achieve?

- Shape raw material by mass removal (cut mass out)
- Requires energy – focused energy
- Many forms of energy
  - Moving mass (momentum); focused using a sharp edge (of many types: single point cutting tool, fixed abrasive, etc.)
  - Electric discharge: tiny sparks/arcs
  - Chemical energy
  - Light energy: laser beam
  - Electron beam, Ion beam, plasma etc.

Unconventional machining processes

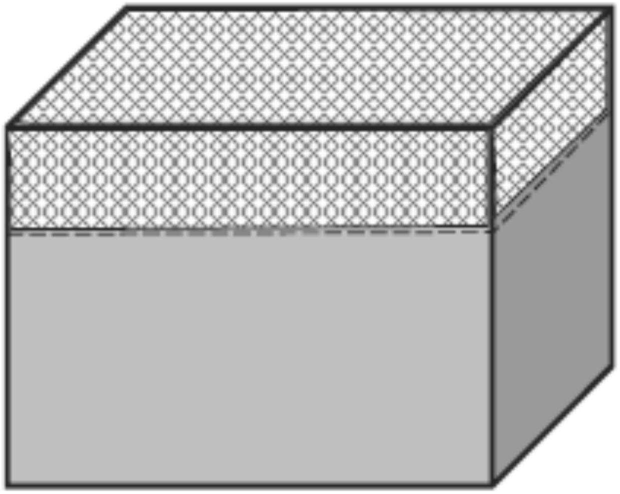
Cutting using energy supplied by impact of a moving mass

- Commonly called machining or mechanical machining
- What impacts to provide the energy? – the raw material or tool relative to each other
- How to focus the energy?

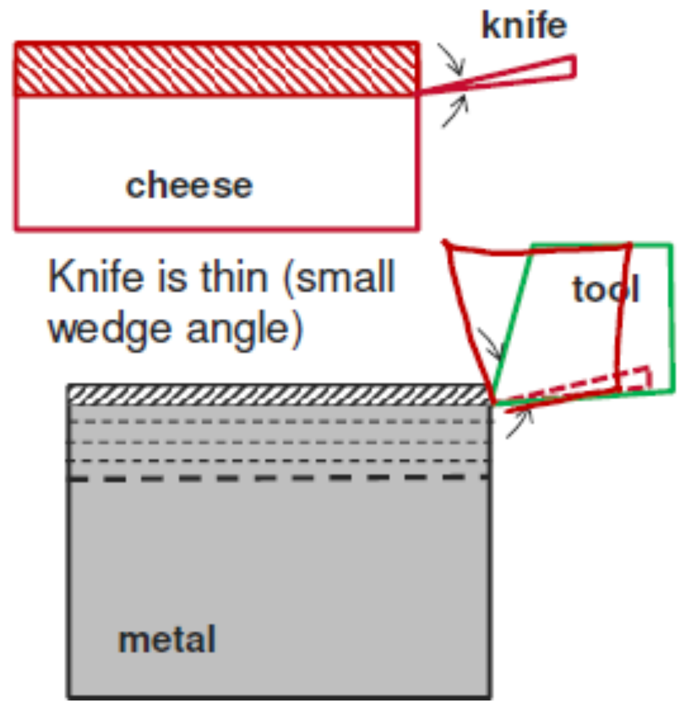
– Sharp edge is often provided to the cutting tool

- Need a rigid machine to hold both raw material and tool and to provide needed motion

Cutting an engineering material

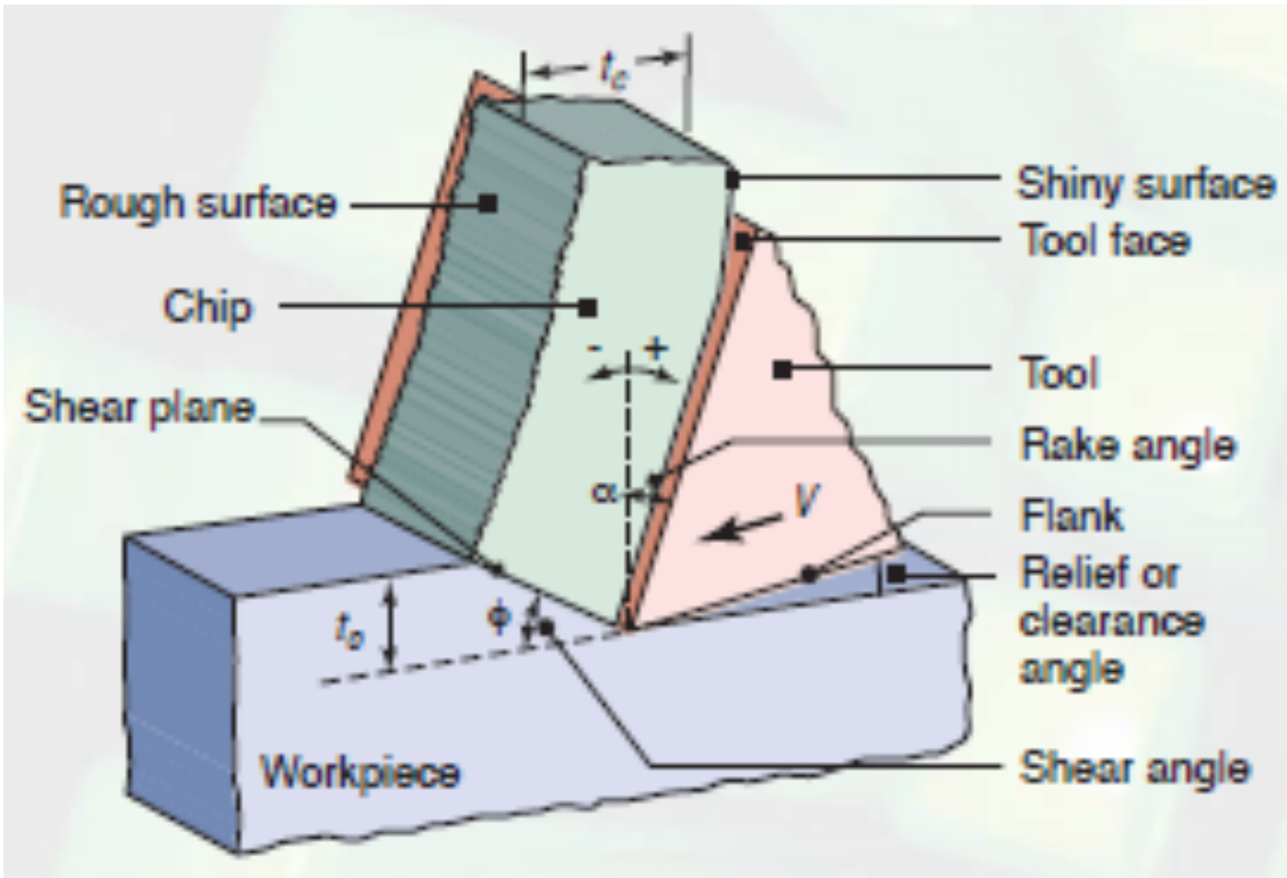


Can we use a knife and slice?

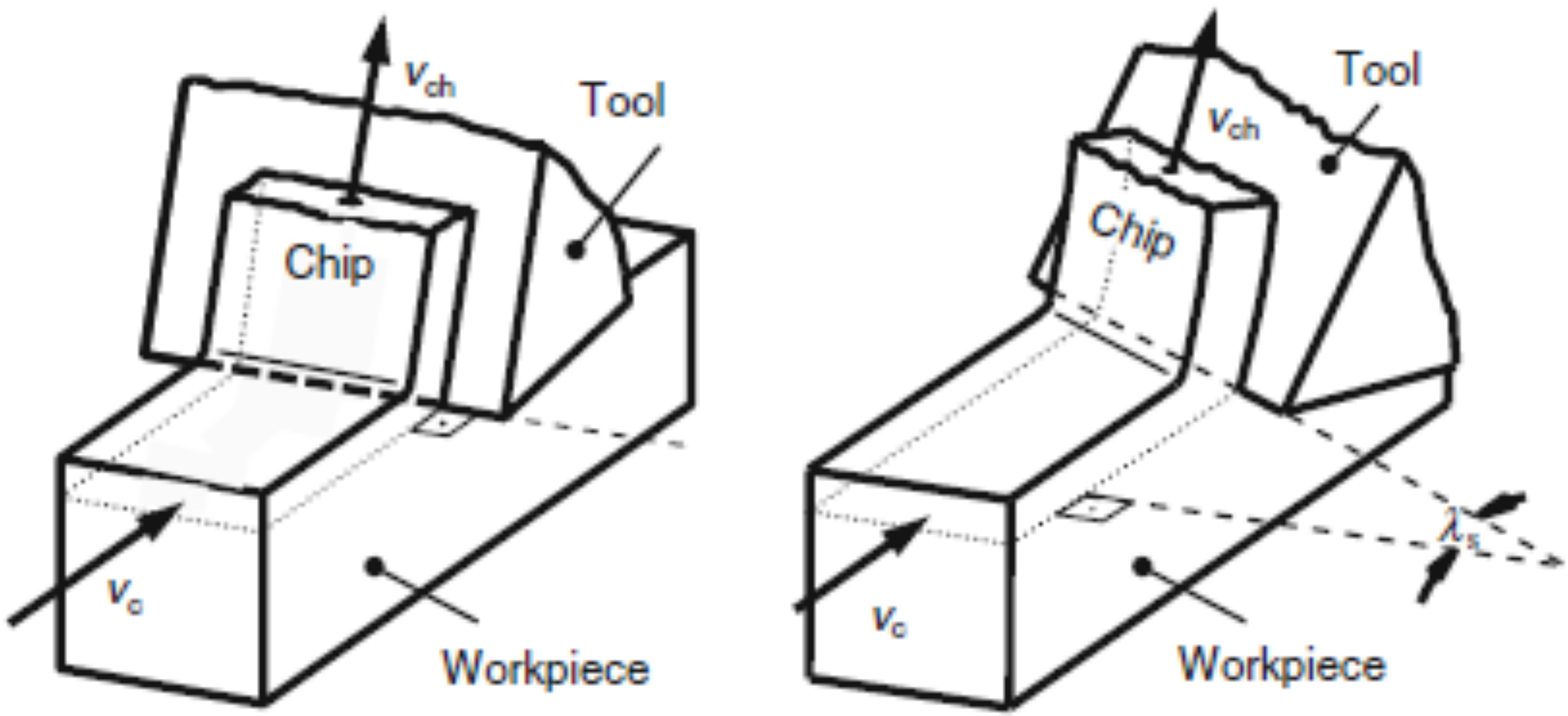


1. Tool has to be made stronger (larger wedge angle) to enable cutting
2. We cannot remove the entire material in one shot – we can only cut little by little

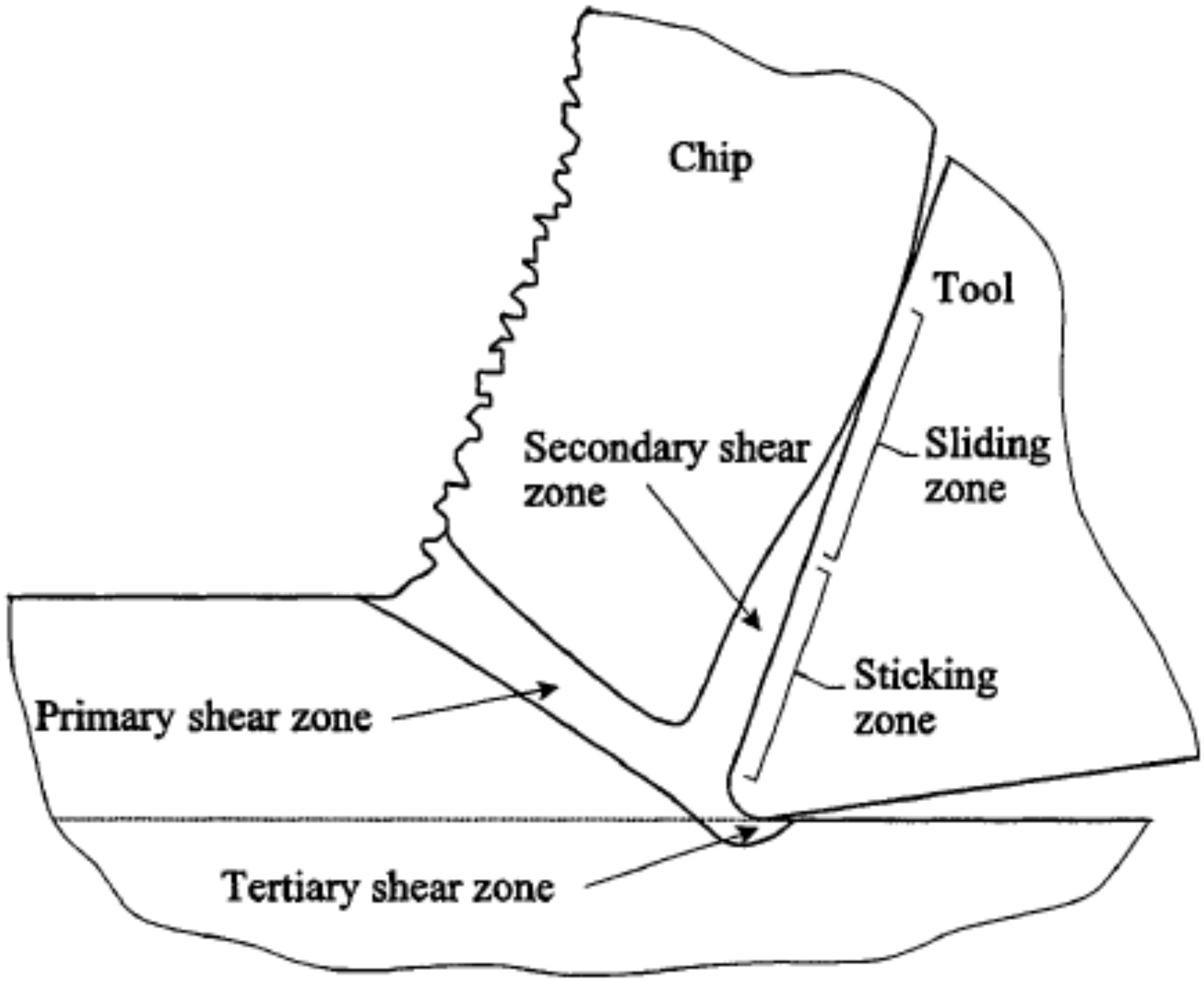
Orthogonal cutting process



Orthogonal and oblique cutting



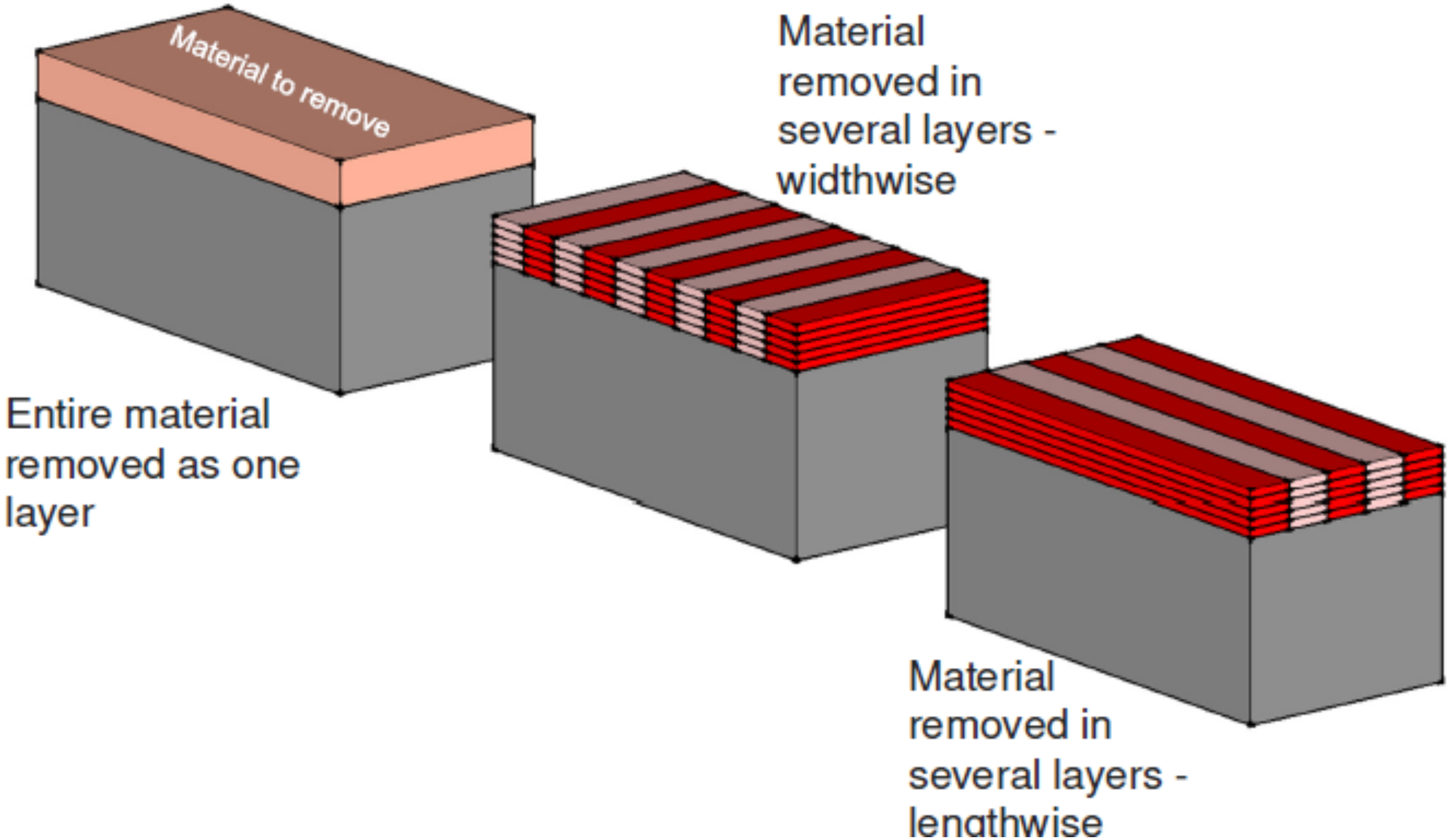
Plastic deformation zone in the cutting process



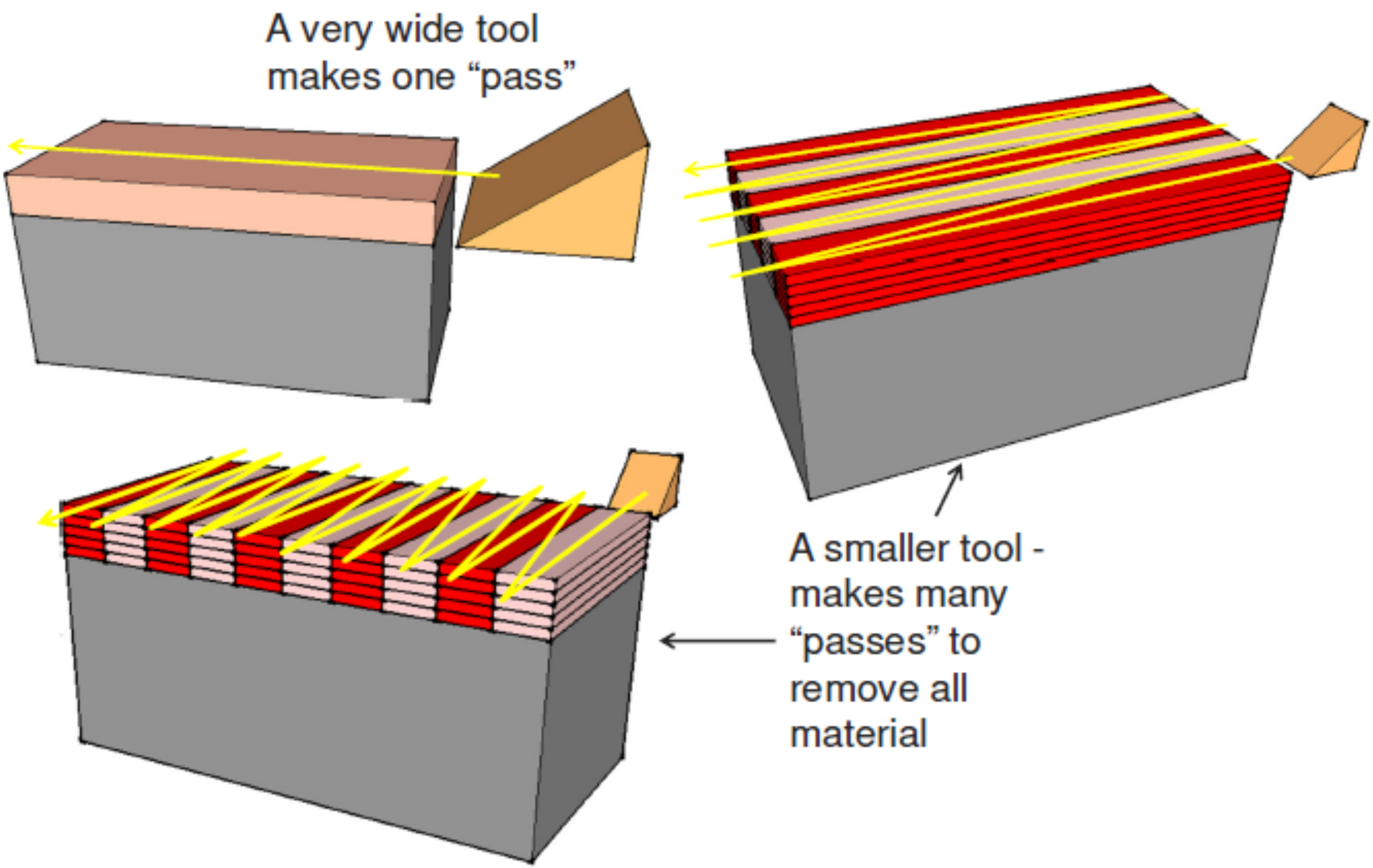
How much material can we remove at a time?

• Cut engineering materials – we can only cut and remove a little bit at a time
• Why?
– Work material is strong (unlike cheese!)
– Cutting tool strength limitations
– Requires high power; machine limitation
• So we have to cut a little at one place, then move over to another location to remove material, and so on over a large area so that a given shape can be created
• Hence, we need to partition the material and strategize on how we can cut each partition out

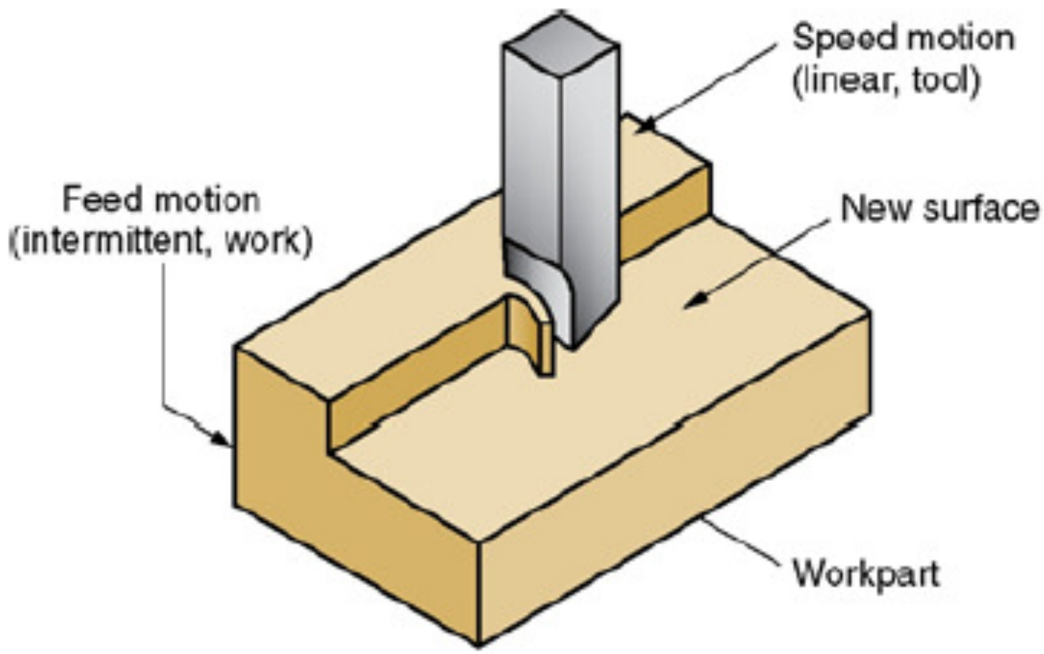
Partitioning the material for removal



Different ways to remove material



Orthogonal cutting process

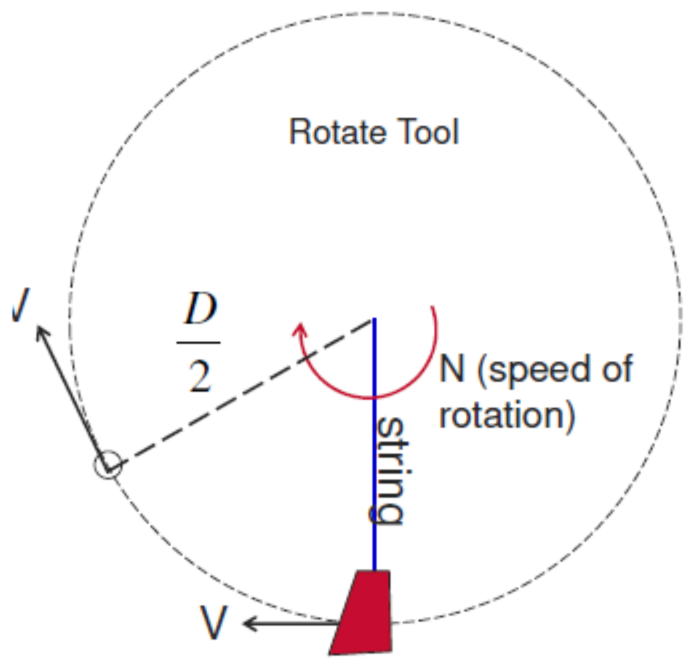


- A simple process to create large planar surfaces
- Tool moves linearly to remove material in layers
- Very seldom used nowadays – since process is very slow
- Limitation is from cutting speed achieved by linear motion – so speeds are very limited

Circular cutting motion

- Very common to use circular motions in machining
- Such motion is provided to:
  - Tool: milling, drilling, boring
  - Work material: boring, turning

Circular cutting motion



- Rotary motion – easier to get high speeds; plus the tool comes back too – convenient

– Tangential speed is the cutting Speed

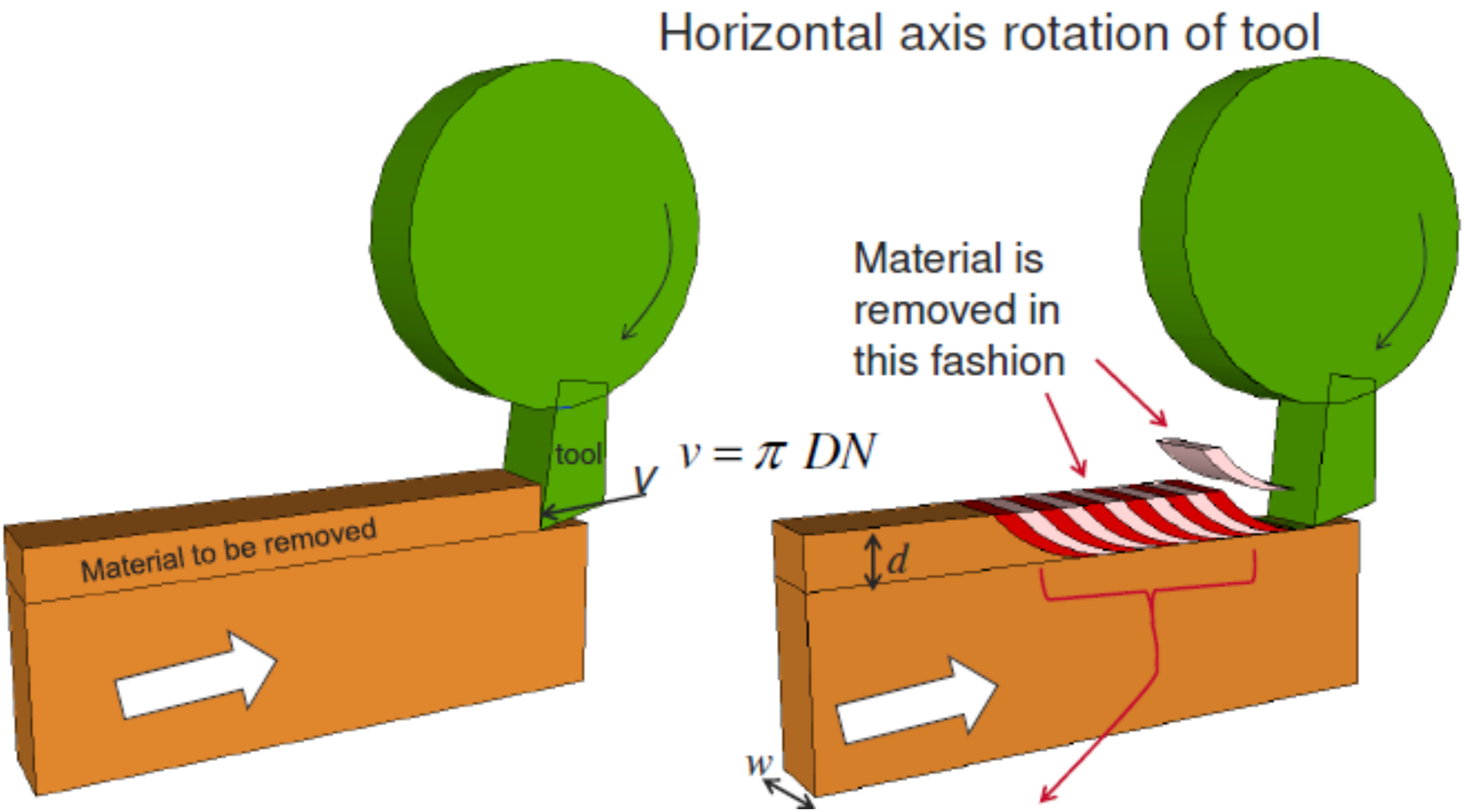
$$v = r\omega = \frac{D}{2}(2\pi N) = \pi DN$$

- We have two options:

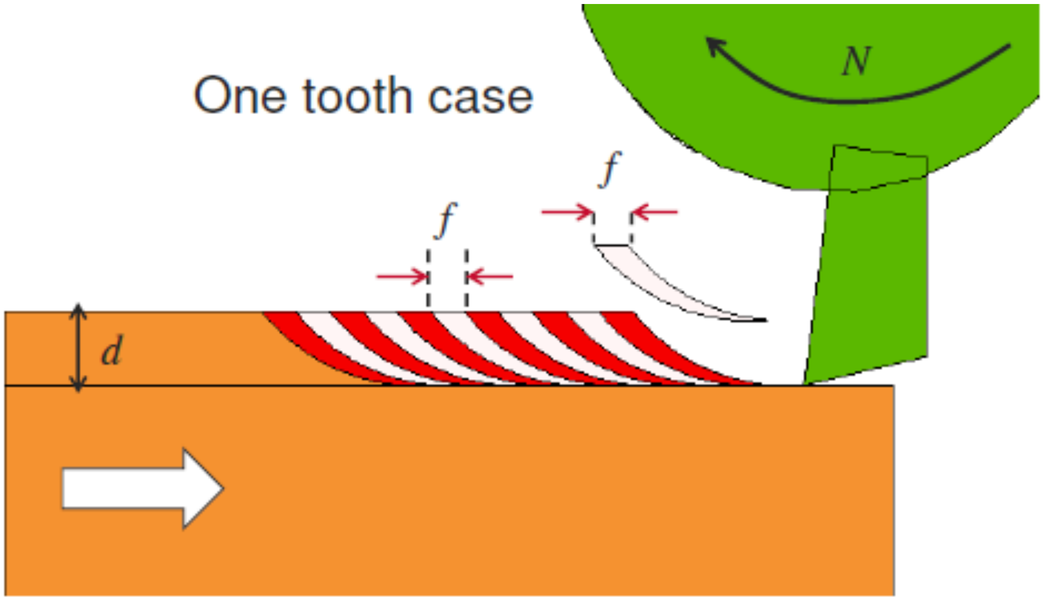
– A: Rotate tool

– B: Rotate work material

Option A: rotate the tool



Option A: rotate the tool



f = feed per tooth (chip load)

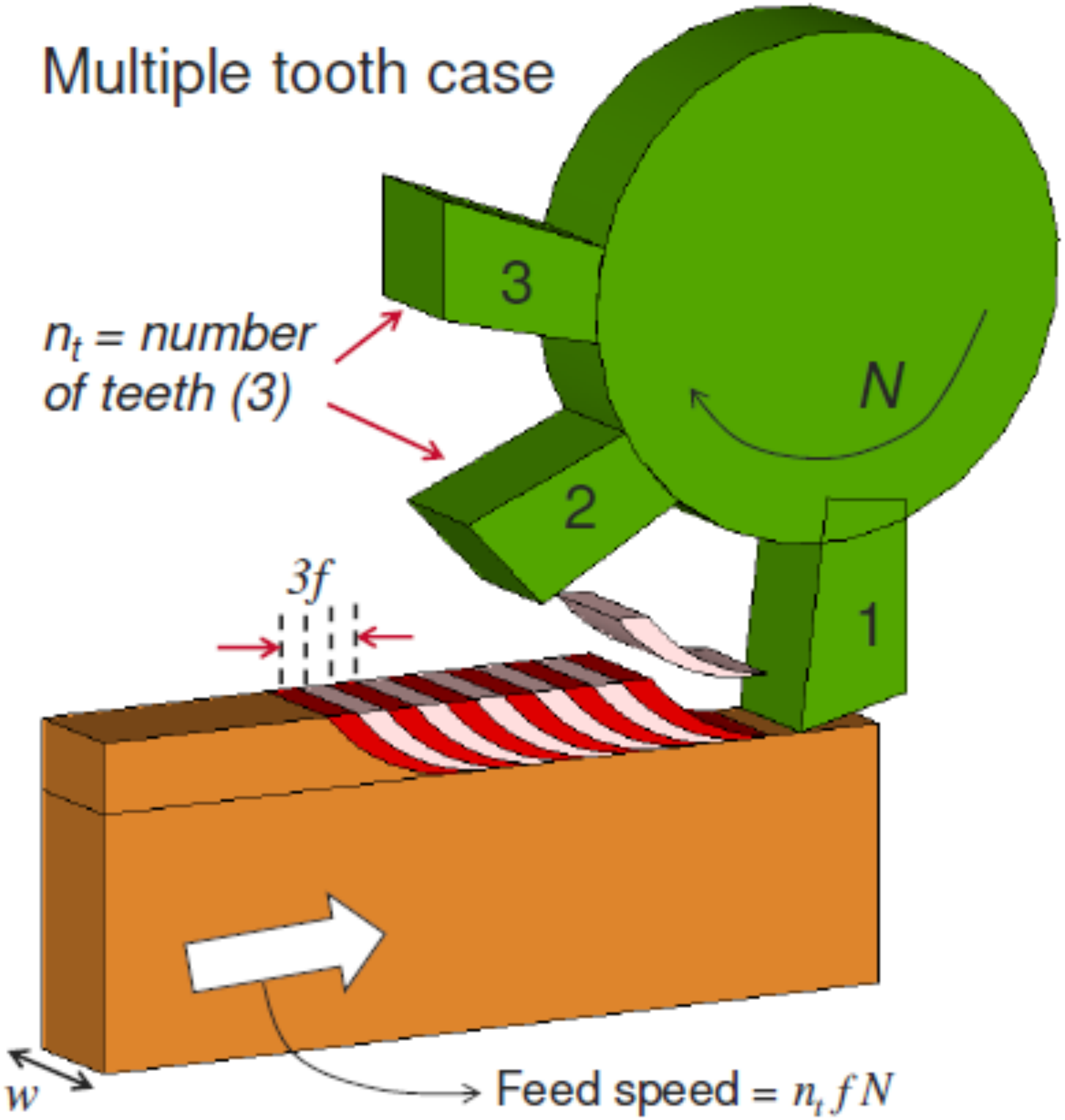
In one revolution, the tooth cuts '*f' amount (horizontal thickness) of material.*

In *N revolutions per minute, (f N) amount of material is cut per minute. This is the*

rate at which work material has to be "fed in".

So MRR = (*w d f N) ; w = width of cut; d = depth of cut*

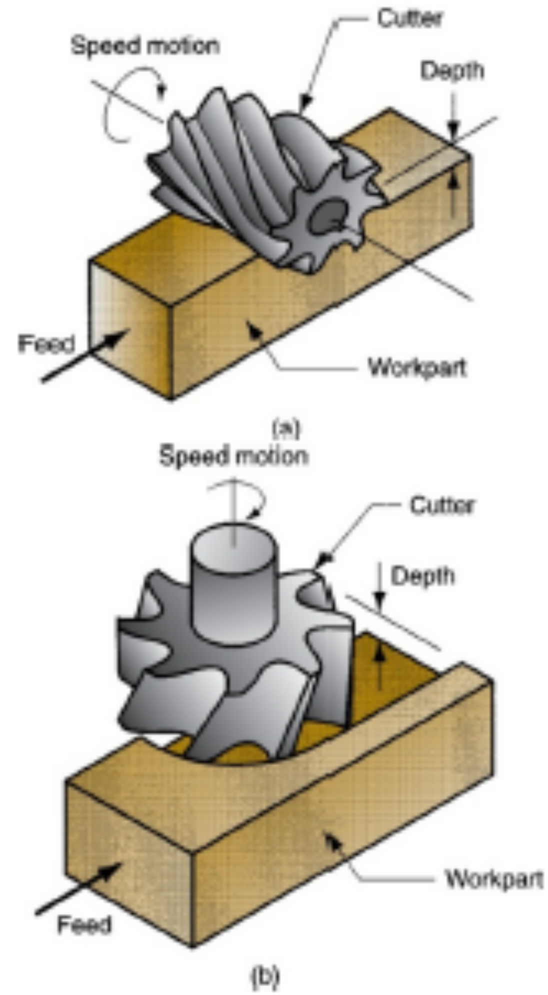
Option A: rotate the tool



Option A: rotate the tool

Another option:
Vertical axis rotation of tool

Peripheral milling

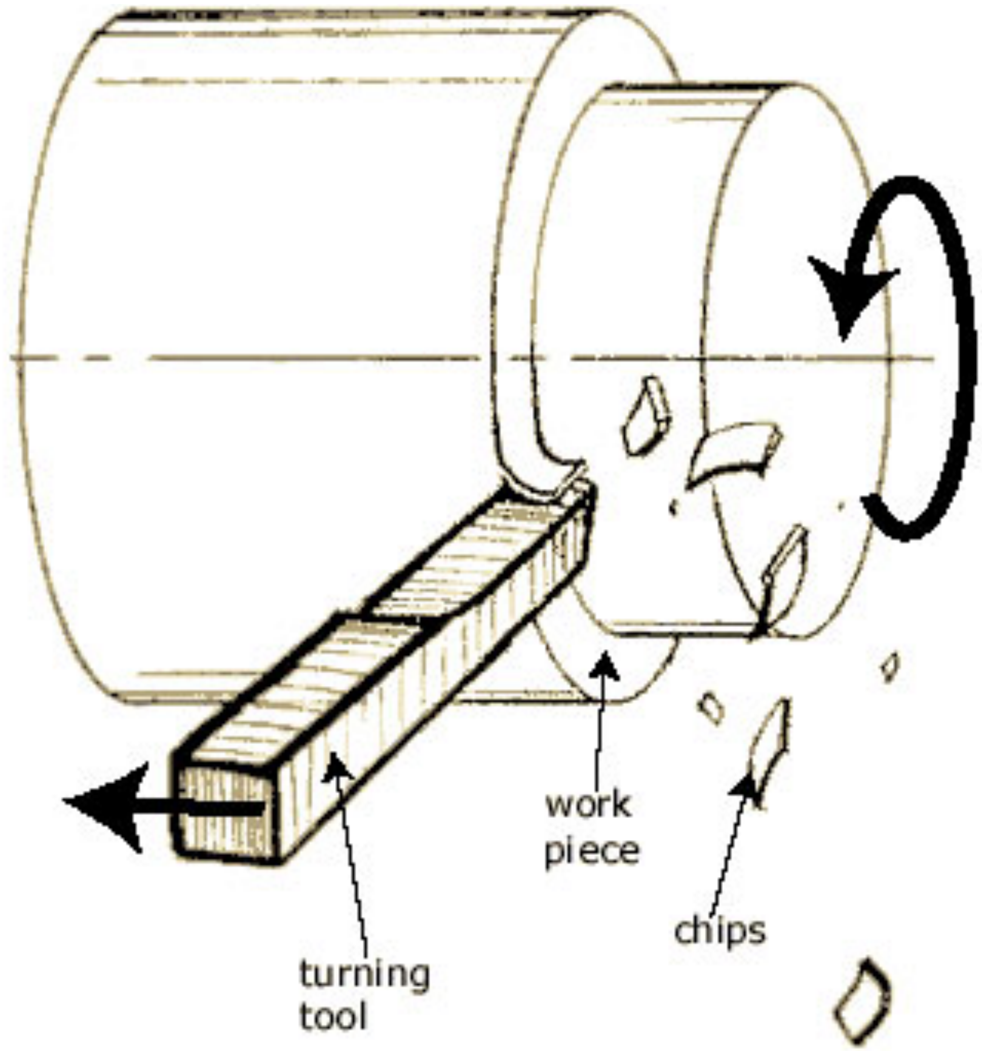


Face milling

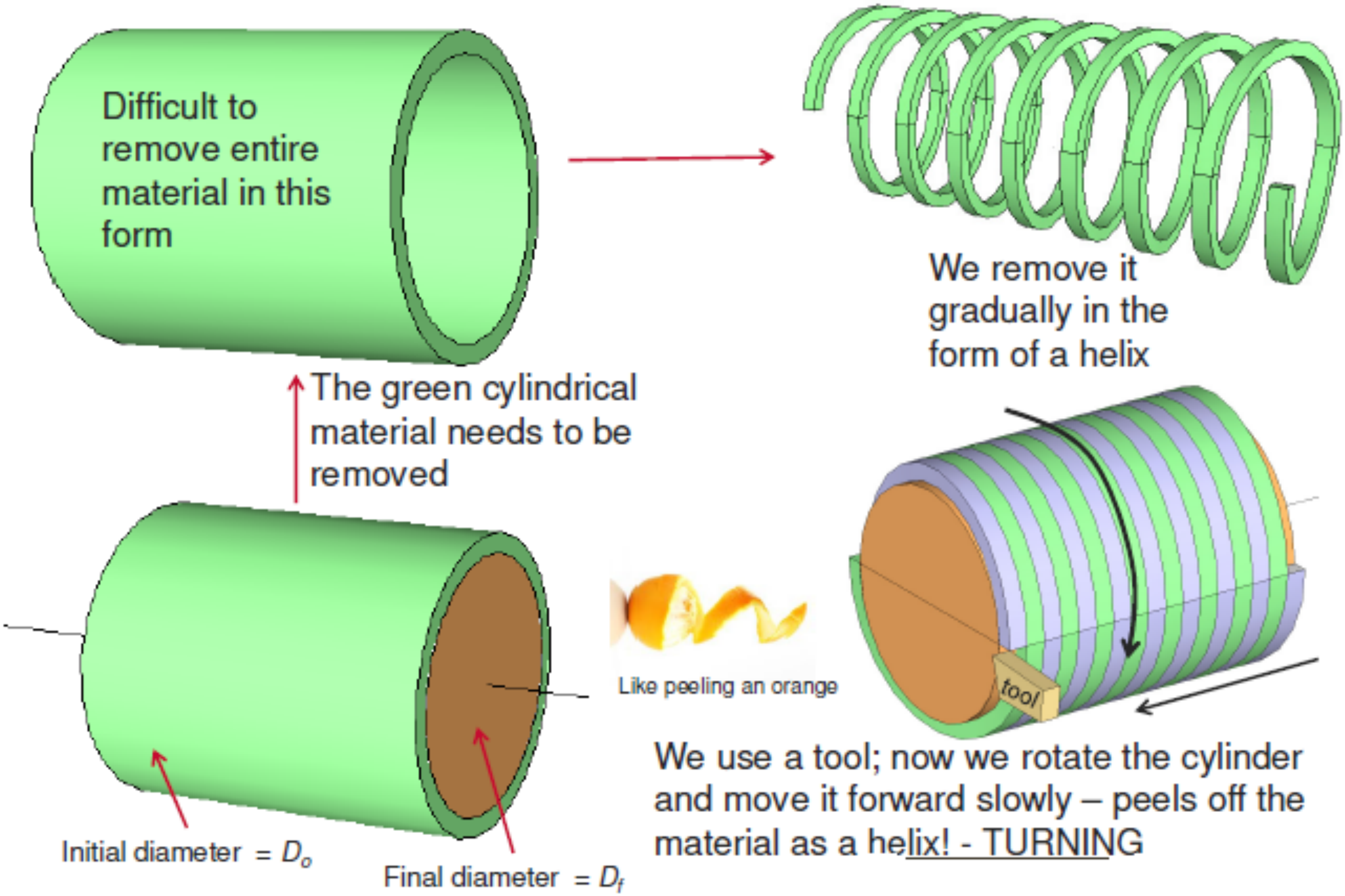
Circular cutting motion - turning

- Here we use option B:
  – Rotate the work material instead of the tool

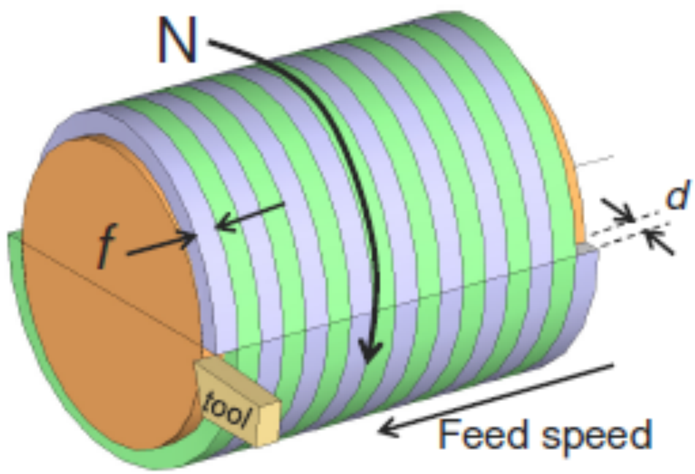
Option B: rotate the workpiece (Turning)



Option B: rotate the workpiece (Turning)



Option B: rotate the workpiece (Turning)



Cutting speed is from circular rotation = tangential speed = $v = \pi D N$

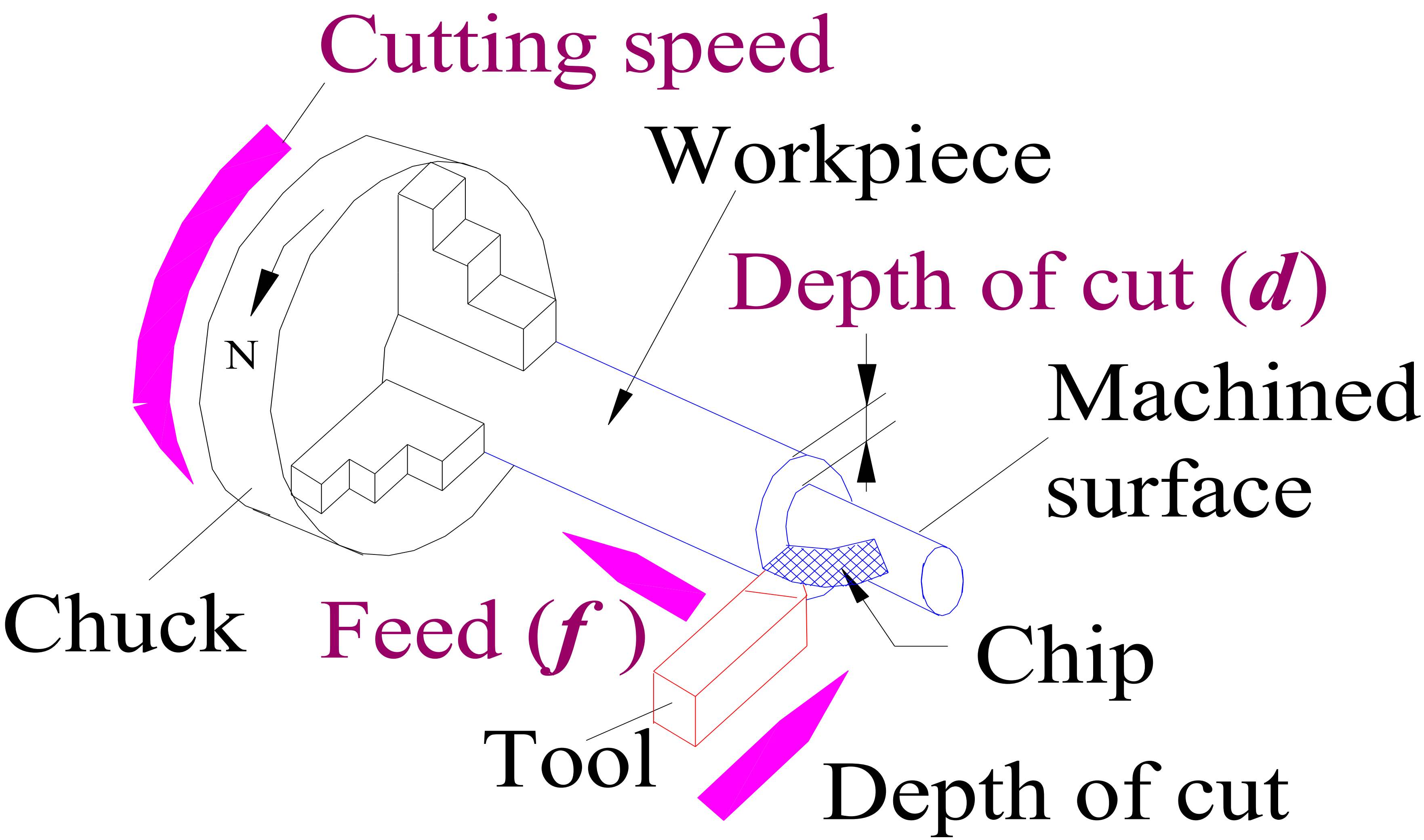
Feed speed = f_r = depends on how wide (f) of a helix you want to take out = $f\,N$; in one revolution 'f' is removed, so in N revolutions per minute, $f\,N$ is removed

Units of f = *mm/rev*

Thickness of helix = depth of cut = d

Material removal rate??

Option B: rotate the workpiece (Turning)



MRR

Volume of material removed in one revolution $\mathrm{MRR} = \pi D d f$ mm^3

- Job makes N revolutions/min

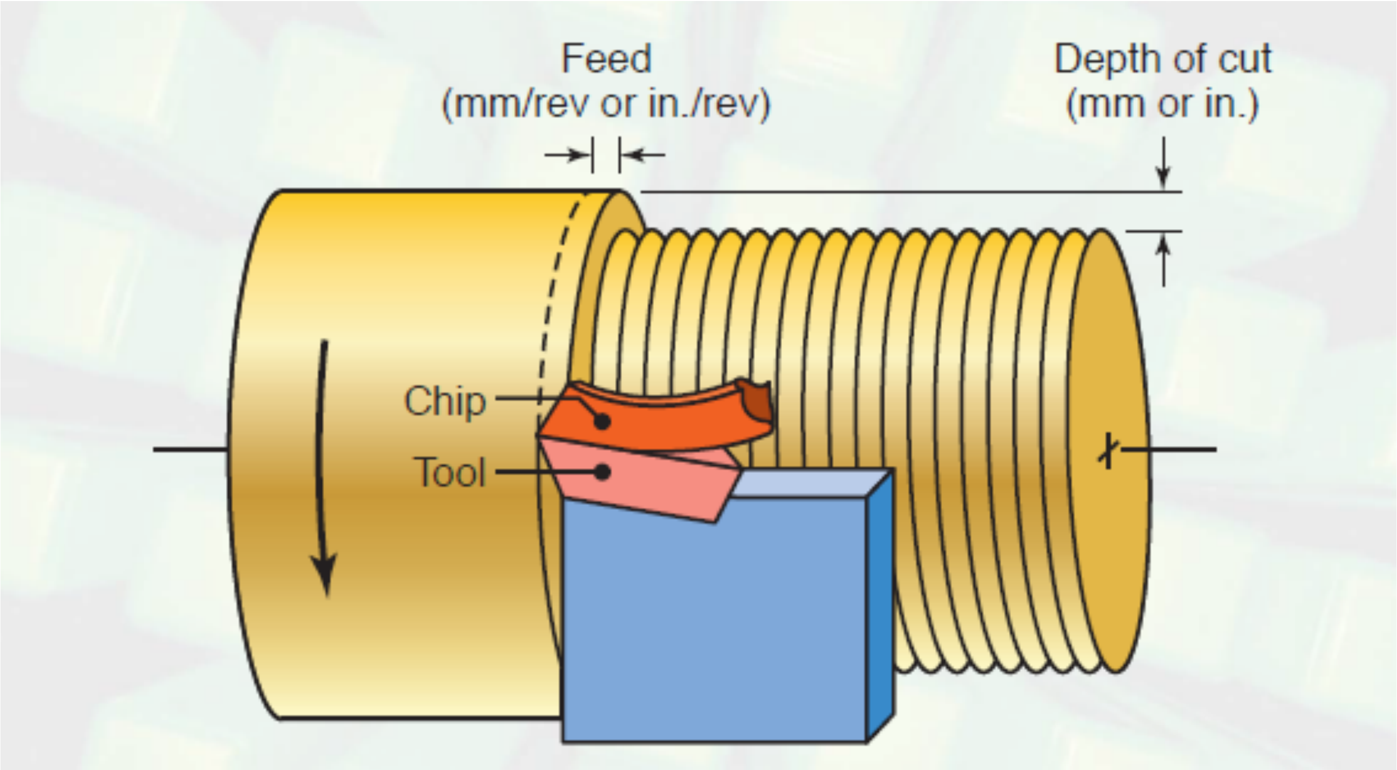
$$\mathbf{MRR} = \pi D d f N \quad (\mathrm{mm}^3/\mathrm{min})$$

- In terms of $\boldsymbol{v}$ MRR is given by

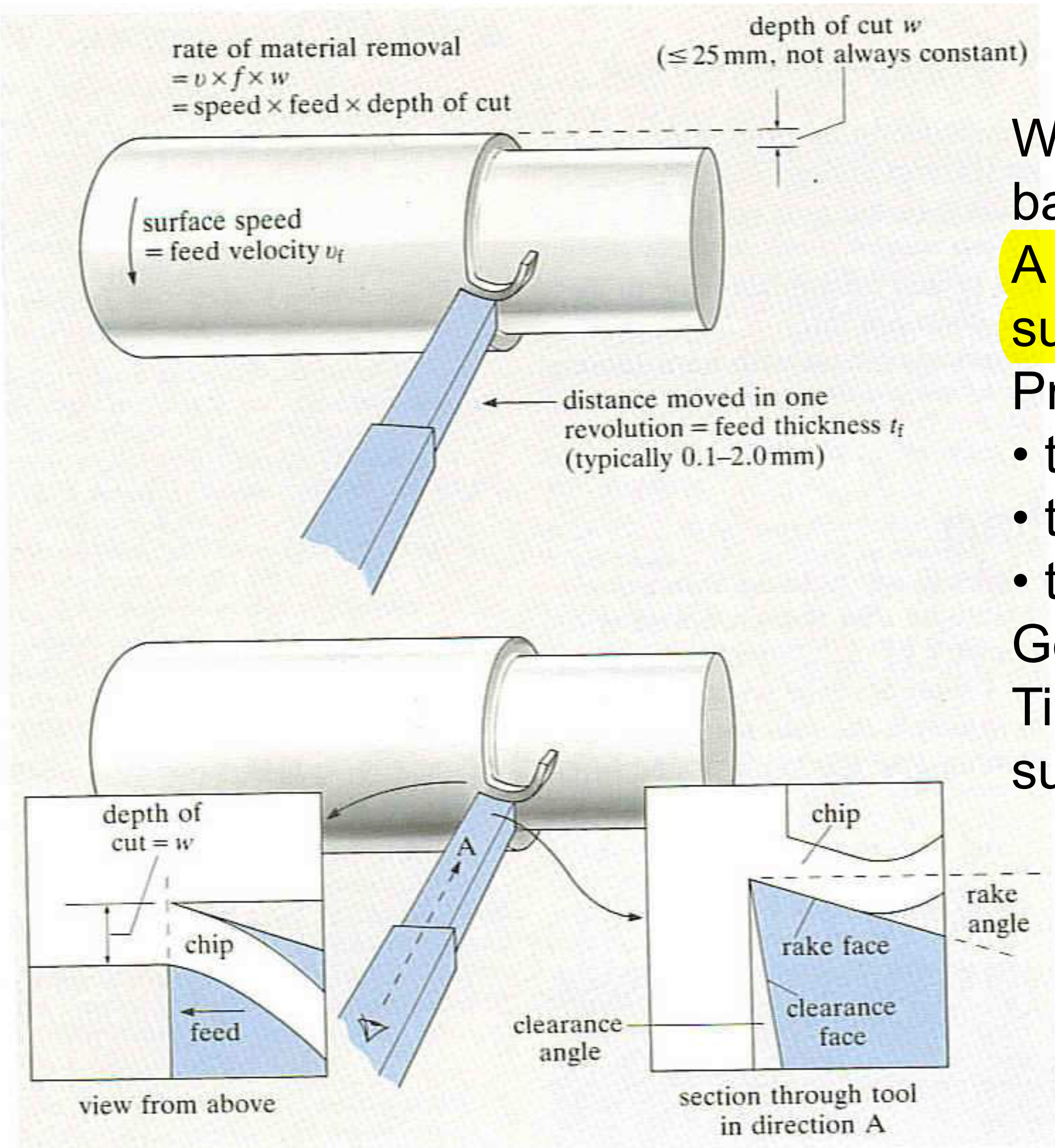
$$\mathbf{MRR} = 1000\, v\, d\, f \quad (\mathrm{mm}^3/\mathrm{min})$$

Mechanics of machining

Terminology in Turning



Turning



What happens during machining of a bar on a lathe?

A chip of material is removed from the surface of the workpiece.

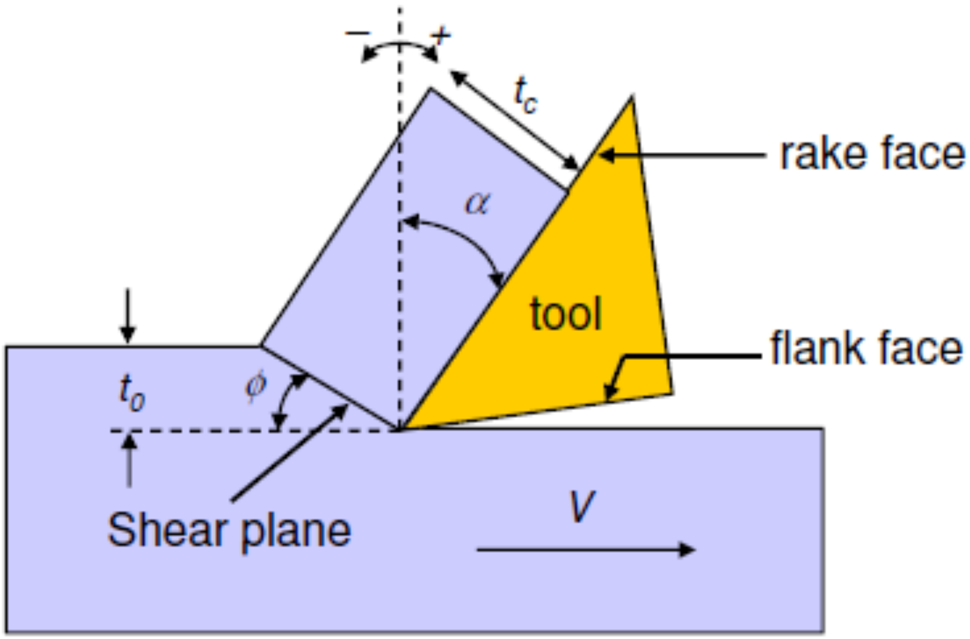
Principal parameters:

- the cutting speed, v
- the depth of cut, w or d
- the feed, f.

Geometry of single-point lathe turning

Time requires to turn a cylindrical surface of length Lw,

Chip formation



t_o : undeformed chip thickness

t_c : deformed chip thickness

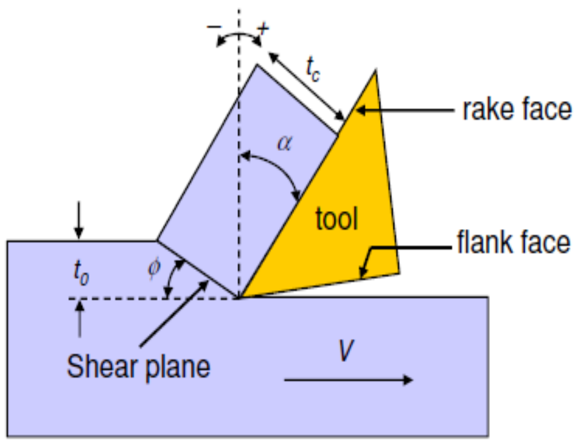
α : rake angle

ϕ : shear angle

V : cutting speed

Chip formation

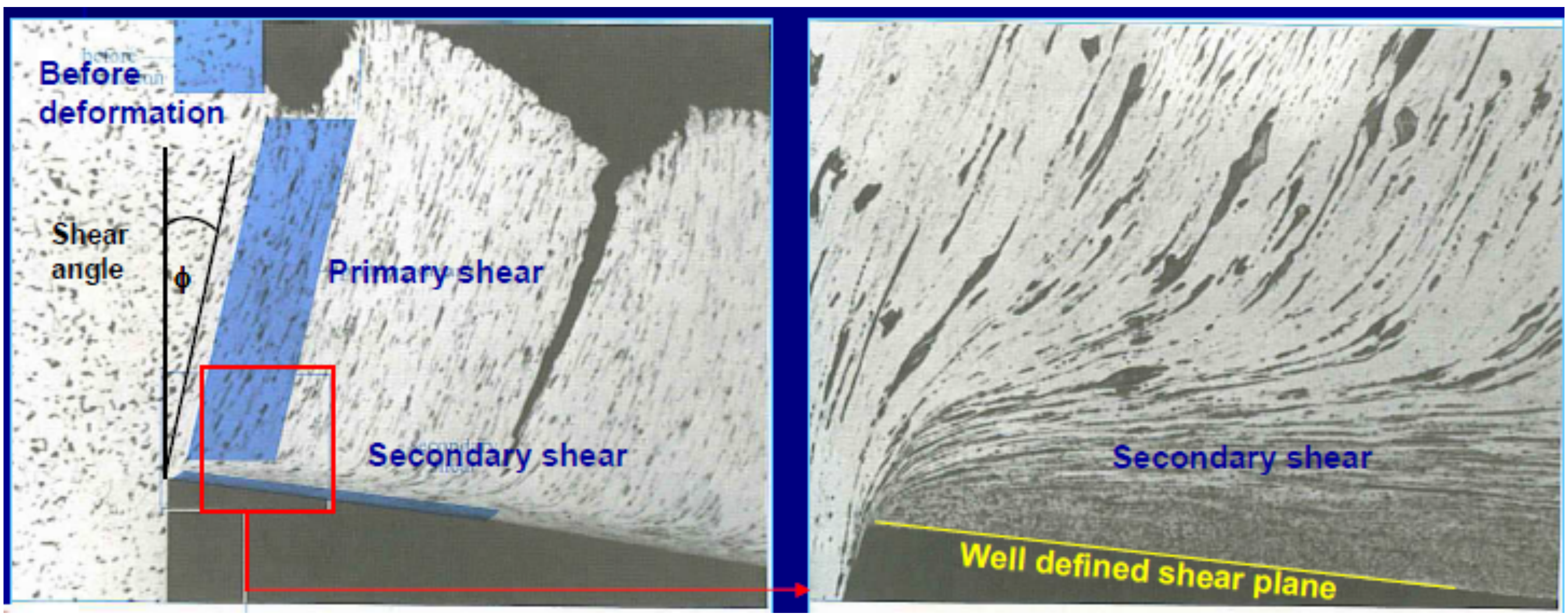
- The tool removes material near the surface of the workpiece by shearing it to form the chip.
- Material with thickness t is sheared and travels as a chip of thickness tc along the rake face of the tool.
- The chip compression ratio (cutting ratio) r = tc/to.



