

# Fundamentals of metalworking

## Subjects of interest

- Introduction/objectives
- Classification of metal processes
- Mechanics of metalworking
- Flow curves
- Effects of temperature on metalworking
  - Hot working
  - Cold working
- Effects of metallurgical structure on forming processes
- Effects of speed of deformation on forming processes
- Effects of friction and lubricant



# Objectives

- This chapter provides classification of metal forming processes based on types of forces applied onto metals.
- Mechanics of metal forming will be outlined to understand stress criterion for plastic deformation.
- Differences between hot and cold working will be highlighted and advantages-disadvantages of hot and cold working will be given.
- Effects of deformation speed and friction on metal working process will be included.



# Classification of metal forming processes

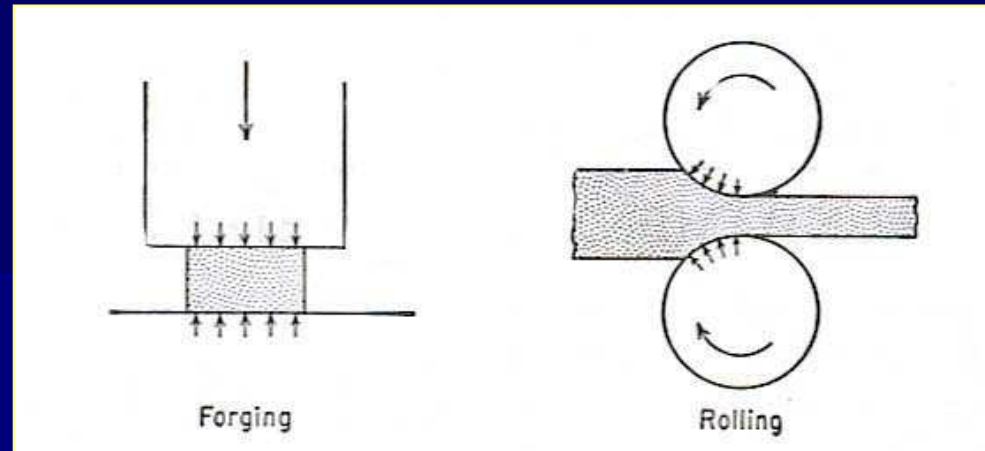
*(based on the type of force applied on to the work piece as it is formed into shape).*

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



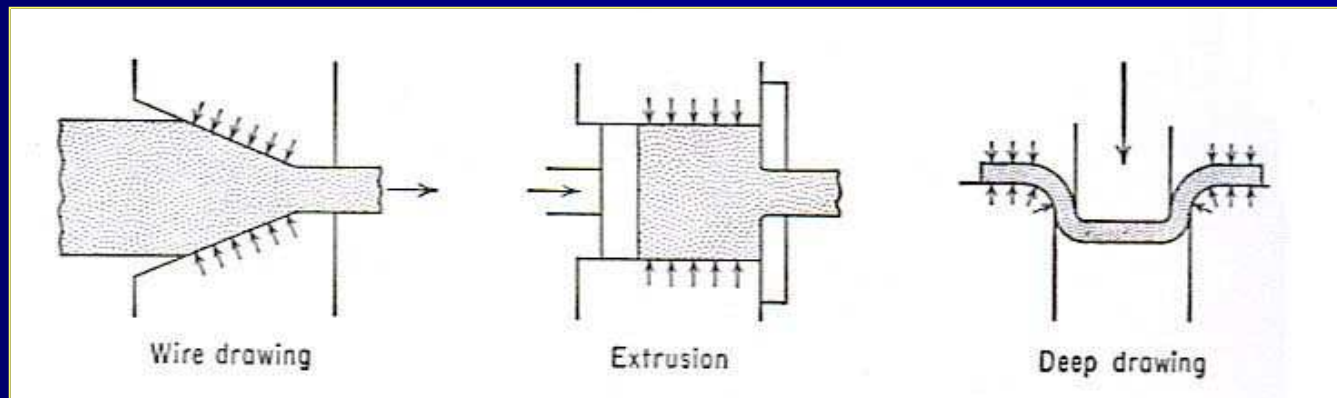
- **Direct-compression type processes:**

*the applied force is normal to the direction of the metal flow in compression, i.e., forging and rolling processes.*



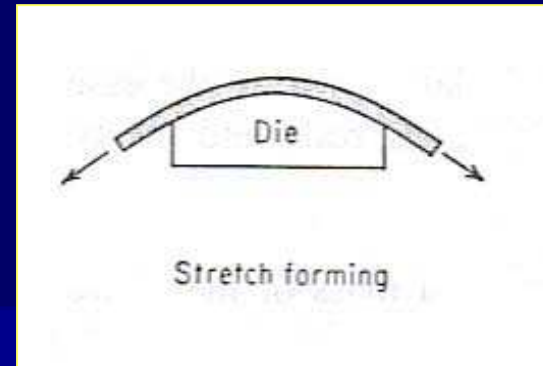
- **Indirect-compression type processes:**

*the primary forces are frequently tensile, with indirect compressive forces developed by the reaction of the work piece. The metal flow is therefore under the combined stress state, i.e., extrusion, wire drawing, tube drawing.*



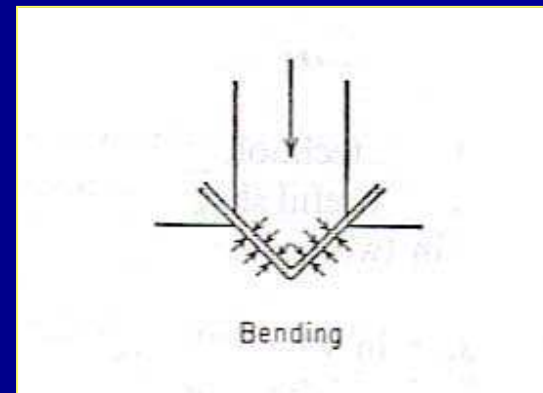
- **Tension type processes:**

*the applied force is tensile, i.e., stretching forming.*



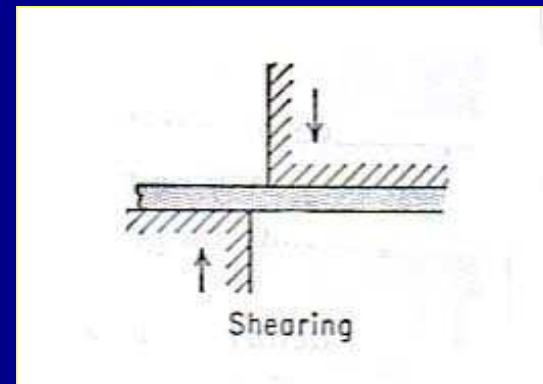
- **Bending processes:**

*the applied force involves the application of bending moments to the sheet.*

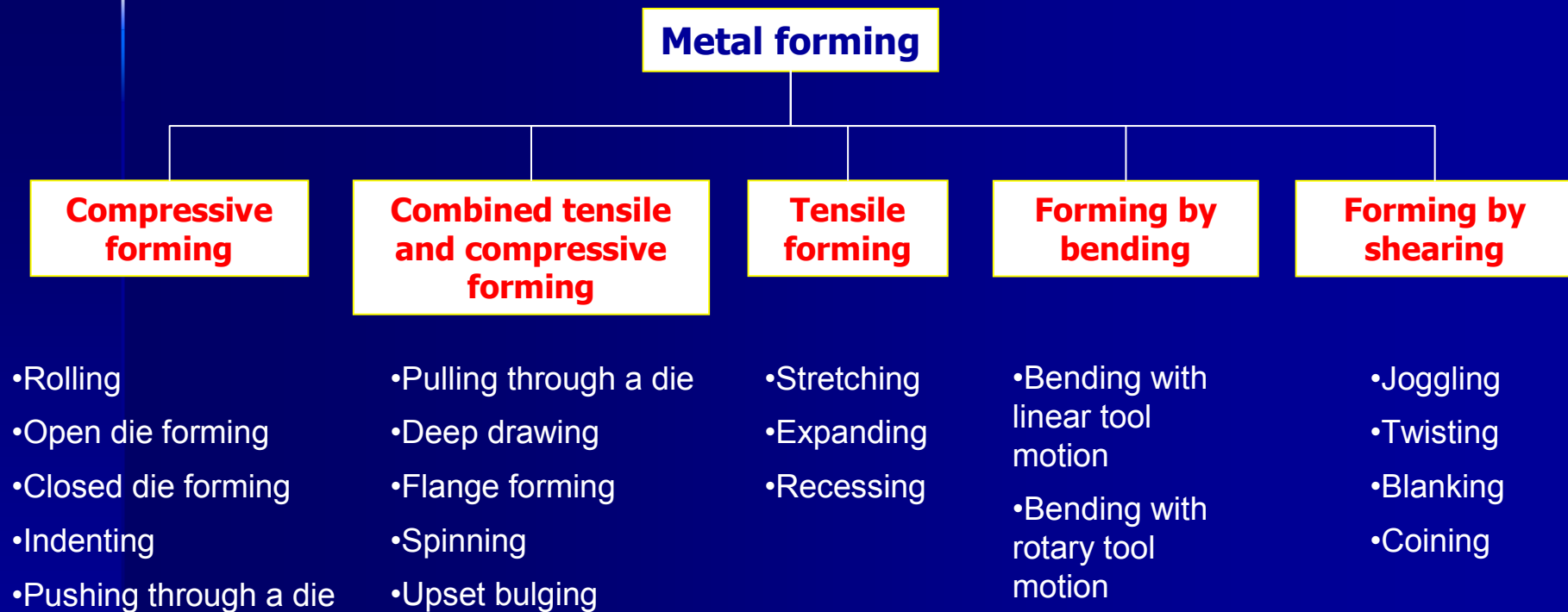


- **Shearing processes:**

*the applied force involves the application of shearing forces of sufficient magnitude to rupture the metal in the plane of shear.*



# *Classification of metal forming by subgroups*



# Mechanics of metal working

- Metal working occurs due to plastic deformation which is associated with analysis of complex stress distribution. → *require simplification.*



Only (large) plastic strain is considered while elastic strain is very small and can be neglected.



Strain hardening is often neglected.

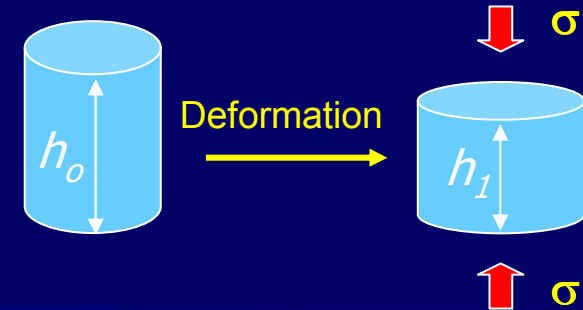


Metal is considered to be isotropic and homogeneous.

***Normally plastic deformation is not uniform and also have frictions, but we need to simplify the stress analysis in order to determine the force required to produce a given amount of deformation to obtain a product in a required geometry.***



- Required theory of plasticity, and for plastic deformation → a **constant-volume relationship** is required.



...Eq. 1

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

In metalworking, compressive stress and strain are predominated. If a block of initial height  $h_o$  is compressed to  $h_1$ , the axial compressive strain will be:

For true strain

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

...Eq. 2

For conventional strain

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

...Eq. 3

Note: the calculated strain is negative → **compressive strains**.





