Metal Forming

Dr.K. Santhy
Associate Professor
Department of Materials and Metallurgical and Engineering
Institution of Technology and Engineering
Indus University
Ahmedabad, Gujarat

Unit I : Fundamentals of Metal forming

- Yield criteria
- Von-Mises equation
- Classification of metal forming processes
- Mechanics of metal working
- Flow curve for materials
- Temperature in Metal Working, Hot working, Cold working & Warm working,
- Strain rate effect of metallurgical structure and non-metallic inclusion on the manufacturing process,
- Workability, Residual stresses, Annealing of cold-worked metals.

Unit I : Fundamentals of Metal forming

- Introduction to Metal forming
- Classification of metal forming processes
- Mechanics of metal working
  - Yield criteria
  - Von-Mises equation
- Flow curve for materials
- Temperature in Metal Working
  - Hot working
  - Cold working
  - Warm working,
- Strain rate effect of metallurgical structure and non-metallic inclusion on the manufacturing process
- Workability
- Residual stresses
- Annealing of cold-worked metals.

Metal Forming

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

Classification of Metal Forming:

- Plastic deformation processes
- Metal removal or machining process

Differentiation of Plastic deformation and metal removal process

Plastic Deformation	Metal removal or machining process
Volume and mass of metal are conserved	Volume and mass of metal are non conserved
Metal is displaced from one location to another	Metal is removed to get required shape
Mechanical properties are controlled during process.	

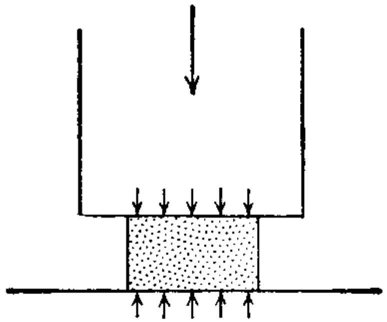
Classification of Plastic Deformation Process:

Based on the type of force applied to get desired shape,

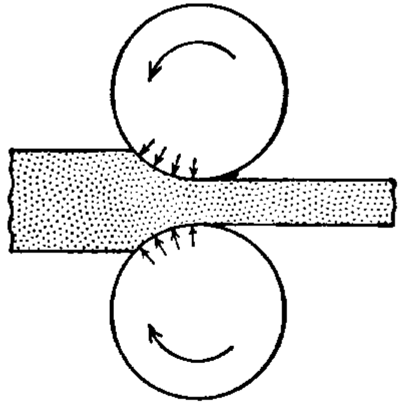
- Direct-compression-type processes
- Indirect-compression processes
- Tension type processes
- Bending processes
- Shearing processes

Direct Compression Process

The applied force is perpendicular to the direction of metal flow.



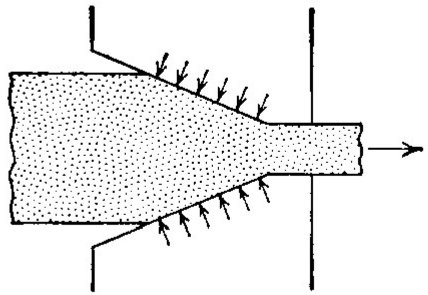
Forging



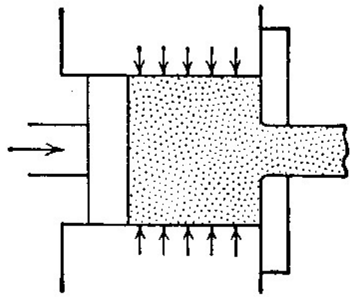
Rolling

Indirect Compression Processes

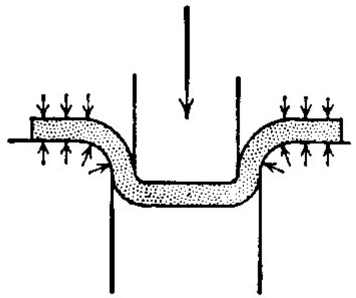
Primary force→ Tensile → indirect compressive force by reaction between workpiece and die



Wire drawing



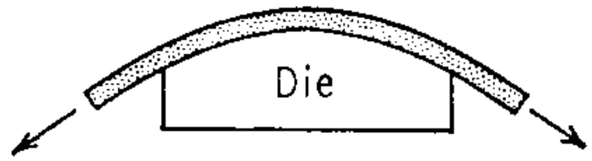
Extrusion



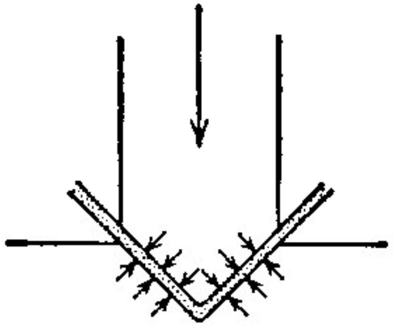
Deep drawing

Tension type processes

Tensile forces applied on a metal sheet which is wrapped to a contour of a die.



Stretch forming



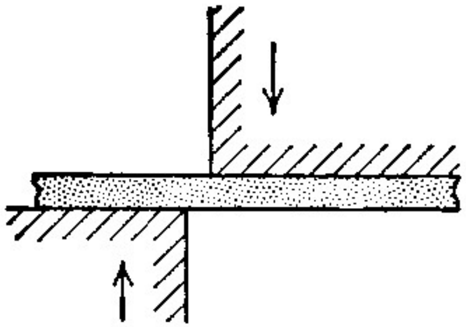
Bending

Bending processes

The application of bending movements to the sheet

Shearing processes

The application of shearing forces to rupture the metal in the plane of shear.



Shearing

- **Primary mechanical working processes or Processing operations:** Plastic working processes which reduce an ingot or billet to simple shape like sheet, plate and bar. Ex. Rolling, extrusion

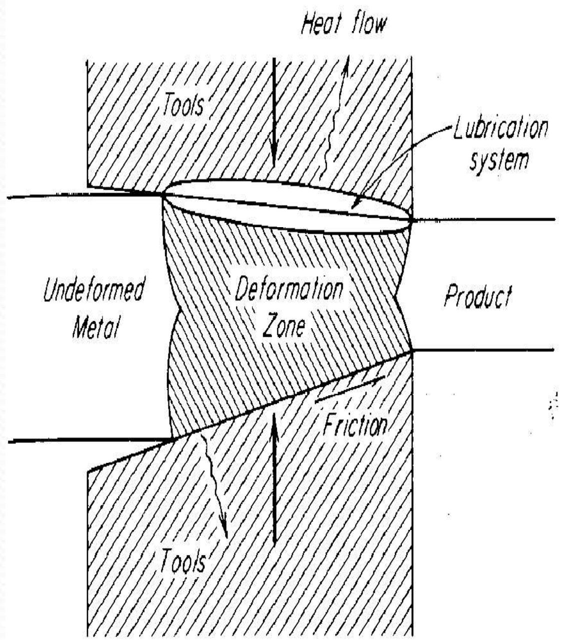
- **Secondary mechanical working processes or fabrication:** Forming methods → final finished shape . Ex: wire drawing, tube drawing

- Metal Forming
  - Compressive forming
    - Rolling, Open die forming, closed die forming, Indenting, Pushing through a die
  - Combined tensile & compressive forming
    - Pulling through a die, deep drawing, flange forming, spinning upset bulging
  - Tensile Forming
    - Stretching, Expanding, Recessing
  - Forming by bending
    - Bending with linear tool motion , Bending with rotary with tool motion
  - Forming by shearing
    - Joggling, twisting, Blanking, Coining

Deformation process:

- The deformation zone is concerned with the distribution of stress, strain and particle velocities, and with overall pressure required to perform the operation.
- The applied force must develop yielding in the material but the stresses must not locally create fracture. Since metallurgical phenomena such as strain hardening, recrystallisation and fracture are important under high strain rate and/or high temperature.
- The flow stress of the materials is function of strain, strain rate and temperature.
- The friction along the interface between work piece and die or tools and heat transfer from the workpiece to

  the die are important.



Mechanics of Metal Working

Metal working occurs to plastic deformation which is associated with analysis of complex stress distribution

Assumption:

- Elastic strain is neglected
- Strain hardening is neglected
- Metal is considered as isotropic and homogeneous
- Friction between workpiece and die are neglected.

The strain is expressed in terms of true strain due to large deformation. In the plastic deformation process, volume is conserved. The constant volume relationship is,

$$\varepsilon_1 + \varepsilon_2 + \varepsilon_3 = 0$$

Compressive stresses and strains predominate in metal working processes. Consider initial height h_o is compressed to h_1, the axial compressive strains is,

True Strain:

$$\varepsilon = \int_{h_0}^{h_1} \frac{dh}{h} = ln\frac{h_1}{h_0} = -ln\frac{h_1}{h_0} \quad where\ h_0 > h_1$$

Conventional Strain:

e = -ve indicating compressive strain. In metal working, compressive stresses and strains are defined

$$e = \frac{h_1 - h_0}{h_0} = \frac{h_1}{h_0} - 1$$

Determine the engineering strain, true strain, and reduction for (a) a bar which is doubled in length and (b) a bar which is halved in length.

- For a bar which is double in length, $L_2 = 2L_1$
- For a bar which is halved in length, $L_2 = L_1/2$

Determine the engineering strain, true strain, and reduction for (a) a bar which is doubled in length and (b) a bar which is halved in length.

- For a bar which is double in length, $L_2 = 2L_1$

$$e = \frac{L_2 - L_1}{L_1} = \frac{2L_1 - L_1}{L_1} = 1.0$$

$$\varepsilon = \ln\frac{L_2}{L_1} = \ln\frac{2L_1}{L_1} = 0.693$$

$$r = \frac{A_1 - A_2}{A_1} = 1 - \frac{A_2}{A_1} = 1 - \frac{L_1}{L_2} = 1 - \frac{L_1}{2L_1} = 0.5$$

- For a bar which is halved in length, $L_2 = L_1/2$

$$e = \frac{L_1/2 - L_1}{L_1} = -0.5 \;\; or \;\; e_c = \frac{L_1 - L_1/2}{L_1} = 0.5$$

$$\varepsilon = \ln\frac{L_1/2}{L_1} = \ln\frac{1}{2} = -\ln 2 = -0.693$$

$$r = 1 - \frac{L_1}{L_1/2} = -1.0$$

The mechanics of metal working process is the ability to predict stress, strain and velocity at every point of deformed work piece. There are three theory for mechanics of metal working. They are

- The static equilibrium of force equations
- The levy-Mises equations (express relationship between stress and strain rate)
- The yield criterion

Scalar: a quantity with magnitude only

(e.g. temperature, time, mass).

Vector: a quantity with magnitude and direction

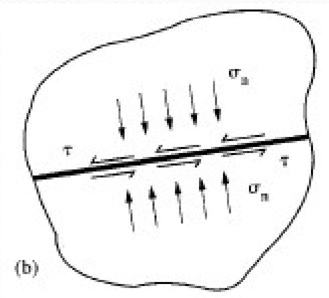
(e.g. force, velocity, acceleration).

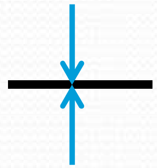
Tensor: a quantity with magnitude and direction, and with reference to a plane it is acting across

(e.g. stress, strain, permeability).

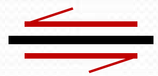
Components of Stress

Components of Stress : On a real or imaginary plane through a material, there can be normal forces and shear forces. These forces create the stress tensor. The normal and shear stress components are the normal and shear forces per unit area.





Normal Stress
σ

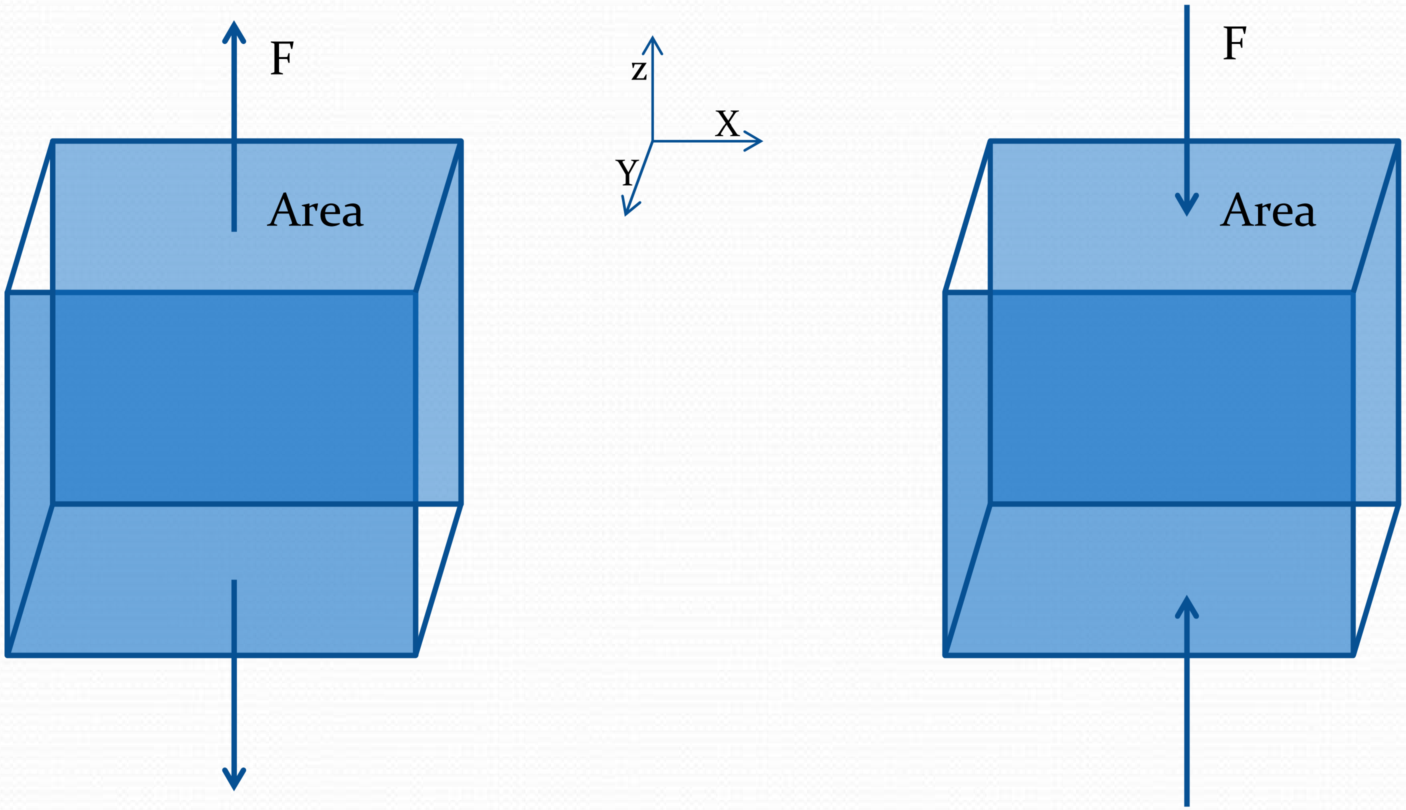


Shear Stress
τ

Note: It should be remembered that a solid can sustain a shear force, whereas a liquid or gas cannot. A liquid or gas contains a pressure, which acts equally in all directions and hence is a scalar quantity.

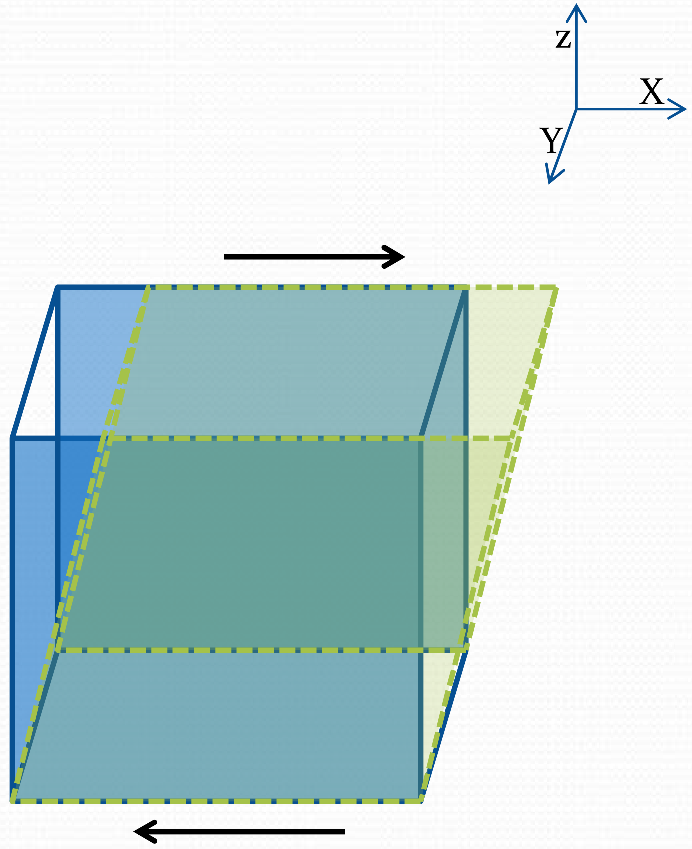
Normal stress

- A *normal stress (compressive or tensile) is one in which the force is normal to the* area on which it acts.