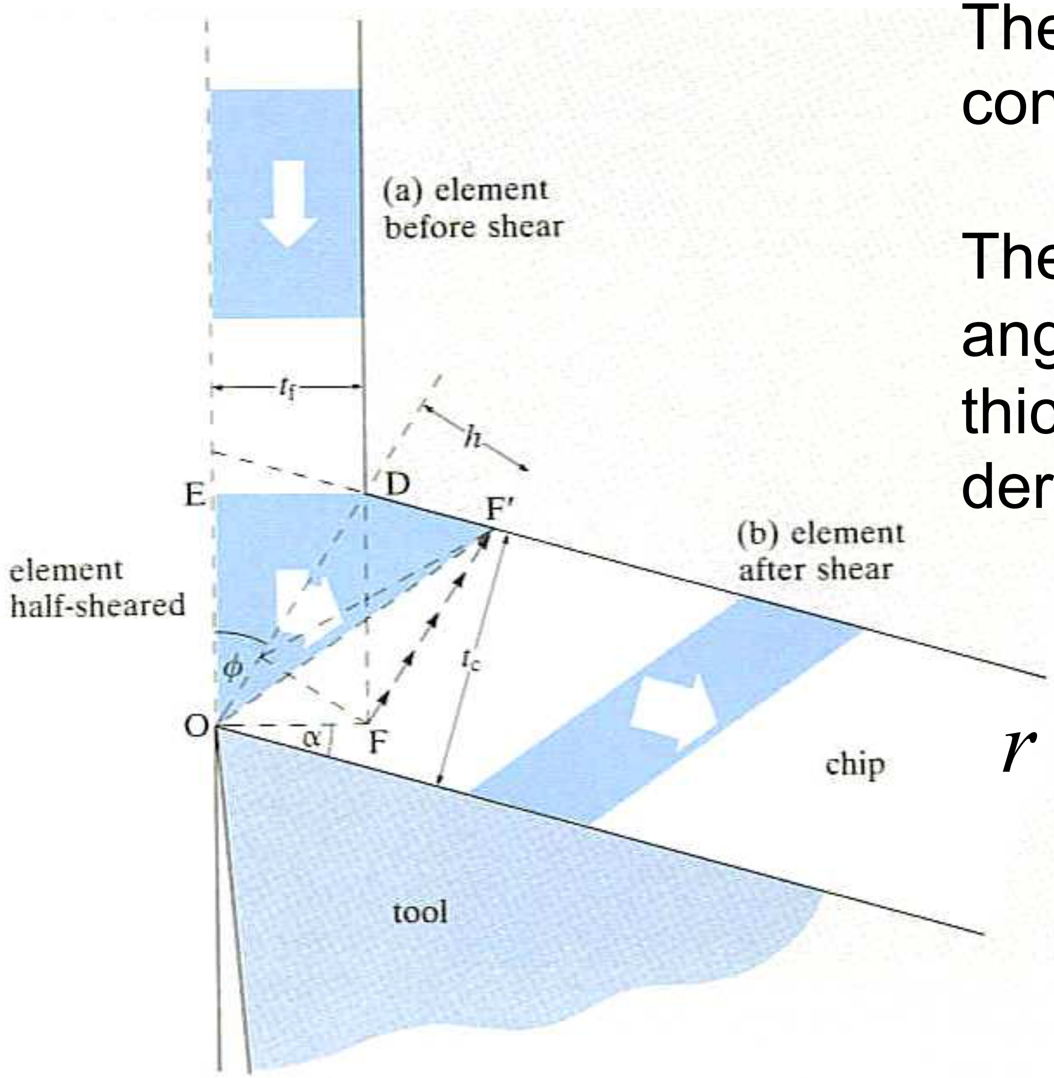
Deformation zone

•The entire chip is deformed as it meets the tool, known as primary shear. Shear plane angle is φ.

•Localized region of intense shear occurring due to the friction at the rake face, known as secondary shear.



Geometry of chip formation



The shear angle φ is controlled by the cutting ratio r.

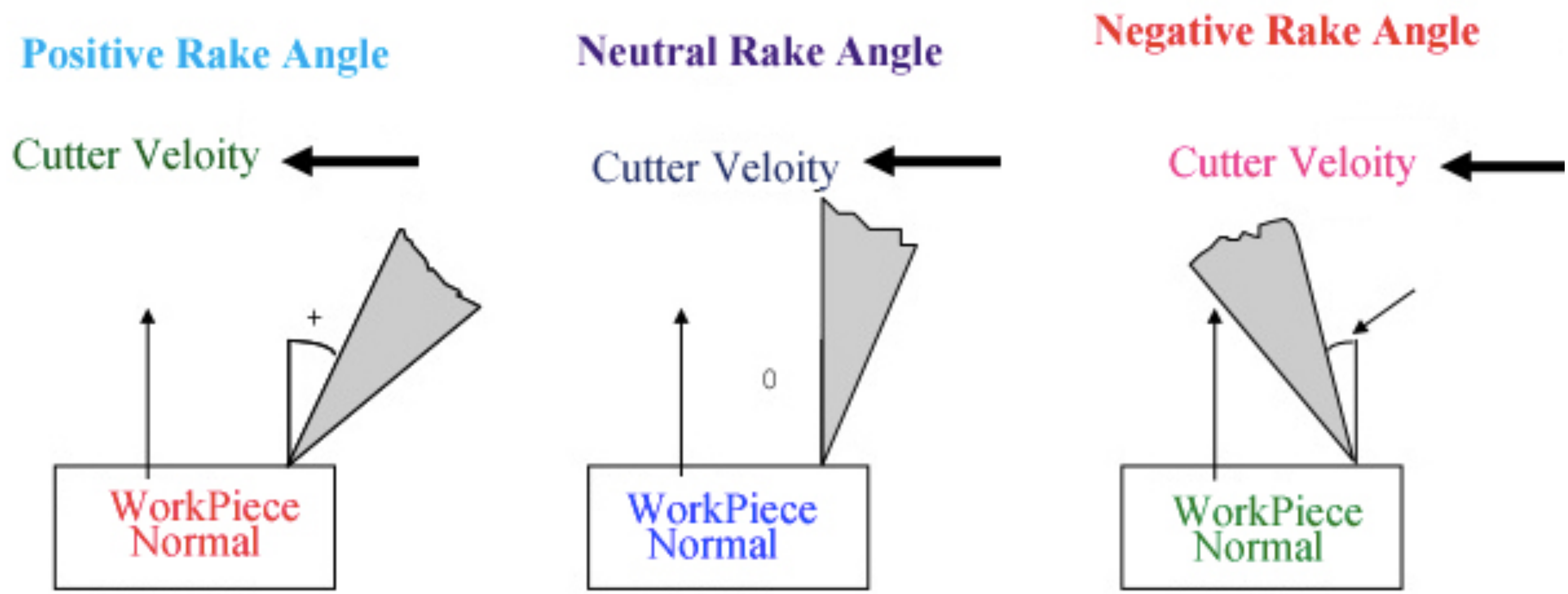
The relationship between rake angle, shear angle, and chip thickness ratio, r can be derived as follows

$$r = \frac{t}{t_c} = \frac{OD\sin\phi}{OD\cos(\phi - \alpha)}$$

Shear angle and chip thickness ratio

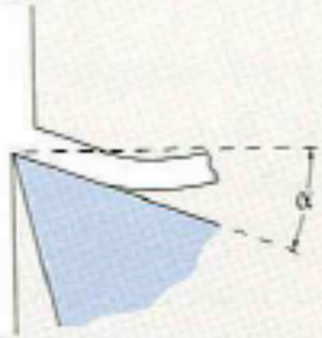
$$\tan\phi = \frac{r\cos\alpha}{1 - r\sin\alpha}$$

Rake angle

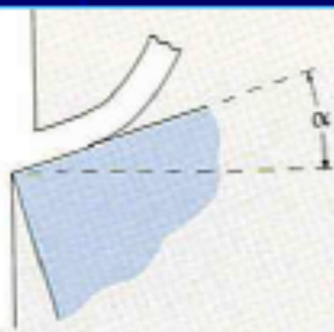


VARIOUS TYPES OF RAKE ANGLES

Rake angle



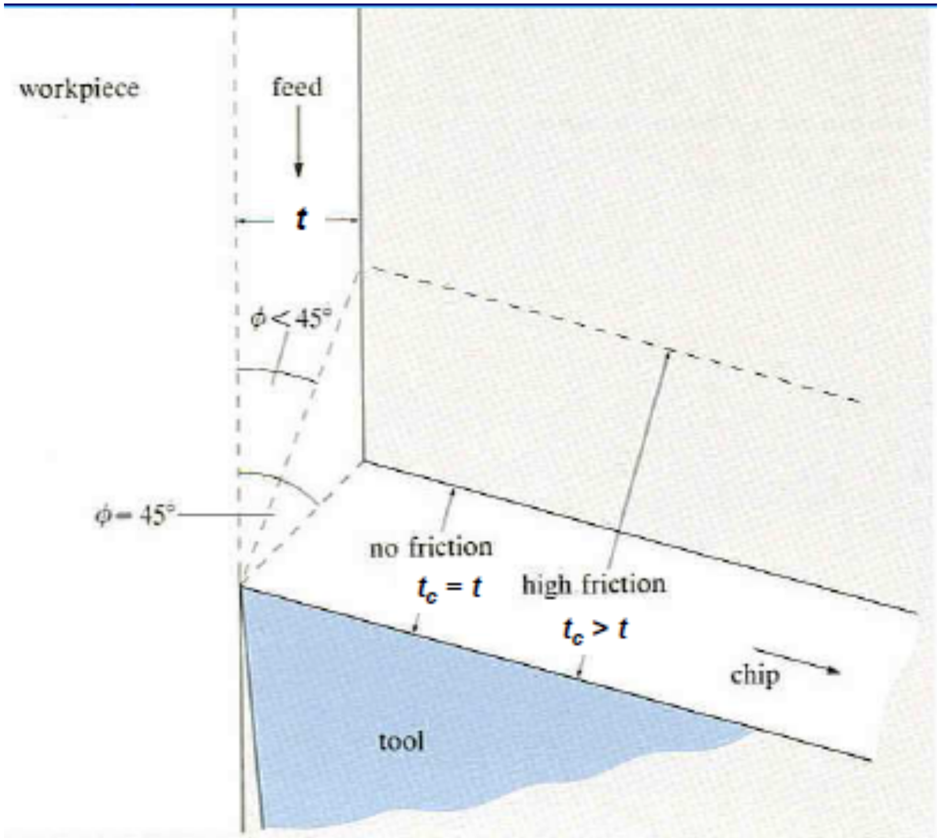
(a) Positive rake angle α (6-30°) leads to low cutting forces but fragile tools



(b) Negative rake angle α produces higher cutting forces and more robust tools.

(c) Negative rake angle tool with chip breaker – a useful compromise.

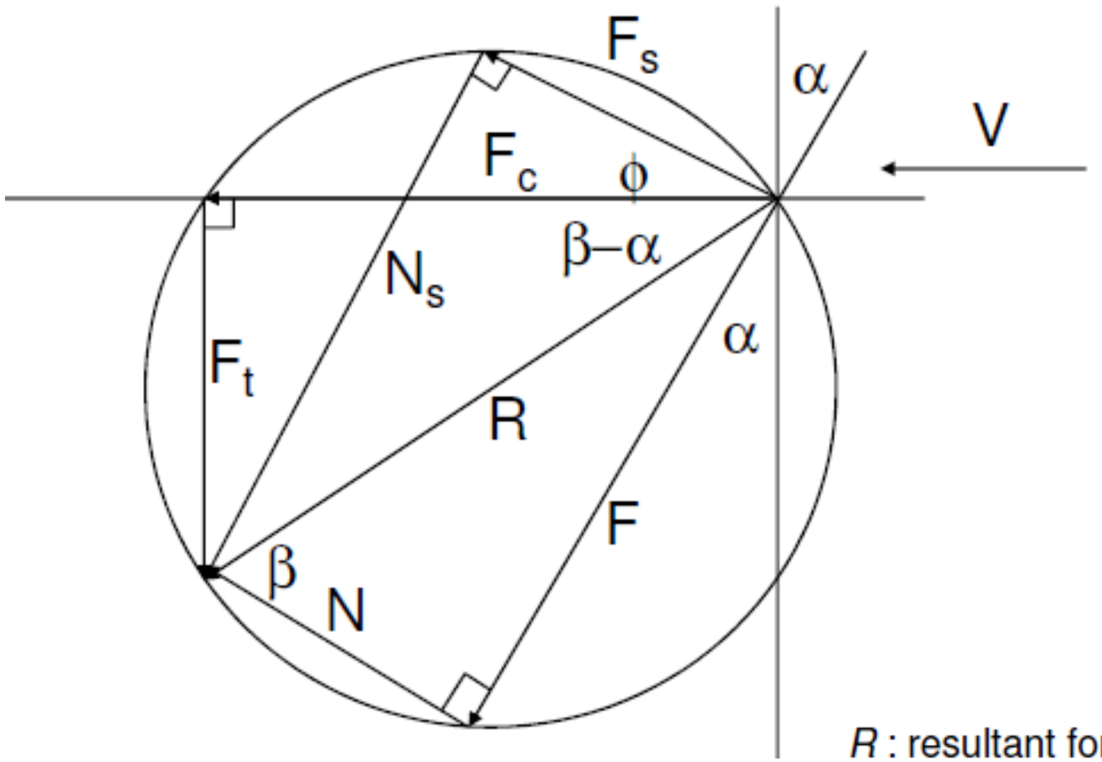
Effect of rake face contact length



- The deformed chip is flowing over a static tool, leading to frictional force similar to friction hill.
- If μ is greater than 0.5, sticky friction will result and flow will occur only within the workpiece but not at the tool-workpiece interface.

Force to move chips ⇧ Chip thickness ⇧ Change in shear angle

Merchant's circle diagram



ıgene Merchant
1913 - 2006

R : resultant force

F_t : thrust force

F_c : cutting force

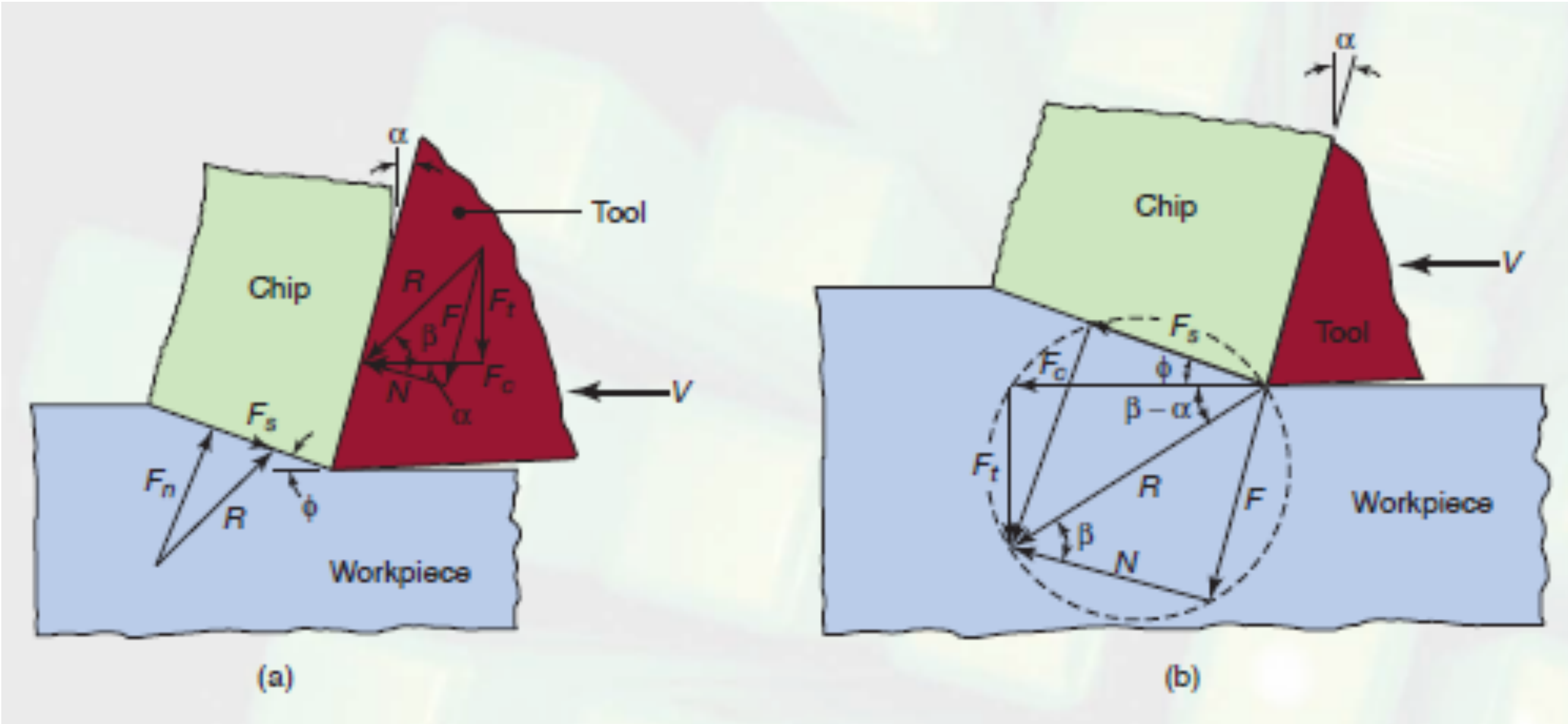
F : friction force

N : normal force

F_s : shear force

N_s : normal force on shear plane

Cutting forces



(a) Forces acting on a cutting tool in two-dimensional cutting. Note that the resultant forces, *R, must be* collinear to balance the forces. (b) Force circle to determine various forces acting in the cutting zone. *Source: After M.E.* Merchant.

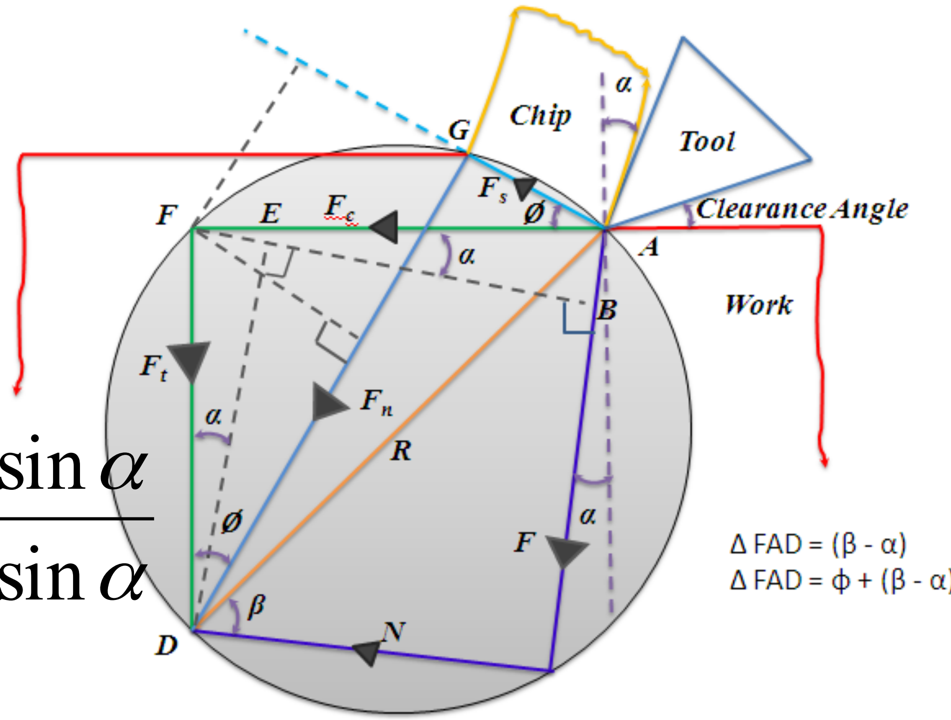
Force analysis

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

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

Coefficient of friction μ

$$\mu = \tan\beta = \frac{F}{N} = \frac{F_t \cos\alpha + F_c \sin\alpha}{F_c \cos\alpha - F_t \sin\alpha}$$



β = Friction angle

$$\mu = \frac{F_t + F_c \tan\alpha}{F_c - F_t \tan\alpha}$$

Also, $\beta = \tan^{-1}(\mu)$

Force analysis

$$F_s = F_c \cos\phi - F_t \sin\phi$$

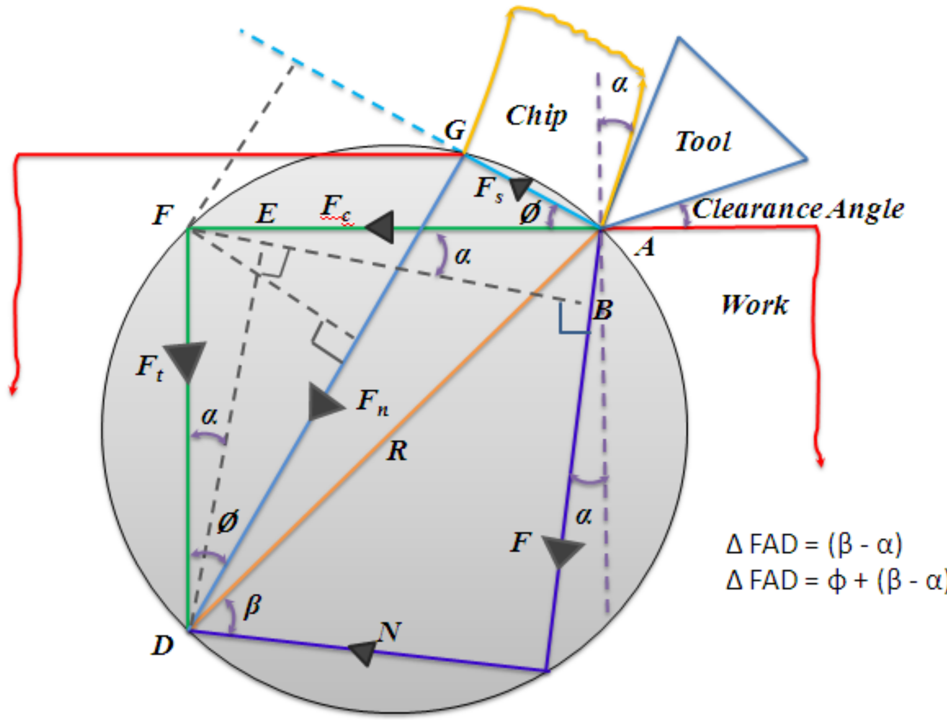
$$F_N = F_t \cos\phi + F_c \sin\phi$$

Also,

$$F_c = R\cos(\beta - \alpha)$$

$$F_s = R\cos(\phi + \beta - \alpha)$$

$$\therefore \frac{F_c}{F_s} = \frac{\cos(\beta - \alpha)}{\cos(\phi + \beta - \alpha)}$$



Shear plane area, A_s $= \dfrac{t_o \times w}{\sin\phi}$

Force analysis

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

Shear strength of material

$$F_c = \left(\frac{t_o w \tau}{\sin\phi}\right)\left(\frac{\cos(\beta-\alpha)}{\cos(\phi+\beta-\alpha)}\right)$$

$$R = \left(\frac{t_o w \tau}{\sin\phi}\right)\left(\frac{1}{\cos(\phi+\beta-\alpha)}\right)$$

$$F_t = R\sin(\beta-\alpha) = \left(\frac{t_o w \tau}{\sin\phi}\right)\left(\frac{\sin(\beta-\alpha)}{\cos(\phi+\beta-\alpha)}\right)$$

$$\frac{F_t}{F_c} = \tan(\beta-\alpha)$$

Force analysis

Mean shear stress on chip

$$\tau_{chip} = \frac{F_s}{A_s}$$

Mean normal stress on chip

$$\sigma_{chip} = \frac{F_N}{A_s}$$

Shear Stress on Tool Face

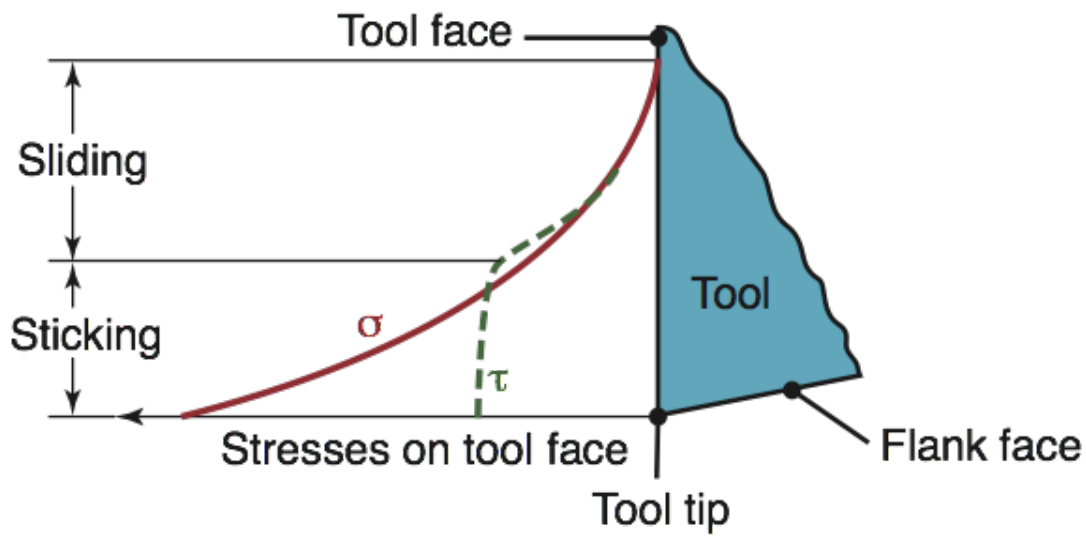


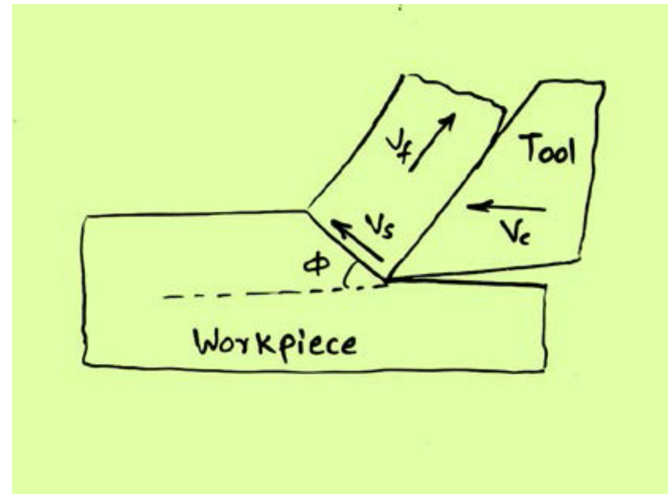
FIGURE 8.14 Schematic illustration of the distribution of normal and shear stresses at the tool-chip interface (rake face). Note that, whereas the normal stress increases continuously toward the tip of the tool, the shear stress reaches a maximum and remains at that value (a phenomenon known as *sticking*; see Section 4.4.1).

Velocity analysis

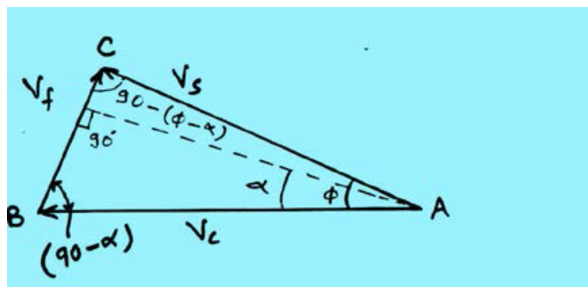
V_c: Cutting velocity

V_f: Chip flow velocity

V_s: Shear velocity



Using sine rule

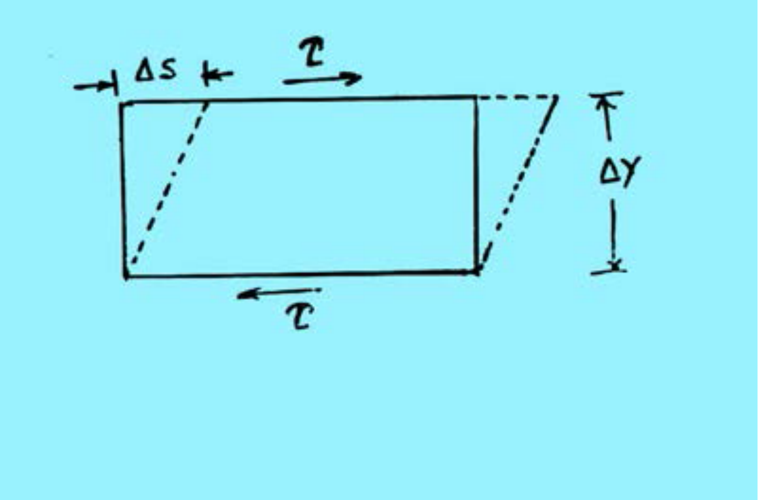


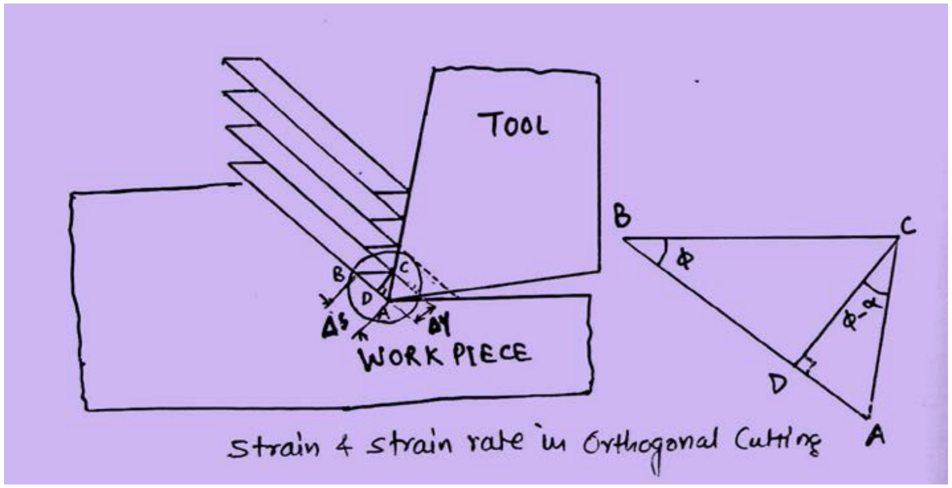
$$\frac{V_c}{\sin(90-(\phi-\alpha))}=\frac{V_f}{\sin\phi}=\frac{V_s}{\sin(90-\alpha)}$$

$$\frac{V_c}{\cos(\phi-\alpha)}=\frac{V_f}{\sin\phi}=\frac{V_s}{\cos\alpha} \quad and \quad V_f=\frac{V_c\sin\phi}{\cos(\phi-\alpha)}=V_c\cdot r_c$$

$$\boxed{V_s=\frac{V_c\cos\alpha}{\cos(\phi-\alpha)}\Rightarrow\frac{V_s}{V_c}=\frac{\cos\alpha}{\cos(\phi-\alpha)}}$$

Shear strain and strain rate





$$ShearStrain(\gamma) = \frac{deformation}{Length}$$

$$\gamma = \frac{\Delta s}{\Delta y} = \frac{AB}{CD} = \frac{AD}{CD} + \frac{DB}{CD} \qquad = \tan(\phi - \alpha) + \cot\phi$$

shear strain rate:

$\dot{\gamma} = \frac{V_s}{d}$, where d is typically $10^{-2} \sim 10^{-3}$ mm

Shear angle relationship

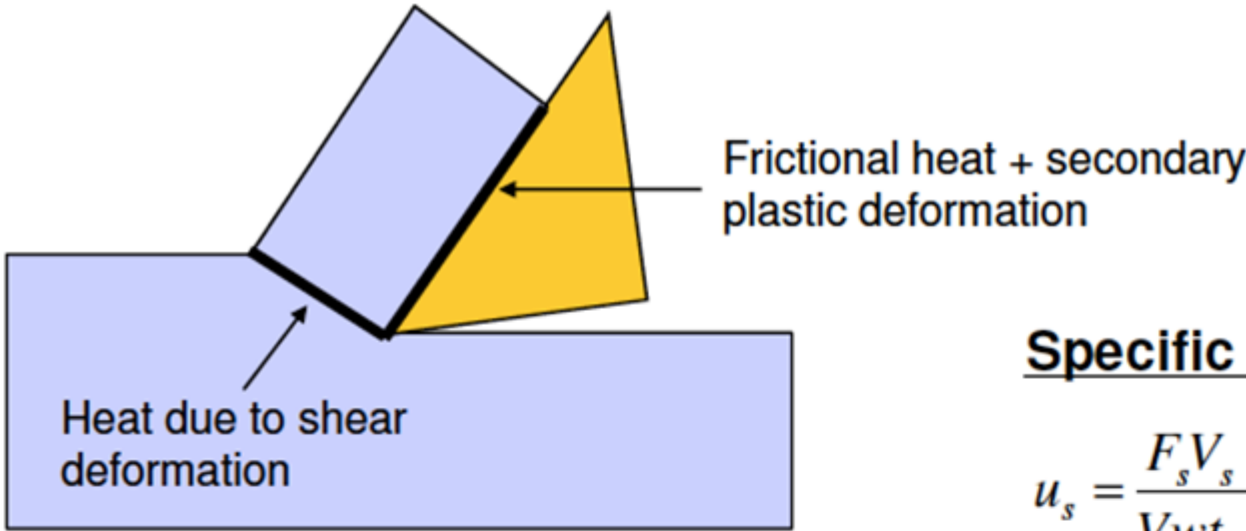
- Merchant's theory: shear angle ϕ assumes a value that minimizes the work done (or cutting force) in metal cutting
- Assuming that β is independent of ϕ and shear yield stress of the work material is constant, we can show that

$$\frac{dF_c}{d\phi} = 0 \Rightarrow \phi = \frac{\pi}{4} - \frac{1}{2}(\beta - \alpha)$$

- General form of shear angle relationship

$$\phi = C_1 + C_2(\beta - \alpha)$$

Energy in cutting



Specific shear energy

$$u_s = \frac{F_s V_s}{Vwt_0} \quad (\mathrm{Jm^{-3}\ or\ Nm^{-2}})$$

Specific cutting energy

$$u_c = \frac{energy}{volume} = \frac{F_c V}{Vwt_0} \quad (\mathrm{Jm^{-3}\ or\ Nm^{-2}})$$

Specific friction energy

$$u_f = \frac{FV_c}{Vwt_0} \quad (\mathrm{Jm^{-3}\ or\ Nm^{-2}})$$

$$\boxed{u_c \approx u_s + u_f} \ \text{OR} \ \boxed{P_c \approx P_s + P_f}$$

Shear angle relationship

P_c = cutting power = $F_c V = u_c(Vwt_0)$

P_s = shear zone power = $F_s V_s = u_s(Vwt_0)$

P_f = friction zone power = $FV_c = u_f(Vwt_0)$

- Typically, 60-70% of the energy in metal cutting is consumed in the shear zone
- Remaining 40-30% is consumed at the tool-chip interface (assuming a perfectly sharp tool)
- Momentum and surface creation energies are negligible

Example

A orthogonal cutting process is being used to machine a 300 mm x 300 mm x 25 mm flat mild steel block. The sharp single point cutting tool has a rake angle α= 10°. Other process parameters are as follows: cutting speed V = 2 m/s, undeformed chip thickness t_0 = 0.25 mm, width of cut per pass w = 2.5 mm, deformed chip thickness t_c = 0.83 mm. The cutting and thrust forces were measured during each pass with a cutting force dynamometer and found to be as follows: F_c = 890 N and F_t = 667 N. (Note: Planing is an orthogonal cutting process). Calculate the percentage of total power dissipated in the primary zone of deformation (shear zone).

Types of Chips

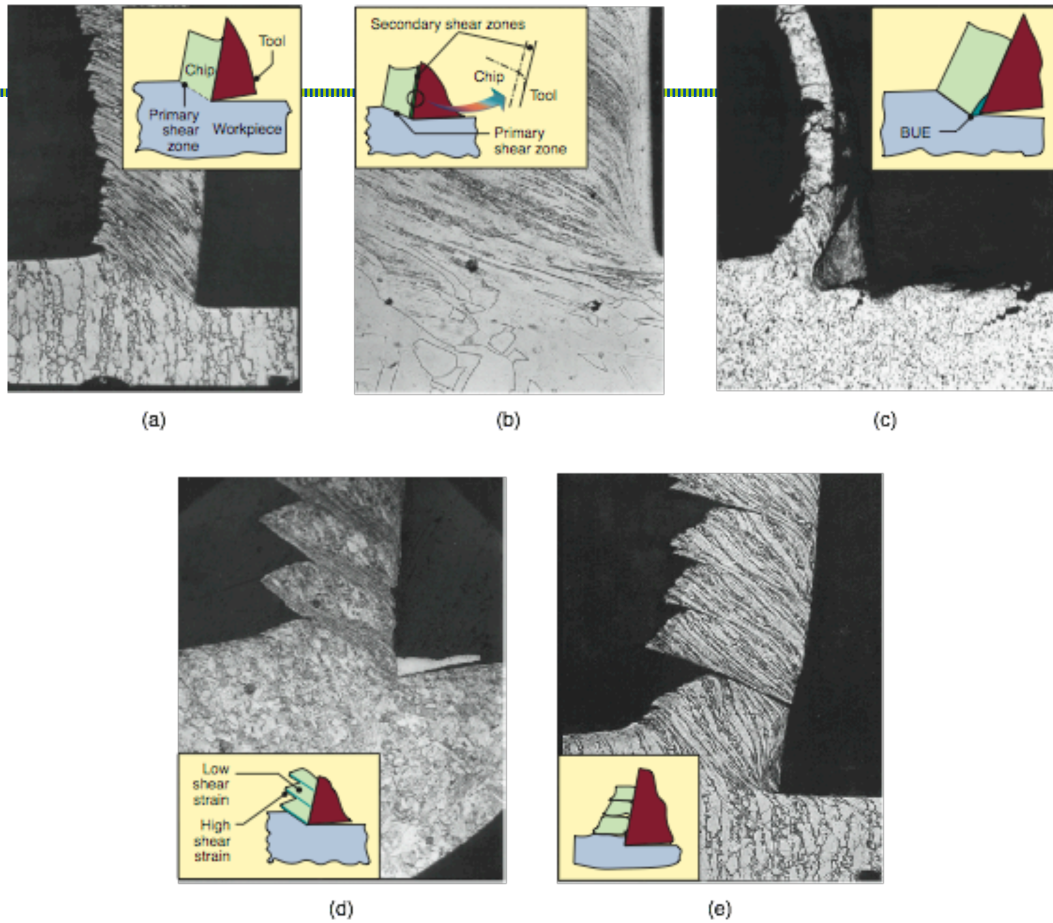


FIGURE 8.4 Basic types of chips produced in metal cutting and their micrographs: (a) continuous chip with narrow, straight primary shear zone; (b) secondary shear zone at the tool-chip interface; (c) continuous chip with built-up edge; (d) segmented or nonhomogeneous chip; and (e) discontinuous chip. *Source:* After M.C. Shaw, P.K. Wright, and S. Kalpakjian.

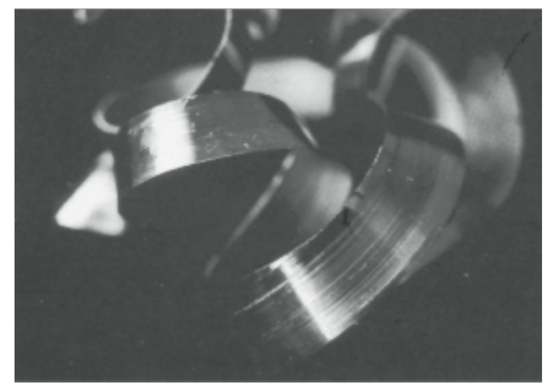
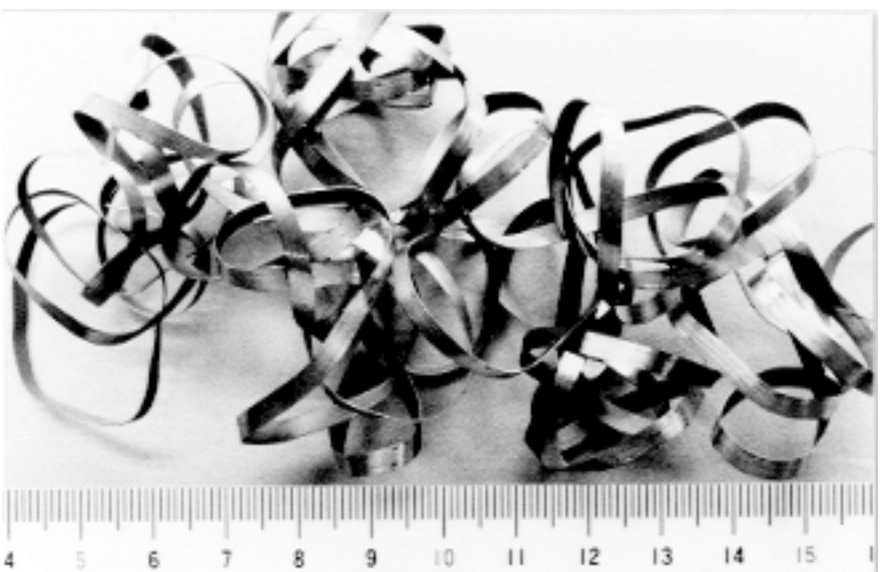


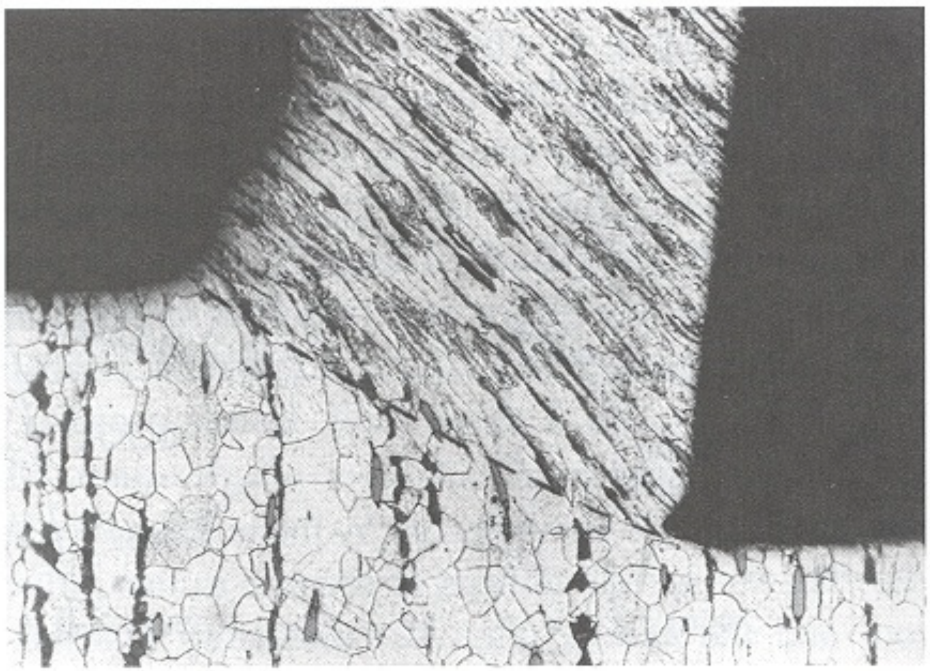
FIGURE 8.5 Shiny (burnished) surface on the tool side of a continuous chip produced in turning.

Major chip types

Continuous chip is characteristic of cutting ductile materials under steady stage conditions. However, long continuous chips present handling and removal problems in practical operation.

- required chip-breaker.





Chip Breakers

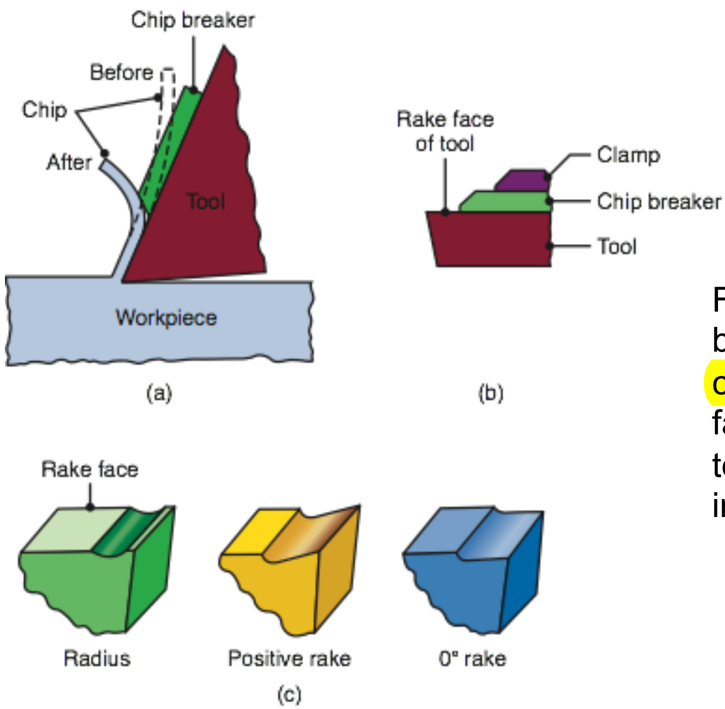
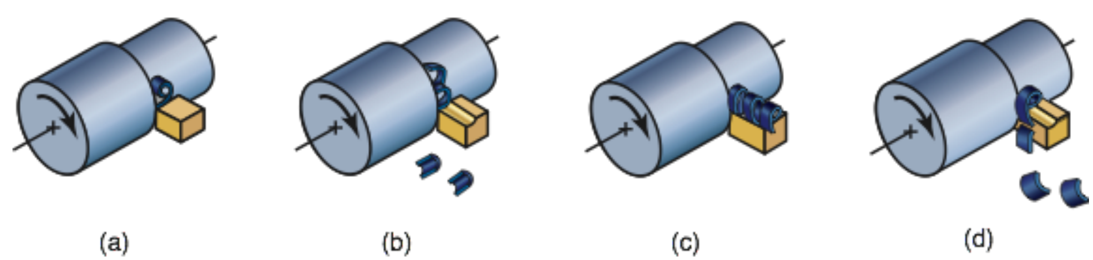


FIGURE 8.7 (a) Schematic illustration of the action of a chip breaker. Note that the chip breaker decreases the radius of curvature of the chip. (b) Chip breaker clamped on the rake face of a cutting tool. (c) Grooves on the rake face of cutting tools, acting as chip breakers. Most cutting tools now are inserts with built-in chip-breaker features.

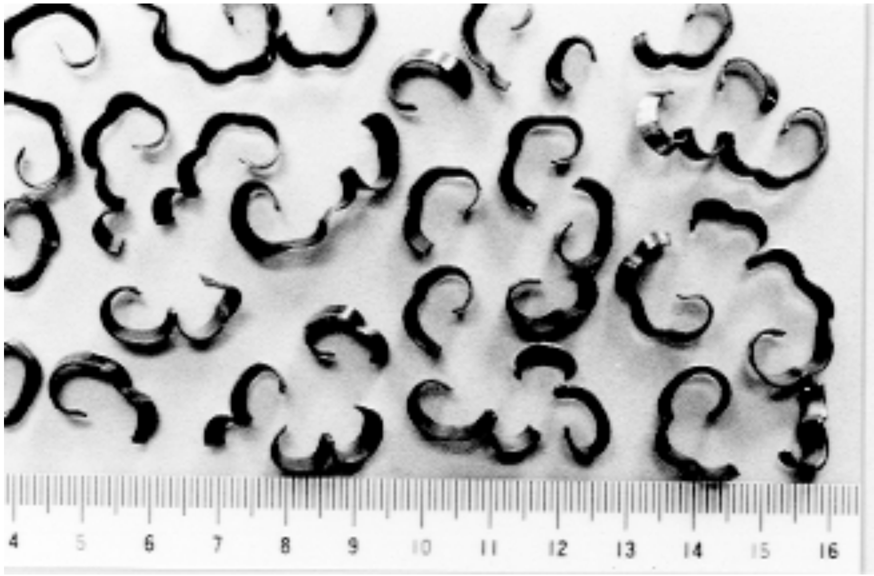
FIGURE 8.8 Various chips produced in turning: (a) tightly curled chip; (b) chip hits workpiece and breaks; (c) continuous chip moving radially outward from workpiece; and (d) chip hits tool shank and breaks off. *Source:* After G. Boothroyd.



Major chip types

Discontinuous chip is formed in brittle materials which cannot withstand the high shear strains imposed during the machining process.

Ex: cast iron and cast brass, may occur in ductile materials machined at very low speeds and high feed.



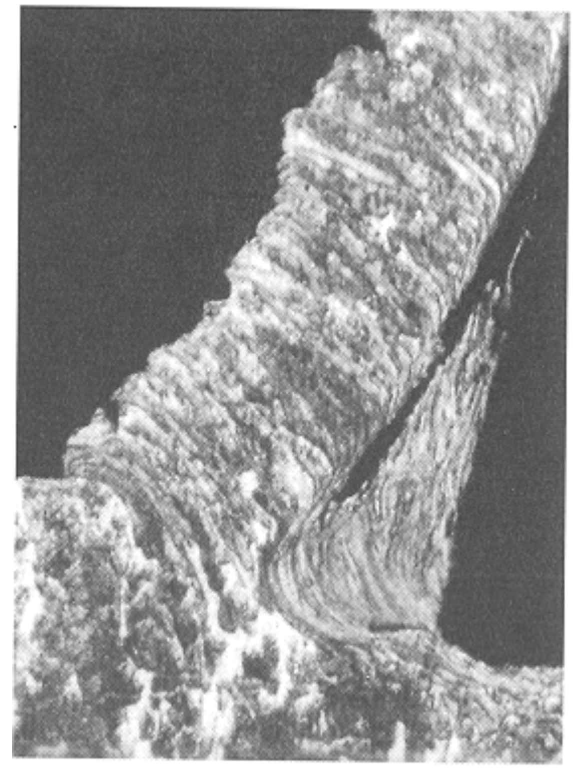
Major chip types

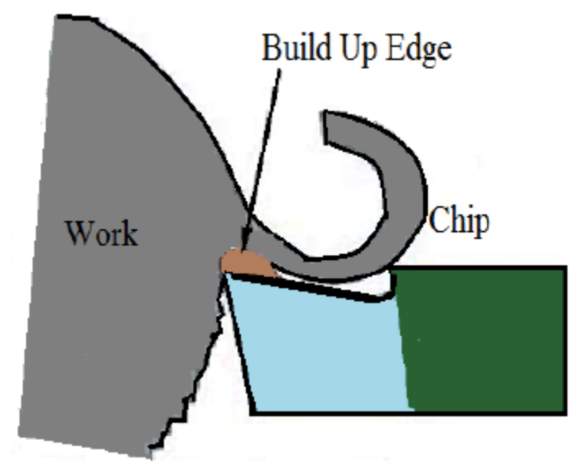
• Under conditions where the friction between the chip and the rake face of the tool is high, the chip may weld to the tool face.

• The accumulation of the chip material is known as a built-up edge (BUE).

• The formation of BUE is due to work hardening in the secondary shear zone at low speed (since heat is transferred to the tool).

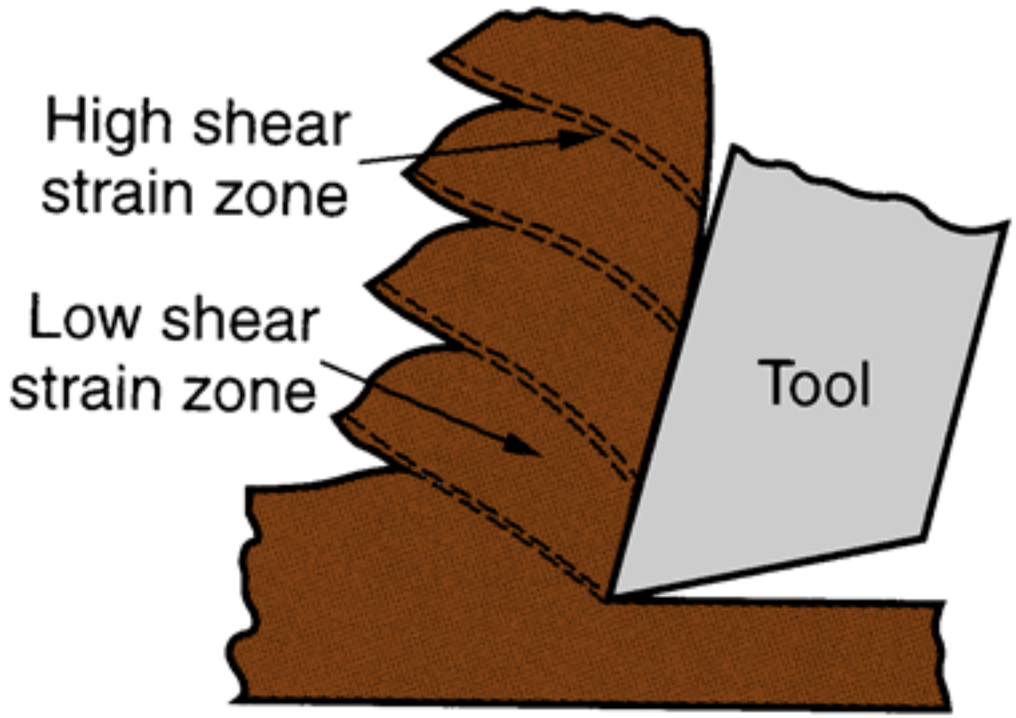
• The BUE acts as a substitute cutting edge (blunt tool with a low rake angle).





Major chip types

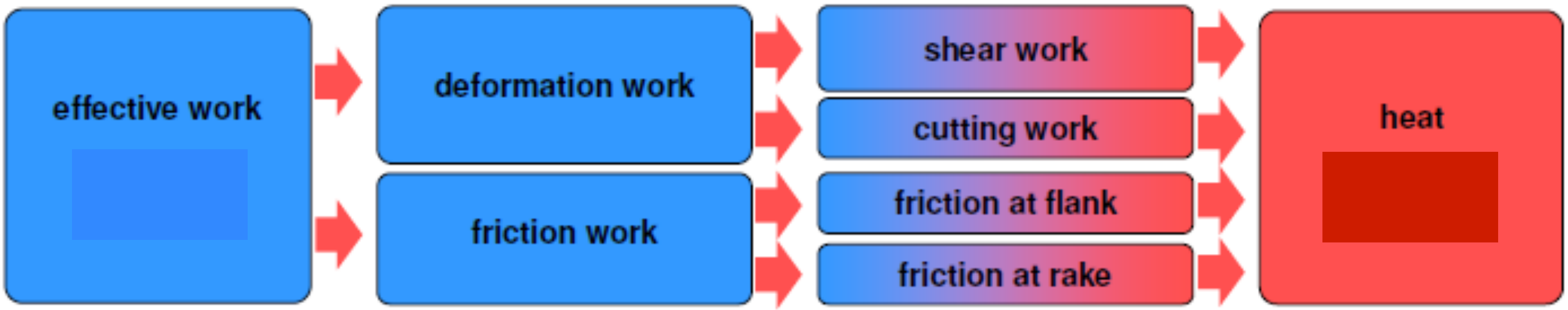
Segmented chips: low thermal diffusivity materials, very hard steels

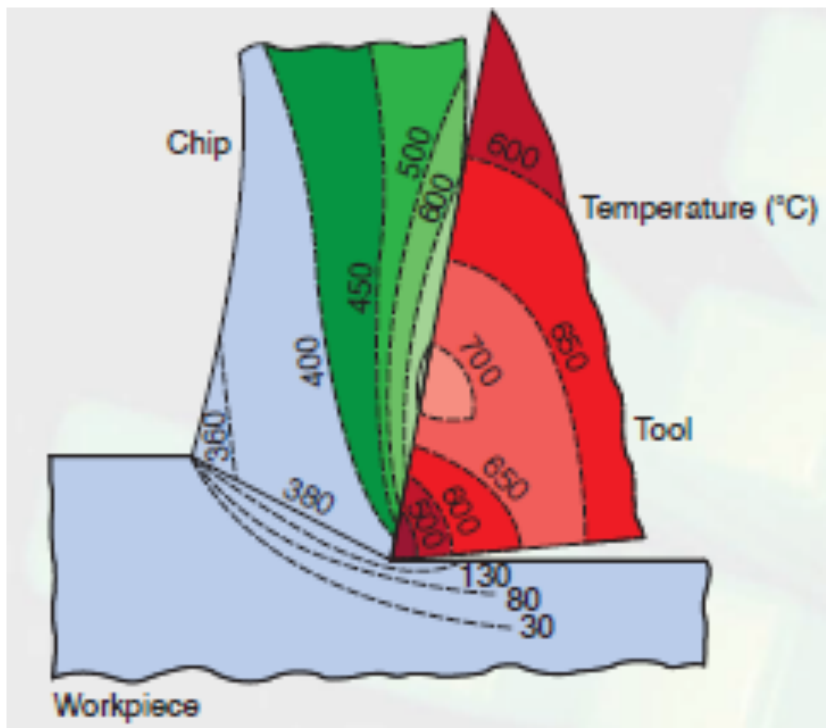


Chip types

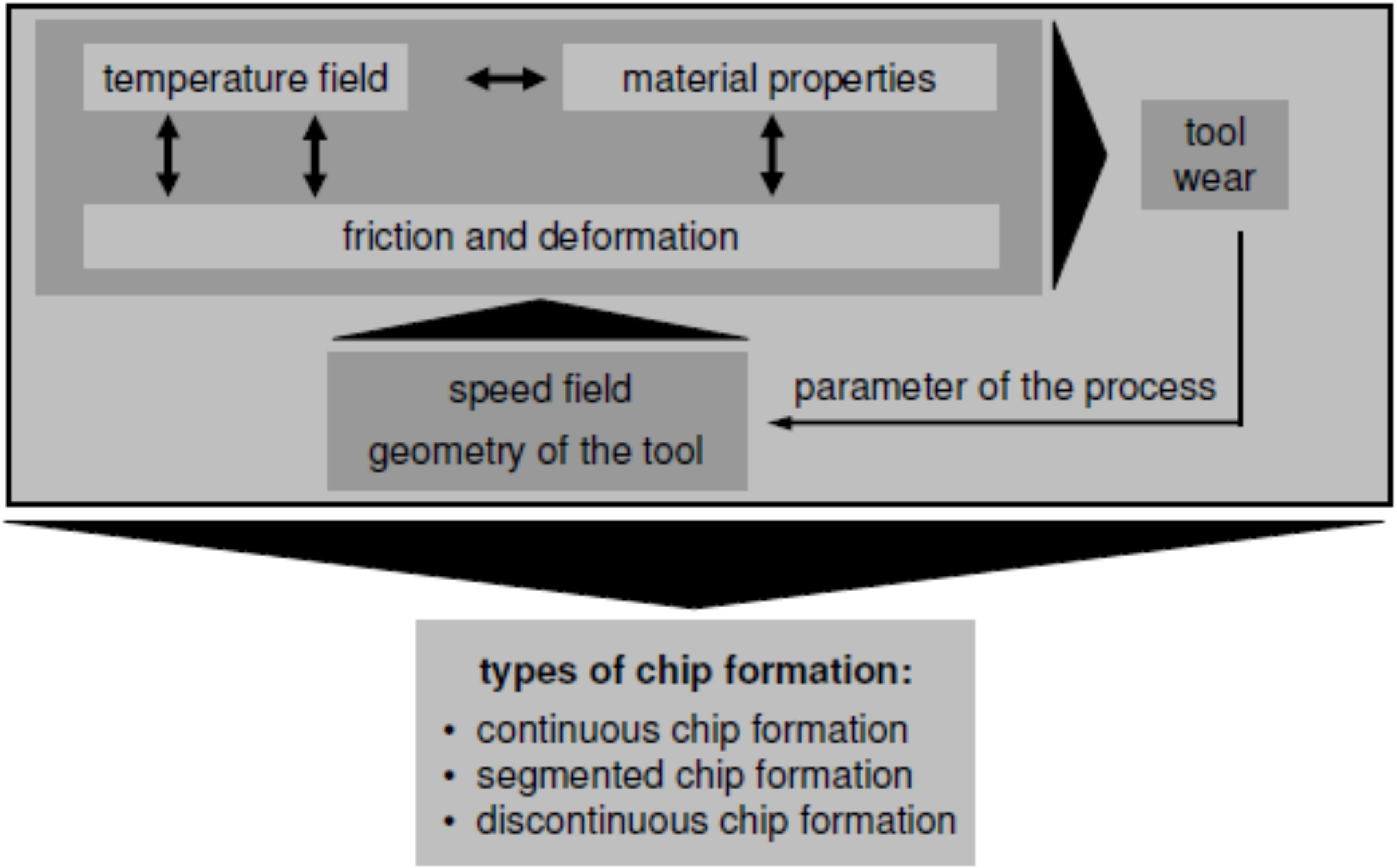
- (a) Continuous chip with narrow primary shear zone
– ductile materials at high speed
– bad for automation (use chip breakers)
- (b) Continuous chip with built up edge (BUE)
– high plastic working
– bad for automation
- (c) Continuous chip with large primary shear zone
– soft metals at low speeds and low rake angles
– poor surface finish and residual stresses
- (d) Segmented chip
– low thermal conductivity materials
- (e) Discontinuous chip
– low ductility materials and/or negative rake angles
– good for automation

Heat source and temperature in cutting



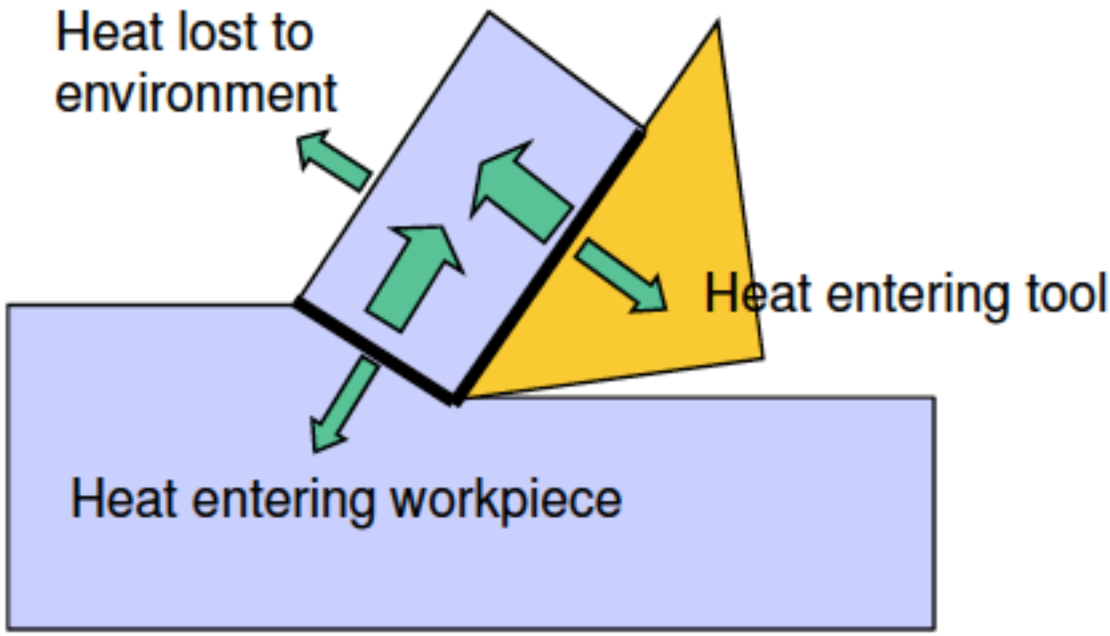


Thermal and mechanical loads



Temperature in metal cutting

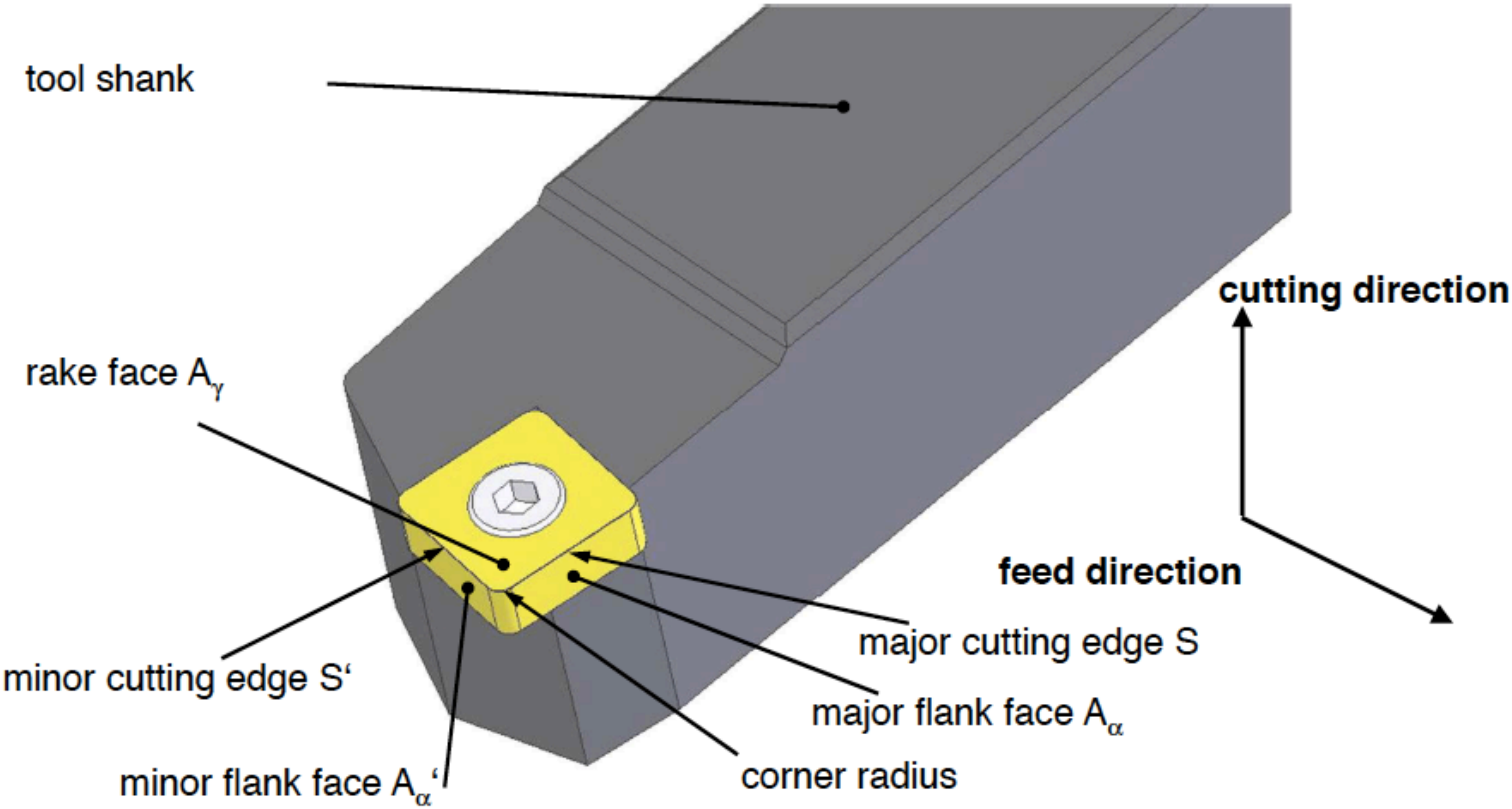
- Energy dissipated in cutting converted into heat in shear zone and tool-chip interface
- Heat transfer to environment is negligible



Temperature in metal cutting

- Adverse effects of temperature rise in tool and workpiece
  – Increases tool wear
  – Harder to achieve part accuracy (due to thermal expansion of part)
  – Sub-surface damage (surface integrity)
- Desirable that most of the heat is carried away by chip

Terms at the cutting edge



Tool Angles

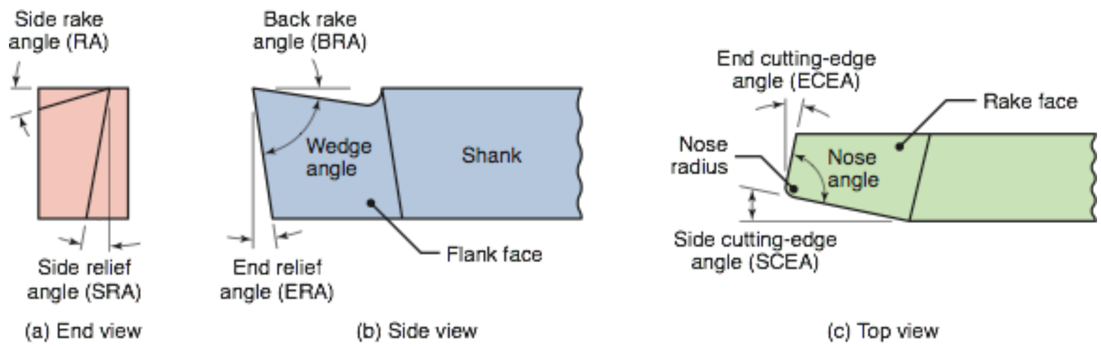


FIGURE 8.41 Designations and symbols for a right-hand cutting tool. The designation "right hand" means that the tool travels from right to left, as shown in Fig. 8.19.