- However the convention is reversed in metalworking problems so that **compressive stresses and strains** are defined as **positive**.  
Note:  $\mathbf{e_c}$  is used as strain in deformation process.

$$\varepsilon_c = \ln \frac{h_o}{h_1}, \quad e_c = \frac{h_o - h_1}{h_o} = 1 - \frac{h_1}{h_o}$$

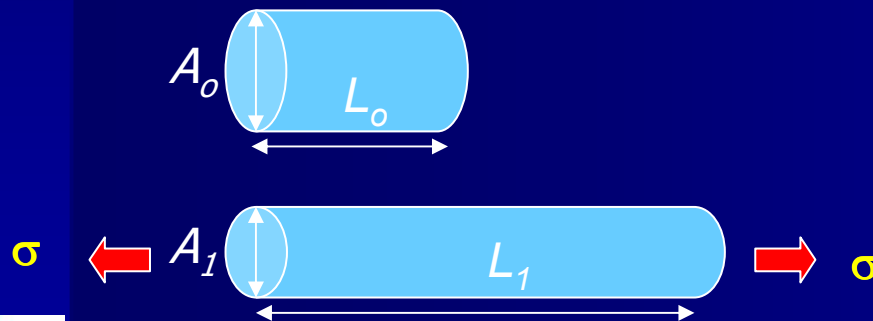
...Eq. 4

And the **fractional reduction** (reduction of area) in metal working deformation is given by

$$r = \frac{A_o - A_1}{A_o}$$

...Eq. 5

From the **constant-volume relation**



$$A_1 L_1 = A_o L_o$$

$$r = 1 - \frac{A_1}{A_o} \quad \text{or} \quad \frac{A_1}{A_o} = 1 - r$$

$$\varepsilon = \ln \frac{L_1}{L_o} = \ln \frac{A_o}{A_1} = \ln \frac{1}{1 - r}$$

...Eq. 6



**Example:** 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.

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

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

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

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

(b) For a bar which is halved in length,  $L_2 = L_1/2$

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

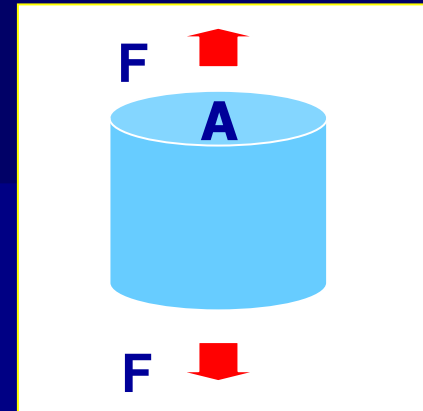
$$\varepsilon = \ln \frac{L_1/2}{L_1} = \ln \frac{1}{2} = -\ln 2 = -0.693$$

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



# Yield criteria and stress-strain relations

- **Yielding in unidirectional tension** test takes place when the stress  $\sigma = F/A$  reaches the critical value.



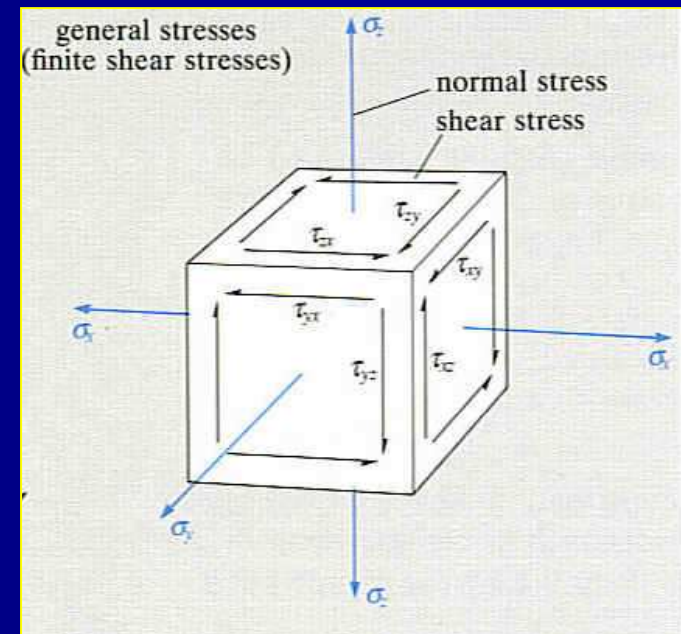
$$\sigma = \frac{F}{A}$$

...Eq. 7

Uniaxial stress

- **Yielding in multiaxial stress states** is not dependent on a single stress but on a combination of all stresses.

- **Von Mises yield criterion (Distortion energy criterion)**
- **Tresca yield criterion (maximum shear stress)**



Triaxial stresses



## Von Mises yield criterion

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

$$\left[ (\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 \right] = 6k^2 \quad \dots \text{Eq. 8}$$

In **uniaxial tension**, to evaluate the constant  $k$ , note  $\sigma_1 = \sigma_o$ ,  $\sigma_2 = \sigma_3 = 0$ , where  $\sigma_o$  is the yield stress;

Therefore

$$2\sigma_o^2 = 6k^2, \text{ then } k = \frac{\sigma_o}{\sqrt{3}} \quad \dots \text{Eq. 9}$$

Substituting  $k$  from **Eq. 9** in **Eq. 8**;

$$\left[ (\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 \right]^{\frac{1}{2}} = \sqrt{2}\sigma_o \quad \dots \text{Eq. 10}$$

In **pure shear**, to evaluate the constant  $k$ , note  $\sigma_1 = \sigma_3 = \tau_y$ ,  $\sigma_2 = 0$ , where  $\sigma_o$  is the yield stress; when yields:  $\tau_y^2 + \tau_y^2 + 4\tau_y^2 = 6k^2$  then  $k = \tau_y$

By comparing with **Eq 9** we then have  $\tau_y = 0.577\sigma_o$  \*\*\* **Eq. 11**



## Tresca yield criterion

Yielding occurs when the **maximum shear stress**  $\tau_{max}$  reaches the value of the shear stress in the uniaxial-tension test,  $\tau_o$ .

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

...Eq.17

Where  $\sigma_1$  is the algebraically largest and  $\sigma_3$  is the algebraically smallest principal stress.

**For uniaxial tension**,  $\sigma_1 = \sigma_o$ ,  $\sigma_2 = \sigma_3 = 0$ , and the shearing yield stress  $\tau_o = \sigma_o/2$ .

$$\tau_{max} = \frac{\sigma_1 - \sigma_3}{2} = \tau_o = \frac{\sigma_o}{2} \quad \text{...Eq.12}$$

Therefore the maximum - shear stress criterion is given by

$$\sigma_1 - \sigma_3 = \sigma_o \quad \text{...Eq.13}$$

**In pure shear**,  $\sigma_1 = -\sigma_3 = k$ ,  $\sigma_2 = 0$ ,  $\rightarrow$

$$\tau_{max} = \tau_y$$

$$\tau_y = 0.5\sigma_o \quad *** \quad \text{...Eq.14}$$



Therefore, from **von Mises** and **Tresca** yield criteria we have

**Von Mises yield criterion**

$$\tau_y = 0.577\sigma_o \quad ***$$

**Tresca yield criterion**

$$\tau_y = 0.5\sigma_o \quad ***$$

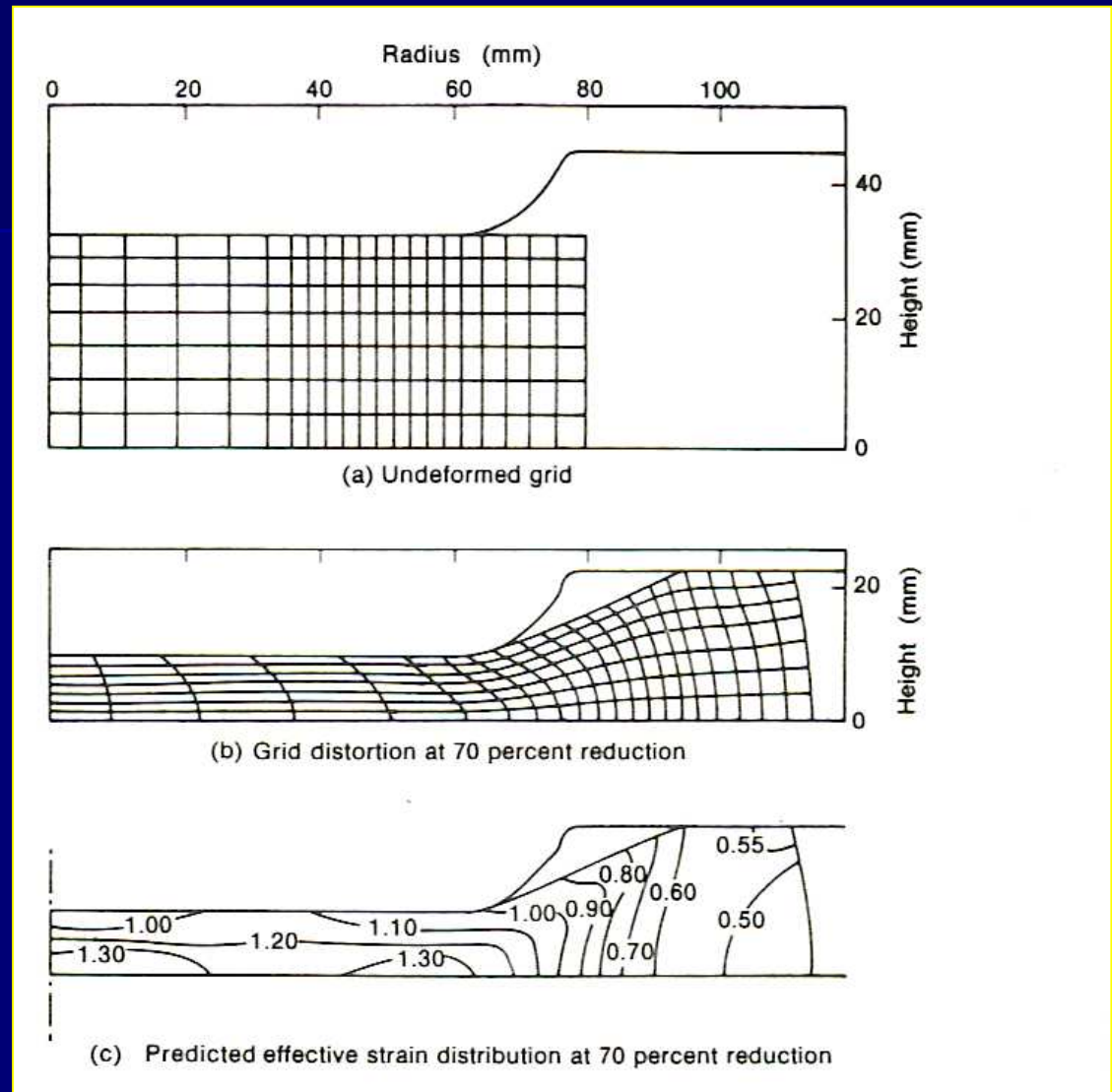
- The differences in the maximum shear stress prediction from both criteria lie between 0-15%.
- However experiments confirmed that the **von Mises criterion** is more accurate to describe the actual situations.

- *Once the metal has reached its yield point, the metal starts to flow under the influence of stress state. This is in the plastic regime where stress is not directly proportional to strain.*
- *The manner of flow or deformation is dependent on the stress state.*



# FEM analysis

- **Finite element method (FEM)** is used in metalworking plasticity where **stresses are complex**.
- **FEM** is a very powerful technique for determining stress-strain distributions in plane strain or plane stress conditions.



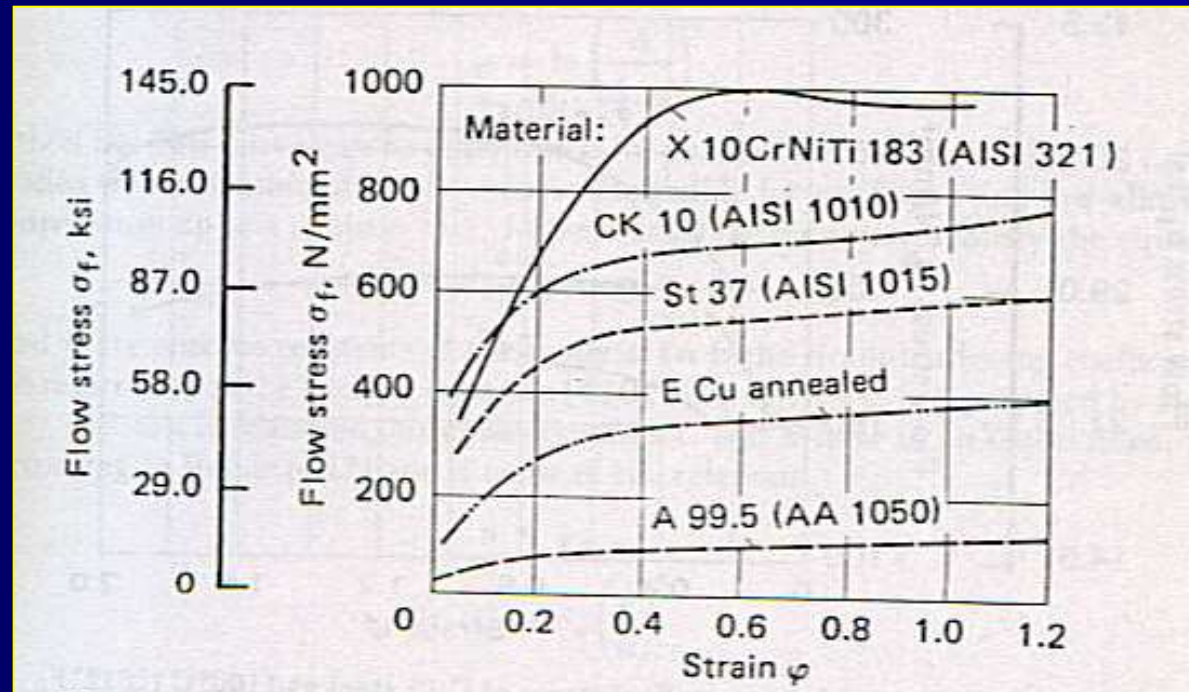
**Distortion of FEM grid in forging of a compressor disk.**





# Flow curves

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



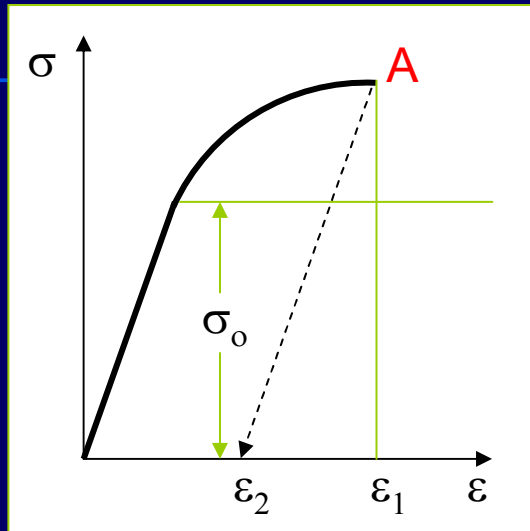
*Flow curves of some metals at room temperature*





# Determination of flow curve

## Stress-strain curve



True stress-strain curve of a ductile metal under uniaxial tensile loading.

