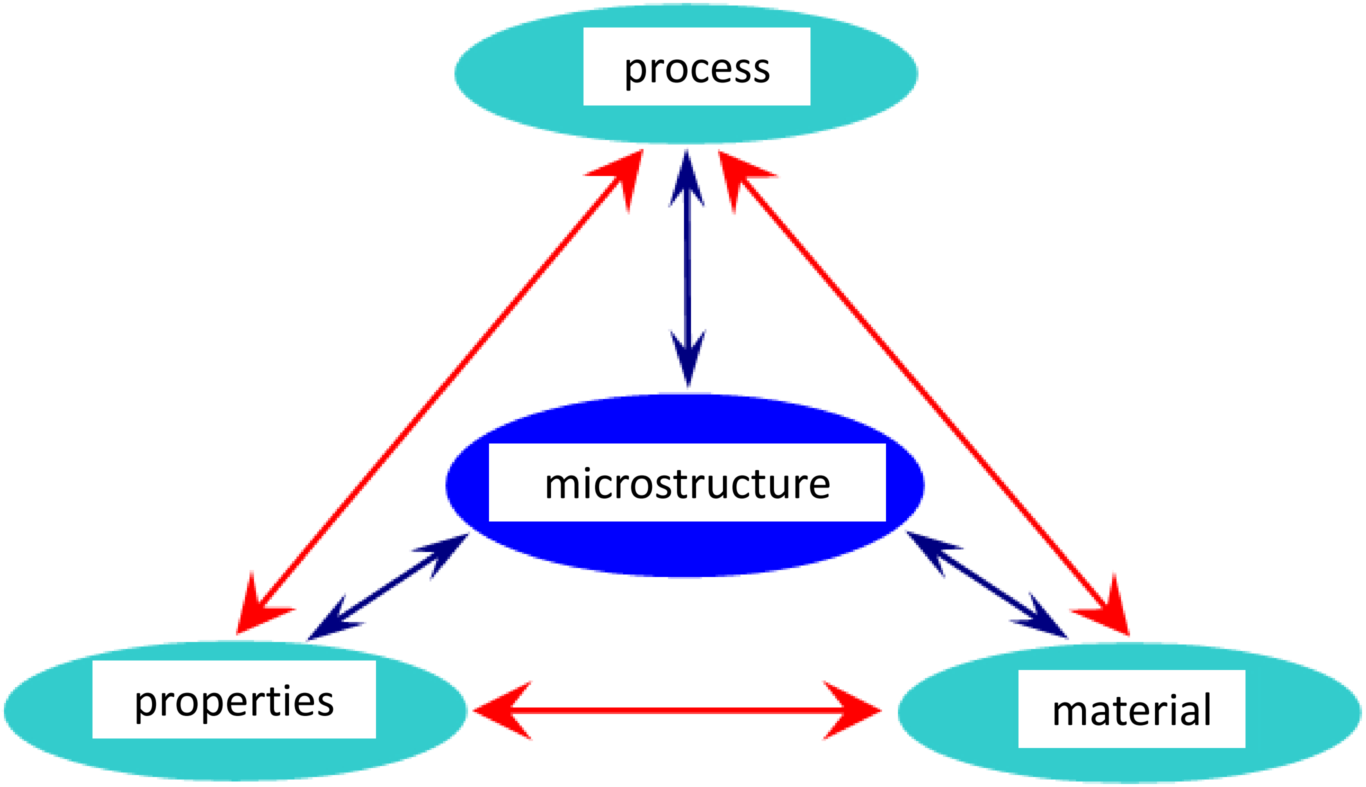
Thermo-mechanical processing of metallic materials

- Plasticity and microstructural characteristics of metals
- Technology - forming techniques
- Thermo-mechanical processing of aluminium alloys
- Thermo-mechanical processing of steels