TABLE 8.8 General recommendations for tool angles in turning.

Material	High-speed steel					Carbide inserts				
	Back rake	Side rake	End relief	Side relief	Side and end cutting edge	Back rake	Side rake	End relief	Side relief	Side and end cutting edge
Aluminum and magnesium alloys	20	15	12	10	5	0	5	5	5	15
Copper alloys	5	10	8	8	5	0	5	5	5	15
Steels	10	12	5	5	15	-5	-5	5	5	15
Stainless steels	5	8-10	5	5	15	-5-0	-5-5	5	5	15
High-temperature alloys	0	10	5	5	15	5	0	5	5	45
Refractory alloys	0	20	5	5	5	0	0	5	5	15
Titanium alloys	0	5	5	5	15	-5	-5	5	5	5
Cast irons	5	10	5	5	15	-5	-5	5	5	15
Thermoplastics	0	0	20-30	15-20	10	0	0	20-30	15-20	10
Thermosets	0	0	20-30	15-20	10	0	15	5	5	15

Machinability

machine tool

- machine tool
- machine condition

production conditions

- production processes
- engagement parameter
- cooling

tool

- tool type
- geometry of the cutting edge
- clamping

machinability

- tool life
- surface integrity
- total force
- chip form

workpiece

- geometry
- surface integrity
- clamping

cutting material

- type of the material
- chemical configuration
- microstructure
- strength property
- surface treatment

material

- type of the material
- chemical configuration
- microstructure
- strength property
- heat treatment

Tool wear

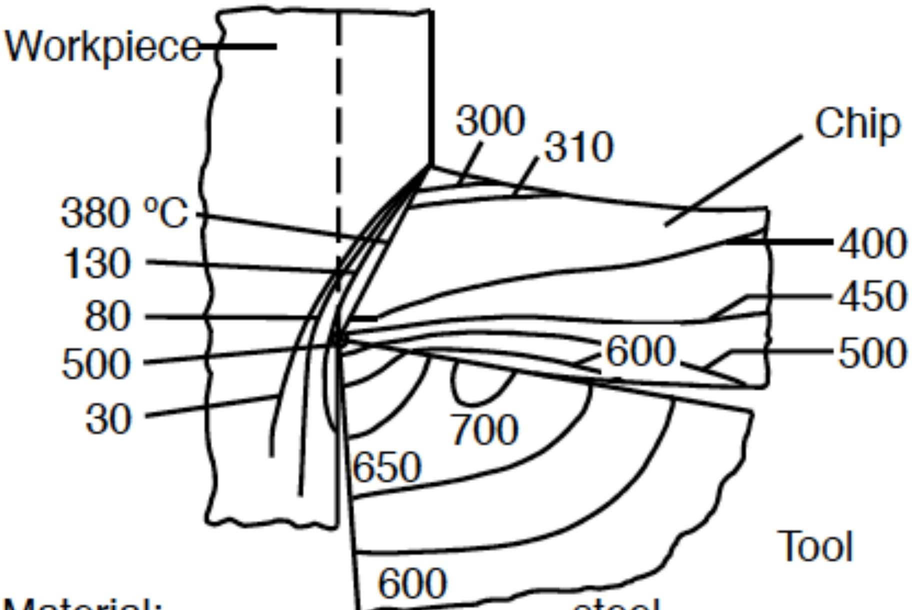
Tool wear
is influenced by high contact stresses, high cutting temperatures and relative sliding velocities

These process values depend on:

- tool and workpiece materials
- tool geometry
- interface conditions
- machining parameters

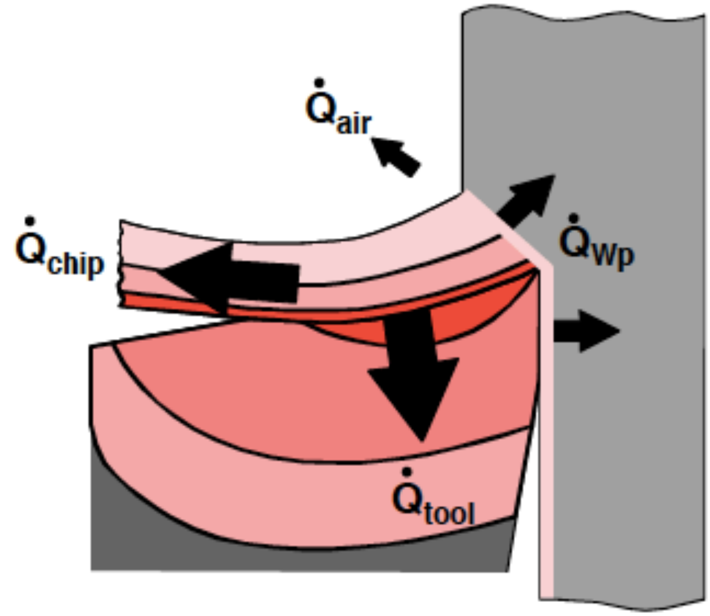
Distribution of heat

Allocation of heat in the machining zone



Material:	steel
Yield stress:	$k_f = 850\ N/mm^2$
Cutting material:	HW-P20
Primary speed:	$v_c = 60$ m/min
Chip width:	h = 0,32 mm
Chip angle:	$\gamma_o = 10°$

Heat flows emerging from the machining zone



Q_{air} = Heat flow to environment

Q_{chip} = Heat flow to chip

Q_{Wp} = Heat flow to workpiece

Q_{tool} = Heat flow to tool

Tool wear locations

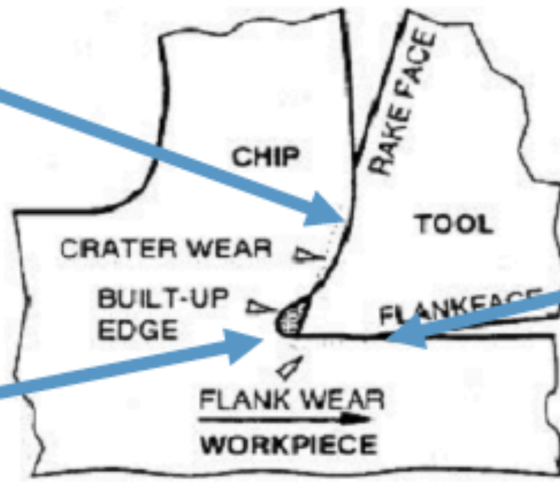
Tool Wear appears at three locations at the cutting tool

Crater Wear

Area of high level of stress and temperature, i.e. of the order of 1200°C.

Built-Up Edge

Observable for ductile materials. Not stable, breaks off frequently

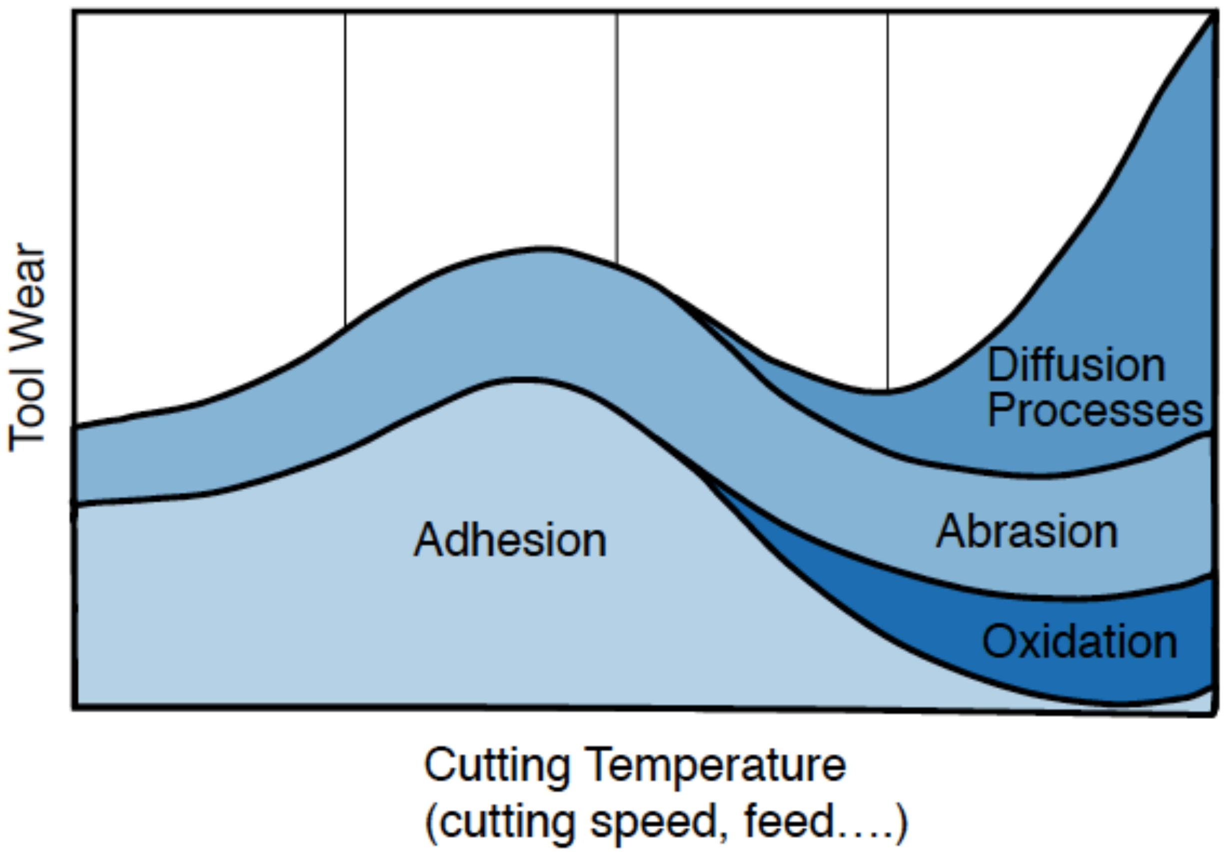


Tool Wear

Flank Wear

Mainly responsible for the resulting surface quality => used as failure criteria.

Wear mechanisms



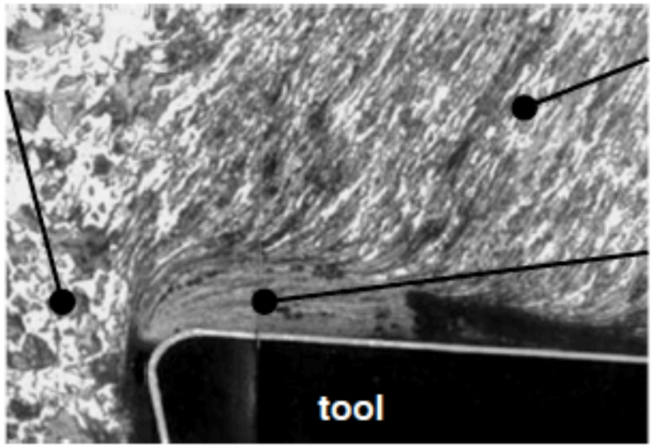
- The total wear at the wedge is a superposition of distinct wear mechanisms.
- During cutting all distinct wear mechanisms occur simultaneously.
- Diffusion and oxidation are dependent on the temperature level and occur mainly at high cutting speeds.

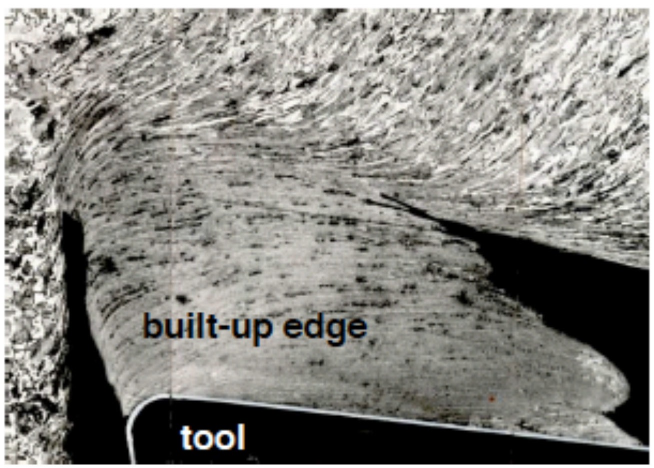
Wear mechanism: Adhesion

undeformed bulk of the workpiece

deformed chip

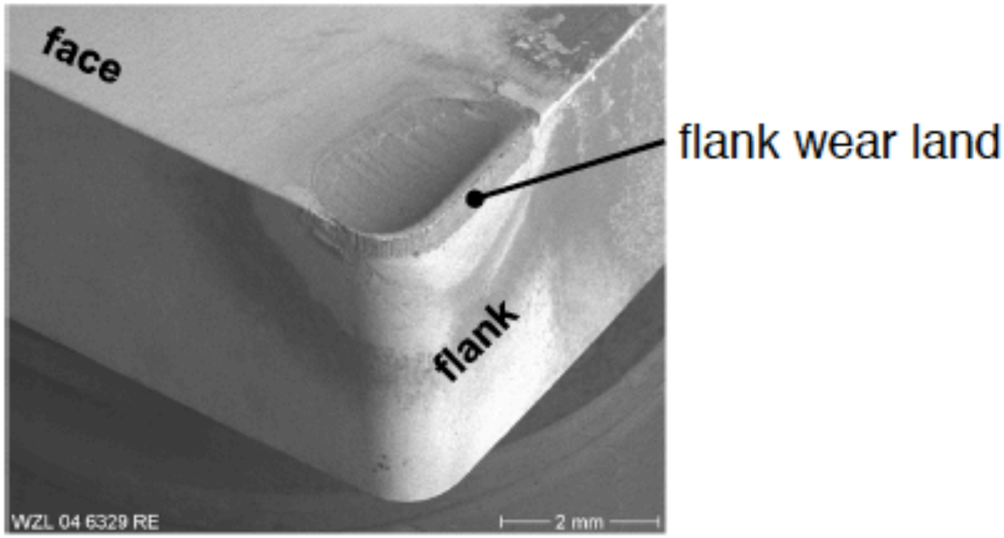
built-up edge

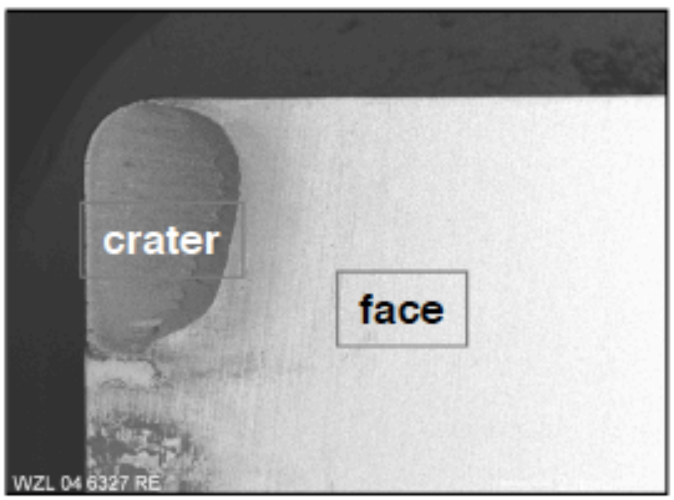




- Low cutting speeds causes low contact temperatures between chip and tool. This goes along with high contact pressure.
- Low contact temperatures, high contact pressure and material affinity lead to adhesion.
- Adhesion at the wedge may cause built-up edges.
- Built-up edges are unstable. They peel away off the edge and slide over the flank and the face periodically.

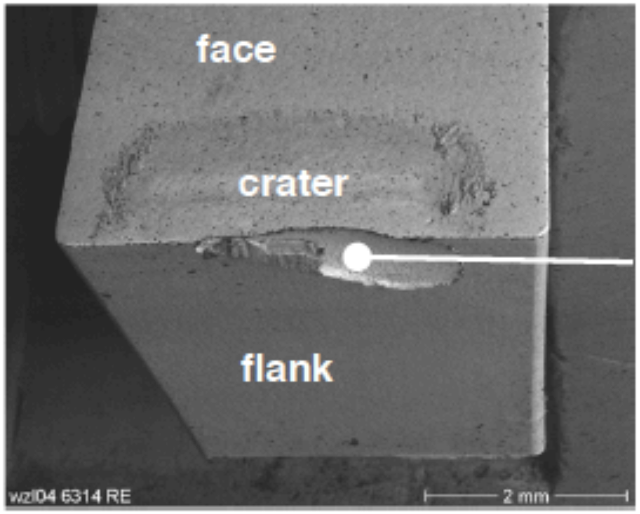
Wear mechanism: Abrasion



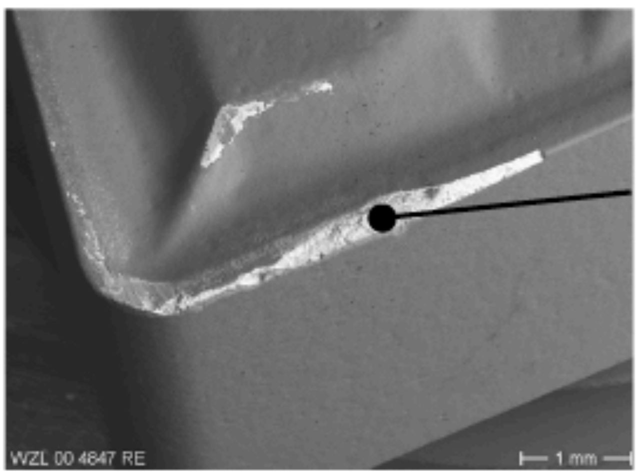


- Abrasion at the wedge is caused by hard particles in the chip, which penetrate into the tool material and slide and scratch over the face.
- As a result on the face a crater is generated.
- As a result on the flank a wear land is generated.

Catastrophic failure of the wedge



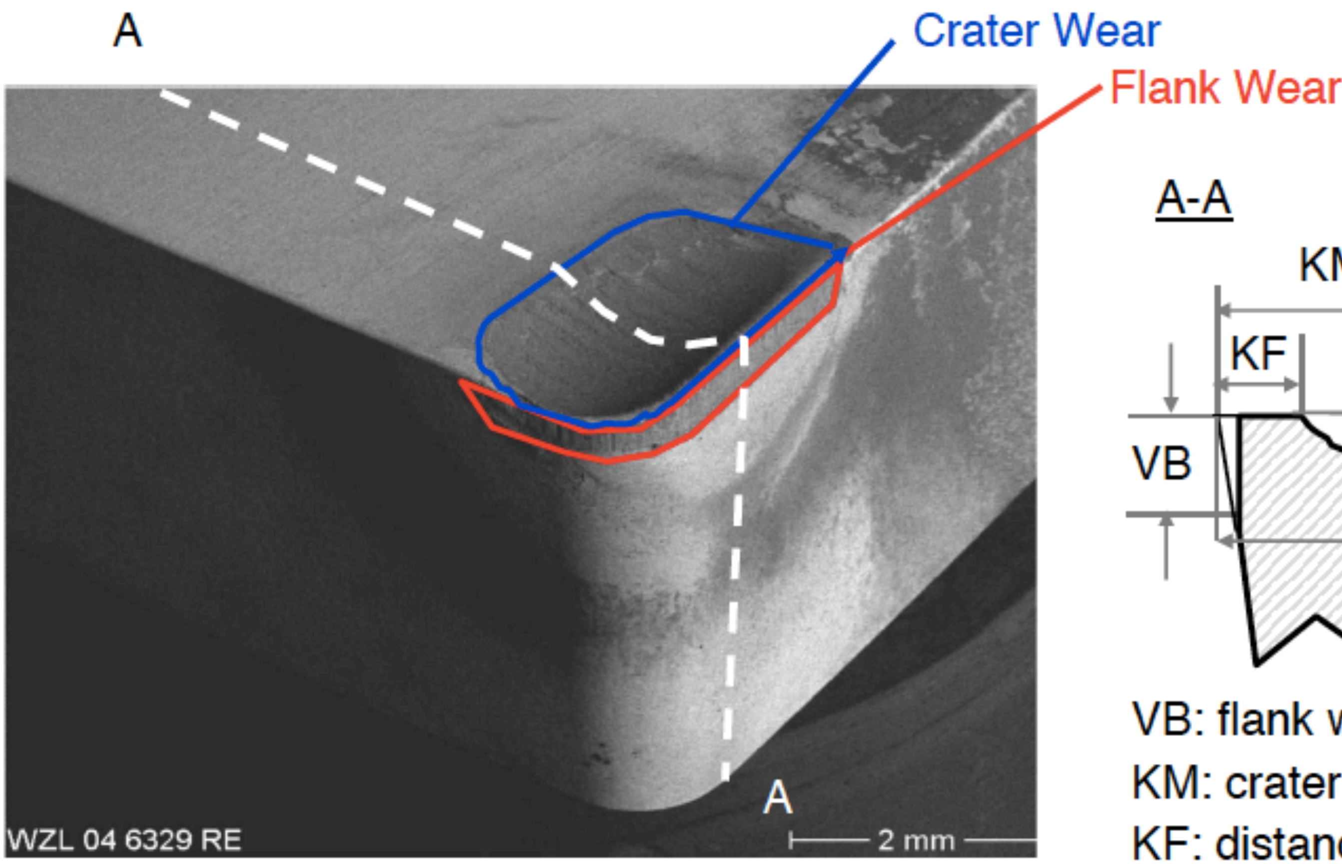
Chipping and break outs
at cutting edge

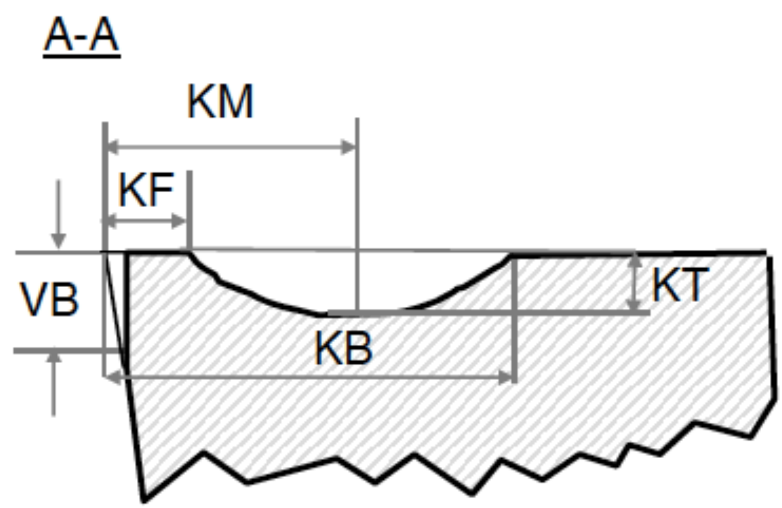


little disruptions
at the cutting edge

- If the mechanical load at the wedge surpasses the resistance of the cutting material, the cutting edge fails.

Wear characterization





VB: flank wear width

KM: crater center distance

KF: distance from crater to edge

KB: crater width

KT: crater depth

Tool Wear

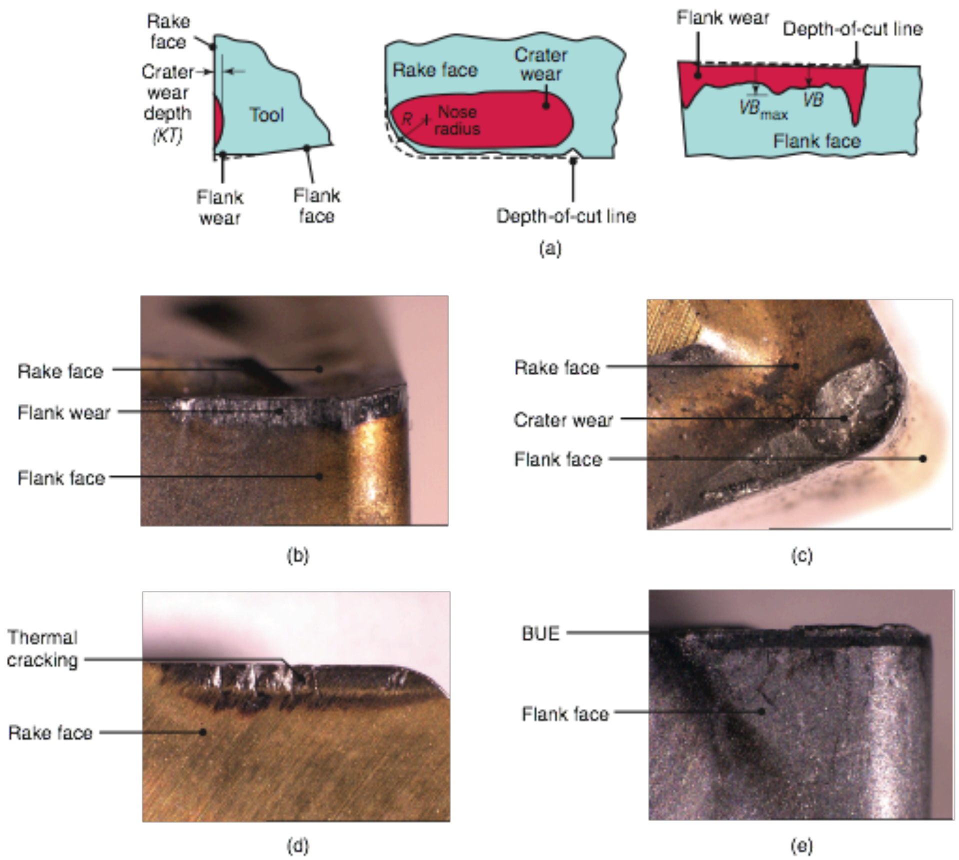


FIGURE 8.20 Examples of wear in cutting tools. (a) Flank wear; (b) crater wear; (c) chipped cutting edge; (d) thermal cracking on rake face; (e) flank wear and built-up edge. *Source:* Courtesy of Kennametal, Inc.

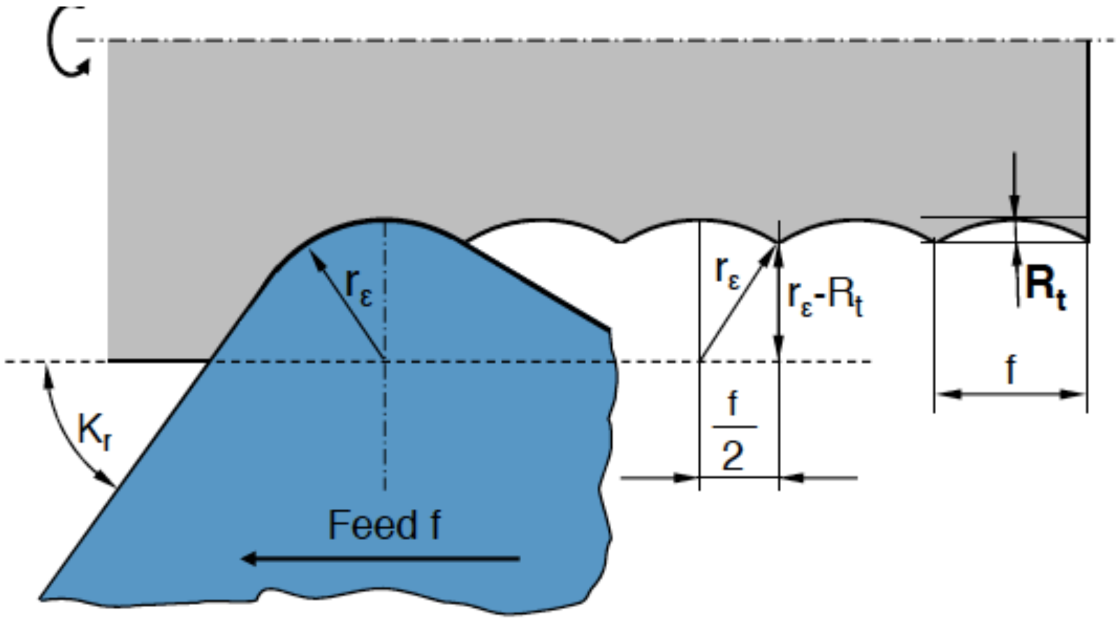
Taylor tool life equation:

$$VT^n = C$$

TABLE 8.4 Range of *n* values for various cutting tool

High-speed steels	0.08-0.2
Cast alloys	0.1-0.15
Carbides	0.2-0.5
Ceramics	0.5-0.7

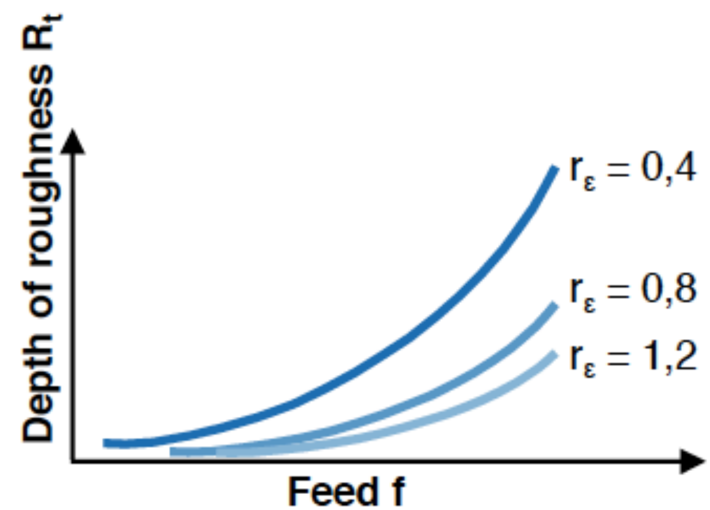
Theoretical surface roughness



$$R_t = r_\varepsilon - \sqrt{r_\varepsilon^2 - \frac{f^2}{4}}$$

or

$$R_t = \frac{f^2}{8 \cdot r_\varepsilon}$$

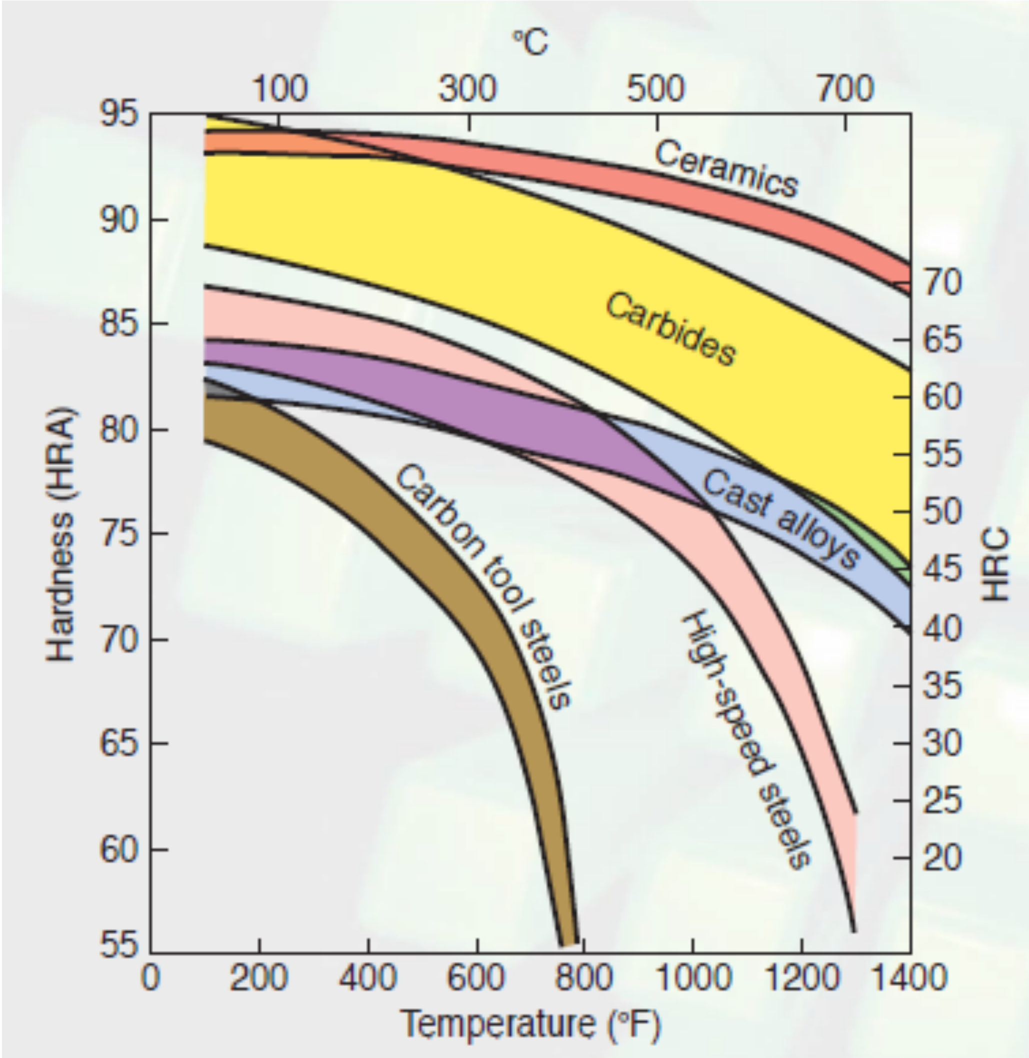


The theoretical depth of roughness R_t can be derived from the geometrical engagement specifications and is a function of the feed and the corner radius r_ε

Problem

If in turning of a steel rod by a given cutting tool (material and geometry) at a given machining condition (So and t) under a given environment (cutting fluid application), the tool life decreases from 80 min to 20 min. due to increase in cutting velocity, Vc from 60 m/min to 120 m/min., then at what cutting velocity the life of that tool under the same condition and environment will be 40 min.?

Hardness of cutting tools



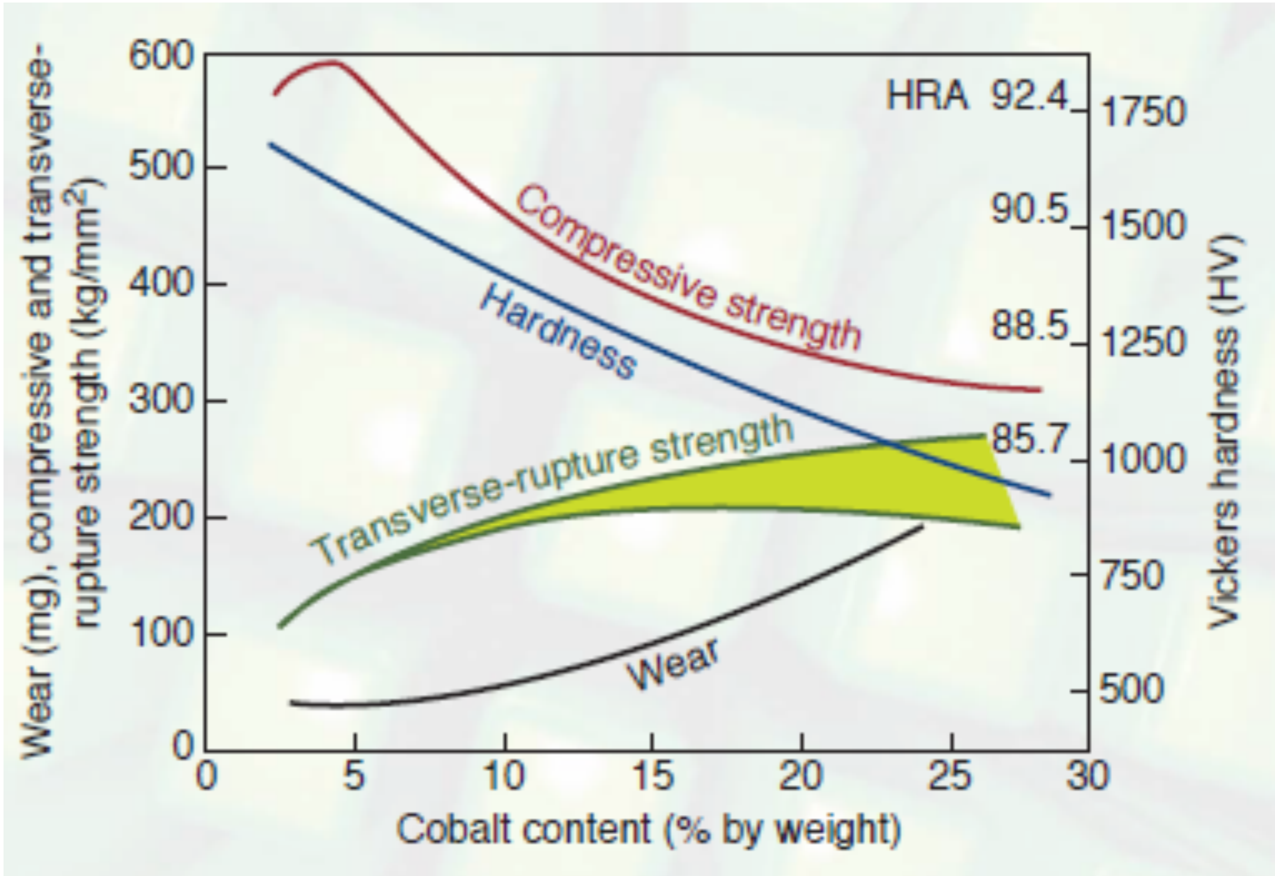
Hardness of various cutting-tool materials as a function of temperature (hot hardness).

Tool materials

Property	High-Speed Steel	Cast Alloys	Carbides: WC	Carbides: TiC	Ceramics	Cubic Boron Nitride	Single Crystal Diamond*
Hardness	83-86 HRA	82-84 HRA	90-95 HRA	91-93 HRA	91-95 HRA	4000-5000 HK	7000-8000 HK
Compressive strength							
MPa	4100-4500	1500-2300	4100-5850	3100-3850	2750-4500	6900	6900
psi $\times 10^3$	600-650	220-335	600-850	450-560	400-650	1000	1000
Transverse rupture strength							
MPa	2400-4800	1380-2050	1050-2600	1380-1900	345-950	700	1350
psi $\times 10^3$	350-700	200-300	150-375	200-275	50-135	105-200	
Impact strength							
J	1.35-8	0.34-1.25	0.34-1.35	0.79-1.24	< 0.1	< 0.5	< 0.2
in.-lb	12-70	3-11	3-12	7-11	< 1	< 5	< 2
Modulus of elasticity							
GPa	200	—	520-690	310-450	310-410	850	820-1050
psi $\times 10^6$	30	—	75-100	45-65	45-60	125	120-150
Density							
kg/m^3	8600	8000-8700	10,000-15,000	5500-5800	4000-4500	3500	3500
lb/in^3	0.31	0.29-0.31	0.36-0.54	0.2-0.22	0.14-0.16	0.13	0.13
Volume of hard phase (%)	7-15	10-20	70-90	—	100	95	95
Melting or decomposition temperature							
°C	1300	—	1400	1400	2000	1300	700
°F	2370	—	2550	2550	3600	2400	1300
Thermal conductivity, W/mK	30-50	—	42-125	17	29	13	500-2000
Coefficient of thermal expansion, $\times 10^{-6}/°C$	12	—	4-6.5	7.5-9	6-8.5	4.8	1.5-4.8

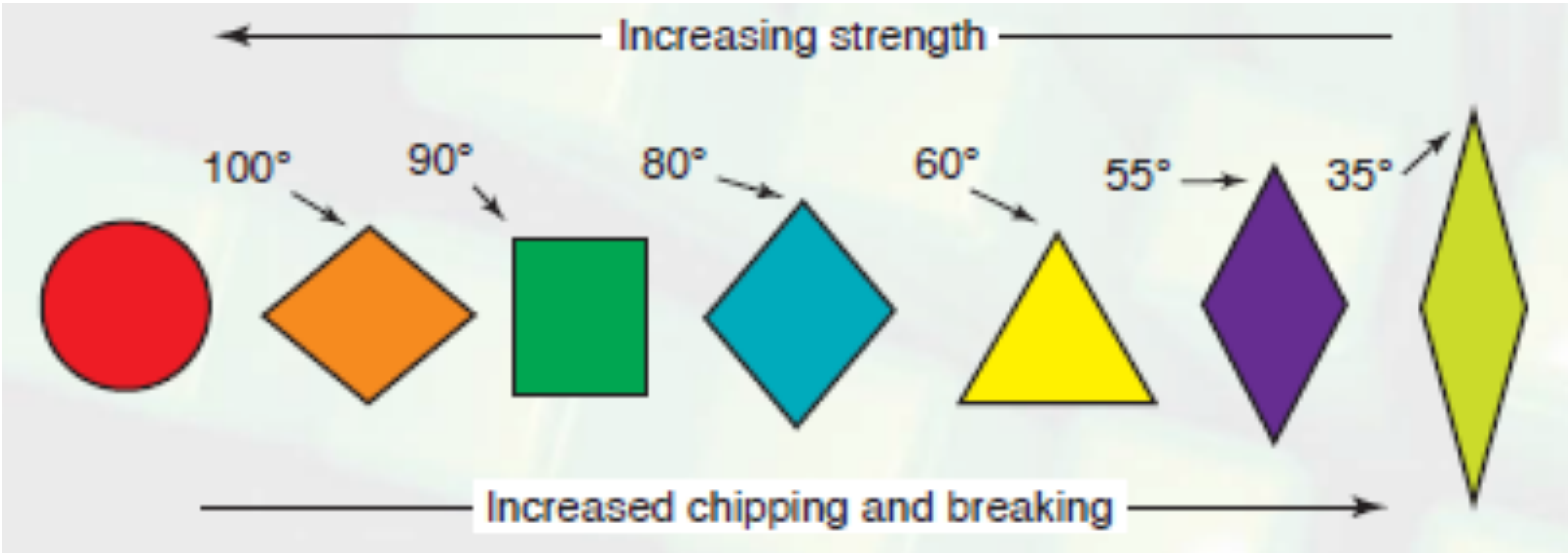
* The values for polycrystalline diamond are generally lower, except impact strength, which is higher.

Properties of WC tools



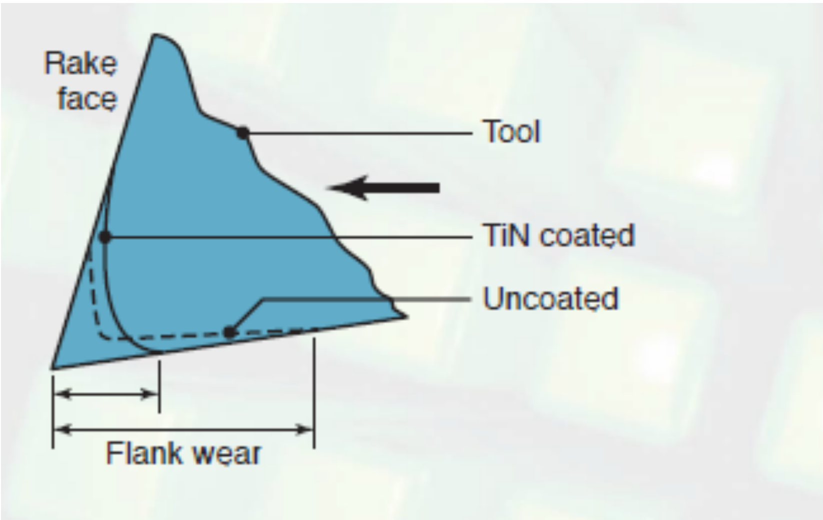
Effect of cobalt content in tungsten-carbide tools on mechanical properties. Note that hardness is directly related to compressive strength (see Section 2.6.8) and hence, inversely to wear

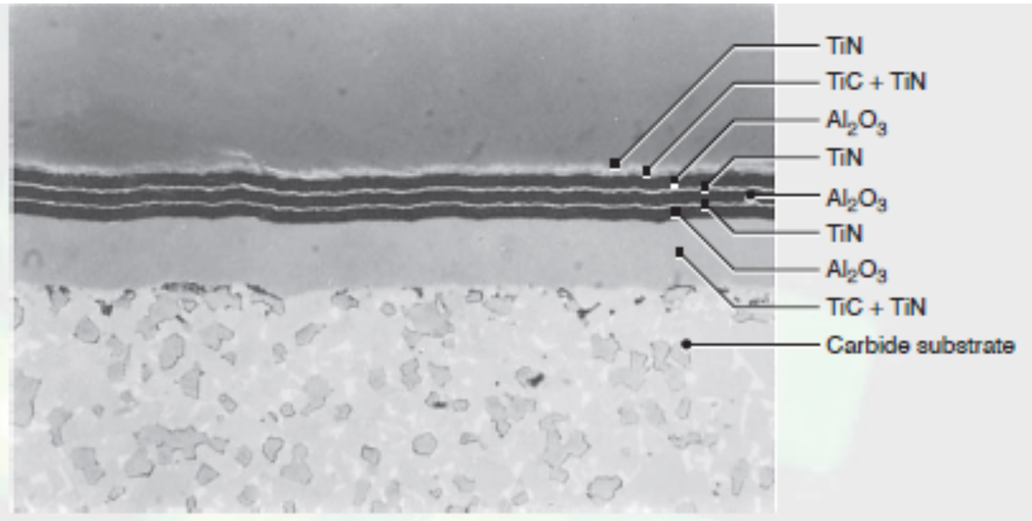
Insert strength (Wedge angle)



Relative edge strength and tendency for chipping and breaking of inserts with various shapes. Strength refers to that of the cutting edge shown by the included angles. *Source: Courtesy of Kennametal, Inc.*

Coated tools

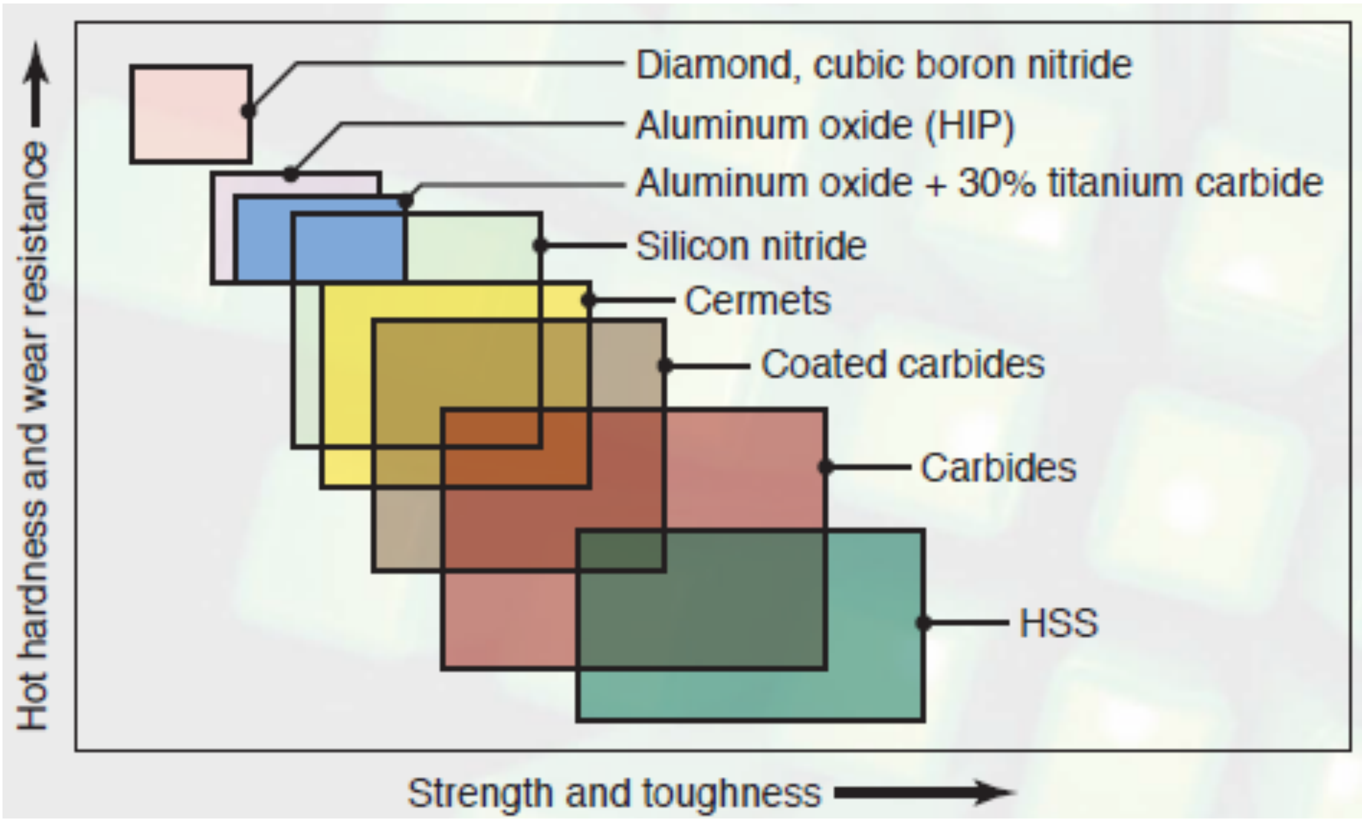


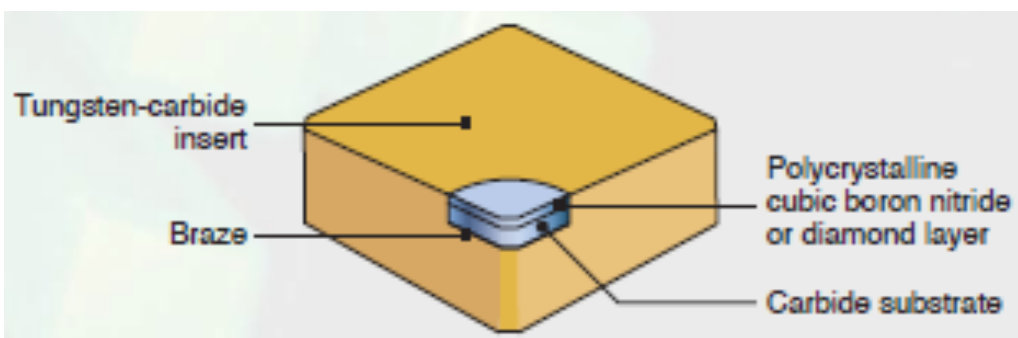


Wear patterns on high-speed-steel uncoated and titanium-nitride-coated cutting tools. Note that flank wear is lower for the coated tool.

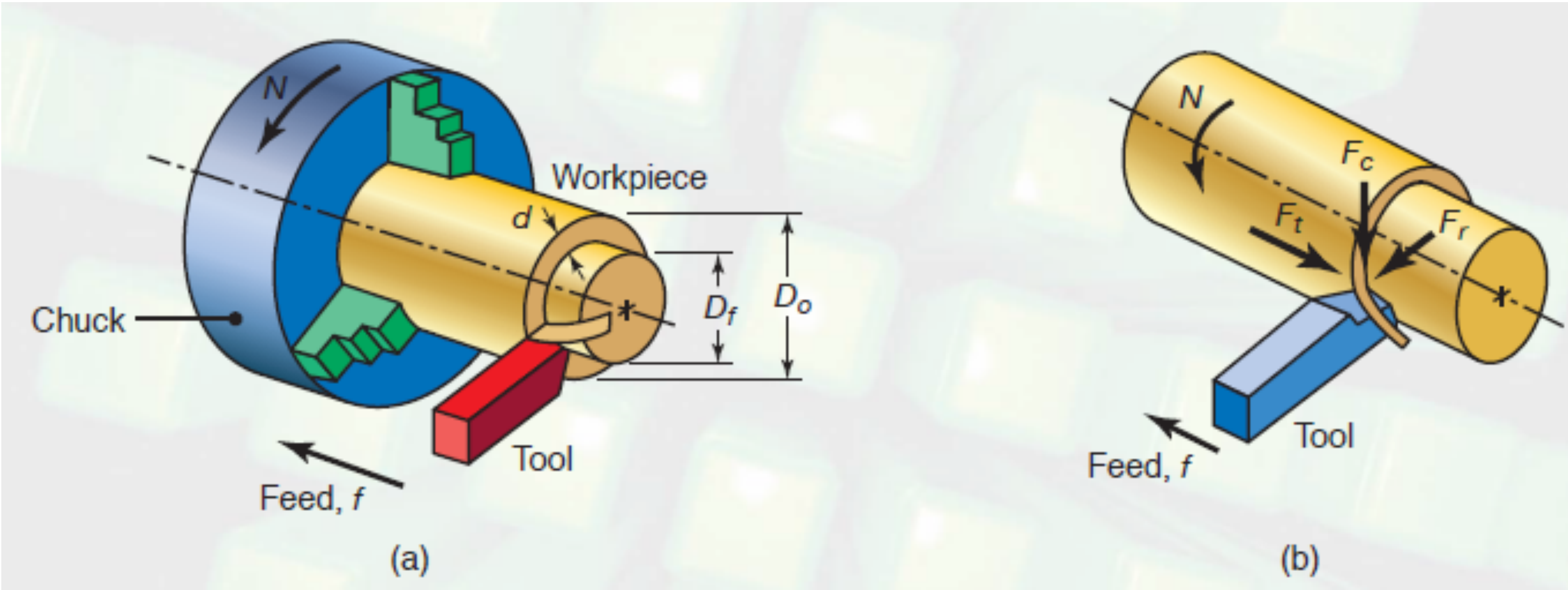
Multiphase coatings on a tungsten-carbide substrate. Three alternating layers of aluminum oxide are separated by very thin layers of titanium nitride. Inserts with as many as 13 layers of coatings have been made. Coating thicknesses are typically in the range of 2 to 10 μm. *Source:* Courtesy of Kennametal, Inc.

Properties of cutting tool materials



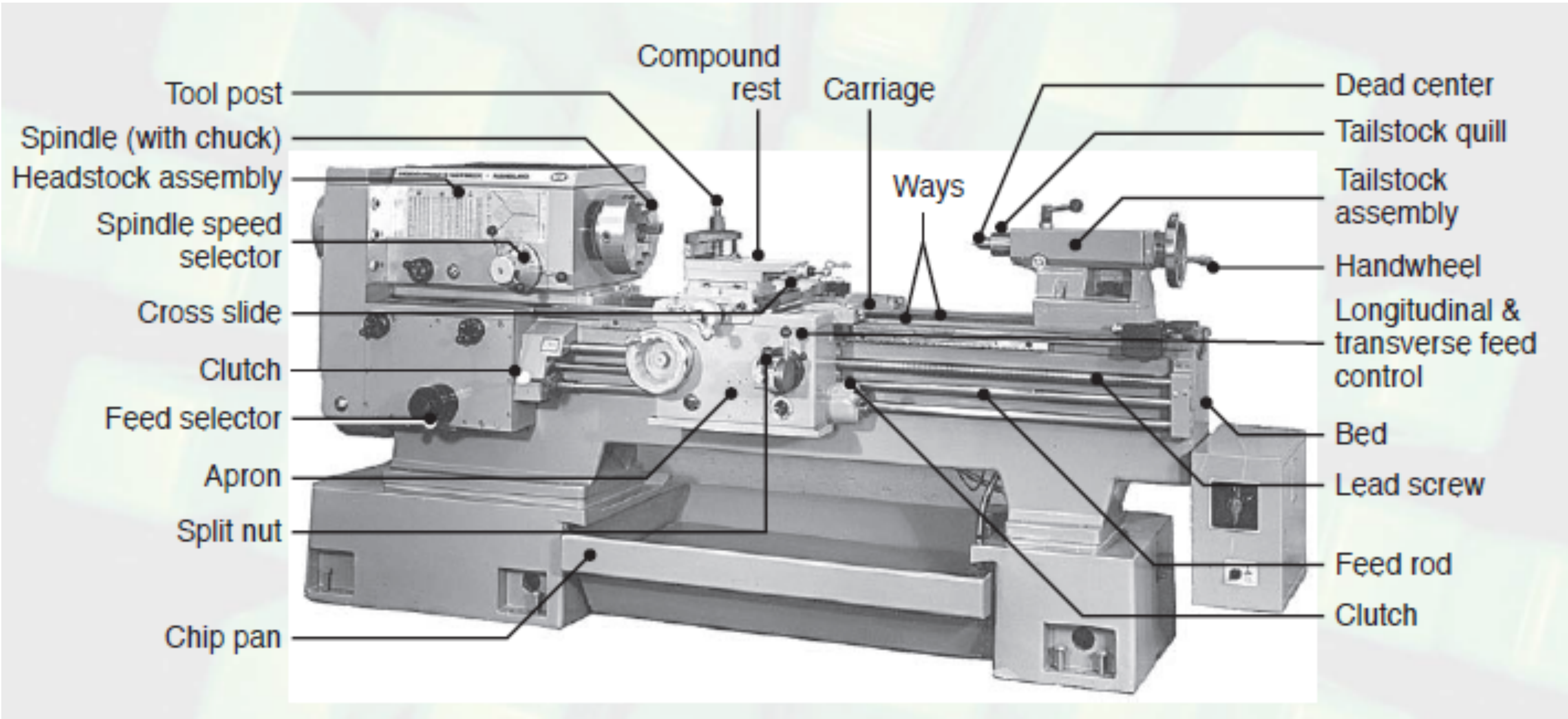


Turning operations



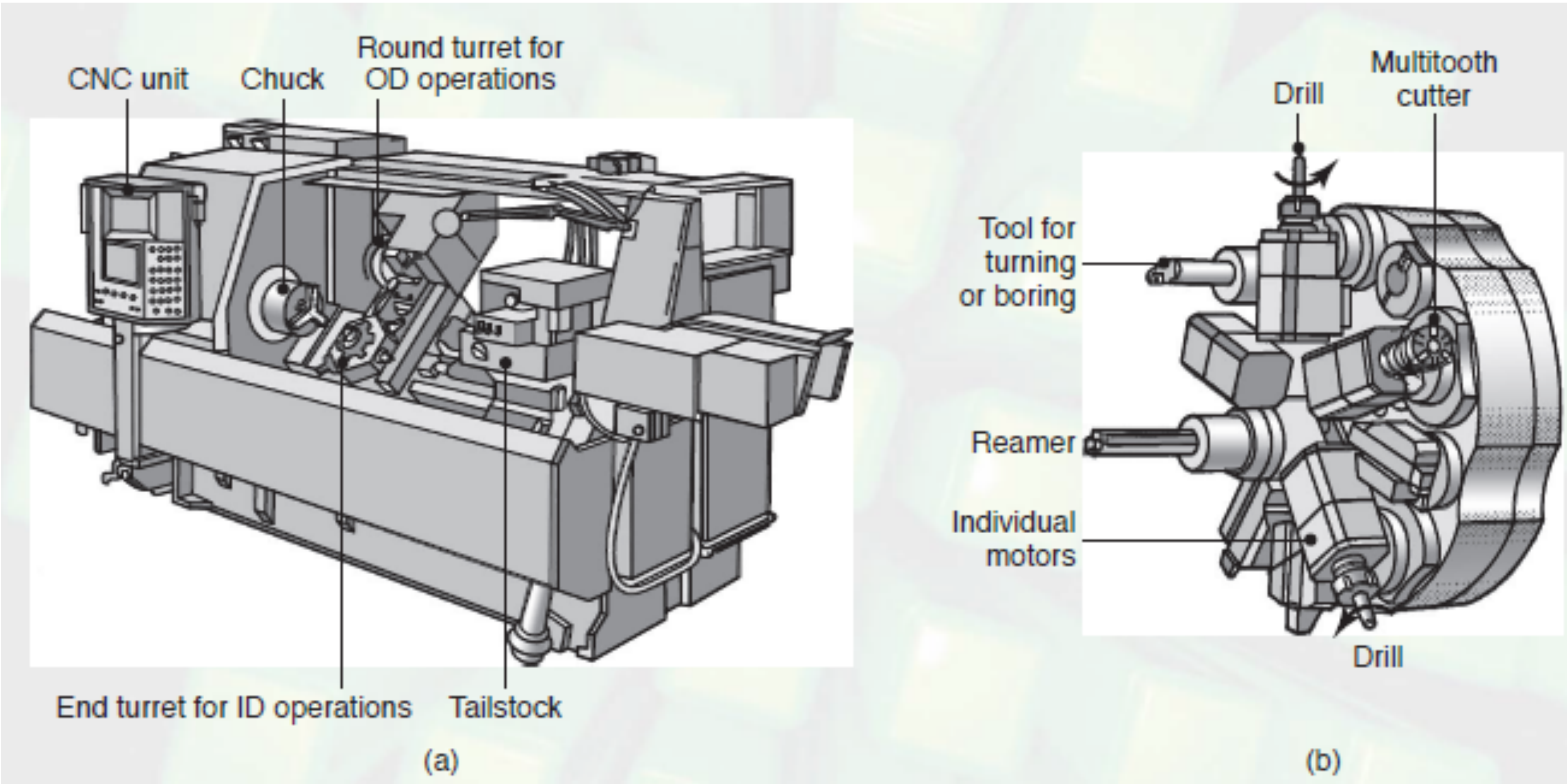
(a) Schematic illustration of a turning operation, showing depth of cut, *d, and feed, f. Cutting speed* is the surface speed of the workpiece at the tool tip. (b) Forces acting on a cutting tool in turning. *Fc is the* cutting force; *Ft is the thrust or feed force (in the direction of feed); and Fr is the radial force that tends to push* the tool away from the workpiece being machined.

Lathe



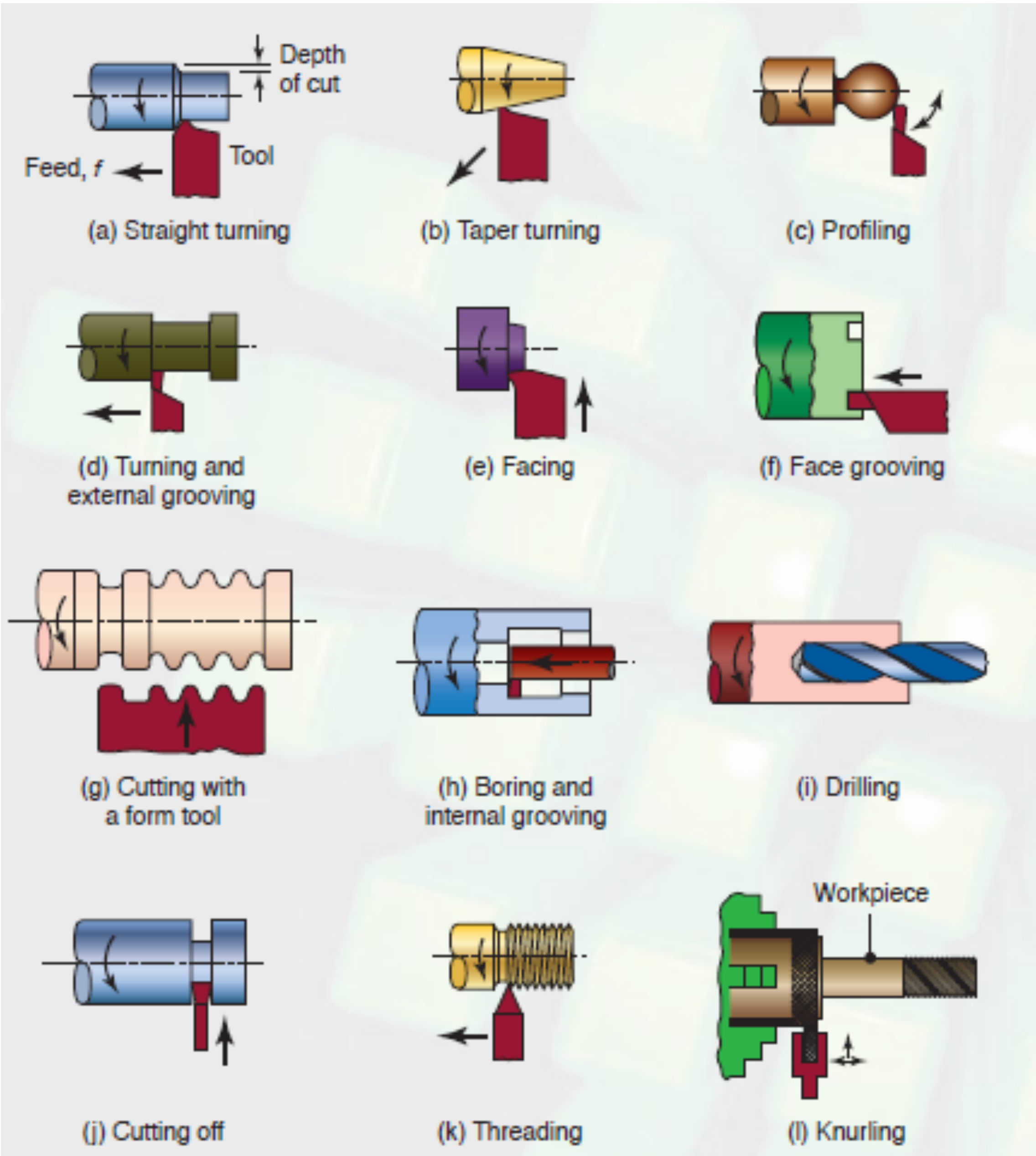
General view of a typical lathe, showing various major components. *Source: Courtesy of* Heidenreich & Harbeck.