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

$\sigma$  is true stress

$\varepsilon$  is true strain

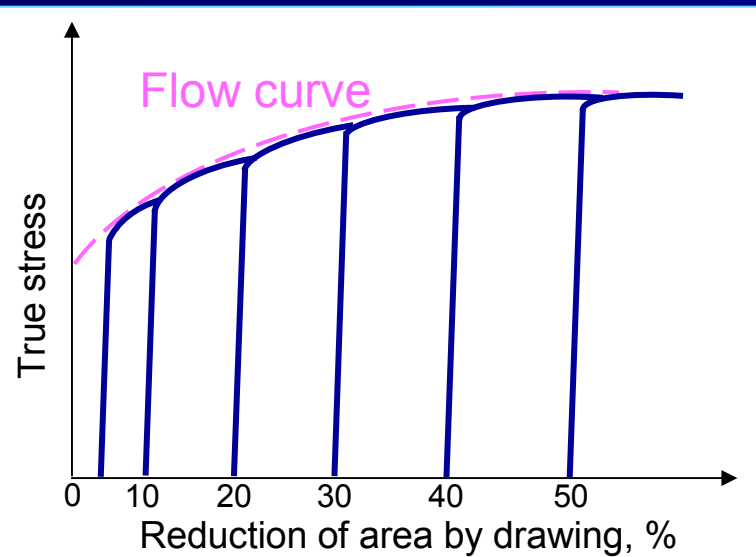
$K$  is constant

$n$  is work hardening exponent  
(this is valid from the beginning of plastic flow to the maximum load at which the specimen begins to neck down.)

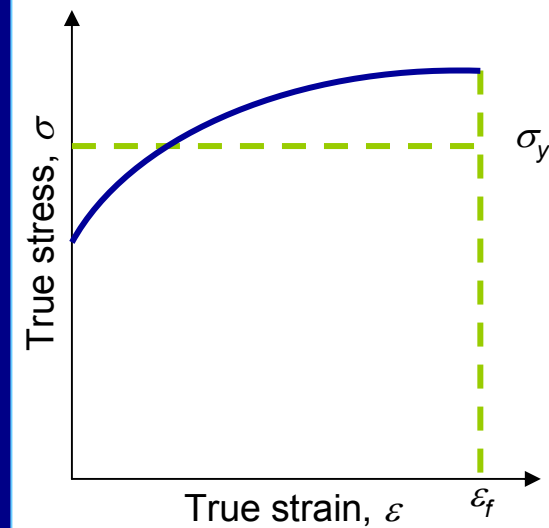
- Hook's law is followed up to the yield point,  $\sigma_0$ .
- Beyond  $\sigma_0$ , metal deforms plastically (strain hardening).
- Unloading from **A** immediately decreases the strain from  $\varepsilon_1$  to  $\varepsilon_2 = \sigma/E$  the strain decrease  $\varepsilon_1 - \varepsilon_2$  is the recoverable elastic strain.



## Flow curve



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



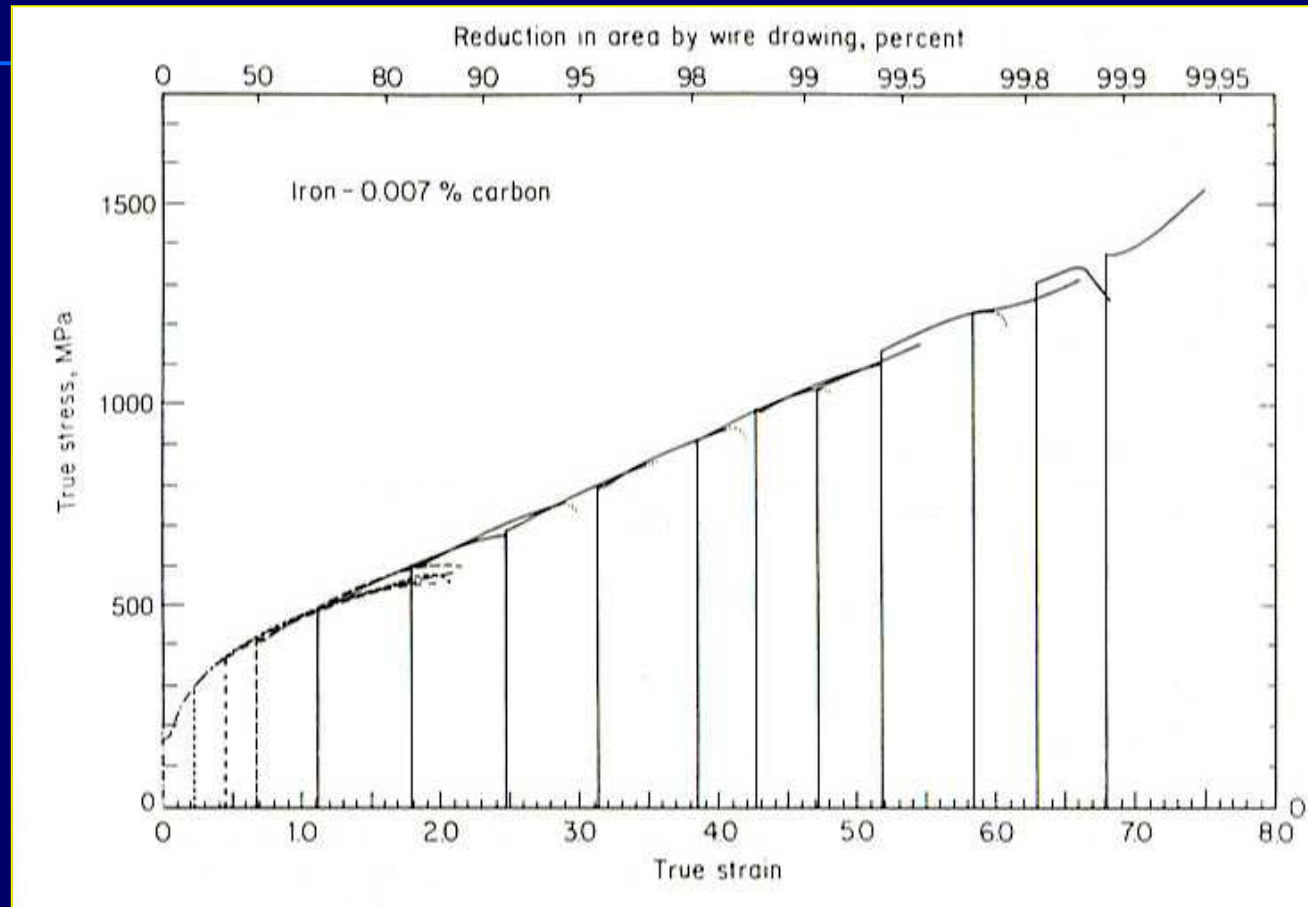
*Method of using average flow stress to compensate for strain hardening.*

Temperature  Flow stress 



## Flow curve

- **Strain hardening** occurred when an iron wire had been drawn to a specific true strain.



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



# Working processes

- The methods used to mechanically shape metals into other product forms are called Working Processes.

## Working processes

Hot working

$$T \sim 0.6-0.8T_m$$

Cold working

$$T \leq 0.3T_m$$

### Hot working ( $0.6-0.8T_m$ )

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



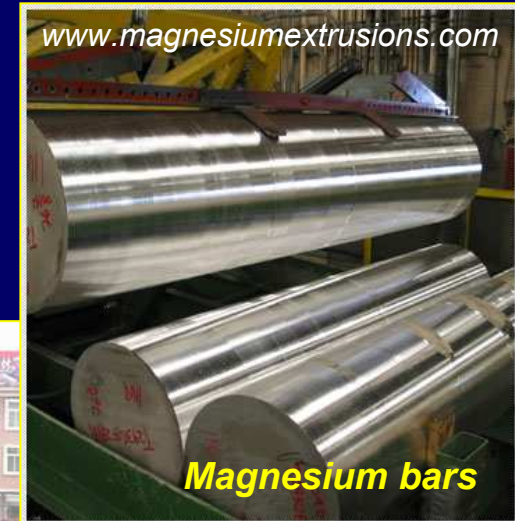
- The products resulting from the working of metals are called **Wrought Products**, such as sheet, plate, bar, forging.
- **Plastic working processes** can also be divided into:

### Primary mechanical working process

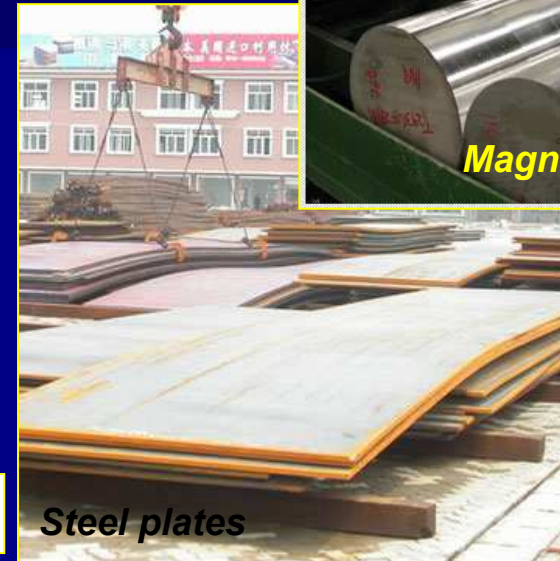
Designed to reduce an ingot or billet to a standard mill product of simple shape, i.e., sheet, plate, bar.

### Secondary mechanical working process

Primary sheets, plates or bars are formed into final finished shapes, i.e., wire & tube drawing, sheet metal forming operation.



**Magnesium bars**



**Steel plates**



**Drawn wires**



# Hot working

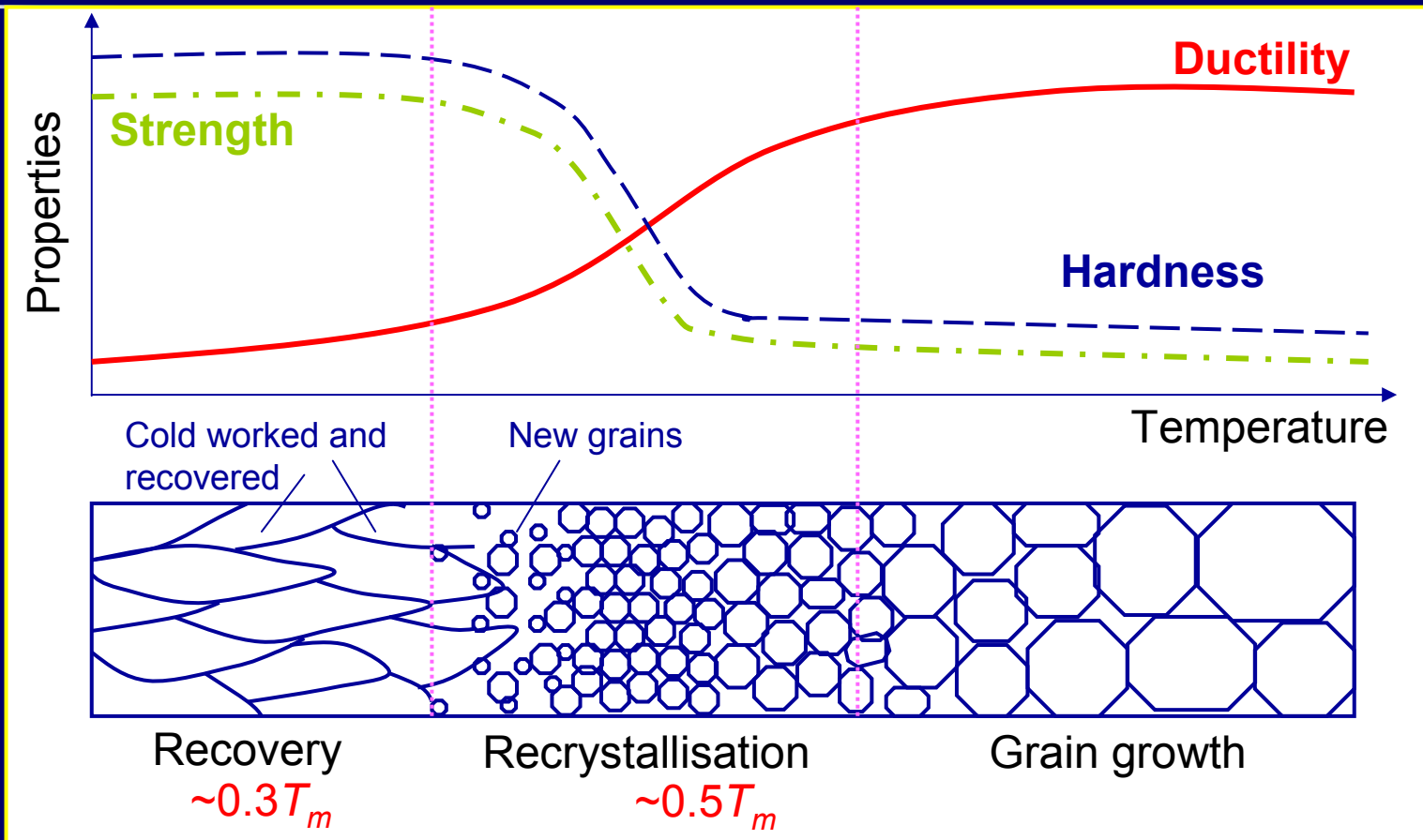
- Hot working involves deformation at temperatures where recrystallisation can occur ( $0.6-0.8 T_m$ ).