Shear stress

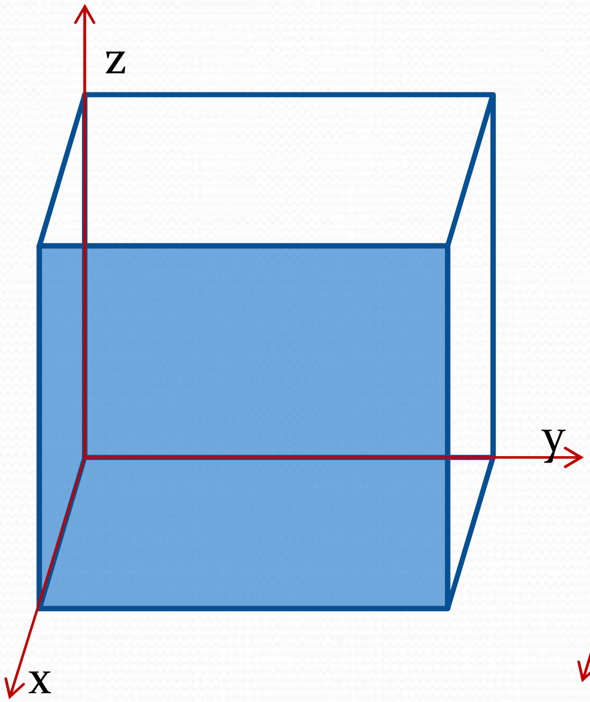
- With a *shear stress, the force is parallel to the area on which it* acts.



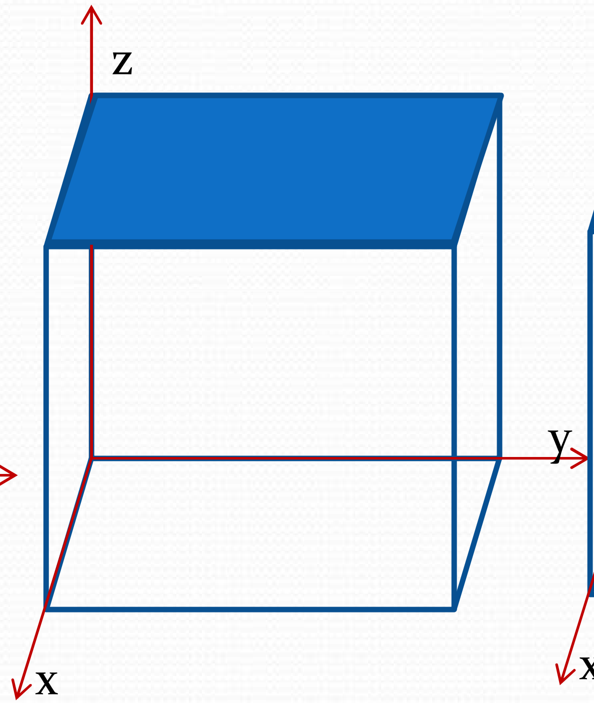
- Two subscripts are required to define a stress.
- The first subscript denotes the normal to the plane on which the force acts.
- The second subscript identifies the direction of the force.
- Example:

$$\sigma_{xx} = \sigma_x = \frac{F_x}{A_x} \qquad \sigma_{xy} = \frac{F_x}{A_y} = \tau_{xy}$$

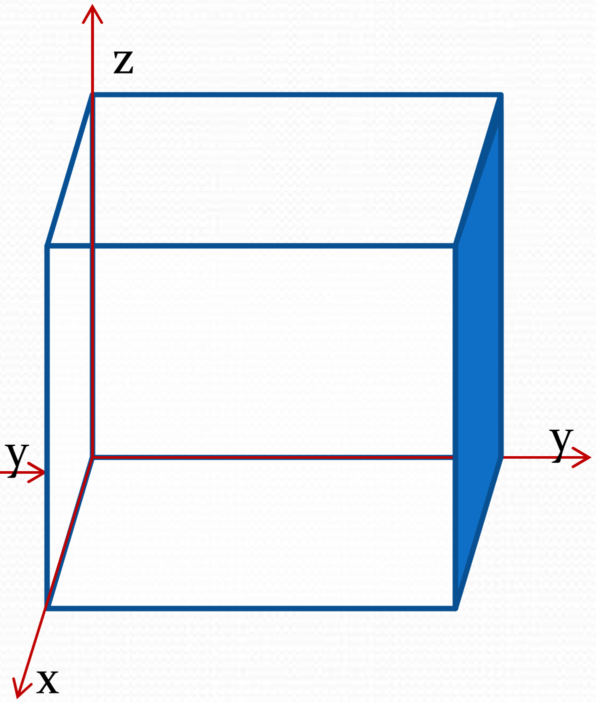
Normal Stress   Shear Stress



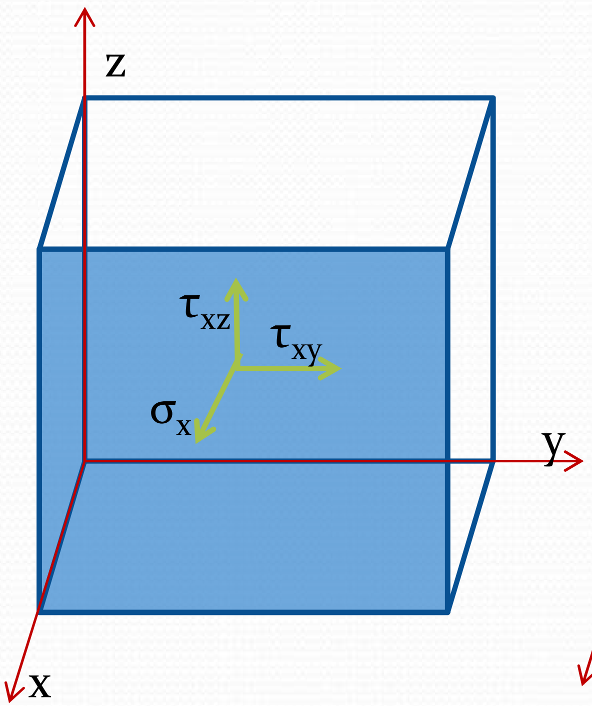
X plane



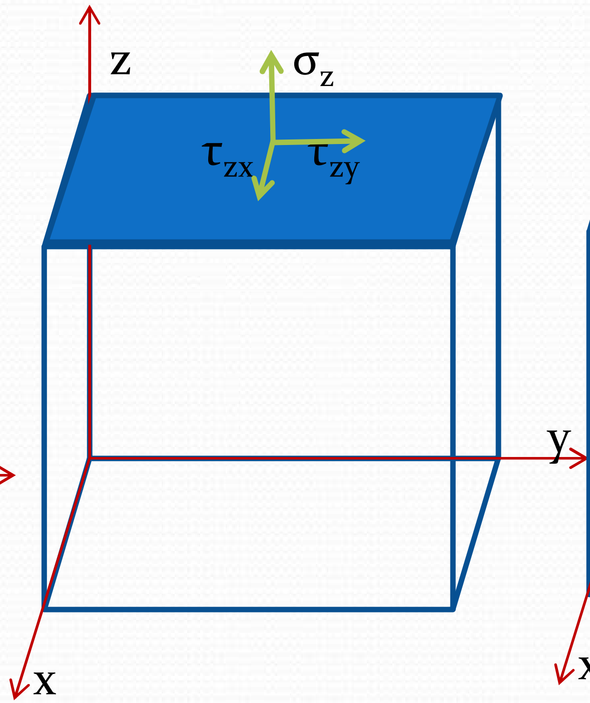
Z plane



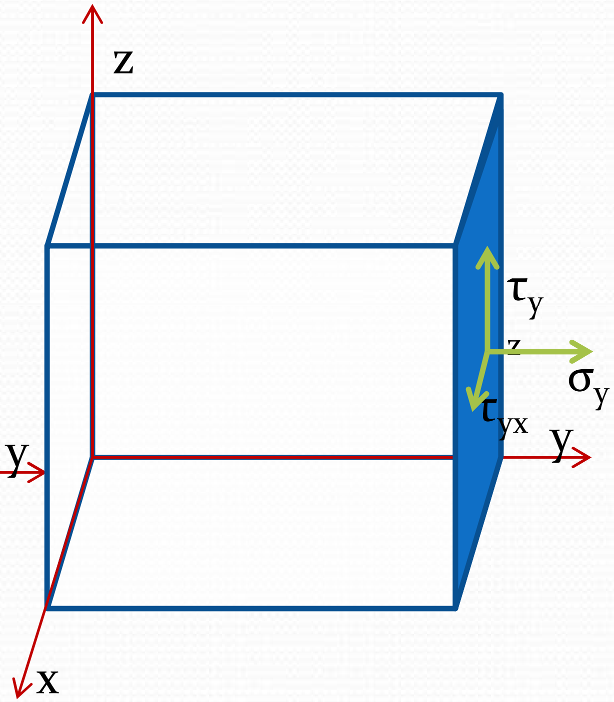
Y plane



X plane



Z plane



Y plane

- Three normal stress

$$\sigma_{xx} \qquad \sigma_{yy} \qquad \sigma_{zz}$$

(Repeated subscript)

- Six shear stress

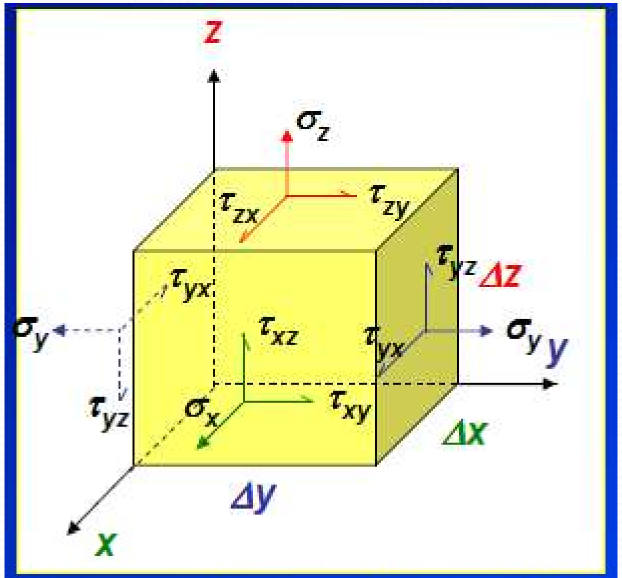
$$\tau_{xy} \qquad \tau_{xz}$$

$$\tau_{yx} \qquad \tau_{yz}$$

$$\tau_{zx} \qquad \tau_{zy}$$

(Mixed subscript)

Totally, nine components are required to represent the point stress



Stress acting on an element cube.

Shear stress are simplified as,

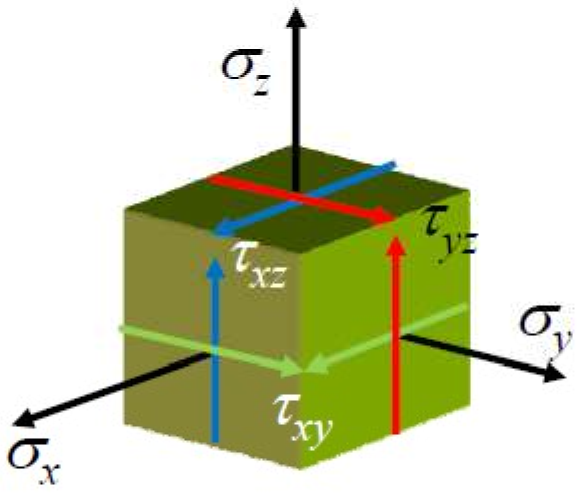
$$\tau_{xy} = \tau_{yx}$$
$$\tau_{xz} = \tau_{zx}$$
$$\tau_{yz} = \tau_{zy}$$

Therefore, only six components are required to represent point stress

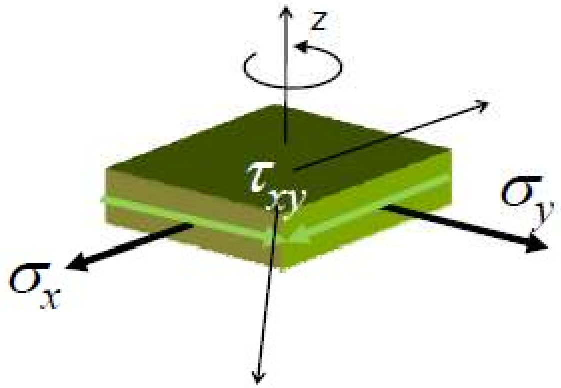
- Stress involve both forces and area, they are represented by Tensor
- Nine components of stress are needed to describe a state of stress fully at a point.
- Tensor notation is used to represent the state of stress

Stress Representation

General 3-D Stress



Plane Stress

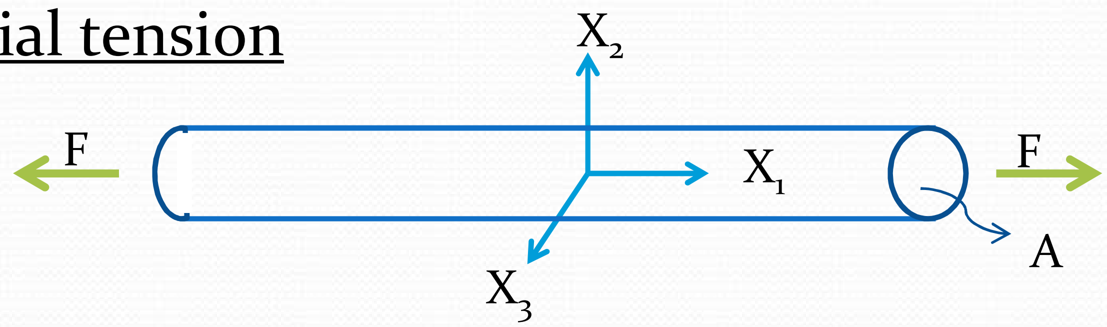


Tensor Notation

$$\begin{bmatrix} \sigma_x & \tau_{xy} & \tau_{xz} \\ \tau_{xy} & \sigma_y & \tau_{yz} \\ \tau_{xz} & \tau_{yz} & \sigma_z \end{bmatrix} = \begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & \sigma_{22} & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} \end{bmatrix} = \sigma_{ij}$$

$$\begin{bmatrix} \sigma_x & \tau_{xy} & 0 \\ \tau_{xy} & \sigma_y & 0 \\ 0 & 0 & 0 \end{bmatrix} = \sigma_{ij}$$

Uniaxial tension

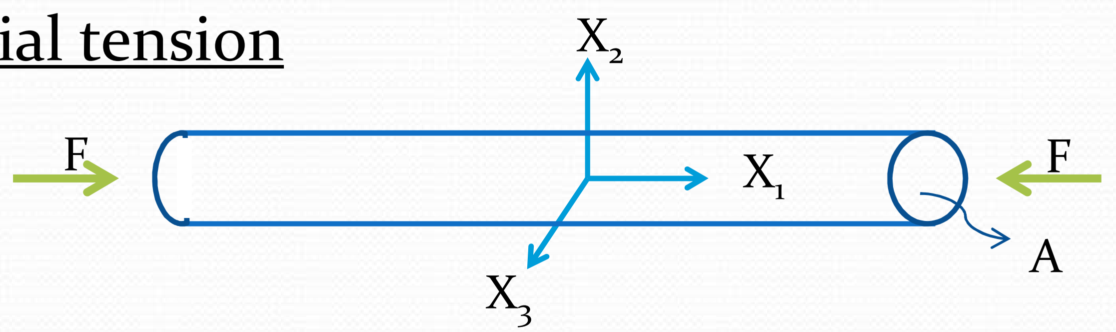


Choosing sensible axes, with one (x_1) along the axis of the rod, $\sigma_{11} = \sigma_1 = \sigma_x$ and all other $\sigma_{ij} = 0$:

$$\begin{bmatrix} \sigma & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

($\sigma > 0$ for tension)

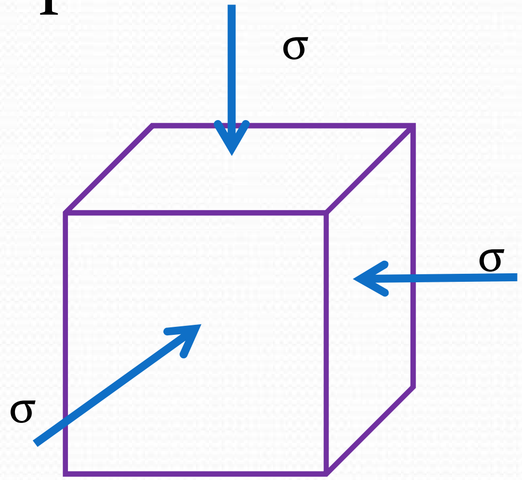
Uniaxial tension



$$\begin{bmatrix} -\sigma & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

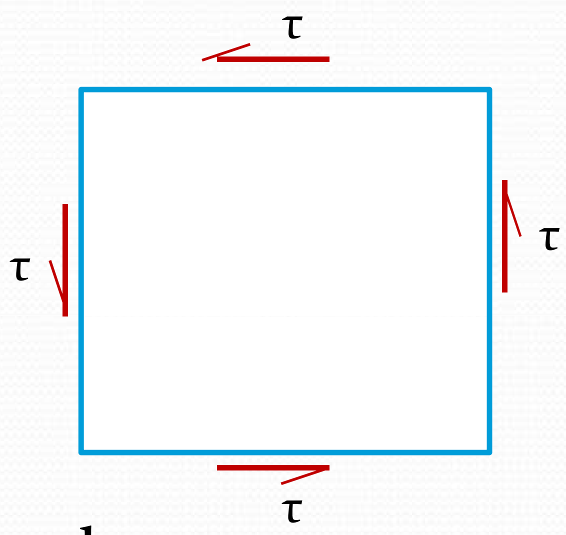
(σ<0 for compression)

Hydrostatic Compression



$$\begin{bmatrix} \sigma & 0 & 0 \\ 0 & \sigma & 0 \\ 0 & 0 & \sigma \end{bmatrix} (\sigma < 0)$$

Pure Shear

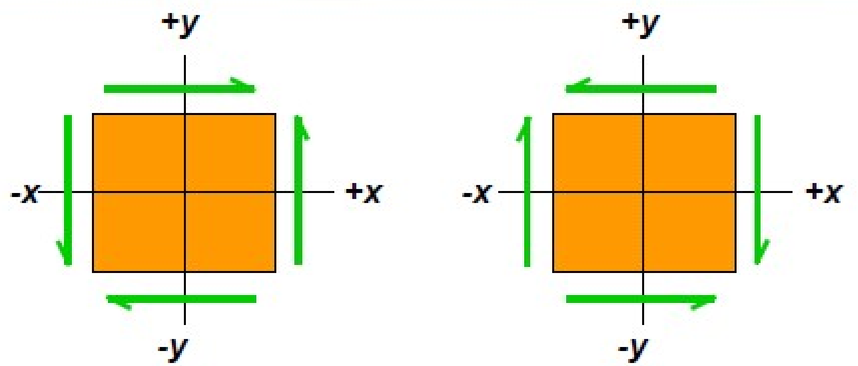


$\tau_{12} = \tau_{21} = \tau$ and all other $\tau_{ij} = 0$, so we have:

$$\begin{bmatrix} 0 & \tau & 0 \\ \tau & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

Sign convention for shear stress

- A shear stress is positive if it points in the positive direction on the positive face of a unit cube. (and negative direction on the negative face).
- A shear stress is negative if it points in the negative direction of a positive face of a unit cube. (and positive direction on the negative face).