CNC lathe



(a) A computer-numerical-control lathe, with two turrets; these machines have higher power and spindle speed than other lathes in order to take advantage of advanced cutting tools with enhanced properties; (b) a typical turret equipped with ten cutting tools, some of which are powered.

Lathe operations



Variety of machining operations that can be performed on a lathe.

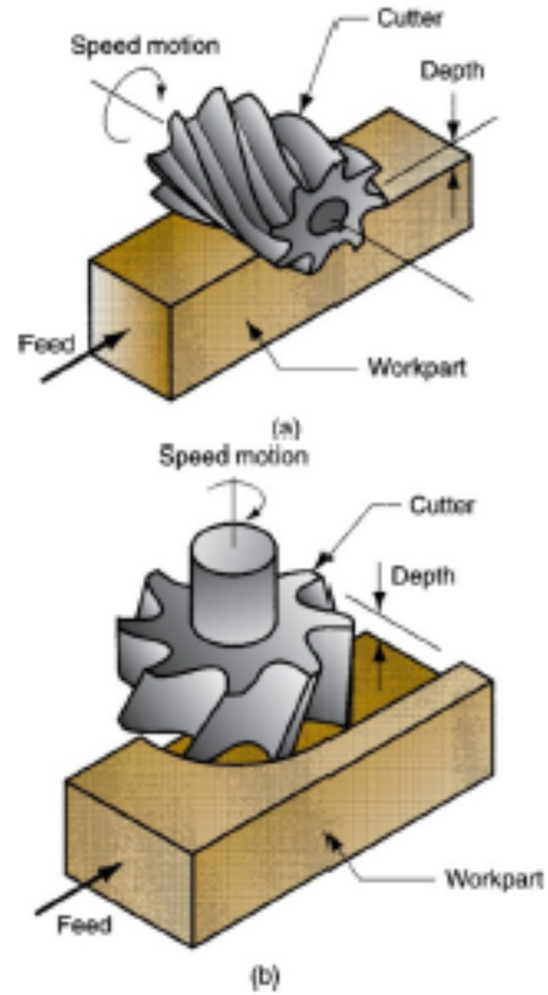
Milling processes

- Slab/Face milling
- Circular milling
- Helical milling
- Hobbing
- Profile milling
- Form milling

Option A: rotate the tool

Another option:
Vertical axis rotation of tool

Peripheral milling

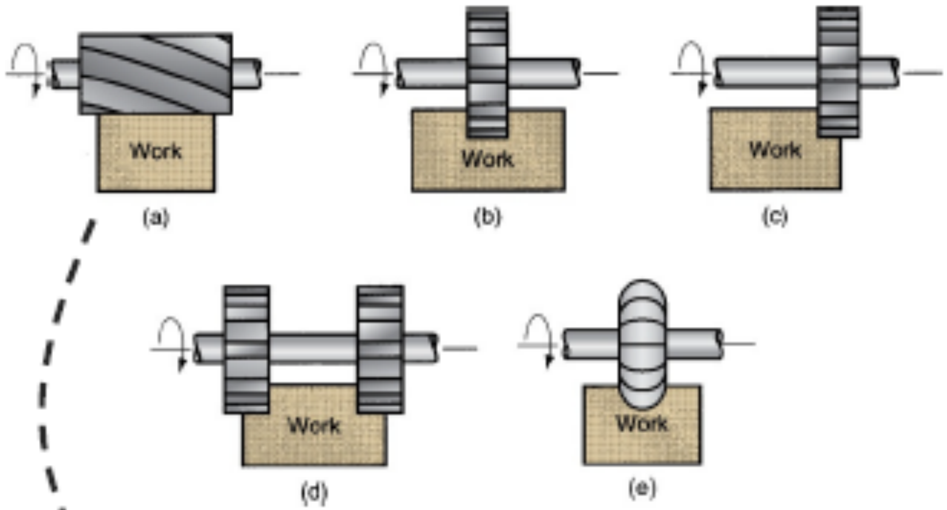


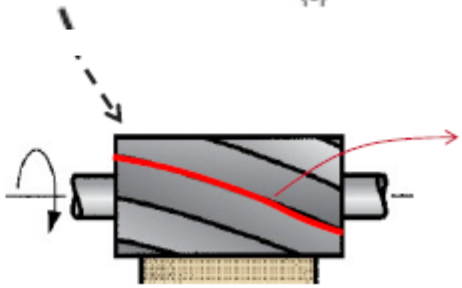
Face milling

Option A: rotate the tool (Milling)

Horizontal axis rotation

(a) Slab milling, (b) slotting, (c) side milling, (e) straddle milling, and (e) form milling



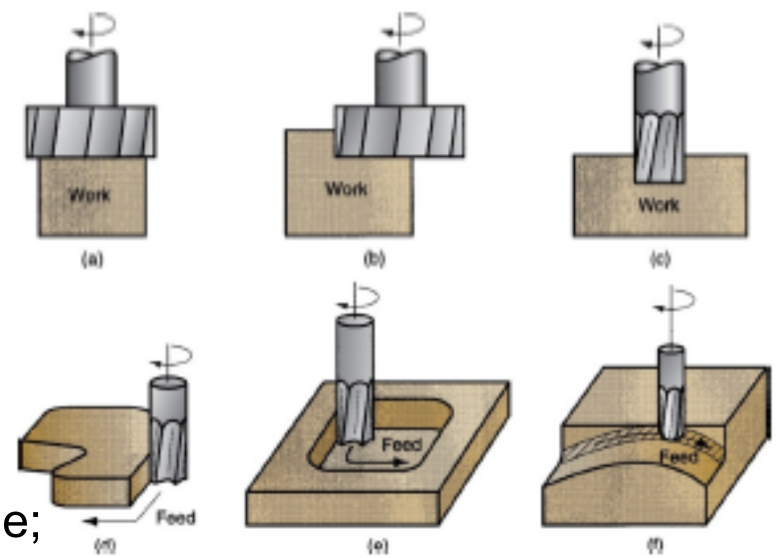


Note the curved cutting edge;
there is a helical angle to the edge
This helps in removing chip and also
allows gradual engagement of cut

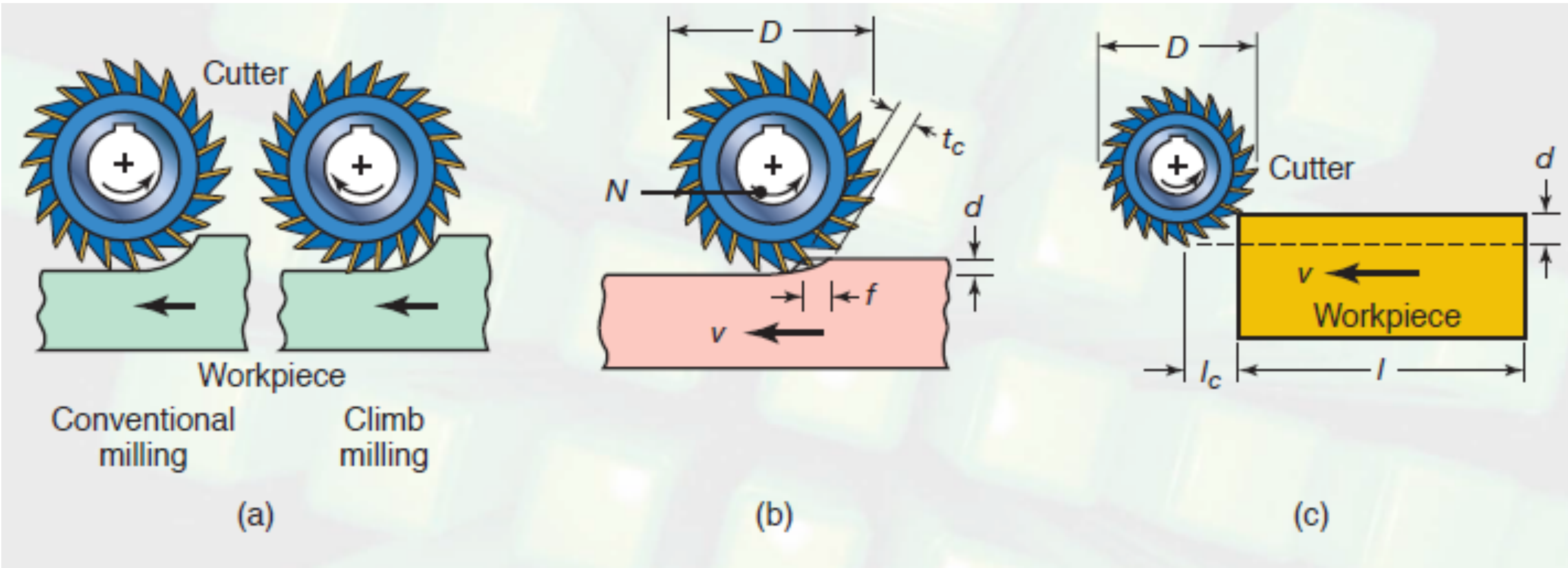
Vertical axis rotation

(a) Conventional face milling, (b) partial face milling, and (c) end milling

(d) Profile milling, (e) pocket milling, and (f) surface contouring

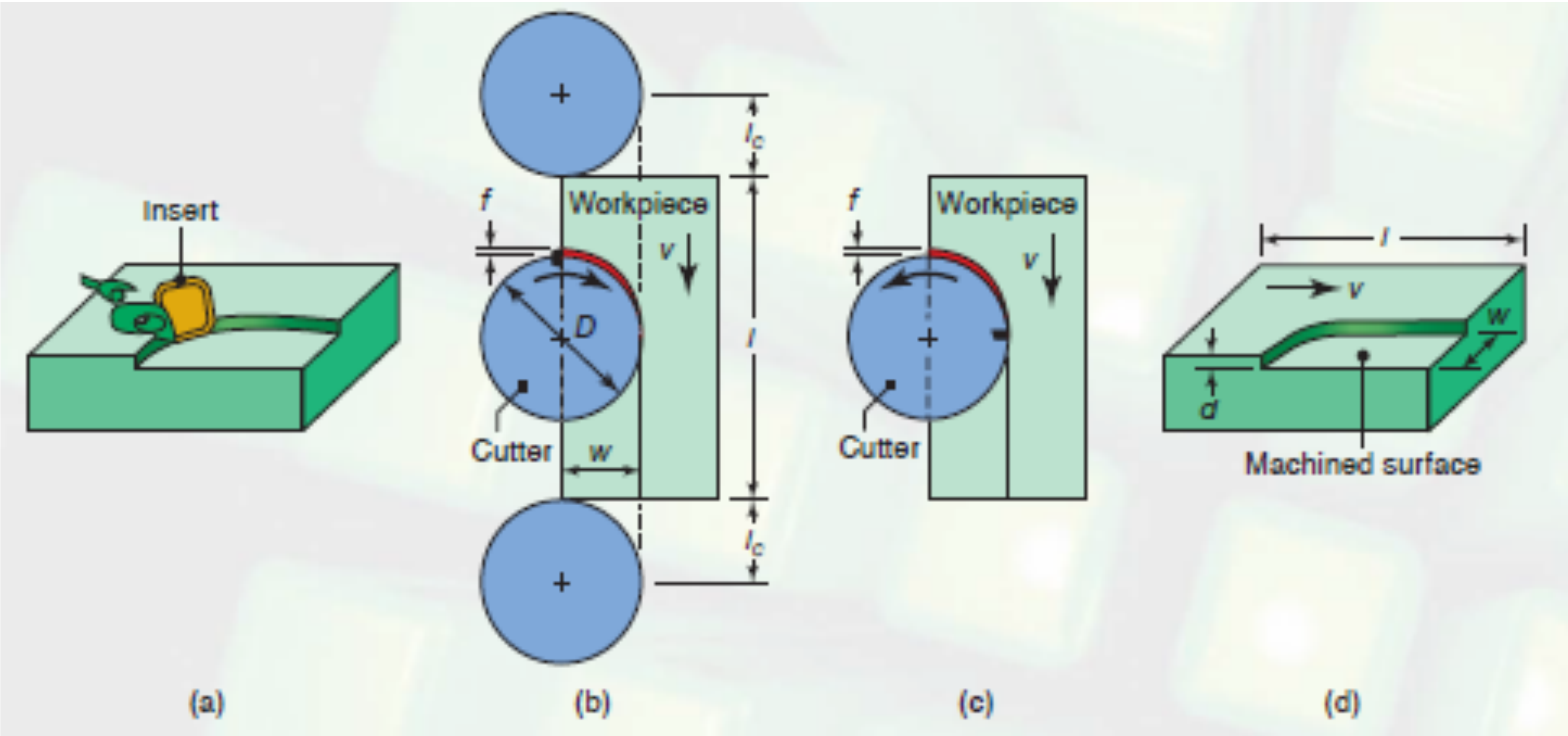


Conventional and climb milling



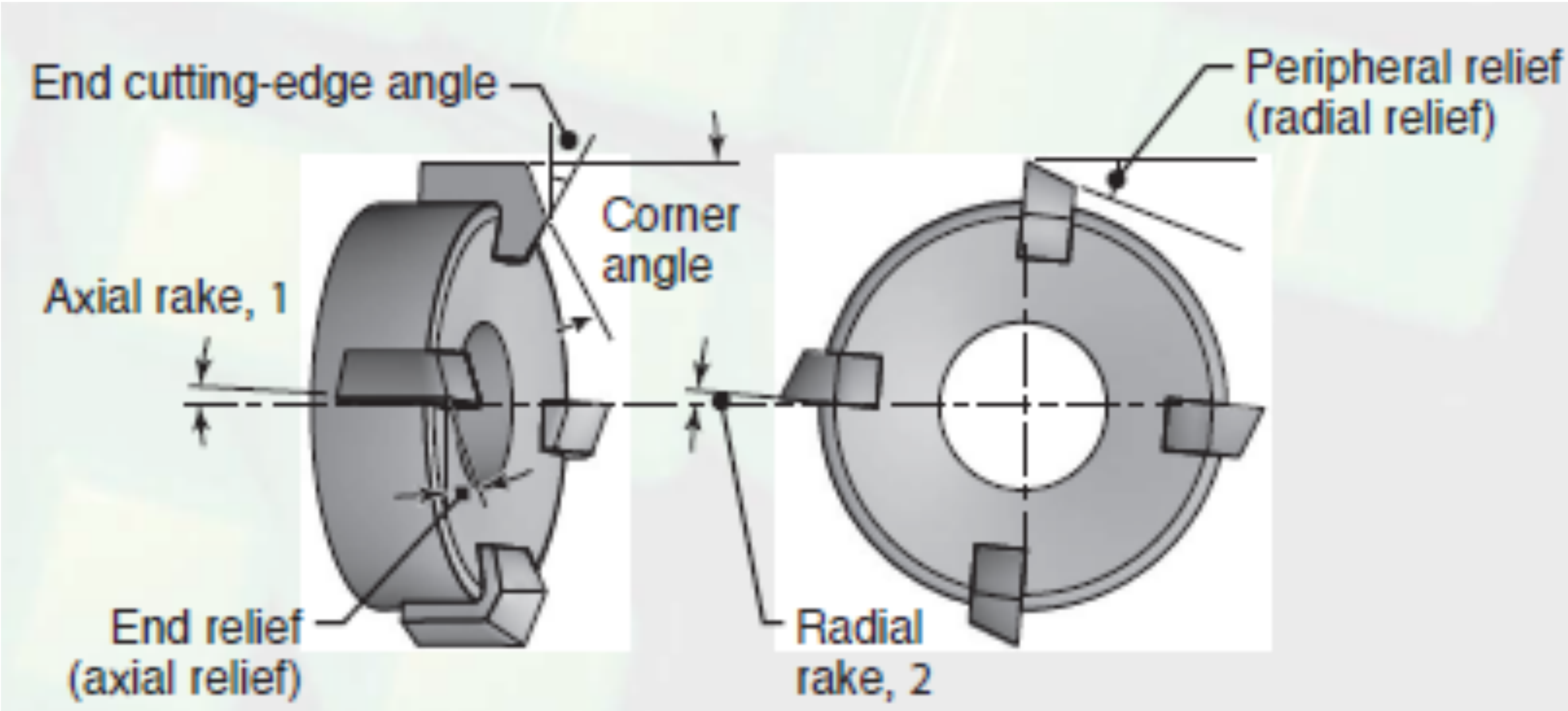
(a) Illustration showing the difference between conventional milling and climb milling. (b) Slab-milling operation, showing depth of cut, *d; feed per tooth, f; chip depth of* cut, *tc and workpiece speed, v. (c) Schematic illustration of cutter travel distance, lc, to reach* full depth of cut.

Face milling



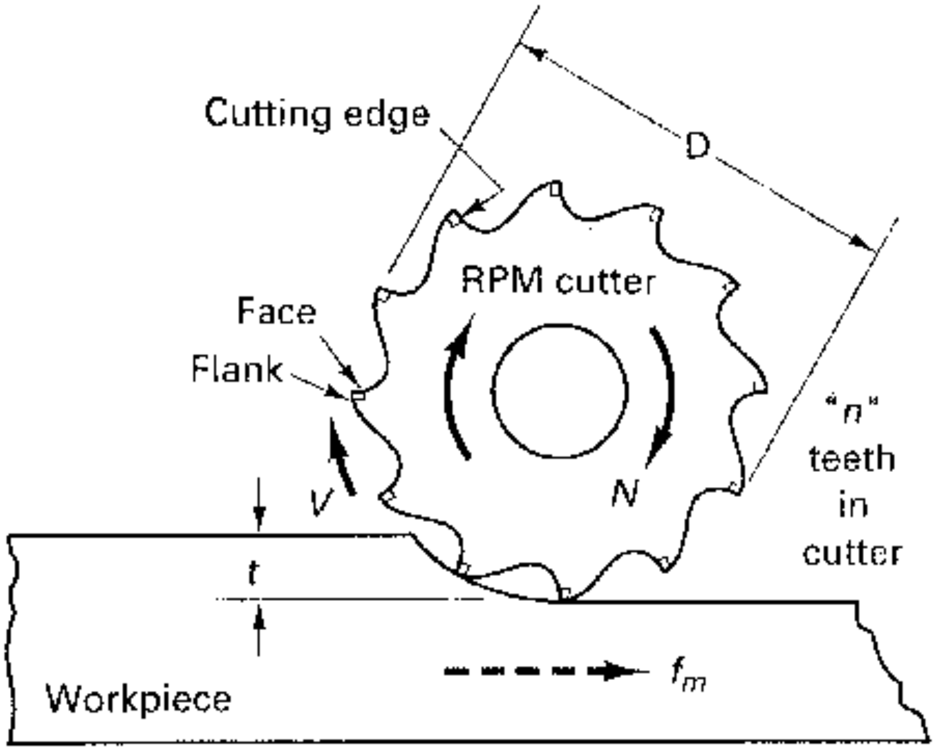
Face-milling operation showing (a) action of an insert in face milling; (b) climb milling; (c) conventional milling; (d) dimensions in face milling.

Face milling cutter

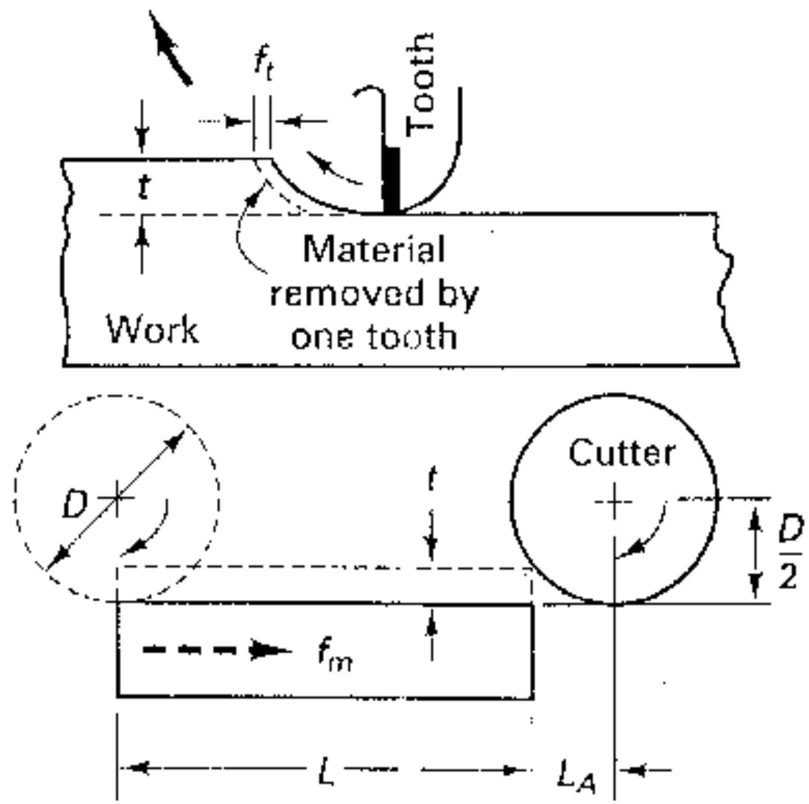


Terminology for a face milling cutter

Milling operation



Slab milling – multiple tooth



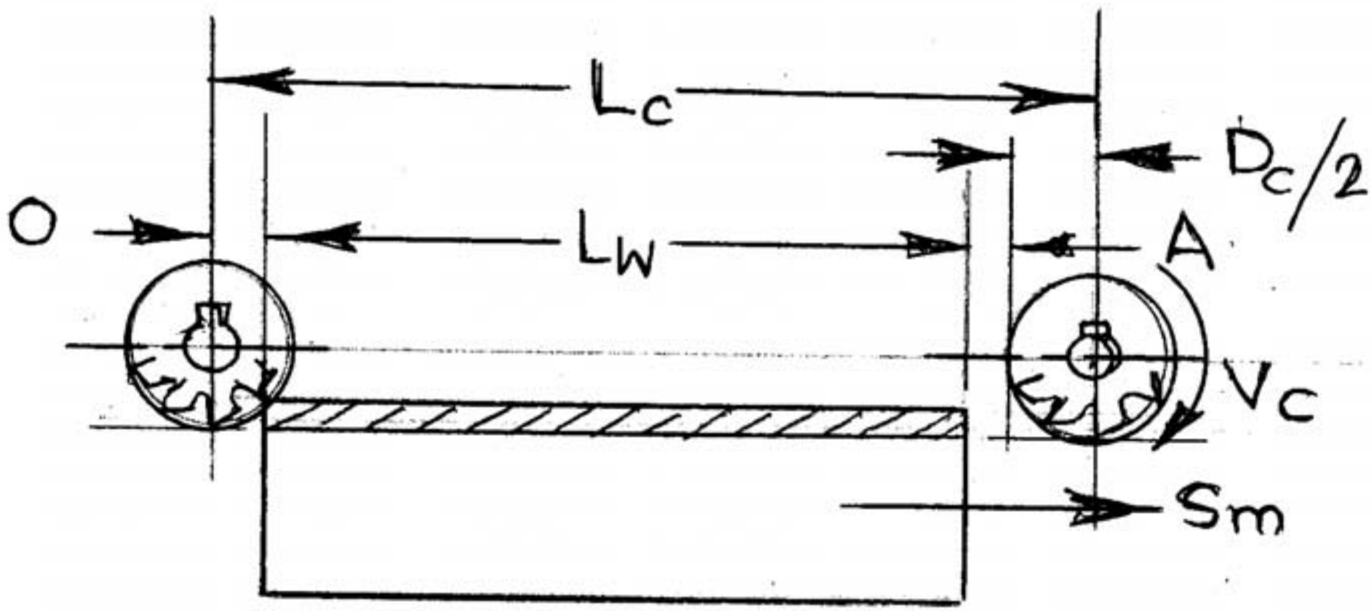
Terms Used:
N: RPM of Cutter
n: Number of Teeth on Cutter
W: Width of cut (may be full cutter or partial cutter)
t: depth of cut
V: cutting speed -- a Handbook value
L: Length of pass or cut
f_m: Table (machine) Feed
f_t: feed/tooth of cutter -- a Handbook value
D: Cutter Diameter

$$N = \frac{kV}{\pi D}$$

$$f_m = f_t * N * n$$

$$MRR = \frac{\text{Vol. Removed}}{CT} = \frac{L * W * t}{CT} = W * t * f_m$$

Machining time in a milling operation



Machining time in a milling operation

$T_C = L_C / s_m$ (for job width < cutter length)

Where, L_C = total length of travel of the job

$= L_w + A + O + D_c/2$

L_w = length of the workpiece

A, O = approach and over run (5 to 10 mm)

D_C= diameter of the cutter, mm

S_m= table feed, mm/min

$= s_o Z_C N$

where, s_o = feed per tooth, mm/tooth

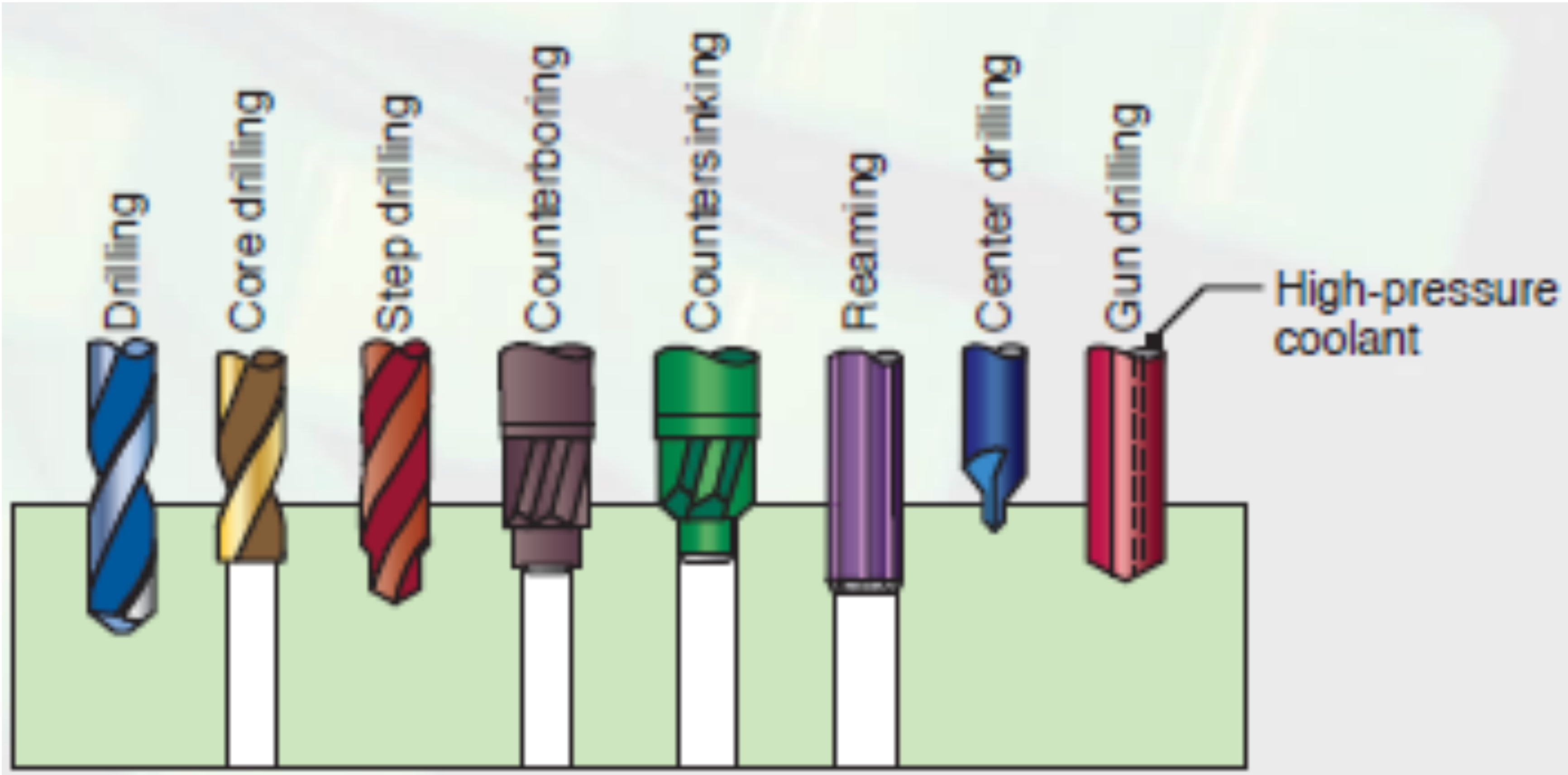
Z_C= number of teeth of the cutter

N = cutter speed, rpm.

Again, N has to be determined from V_C as

$$V_C = \frac{\pi D_C N}{1000} \quad \text{m/min}$$

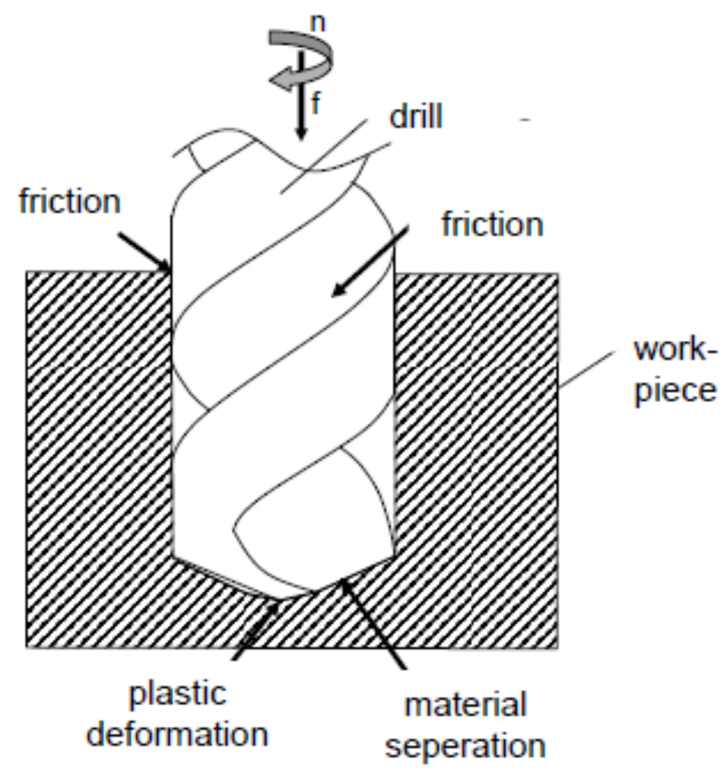
Drilling operations



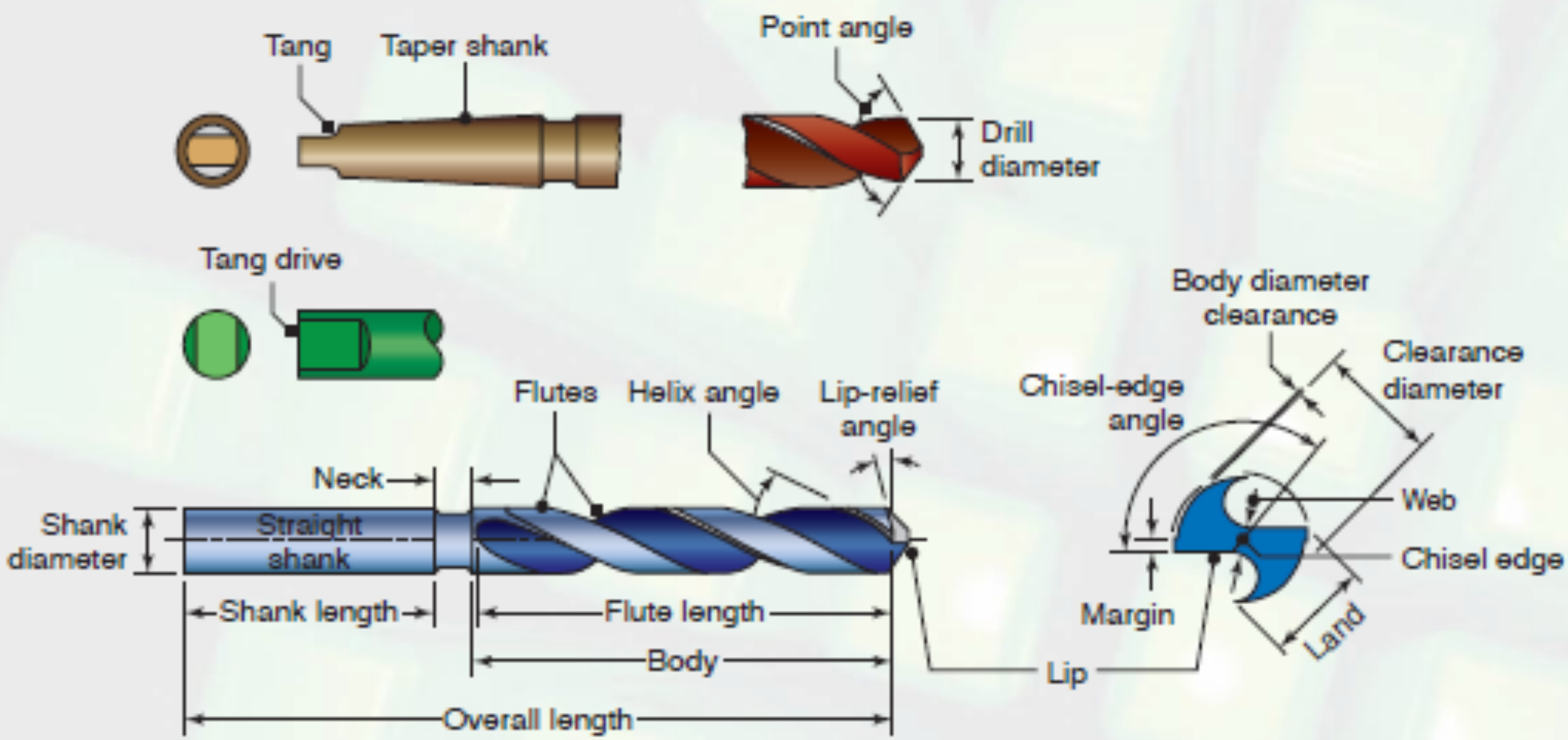
Various types of drills and drilling operations

Criteria for drilling

- Material separation and reaming at the major cutting edge
- Plastic deformation at the chisel edge
- Cutting speed drops down to zero in the centre of the drill
- Chips are difficult to remove
- Unfavourable heat distribution at the interface
- Increased wear at the sharp-edged corner
- Reaming between leading lands and drilling wall



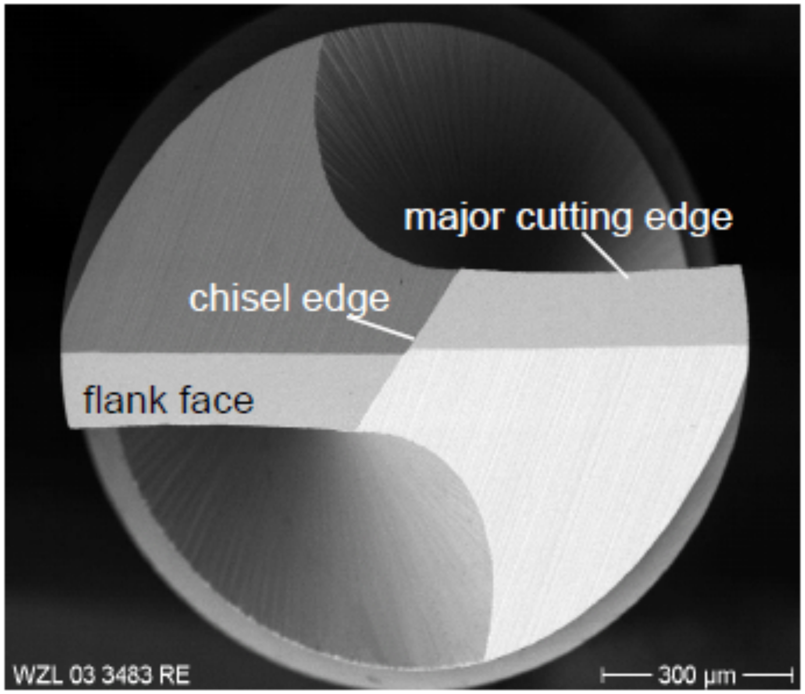
Geometry of a twist drill

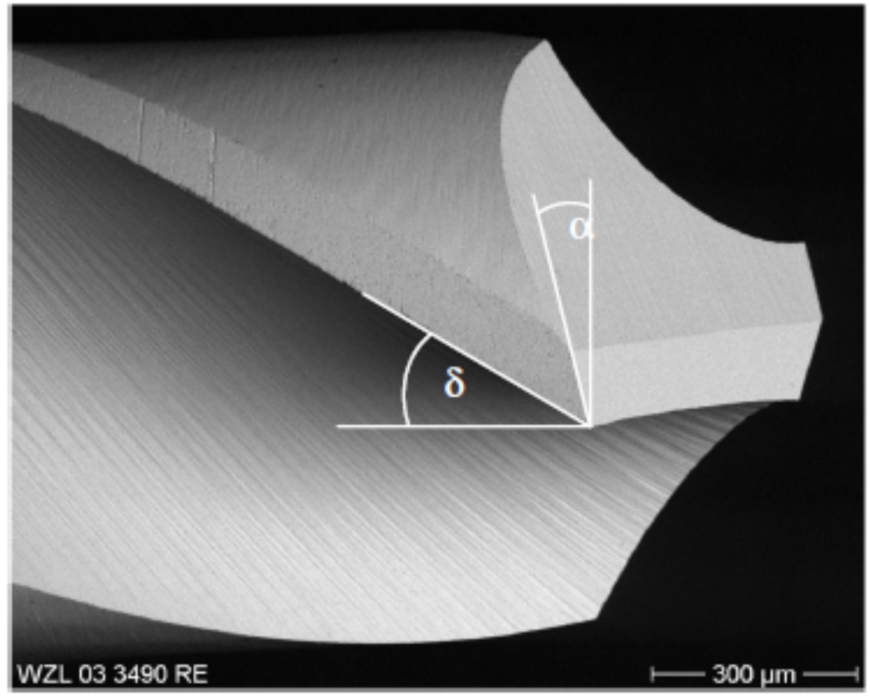


(a) Chisel-point drill

(b) Crankshaft-point drill

Geometry of a twist drill



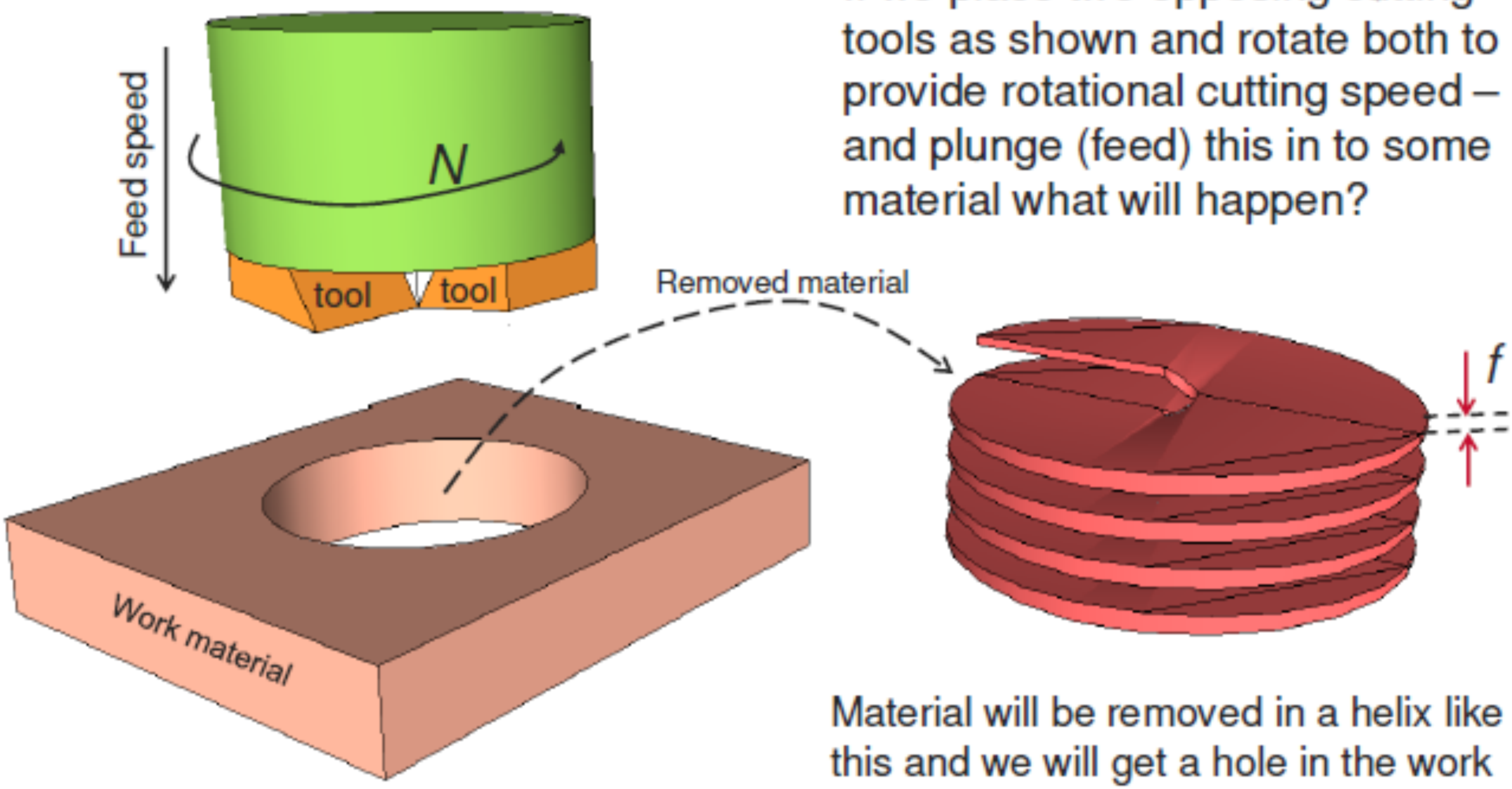


construction dimensions	DIN 6539, Typ N
diameter d:	1 mm
drill-point angle σ:	118°

major clearance angle α:	10°
angle of twist δ:	35°
cutting material:	HW-K20
grain size D_K:	0.5 - 0.7 µm

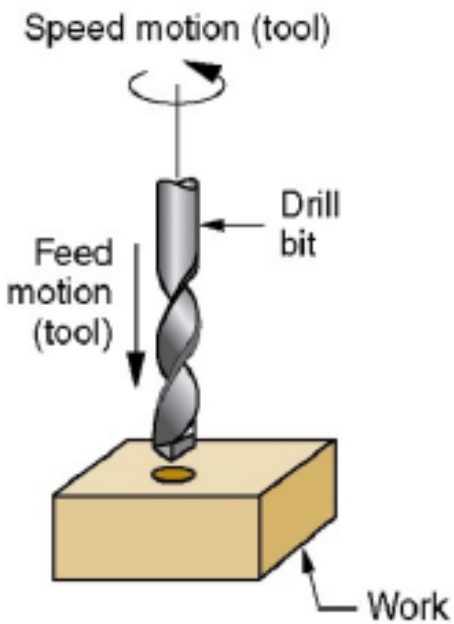
Circular cutting motion: Drilling concept

If we place two opposing cutting tools as shown and rotate both to provide rotational cutting speed – and plunge (feed) this in to some material what will happen?

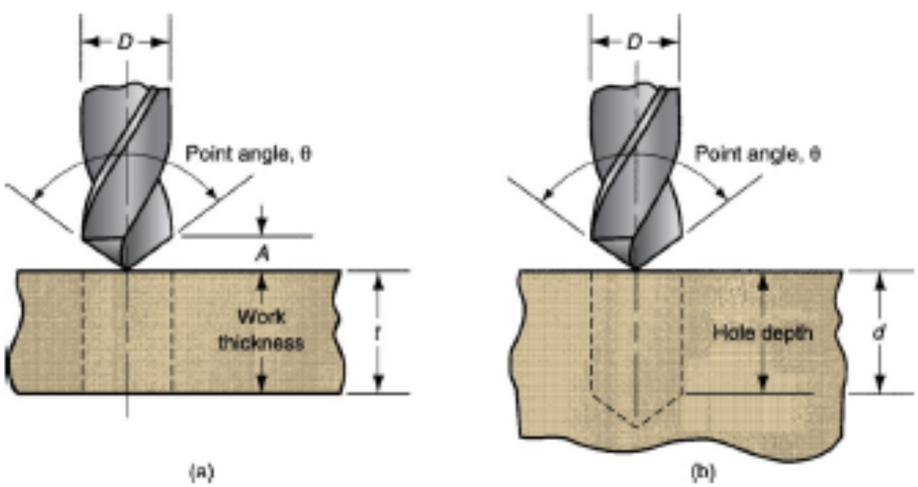


Material will be removed in a helix like this and we will get a hole in the work material! - DRILLING

Circular cutting motion: Drilling concept

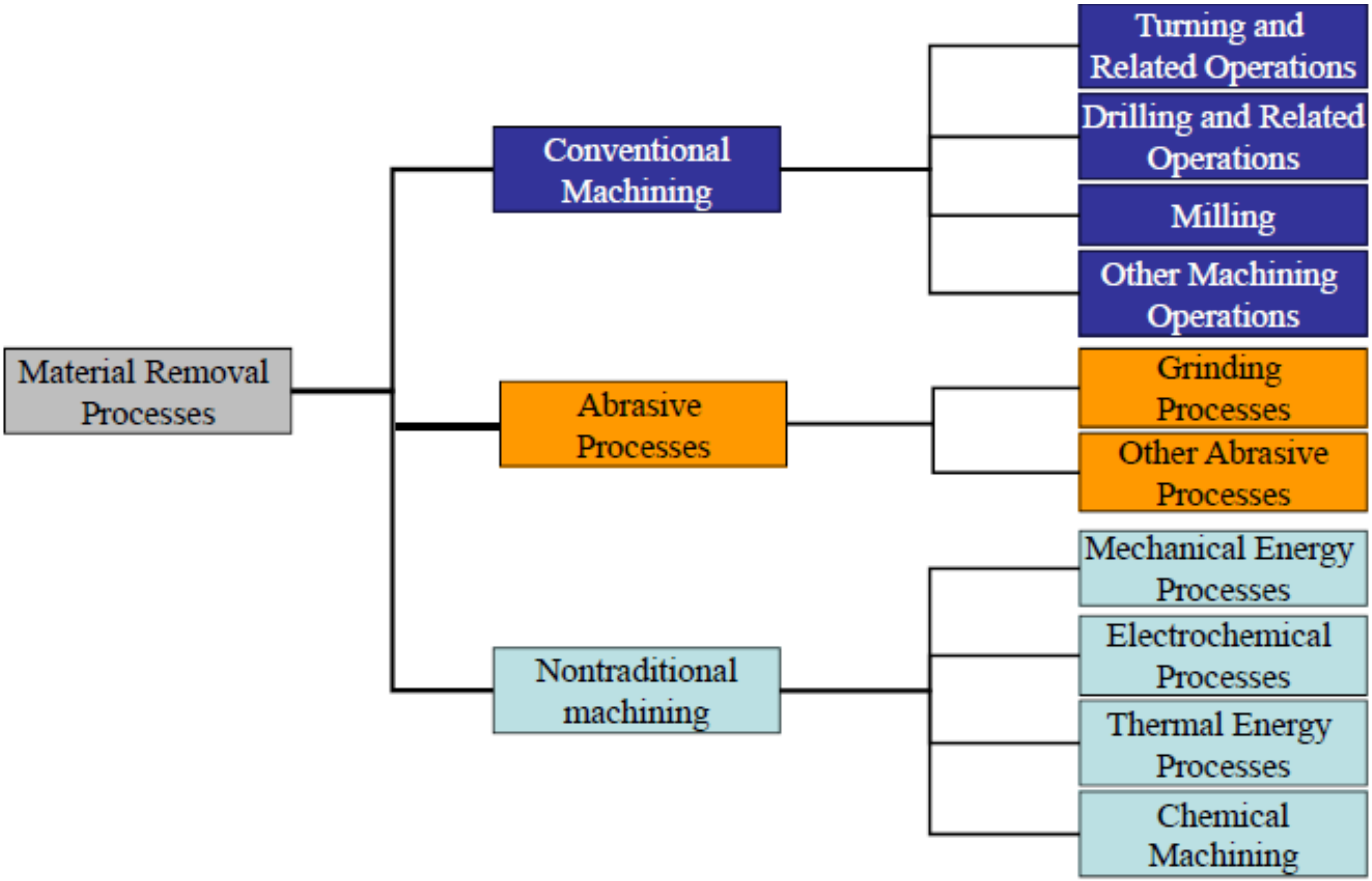


Material removal rate??
Cutting speed/RPM
Feed (mm/r) (mm/min)
D
Area*f*N (RPM)



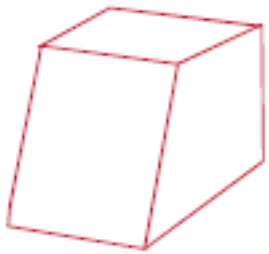
Abrasive Machining and Finishing Operations

Classification



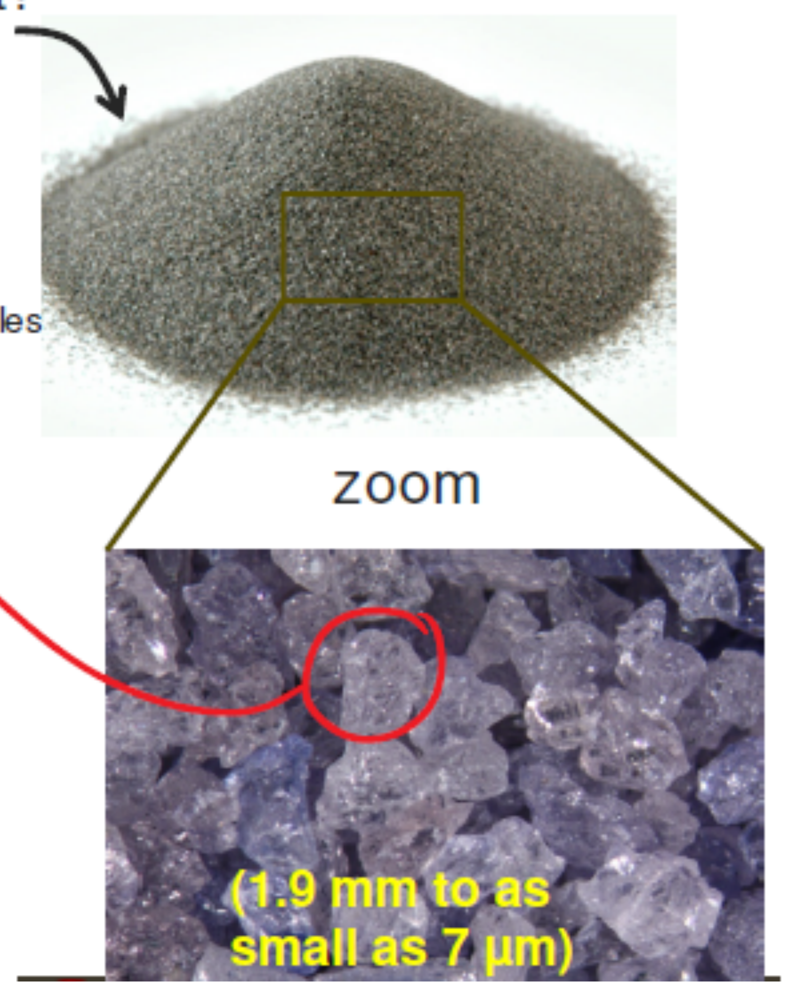
Cutting using abrasive particles

This we know can cut



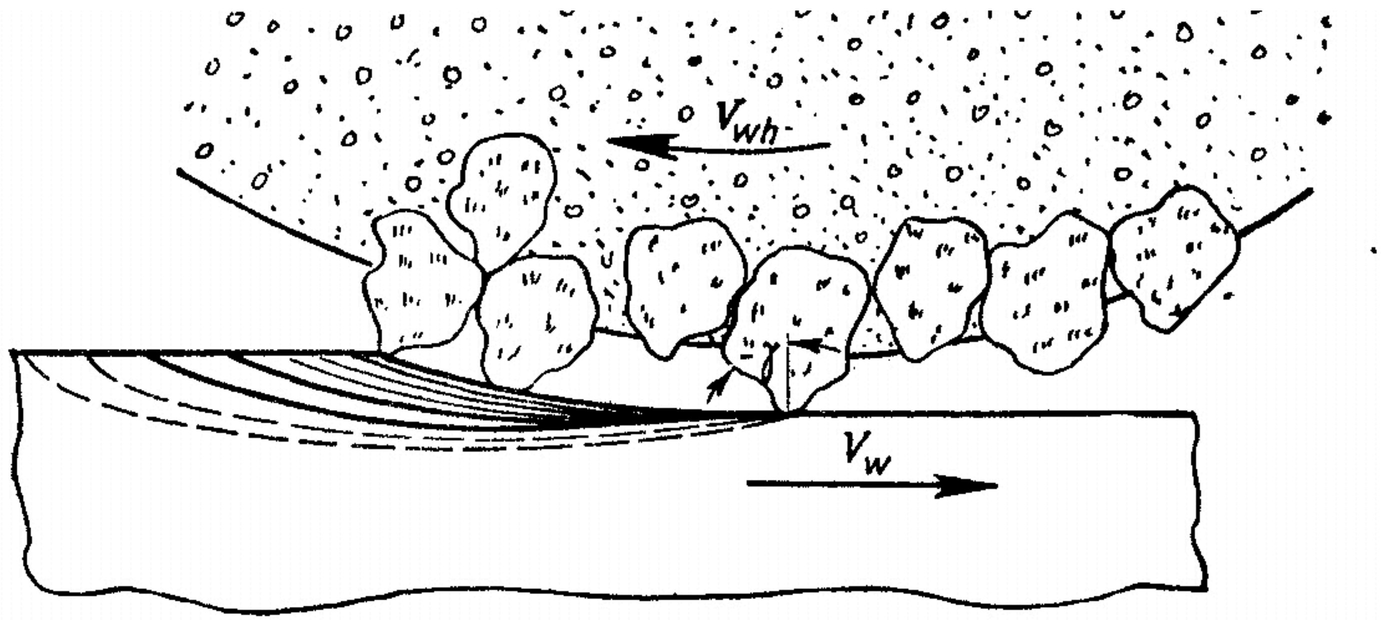
Can this cut?

Irregularly shaped hard abrasive particles

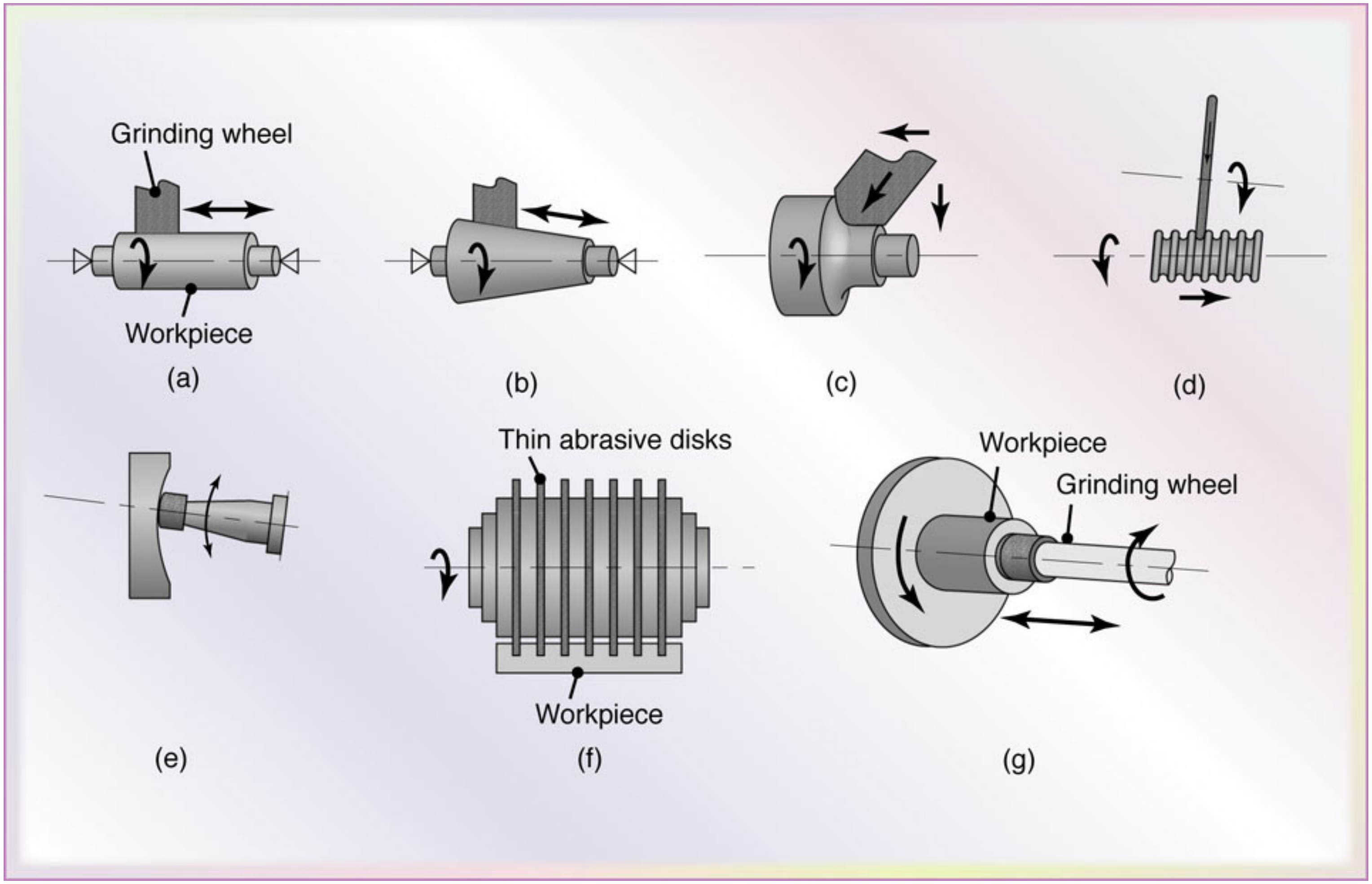


Grinding

Grinding is the most common form of abrasive machining. It is a material cutting process which engages an abrasive tool whose cutting elements are grains of abrasive material known as grit. These grits are characterized by sharp cutting points, high hot hardness, chemical stability and wear resistance. The grits are held together by a suitable bonding material to give shape of an abrasive tool.



Workpieces and Operations Used in Grinding



The types of workpieces and operations typical of grinding: (a) cylindrical surfaces, (b) conical surfaces. (c) fillets on a shaft, (d) helical profiles, (e) concave shape, (f) cutting off or slotting with thin wheels, and (g) internal grinding.

Grinding

Advantage

A grinding wheel requires two types of specification

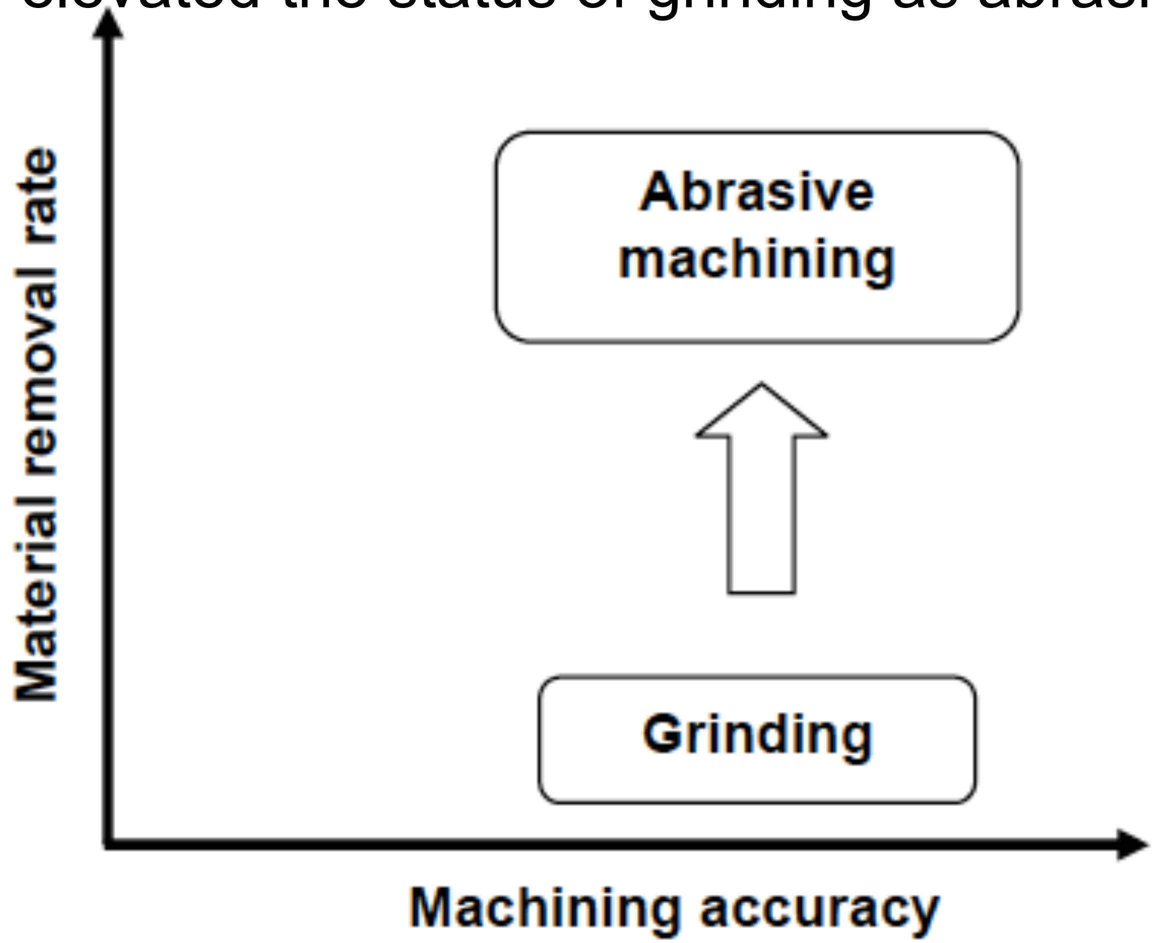
- dimensional accuracy and good surface finish
- good form and locational accuracy applicable to both hardened and unhardened material

Applications

- surface finishing
- slitting and parting
- descaling, deburring
- stock removal (abrasive milling)
- finishing of flat as well as cylindrical surface
- grinding of tools and cutters and re-sharpening of the same.