Plasticity vs. microstructural characteristics of metals

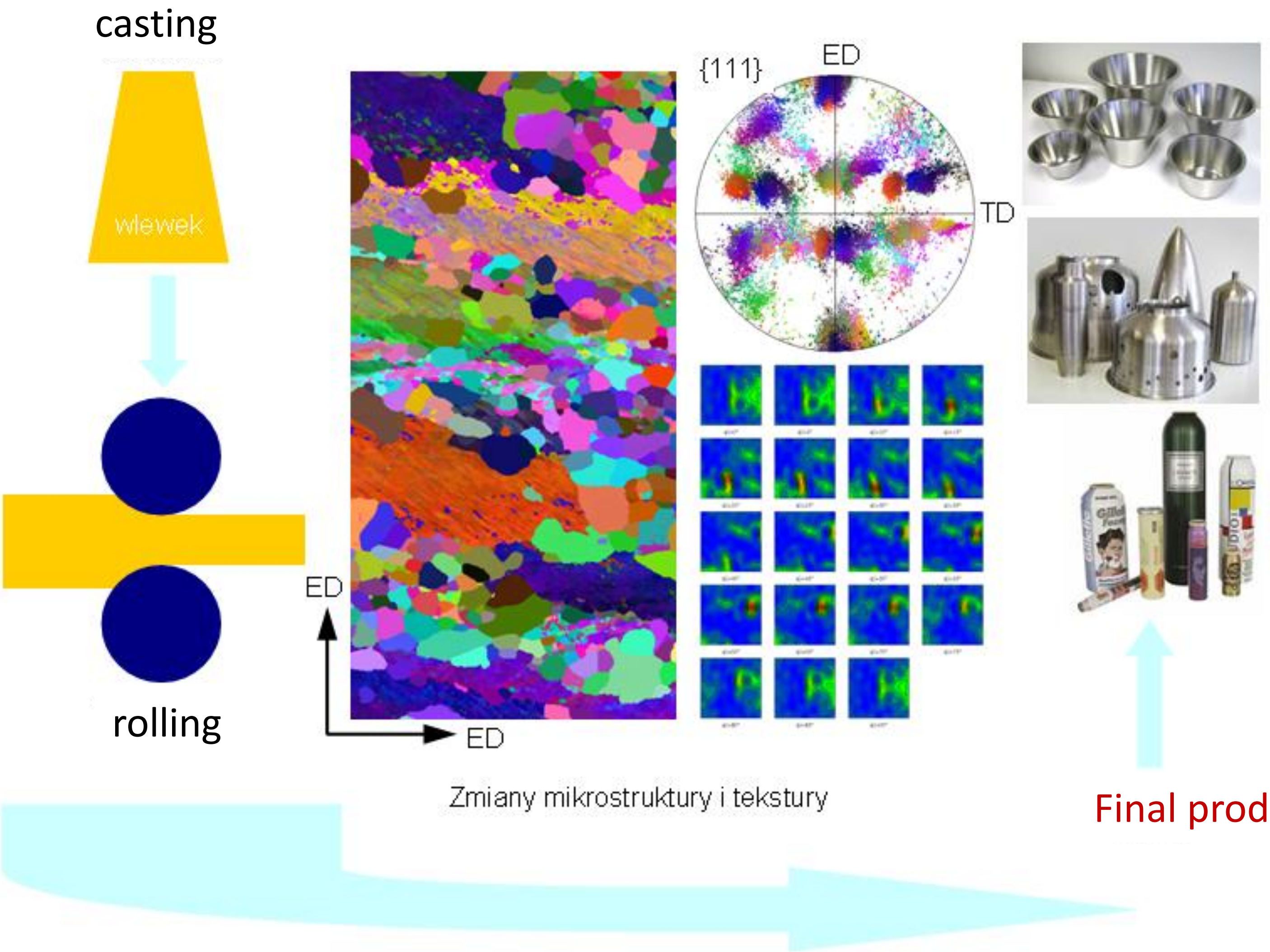
part 1

Interrelation between: process → properties → material



Thermo-mechanical process (**TMP**) – all shaping and heating operations applied to the initial material leads to semi- or final products characterized by new, better properties (with respect to the initial material). Microstructure and texture evolutions are key of importance for expected changes.

Schematic presentation of the technological process of flat semi-products shaping



casting

rolling

Zmiany mikrostruktury i tekstury

Final product

(Micro)structural and (micro)tekstural changies during processing strongly influence final properties of products.

Plastic flow - the ability to form metals to particular shapes by plastic deformation has been in use since the Bronze Age and is still a critical feature of many productive operations in the engineering industries.