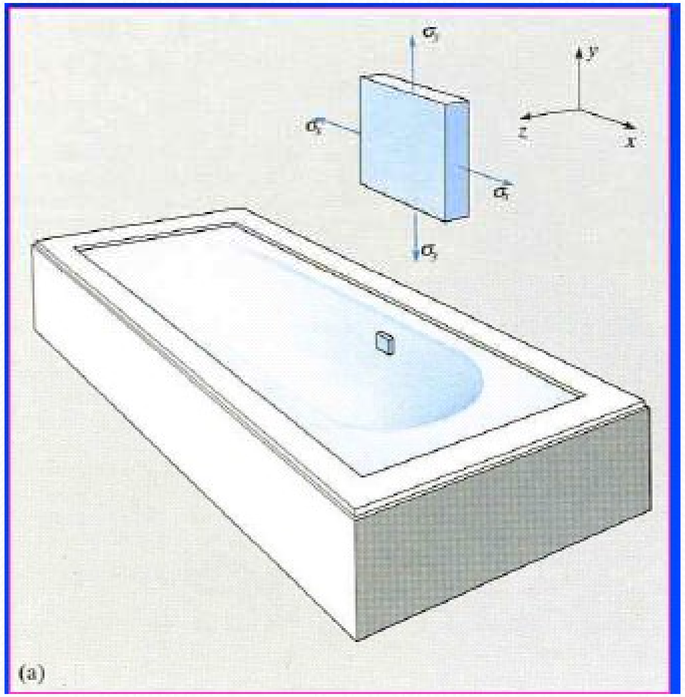


(a) Positive shear stresses.

(b) Negative shear stresses.

State of stress in two dimensions (Plane stress)

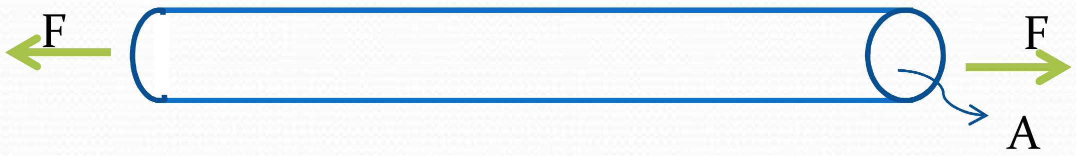
- Plane stress is a stress condition in which one of the primary direction stresses are zero.
- In a thin plate where load will be on the plane of the plate and there will be no stress acting perpendicular to the surface of the plate.
- The stress system consists of two normal stresses σ_x and σ_y and a shear stress τ_{xy}.



(a)

Yield Criteria

- Detecting mathematical relationship between combination stresses and plastic yielding.
- For unidirectional tension, yielding take places when stress σ=F/A reaches the critical value.



- If stress acts on multiaxial, then yield depends on combination of all the stress.
- Yielding in ductile material is predicted by two criteria.
  - Von Mises yield criterion (Distortion energy criterion)
  - Tresca yield criterion (Maximum shear stress)

Von Mises or Distortion Energy Criterion

Yielding occurs when the second invariant of the stress deviator J_2 > critical value k^2.

$J_2 = k^2$

Where $J_2 = \frac{1}{6}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right]$ & k is constant

For uniaxial tension, $\sigma_1 = \sigma_0, \sigma_2 = \sigma_3 = 0$ where σ_o is yield stress.

$$J_2 = \frac{1}{6}[2\sigma_0^2] = k^2$$

$$2\sigma_0^2 = 6k^2$$

$$\sigma_0^2 = 3k^2$$

$$\frac{1}{3}\sigma_0^2 = k^2$$

$$\frac{1}{3}\sigma_0^2 = k^2$$

$$J_2 = \frac{1}{6}\left[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2\right] > K^2$$

$$\frac{1}{6}\left[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2\right] > \frac{1}{3}\sigma_0^2$$

$$\sigma_0 = \frac{1}{\sqrt{2}}\left[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2\right]^{1/2}$$

The yielding occurs when,

$$\sigma_0 < \frac{1}{\sqrt{2}}\left[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2\right]^{1/2}$$

For pure shear stress (torsion test), σ_1=-σ_3 =τ, σ_2=0

$$J_2 = \frac{1}{6}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right]$$

$$\sigma_1^2 + \sigma_1^2 + 4\sigma_1^2 = 6k^2$$

$$\therefore \sigma_1 = k$$

The yield will occurs if,

$$\sigma_0 < \frac{1}{6}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right]^{1/2}$$

Comparing uniaxial tensile and torsion stress, yield stress for torsion is less than uniaxial tensile stress.

J2 can be represented as,

$$J_2 = \frac{1}{6}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 + 6(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{xz}^2)\right]$$

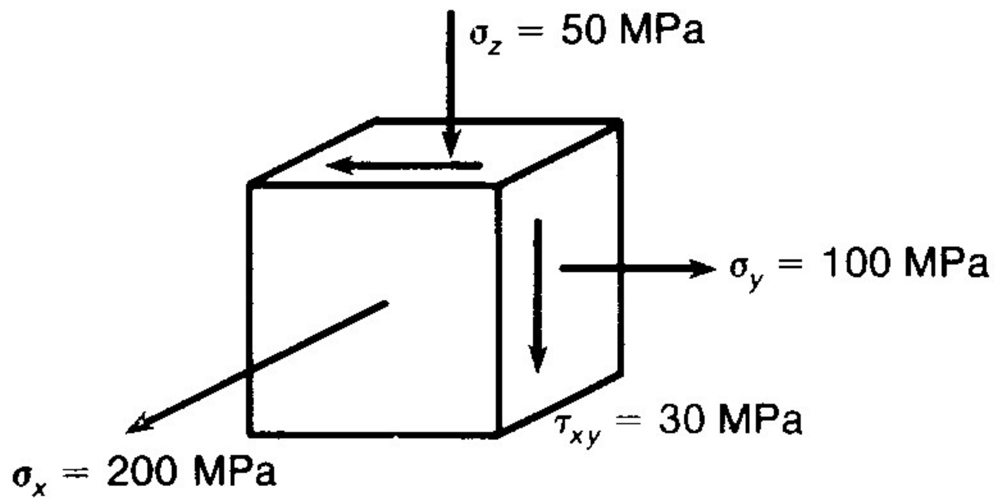
Then

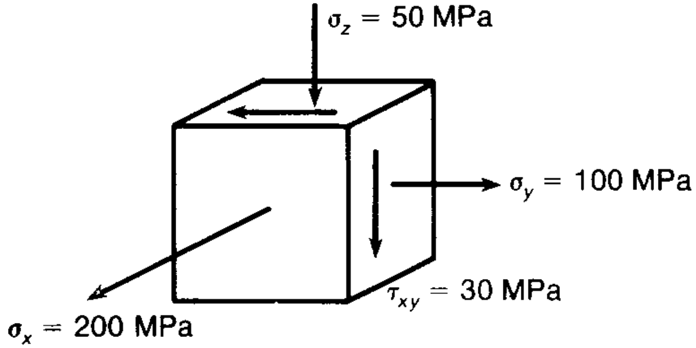
$$\sigma_0 = \frac{1}{\sqrt{2}}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 + 6(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{xz}^2)\right]^{1/2}$$

The yielding occurs when,

$$\sigma_0 < \frac{1}{\sqrt{2}}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 + 6(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{xz}^2)\right]^{1/2}$$

Problem: Stress analysis of a spacecraft structural member gives the state of stress shown below. If the part is made from 7075-T6 aluminium alloy with σ_o=500MPa, will it exhibit yielding? If not, what is the safety factor?





$$\sigma_0 < \frac{1}{\sqrt{2}}\left[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2+6(\tau_{xy}^2+\tau_{yz}^2+\tau_{xz}^2)\right]^{1/2}$$

$$\sigma_0 = \frac{1}{\sqrt{2}}\left[(200-100)^2+(100-(-50))^2+(-50-200)^2+6(30)^2\right]^{1/2}$$

$$\sigma_0 = \frac{1}{\sqrt{2}}(100{,}400)^{1/2} = \frac{316.859}{\sqrt{2}} = 224 \text{ MPa}$$

Safety factor = 500/224=2.2

Von Mises yield criterion implies that yielding is independent of normal or shear stress. It depends on a function of all three values of principal stress.

Maximum Shear Stress or Tresca Criterion

Yielding occurs when the maximum shear stress τ_{max} reaches the value of shear stress in the uniaxial-tension test.

$$\tau_{max} = \frac{\sigma_1 - \sigma_3}{2}$$

$$\sigma_1 > \sigma_3$$

For uniaxial tension, $\sigma_1 = \sigma_0, \sigma_2 = \sigma_3 = 0$

Therefore,

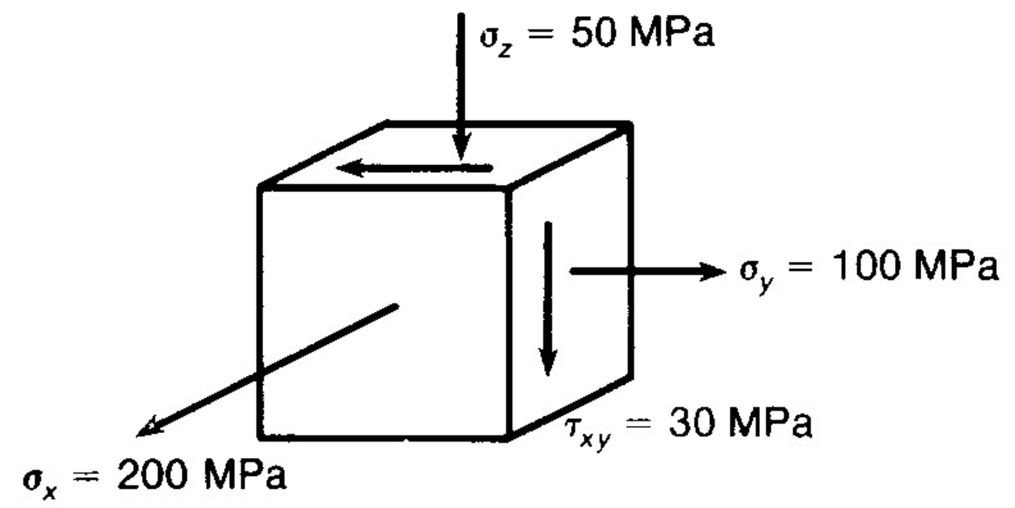
$$\tau_{max} = \frac{\sigma_1 - \sigma_3}{2} = \frac{\sigma_0}{2}$$

Pure stress condition, $\sigma_1 = -\sigma_3 = \sigma_0$, $\sigma_2 = 0$

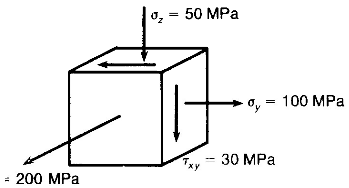
Then

$$\tau_{max} = \frac{\sigma_1 - \sigma_3}{2} = \frac{\sigma_1 - (-\sigma_1)}{2} = \sigma_0$$

Problem: Stress analysis of a spacecraft structural member gives the state of stress shown below. If the part is made from 7075-T6 aluminium alloy with σ_o=500MPa, will it exhibit yielding? (try with Tresca criterion)



Problem: Stress analysis of a spacecraft structural member gives the state of stress shown below. If the part is made from 7075-T6 aluminium alloy with σ_o=500MPa, will it exhibit yielding? (try with Tresca criterion)



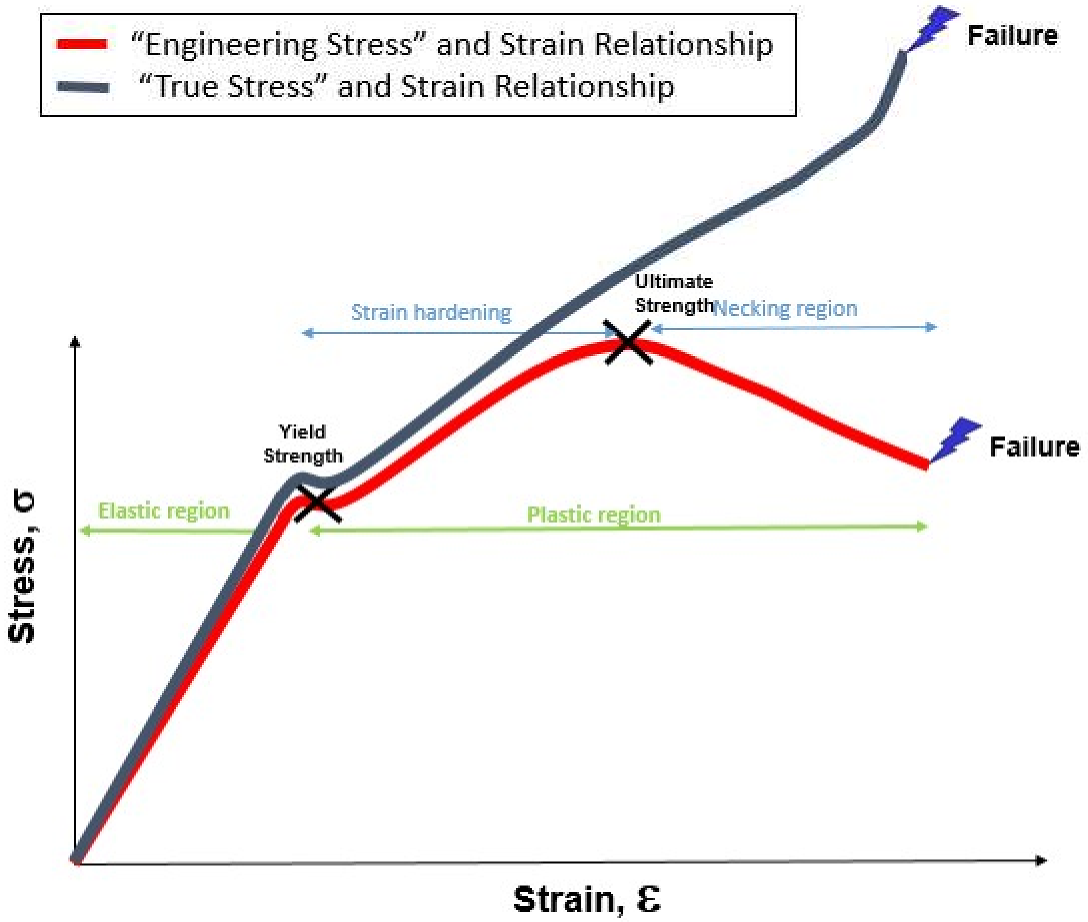
$$\tau_{max} = \frac{\sigma_x - \sigma_z}{2} = \frac{\sigma_0}{2}$$

$$200 - (-50) = \sigma_0$$

$$\sigma_0 = 250 \text{ MPa}$$

Calculated value is less than the yield strength.