Grinding

Conventionally grinding is characterized as low material removal process capable of providing both high accuracy and high finish. However, advent of advanced grinding machines and grinding wheels has elevated the status of grinding as abrasive machining



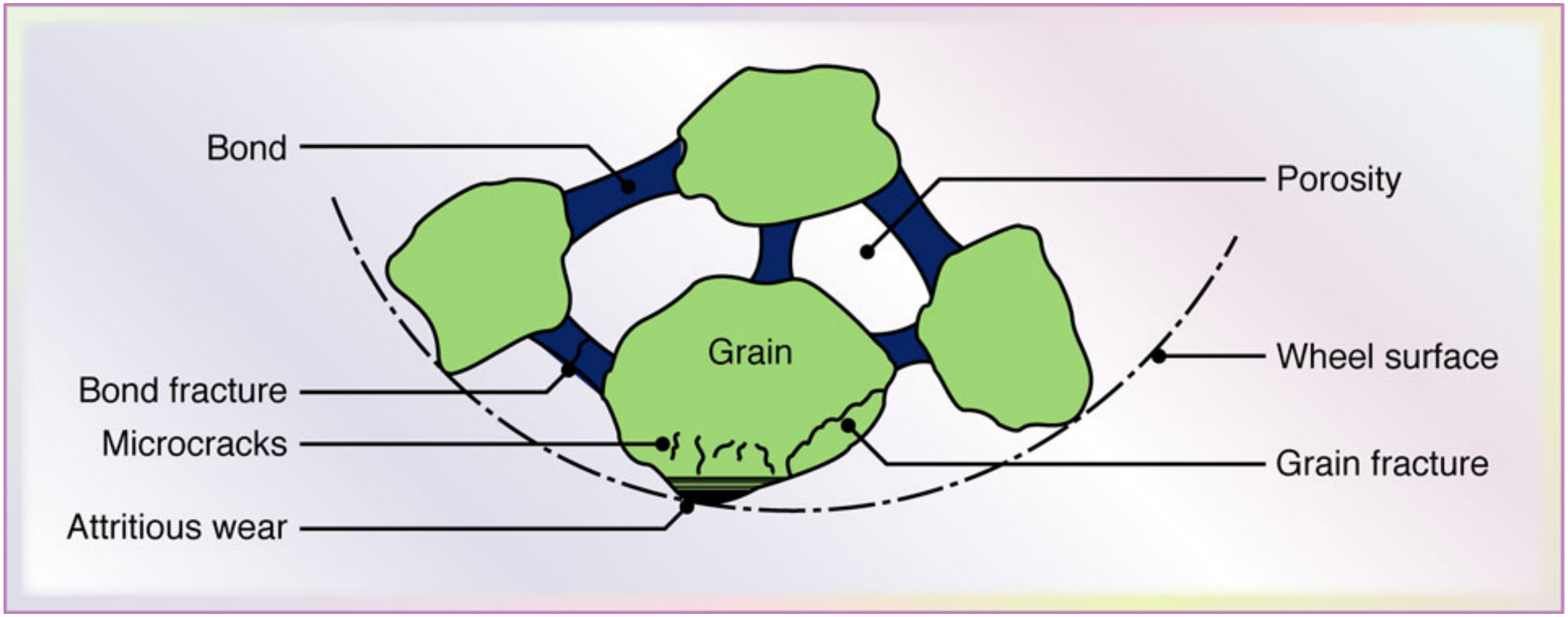
Ranges of Knoop Hardness for Various Materials and Abrasives

TABLE 26.1

Ranges of Knoop Hardness for Various Materials and Abrasives

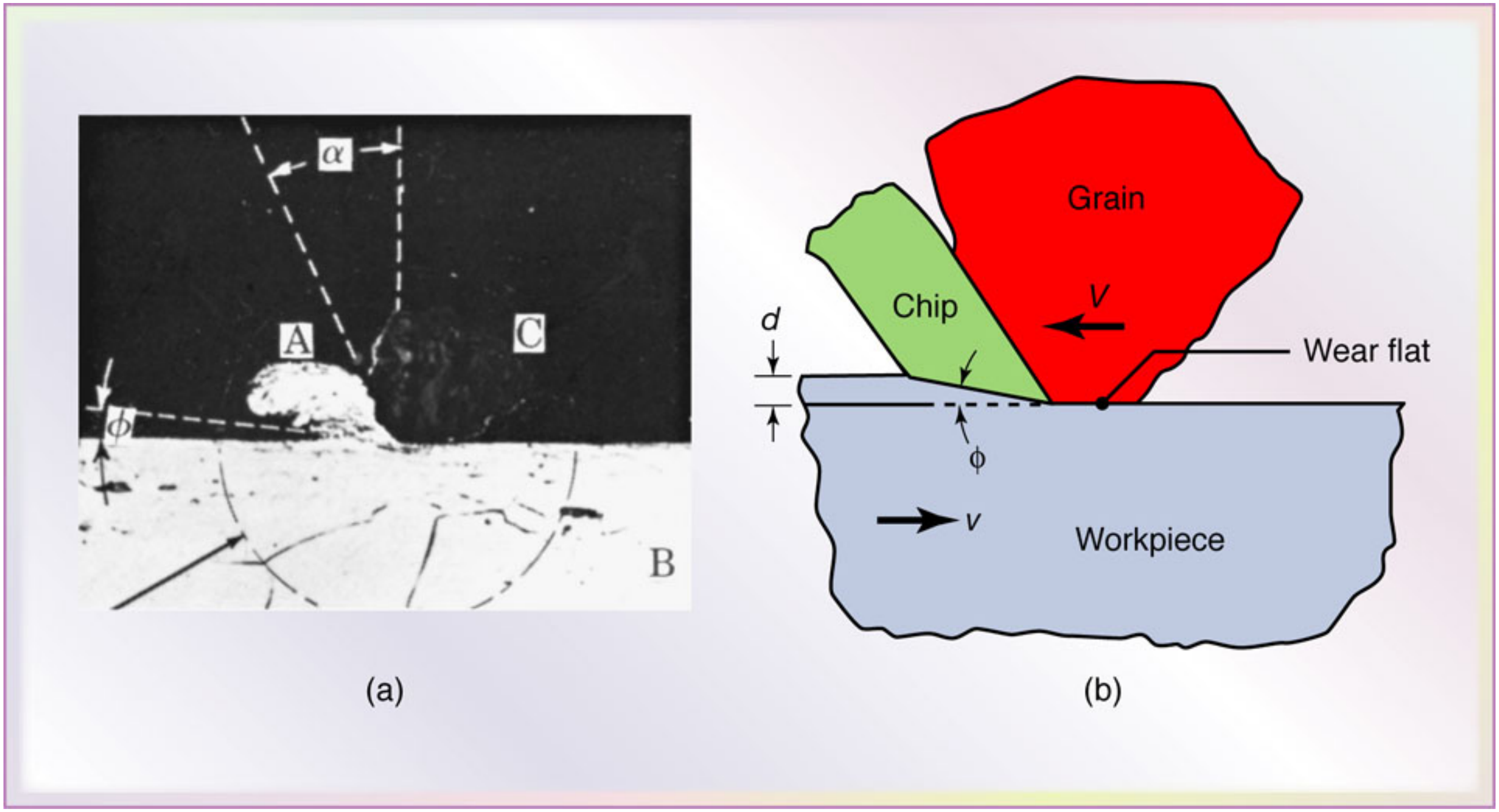
Common glass	350–500	Titanium nitride	2000
Flint, quartz	800–1100	Titanium carbide	1800–3200
Zirconium oxide	1000	Silicon carbide	2100–3000
Hardened steels	700–1300	Boron carbide	2800
Tungsten carbide	1800–2400	Cubic boron nitride	4000–5000
Aluminum oxide	2000–3000	Diamond	7000–8000

Grinding Wheel Model



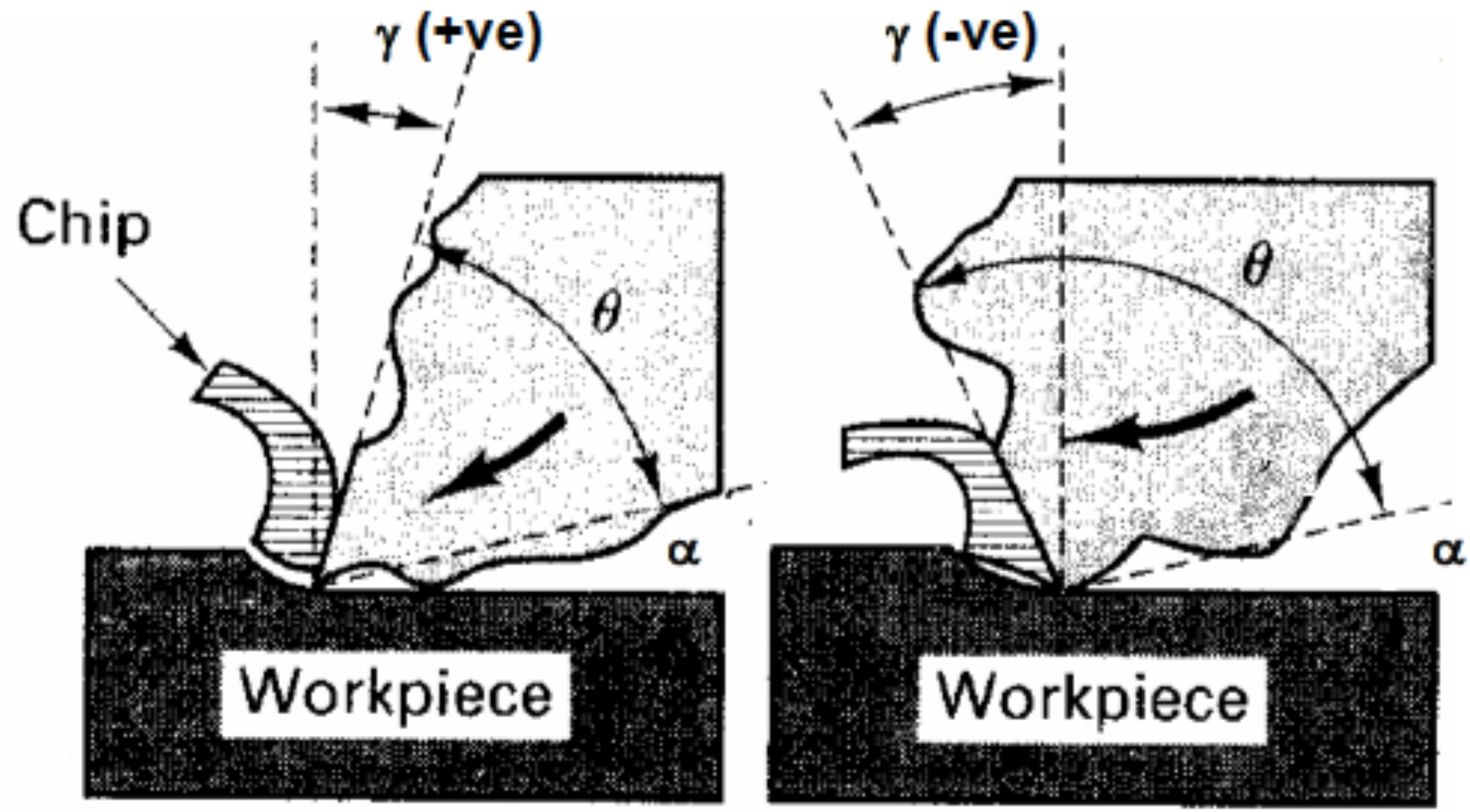
Schematic illustration of a physical model of a grinding wheel showing its structure and wear and fracture patterns.

Chip Formation by Abrasive Grain

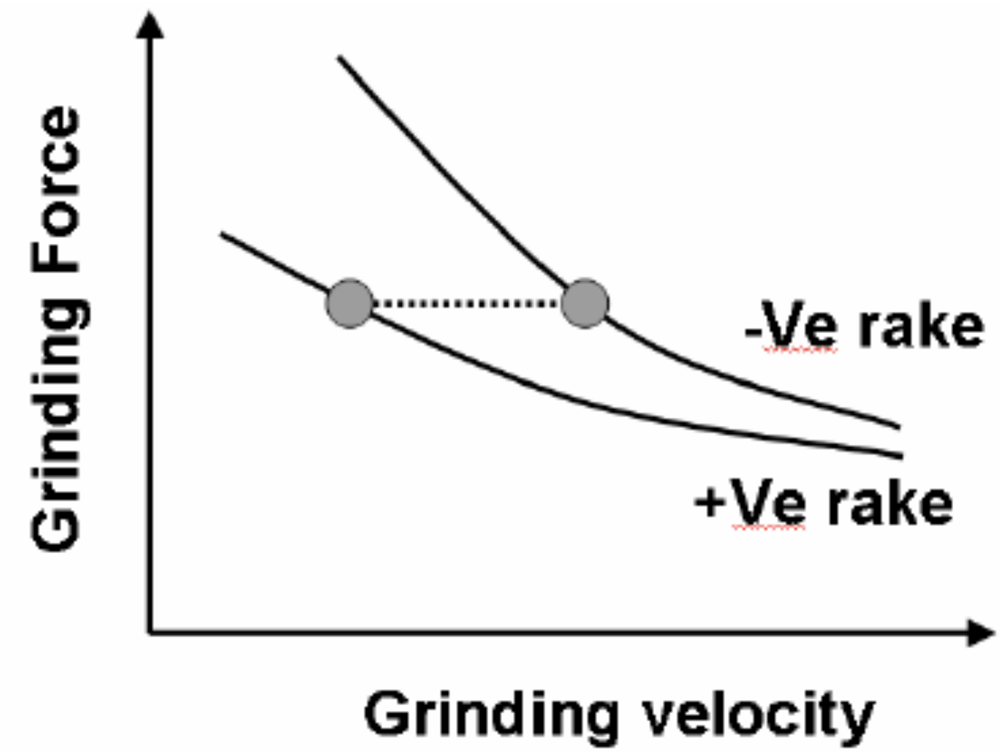


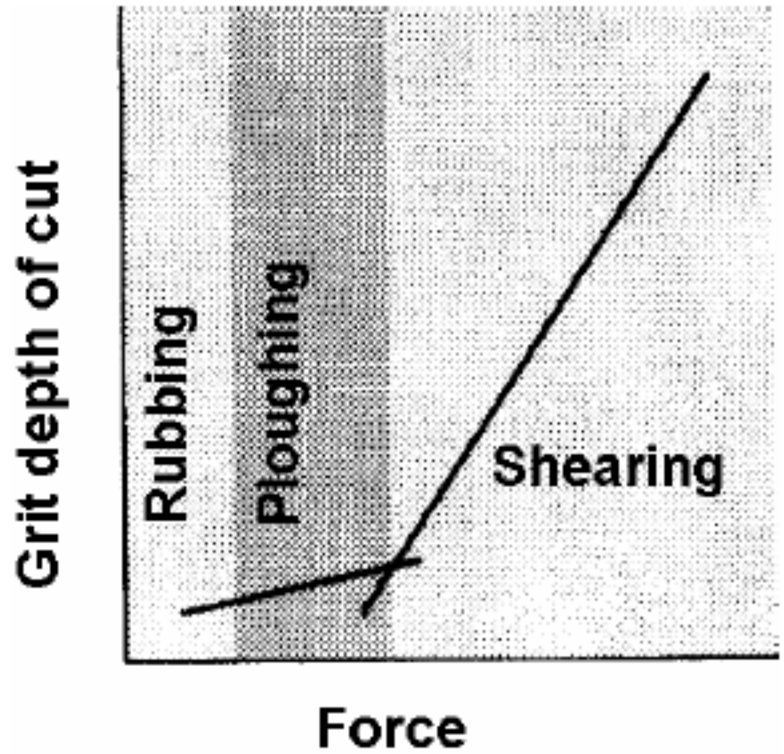
(a) Grinding chip being produced by a single abrasive grain: (A) chip, (B) workpiece, (C) abrasive grain. Note the large negative rake angle of the grain. The inscribed circle is 0.065 mm (0.0025 in.) in diameter. (b) Schematic illustration of chip formation by an abrasive grain with a wear flat. Note the negative rake angle of the grain and the small shear angle. *Source:* (a) After M.E. Merchant.

Abrasive Grain Ploughing Workpiece Surface

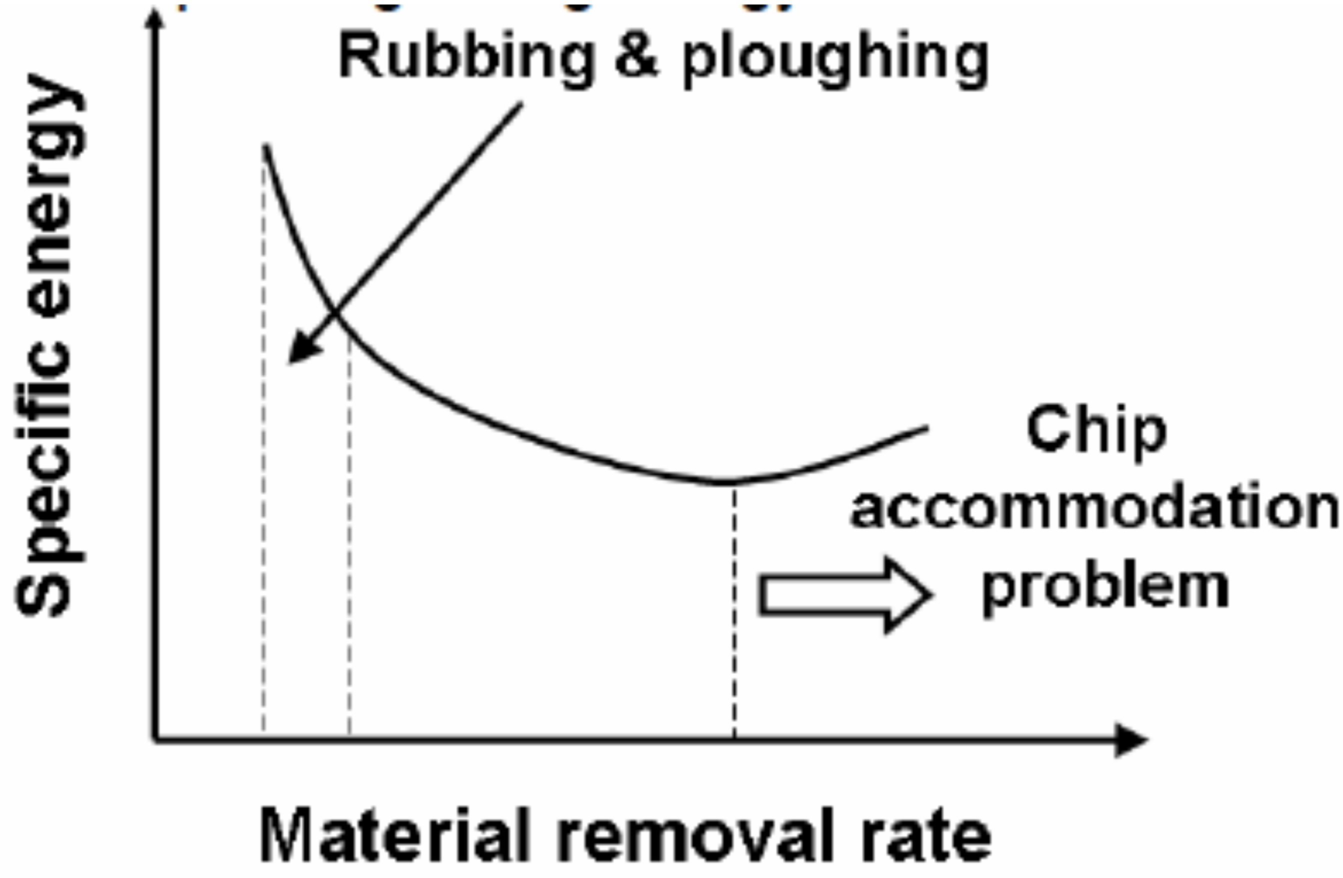


Grinding velocity, Rake angle and Grit depth

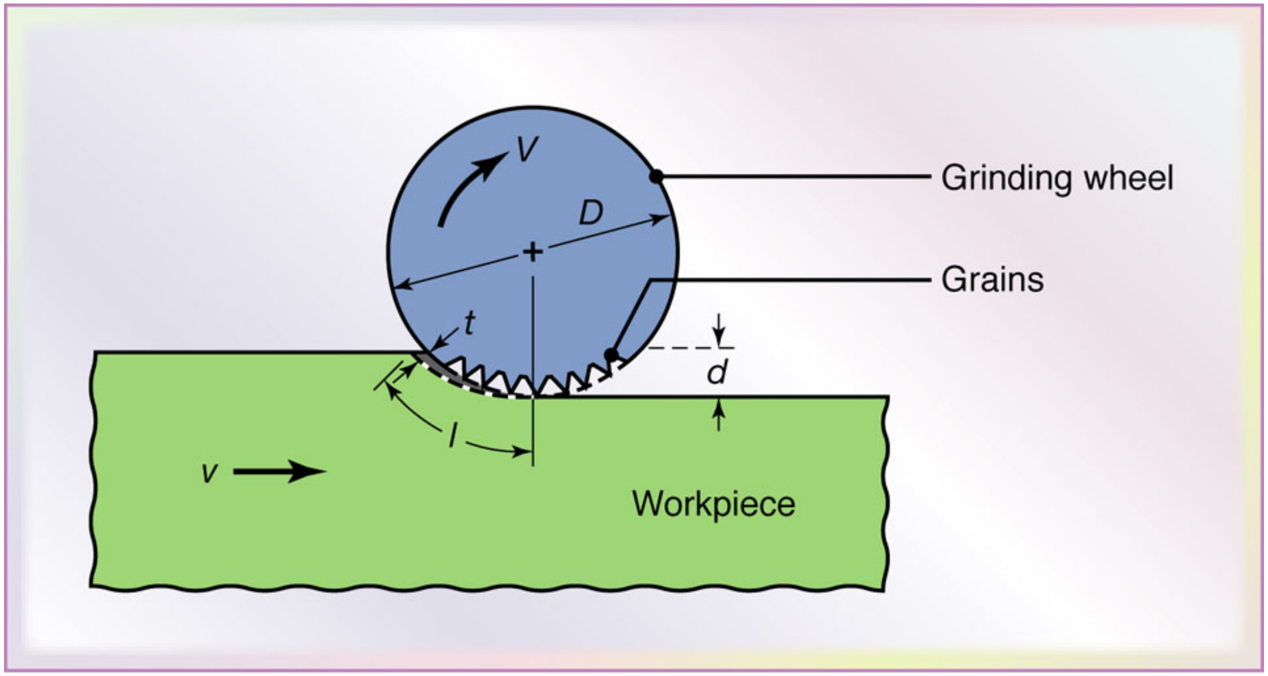




Specific cutting energy



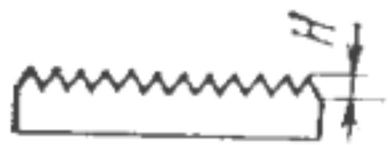
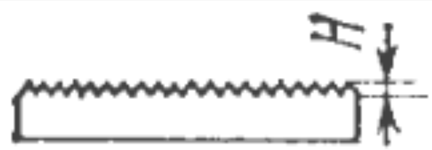
Grinding ratio



$$\text{Grinding ratio, } G = \frac{\text{Volume of material removed}}{\text{Volume of wheel wear}}$$

Superfinishing processes: Honing, Lapping and Superfinishing

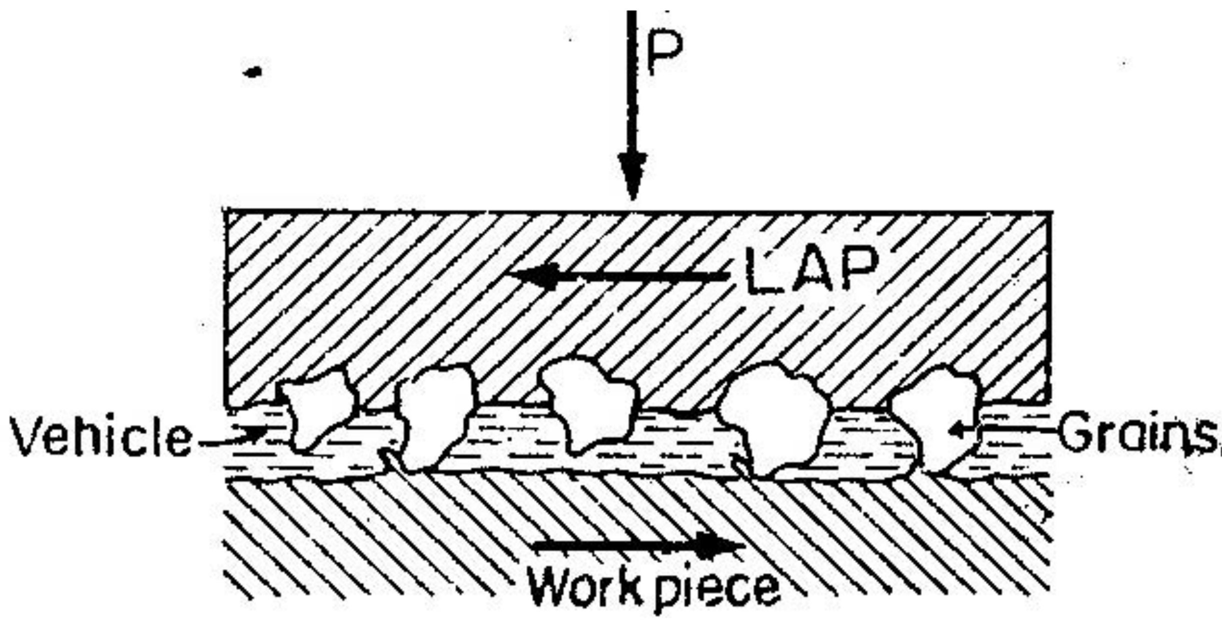
Improvement of surface roughness

Process	Diagram of resulting surface	Height of micro irregularity (μm)
Precision Turning		1.25-12.50
Grinding		0.90-5.00
Honing		0.13-1.25
Lapping		0.08-0.25
Super Finishing		0.01-0.25

Lapping process

Characteristics of lapping process:

- Use of loose abrasive between lap and the workpiece
- Usually lap and workpiece are not positively driven but are guided in contact with each other
- Relative motion between the lap and the work should change continuously so that path of the abrasive grains of the lap is not repeated on the workpiece.



Lapping

Abrasives of lapping:

- Al_2O_3 and SiC, grain size 5~100μm
- Cr_2O_3, grain size 1~2 μm
- B_4C_3, grain size 5-60 μm
- Diamond

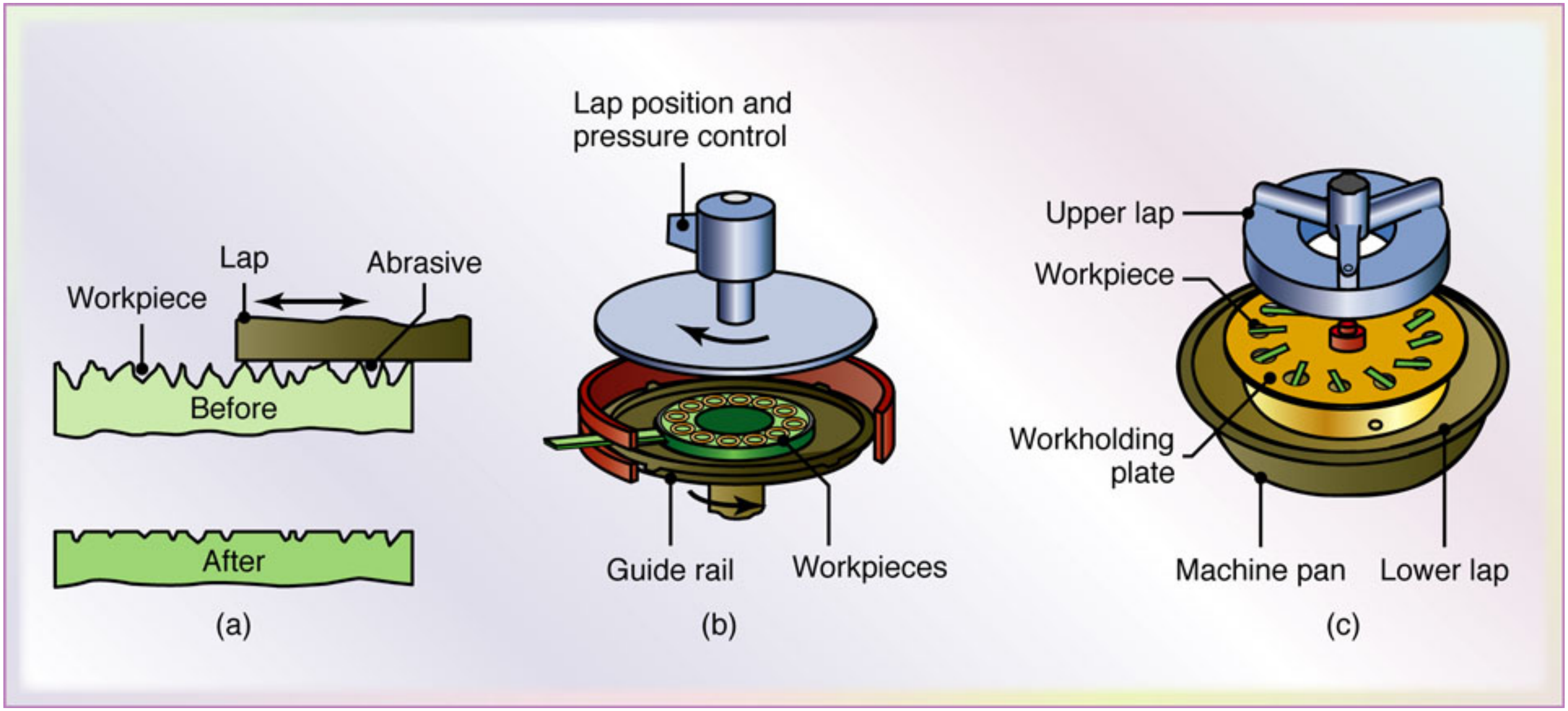
Materials for lapping

- Machine oil
- grease

Technical parameters affecting lapping processes are:

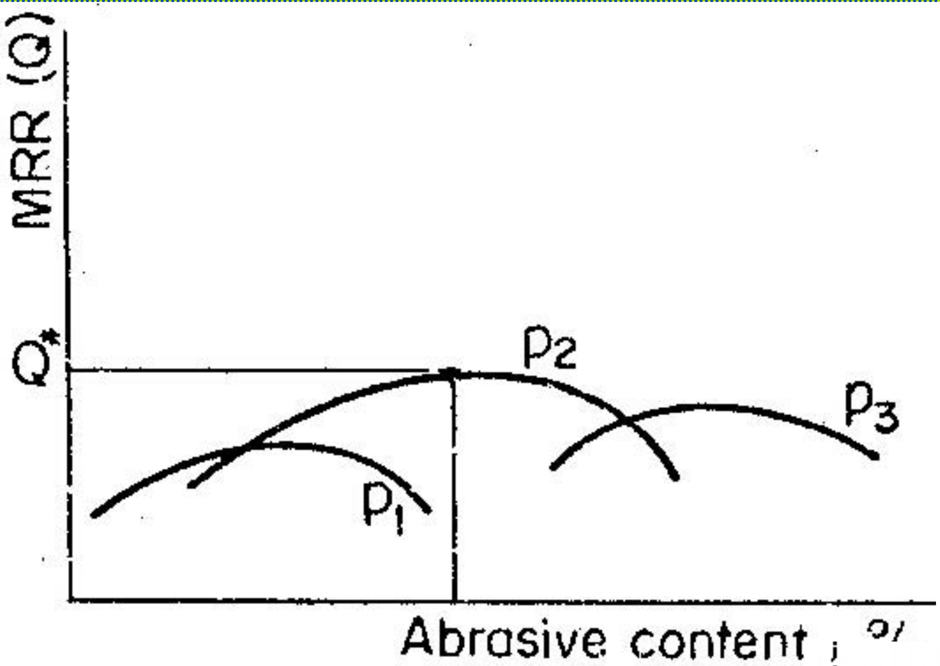
- unit pressure
- the grain size of abrasive
- concentration of abrasive particles
- lapping speed

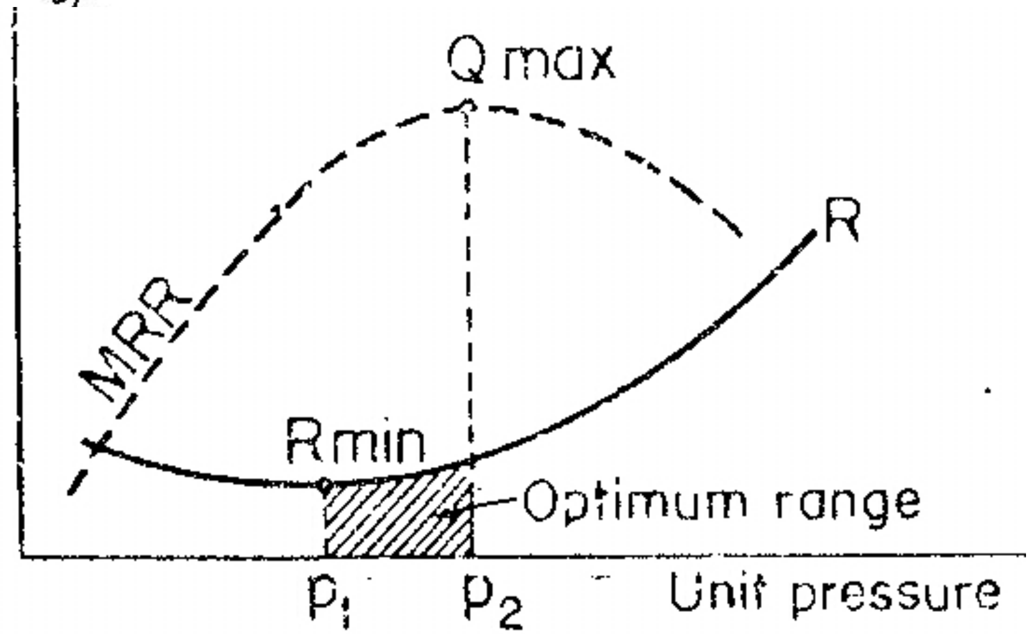
Production Lapping



(a) Schematic illustration of the lapping process. (b) Production lapping on flat surfaces. (c) Production lapping on cylindrical surfaces.

Production Lapping



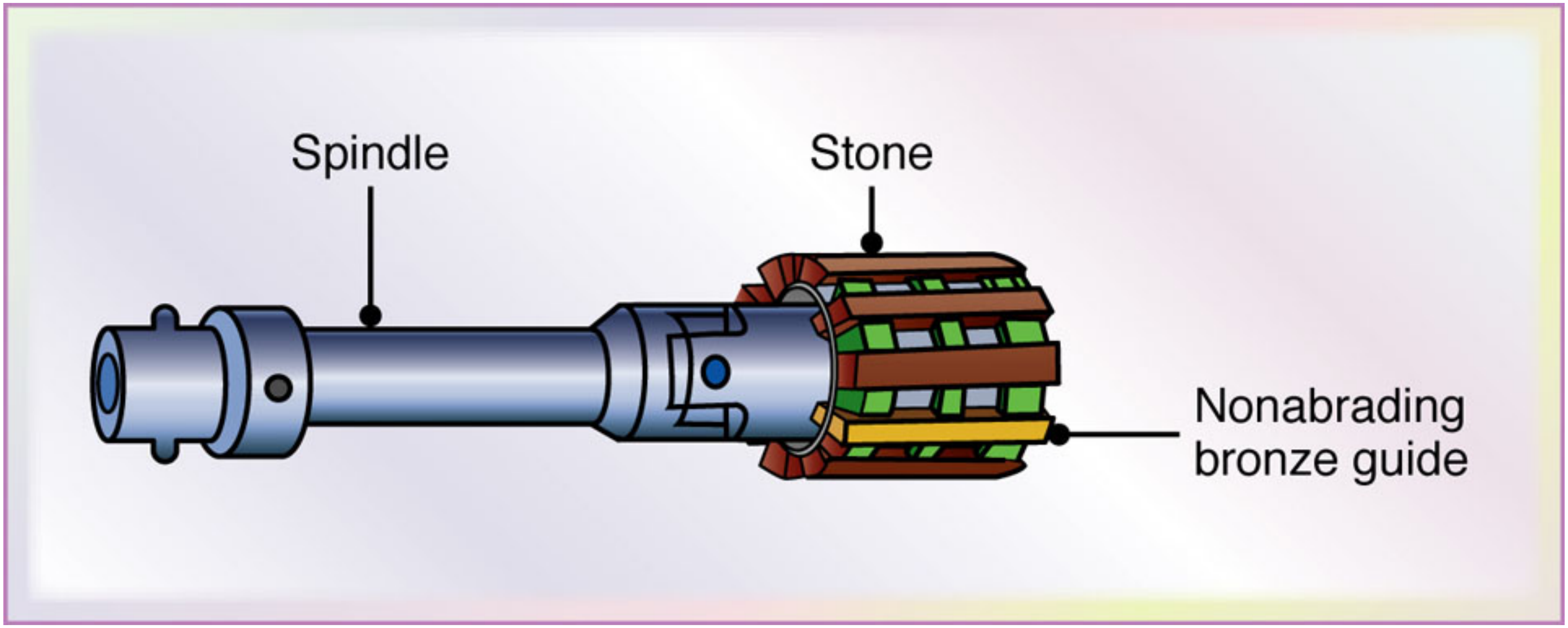


Honing process

Honing is a finishing process, in which a tool called hone carries out a combined rotary and reciprocating motion while the workpiece does not perform any working motion. Most honing is done on internal cylindrical surface, such as automobile cylindrical walls. The honing stones are held against the workpiece with controlled light pressure. The honing head is not guided externally but, instead, floats in the hole, being guided by the work surface. It is desired that

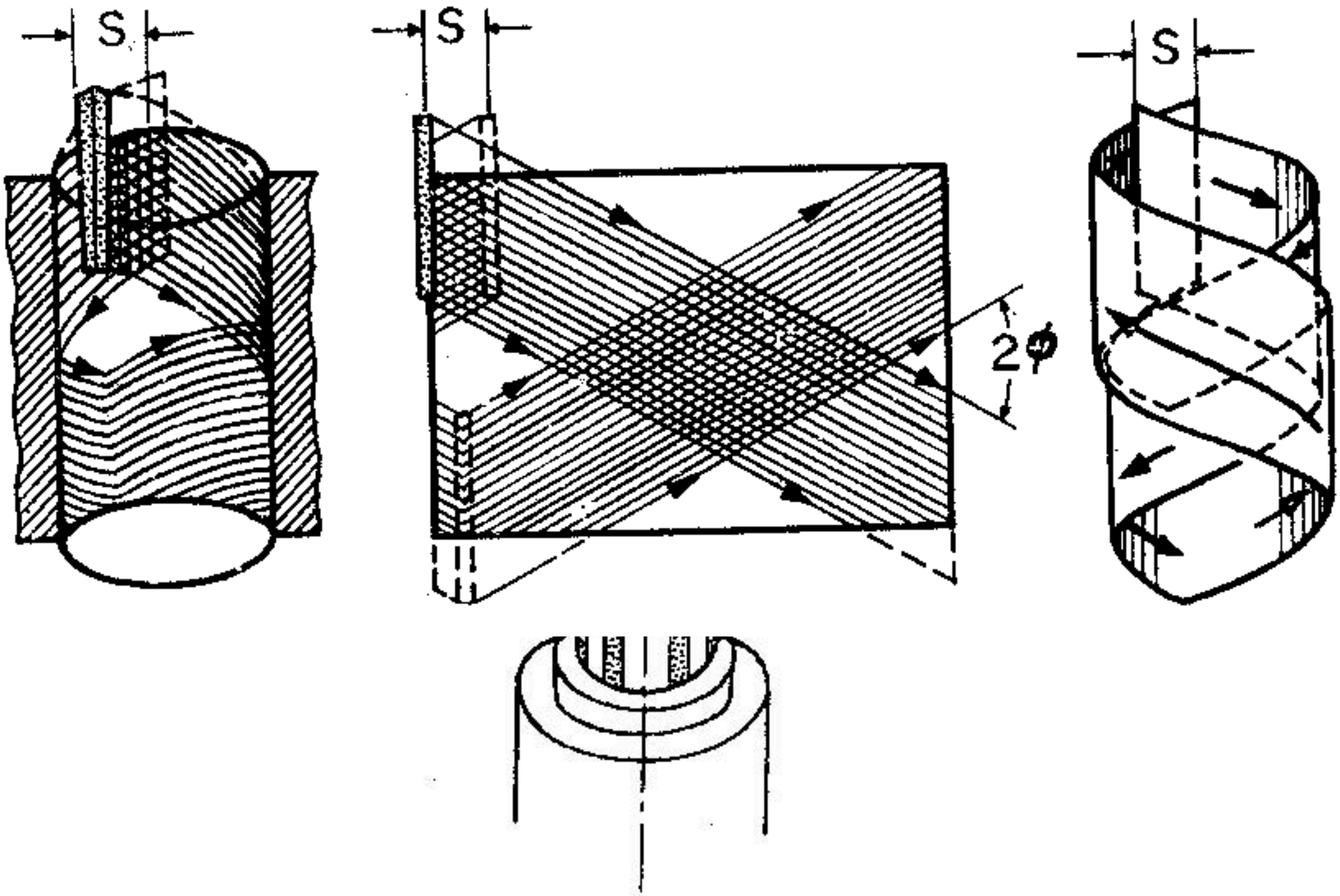
1. honing stones should not leave the work surface
2. stroke length must cover the entire work length.

Honing Tool



Schematic illustration of a honing tool used to improve the surface finish of bored or ground holes.

Honning process



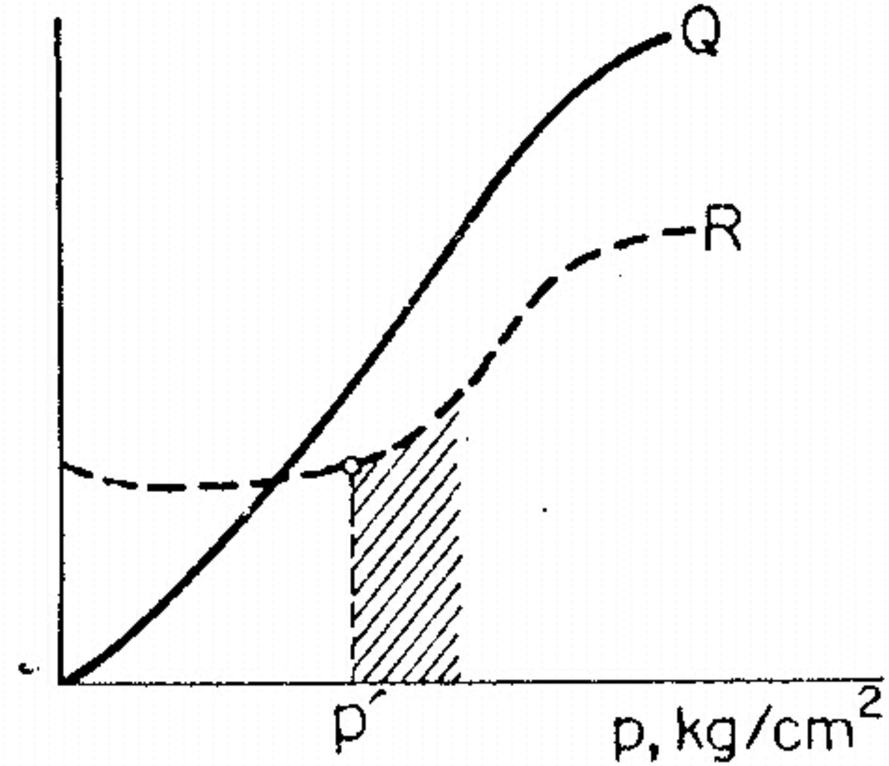
Honing Tool

The important parameters that affect material removal rate (MRR) and surface roughness (R) are:

(i) unit pressure, p

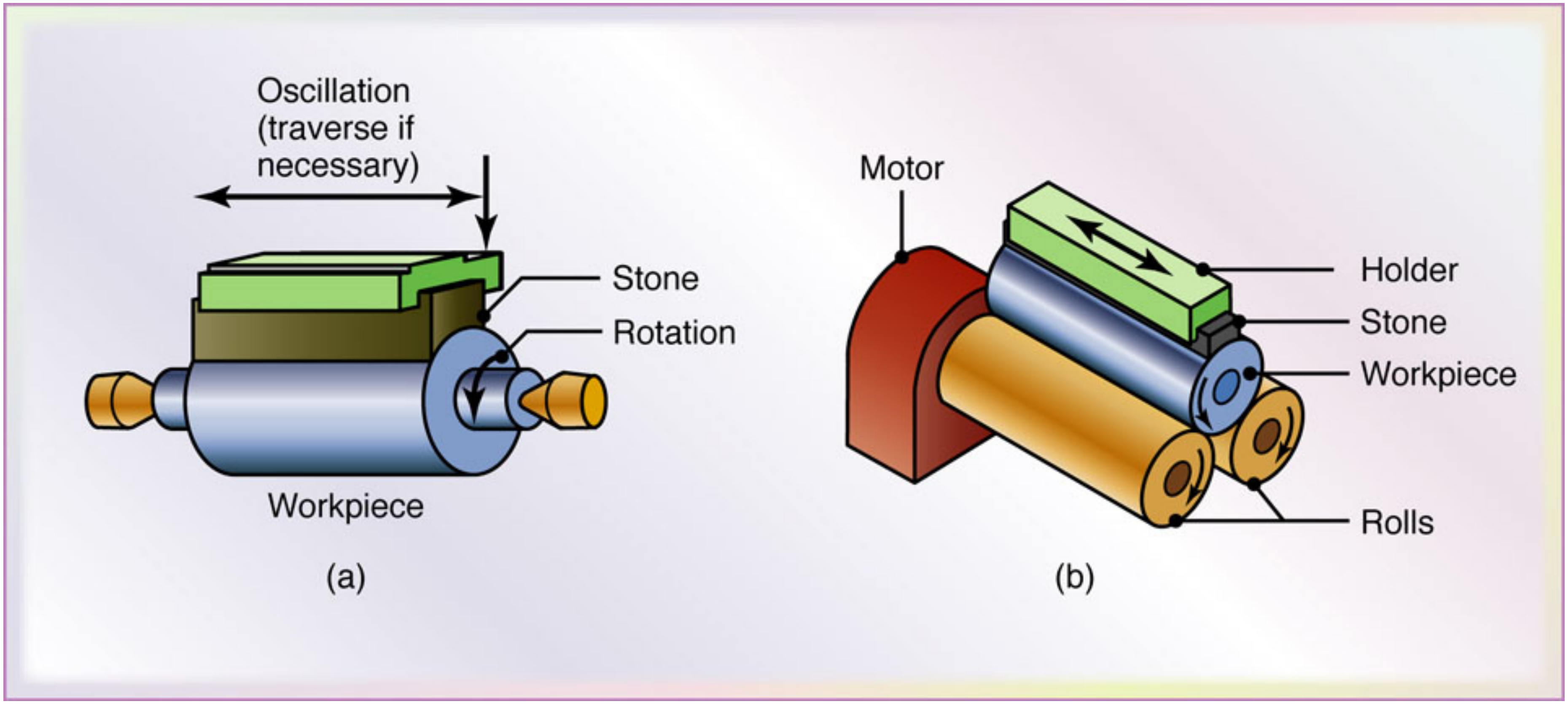
(ii) peripheral honing speed, Vc

(iii) honing time, T



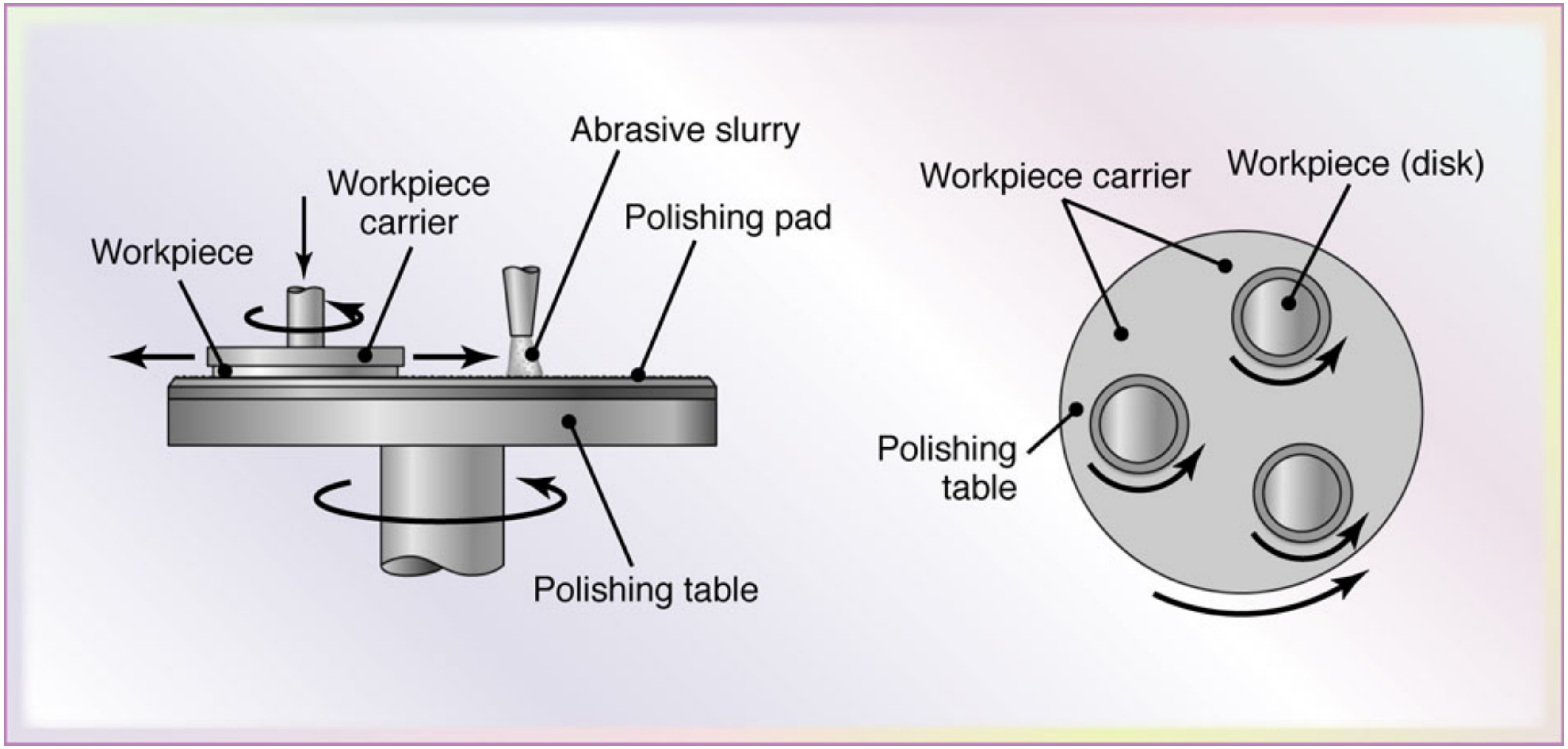
Effect of honing pressure on MRR and surface finish

Super-finishing Process



Schematic illustration of the superfinishing process for a cylindrical part. (a) Cylindrical microhoning. (b) Centerless microhoning.

CMP Process (Chemical-mechanical polishing)

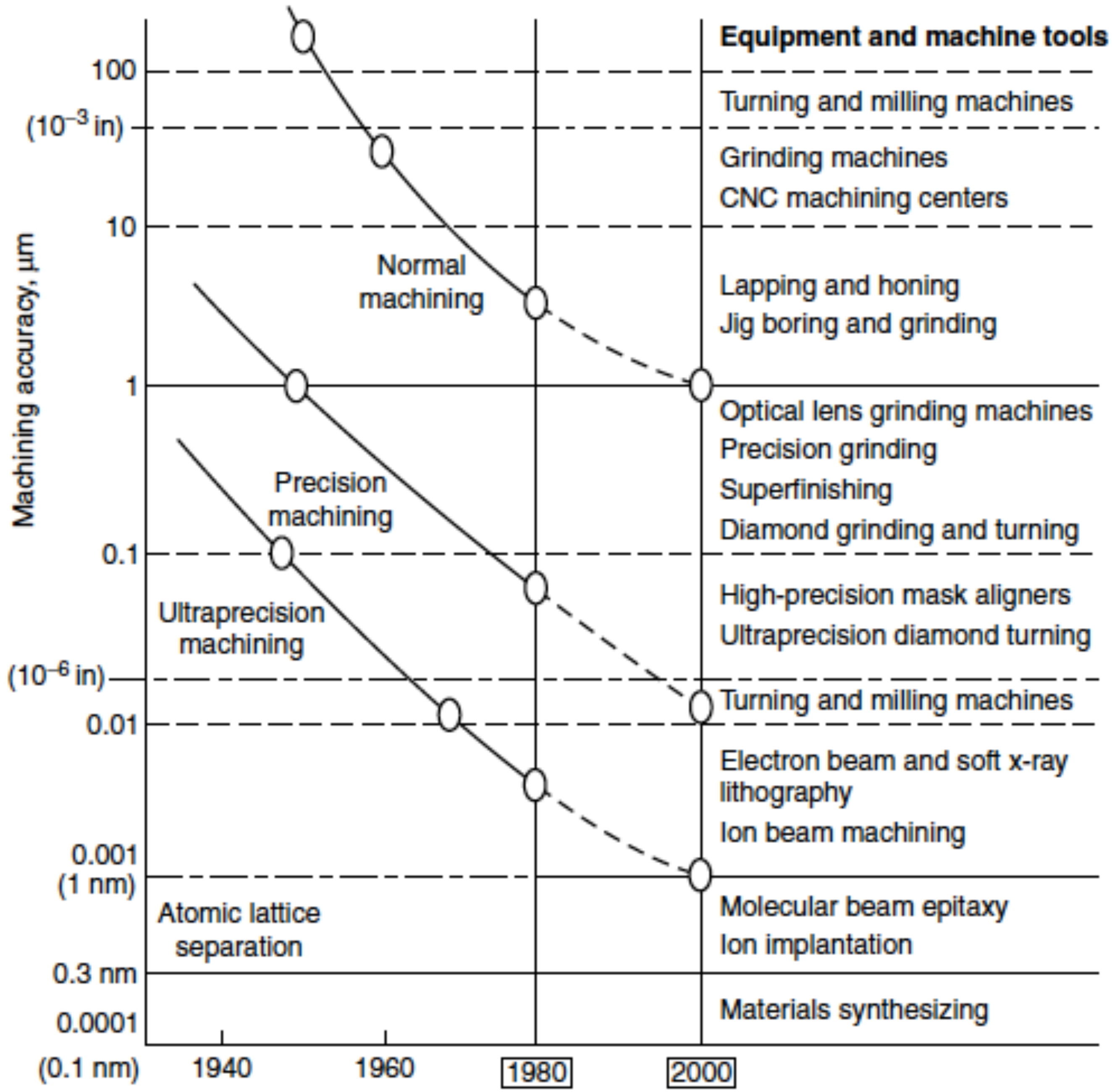


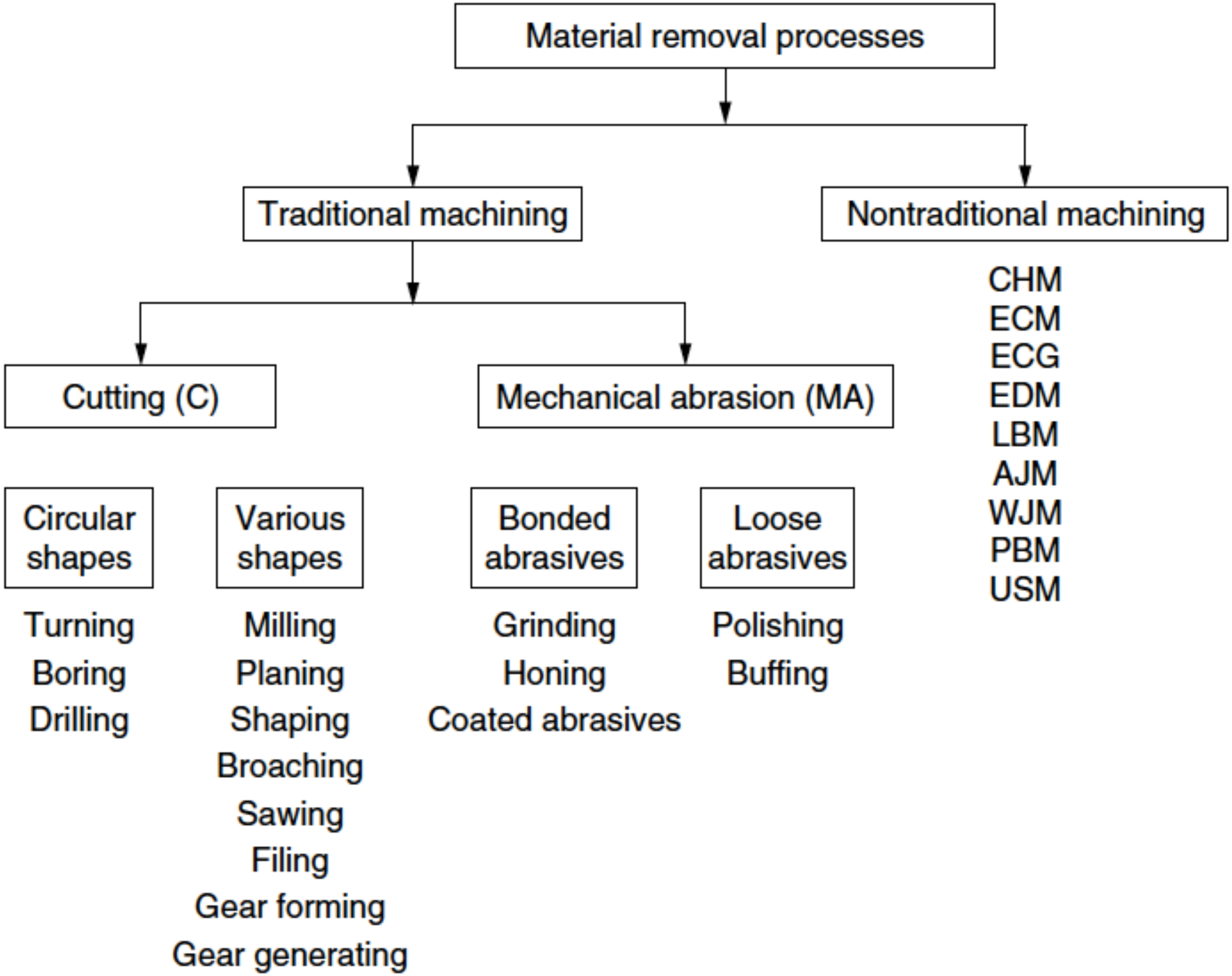
(a) Schematic illustration of the chemical-mechanical polishing (CMP) process. This process is used widely in the manufacture of silicon wafers and integrated circuits and also is known as chemical-mechanical planarization. For other materials, more carriers and more disks per carrier are possible.

ME2300: Manufacturing Processes
Jan-May 2020

Non traditional & hybrid machining processes

Introduction





Material removal processes
Traditional machining
Nontraditional machining
CHM
ECM
ECG
EDM
LBM
AJM
WJM
PBM
USM
Cutting (C)
Mechanical abrasion (MA)
Circular shapes
Various shapes
Bonded abrasives
Loose abrasives
Turning
Boring
Drilling
Milling
Planing
Shaping
Broaching
Sawing
Filing
Gear forming
Gear generating
Grinding
Honing
Coated abrasives
Polishing
Buffing

Introduction

Manufacturing processes can be broadly divided into two groups:

a) primary manufacturing processes : Provide basic shape and size
b) secondary manufacturing processes : Provide final shape and size with tighter control on dimension, surface characteristics

Material removal processes once again can be divided into two groups

1. Conventional Machining Processes
2. Non-Traditional machining Processes or non-conventional machining processes

Conventional Machining Processes mostly remove material in the form of chips by applying forces on the work material with a wedge shaped cutting tool that is harder than the work material under machining condition

Introduction

The major characteristics of conventional machining are:

- Generally macroscopic chip formation by shear deformation

- Material removal takes place due to application of cutting forces – energy domain can be classified as mechanical

- Cutting tool is harder than work piece at room temperature as well as under machining conditions

Introduction

Non-conventional machining processes is defined as a group of processes that remove excess material by various techniques involving **mechanical, thermal, electrical or chemical energy** or combinations of these energies but do not use a sharp cutting tools as it needs to be used for traditional manufacturing processes.

The major characteristics of Non-conventional machining are:

1. Material removal may occur with chip formation or even no chip formation may take place. For example in AJM, chips are of microscopic size and in case of Electrochemical machining material removal occurs due to electrochemical dissolution at atomic level.

Introduction

The major characteristics of Non-conventional machining:

2. In NTM, there may not be a physical tool present. For example in laser jet machining, machining is carried out by laser beam. However in Electrochemical Machining there is a physical tool that is very much required for machining
3. In NTM, the tool need not be harder than the work piece material. For example, in EDM, copper is used as the tool material to machine hardened steels.
4. Mostly NTM processes do not necessarily use mechanical energy to provide material removal. They use different energy domains to provide machining. For example, in USM, AJM, WJM mechanical energy is used to machine material, whereas in ECM electrochemical dissolution constitutes material removal.

Classifications

Classification of NTM processes is carried out depending on the nature of energy used for material removal.

1. Mechanical Processes

- Abrasive Jet Machining (AJM)
- Ultrasonic Machining (USM)
- Water Jet Machining (WJM)
- Abrasive Water Jet Machining (AWJM)

2. Electrochemical Processes

- Electrochemical Machining (ECM)
- Electro Chemical Grinding (ECG)
- Electro Jet Drilling (EJD)

3. Electro-Thermal Processes

- Electro-discharge machining (EDM)
- Laser Jet Machining (LJM)
- Electron Beam Machining (EBM)

4. Chemical Processes

- Chemical Milling (CHM)
- Photochemical Milling (PCM)

Why non traditional machining?

- Need to machine newly developed metals and non-metals with special properties that make them difficult or impossible to machine by conventional methods
- Need for unusual and/or complex part geometries that cannot easily be accomplished by conventional machining
- Need to avoid surface damage that often accompanies conventional machining

Classification of Non-traditional Processes by Type of Energy Used

•*Mechanical* - erosion of work material by a high velocity stream of abrasives or fluid (or both) is the typical form of mechanical action

•*Electrical* - electrochemical energy to remove material (reverse of electroplating)

•*Thermal* – thermal energy usually applied to small portion of work surface, causing that portion to be removed by fusion and/or vaporization

•*Chemical* – chemical etchants selectively remove material from portions of workpart, while other portions are protected by a mask

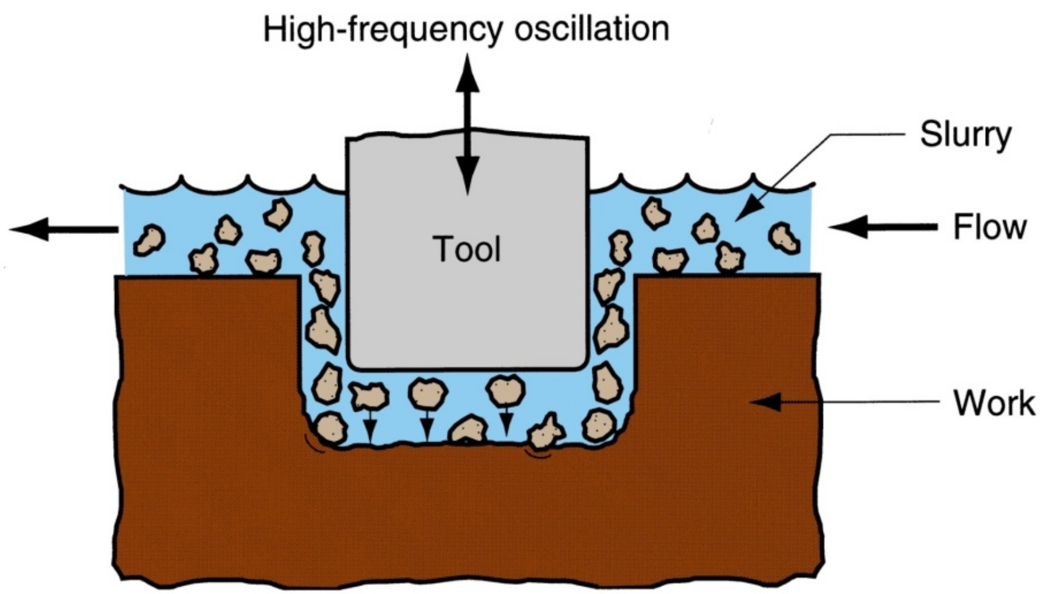
Mechanical energy processes

- Ultrasonic machining (USM)
- Water jet cutting (WJM)
- Abrasive water jet cutting (AWJM)
- Abrasive jet machining (AJM)

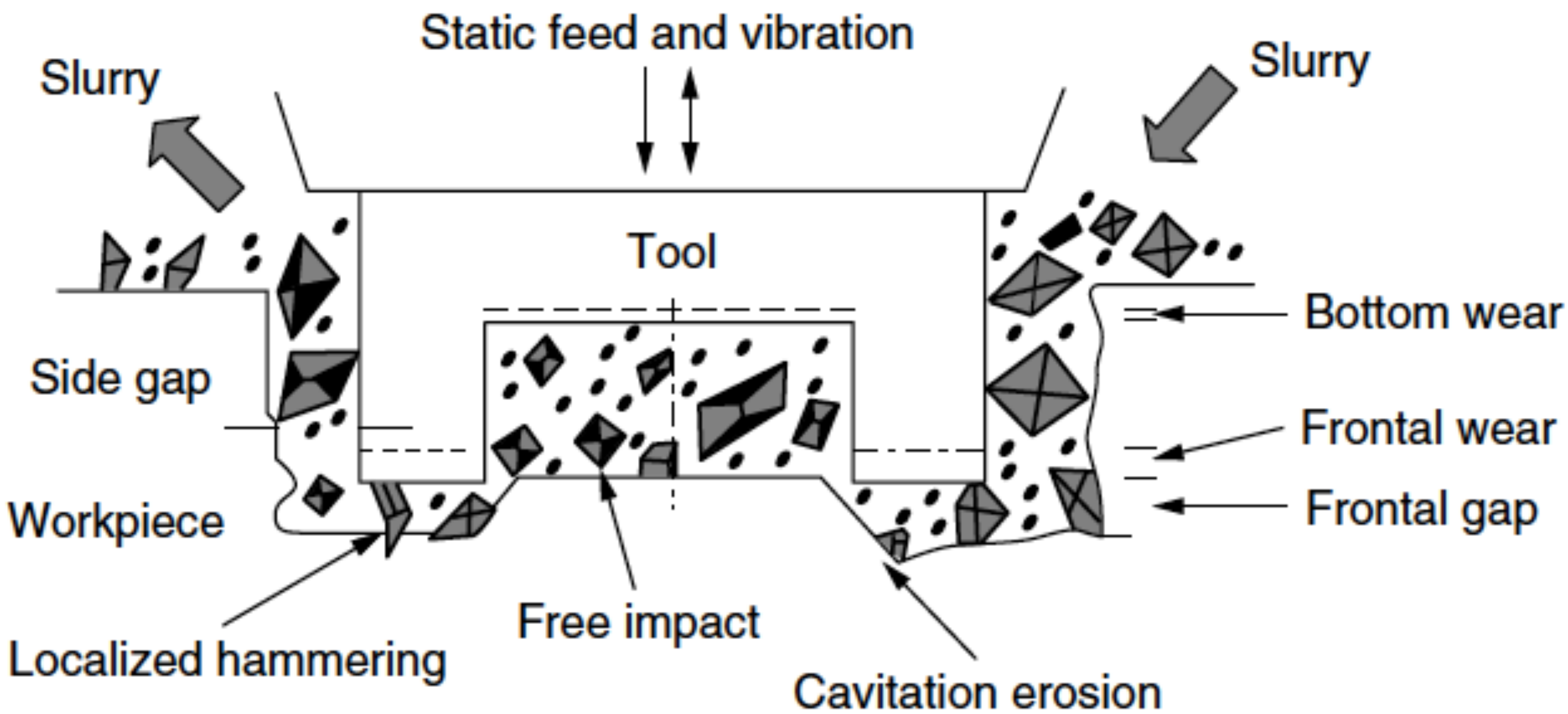
Ultrasonic Machining (USM)

Abrasives contained in a slurry are driven at high velocity against work by a tool vibrating at low amplitude and high frequency

- Tool oscillation is perpendicular to work surface
- Tool is fed slowly into work
- Shape of tool is formed in part



Ultrasonic Machining (USM)



Material removal mechanisms in USM

Ultrasonic Machining (USM)

- Mechanical abrasion by localized direct hammering of the abrasive grains stuck between the vibrating tool and adjacent work surface.