## *Examples of hot working temperatures for each metal*

Metal	Melting point (°C)	Recrystallisation temperature (°C)	Hot working range (°C)
Iron	1535	450	900-1200
Copper	1083	200	650-900
Aluminium (alloys)	660	150	350-500
Zinc	420	20	110-170



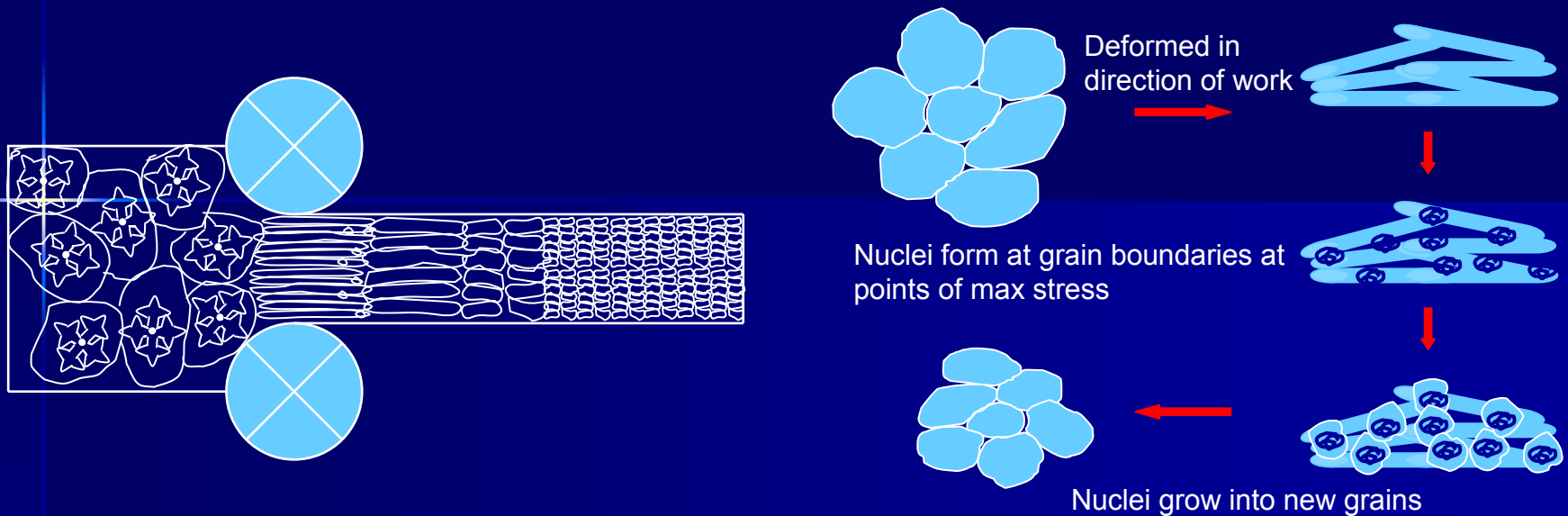
# Effects of temperature on metal forming processes



**Annealing mechanisms in cold worked metals**



# Recrystallisation during hot working



- The minimum temperature at which reformation of the crystals occurs is called **Recrystallisation Temperature**.
- Above the recrystallisation temperature the kinetic energy of atoms increases and therefore they are able to attach themselves to the newly formed nuclei which in turn begin to grow into crystals. This process continues until all the distorted crystals have been transformed.
- Hot working results in **grain refining**.



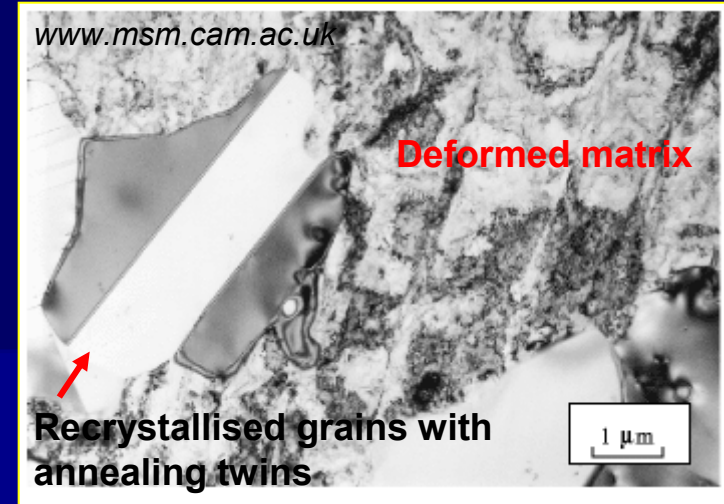


# Recrystallisation

- Recrystallisation takes place at higher temperatures than recovery which leads to a new formation of grains.
- The process includes 1) primary recrystallisation and 2) secondary recrystallisation and grain growth.

## Primary recrystallisation

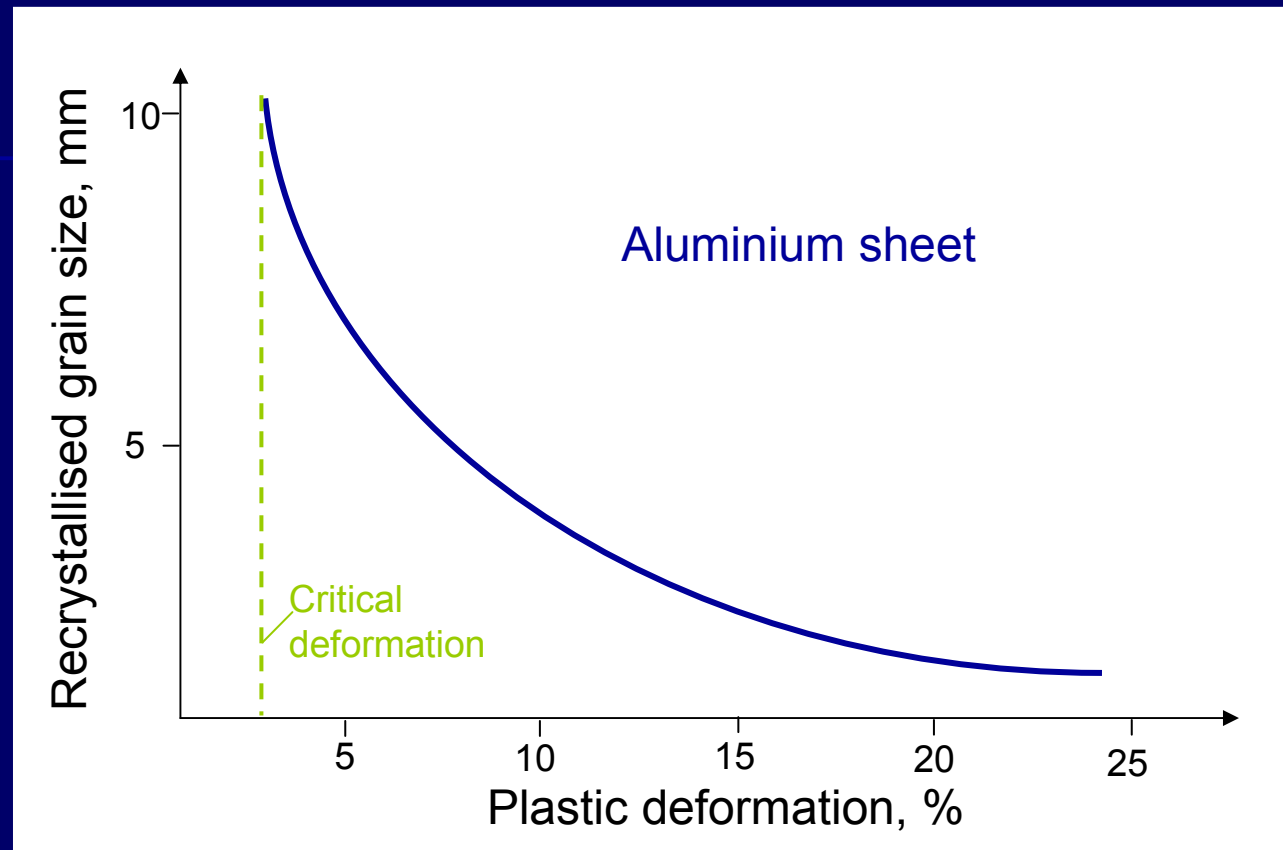
- **Primary recrystallisation** occurs at the beginning of the new grain formation process.
- **Recrystallisation temperature** does not depend on the metal alone, but on a whole number of variables temperature, strain and minimum dislocation density available (amount of deformation)
- **Small impurities** in pure metals can considerably increase the recrystallisation temperature.



*Recrystallised grain with annealing twins surrounded by deformed matrix with high density of dislocations.*



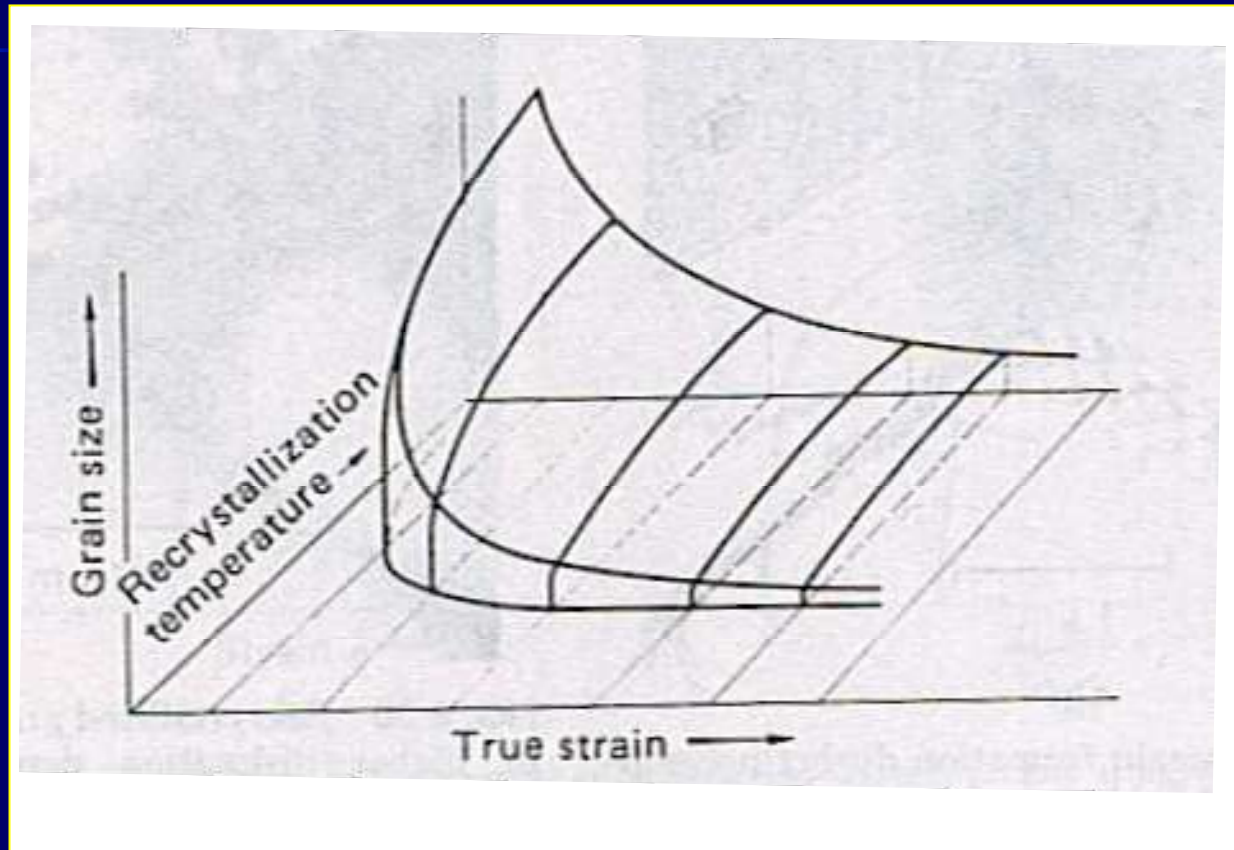
## *Recrystallised grain size and prior plastic strain*



The greater the driving force (greater prior plastic deformation), the greater the number of nuclei that will form and the finer will be the final grain size.