True Stress-Strain Diagram



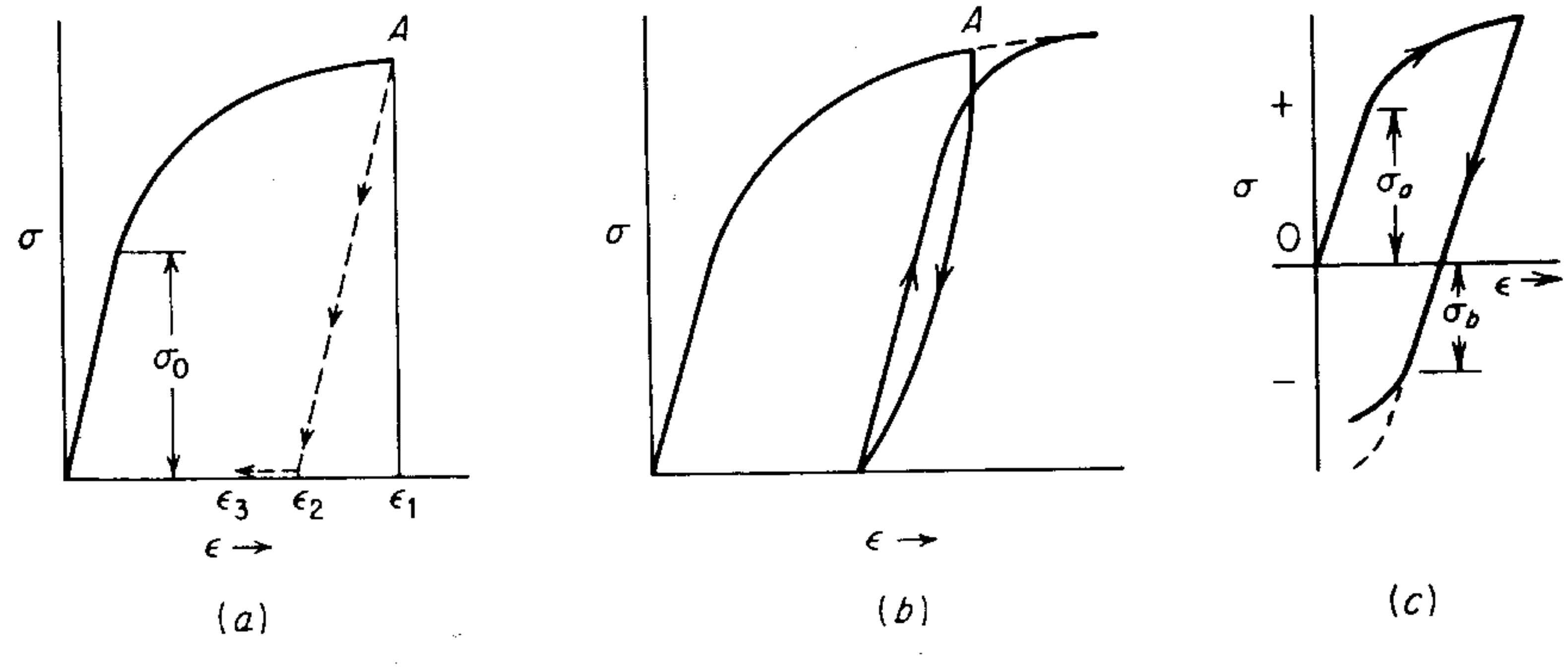


Figure 3-1 Typical true stress-strain curves for a ductile metal.

ε_1-ε_2 → recoverable elastic strain

ε_2-ε_3 → anelastic behaviour (depends on the metal, temperature and time)

(b) Unloading from plastic strain and reloading the curve bend over as the stress approaches to the original value

(c) Yeild stress on reloading is less than the original yield stress. $\sigma_b < \sigma_a$. The dependence of yield stress on loading path and direction is called the Bauschinger effect.

Flow Curve

True stress-strain curve is called as flow curve.

(Flow curve is the stress-strain curve for a material in the plastic range.)

From flow curve, flow stress determined by

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

K is the stress at ε=1.0

n is the strain hardening coefficient

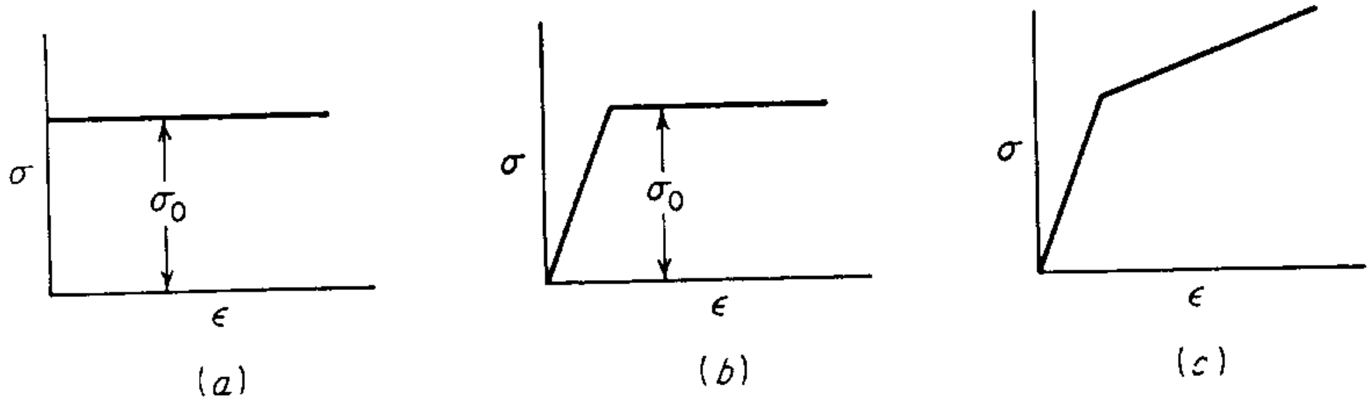
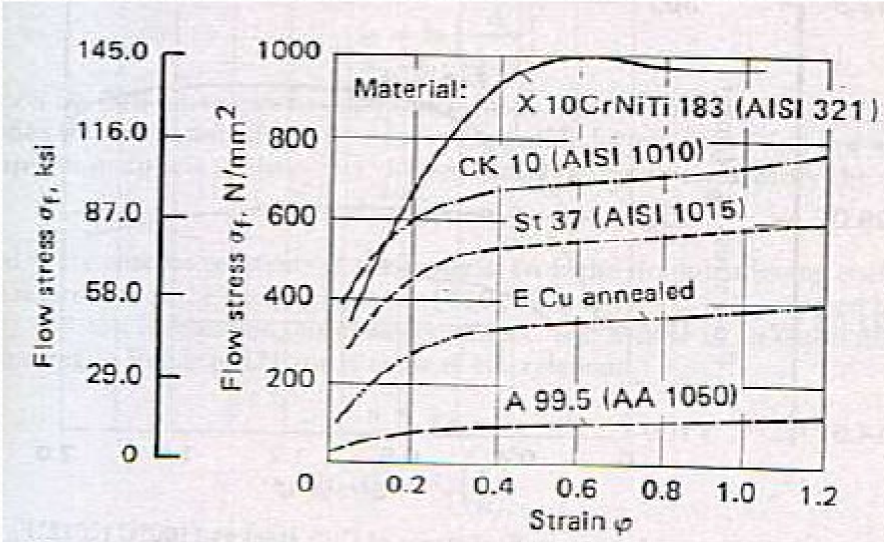


Figure 3-2 Idealized flow curves. (*a*) Rigid ideal plastic material; (*b*) ideal plastic material with elastic region; (*c*) piecewise linear (strain-hardening) material.

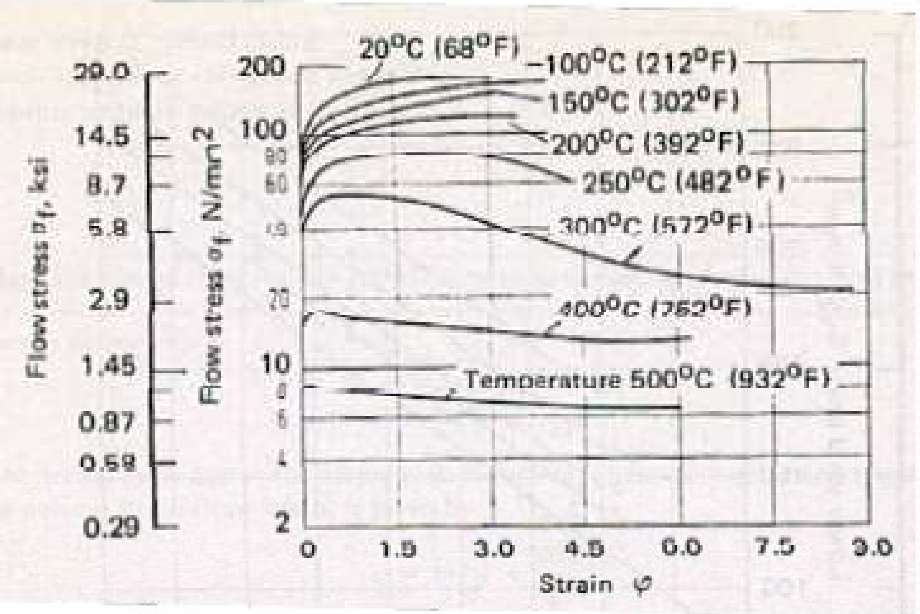
a) Flow curve for rigid material. Completely rigid (zero elastic strain) until the axial stress equals to σ_o. where upon the material flows plastically at a constant flow stress (n=o). Ex.: highly cold worked ductile material.
b) Perfectly plastic material has elastic and plastic region. Ex.: Plain carbon steel
c) Ideal plastic material has both elastic and plastic region.

- Flow curves indicates whether metal is readily deformed at given conditions, i.e., strain rate, temperature
- Flow curve is strongly dependent on strain rate and temperature.

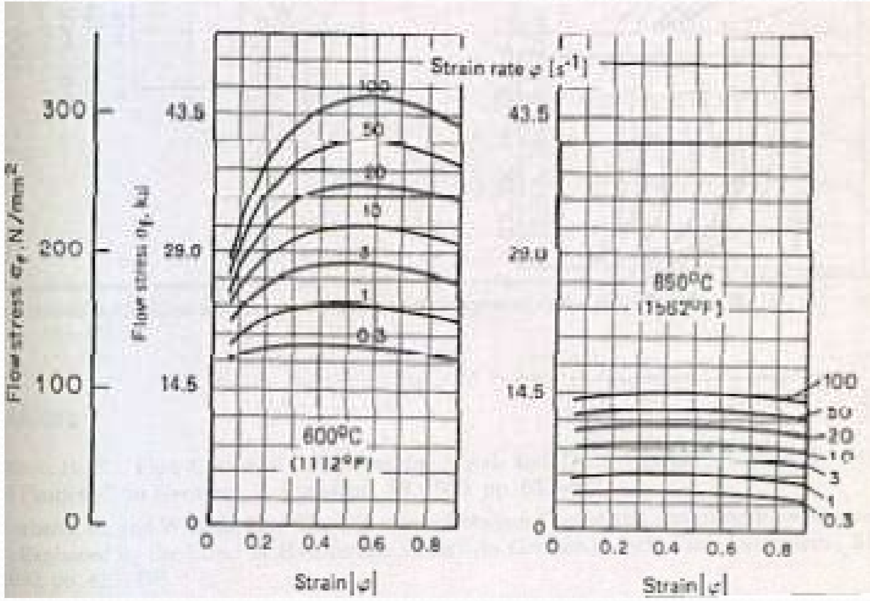


Flow curves of some metals at room temperature

Effect of strain rate & temp. on flow stress



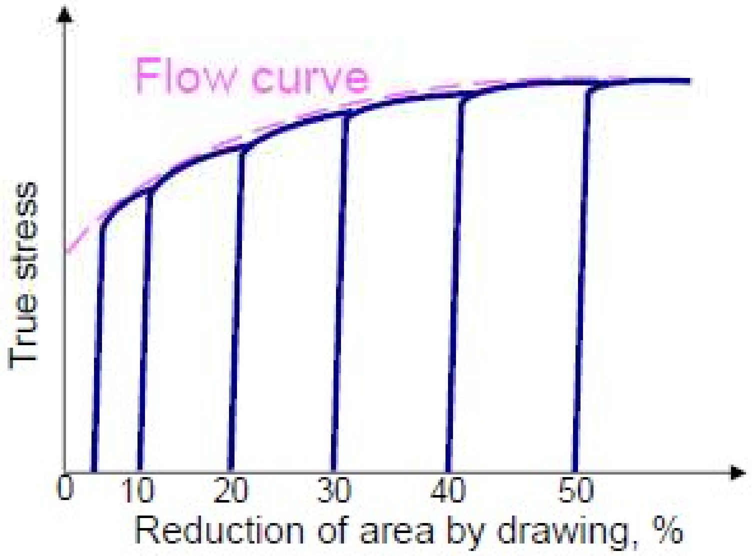
Flow stress of Al (Flow stress vs Strain)



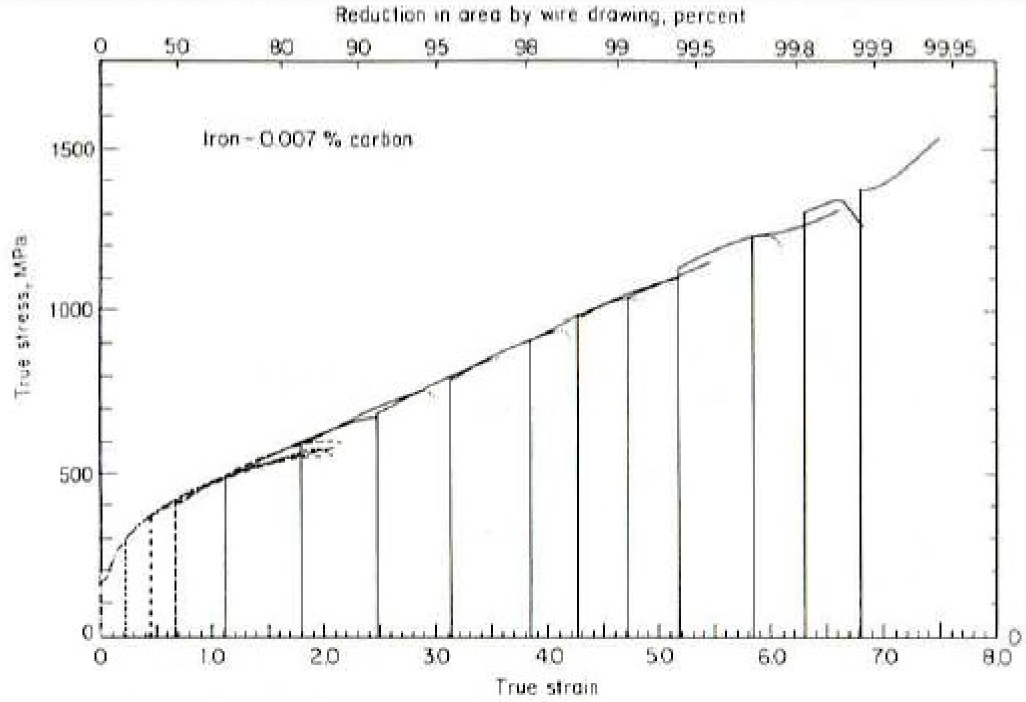
Flow curves of CuZn28

- If temperature increases flow stress decreases
- If strain rate increases, flow stress increases

Strain hardening occurred when an iron wire has been drawn to a specific true strain



Flow curve constructed from stress-strain curves after different amounts of reduction.



True stress-strain curve for iron wire deformed by wire drawing at room temperature

Flow Stress Determination

Stress required for continuous deformation is called as flow stress or forming stress or pressure.

$$p = \bar{\sigma}_o g(f) h(c)$$

Where $\bar{\sigma}_o$ - The stress which require to overcome the flow resistance of the material. It is function of strain, temperature and strain rate.

g(f) – An expression for the friction at the tool workpiece interface.

h(c) - a function of the geometry of tooling and geometry of deformation.

Metal working processes involve large plastic strains, it is possible to measure using flow curve or flow stress experimentally. But it require more facilities.

Metal working involves large plastic strain.

- Using flow curve, it is desirable to measure if true strain is between 2.0 to 4.0.
- Many process involves high strain rate ($\dot{\varepsilon} = 100 \sec^{-1}$) which is not possible to measure in ordinary laboratory test.
- Also, many metal working process take place in elevated temperature. Flow stress is depends on strain-rate and temperature and independent of strain.
- In test, flow stress is obtained under controlled conditions of temperature and constant true strain rate.
- In tension test, necking limits uniform deformation to true strains<0.5. Depends on the strain rate, necking limit is also varies.

Since flow stress is obtained by compression test to avoid necking.

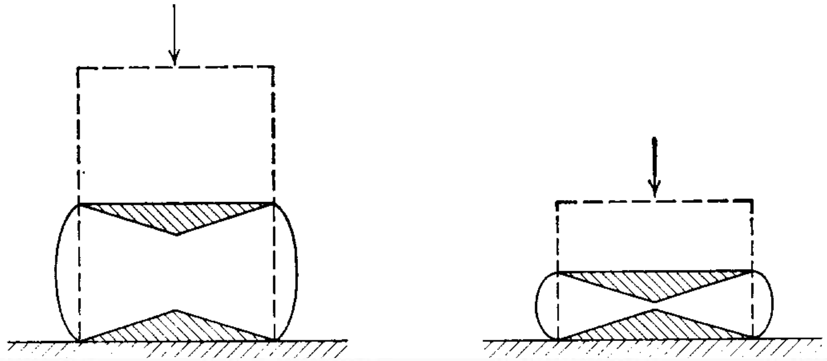
Consider a short cylinder of diameter D_o and initial height h_o is compressed. By controlling, the friction between specimen and anvil, the specimen reached height h and diameter D.