- The microchipping by free impacts of particles that fly across the machining gap and strike the workpiece at random locations.

- The work surface erosion by cavitation in the slurry stream.

USM

- Applications

– USM is best suited for hard, brittle materials, such as ceramics, carbides, glass, precious stones, and hardened steels.

- Capability

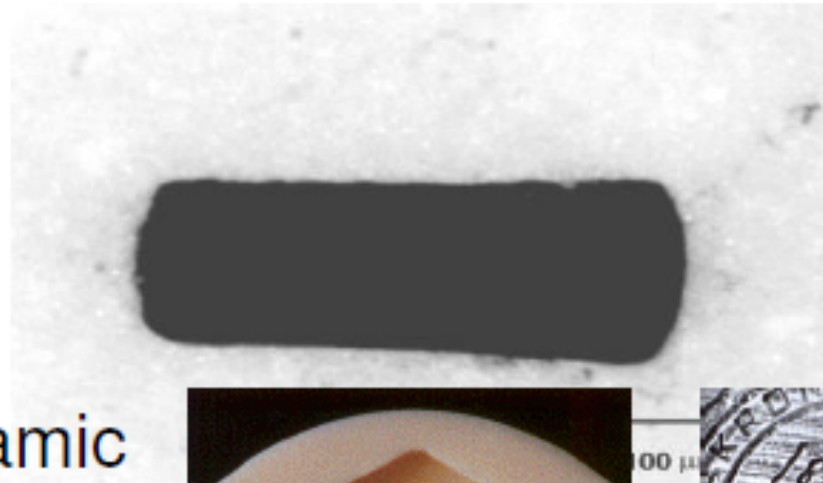
– With fine abrasives, tolerance of 0.0125 mm or better can be held. Ra varies between 0.2 – 1.6 μm.

- Pros & Cons:

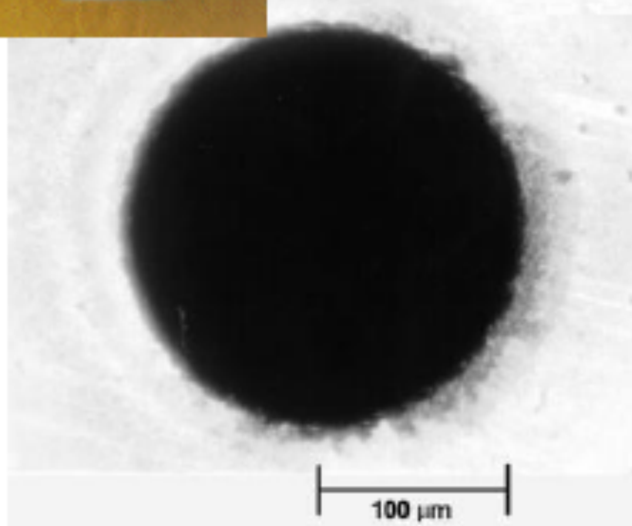
– *Pros: precise machining of brittle materials; makes tiny holes (0.3* mm); does not produce electric, thermal, chemical damage because it removes material mechanically.

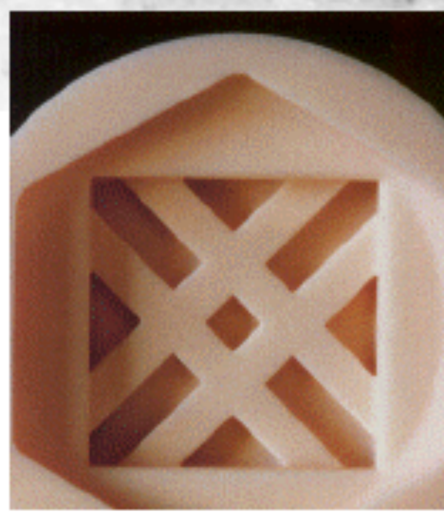
– *Cons: low material removal rate (typically 0.8* cm^3*/min); tool wears* rapidly; machining area and depth are limited.

USM Parts



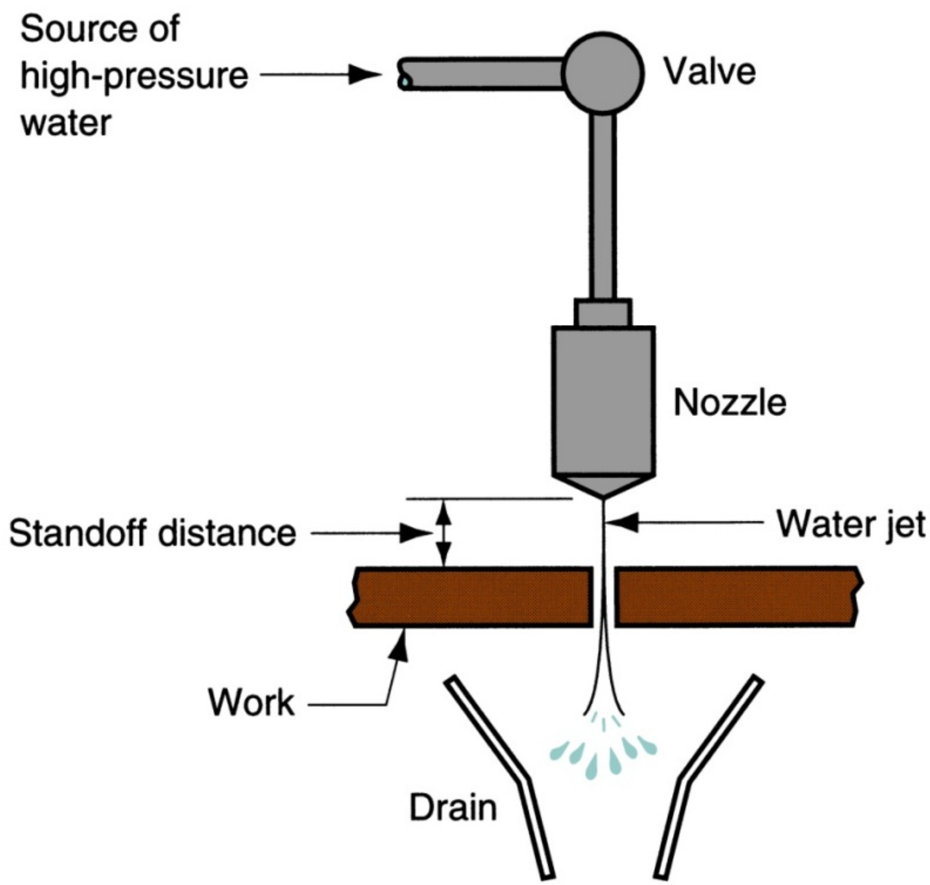
Ceramic



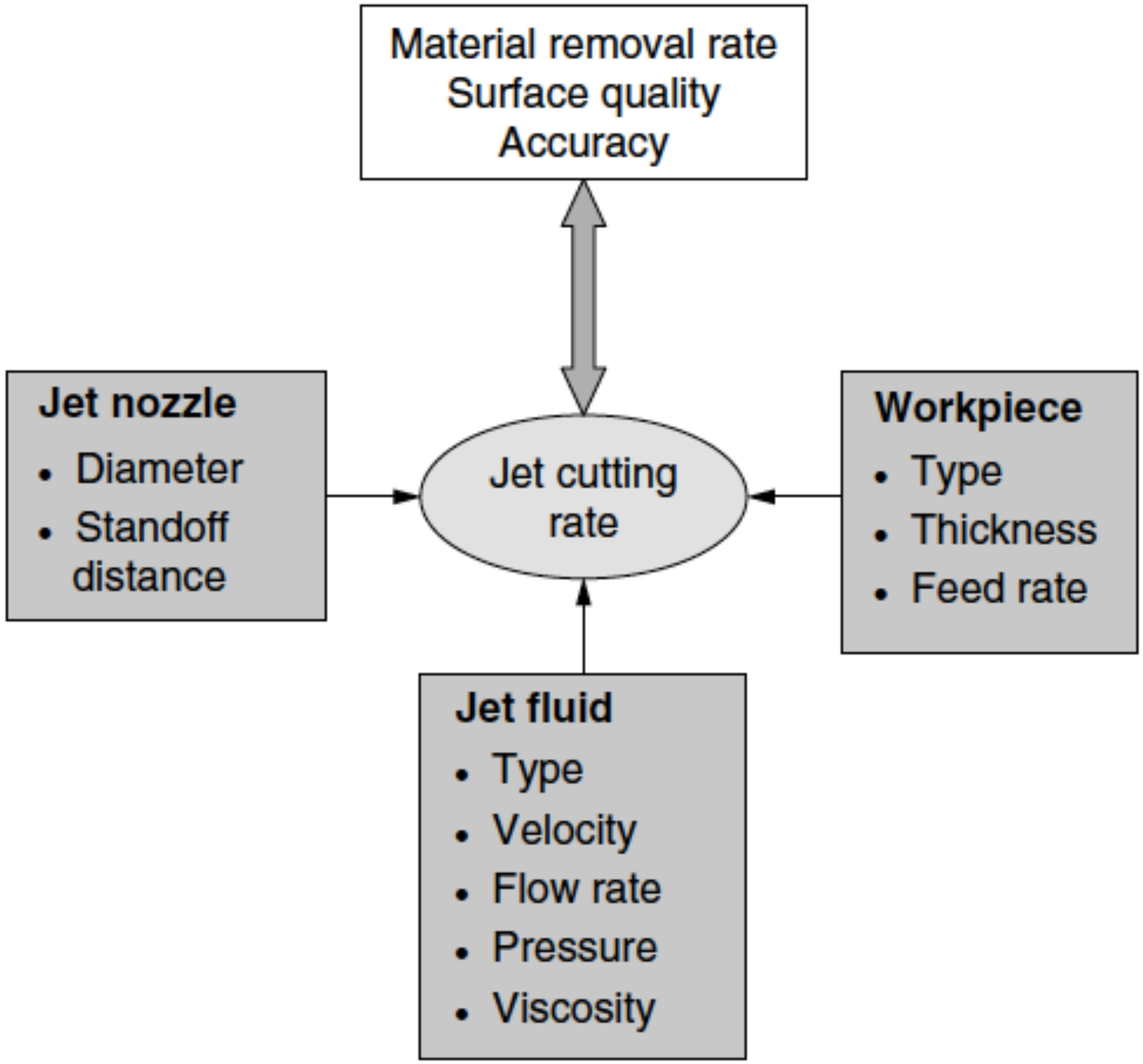


Water Jet Machining (WJM)

Uses a fine, high pressure, high velocity stream of water directed at work surface for cutting



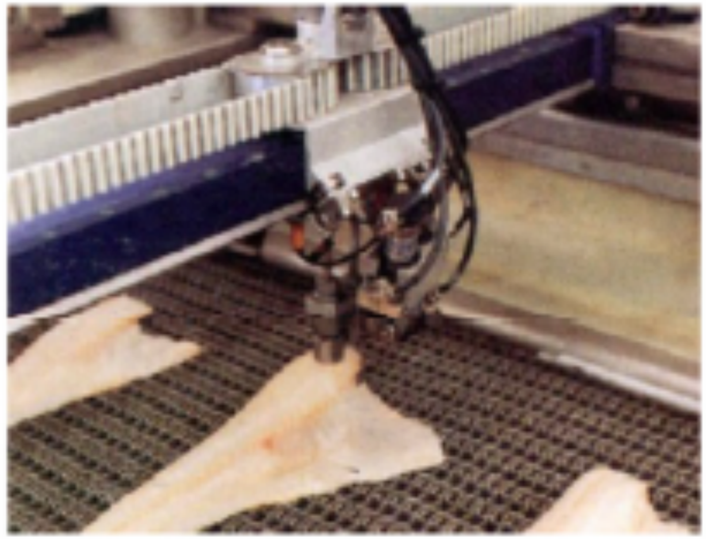
Water Jet Machining (WJM)



WJM Applications

- Usually automated by CNC or industrial robots to manipulate nozzle along desired trajectory
- Used to cut narrow slits in flat stock such as plastic, textiles, composites, floor tile, carpet, leather, and cardboard
- Not suitable for brittle materials (e.g., glass)
- WJC advantages: no crushing or burning of work surface, minimum material loss, no environmental pollution, and ease of automation

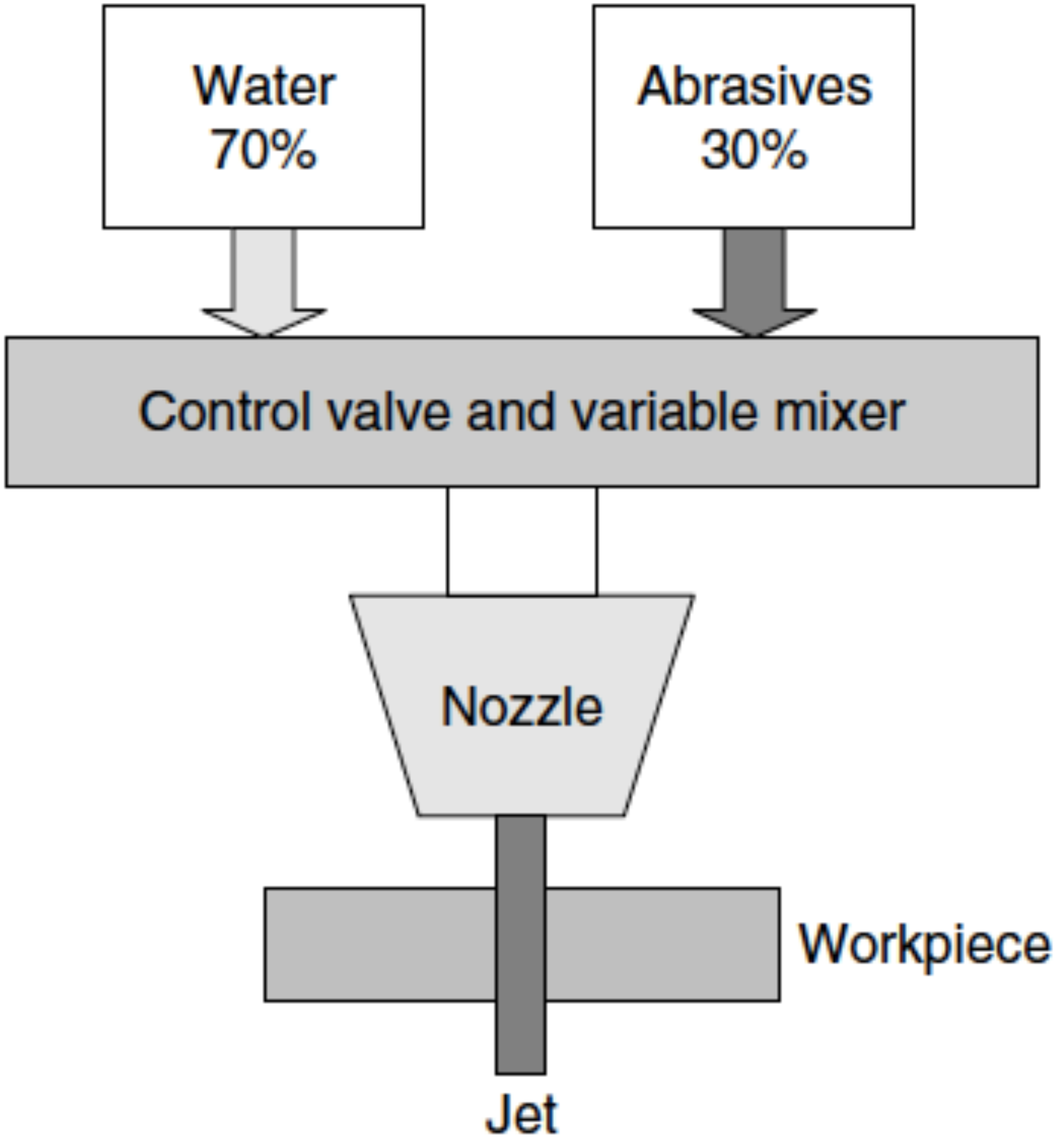
WJM Parts



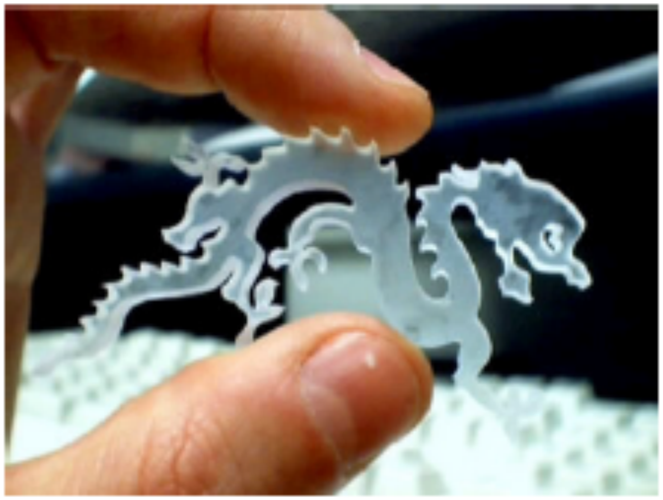
Abrasive Water Jet Machining (AWJM)

- When WJM is used on metals, abrasive particles must be added to jet stream usually
- Additional process parameters: abrasive type, grit size, and flow rate
  - Abrasives: aluminum oxide, silicon dioxide, and garnet (a silicate mineral)
  - Grit sizes range between 60 and 120
  - Grits added to water stream at about 0.25 kg/min

Abrasive Water Jet Machining (AWJM)

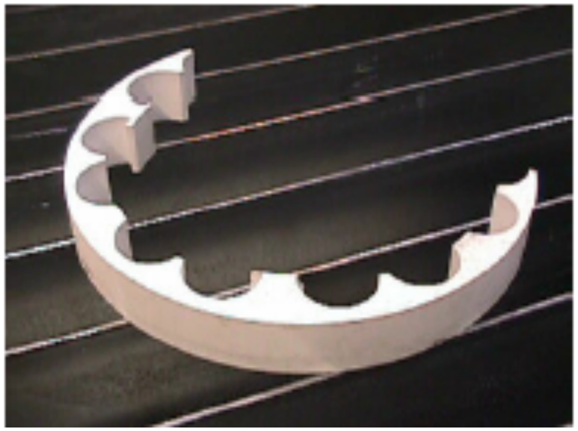


AWJM Parts



Bullet Proof Glass Part

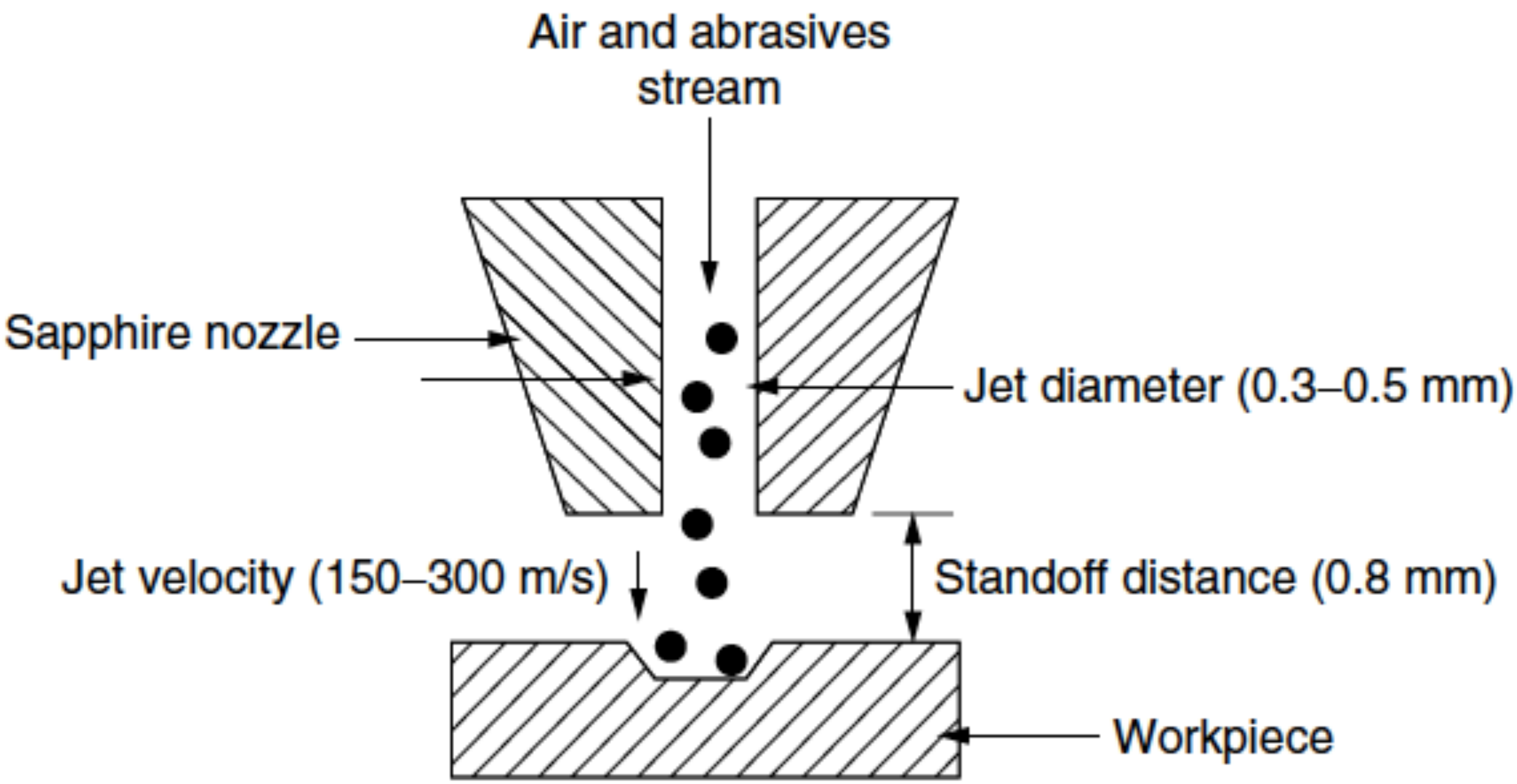
Steel rack (75 mm thick)



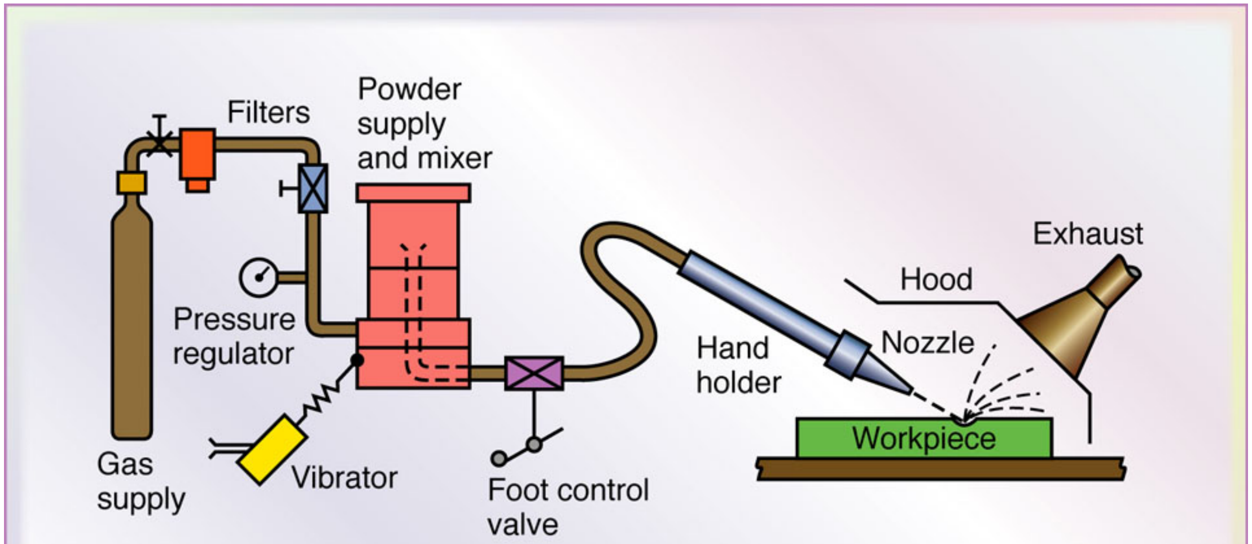
Ceramic Part

Abrasive Jet Machining (AJM)

- High velocity stream of gas containing small abrasive particles



Abrasive Jet Machining (AJM)



(a)

A high-velocity jet of dry air, nitrogen, or carbon dioxide containing abrasive particles is aimed at the workpiece surface under controlled conditions.

The gas supply pressure is on the order of 850 kPa (125 psi) and the jet velocity can be as high as 300 m/s and is controlled by a valve.

AJM Application Notes

- Usually performed manually by operator who directs nozzle
- Normally used as a finishing process rather than cutting process
- Applications: deburring, trimming and deflashing, cleaning, and polishing
- Work materials: thin flat stock of hard, brittle materials (e.g., glass, silicon, ceramics)

AJM process capability

- Material removal
  - Typical cutting speeds vary between 25 -125 mm/min
- Dimensional Tolerances
  - Typical range ± 2 - ± 5 µm
- Surface Finish
  - Typical R_a values vary from 0.3 - 2.3 µm

AJM

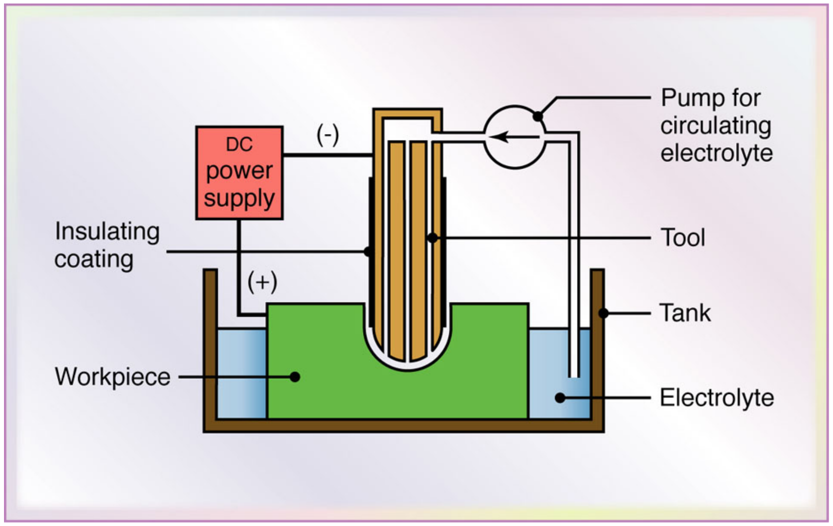
- Applications
  - Can cut traditionally hard to cut materials, e.g., composites, ceramics, glass
  - Good for materials that cannot stand high temperatures

- Limitations
  - Expensive process
  - Flaring can become large
  - Not suitable for mass production because of high maintenance requirements

II. Electrochemical Machining Processes

- Electrochemical machining (ECM) is a modern machining process that relies on the removal of workpiece atoms by electrochemical dissolution (ECD) in accordance with the principles of Faraday (1833).
- Reverse of electroplating
- Work material must be a conductor
- Processes:
  - Electrochemical machining (ECM)
  - Electrochemical grinding (ECG)

Electrochemical Machining (ECM)



- Process description:

– In ECM, a dc voltage (10-25 V) is applied across the gap between a pre-shaped cathode tool and an anode workpiece. The workpiece is dissolved by an electrochemical reaction to the shape of the tool.

– The electrolyte flows at high speed (10-60 m/s) through the gap (0.1-0.6 mm) to dissipate heat and wash away the dissolved metal.

Electrochemical Machining (ECM)

The amount of metal dissolved (removed by machining) or deposited is calculated from Faraday's laws of electrolysis, which state that

- The amount of mass dissolved (removed by machining), m , is directly proportional to the amount of electricity.
- The amount of different substances dissolved, m, by the same quantity of electricity is proportional to the substances' chemical equivalent weight e.

Electrochemical Machining (ECM)

- The material removal rate by ECM is given by:

$$MRR = C\, I\, \eta$$

where, MRR=mm^3/min, I=current in amperes,

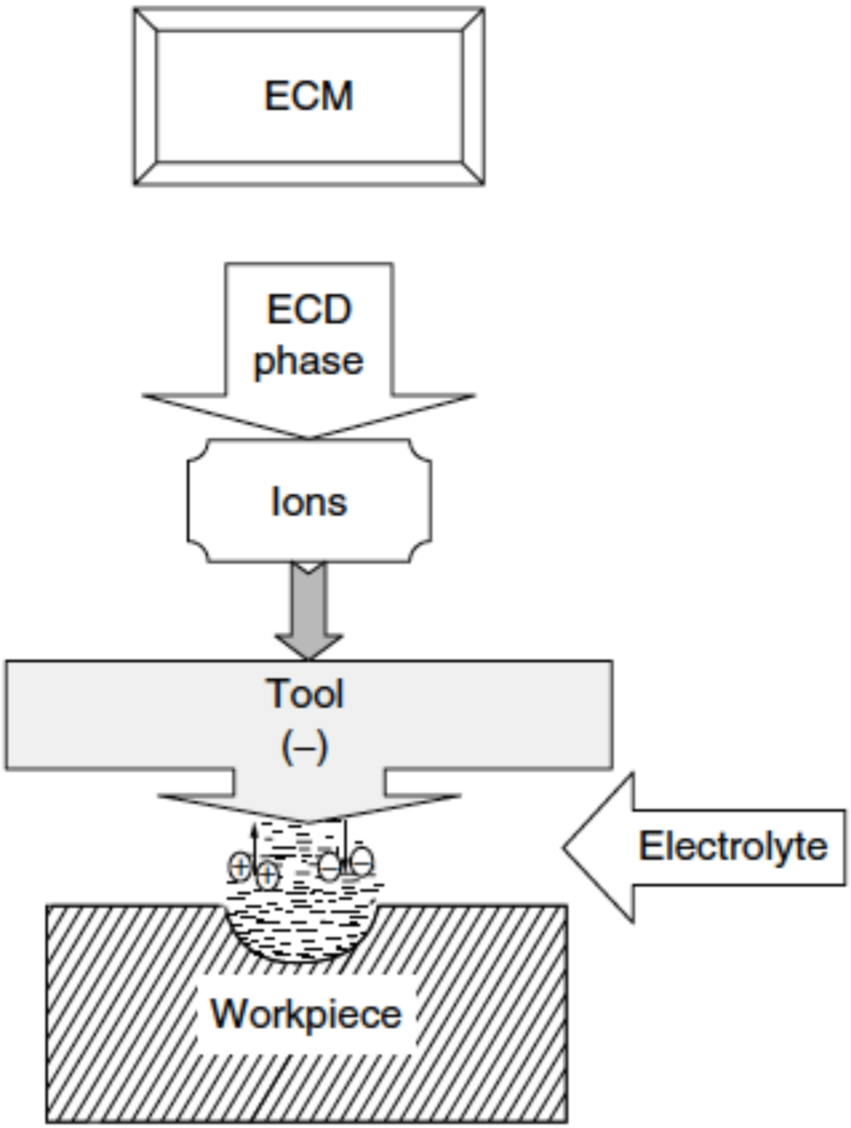
η=current efficiency, which typically ranges from 90-100%,

C is a material constant in mm^3/A·min.

Feed rate (mm/min): $f = MRR / A_0$

Assuming a cavity with uniform cross-sectional area A_0

Electrochemical Machining (ECM)

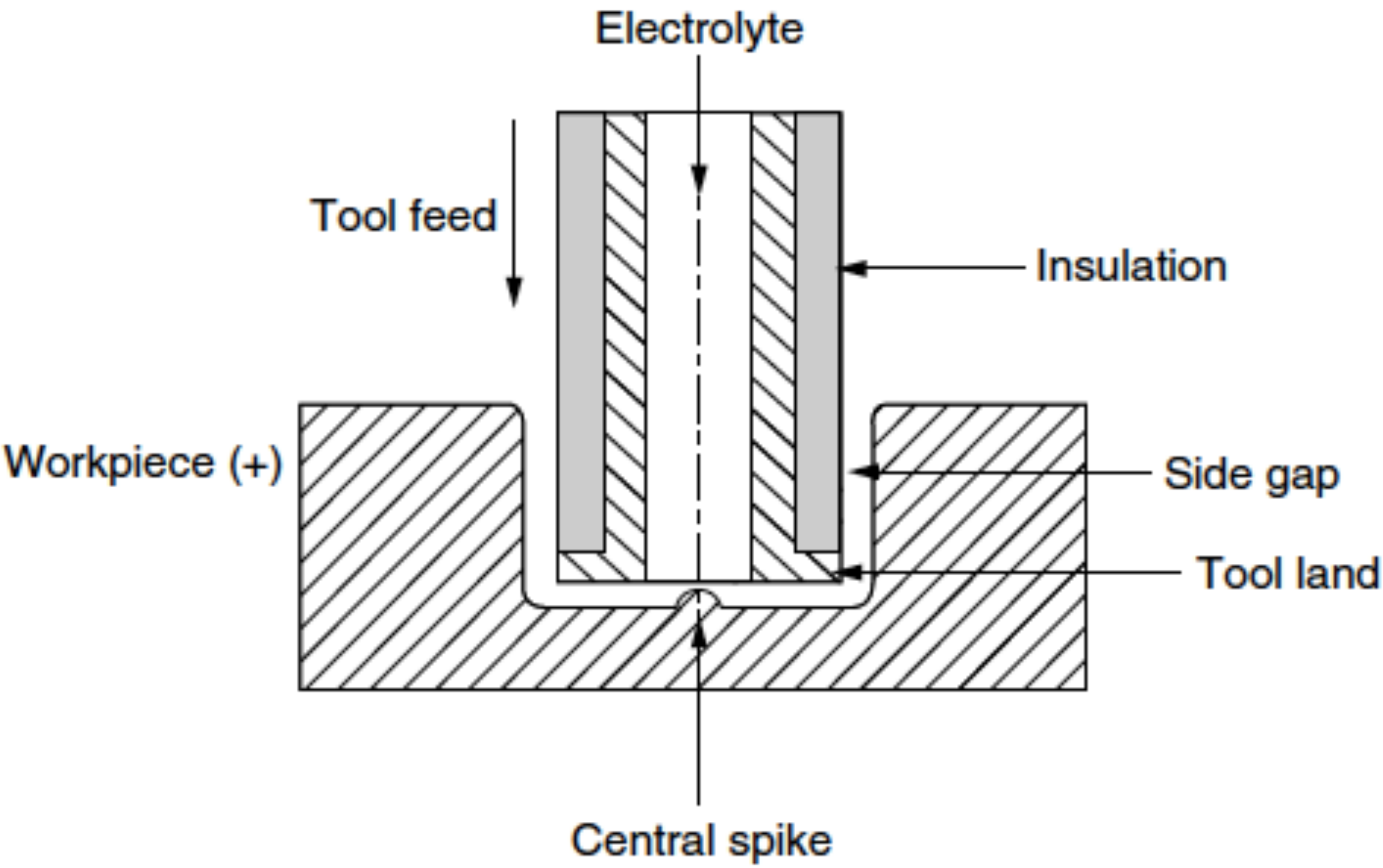


ECM process components

Electrochemical Machining (ECM)

- There is no wear in the tool because there is no contact between the tool and the workpiece.
- Machining is done at low voltages, compared to other processes, with high metal removal rates.
- Very small dimensions up to 0.05 mm can be controlled.
- Complicated profiles can be machined easily in a single operation.

Electrochemical Drilling (ECDR)



ECDR configuration

III. Thermal Energy Processes

- Very high local temperatures
  - Material is removed by fusion or vaporization
- Physical and metallurgical damage to the new work surface
- In some cases, resulting finish is so poor that subsequent processing is required

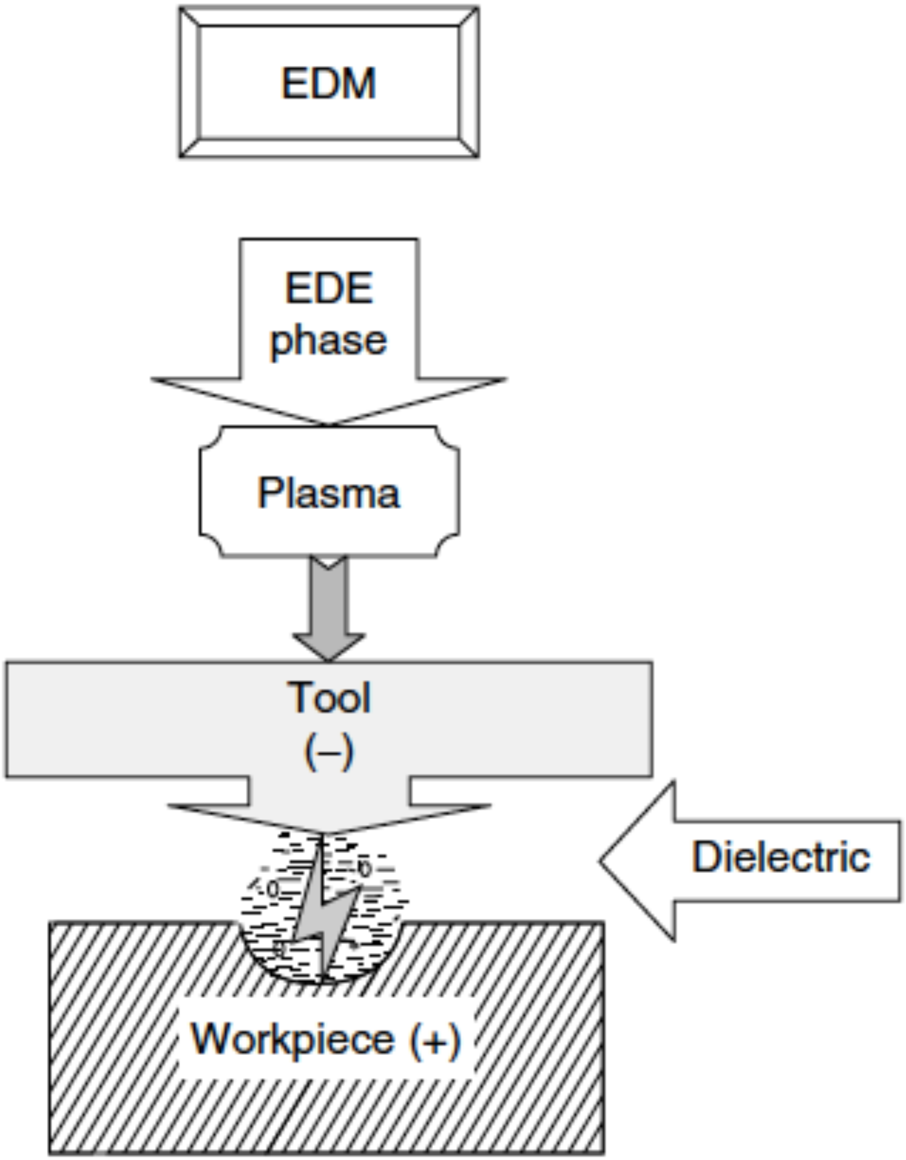
Thermal Energy Processes

- Electric discharge machining
- Electric discharge wire cutting
- Electron beam machining
- Laser beam machining
- Plasma arc machining

Electric Discharge Processes

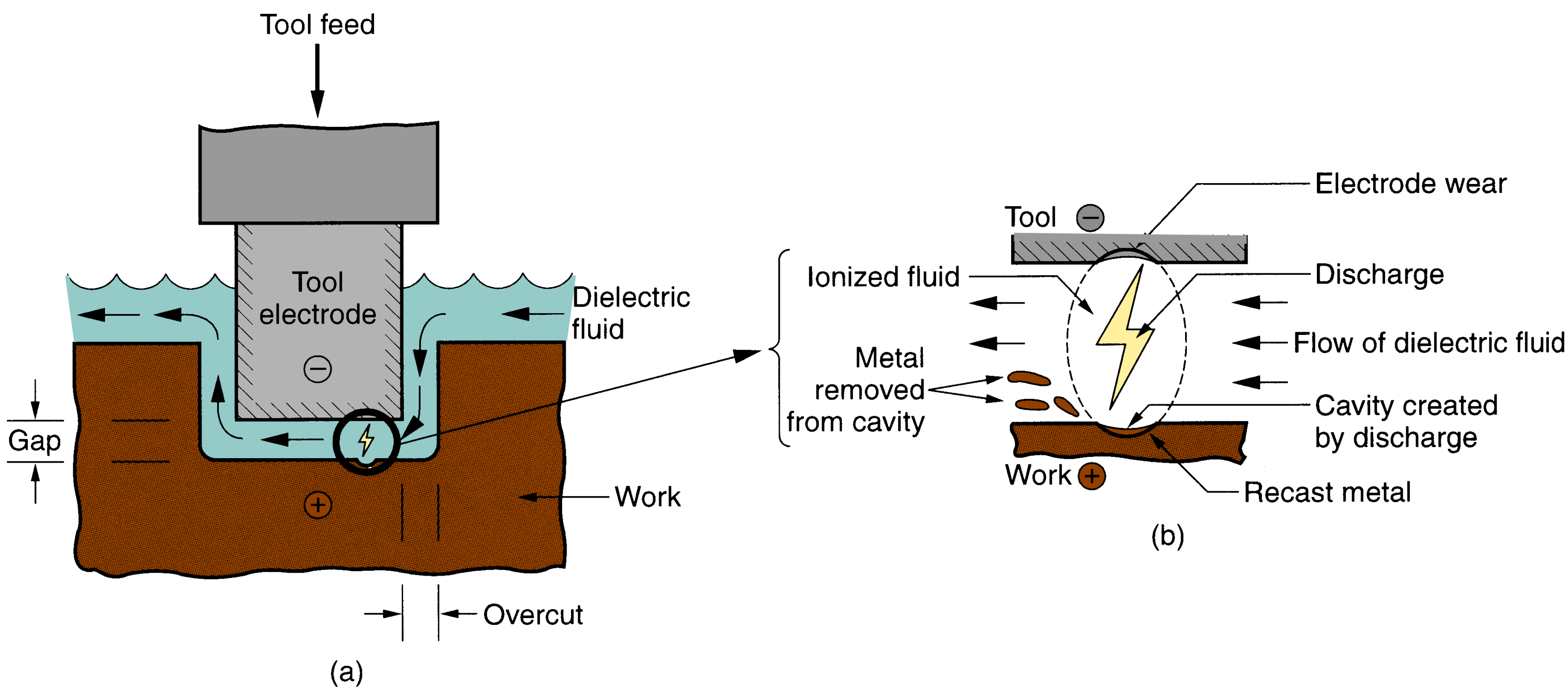
- In EDM, the removal of material is based upon the electro-discharge erosion (EDE) effect of electric sparks occurring between two electrodes that are separated by a dielectric liquid.
- Metal removal takes place as a result of the generation of extremely high temperatures generated by the high-intensity discharges that melt and evaporate the two electrodes.
- A series of voltage pulses of magnitude about 20 to 120 V and frequency on the order of 5 kHz is applied between the two electrodes, which are separated by a small gap, typically 0.01 to 0.5 mm.

Electric Discharge Processes



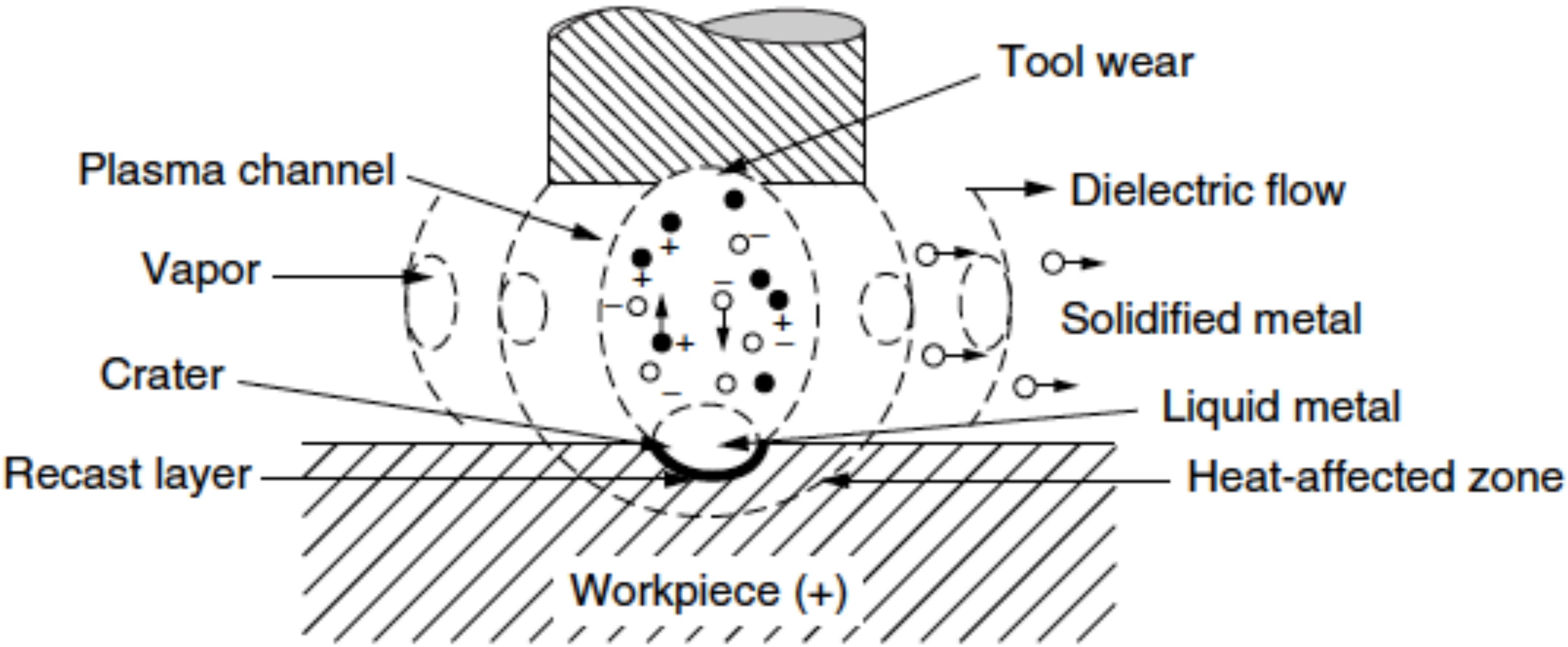
EDM components

Electric Discharge Machining (EDM)



EDM is a thermal erosion process whereby material is melted and vaporized from an electrically conducive workpiece immersed in a liquid dielectric with a series of spark discharges between the tool electrode and the workpiece created by a power supply.

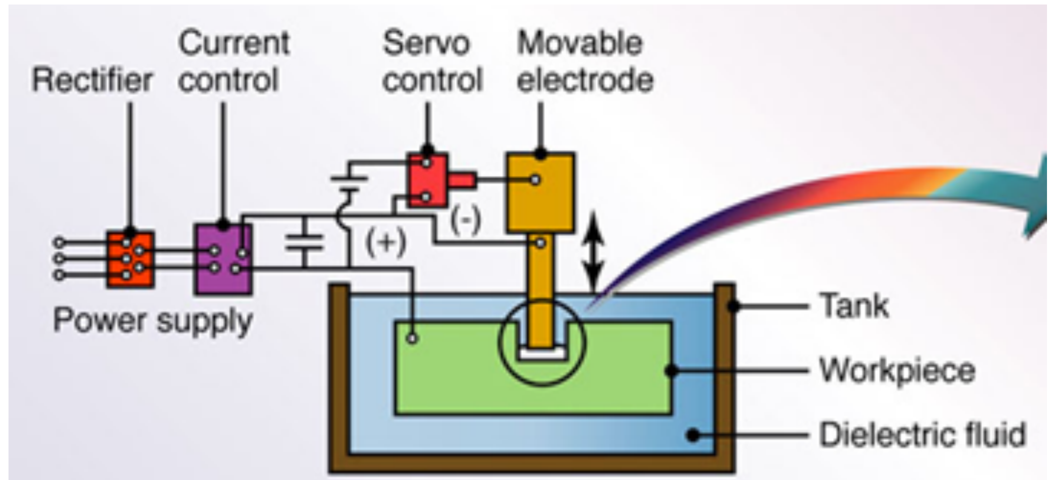
EDM machining



EDM spark description

Electric Discharge Machining (EDM)

The EDM system consists of a shaped tool or wire electrode, and the part. The part is connected to a power supply to create a potential difference between the workpiece and the tool. When the potential difference is sufficiently high, a transient spark discharges through the fluid, removing a very small amount of metal from the workpiece.



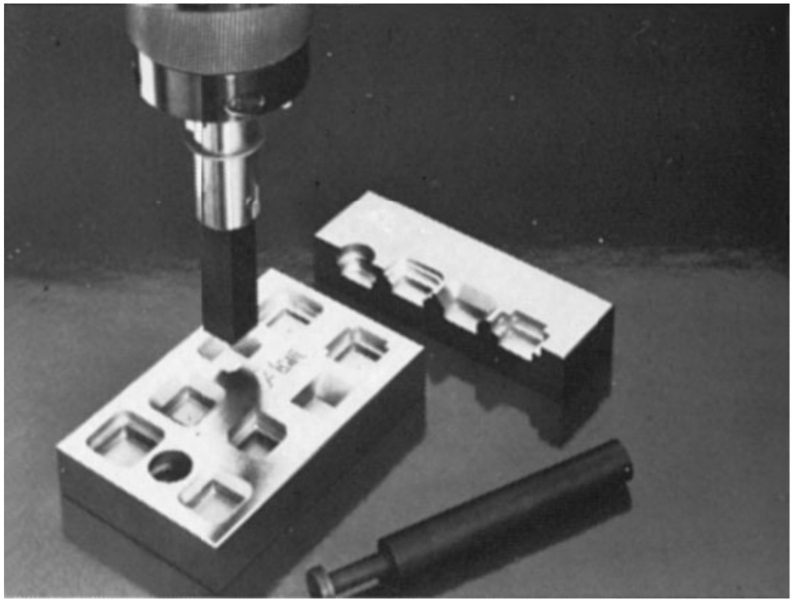
The dielectric fluid 1) acts as an insulator until the potential is sufficiently high, 2) acts as a flushing medium, and 3) provides a cooling medium.

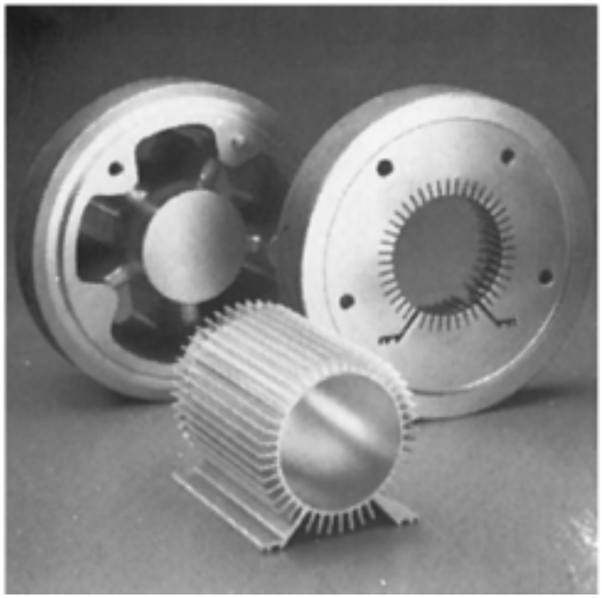
EDM process capabilities

- MRR
  - Range from 2 to 400 mm^3/min. High rates produce rough finish, having a molten and recast structure with poor surface integrity and low fatigue properties.
- Dimensional Tolerances
  - Function of the material being processed
  - Typically between $\pm$0.005 - $\pm$0.125 mm
- Surface Finish
  - Depends on current density and material being machined
  - R_a varies from 0.05 – 12.5 μm
  - New techniques use an oscillating electrode, providing very fine surface finishes.

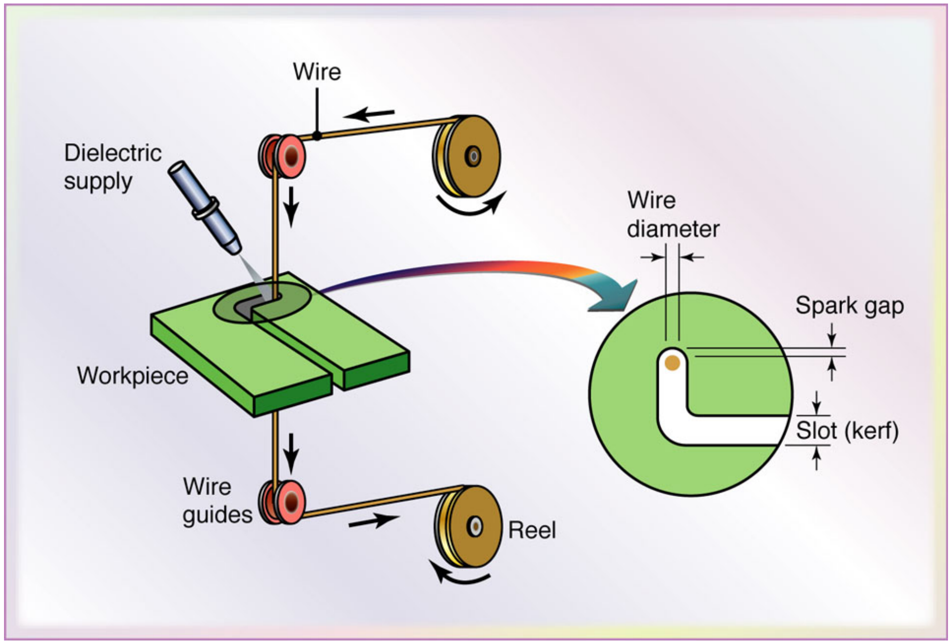
EDM Applications

- Tooling for many mechanical processes: molds for plastic injection molding, extrusion dies, wire drawing dies, forging and heading dies, and sheet metal stamping dies





Wire EDM



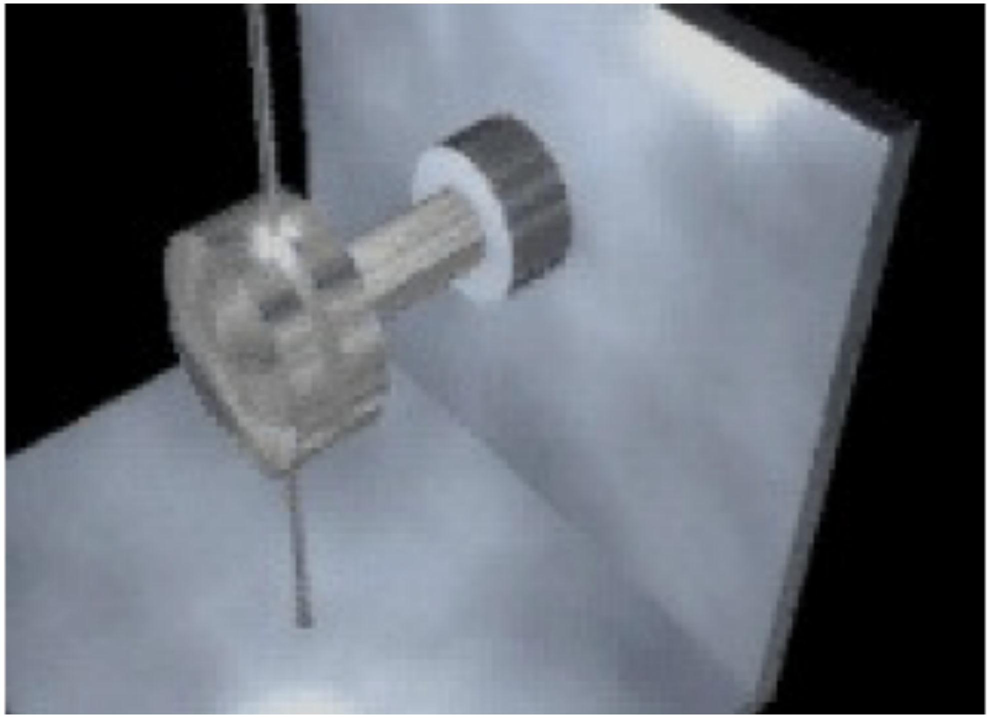
A wire travels along a prescribed path, cutting the workpiece, with the discharge sparks acting like cutting teeth.

Wire EDM

MRR in Wire EDM

$$MRR = V_f \, h \, b$$

$$where,\ b = d_w + 2s$$



MRR = mm³/min

V_f = feed rate of wire into the workpiece in mm/min

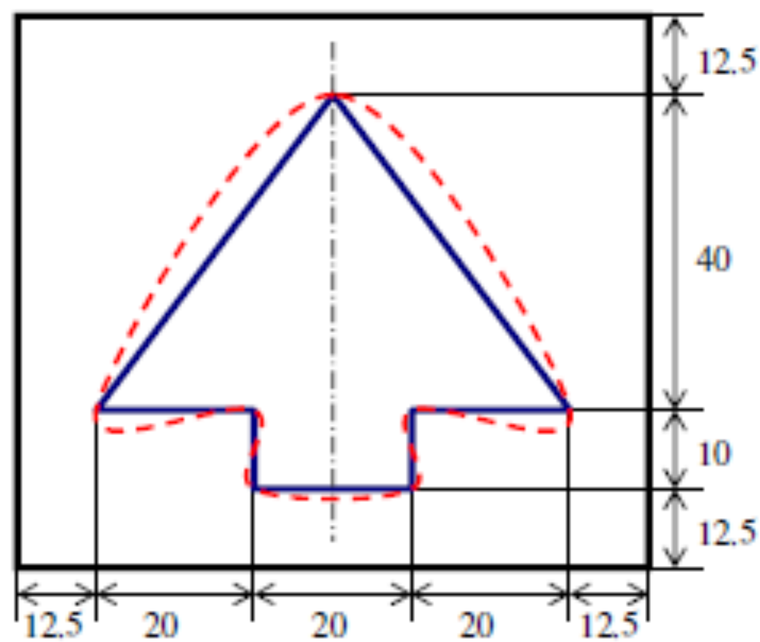
h = workpiece thickness

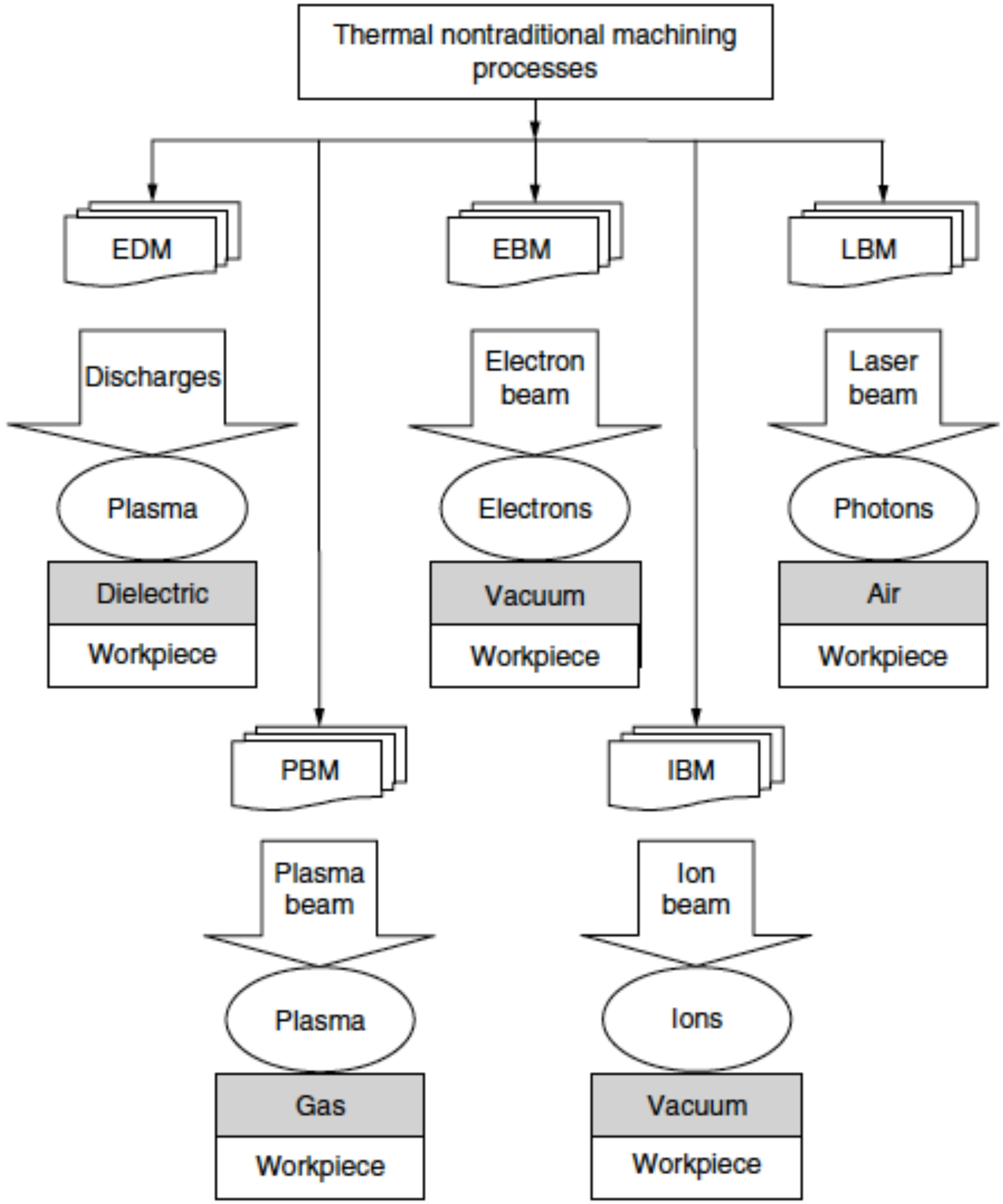
d_w = wire diameter in mm
s = gap between wire and workpiece in mm

Example

You have to machine the following part from a 85mmx75mmx20mm steel block. You have to choose between EDM and Conventional machining. Your objective is to minimize the cutting power required, which process will you choose?

Assumptions:
– EDM process:
• Wire diameter: d_w=0.2 mm
• Gap: s=0.1 mm
– Conventional machining:
• Negative of the part has to be removed

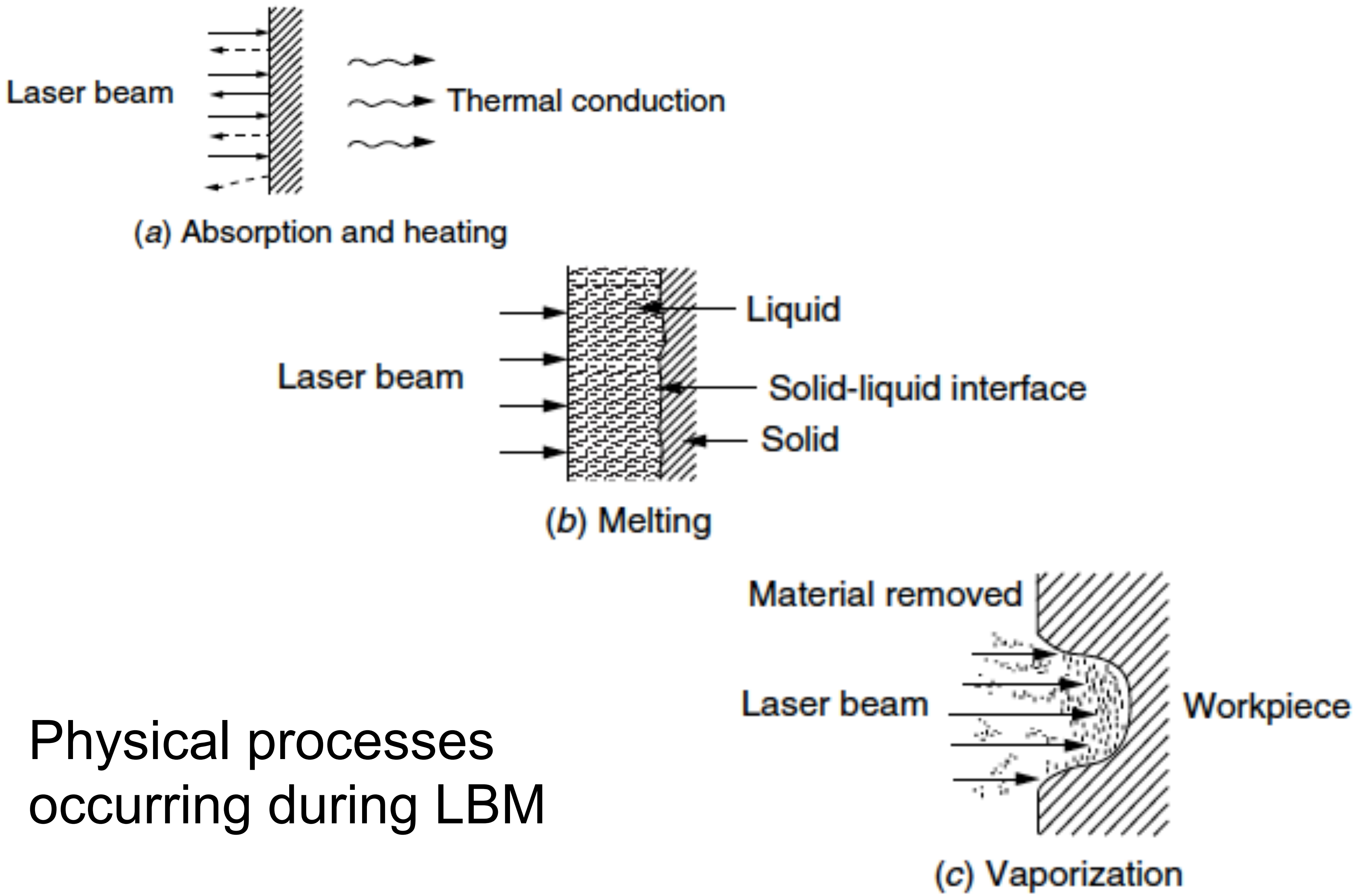



Thermal nontraditional machining processes
EDM
EBM
LBM
Discharges
Electron beam
Laser beam
Plasma
Electrons
Photons
Dielectric
Workpiece
Vacuum
Workpiece
Air
Workpiece
PBM
IBM
Plasma beam
Ion beam
Plasma
Ions
Gas
Workpiece
Vacuum
Workpiece

Laser Beam Machining (LBM)

- Modern machining methods are established to fabricate difficult-to-machine materials such as high-strength thermal-resistant alloys; various kinds of carbides, fiber-reinforced composite materials, Stellites, and ceramics.
- Laser beam machining (LBM) offers a good solution that is indeed more associated with material properties such as thermal conductivity and specific heat as well as melting and boiling temperatures.
- A highly collimated, monochromatic, and coherent light beam is generated and focused to a small spot. High power densities (10^6 W/mm^2) are then obtained.