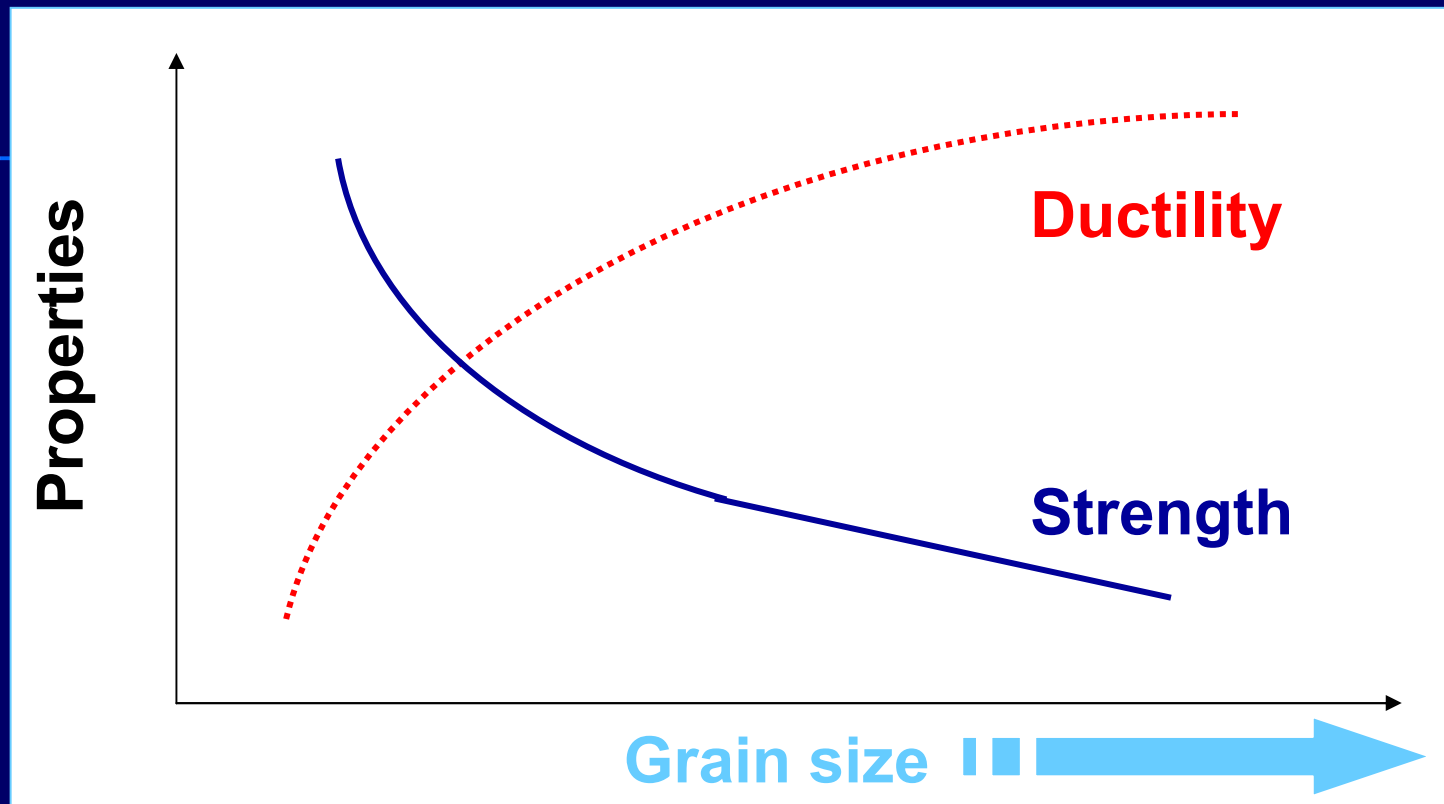
## *Effects of grain size and strain on recrystallisation temperature*



*Schematic of recrystallisation diagram*



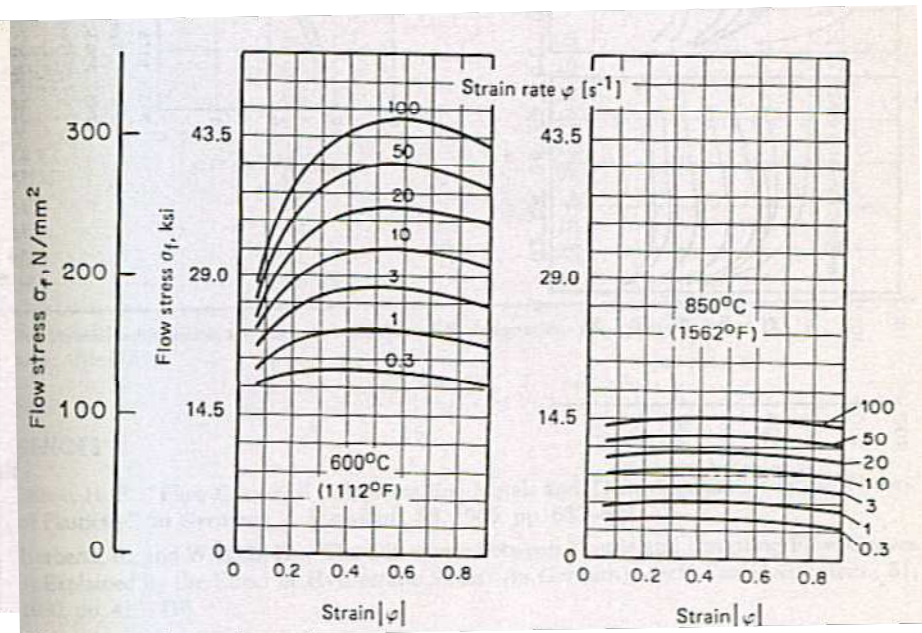
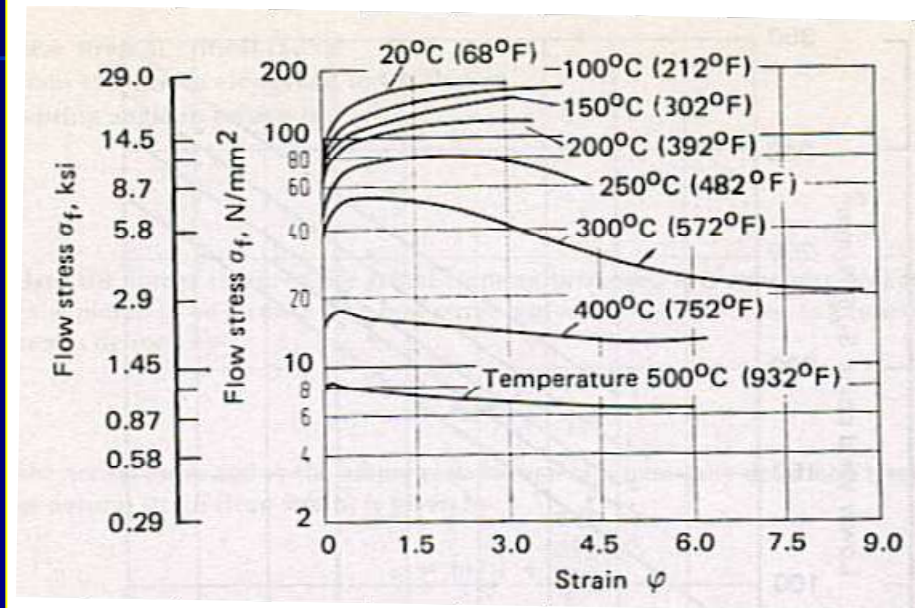
## Effects of grain size on properties



- Small grains make dislocations more difficult to move
- More slip plane, therefore, greater ductility



# Effects of strain rate and temperature



*Flow stress of aluminium as a function of strain at different temperature*

*Flow curves of Cu Zn28*

Temp



Flow stress



Strain rate



Flow stress



## Secondary recrystallisation and grain growth

- At higher temperature and longer annealing time, **further grain growth processes** take place in the primary recrystallisation structure.
- The **driving force energy** from the energy gained by lowering the ratio of the grain boundary area to the enclosed volume.

Secondary  
recrystallisation



*Only individual grains grow preferentially, resulting in very large grains present near the primarily recrystallised grains.*

Grain growth



*Result in an increase in average grain diameter.*

Mechanical  
property  
deterioration

Ductility ↓

Formability ↓

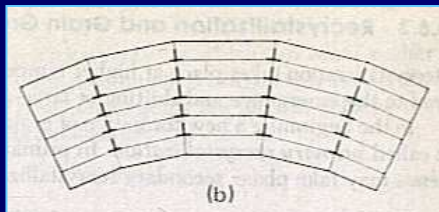
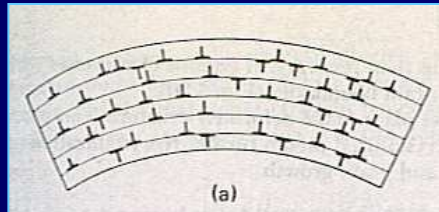




# Recovery

- Recovery is a **thermally activated process**, which results in lower density of dislocations or rearrangement of dislocation structure (as a consequence of strain hardening during deformation process).

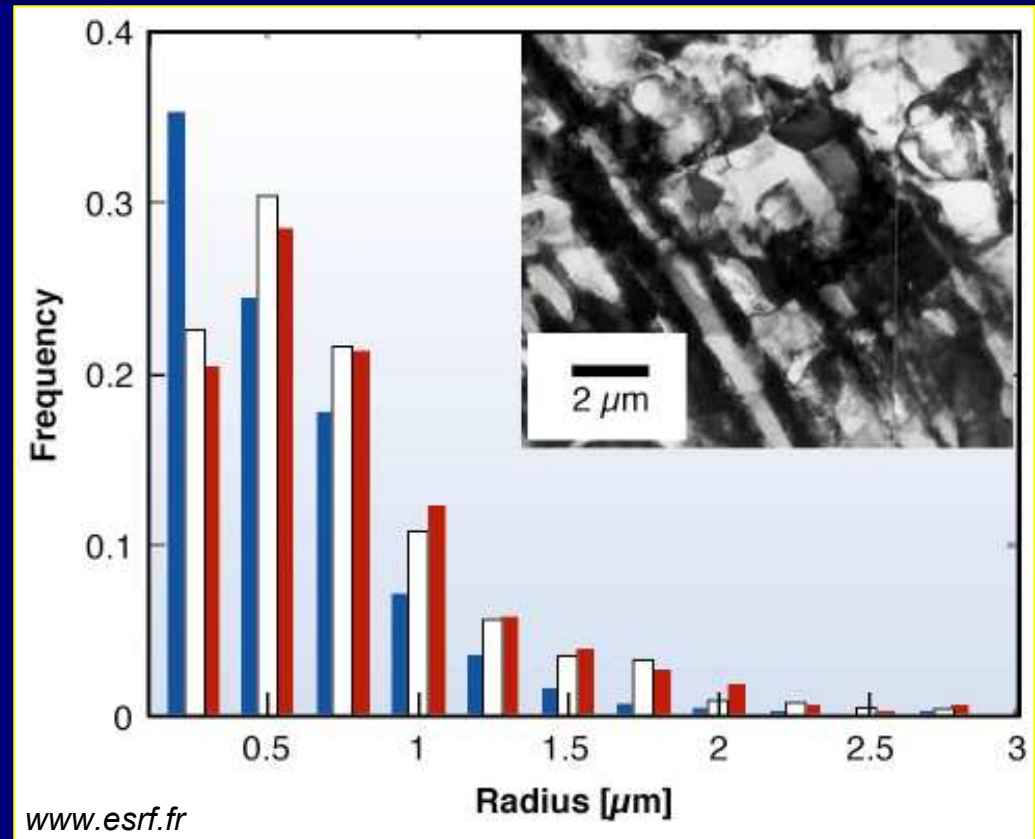
- Recovery process** includes annihilation of dislocation, polygonization of dislocation, dislocation climb.
- Certain amount of stored energy** is released during annealing without an obvious change in optical microstructure.