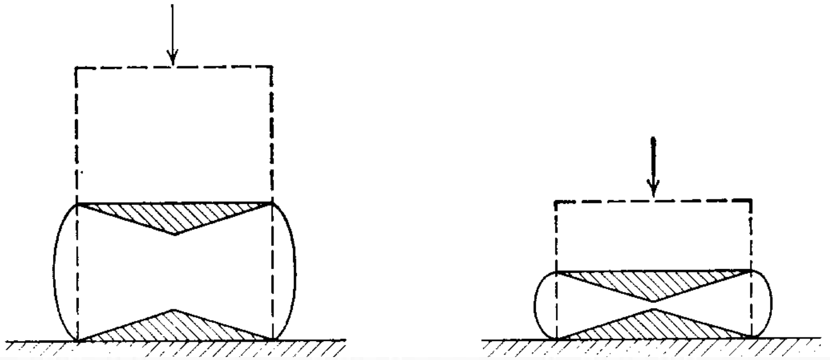
By law of constancy of volume,

$$D_0^2 h_0 = D^2 h$$

During the deformation, the frictional resistance occurs in the contact of specimen with anvil, where undeformed metals are created near the anvil surfaces. This leads to a barreled specimen profile.

The cone shaped undeformed metal zone approaches each other and overlab, then they raise the force required for deformation.





Using low value of D_o/h_o , barreling and non uniform deformation can be minimized. Practical limit for $D_o/h_o \sim 0.5$. Below this value , the specimen buckles instead of barreling.

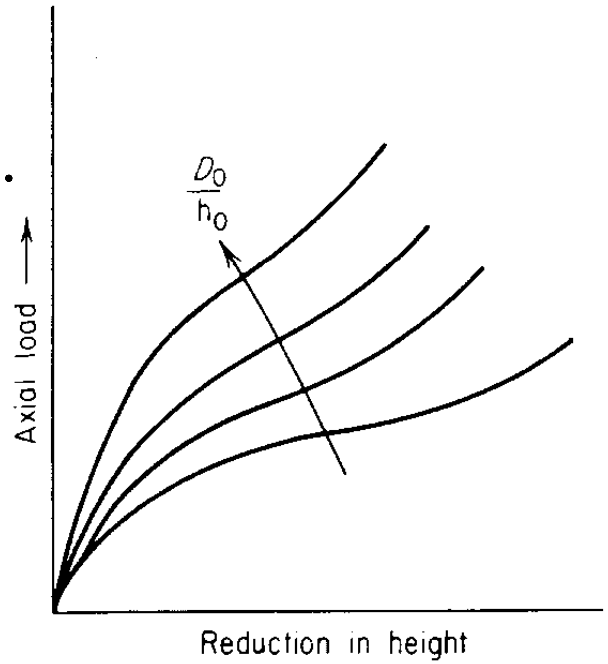


Figure : The load deformation curves for compression test with different values of D_o/h_o

The friction at the specimen and die interface can be minimized by using smooth, hardened platens, grooving the ends of the specimen to retain the lubricant. Teflon sheet for cold deformation and glass for hot deformation are effective lubricants.

When friction is not present the uniaxial compressive force required to produce yielding is

$$P = \sigma_o A \qquad \textit{P -force}$$

The true compressive stress p produced by this force is P is,

$$p = \frac{4P}{\pi D^2} \qquad \text{p-stress}$$

Using constant volume relationship, $D_0^2 h_0 = D^2 h$

$$p = \frac{4Ph}{\pi D_o^2 h_o}$$

Where D_o and h_o are initial diameter and height, h is height of the sample.

The true compressive strain is,

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

In a compression test, the true strain rate is continuously increases with the deformation.

Strain rate ≤ 10 s^{-1} → servo controlled testing machine – constant true strain rate.

1 ≤ strain rate ≤ 10^3 s^{-1} → Cam plastometer - constant true strain rate.

Temperature in Metal forming /Working Process

The methods used to mechanically shape metals into other product forms are called Working Processes which is classified as

- hot-working,
- cold-working
- warm working

Hot working ($0.6\text{-}0.8T_m$)

Definition : Deformation under conditions of temperature and strain rate such that recrystallisation process take place simultaneously with the deformation.

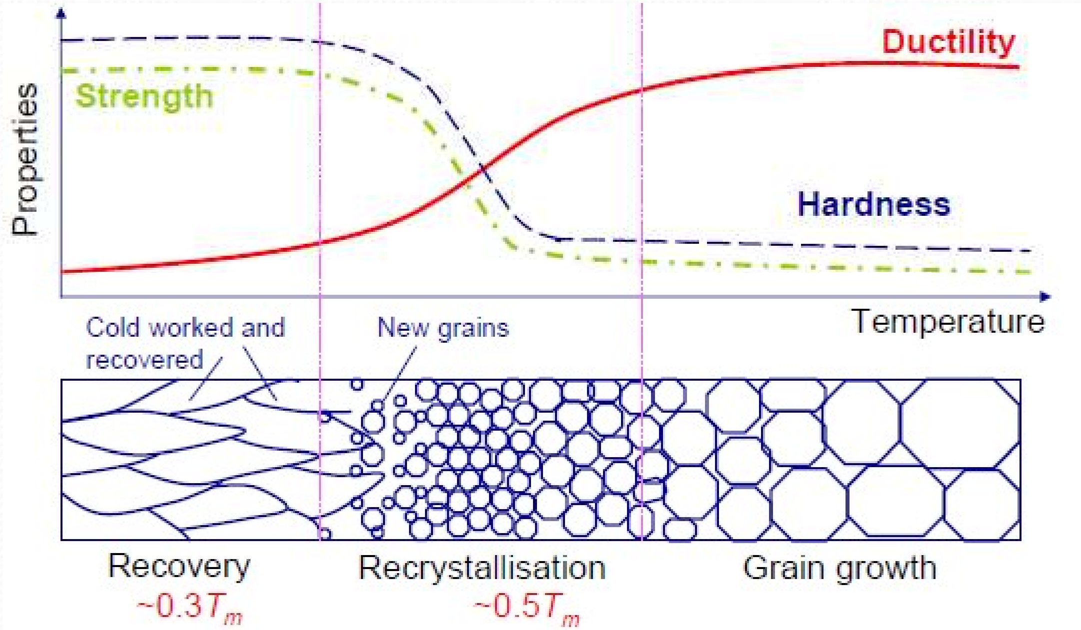
Examples : rolling, forging, extrusion

Cold working ($< 0.3T_m$)

Definition : Deformation carried out under conditions where recovery processes are not effective.

Examples : rolling, forging, extrusion, wire/tube drawing, swaging, coining

Effect of temperature on cold working



Hot Working

- Hot working involves deformation at temperatures where recrystallisation can occur (0.6-0.8 Tm) and at high strain rates in the range 0.5 to 500 s^{-1}.
- Recrystallization temperature = about one-half of melting point on absolute scale
- Metal continues to soften as temperature increases above 0.5Tm, enhancing advantage of hot working above this level
- Hot working processes such as rolling, extrusion or forging. (Normally cast ingot is converted into wrought product).

Hot Working

- The strain in hot working is large compared with tension or creep tests.
- Hot torsion test is used for studying metallurgical changes in hot working.

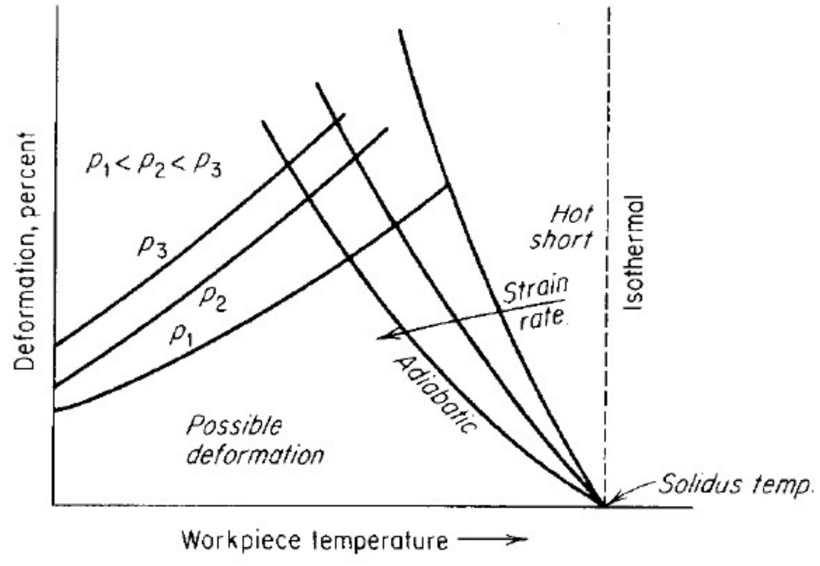
Advantages: In hot working,

- energy required to deform the metal is less and also deformation take place without cracking.
- Due to rapid diffusion, chemical homogeneities is also maintained in the cast ingot structure.
- Blow holes and porosity are eliminated by welding together of these cavities
- The coarse columnar grain of the casting are refined into smaller equiaxed recrystallized grains.
- It result in an increase in ductility and toughness over the cast state.

Disadvantages: In hot working,

- high temperatures are usually involved, surface of metal react with furnace atmosphere. Due to corrosion, considerable amount of metal may be lost.
- Highly reactive metal, like Ti undergo severely embrittlement by oxygen. Since those metals require inert atmosphere or protected from the air by a suitable barrier.

- In steel, surface undergoes decarburization which require extensive surface finishing by removal of decarburized layer. Rolled-in oxide makes difficult for good surface finished.

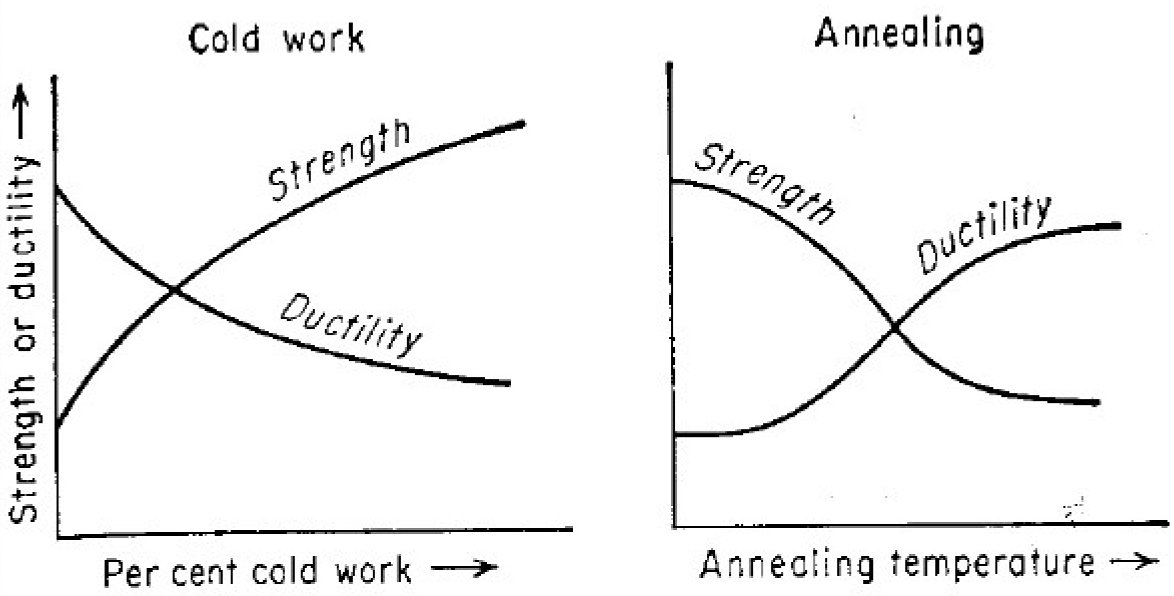


- Structure and properties of hot worked metals are not uniform throughout hot worked metals. In the surface, the metal will have a finer recrystallized grain size than core due to temperature gradient in cooling.

Cold Working:

- Strength and hardness of cold working of metal increases obviously decreases the ductility.
- When cold working is excessive, metal undergoes fracture before end shape and size.
- In order to avoid fracture, intermediate annealing is required to restore ductility.
- The repeated cold working and anneanling sequence is called as cold-work-anneal cycle.
- The need of annealing operation increases the cost of forming by cold-working.
- Some of reactive metals requires annealing in vacuum or inert atmosphere to avoid corrosion.

- By suitable cold work anneal cycle, desired degree of strain hardening is possible.
- In cold working products like strip and wire in different tempers (annealing)is done based on the degree of cold reduction.
- The cold worked condition is described as the annealed (soft) temper: quarter-hard, half-hard, three-quater-hard, full-hard, and spring temper. Each temper condition indicates a different percentage of cold reduction following the annealing treatment.



Warm Working

- Warm working is the plastic deformation of a metal at temperatures below the temperature range for recrystallization and above room temperature.
- It has the advantages of both hot and cold working into one operation.

Ex: Forging of steel which require fewer forging steps, reduced forging loads and lower energy (due to elimination of annealing steps) the cold forging.

When compared to hot forging, improved dimensional control, higher quality surfaces and lower energy costs.

- For better warm working requires proper lubricant and selection of material and die design.

Cold working	Hot working
Strain hardening is nor relieved in cold working	Strain hardening and distorted grain structure produced by deformation are rapidly eliminated by the formation of new strain free grains due to recrystallisation
Limited deformation is possible. Since recovery processes is not effective.	Very large deformation is possible due to recovery processes which take place along with deformation
The flow stress increases with deformation	Hot working takes place, at constant flow stress.
Energy required for deformation is high than hot working.	Energy required for deformation is much less than cold working.
Possibility for fracture is high in cold working. In intermediate annealing is necessary for cold working to avoid fracture.	Possible for fracture is less than cold working
Increases the strength and hardness but decreases the ductility	Ductility of materials maintained as such.

Temperature in Metal working

The temperature of the work-piece in metal working depends on,

- The initial temperature of the tools and the material
- Heat generation due to plastic deformation
- Heat generated by friction at the die/material interface
- Heat transfer between the deforming material and the dies and surrounding environment.

For a frictionless deformation process, the maximum increases in temperature is

$$T_d = \frac{U_p}{\rho c} = \frac{\overline{\sigma \varepsilon} \beta}{\rho c}$$

Where U_p = the work of plastic deformation per unit volume

ρ = the density of workpiece

c = the specific heat of the workpiece

β = fraction of deformation work converted into heat. Typically β=0.95. The remaining work stored in the material as energy associated with the defect structure.

The temperature increase due to friction is given by

$$T_f = \frac{\mu p \upsilon A \Delta t}{\rho c V}$$

Where μ = friction coefficient at material/tool interface

p = stress normal to interface

ν = velocity at the material /tool interface

A = surface area at the material /tool interface

Δt = time interval of consideration

V = volume subjected to the temperature rise

- The average instantaneous temperature of the deforming materials at the interface is given by,

$$T = T_1 + (T_0 - T_1)\exp\left(\frac{-ht}{\rho c \delta}\right)$$

where, *h*- heat transfer coefficient between the material and the dies

δ - material thickness between the dies.

T_o - work piece initial temperature

T_1 - die initial temperature

The final average material temperature at a time '*t*' is,

$$T_m = T_d + T_f + T$$

Problem: Compare the temperature rise when a cylinder of Al and Ti is quickly deformed to $\bar{\varepsilon}$ = 1.0 at room temperature.

	$\bar{\sigma}$, MPa	$\bar{\varepsilon}$	ρ, kg m^{-3}	c, J kg^{-1} K^{-1}
Al	200	1.0	2690	900
Ti	400	1.0	4500	519

Problem: Compare the temperature rise when a cylinder of Al and Ti is quickly deformed to $\bar{\varepsilon}$ = 1.0 at room temperature.

	$\bar{\sigma}$, MPa	$\bar{\varepsilon}$	ρ, kg m^{-3}	c, J kg^{-1} K^{-1}
Al	200	1.0	2690	900
Ti	400	1.0	4500	519

For aluminum

$$\Delta T_d = \frac{\bar{\sigma}\bar{\varepsilon}\beta}{\rho c} = \frac{(200 \times 10^6)(1.0)(0.95)}{(2690)(900)} = 78 \text{ K}$$

For titanium

$$\Delta T_d = \frac{(400 \times 10^6)(1.0)(0.95)}{(4500)(519)} = 162 \text{ K}$$

Friction and Lubricants

- The frictional force developed between tools and workpiece which place major role in metal working,
- The frictional coefficient μ,

$$\mu = \frac{\tau}{p}$$

where τ – shear stress between tool and workpiece

p – normal stress between tool and workpiece

- Average deformation pressure increases with frictional coefficient.
- Surface finish of workpiece depends on tool surface.
  - In cold working, smooth tool produce shiny surface finish and vice versa. Rough tool with lubricant produce dull and matte surface.

- Ploughing: Hard surface of the tool penetrate the softer surface and displace the volume of metal proportional to the length of sliding and cross sectional area of the asperity.
  - The plouging force is related to the flow properties of workpiece and size and shape of the asperity
  - Smooth dies are important to avoid ploughing
- Pick up: The inadequate lubrication in metal working transfer the workpiece material to the tools. Metal transfer occurs in two ways.
  - If lubricant film is decreases at the interface of a rough tool surface.
  - If the lubricant breaks down under high pressure.
- Wear: Due to many sliding cylces, tool surface undergoes wear. Chief wear mechanism → abrasion by hard oxide particles on the workpiece.
- Fatigue: Due to buildup and release of the interface pressure, surface fatigue take place on the tool.
- Crack: Thermal stresses arising from heating and cooling of the tools.