Laser Beam Machining (LBM)



Physical processes occurring during LBM

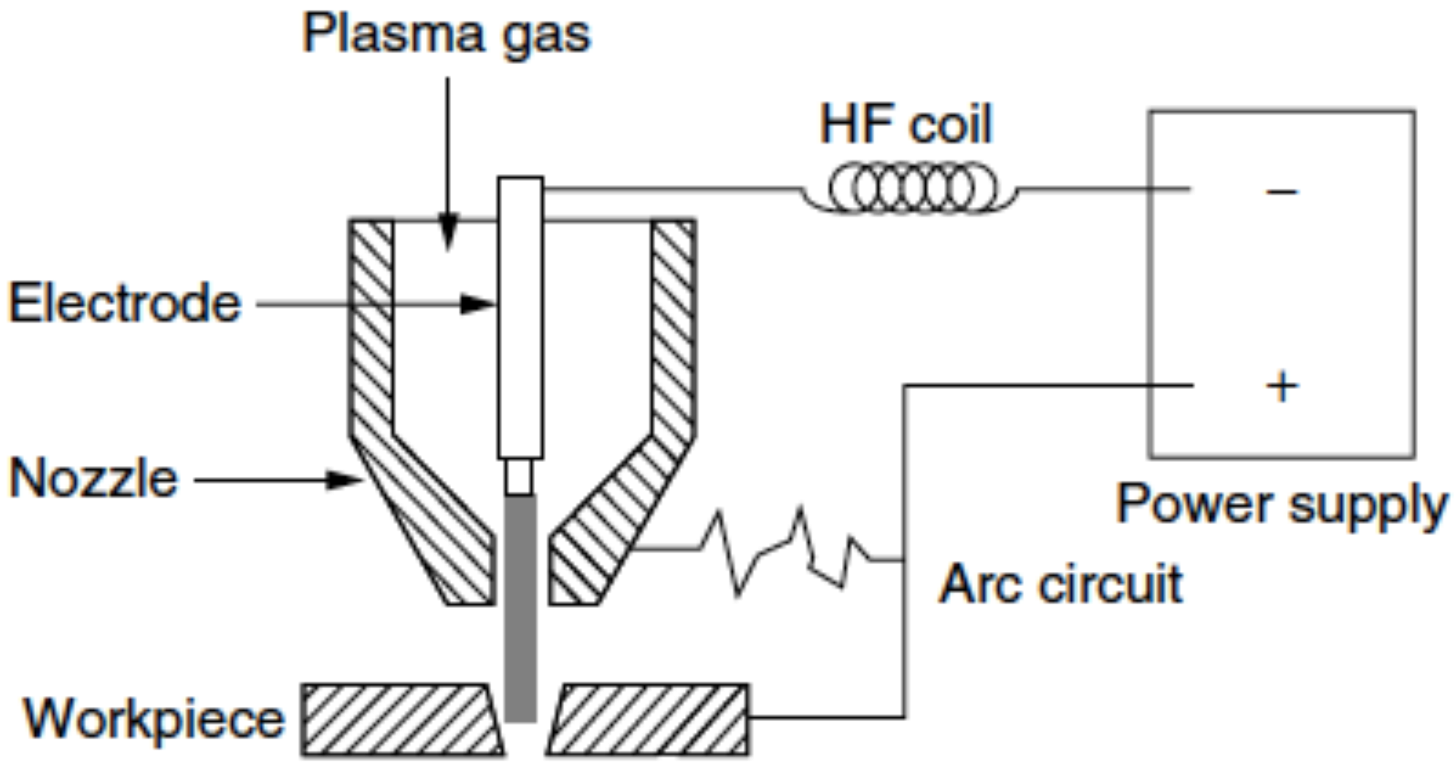
Plasma Beam Machining (PBM)

When the temperature of a gas is raised to about 2000°C, the gas molecules become dissociated into separate atoms. At higher temperatures, 30,000°C, these atoms become ionized. The gas in this stage is termed plasma.

Parameter	Level
Velocity of plasma jet	500 m/s
Material removal rate	150 cm^3/min
Specific energy	100 W/($cm^3 \cdot$ min)
Power range	2–200 kW
Voltage	30–250 V
Current	Up to 600 A
Machining speed	0.1–7.5 m/min
Maximum plate thickness	200 mm

Plasma Beam Machining (PBM)

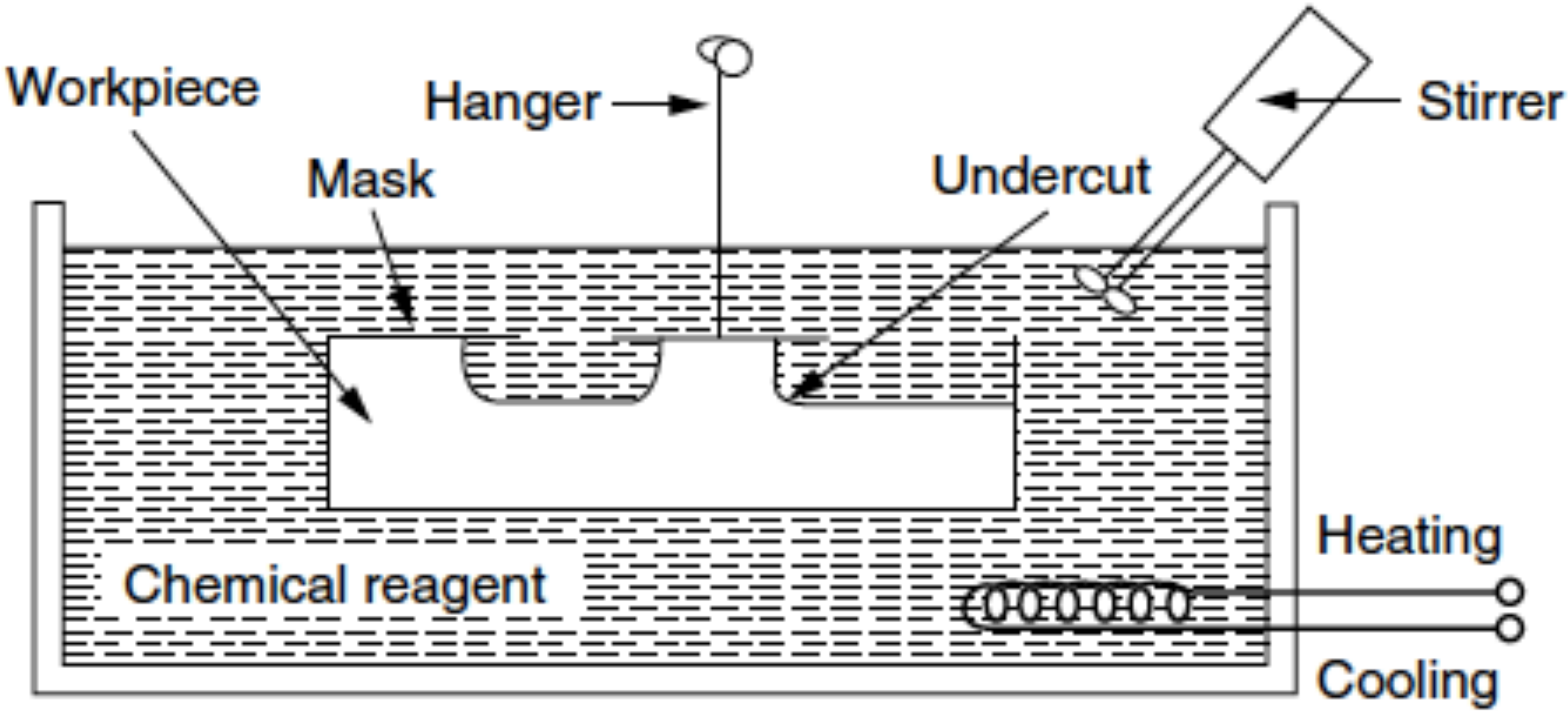
The temperature, in the narrow orifice around the cathode, reaches 28,000°C, which is enough to produce a high-temperature plasma arc. Under these conditions, the metal being machined is very rapidly melted and vaporized.



Chemical Machining (CHM)

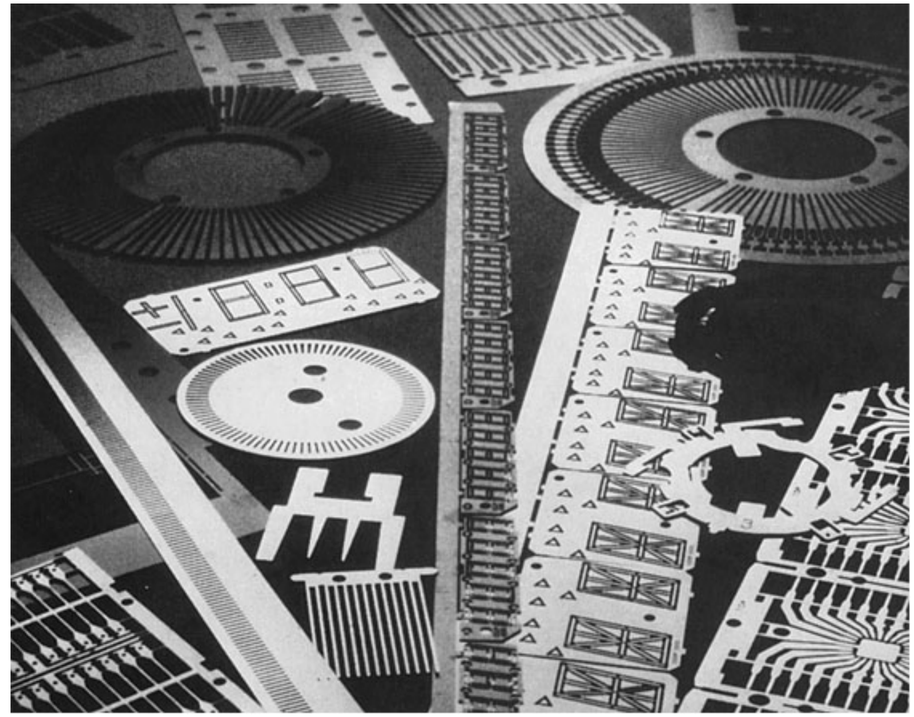
- Chemical machining, basically an etching process, is the oldest nontraditional machining process.
- Material is removed from a surface by chemical dissolution using chemical reagents, or etchants, such as acids and alkaline solutions.
- The workpiece is immersed in a bath containing an etchant. The area that is not required to be etched is masked with “cut and peel” tapes, paints, or polymeric materials.
- In chemical milling, shallow cavities are produced on plates, sheets, forgings, and extrusions for overall reduction of weight (e.g., in aerospace industry). Depths of removal can be as much as 12 mm.

Chemical Machining (CHM)



CHM setup

Chemical Machining (CHM)



- Typical applications

– Chemical blanking: burr-free etching of printed-circuit boards (PCB), decorative panels, thin sheet-metal stampings, and the production of complex or small shapes.

– Chemical milling: weight reduction of space launch vehicles.

Pros: low setup, maintenance, and tooling costs; small, delicate parts can be machined; suitable for low production runs on intricate designs.

Cons: slow (0.025-0.1 mm/min); surface defects; chemicals can be extremely dangerous to health.

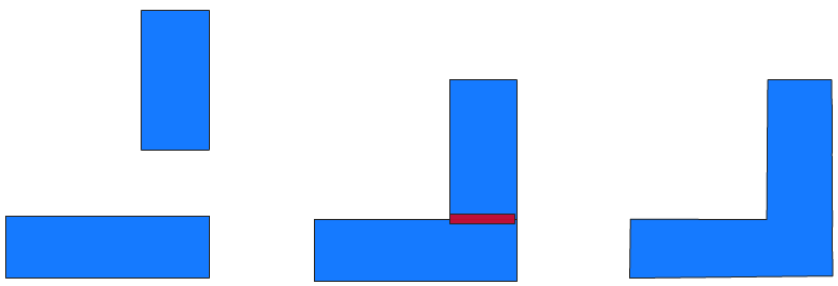
ME2300: Manufacturing Processes
Jan-May 2020

Shaping by joining (Introduction)

Introduction

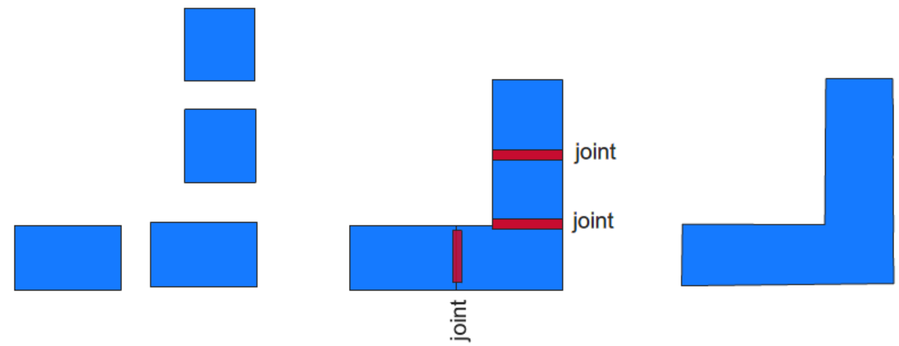
Raw material

Final shape



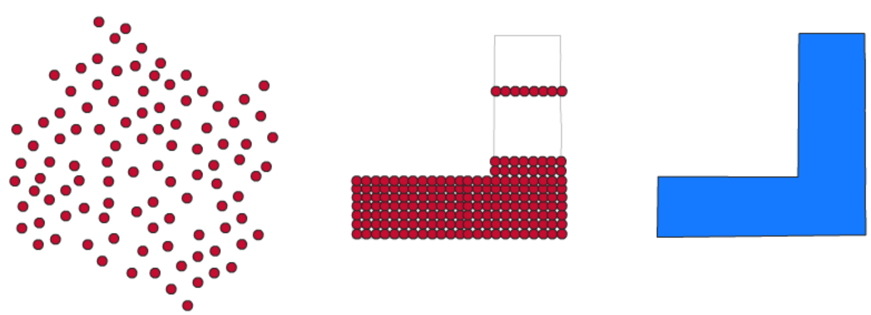
Raw material

Final shape



Raw material

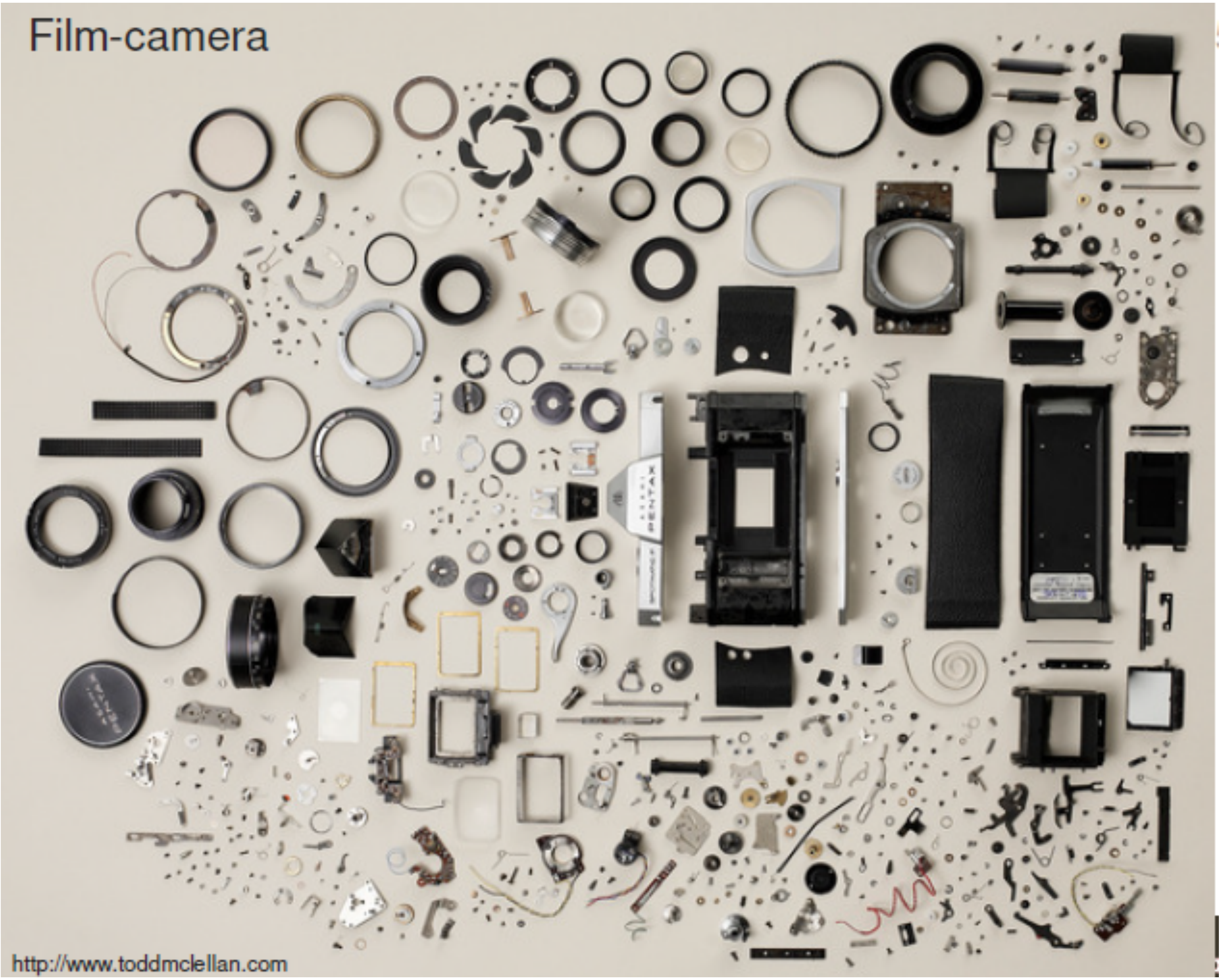
Final shape



Can we think of some single component product

Products are usually made up of multiple parts

Products are usually made up of multiple parts



Joining finite shapes

• Make finite shapes separately using primary manufacturing methods (phase change, deformation, mass change etc.) and then join them

• Why do this? Can we not make one comprehensive shape?

– Many times different materials are needed for different functions and applications in the same product

– It may not be possible to make an integral big complex shape

• Joining or assembly of finite shapes may be done

– To completely arrest movement of the joined parts - e.g in all 6 degrees of freedom (DoF)

– To arrest movement in only some DoF while permitting motion in others

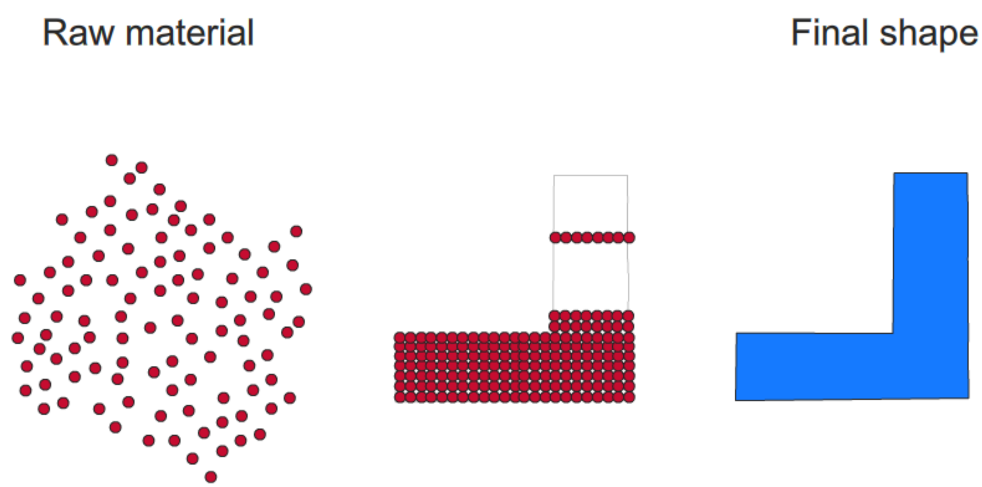
-Material specific functions

Joining powders

- Powders are tiny (could be mm or μm) random shaped particles
- There are two problems to solve here:

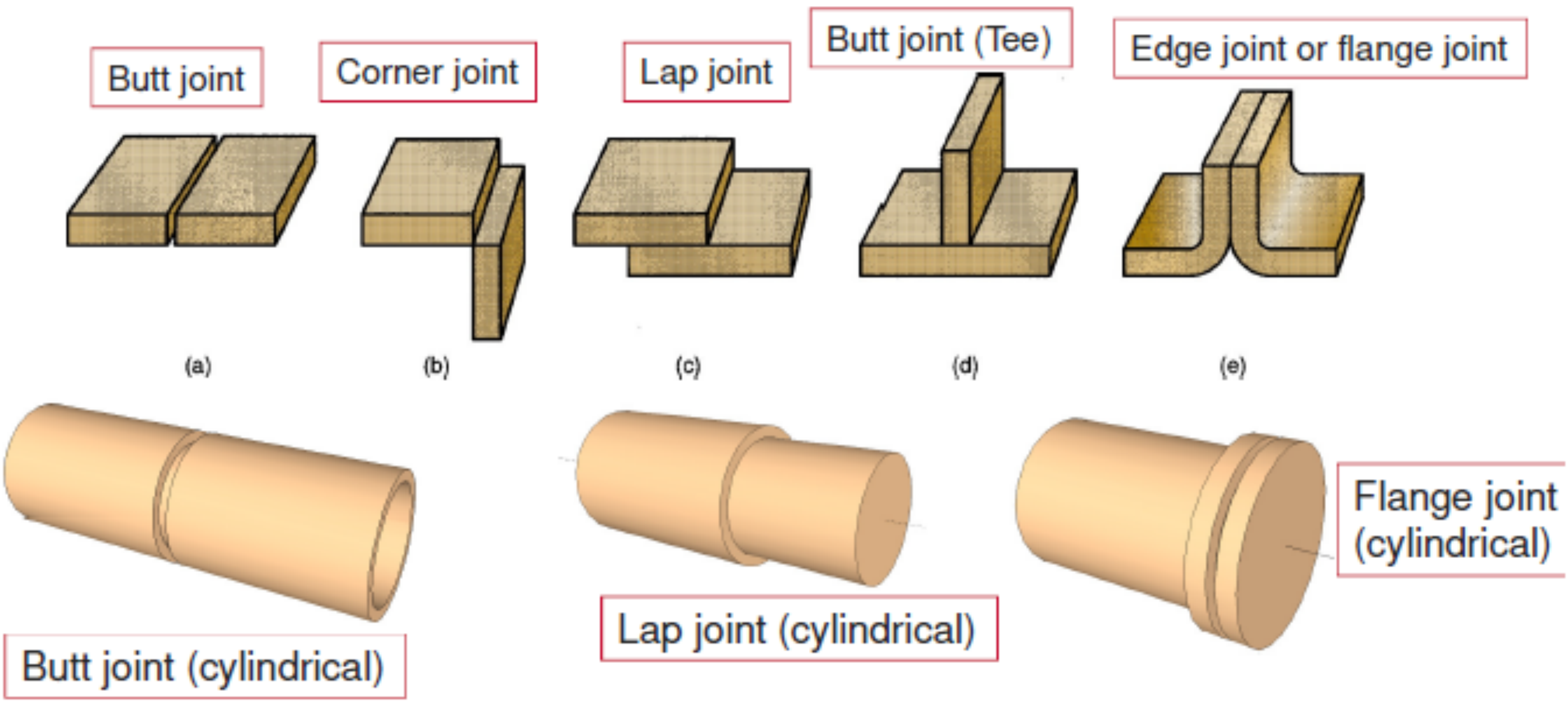
– How to join such teeny-tiny powders together strongly ?

– How to form a macro-sized geometrical shape from such numerous joined powders?



Where to join?

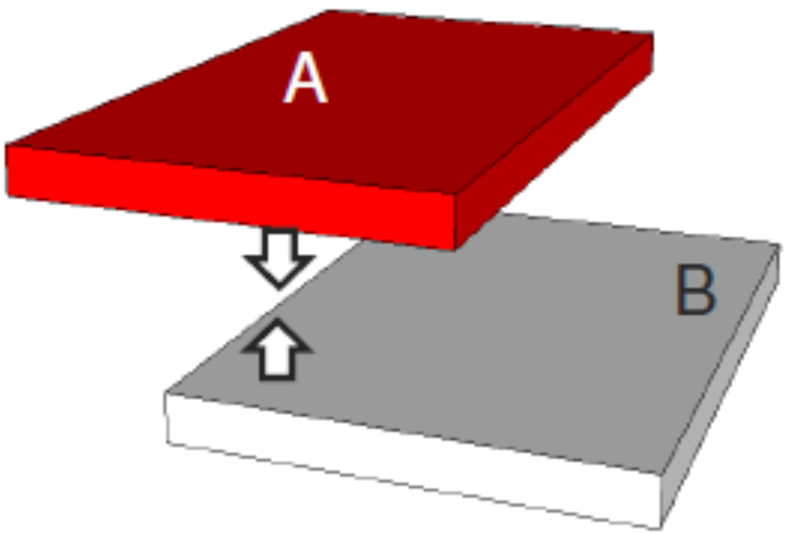
• Two conforming surfaces have to be brought together to effect a joint – many possible joint configurations

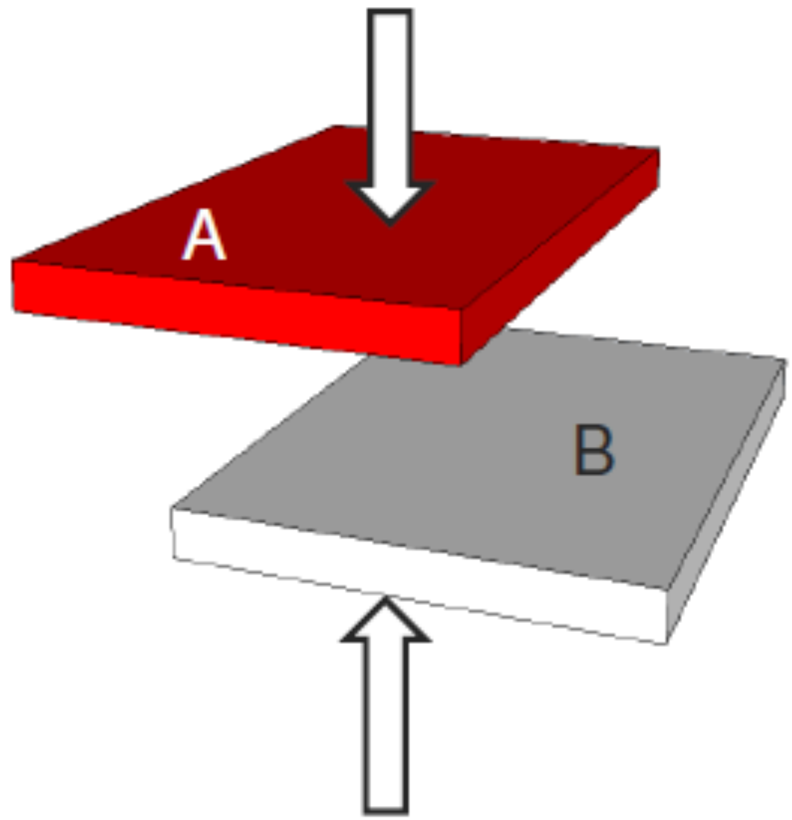


Forces needed to bring and keep two surface together

We have two choices of forces to bring and hold the surface together

We can supply forces from outside



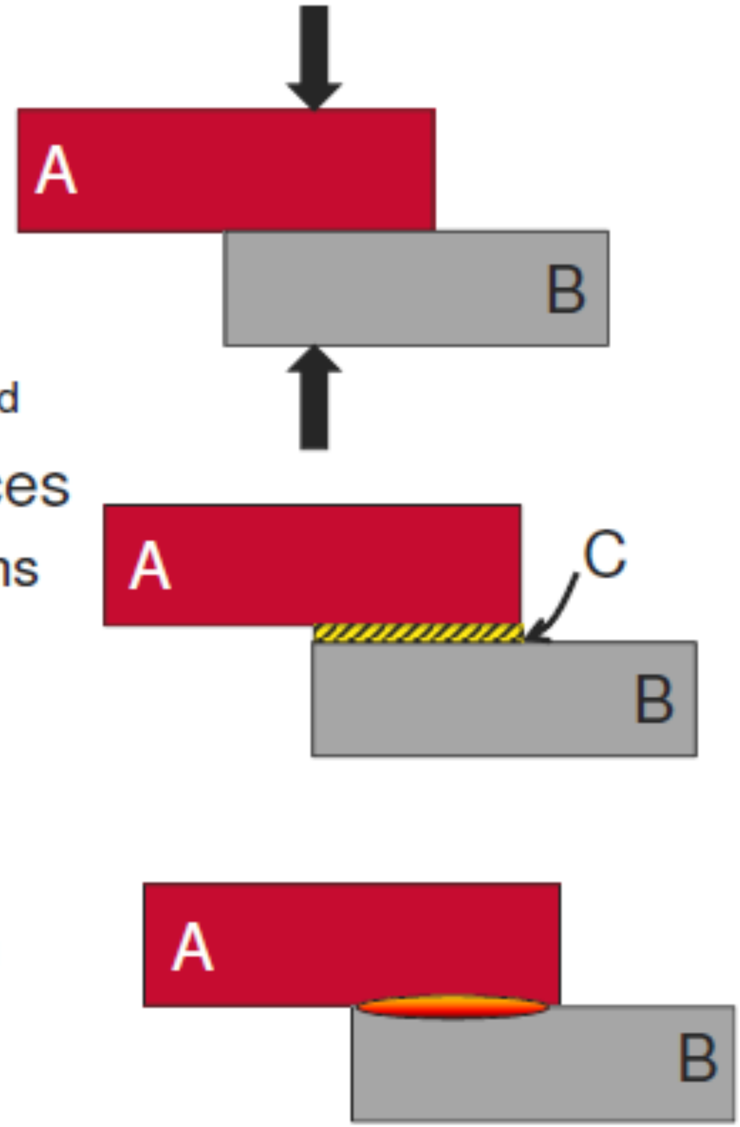


We can induce forces in the inside (within the surfaces)

Basically three ways to join materials

Need to join 2 parts 'A' and 'B':

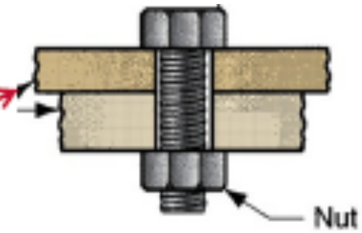
- Use mechanical forces from outside
  - E.g. tie the two parts with a string!
  - E.g use bolts
- Use surface forces – provided by a 3rd material 'C' in between the two surfaces
  - A joins to C and C holds on to B; so A joins to B!
  - E.g. adhesive, soldering, brazing
- Use molecular forces
  - Locally (near the surfaces) "mix" material from the 2 objects; they then hold to each other using inter-molecular forces
  - E.g. welding

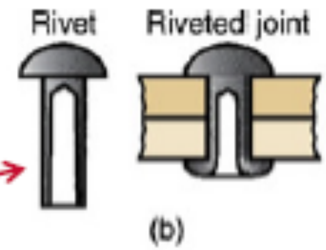


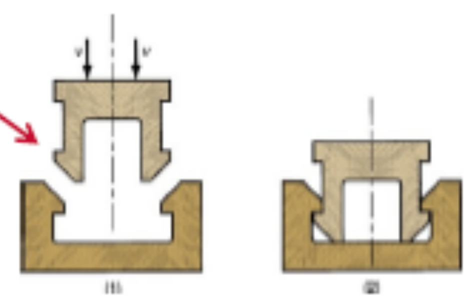
Joining mechanical forces

Mechanical force can be provided by interlocking (physical obstructions). Many interlocking methods are available:

- A: Using threads
- B: Using plastic deformation (e.g. rivets)
- C: Using protrusions (snap fit)
- D: Using microscopic surface interlocks - friction (e.g. shrink fit)



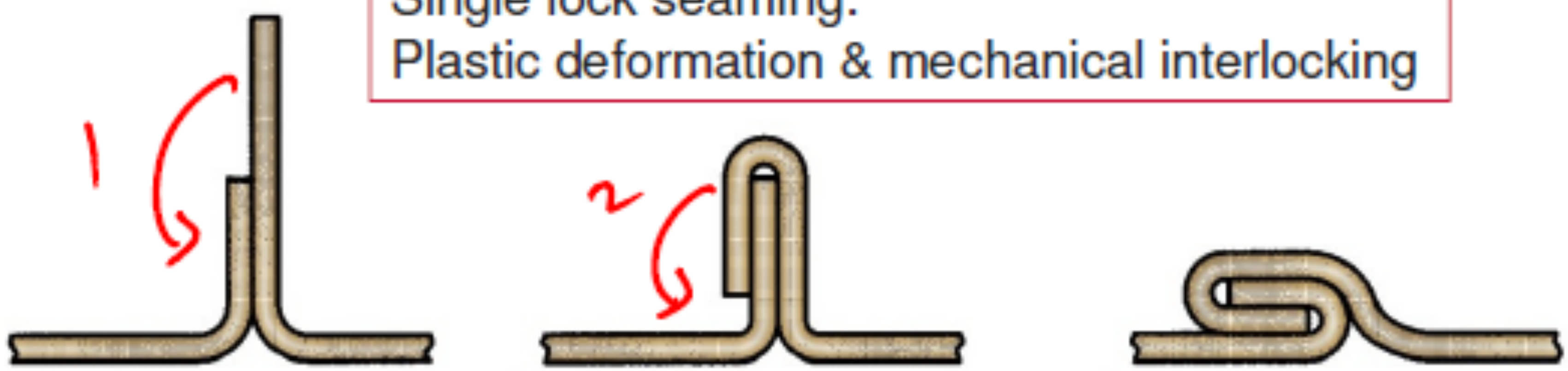




Joining (Plastic deformation)

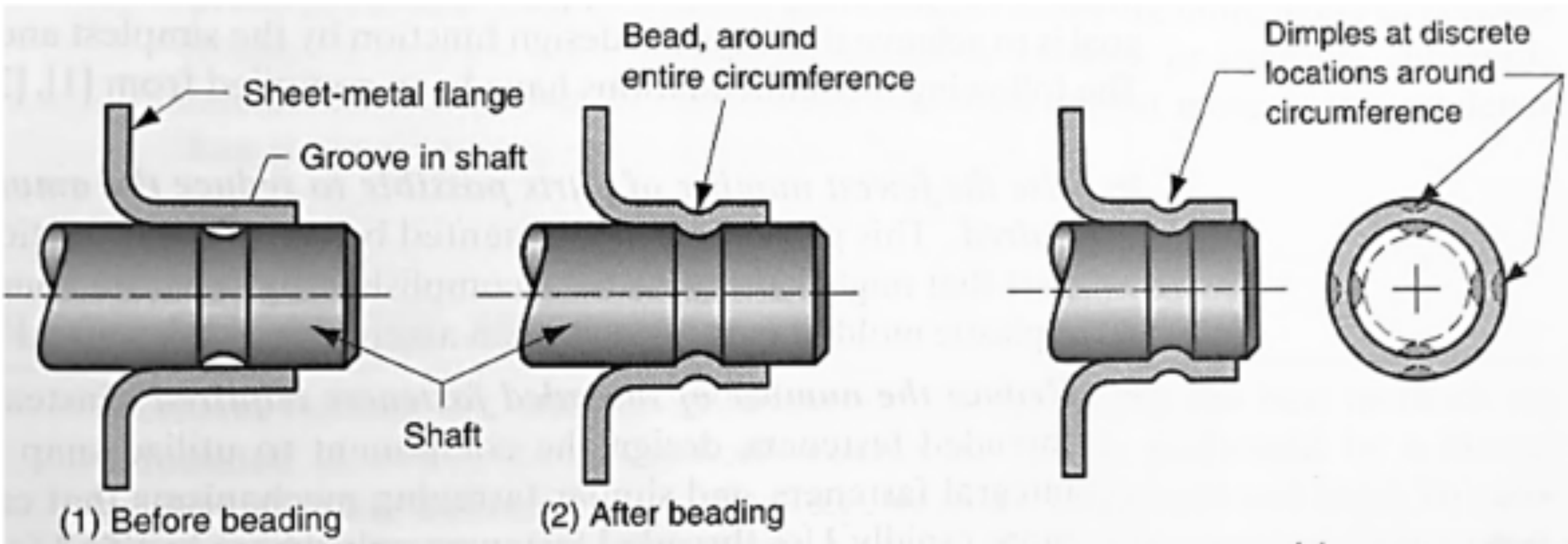
- Combination of the several mechanical forces can also be used to create a rigid joint

Single lock seaming:
Plastic deformation & mechanical interlocking



(1) Bent edges on two parts (2) One edge bent over other (3) Seam is bent down and flattened.

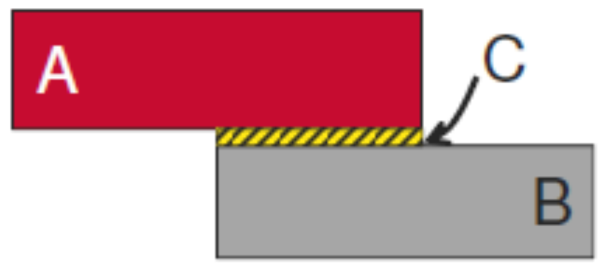
Joining (Plastic deformation)



Joining using surface forces

• Using surface force – provided by a 3rd material ‘C’ in between the two surfaces – A joins to C and C holds on to B; so A is joined to B!

• Different types of materials available for ‘C’ to create the joint. ‘C’ can be:
– (i): Polymers (adhesive joint)
– (ii): Metallic alloys
• (iii): High-temperature melting alloys (brazing)
• (iv): Low-temperature melting alloys (soldering)



Material "C"

- Adhesive or glue
- Many types
  - Natural
- Starch, soya flour
  - Inorganic
- Sodium Silicate, Magnesium Oxychloride
  - Synthetic
- Most popular
- See table

Adhesive	Description and Applications
Anaerobic	Single-component, thermosetting, acrylic-based. Cures by free radical mechanism at room temperature. Applications: sealant, structural assembly.
Modified acrylics	Two-component thermoset, consisting of acrylic-based resin and initiator/hardener. Cures at room temperature after mixing. Applications: fiberglass in boats, sheet metal in cars and aircraft.
Cyanoacrylate	Single-component, thermosetting, acrylic-based that cures at room temperature on alkaline surfaces. Applications: rubber to plastic, electronic components on circuit boards, plastic and metal cosmetic cases.
Epoxy	Includes a variety of widely used adhesives formulated from epoxy resins, curing agents, and filler/modifiers that harden upon mixing. Some are cured when heated. Applications: aluminum bonding applications and honeycomb panels for aircraft, sheet-metal reinforcements for cars, lamination of wooden beams, seals in electronics.
Hot melt	Single-component, thermoplastic adhesive hardens from molten state after cooling from elevated temperatures. Formulated from thermoplastic polymers including ethylene vinyl acetate, polyethylene, styrene block copolymer, butyl rubber, polyamide, polyurethane, and polyester. Applications: packaging (e.g., cartons, labels), furniture, footwear, bookbinding, carpeting, and assemblies in appliances and cars.
Pressure-sensitive tapes and films	Usually one component in solid form that possesses high tackiness resulting in bonding when pressure is applied. Formed from various polymers of high molecular weight. Can be single-sided or double-sided. Applications: solar panels, electronic assemblies, plastics to wood and metals.
Silicone	One or two components, thermosetting liquid, based on silicon polymers. Curing by room-temperature vulcanization to rubbery solid. Applications: seals in cars (e.g., windshields), electronic seals and insulation, gaskets, bonding of plastics.
Urethane	One or two components, thermosetting, based on urethane polymers. Applications: bonding of fiberglass and plastics.

Adhesive joints: surface preparation

Surface preparation is important.

For adhesive bonding to succeed, part surfaces must be extremely clean

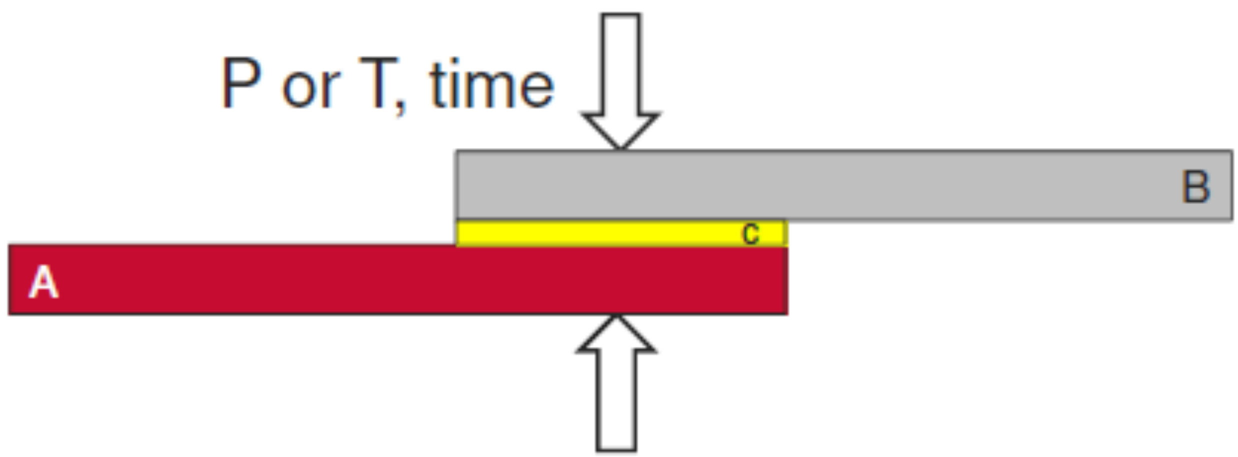
Bond strength depends on adhesion between adhesive (C) and adhered (A or B), which depends on clean surfaces

For metals, solvent wiping often used for cleaning, and sandblasting improves surface adhesion

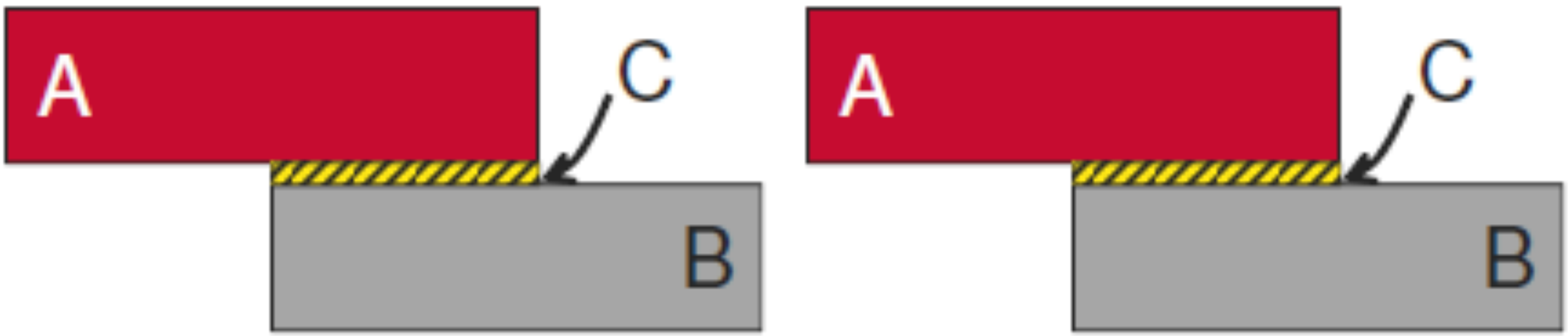
For non-metallic parts, surfaces can be mechanically abraded or chemically etched to increase roughness

Adhesive joints (curing)

- Process by which physical properties of the adhesive are changed from liquid to solid, usually by chemical reaction, to accomplish surface attachment of parts
  - Curing often aided by heat and/or a catalyst
    - If heat is used, temperatures are relatively low
  - Curing takes time - a disadvantage in production
  - Pressure sometimes applied between parts to activate bonding process



Adhesion vs. cohesion



Adhesion vs. cohesion

Cohesion (welding): The joining of two or more pieces of material by means of heat, pressure, or both, with or without a filler metal, to produce bonding through fusion or recrystallization. The force of attraction in the bond is primarily cohesion. A few of the cohesion processes are arc welding, laser welding, diffusion bonding, and forge welding.

Adhesion (gluing): The joining of two or more pieces of material by the forces of attraction between the adhesive and the materials being joined (adherends). Gluing processes depend primarily upon adhesive bonding. It includes processes such as brazing, soldering, and epoxy bonding.

Adhesive joints advantages

- Applicable to a wide variety of materials
- Bonding occurs over entire surface area of joint
- Low temperature curing avoids damage to parts being joined
- Can be used for sealing as well as bonding
- Joint design is often simplified, e.g., two flat surfaces can be joined without providing special part features such as screw holes

Material ‘C’ is a high-melting metallic alloy - BRAZING

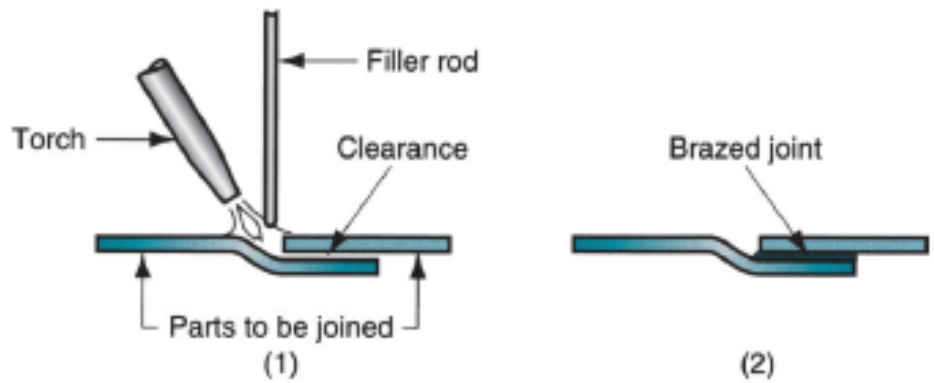
- Process is called Brazing
- Material ‘C’ is also called “filler metal”
- Filler metal has a melting point (liquidus temp) more than 450°C – but smaller than that of A or B

  (why 450 - it is rather arbitrary)
- ‘A’ and ‘B’ themselves do not melt
- Dissimilar metals can be joined using this method
- Joint is typically stronger than the strength of ‘C’ itself

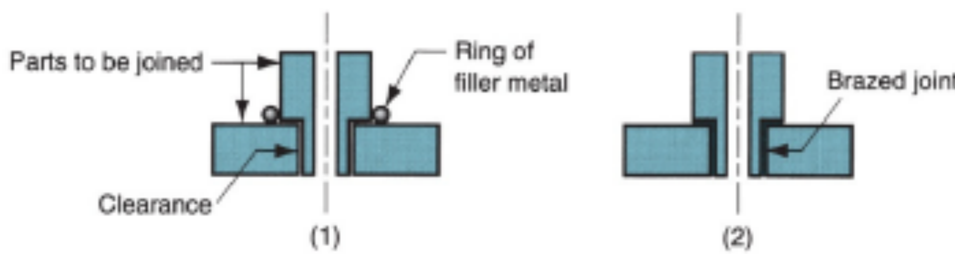
Filler material BRAZING	Melting temp
Al & Si	600 °C
Cu & P	850 °C
Ag, Cu, Zn Cd	730 °C
Cu and Zn	925 °C
Au and Ag	950 °C
Ni, Cr, etc	1120 °C

Brazing

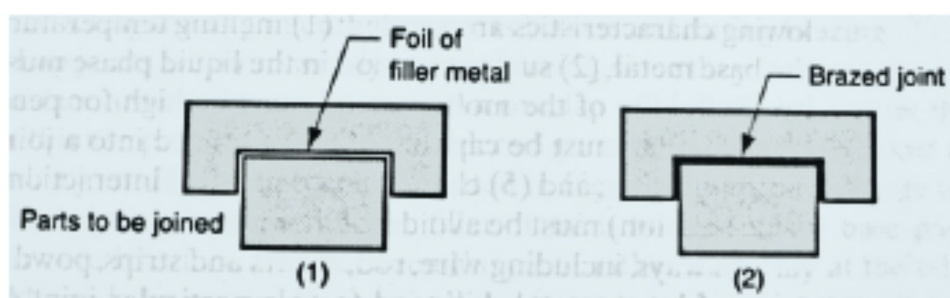
- ‘C’ can be in the form of powder/paste, solid bulk form (wire, rod, sheet/foil, preformed shape)
- Heat sources (to melt ‘C’):
  – Torch (flame)
  – Furnace
  – Induction heating
  – Resistance heating
  – Dip in molten salt or molten metal bath
  – Infrared heating
- “Flux” material is added to the joint during melting to prevent oxidation of the molten metal



(a)

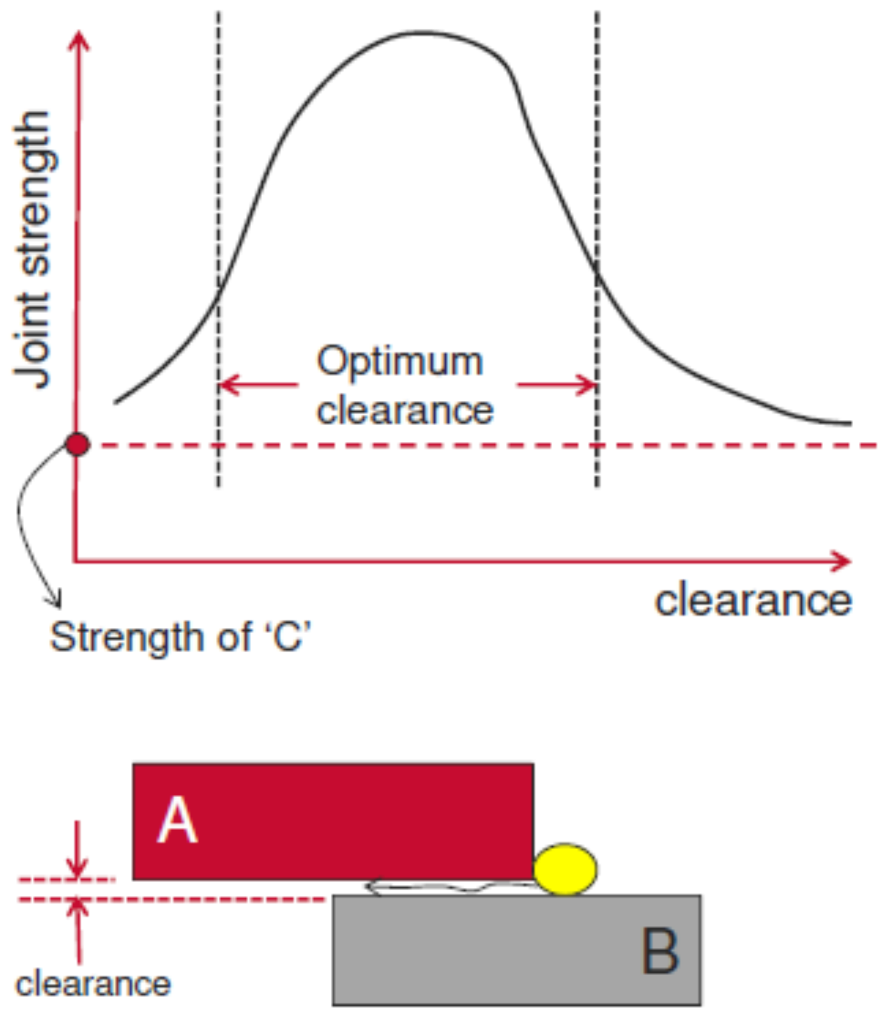


(b)



Brazing: clearance and capillary action

- 'C' melts and flows into the joint by capillary action in the thin clearance area between 'A' and 'B'
- If clearance is too small – 'C' cannot flow into joint area
- If clearance is too large – capillary action will fail and result in a poor joint
- Typical clearance ranges from 0.025 mm to 0.25 mm
- Surfaces must be cleaned properly to promote wetting and capillary attraction



Material ‘C’ is a low-melting metallic alloy - SOLDERING

- Process is called Soldering
- Material ‘C’ is also called “filler metal”
- Filler metal has a melting point (liquidus temp) less than 450°C – and smaller than that of ‘A’ or ‘B’
- Otherwise the process is similar to brazing.
- So, again ‘A’ and ‘B’ do not melt
- ‘A’ and ‘B’ surfaces are kept apart at a small clearance; material ‘C’ is placed near this clearance and melted; it flows into the clearance to form a joint
- Flux is also needed here

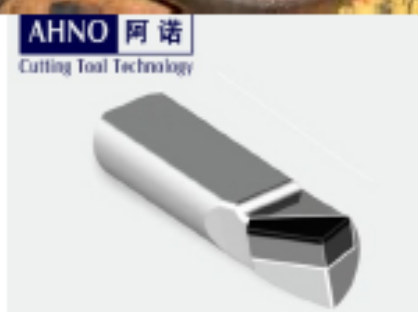
Filler material SOLDERING	Melting temp
Lead-Silver	305 °C
Tin-Antimony	238 °C
Tin-Lead	183-207 °C
Tin-Silver	221 °C
Tin-Zinc	199 °C
Tin-Silver-Copper	217 °C

Brazing/soldering applications

Brazing

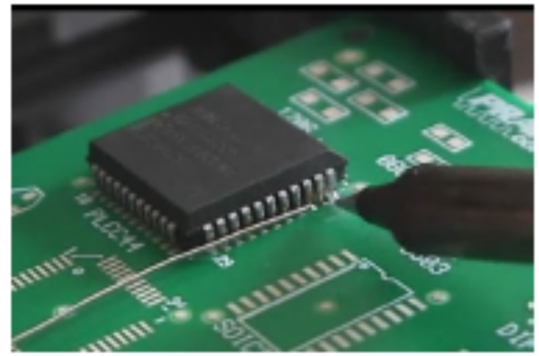
jewelry

pipes

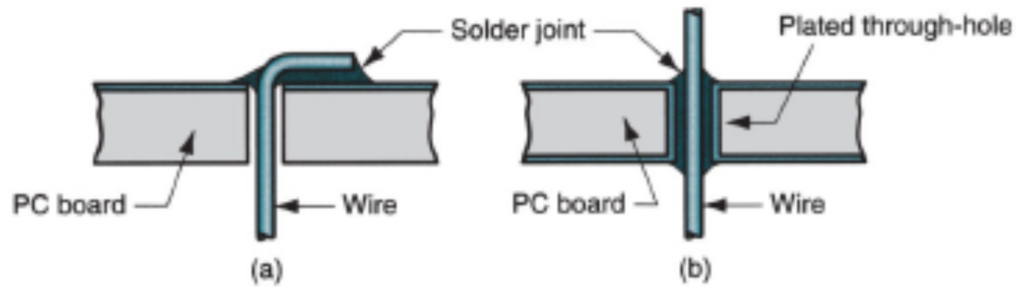


cutting tools

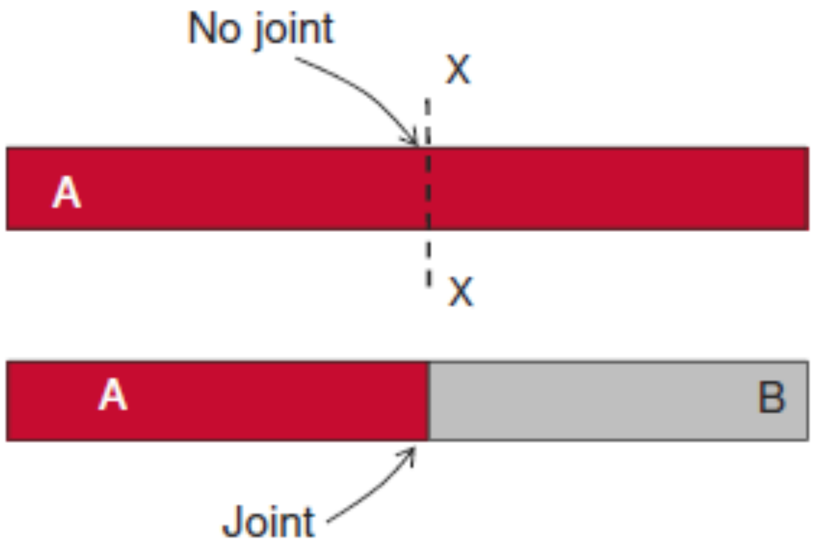
Soldering



electronics



Joining by direct molecular forces



What holds the material that is on either side of the imaginary section X-X?

How can we get similar forces to develop at the joint surfaces between A and B?

- One way to join these two surfaces is by creating atomic bonds directly between A and B without introducing any 3rd material in between
- How to do this? (assume A and B are similar materials)
- There are two ways to do this
  - In the solid state
  - By going into the liquid state

Welding process

Welding is a process in which materials of the same fundamental type or class are brought together and cause to join by heating them to the melting temperature with or without the application of pressure and filler metal.

Welding processes based on state of base material

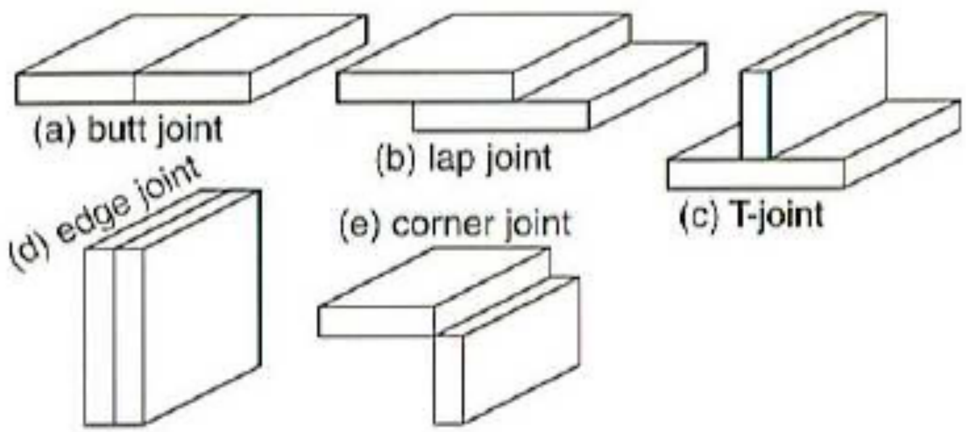
Liquid state welding (Fusion welding)

- Oxyacetylene welding
- Arc welding
- Resistance welding

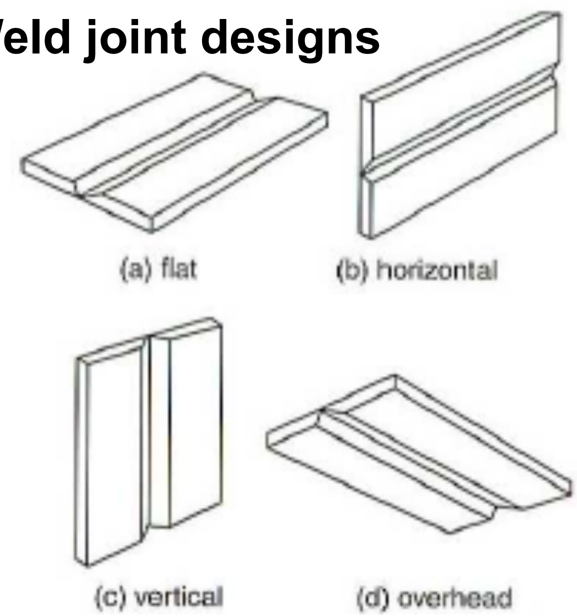
Solid state welding

- Diffusion welding
- Friction welding

Types of joints and welding positions

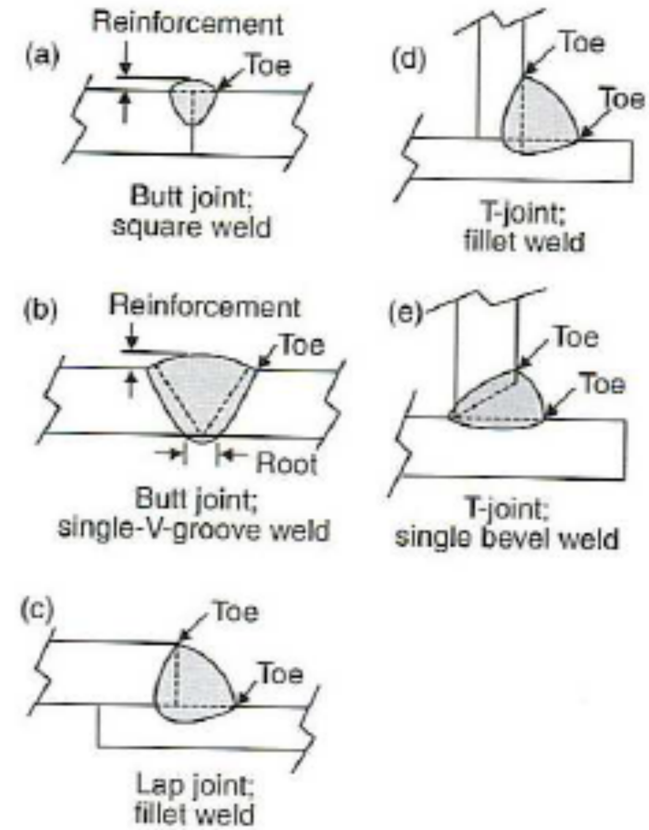


Weld joint designs



Welding positions

Weld-joint variations



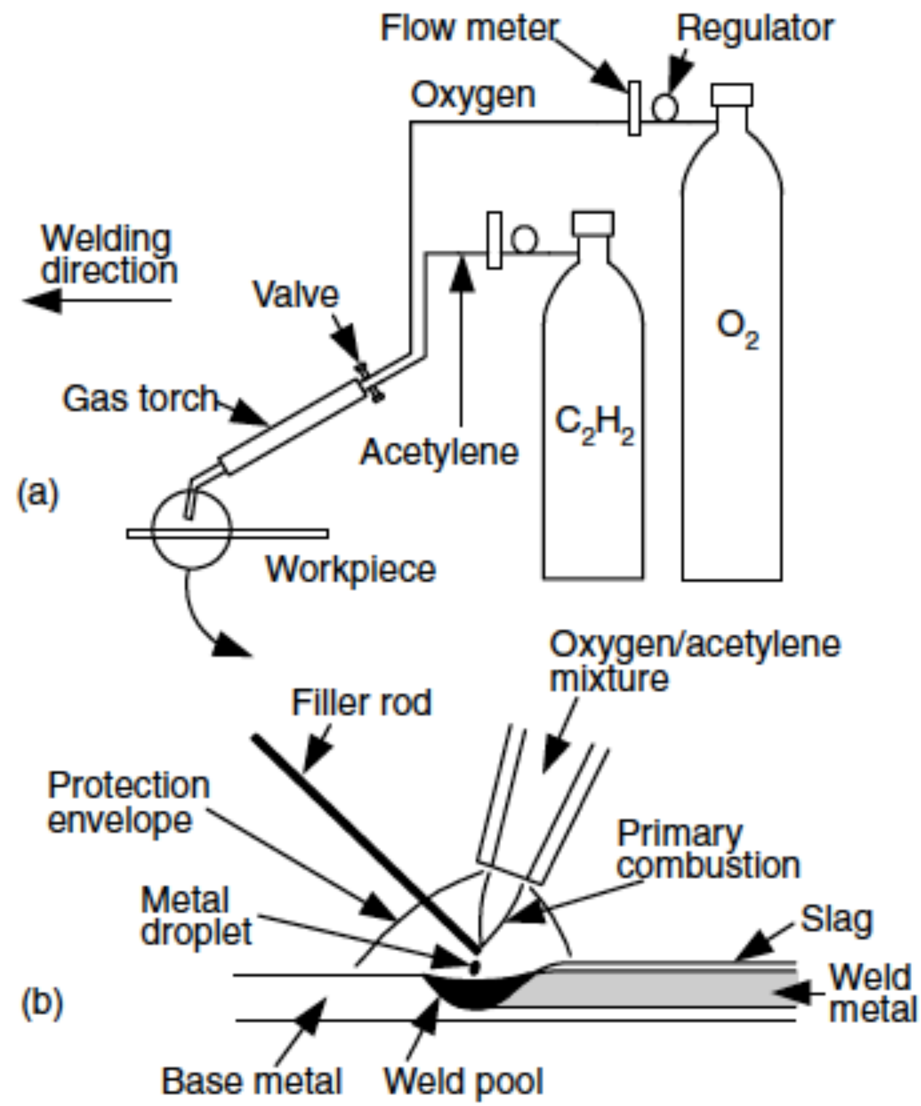
- The surface of the weld is called the face.
- The two junctions between the face and the workpiece surface are called the toes.
- The portion of the weld beyond the workpiece surface is called the reinforcement.