Polygonization



Suranaree University of Technology



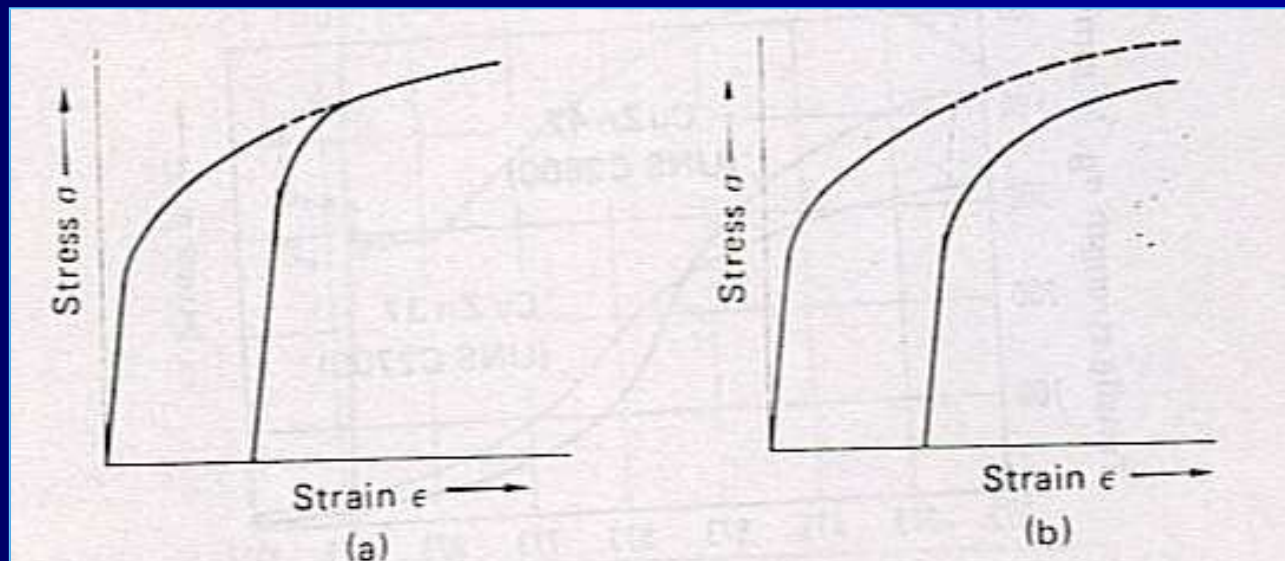
**Recovery of 38% cold-rolled aluminium showing different sizes of subgrains.**

Tapany Udomphol

Jan-Mar 2007

## ***Effect of recovery annealing on stress-strain diagram***

- Recovery process depends strongly on temperature.
- Increasing temperature ( $T \geq 0.5T_m$ ) during step tensile tests fig. (b) reduces the yield stress, due to the rearrangement and reactions of dislocations during recovery.

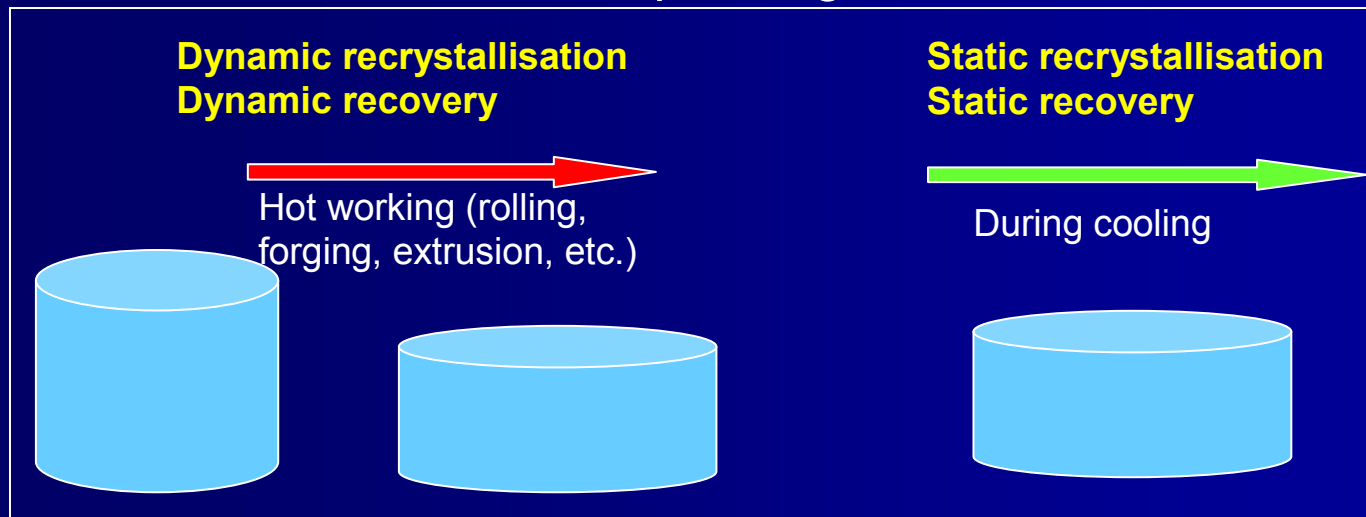


***Effect of recovery annealing on stress-strain diagram***



## Static and dynamic changes of structure during hot forming

- During plastic deformation, **new dislocations and vacancies** are produced continuously, which leads to a new state of equilibrium through **dynamic recrystallisation and dynamic recovery**.
- These two processes take place in the **forming zone** during plastic deformation at corresponding stresses and strain rates.



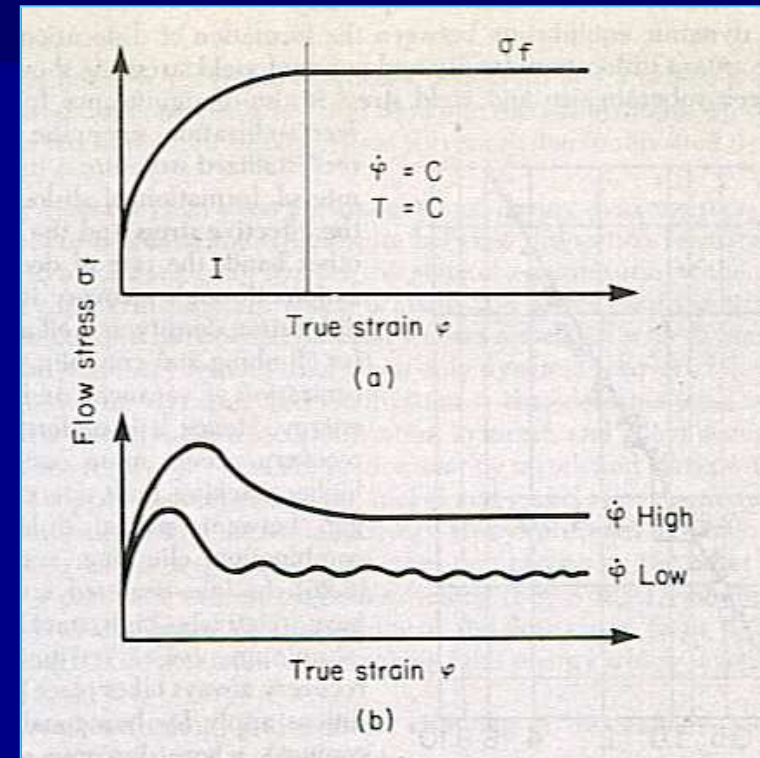
### Note:

- During forming, structure changes through dynamic recrystallisation and dynamic recovery.
- During cooling or heating, structure changes through static recrystallisation and static recovery.



# Static and dynamic changes of structure during hot forming

- **Dynamic and static recovery** are strongly encouraged in metals with **high stacking fault energy** (easy for climb and cross slip) such as aluminium,  $\alpha$ -Fe, ferritic alloys.
- Hot flow curve with a constant or slightly drop of yield stress are typical for **dynamic recovery**.
- On the contrary, the flow curves with **dynamic recrystallisation** (after initial hardening) show a sudden drop in yield stress.



**Schematic form of hot flow curves by**  
(a) **dynamic recovery alone**  
(b) **both dynamic recovery and recrystallisation.**



# *Advantages and disadvantages of hot working*

## Advantages

- Higher ductility – more deformation without cracking.
- Lower flow stress – less mechanical energy required for deformation.
- Pores seal up.
- Smaller grain size.
- Microsegregation is much reduced or removed due to atomic diffusion, which is higher at high temperatures.
- Stronger, tougher and more ductile than as-cast metals due to breaking down and refinement of coarse columnar grains in the cast ingot.

## Disadvantages

- Surface reactions between the metal and the furnace atmosphere, i.e., oxidation (oxide scales), decarburisation in steels.
- Hot shortness, when the working temperature exceeds the melting temperature of constituent at grain boundaries such as FeS.
- Dimension tolerance is poor due to thermal expansion at high temperatures.
- Handling is more difficult (from furnace to machine).



# Cold working

- Normally performed at room temperature but *in general*  $< 0.3T_m$ , where recovery is limited and recrystallisation does not occur.
- **Work hardening occurs** (strength and hardness increase but ductility decreases).
- The extent of deformation is rather limited if cracks are to be avoided, therefore intermediate anneals that enable recrystallisation are frequently used afterwards.
- The materials suitable for cold working should have a relatively **low yield stress** and a relatively **high work hardening rate** (determined primarily by its tensile properties).



# *Advantages and disadvantages of cold working*

## Advantages

- Provide work hardening, materials are stronger.
- Provide fine grain size and good surface finish.
- Dimension tolerance is better than in hot working.
- Easier handling (low operating temperatures).

## Disdvantages

- Use high amount of deformation due to low operating temperatures, therefore, require soft materials.
- Equipment (rolls, dies, presses) is big and expensive.
- Reduced ductility, therefore, require subsequent annealing treatments.

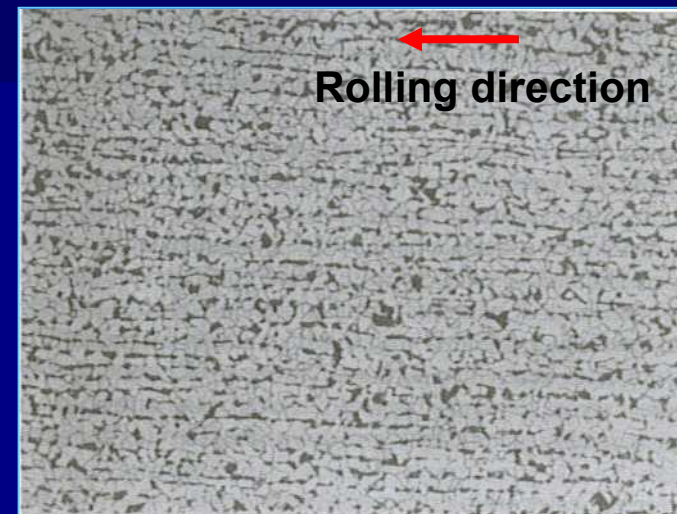
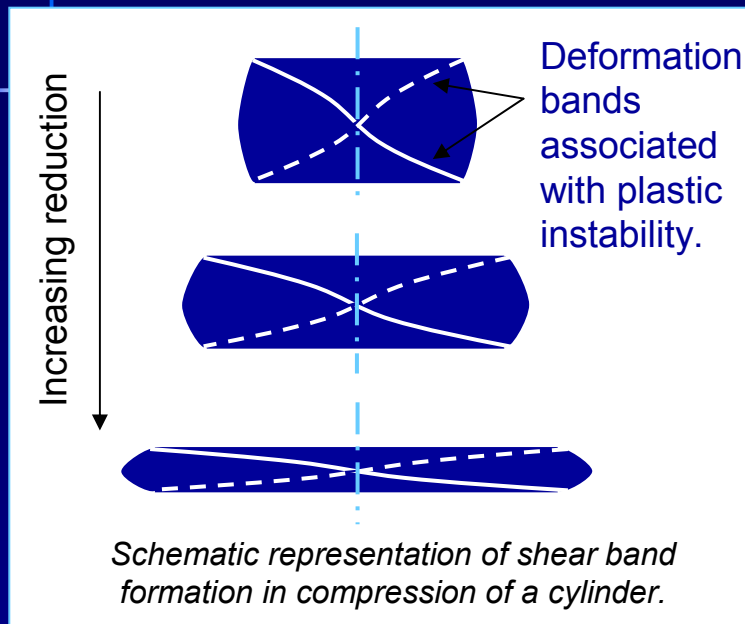


## *Properties of steels (C10) after hot-cold working*

<b>Mechanical properties</b>	<b>Hot rolled</b>	<b>Cold rolled</b>
<b>Ultimate tensile strength, <math>\sigma_{TS}</math> (MPa)</b>	<b>427</b>	<b>558</b>
<b>Yield stress, <math>\sigma_y</math> (MPa)</b>	<b>220</b>	<b>345</b>
<b>Brinell hardness (HB)</b>	<b>94</b>	<b>174</b>



# Effects of metallurgical structure on working processes



*Fibrous texture in rolled plate.*

- The presence of preferred orientation causes **anisotropy of mechanical properties**, especially in rolled sheets.
- The development of texture is the formation of **deformation bands or shear bands**, which are regions of distortion where a portion of grains have rotated towards another orientation to accommodate the applied strain.