Functions of a lubricant in metal working:

- Reduces deformation load
- Raises the unifrom deformation of workpiece
- Controls surface finish
- Minimizes metal pickup on tools
- Minimizes tool wear
- Thermally insulates the workpiece and the tool
- Cools the workpiece and/or tools

Properties of Lubricants

- Lubricant has to function over a wide range of pressure, temperature and sliding velocities
- Lubricant must have spreading and wetting characteristics
- Should have thermal stability and resistance to minor contaminates.
- Good lubricant produces a harmless residue which does not affect subsequent heat treatment or welding
- Lubricant should be easily removed
- Lubricant should be nontoxic, free of fire hazard and inexpensive

Types of Lubricants

Boundary Lubricants:

- Thin organic film physically absorbed or chemisorbed on the metal surface.
- They are polar substances

  Ex.: Fatty acids, alcholols and fatty oil derivatives
- The film formed by these lubricants have a low shear strength
- They are pressure and temperature dependent
- μ vary from 0.1 to 0.4

Full Fluid Film lubrication:

- Tool and surfaces are fully separated by fluid film
- These lubricants are used in high speed wiredrawing and rolling.
- Fluid film thickness is quite high which completely avoid wear.
- μ vary from 0.001 and 0.02

Mixed Film Lubrication:

- Boundary lubricants with extreme pressure additives

Conversion coatings:

To retain the lubricant in the workpeice , a base like oxides, phosphates or chromates applied on the workpeice surface.

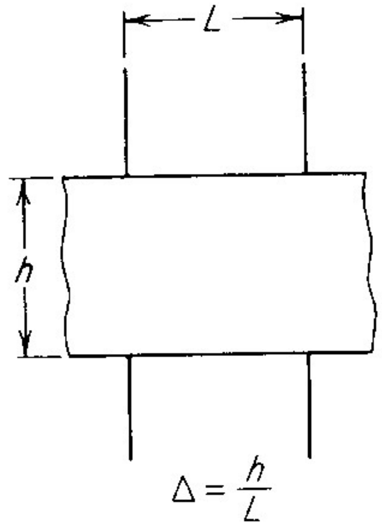
These coatings also have lubricating properties.

Deformation Zone Geometry

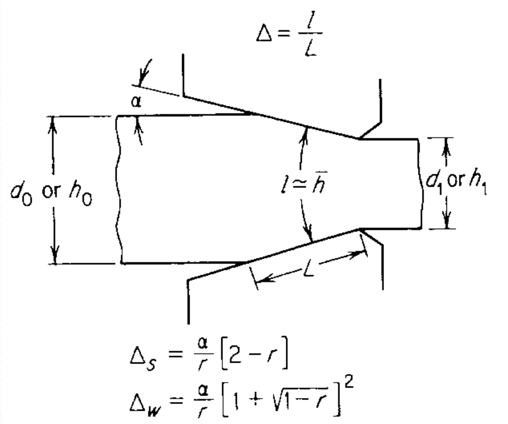
- During deformation, materials flow through a channel i.e. Dies.
- The basic feature of each channel is ratio of the mean thickness to the length of the deformation zone.

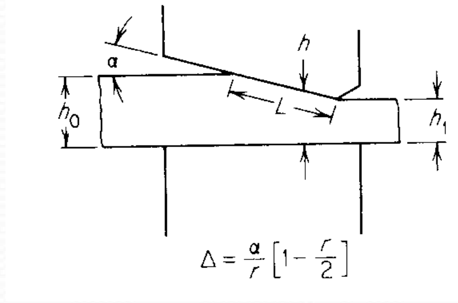
$$\Delta = \frac{h}{L}$$

- The value of Δ vary with respect to geometry



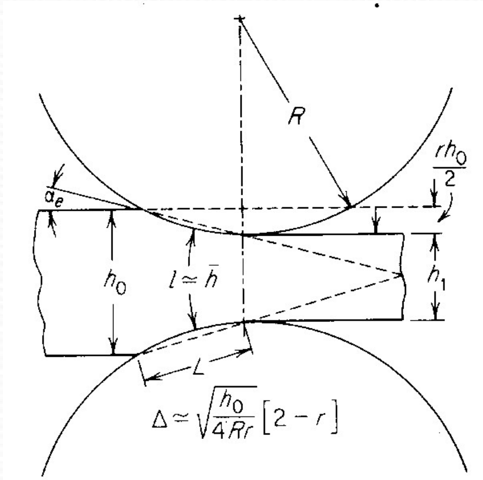
Parallel indenters
(Plane-strain compression)





Tube drawing over a mandrel

Drawing or extrusion of strip or wire



The die pressure increases the greater the ratio of h/L and neglects friction.

The smaller h/L ratio the greater the effect of friction at the tool-workpiece interface

Rolling

Workability

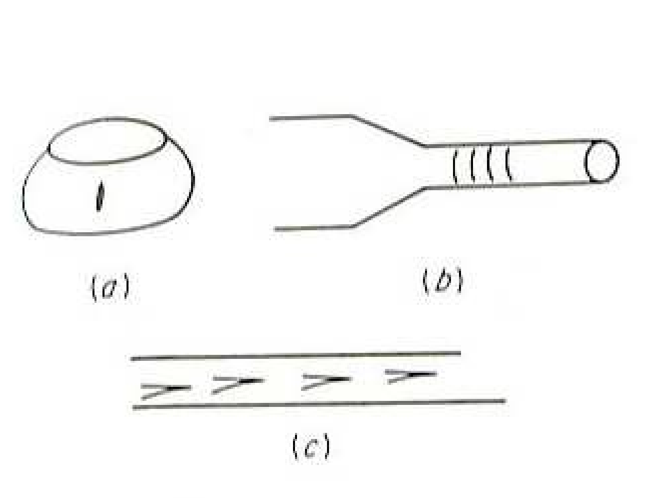
The extent to which a material can be deformed in a specific metal working process without the formation of cracks.

It depends on two factors such as

1. Properties of materials which can be obtained from lab testing
2. Parameters of the deformation process like die geometry, lubrication conditions and workpiece geometry

Cracks which occurs during the process are classified under three categories such as

1. Cracks at free surface
2. Cracks at surface due to interface frictions
3. Internal cracks



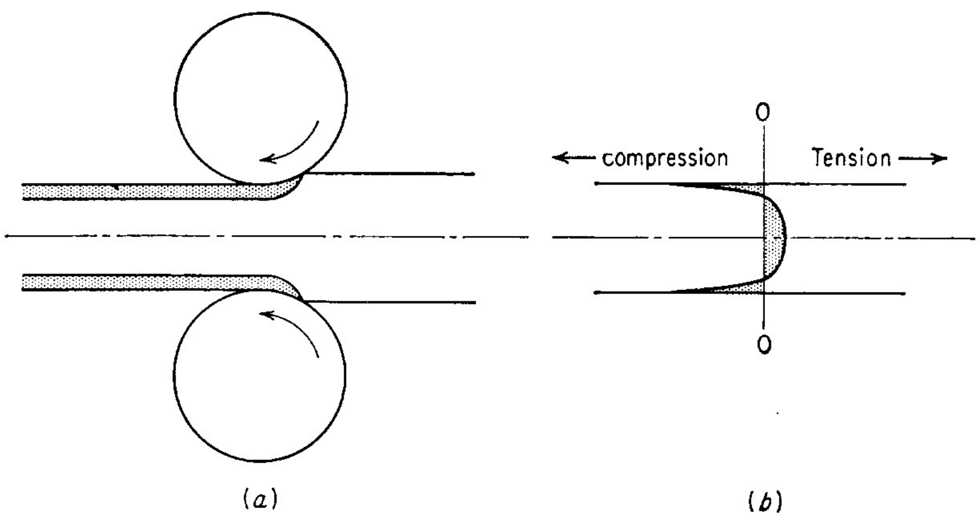
Examples of cracks in metalworking (a) free surface crack (b) surface crack from heavy die friction in extrusion, (c) centre burst or chevron cracks in a drawn rod.

- Internal cracks develop due to secondary tensile stresses ($\Delta = h/L$ which is very high)
- Temperature gradient
- In ductile material, during deformation formation and growth of holes around second phase particles leads to ductile fracture.

Residual Stress

Residual stresses is generated by non-uniform plastic deformation when external stresses are removed.

Ex: in rolling process, the surface grains in the sheet are deformed and tend to elongate, while the grain in the centre are unaffected.



(a) Inhomogeneous deformation in rolling of sheet, (b) resulting distribution of longitudinal residual stress over thickness of sheet.

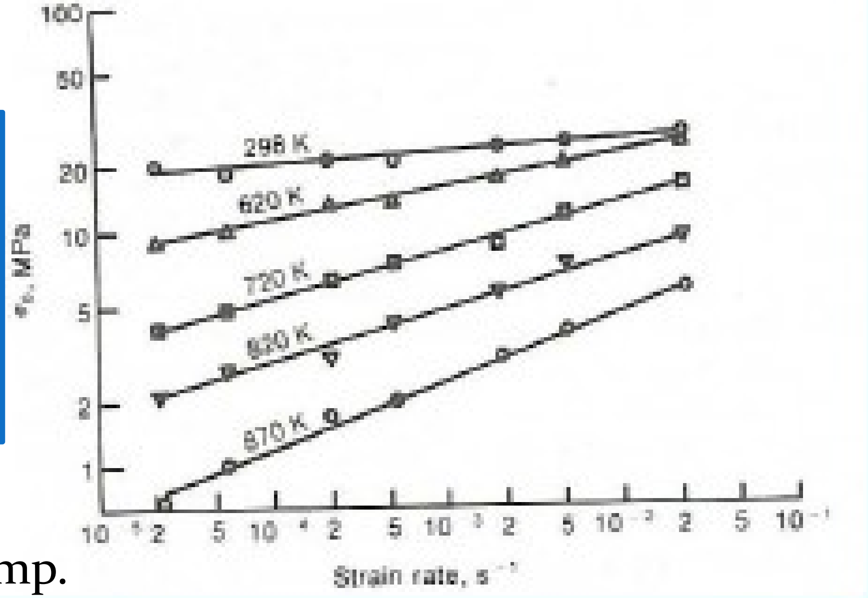
- Due to continuity of the sheet, the central fibres tend to restrain the surface fibres from elongating while the surface fibres tend to stretch the central fibres.
- Residual stress pattern consisting of high compressive stress at the surface and tensile stress in the centre
- The residual stress in a body must be in equilibrium. The area under the curve subjected to compressive residual stresses must balance the area subjected to tensile stress.
- Residual stresses are only elastic stresses. The maximum it can reach up to yield stress of the material.

- Residual stress can be relieved partially or completely by heating to a required temperature. Slow cooling from the annealing temperature is important.
- Differential strains that produce residual stresses can be reduced by substantially at room temperature by plastic deformation.
  - Sheet, plate, and extrusions are often stretched several percent beyond the yield stress to relieve differential strains by plastic deformation.
  - Cold-drawn rod and tube are relieved by roller strainghtening
- Residual stress calculation is difficult by analytical methods. Since it is mostly determined by experimental techniques. They are,
  - Destructive techniques (XRD, Neutron diffraction method, synchrotron diffraction method)
  - Non destructive techniques (Hole drilling strain gauge method)

Strain rate effect

- Strain rate is also called ad deformation velocity
- The three principal effects in high strain rate metalworking,
  - The flow stress of the metal increases with strain rate
  - The temperature of the workpeice is increases due to adiabatic heating
  - Improved lubrication at the tool metal interface, when lubricant film is maintained.

Very high strain rate induces,
- metal cracking
- plastic instability in cold working
- hot shortness in hot working



Flow stress depends on strain rate and temp.

- The true strain is represented as,

$$\dot{\varepsilon} = \frac{d\varepsilon}{dt} = \frac{1}{h}\frac{dh}{dt} = \frac{\upsilon}{h}$$

Where h – instantaneous height

υ – the formation velocity

- h varies with axial distance, the average or mean strain rate is used.

$$\bar{\dot{\varepsilon}} = \frac{1}{L}\int_0^L \dot{\varepsilon}\,dx$$

where L – length of contact between tool and workpiece

- The mean strain rate in terms of the time,

$$\bar{\dot{\varepsilon}}_t = \frac{1}{t_f}\int_0^{t_f} \dot{\varepsilon}\,dt$$

Where t_f – the element to travel through the die

- For large reductions (like hot extrusion), strain rate depends on strain rate sensitive of materials which is represented as,

$$\dot{\varepsilon}_{rmp} = \left[\frac{1}{\ln R}\int_o^{\ln R} (\dot{\varepsilon})^m \, d\varepsilon\right]^{1/m}$$

Where R=Ao/A is the deformation ratio

m – strain-rate sensitivity (always < 0.1, for hot working 0.1 – 0.2)

Typical values of velocity encountered in different testing and forming operations

Operation	Velocity, m s^{-1}
Tension test	6×10^{-7} to 6×10^{-3}
Hydraulic extrusion press	3×10^{-3} to 3
Mechanical press	0.1 to 1
Charpy impact test	3 to 6
Forging hammer	3 to 10
Explosive forming	30 to 120

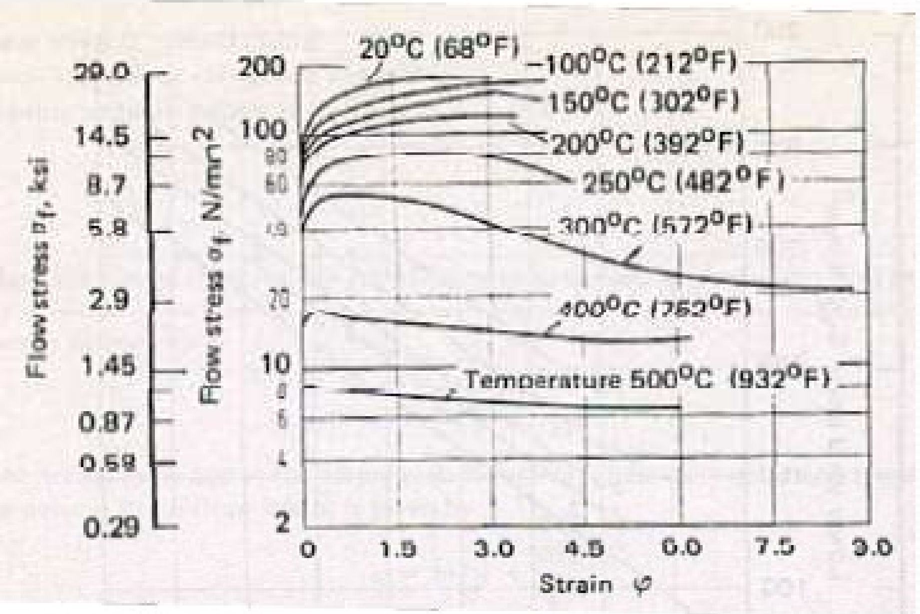
- Normal forming velocity with small deformation zone produce very high strain rates.

Ex: wire drawing (strain rate 10^5 S^{-1})

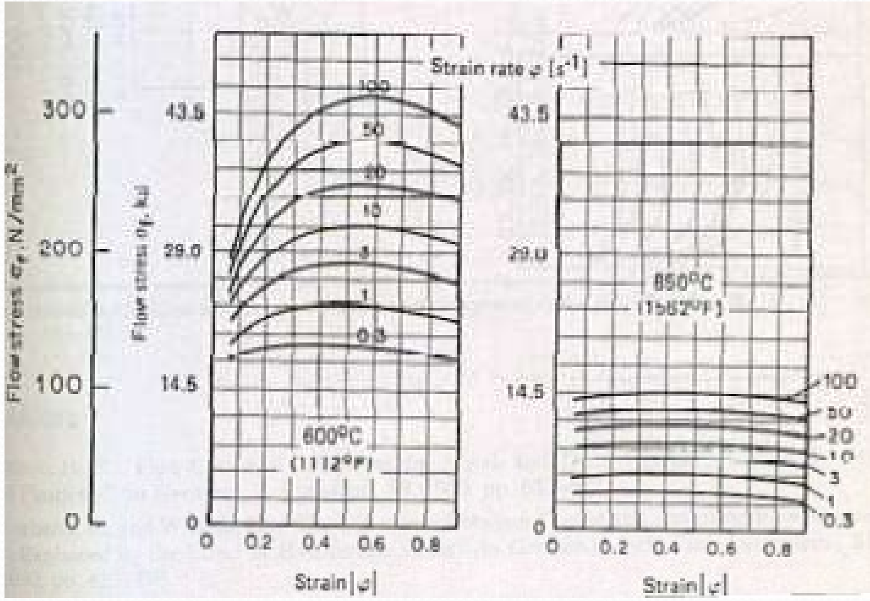
- Metal working which utilize very high velocities as $200ms^{-1}$, then the processes are called as High Energy Rate Forming (HERF).
  - These process use exploding gas or conventional explosive to produce high particle velocities.
  - Explosive hardening, grain distortion may or may not take place(depends of the material)
- superplasticity forming:
  - strain-rate sensitivity $0.3 < m < 1.0$
  - Deformation temperatures $> 0.4T_m$
  - Grain size of material of the order of 1 μm
  - Superplastic material have limiting stain rate above which it is no longer superplastic material.