Important features of metal plasticity:

relatively high stress required to initiate plastic deformation at room temperature,

capacity to work harden during plastic straining (this gives rise to their tenacity or capacity to resist failure),

when heated, plastic flow becomes relatively easy (so the material can be shaped into components or semi-finished products involving very large strains).

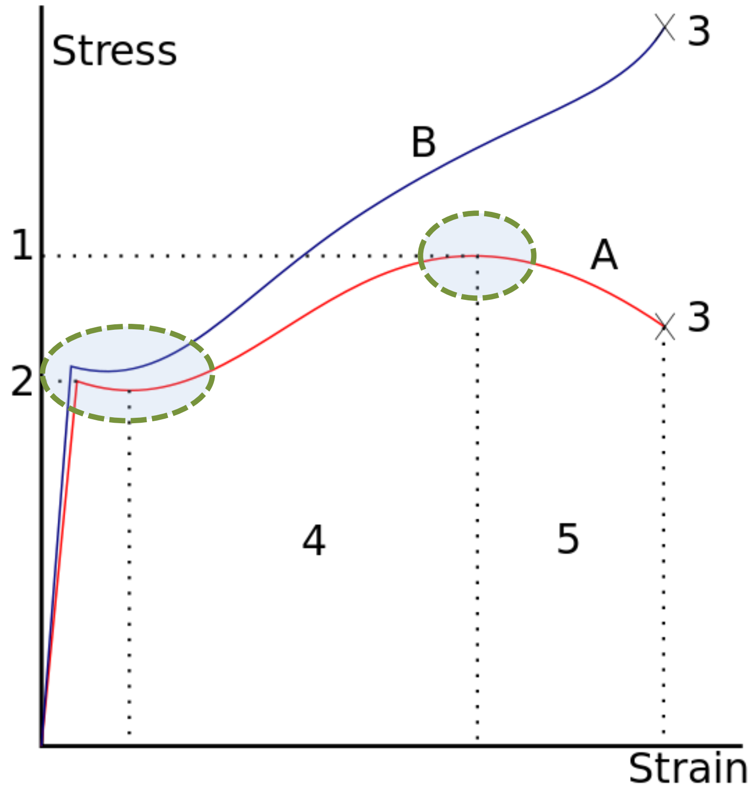
The ‘mechanical’ part of thermo-mechanical processing (TMP) essentially refers to the mechanics of plastic deformation, whereas ‘thermo-’ to the influence of the heat treatment.

Ductile materials can sustain large plastic deformations without fracture. However, even ductile metals will fracture when the strain becomes large enough - this is as a result of work hardening of the material, which causes it to become brittle. Heat treatment such as annealing can restore the ductility of a worked piece, so that shaping can continue.

Practical problems solution:

1. yield stress determination,
2. the terms of plastic flow after yielding,
3. ultimate strenght determination.

after yielding → the result of external forces on metal flow, or how large forces must be applied to obtain determined result.