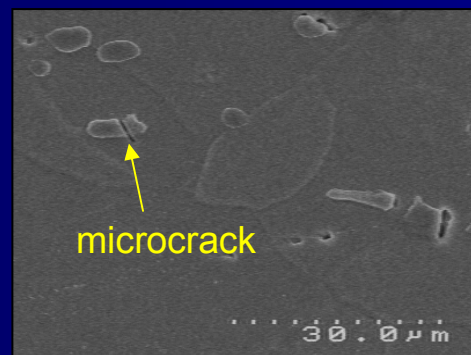


## Example: Plastic working in two-phase alloys

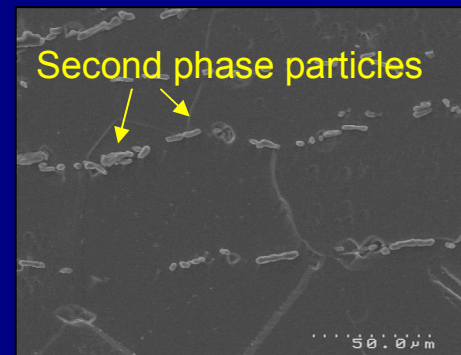
*The plastic working characteristics of two-phase alloys depends on the microscopic distribution of the two phases.*

- A high  $V_f$  of hard uniformly dispersed particles increases the flow stress and makes working difficult.
- **Hard and massive particles** tend to fracture on deformation with softer matrix.
- Second phase particles or inclusions will be distorted in the principal working direction (**fibrous structure**)- affect mechanical properties.
- Precipitation hardening during hot working results in high flow stress and lowered ductility.

←  
Working  
direction



*Cracked particle in softer matrix.*



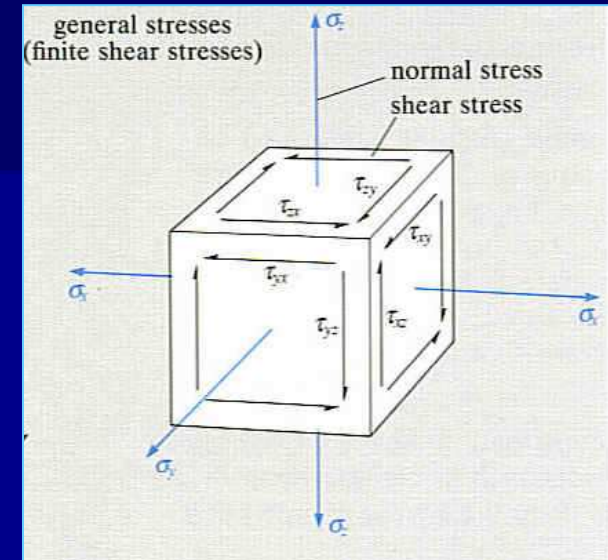
*Alignment of second phase particles along the principal working direction.*





# Effect of principal stresses in metal working

- When there is no shear stresses acting on the planes  $\rightarrow$  giving the maximum normal stress acting on the planes.
- These planes are called the **principal planes**, and stresses normal to these planes are the **principal stresses**  $\sigma_1$ ,  $\sigma_2$  and  $\sigma_3$  which in general do not coincide with the **cartesian-coordinate axes**  $x$ ,  $y$ ,  $z$ . Directions of principal stresses are 1, 2 and 3.

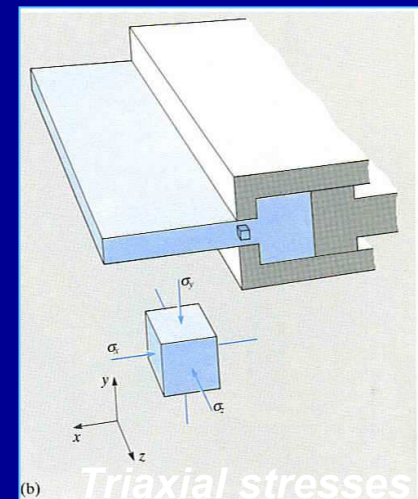
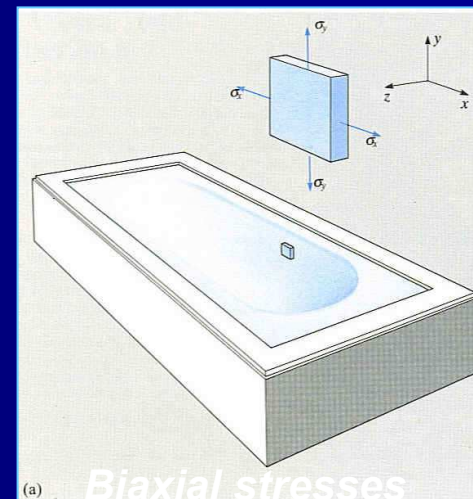


## Biaxial-plane stress condition

- Two principal stresses,  $\sigma_1$  and  $\sigma_2$ .

## Triaxial-plane strain condition

- Three principal stresses,  $\sigma_1$ ,  $\sigma_2$  and  $\sigma_3$ , where  $\sigma_1 > \sigma_2 > \sigma_3$ .



# Effects of speed of deformation

High deformation speed  
(high strain rate)



- High flow stress.
- Increased the temperature of the workpiece.
- improved lubrication at the tool-metal interface.

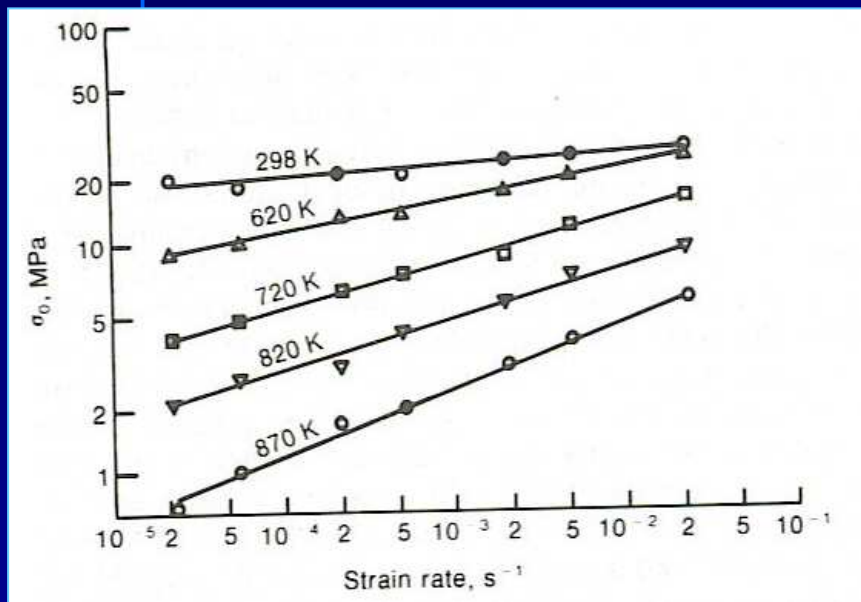


Table 15-1 Typical values of velocity encountered in different testing and forming operations

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

Flow stress dependence on strain rate and temperature

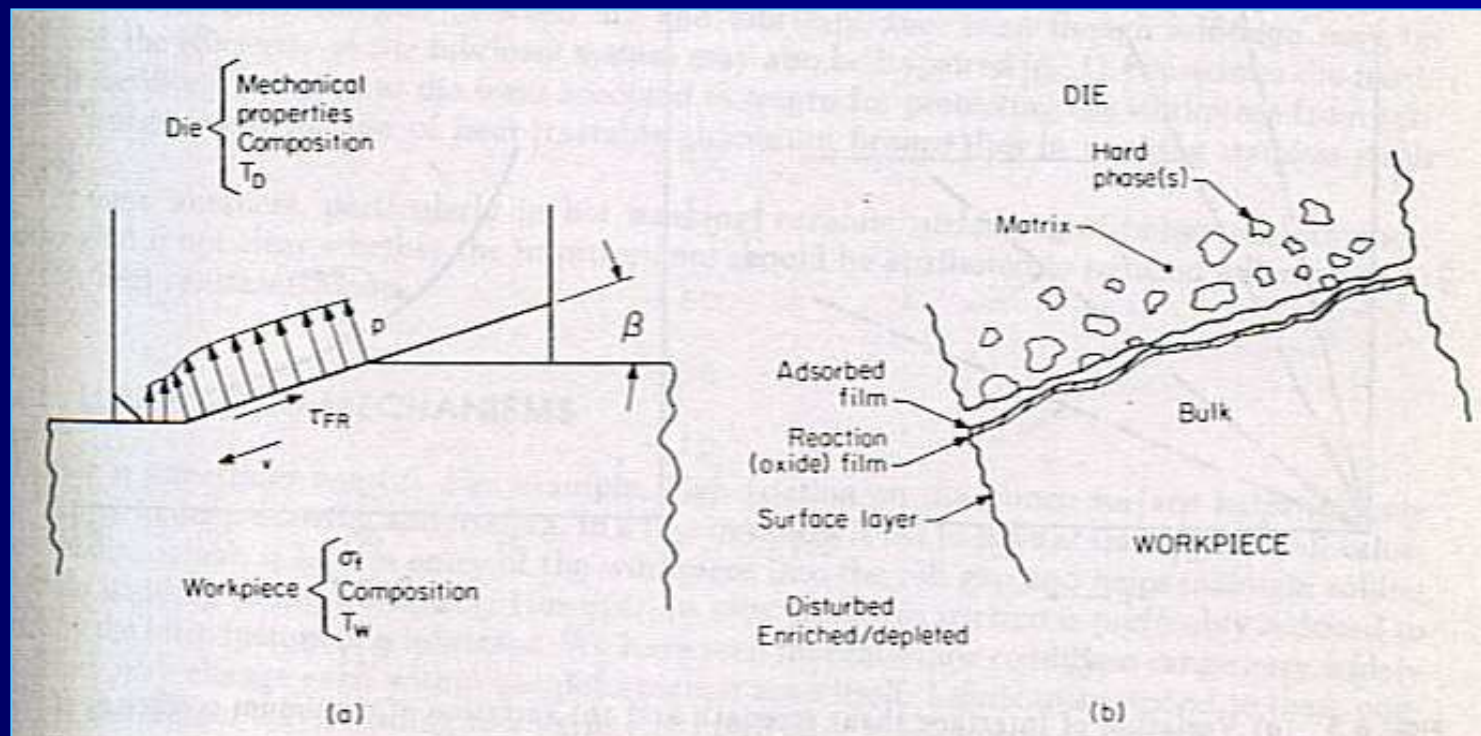
**Note:**

- If the speed of deformation is too high, **metal cracking** is possible.
- Can cause **plastic instability** in cold working
- Can cause **hot shortness** in hot working



# Effects of friction and lubrication

**Friction at tool-workpiece interface** depends on geometry of the tooling and the geometry of the deformation, temperature, nature of metal, speed of deformation.



**Die-workpiece interface (a) on the macroscale, (b) on the microscale.**



# Effects of friction and lubrication

When two surfaces are brought into contact, the high spot (**asperities**) will come into contact.