    (Strain rate < $0.01ms^{-1}$,)
  - Low flow stress 5 to 40MPa.

Effect of strain rate & temp. on flow stress



Flow stress of Al (Flow stress vs Strain)



Flow curves of CuZn28

- If temperature increases flow stress decreases
- If strain rate increases, flow stress increases

Effects of metallurgical structure on working processes

- During deformation, material undergoes strain hardening.
- The dislocation structure of strain hardened metal was shown in below which consists of cellular substructure with cell walls composed of dislocation.

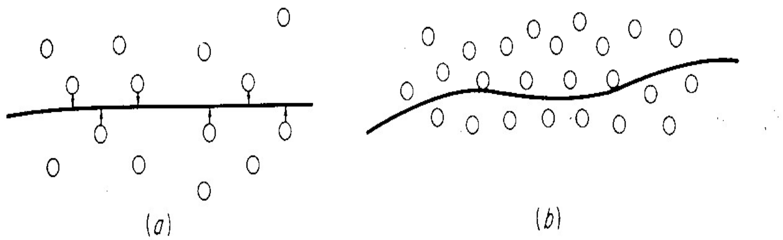


Figure 6-13 (*a*) Straight dislocation line in random solid solution; (*b*) flexible dislocation line.

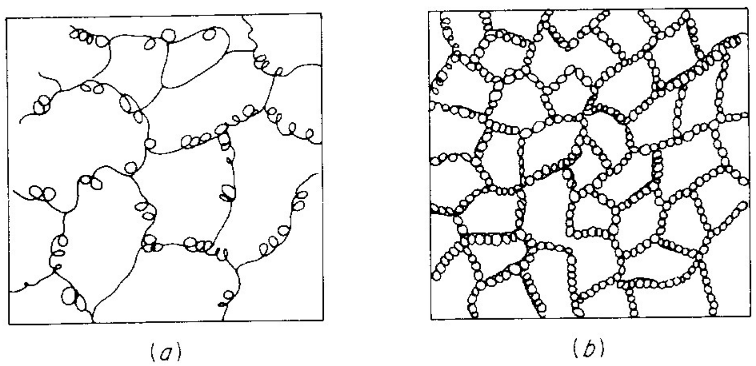
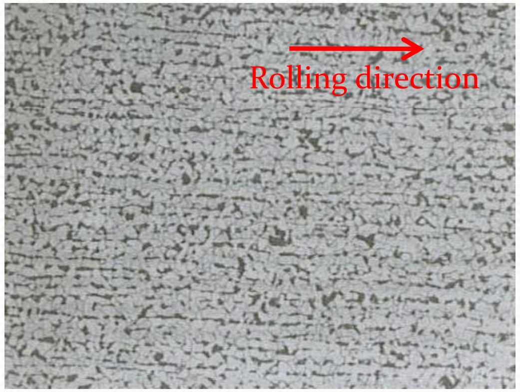


Figure 6-28 (*a*) Deformed to 10 percent strain. Beginning of cell formation with dislocation tangles; (*b*) deformed to 50 percent strain. Equilibrium cell size with heavy dislocation density in cell walls (schematic).

- For large plastic strains like wire drawing and rolling of cold worked structure have highly elongated grains containing relatively equiaxed dislocation cell structure.
- The dislocation cell structure decreases with plastic strain.
- The relationship between flow stress and dislocation cell size 'd' for cold drawn iron wire is,

$$\sigma_o = a + md^{-1}$$

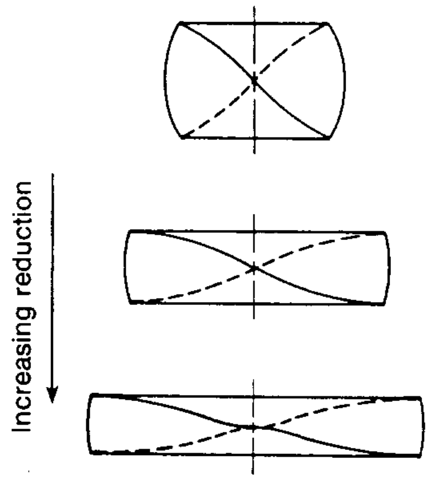
a and m are material constants.



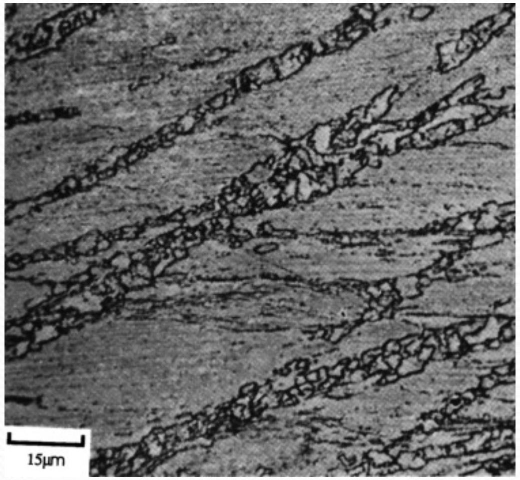
Fibrous texture in rolled sheet

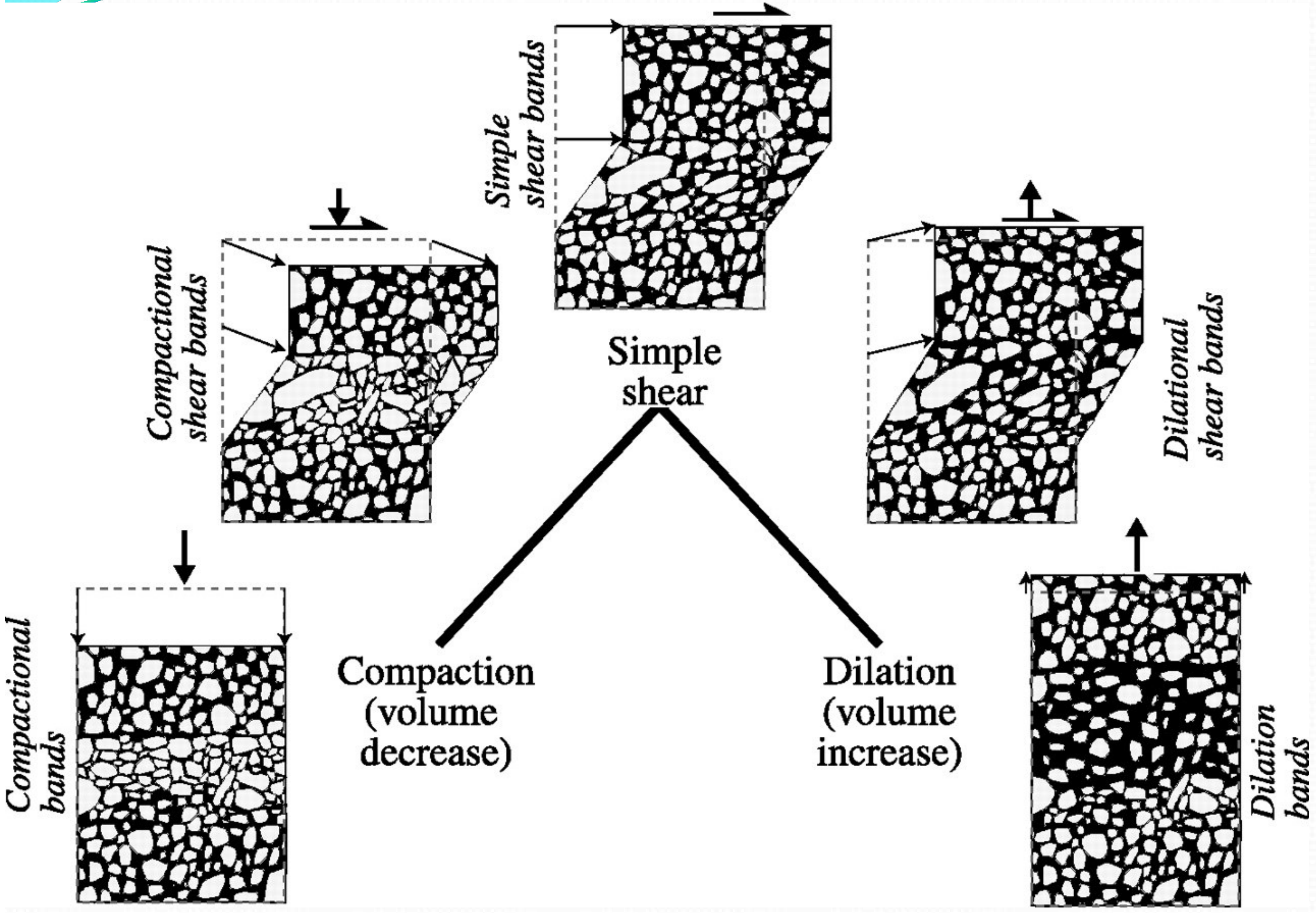
- Severely cold worked metal characterized by crystallographic texture. (preferred orientation of grains along the maximum strain direction is called as texture)
- Presence of preferred orientation causes anisotropy of mechanical properties

- The development of texture is the formation of deformation bands or shear bands
- Deformation bands: are regions of distortion where a portion of grains have rotated towards another orientation to accommodate the applied strain. When these regions are extend across many grains then they are called as shear bands.
- Shear bands associated with plastic instability in compression.



Shear band formation in compression of a cylinder

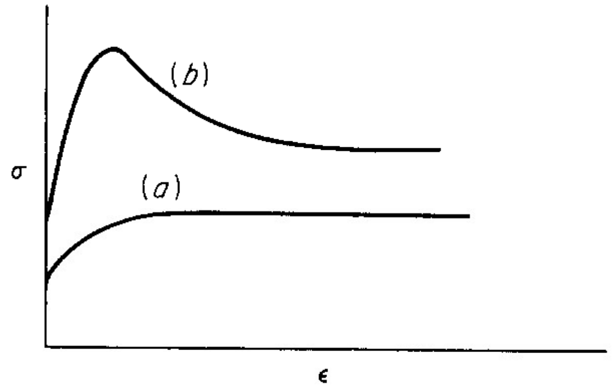



Simple shear bands
Compactional shear bands
Simple shear
Dilational shear bands
Compactional bands
Compaction (volume decrease)
Dilation (volume increase)
Dilation bands

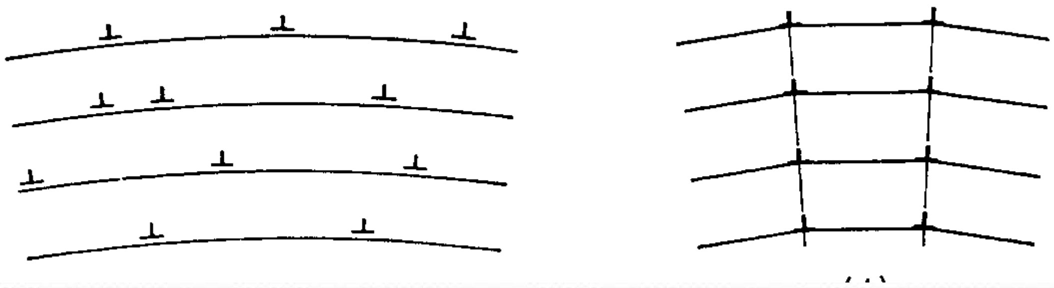
- In metal forming, the following mechanism are active for recovery and recrystallization.
  - Process which occur during deformation is called dynamic processes. (mechanisms for hot working)
    - Dynamic recovery
    - Dynamic recrystallization
  - Process in between the deformation or after deformation is completed is called as static processes.
    - Static recovery
    - Static recrystallization

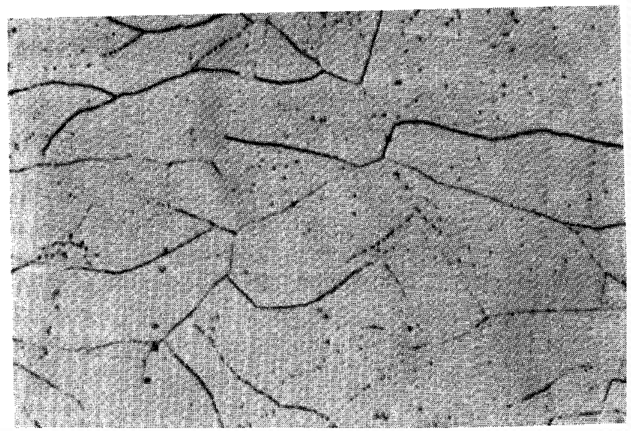
Dynamic recovery:

- Basic mechanism is annihilation of pairs of dislocations during straining.
- The low dislocation densities associated with deformation due to cross slip, climb and dislocation unpinning at nodes in this temperature region.
- This mechanism leads the microstructure to elongated grains , inside with a well developed fine-grain substructure, in the order of 1 to 10μm .
- The sub-grain boundaries undergoes broken up and reformed during deformation.
- It occurs in metals having high stacking-fault energy such as Al, α-Fe and most bcc metals.



a) Dynamic recovery
b) Dynamic recrystallization

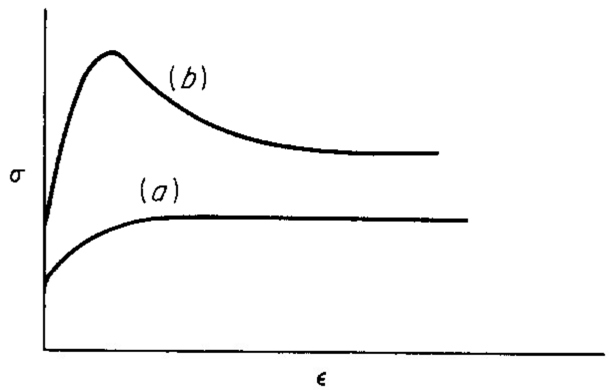




Formation of low angle grain boundaries

Dynamic recrystallization:

- Dislocation annihilation occurs only when the dislocation density reaches high level. Since the rate of strain hardening is high until recrystallization begins.
- When first recrystallization, the flow curve become unstable.
- When dynamic recrystllization accompanied by localized deformation leads to catastrophic strain localization. Because dislocation densities and flow stresses are higher in dynamic recrystallization since more susceptible to internal crack and cavity formation during deformation.



a) Dynamic recovery
b) Dynamic recrystallization

- Once dynamic recrystallization begins, the grain boundary migration tends to isolate the cavities to prevent joining up to cause catastrophic failure.
- It predominant softening mechanism in the hot working for all fcc metals except Al.

- Static recovery: Occurs b/w intervals of deformation which decreases the density of dislocation. But decreases in the flow stress is relatively small.
- It is responsible for the formation of recrystallization nuclei.
- Static recrystallization: time duration is only 0.1 to 0.01sec even in highest working temperatures.
- If deformation temp. reduced the recrytsllization time gradually increases to 100sec. To avoid recrystallization, the working materials is cooled rapidly and gain the strength.
- Other factor which affect recrystallizations are prestrain, strain rate and alloy composition.

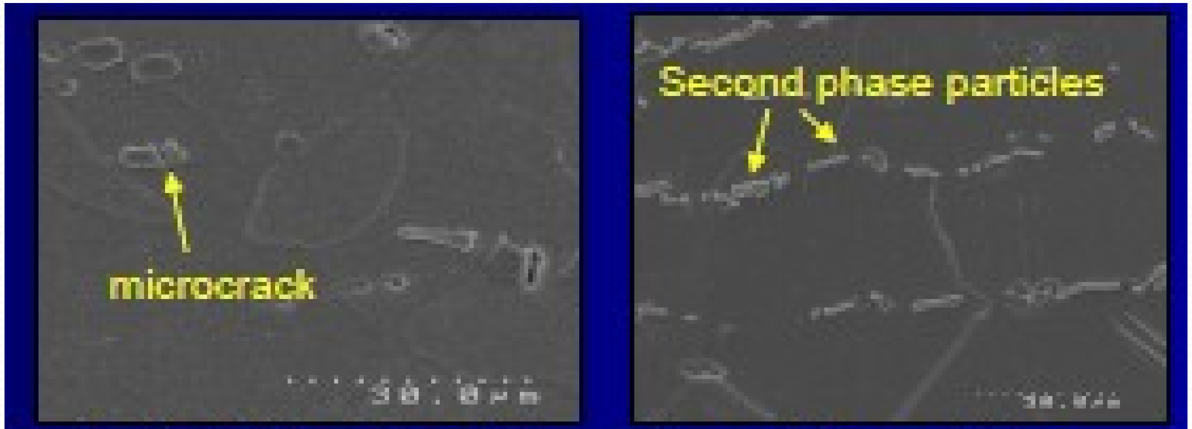
- Two softening mechanism which produce the low flow stress for hot working are static recrystallization or dynamic recovery, depending on the stacking fault energy.
- Dynamic recovery→static recrystallization

  Dynamic recovery + rapidly cooling → avoids static recrystallization and dynamic recovery structure is maintained. Ex: Al-Mg alloys
- Dynamic recrystallization → static recrystallization (rapidly)

  it is not possible to retain dynamic recrystallization structure due to rapid static recrystallization.