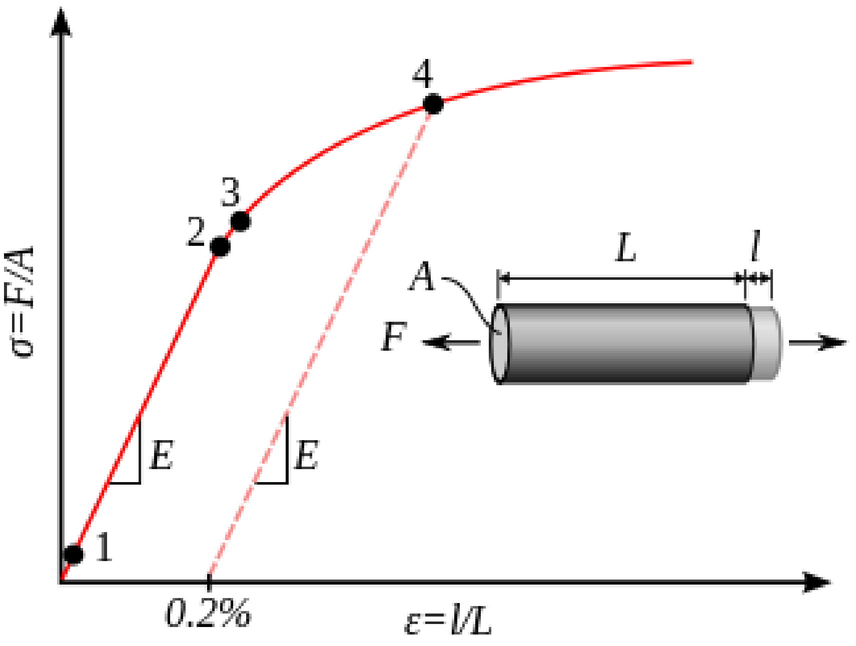


A stress–strain curve typical of structural steel

1. Ultimate Strength
2. Yield Strenght
3. Rupture
4. Strain hardening region
5. Necking region.

A: Apparent stress (F/A_0)

B: Actual stress (F/A)

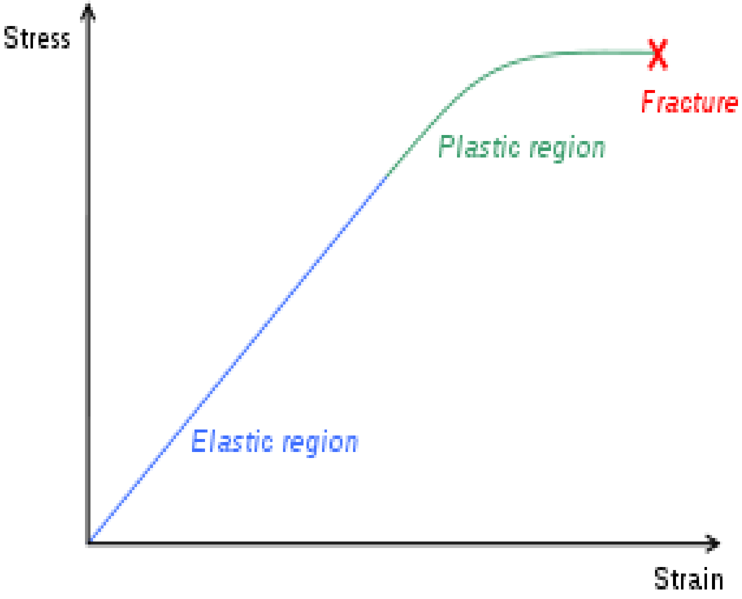


Stress-strain curve showing typical yield behavior for nonferrous alloys. Stress (σ) is shown as a function of strain (ε):

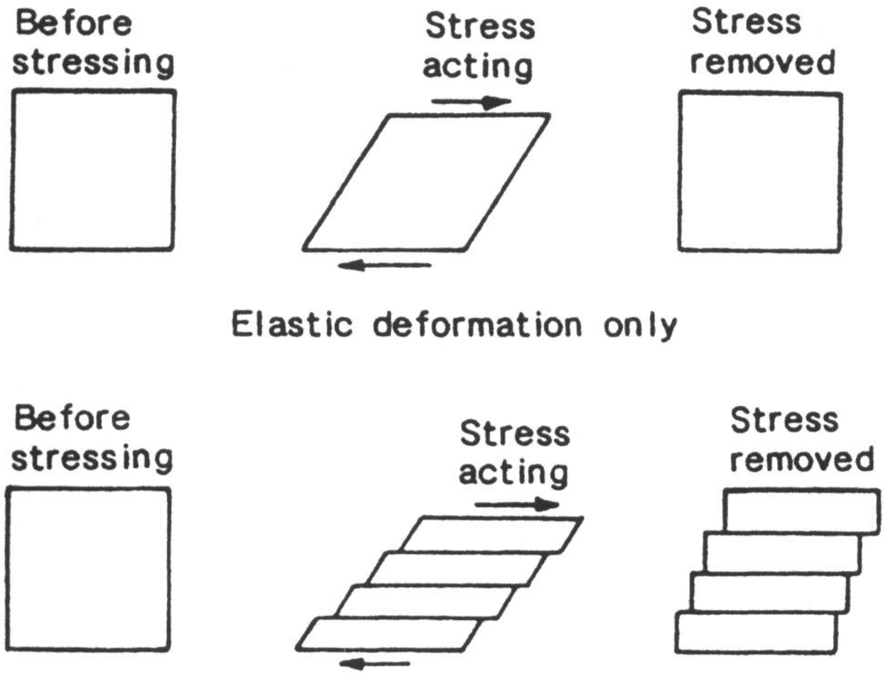
1: True elastic limit
2: Proportionality limit
3: Elastic limit
4: Offset yield strength

There are several mathematical descriptions of plasticity. One is deformation theory where the stress tensor (of order d in d dimensions) is a function of the strain tensor. Although this description is accurate when a small part of matter is subjected to increasing loading (such as strain loading), this theory cannot account for irreversibility.