Gas welding

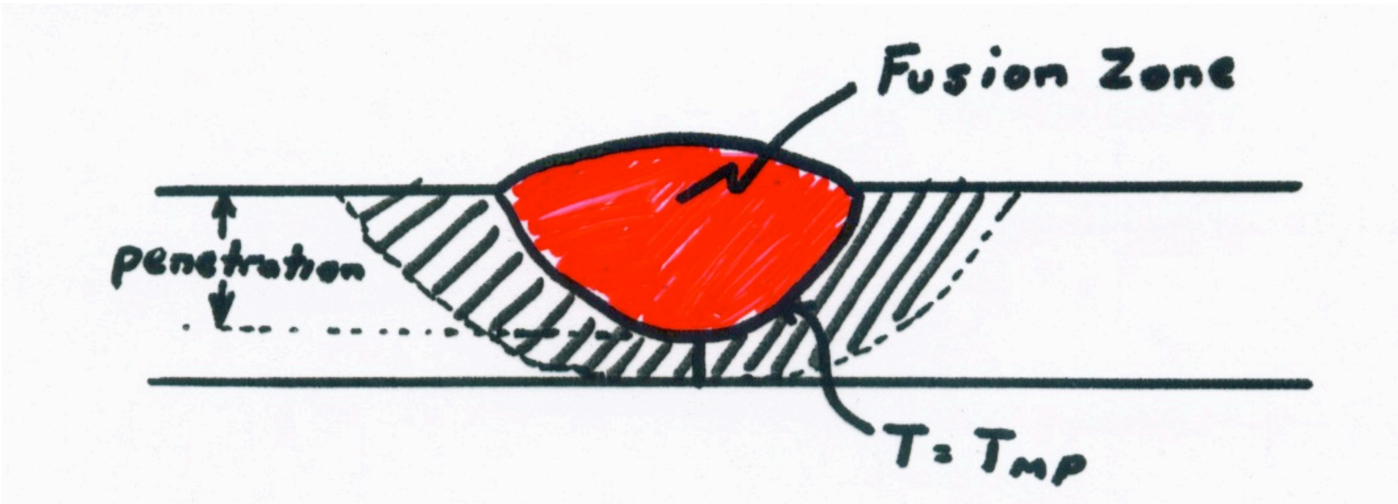
•Gas welding is a welding process that melts and joints metals by heating them with a flame caused by a reaction of fuel gas and oxygen.

•The most commonly used method is oxyacetylene welding, due to its high flame temperature.

•The flux melts, solidifies and forms a slag skin on the resultant weld metal.



Gas welding



Fusion Zone

Material that was molten during the welding process

Heat-Affected Zone (HAZ)

Heating above some critical temperature will almost always induce some undesirable changes in structure and properties of the materials

The zone is usually described by its width

Typically want to minimize

Often hard to control

Unaffected base material

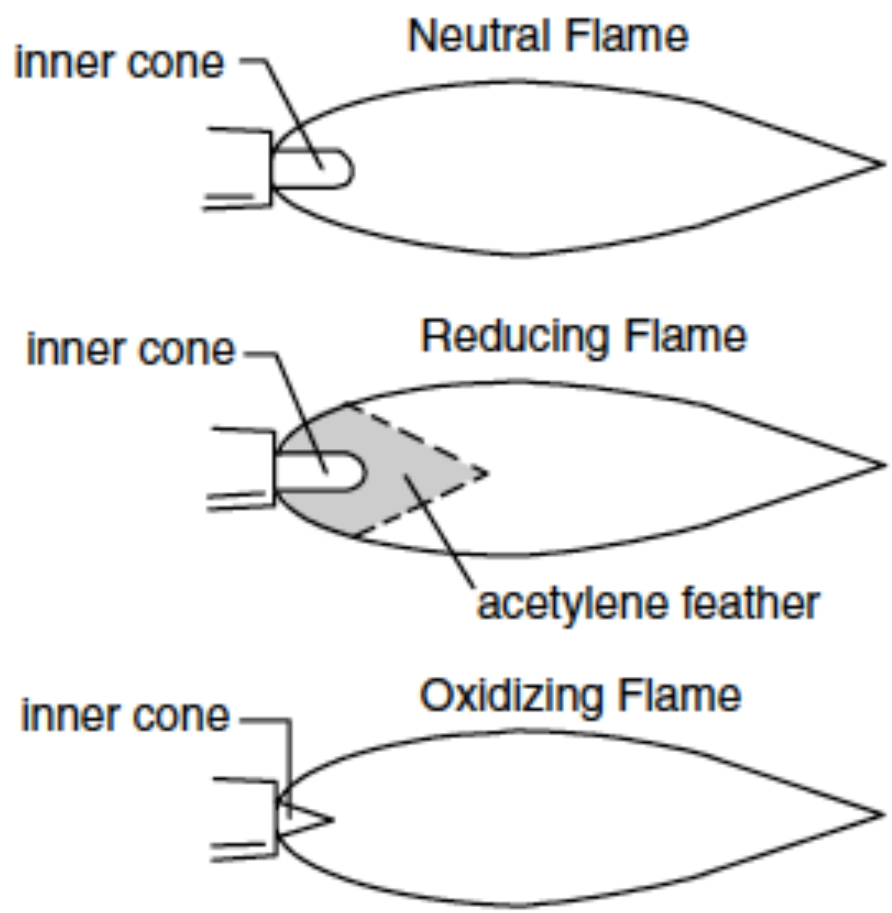
The region where the temperature did not reach the critical

Oxyacetylene welding (types of flames)

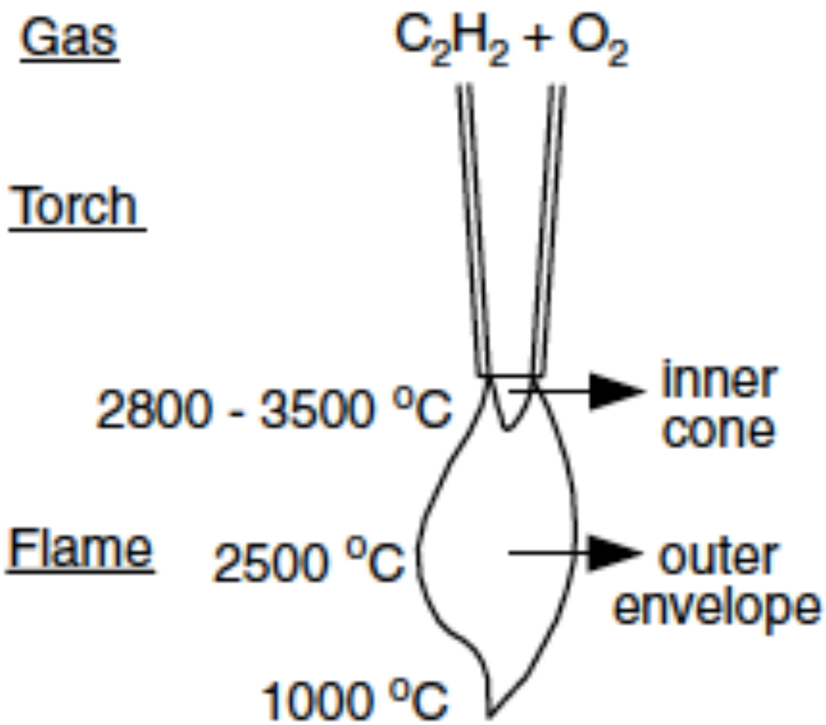
Neutral flame: Acetylene (C_2H_2) and O_2 are mixed in equal amounts and burn at the tip of the welding torch. The inner cone gives 2/3 of heat whereas the outer envelope provides 1/3 of the energy.

Reducing flame: The excess amount of acetylene is used, giving a reducing flame. The combustion of acetylene is incomplete (greenish) between the inner cone and the outer envelope. Good for welding aluminium alloys, high carbon steels.

Oxidizing flame: The excess amount of O_2 is used, giving an oxidizing flame. Good for welding brass.



Oxyacetylene welding



Primary combustion in inner cone (2/3 total heat) :

$2C_2H_2 + 2O_2$ (from cylinder) $\longrightarrow 4CO + 2H_2$

Secondary combustion in outer envelope (1/3 total heat) :

$4CO + 2O_2$ (from air) $\longrightarrow 4CO_2$

$2H_2 + O_2$ (from air) $\longrightarrow 2H_2O$

The secondary combustion is also called the protection envelope since CO and H_2 here consume the O_2 entering from surrounding air, thereby protecting the weld from oxidation.

Oxyacetylene welding

Advantages

- Simple equipment
- Portable
- Inexpensive
- Easy for maintenance and repair

Disadvantages

- Limited power density
- Very low welding speed
- High total heat input per unit length
- Large heat affected zone
- Severe distortion
- Not recommended for welding reactive metals such as titanium and zirconium.

Pressure gas welding

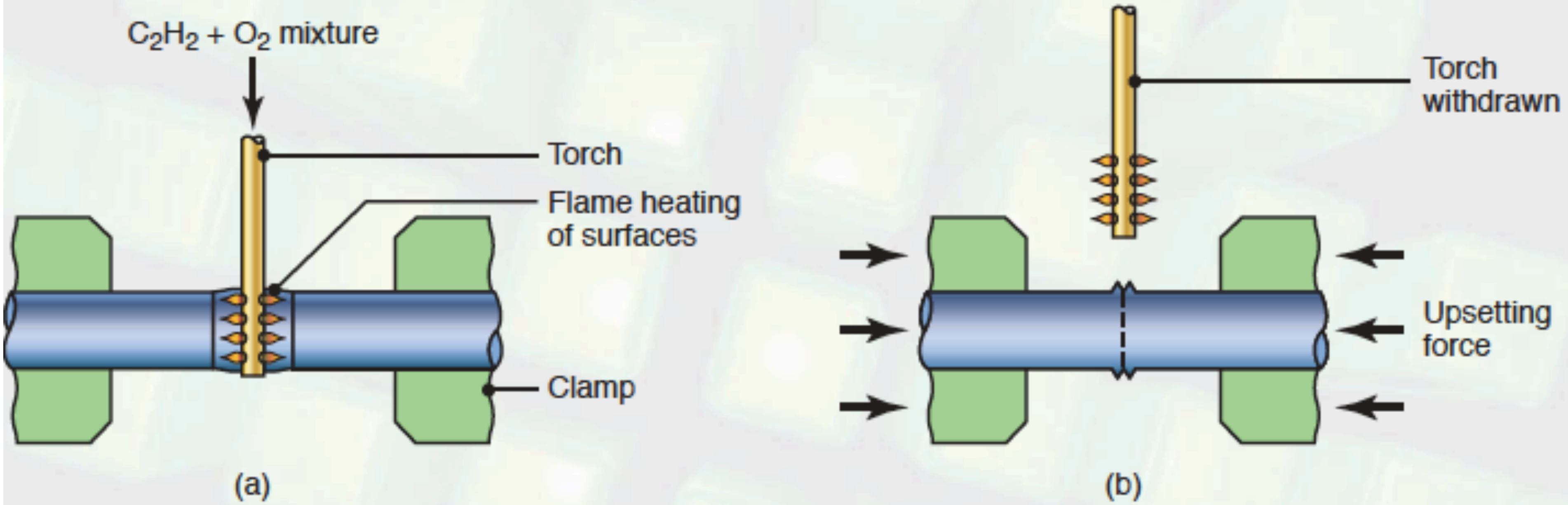


FIGURE 12.3 Schematic illustration of the pressure gas welding process; (a) before, and (b) after. Note the formation of a flash at the joint, which can later be trimmed off.

Heat transfer in welding

Material	Specific Energy, u J/mm^3	Specific Energy, u BTU/in^3
Aluminum and its alloys	2.9	41
Cast irons	7.8	112
Copper	6.1	87
Bronze (90Cu-10Sn)	4.2	59
Magnesium	2.9	42
Nickel	9.8	142
Steels	9.1-10.3	128-146
Stainless steels	9.3-9.6	133-137
Titanium	14.3	204

TABLE 12.3 Approximate specific energy required to melt a unit volume of commonly welded materials.

Heat input

$$\frac{H}{l} = e\frac{VI}{v}$$

Welding speed

$$v = e\frac{VI}{uA}$$

Heat transfer in welding

$$\frac{H}{l} = e\frac{VI}{v}$$

$$H = u(volume) = uAl$$

$$v = e\frac{VI}{uA}$$

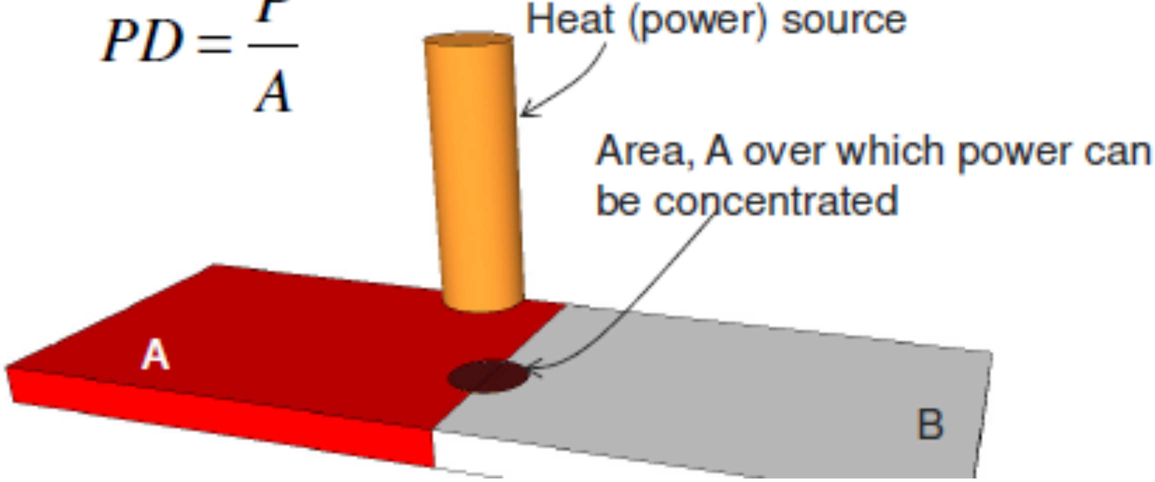
H is the heat input in J
l is the weld length
V is voltage applied
I is the current in amperes
v is the welding speed
e is the efficiency

u is the specific energy required for melting

Fusion welding: heat sources

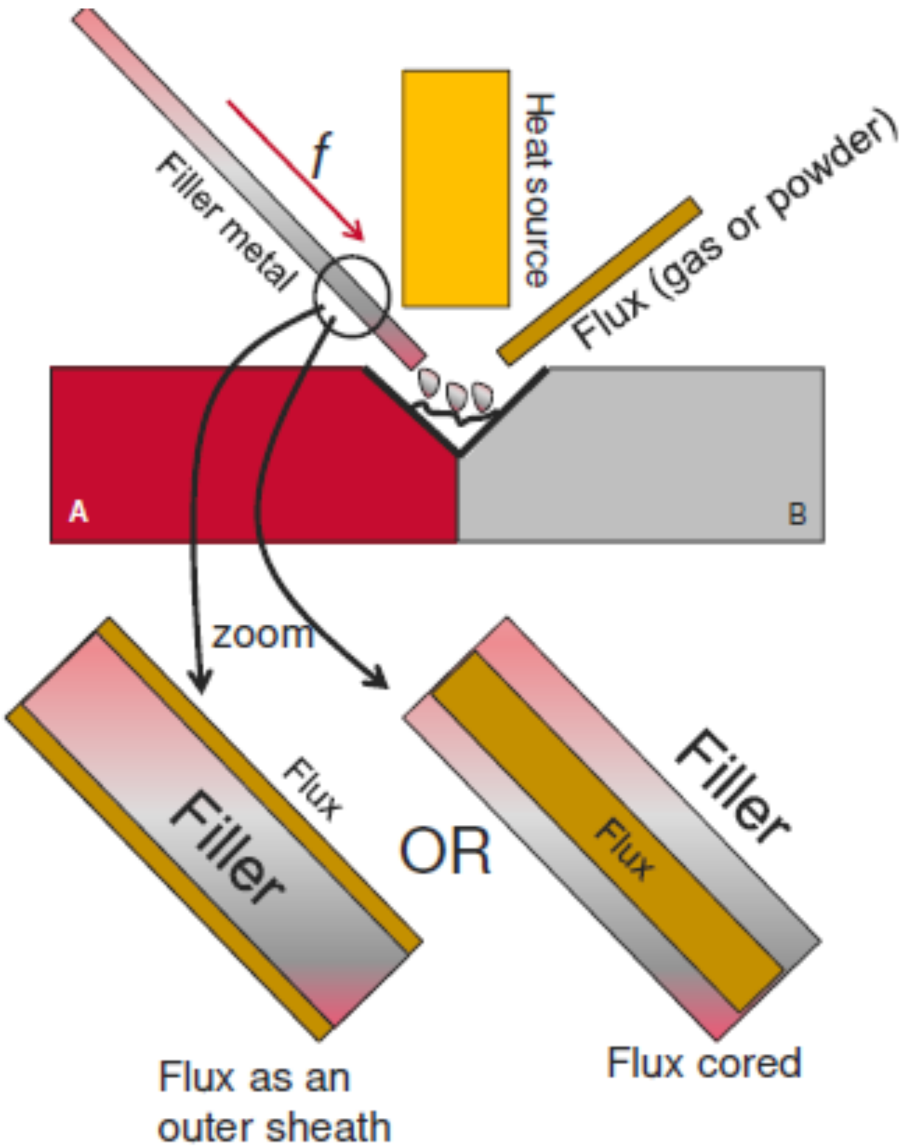
Heat source	Power Density
A. Oxyfuel torch	10 W/mm^2
B. Electric Arc	50 W/mm^2
C. Interface electrical resistance heating	1000 W/mm^2
D. Laser beam	9000 W/mm^2
E. Electron beam	10,000 W/mm^2

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



- *PD*: Power transferred to work per unit surface area, W/mm^2 (Btu/sec-in^2)
  - If power density is too low, heat is conducted into work, so melting never occurs
  - If power density too high, localized temperatures vaporize metal in affected region
  - There is a practical range of values for heat density within which welding can be performed

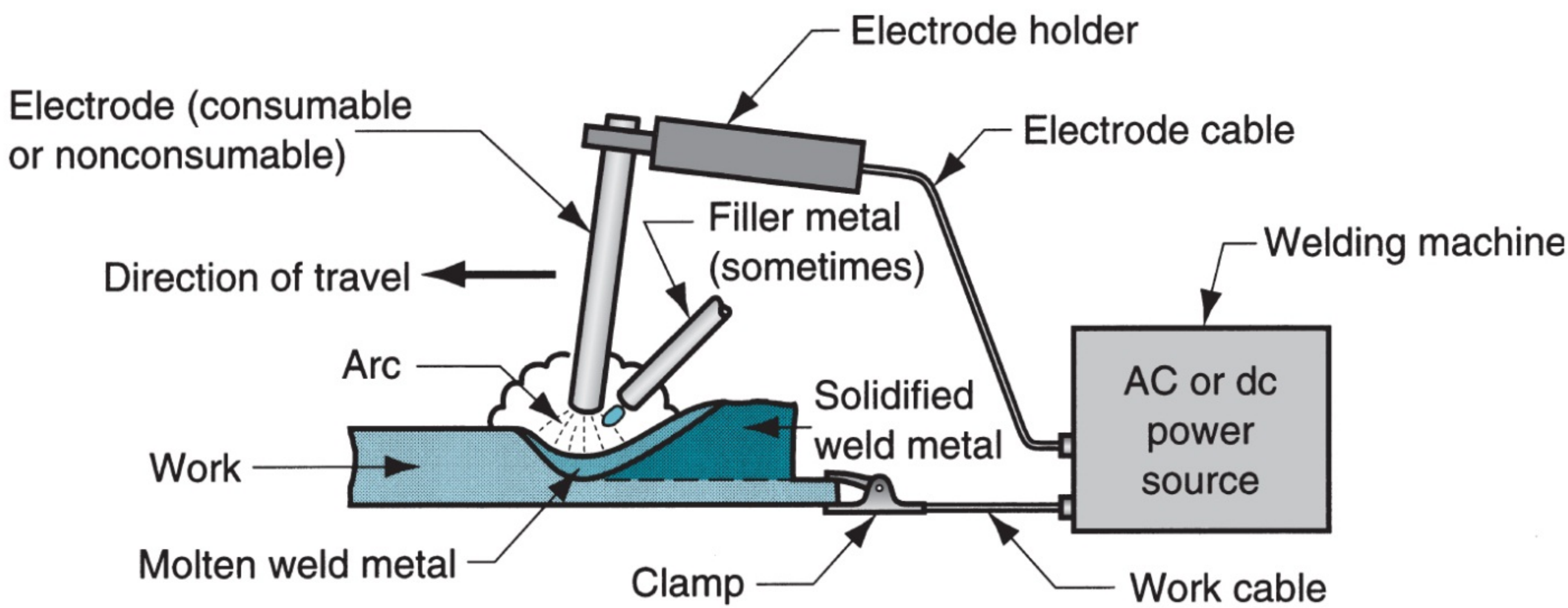
Fusion welding: flux and its application



- We saw flux earlier in brazing/soldering
- Fusion welding involves melting; molten metal can react with the environment – can form oxides (these are very hard and undesirable in the weld).
- Flux helps in preventing oxygen to react with the metal
- Flux can be applied separately as a powder or gas or along with the filler rod (as outside sheath or in the core)
- After welding, flux comes out (floats on weld pool) as slag on top of the weld – it can be broken and taken off (it is brittle); if flux is gas – then there is no slag

Arc Welding: The most common fusion welding

- A pool of molten metal is formed near electrode tip, and as electrode is moved along joint, molten weld pool solidifies in its wake

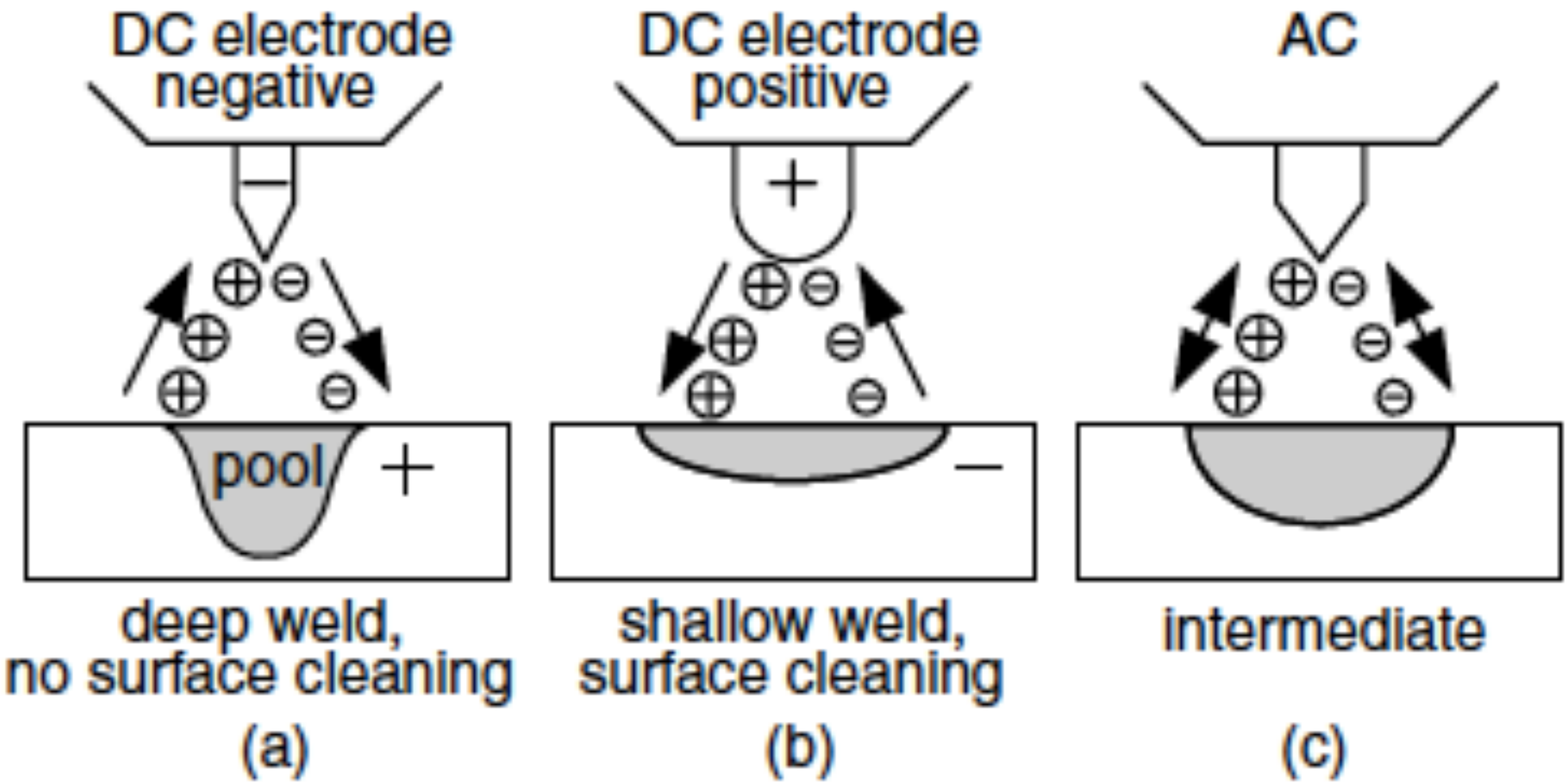


Arc Welding: The most common fusion welding

Functions of Electrode Covering

- **Protection:** It provides a gaseous shield to protect the molten metal from air.
- **Deoxidation:** It provides deoxidizers and fluxing agents to deoxidize and cleanse the weld metal. The solid slag formed also protects the already solidified but still hot weld metal from oxidation.
- **Arc Stabilization:** It provides arc stabilizers to help maintain a stable arc. The arc is an ionic gas (a plasma) that conducts the electric current.
- **Metal Addition:** It provides alloying elements and/ or metal powder to the weld pool.

Polarity (arc welding)



a. Direct-Current Electrode Negative (DCEN)
b. Direct-Current Electrode Positive (DCEP)
c. Alternating Current (AC)

Two Basic Types of Arc Welding Electrodes

- Consumable – consumed during welding process
  - Source of filler metal in arc welding
- Non-consumable – not consumed during welding process (e.g. Tungsten)
  - Filler metal must be added separately if it is added

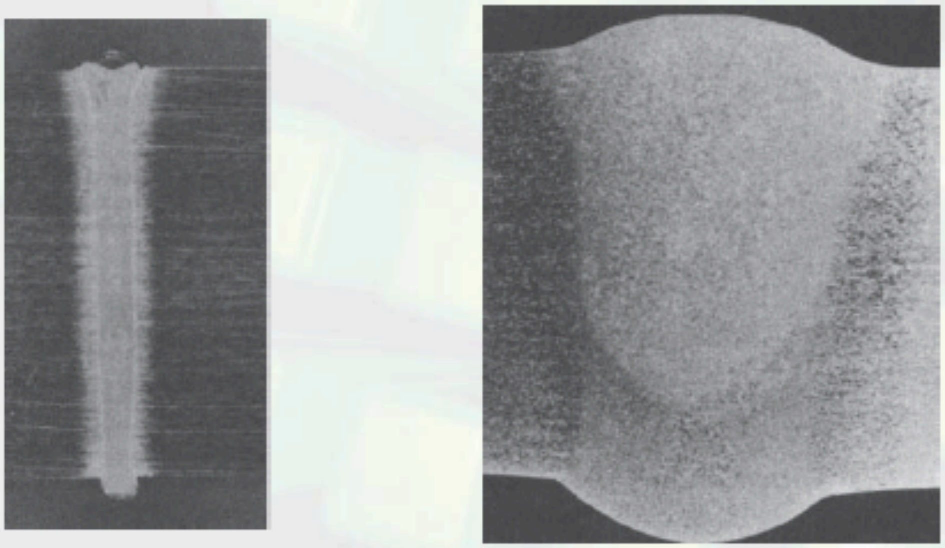
Consumable Electrode Arc Welding Processes

- Shielded Metal Arc Welding (SMAW)
- Gas Metal Arc Welding (GMAW)
- Flux-Cored Arc Welding (FCAW)
- Submerged Arc Welding (SAW)

Arc welding

Process	Filler	Electrode	Flux	Heat source
SMAW	Filler rod is also the electrode		Coated on OD of filler	Arc
FCAW	Filler rod is also the electrode; fed continuously		Flux is in the core of filler rod; Gas also may be applied	Arc
GMAW	Filler rod is also the electrode; fed continuously		Gas is supplied via nozzle	Arc
SAW	Filler rod is also the electrode; fed continuously		Flux applied as powder/granules	Arc
GTAW	In rod shape; fed continuously	Electrode made of Tungsten (Separate from filler)	Gas is supplied via nozzle	Arc

Weld bead comparisons



(a) (b)

FIGURE 12.13 Comparison of the size of weld beads in (a) electron-beam or laser-beam welding with that in (b) conventional (tungsten arc) welding. *Source:* American Welding Society, *Welding Handbook*, 8th ed., 1991.

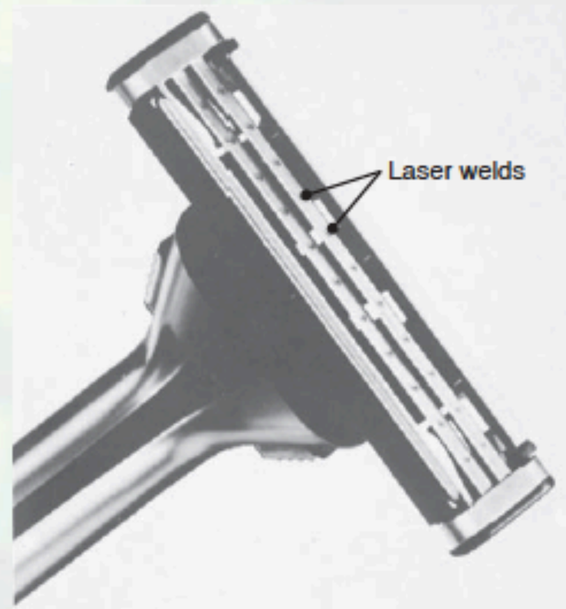


FIGURE 12.14 Gillette Sensor razor cartridge, with laser-beam welds.

Fusion Weld Characteristics

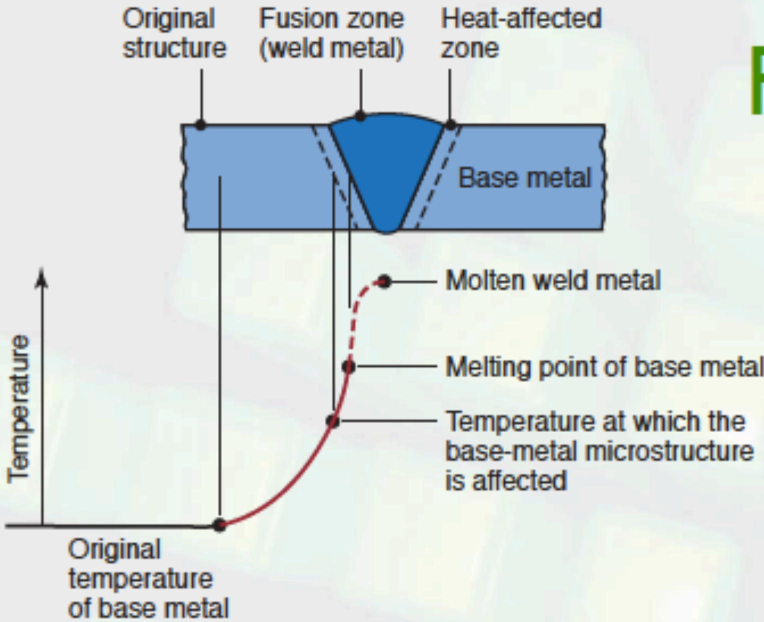
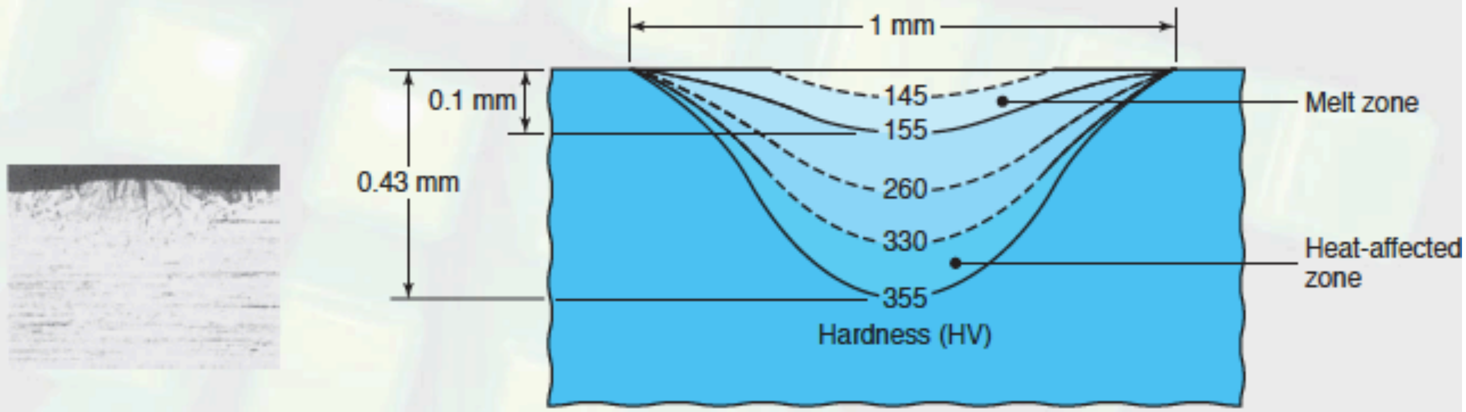


FIGURE 12.15 Characteristics of a typical fusion weld zone in oxyfuel gas welding and arc welding processes.

(a) (b)

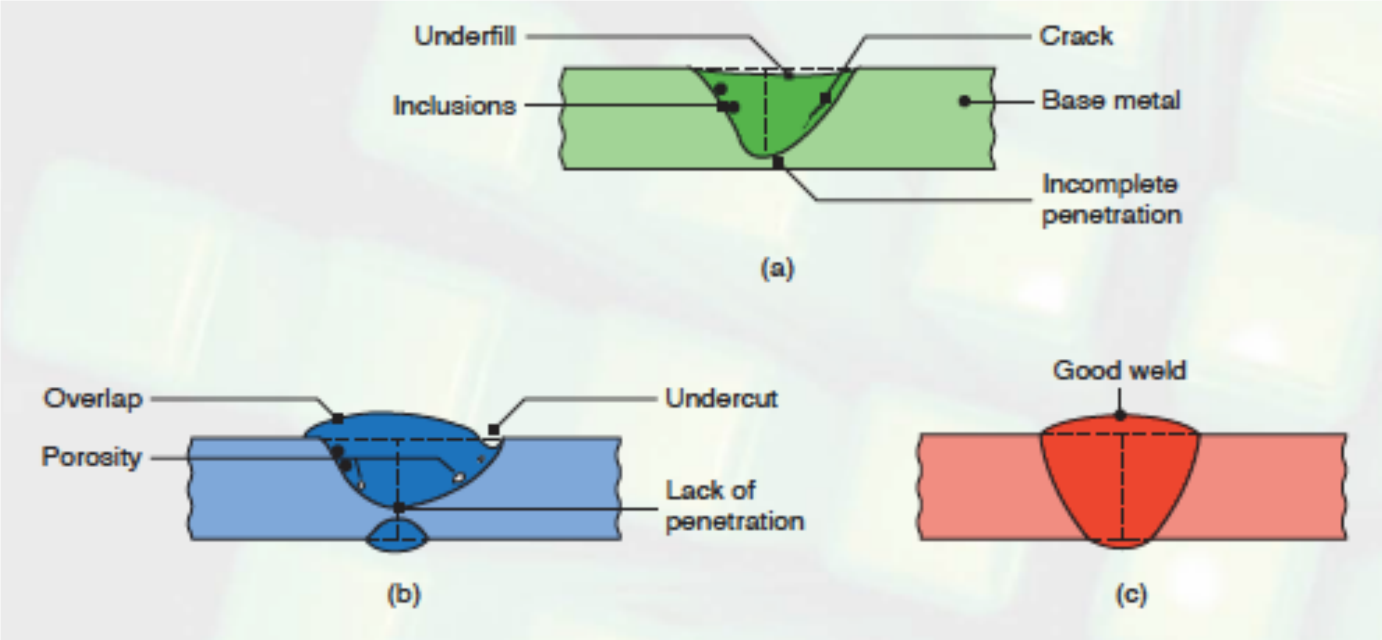
FIGURE 12.16 Grain structure in (a) a deep weld and (b) a shallow weld. Note that the grains in the solidified weld metal are perpendicular to their interface with the base metal.

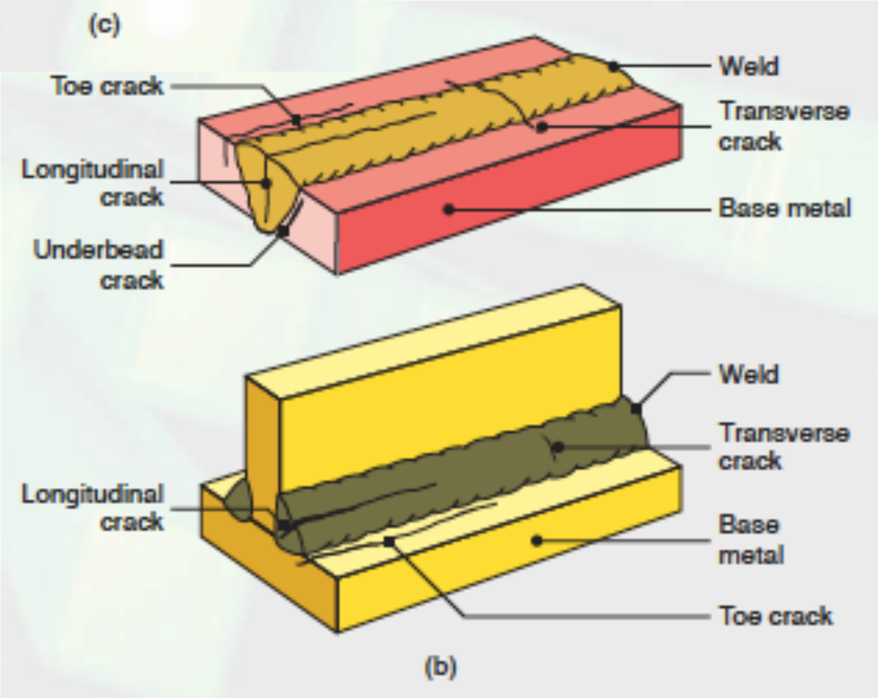


(a) (b)

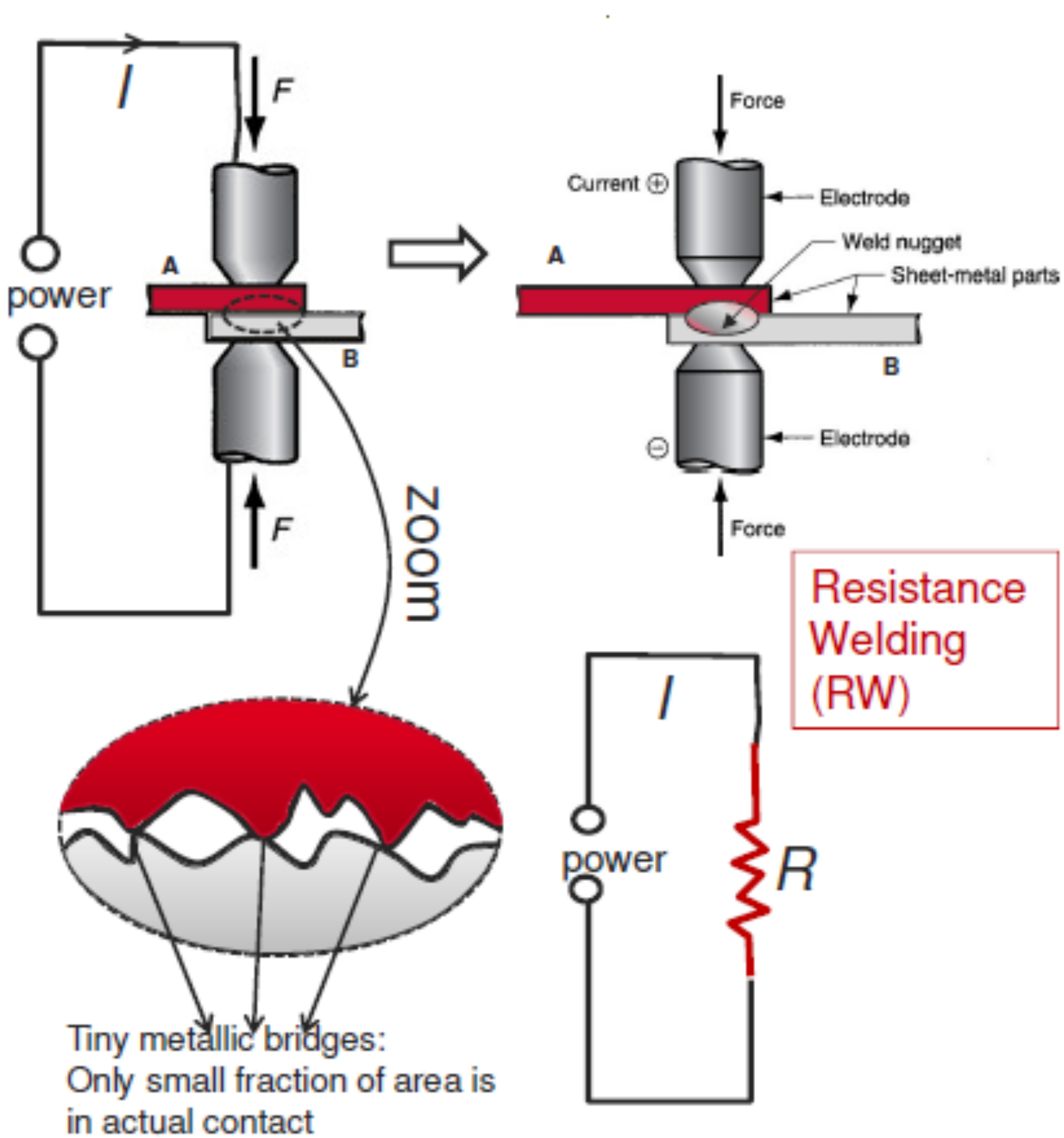
FIGURE 12.17 (a) Weld bead on a cold-rolled nickel strip produced by a laser beam. (b) Microhardness profile across the weld bead. Note the lower hardness of the weld bead as compared with the base metal. *Source:* IIT Research Institute.

Defects in welded joints



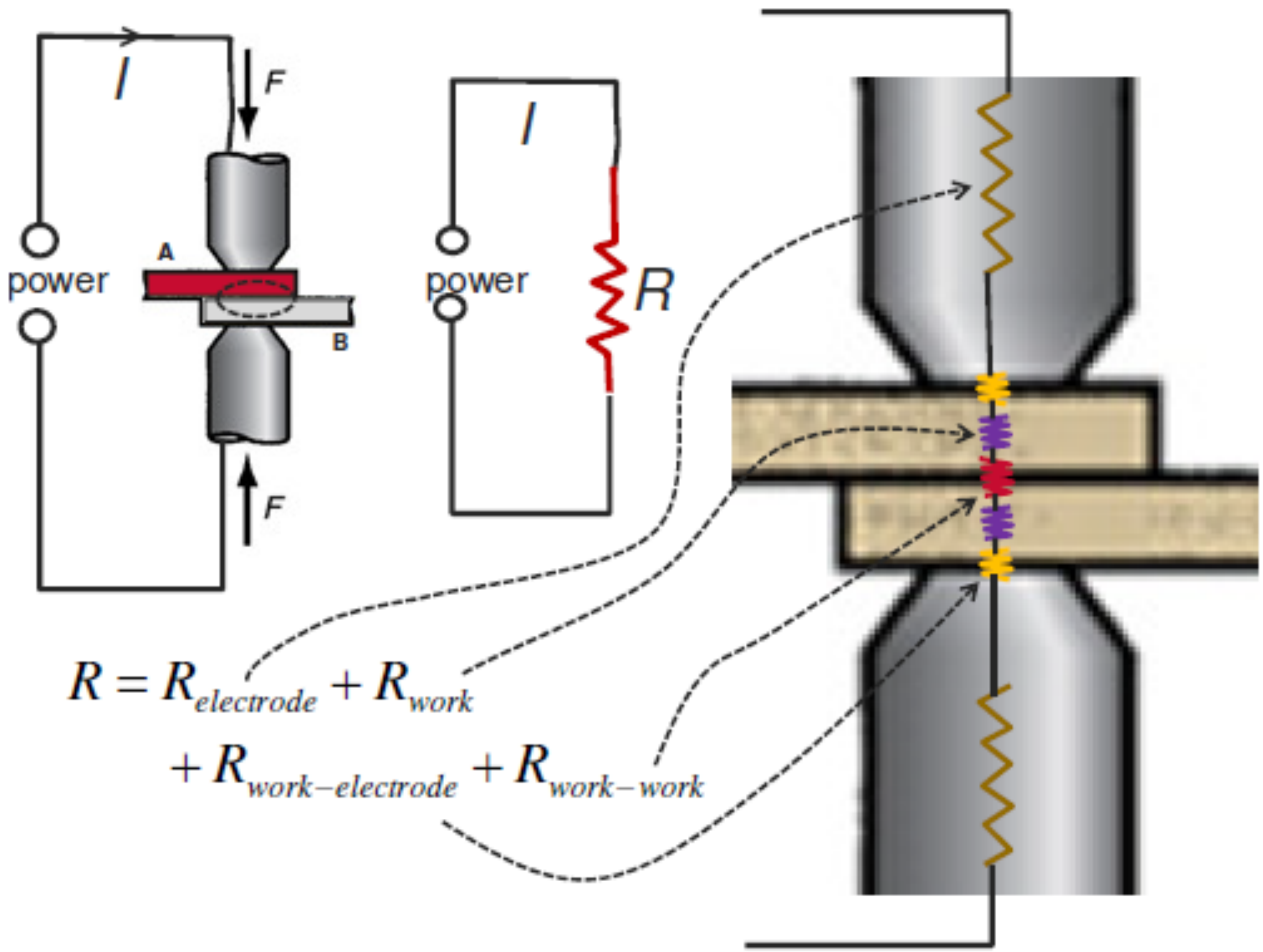


Fusion welding: electrical



- Two surface to be joined are kept in contact and large electrical current (5000-20,000 A) made to flow
- Since actual area of contact is much small – current flow is constricted to tiny metallic bridges – this causes resistance to flow
- Resistance – causes heating at the junction
- Local melting occurs and fusion welding happens
- No filler is used

Resistance welding

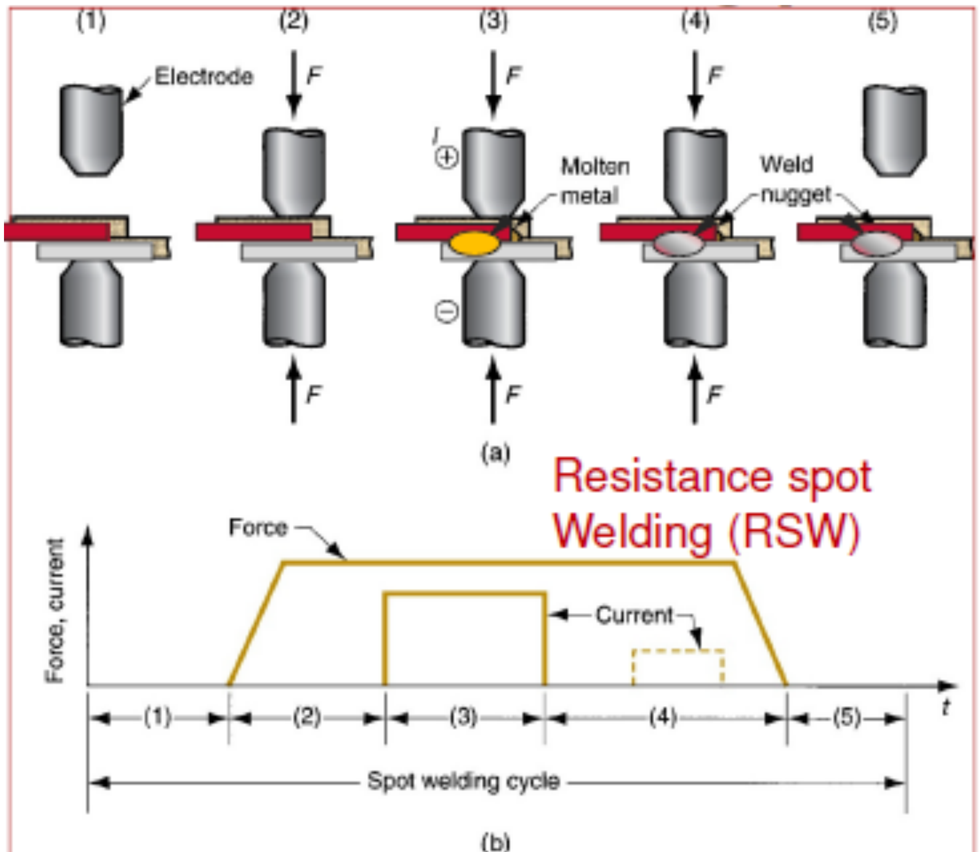


$$R = R_{electrode} + R_{work} + R_{work-electrode} + R_{work-work}$$

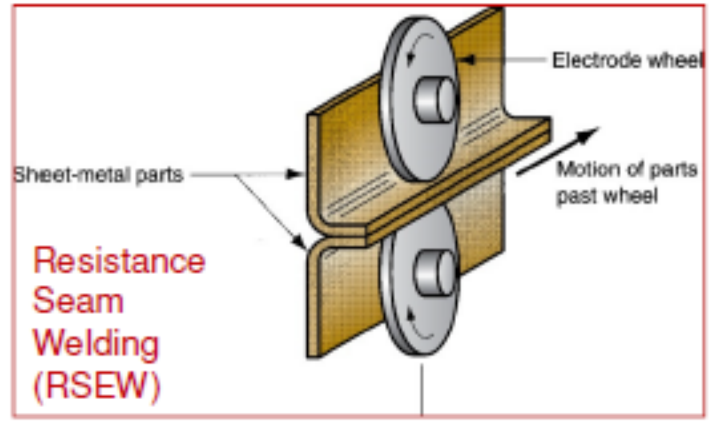
R is usually very small ~ $10^{-4}\ \Omega$; so current has to be high to cause sufficient heating

R has several components; we try to minimize all components except for $R_{work\text{-}work}$

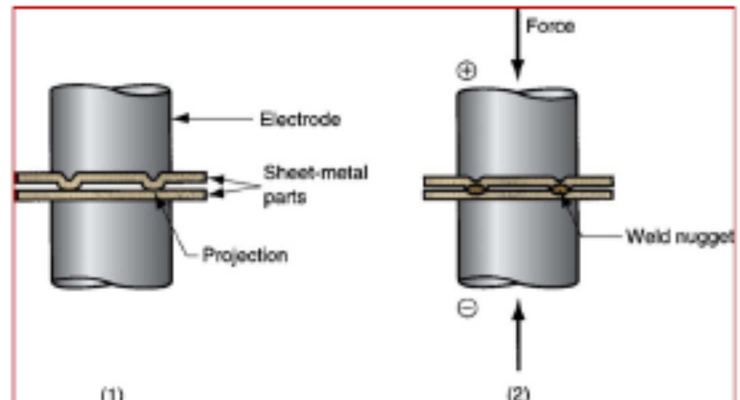
Resistance welding processes

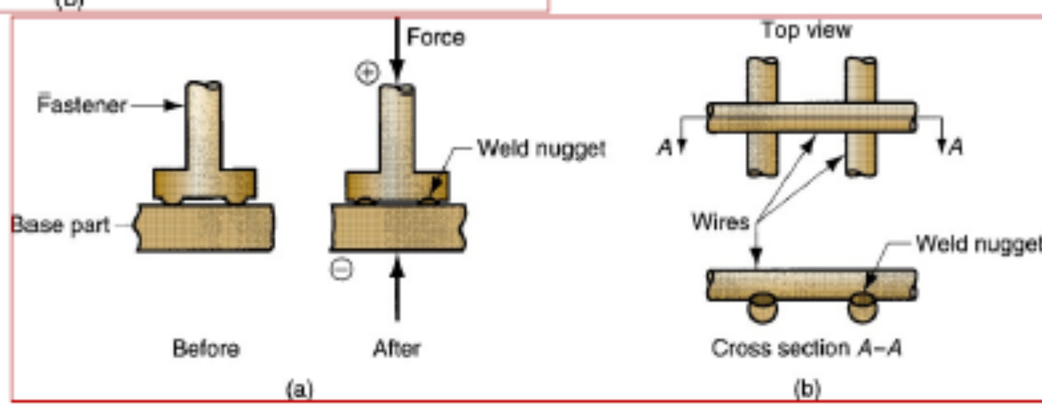


Resistance spot Welding (RSW)



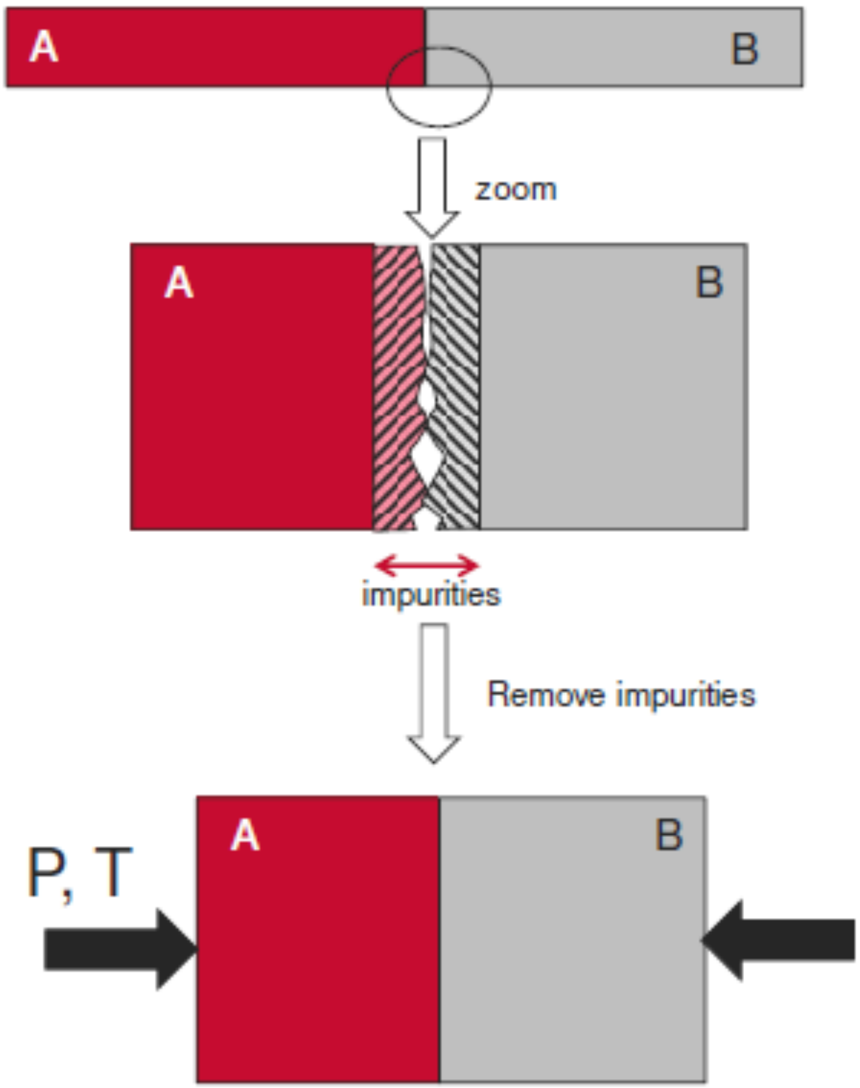
Resistance Seam Welding (RSEW)





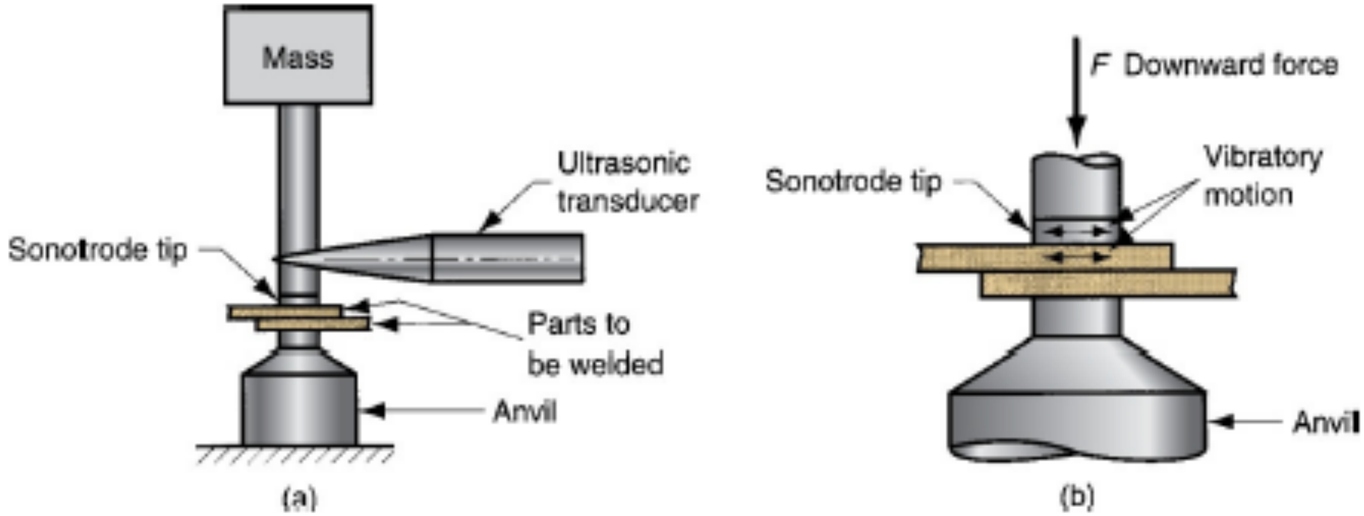
Resistance Projection Welding (RPW)

Solid state welding (SSW)



- Normally surfaces have oxide films and impurities etc on them
- If we can break these films and bring the *nascent* surfaces into contact – then the atoms on the surface will bond naturally
- Bonding can be aided by pressure (P) and/or temperature (T)
- Called SOLID STATE WELDING:
  - Diffusion welding
  - Friction welding
  - Ultrasonic welding

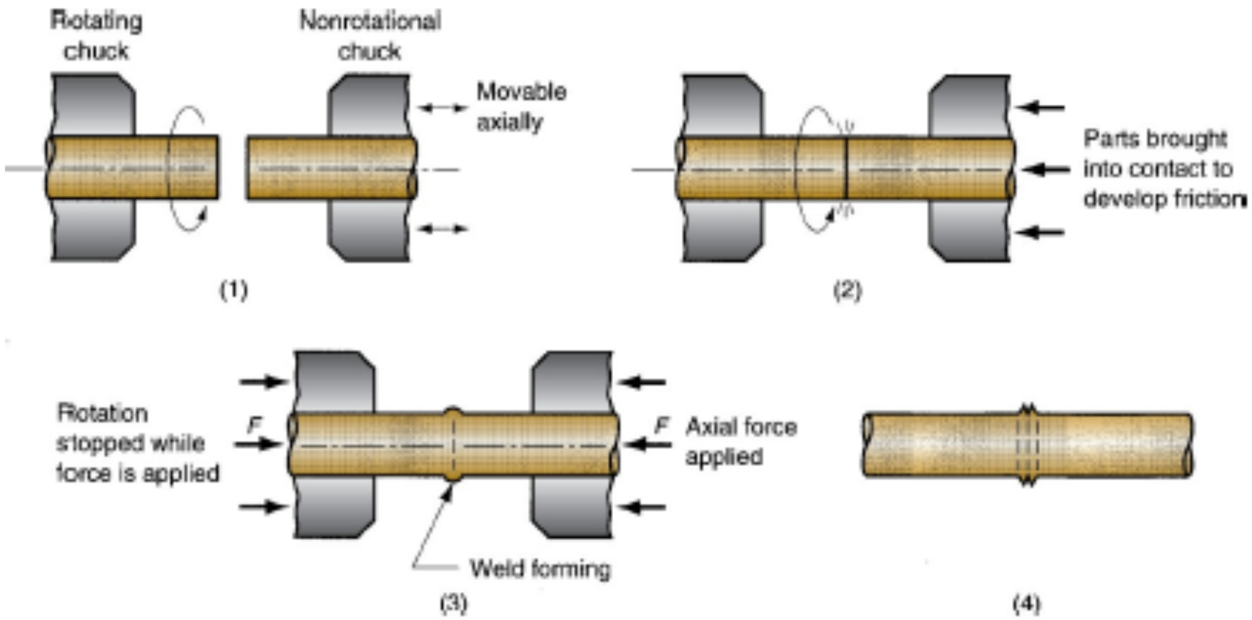
Ultrasonic welding

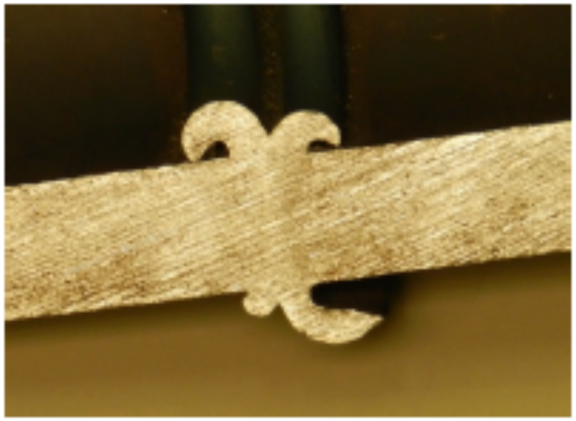


ULTRASONIC WELDING

- Two components are held together, and oscillatory shear stresses of ultrasonic frequency (15-75 kHz) are applied to interface to cause coalescence
  - Oscillatory motion breaks down any surface films to allow intimate contact and strong metallurgical bonding between surfaces
  - Temperatures are well below T_m
  - No filler metals, fluxes, or shielding gases

Friction welding



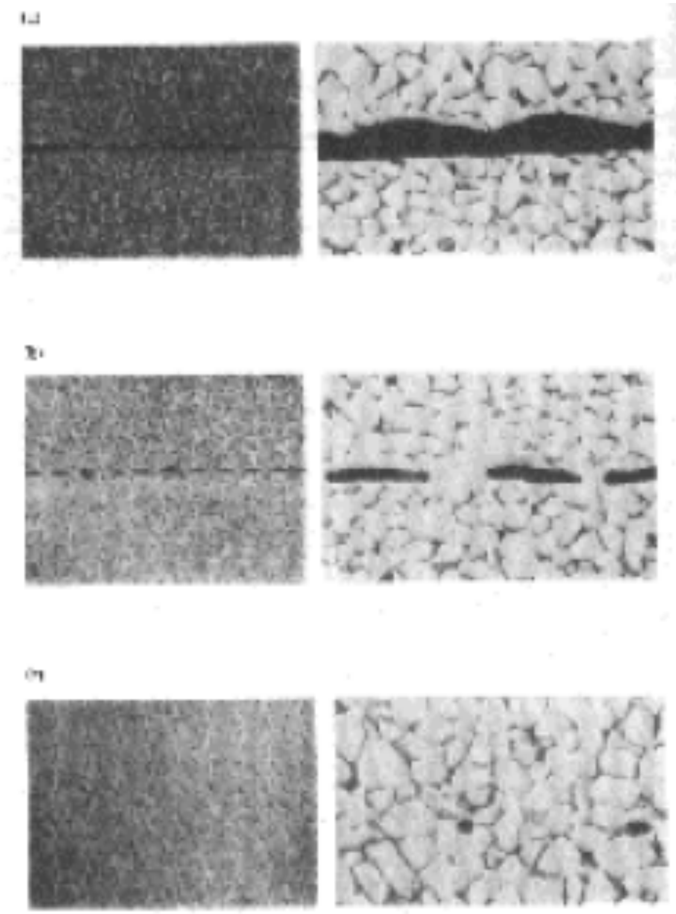


- SSW process in which coalescence is achieved by frictional heat combined with pressure
  - When properly carried out, no melting occurs at faying surfaces
  - No filler metal, flux, or shielding gases normally used
  - Can be used to join dissimilar metals
  - Widely used commercial process, amenable to automation and mass production

Diffusion bonding

DIFFUSION BONDING

- A SSW process that uses heat and pressure, usually in a controlled atmosphere, with sufficient time for diffusion and coalescence to occur
  - Temperatures $\leq 0.5\ T_m$
  - Plastic deformation at surfaces is minimal
  - Primary coalescence mechanism is solid state diffusion
  - Limitation: time required for diffusion can range from seconds to hours



(Diffusion bonding of Ti alloy)