- As we increase the load, the metal at the asperities deform plastically and produce sub-shear zone.
- The coefficient of friction is given by

$$\mu = \frac{F}{P} = \frac{\tau_i A_r}{p A_r} = \frac{\tau_i}{p} \quad \dots \text{Eq.15}$$

Where

$\mu$  = frictional coefficient

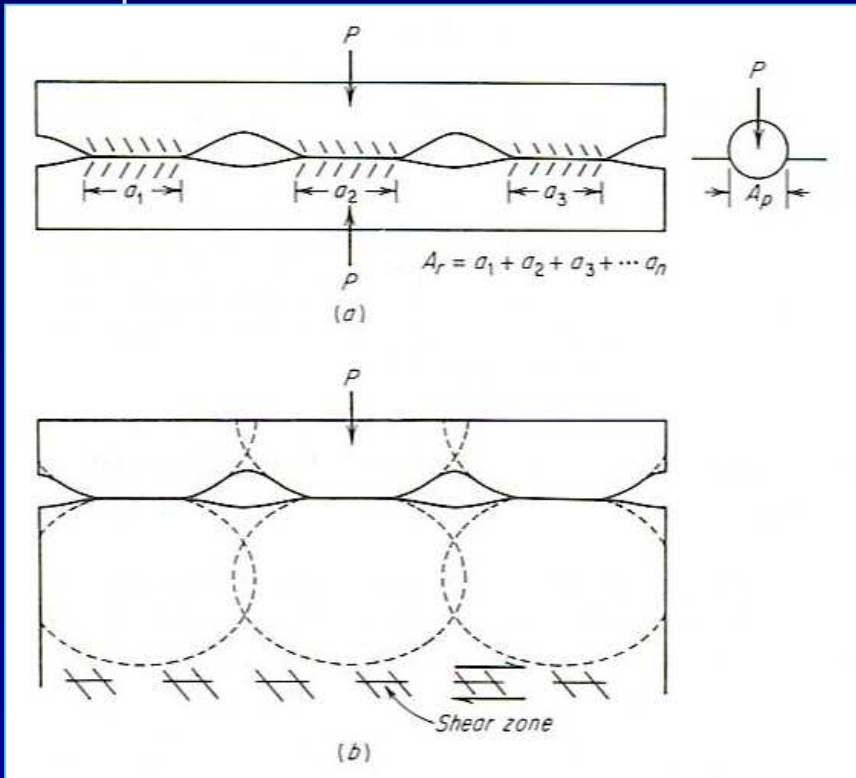
$\tau$  = the shearing stress at the interface

$P$  = the load normal to the interface

$F$  = the shearing force

$A_r$  = summation of asperity areas in contact

$p$  = the stress normal to the interface



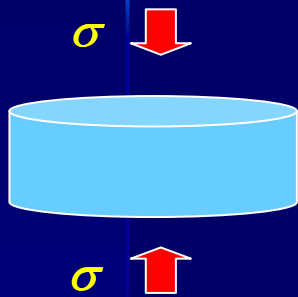
(a) Contact at asperities (b) overlap of deformation zones to produce subsurface shear zone.





### Example : homogeneous compression of a flat circular disk

**Assumption:** no barrelling and small thickness, then the frictional conditions on the top and bottom faces of the disk are described by a constant coefficient of Coulomb friction;



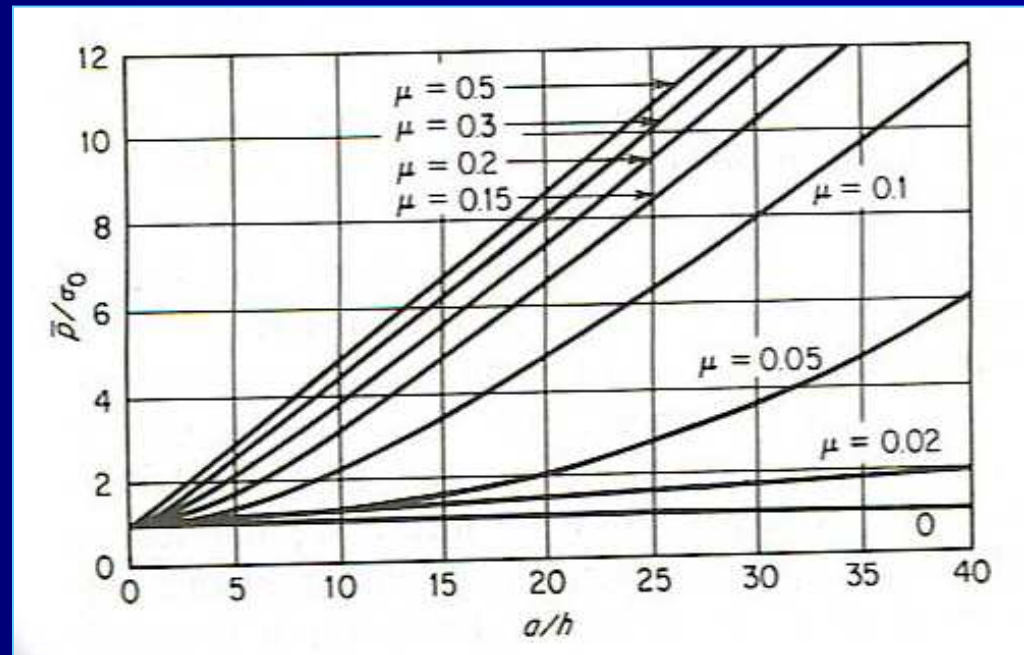
$$\mu = \frac{\tau}{p}$$

Where

$\mu$  = frictional coefficient

$\tau$  = the shearing stress at the interface

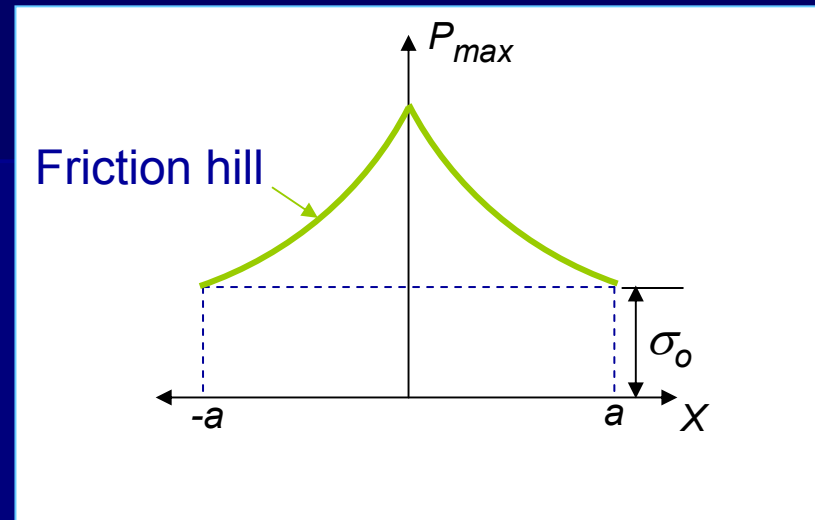
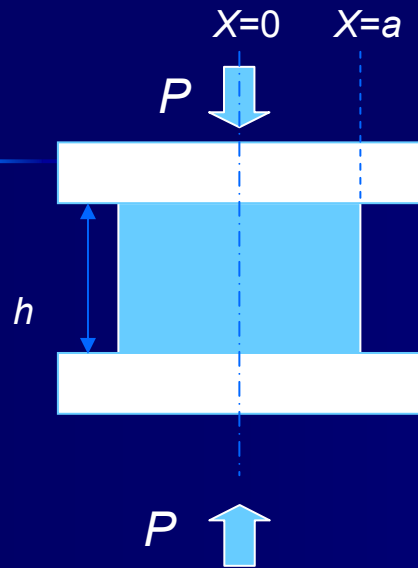
$p$  = the stress normal to the interface



*Deformation pressure in compression as a function of  $\mu$  and  $a/h$ .*



### Example: friction in forging



### Functions of a metal working lubricant

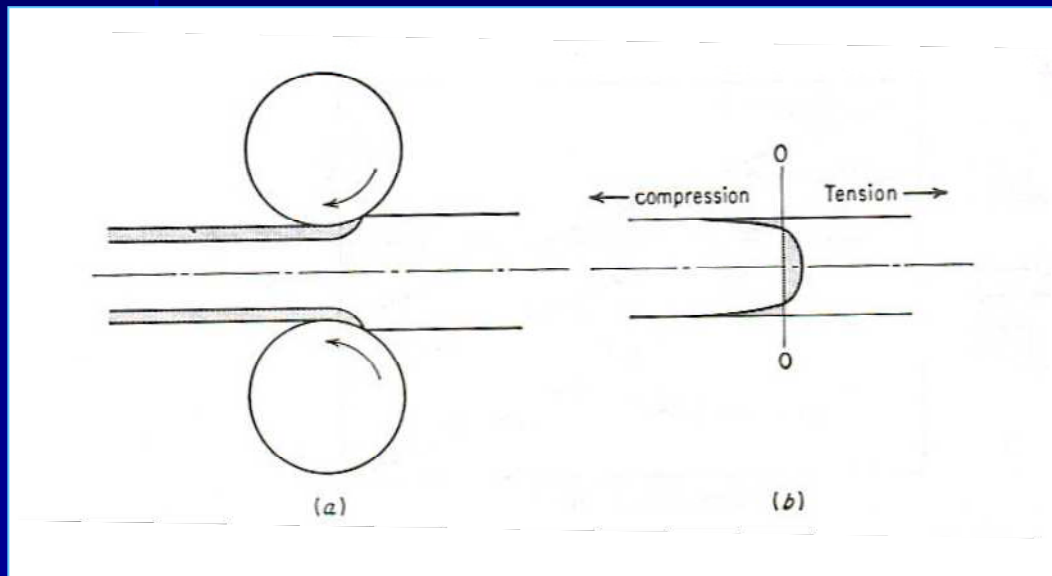
- Reduces deformation load
- Increases limit of deformation before fracture
- Controls surface finish
- Minimises metal pickup on tools
- Minimises tool wear
- Thermally insulates the workpiece and the tools
- Cools the workpiece and/or tools



# Effect of residual stresses

- **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.





# *Effect of residual stresses*

- **Residual stresses** are only elastic stresses. The maximum value which a residual stress can reach is the yield stress of the material.
- Residual stresses can be considered the same as ordinary applied stresses.
- Compressive residual stress can effectively **subtracts** from the applied tensile stresses.
- Metals containing residual stresses can be **stress relieved** by heating to a temperature where the yield strength of the material is the same or lower than the value of the residual stress such that the material can deform and release stress.
- However **slow cooling** is required otherwise residual stress can again develop during cooling.

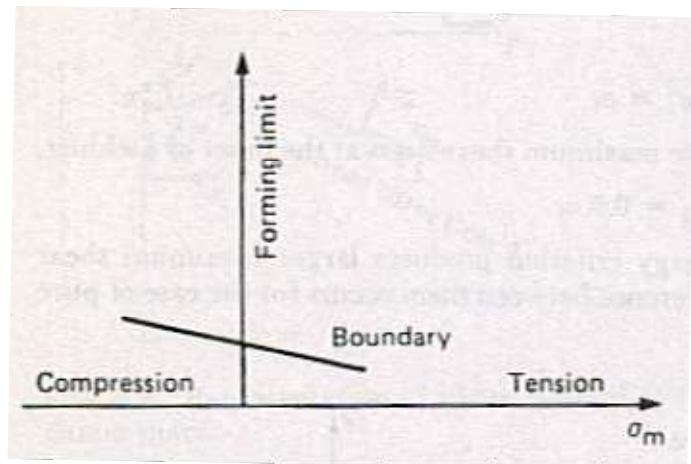


# Workability

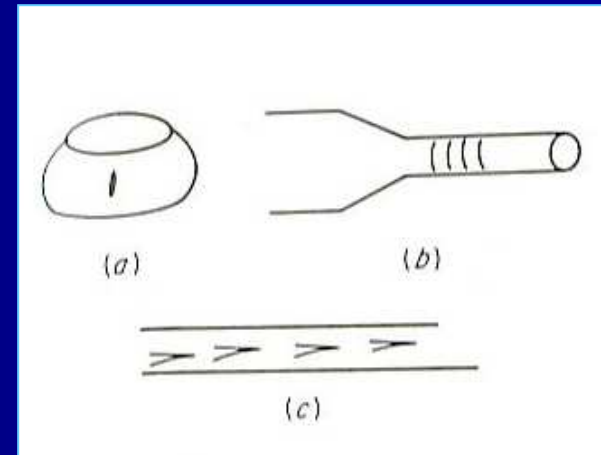
- **Workability** is concerned with the extent to which a material can be deformed in a specific metal working process **without the formation of cracks.**

- Cracks which occur in metal working processes can be grouped into three broad categories:

1. **Cracks at a free surface**
2. **Cracks that develop in a surface where interface friction is high**
3. **Internal cracks.**



Dependence of forming limit of mean normal stress  $\sigma_m$ .



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.



# References

- Dieter, G.E., **Mechanical metallurgy**, 1988, SI metric edition, McGraw-Hill, ISBN 0-07-100406-8.
- Edwards, L. and Endean, M., **Manufacturing with materials**, 1990, Butterworth Heinemann, ISBN 0-7506-2754-9.
- Lange, K., **Handbook of metal forming**, 1985, R.R Donnelly & Sons Company, ISBN 0-07-036285-8.
- Lecture notes, Birmingham, UK, 2003
- Metal forming processes, Prof Manus