Two phase alloys

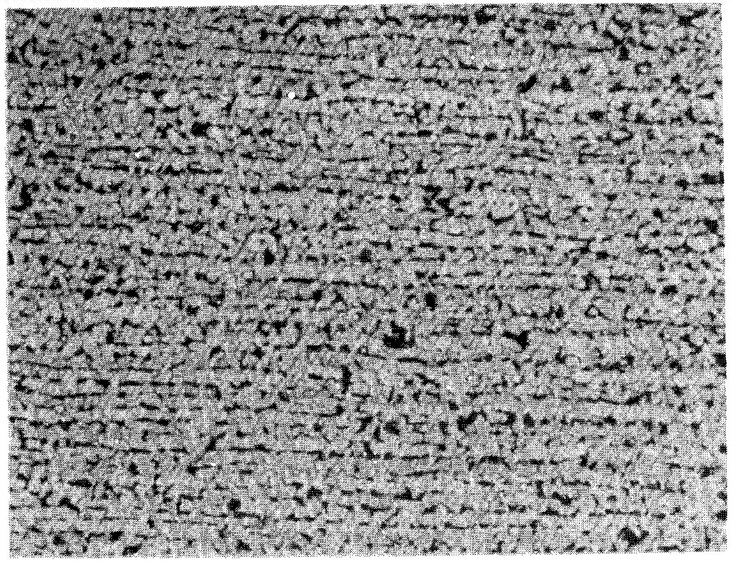
- Second phase is hard and more massive (like super alloys)
  - Second phase tend to fracture during deformation
  - Softer matrix extruding into the voids created by this fracturing.
- Second phase is ductile, failure usually occurs by matrix pulling apart between particles.
- If second phase particles are softer then, during deformation it will distorted and oriented towards working direction.



Cracked particle in softer matrix.

Alignment of second phase particles along the principal working direction.

- If second phase particles are brittle, then during deformation second phase particles are broken into fragments which will oriented parallel to the working direction. During cold working shows mechanical fibering is observed in wrought products.

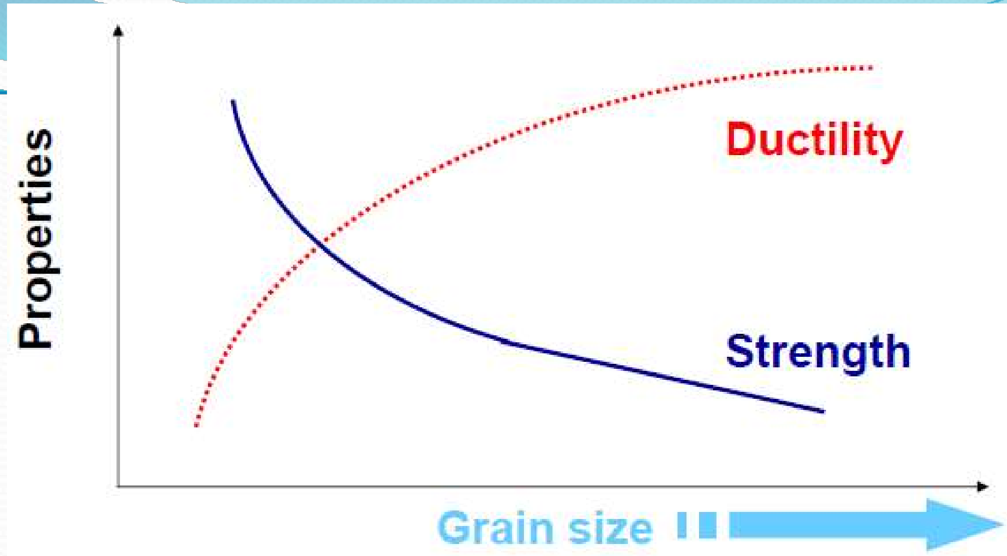


Strain induced phase transformation or precipitation:

- In some alloys, during deformation phase transformation or precipitation reaction occurs which increase the flow stress required for deformation and decreases the ductility.
- Example: austenitic stainless steels based on Cr:Ni ratio austenite phase is unstable. During cold working, the austenite phase transforms to ferrite along the slip lines.

Grains size:

Grain size influence the strength and fracture toughness



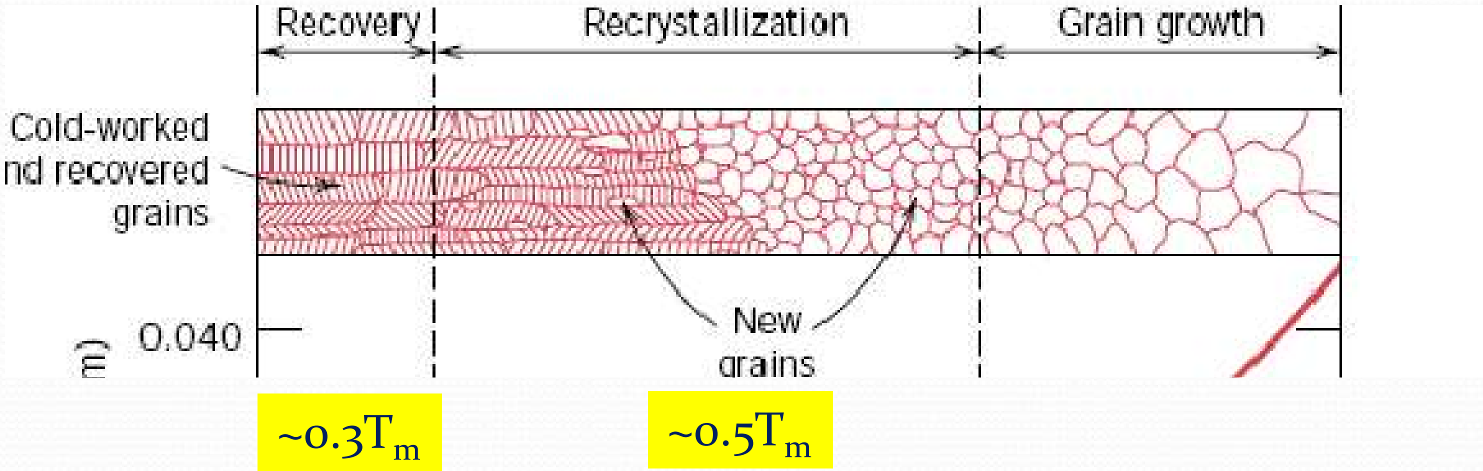
- In hot working, obtained by low finishing temperature and a rapid cooling rate from working temperature.
- In steel, cooling after hot deformation austenite transforms into ferrite. Ferrite grain size is depends on austenite grain size.
  - Fine austenite grain size is promoted by large reduction in final pass and working at the lowest possible temperature in austenite phase field.
- The optimization of mechanical properties possible by appropriate thermo mechanical treatments.

Annealing of cold worked metals

To revert back to the precold worked properties and structure, heat treatment such as annealing treatment is done.

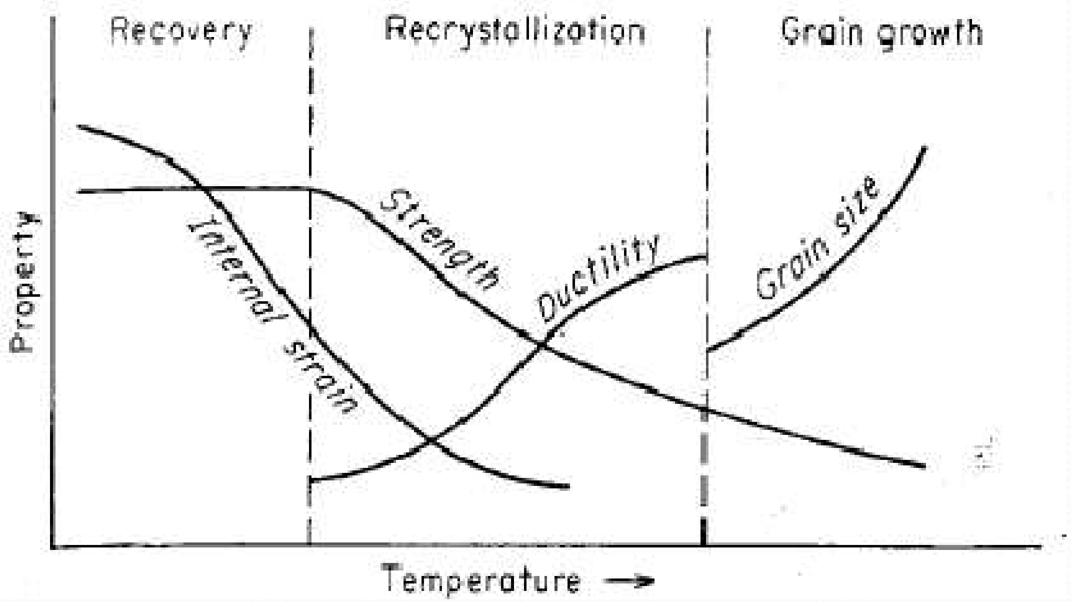
Stages of Annealing

- Recovery
- Recrystallisation
- Grain growth



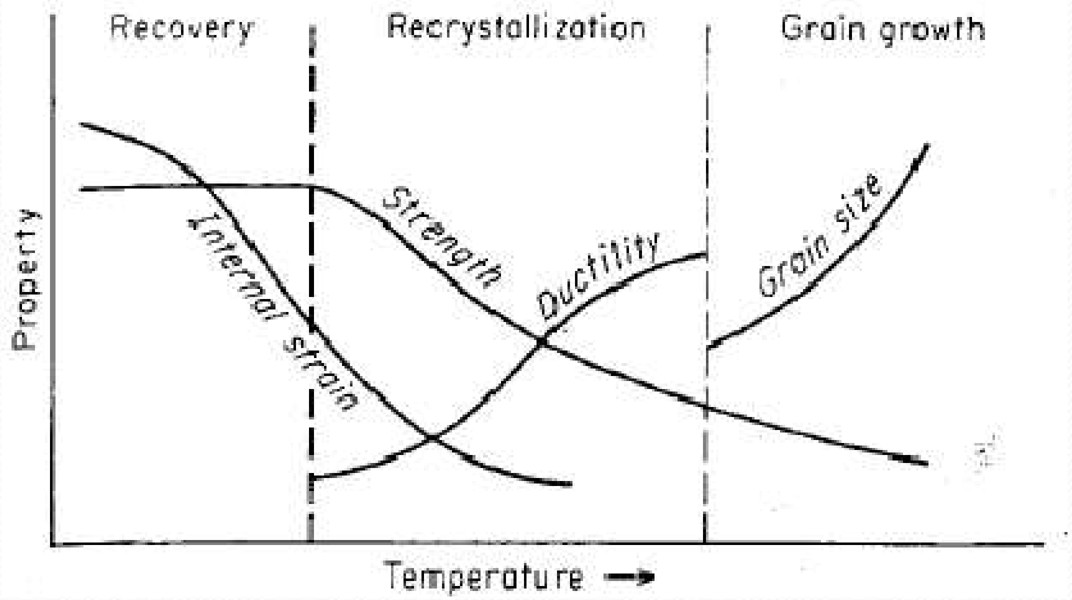
Recovery

- Some of the stored internal strain energy is relieved by virtue of dislocation motion, as a result of enhanced atomic diffusion at the elevated temperature.
- Physical properties such as electrical thermal conductivity and the like are recovered to their precold worked states.

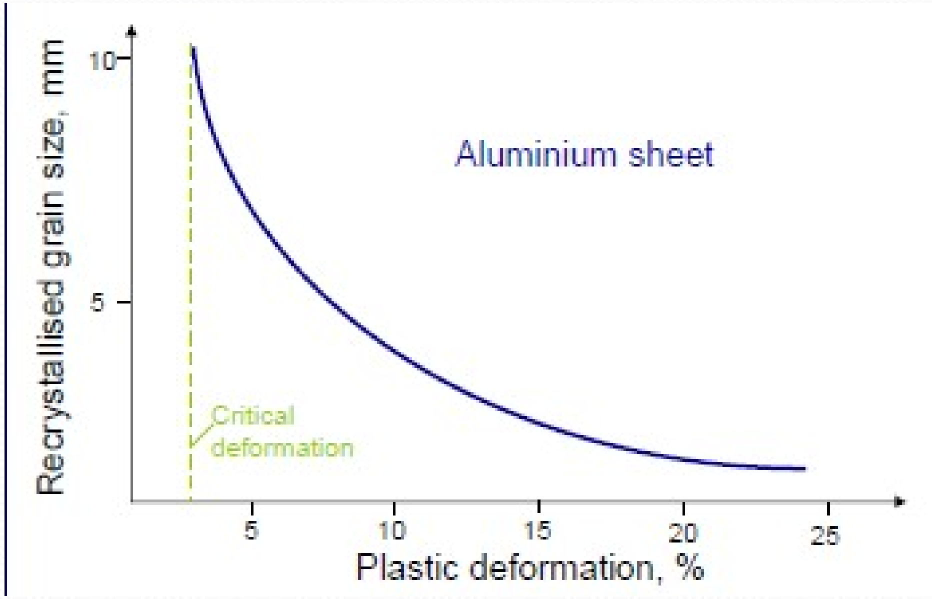


Recrystallization

- Recrystallization is the formation of a new set of strain-free and equiaxed grains.
- The driving force to produce this new grain structure is the difference in internal energy between the strained and unstrained material.
- During recrystallization, the metal becomes softer, weaker and more ductile.
- Recrystallization process depends on both time and temperature.



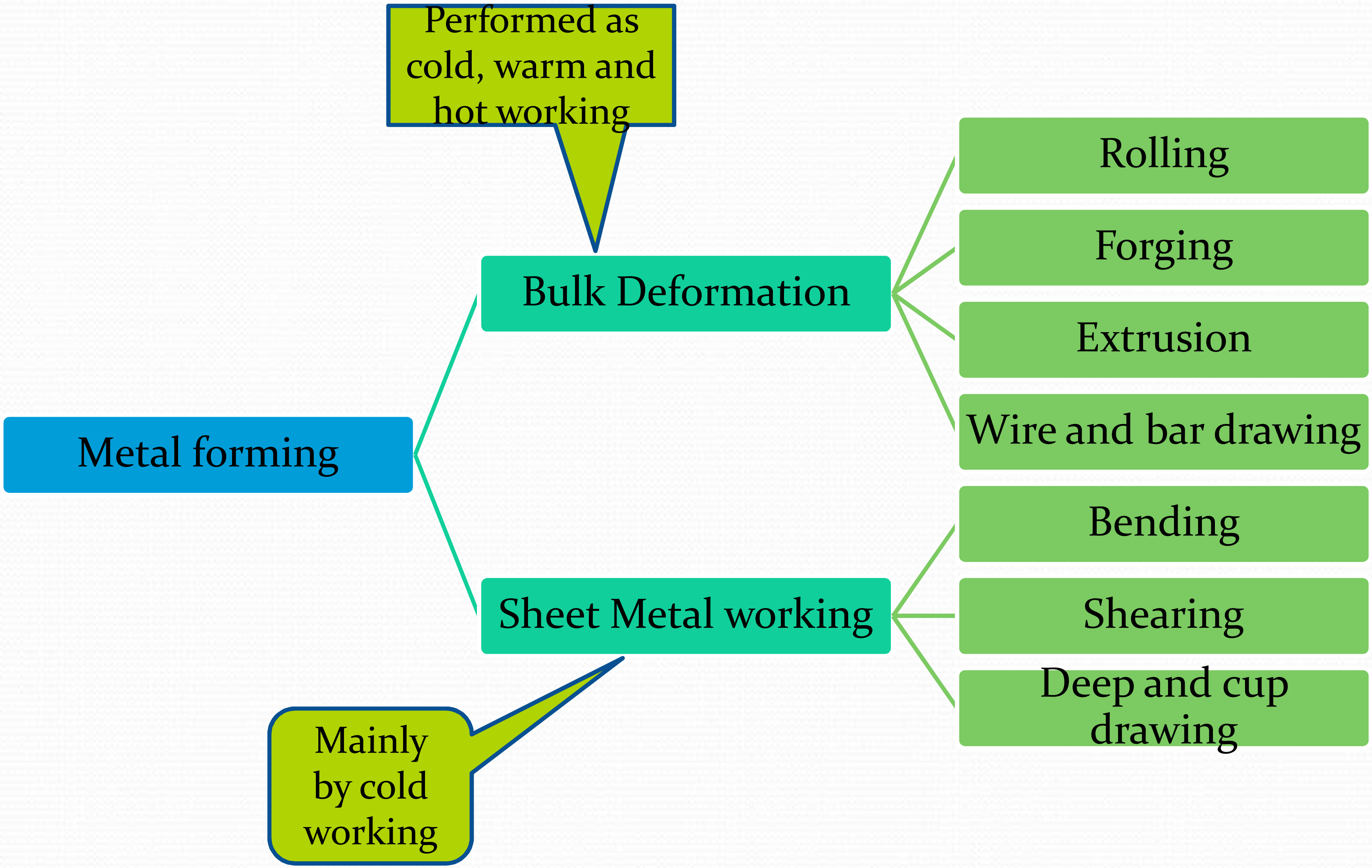
- Recrystallization temp. depends on material, strain, dislocation density, impurities.
- Presence of impurities increases the recrystallization temp.
- Plastic deformation is more, more number of nuclei which gives finer grain size. Also driving force is more for recrytsallization.



Grain Growth

- After recrystallization is complete, the strain free grain continues to grow during grain growth.
- Grain growth does no need to be preceded by recovery and recrystallization.
- Grain growth occurs by the migration of grain boundaries.

Note:



Performed as cold, warm and hot working
Metal forming
Bulk Deformation
Sheet Metal working
Rolling
Forging
Extrusion
Wire and bar drawing
Bending
Shearing
Deep and cup drawing
Mainly by cold working