Hook’s law: $\sigma = E(\varepsilon)$



An idealized uniaxial stress-strain curve showing elastic and plastic deformation regimes for the deformation theory of plasticity



$$\sigma = E'(\varepsilon): \text{ where } E' = f(\varepsilon)$$

The beginning of yielding:

If the stress exceeds a critical value, as was mentioned above, the material will undergo plastic, or irreversible, deformation. This critical stress can be tensile or compressive. The Tresca and the von Mises criteria are commonly used to determine whether a material has yielded. However, these criteria have proved inadequate for a large range of materials and several other yield criteria are in widespread use.

Treska criterion:

$$\tau_{max} = \frac{1}{2}(\sigma_{max} - \sigma_{min}) = \frac{1}{2}\sigma_f$$

$$(\sigma_1 - \sigma_3) = \pm\sigma_f \quad (\sigma_2 - \sigma_1) = \pm\sigma_f \quad (\sigma_3 - \sigma_2) = \pm\sigma_f$$

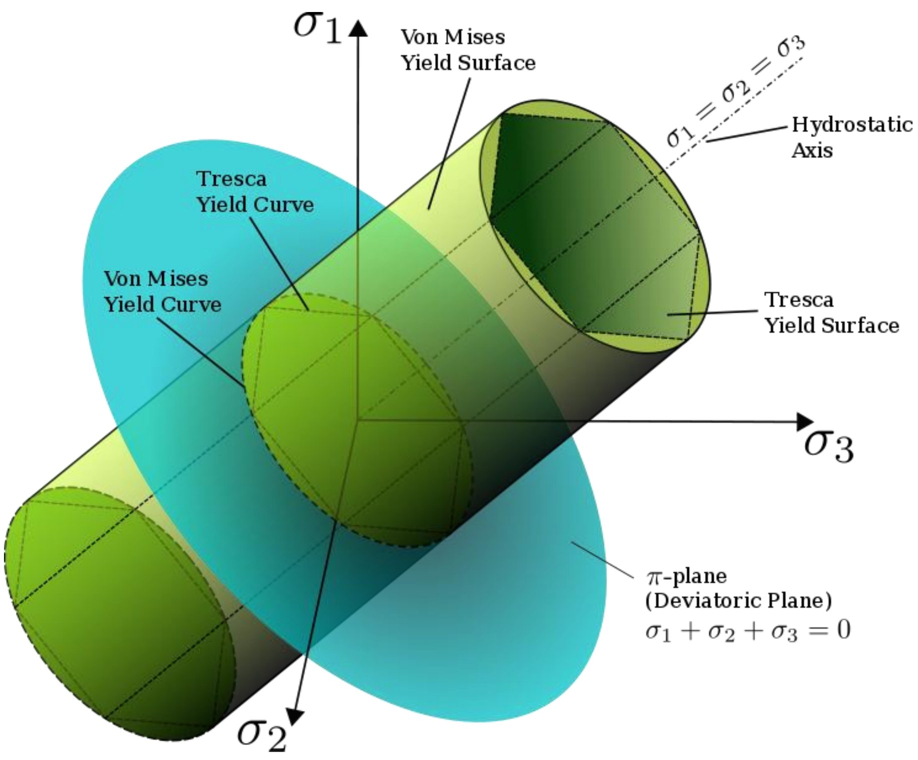
H-M-H criterion:

$$\sigma_{\text{effective}}^2 = \tfrac{1}{2}\left[(\sigma_{11} - \sigma_{22})^2 + (\sigma_{22} - \sigma_{33})^2 + (\sigma_{11} - \sigma_{33})^2\right] + 6\left(\sigma_{12}^2 + \sigma_{13}^2 + \sigma_{23}^2\right)$$

$$f(\sigma_i) = c = (\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2$$

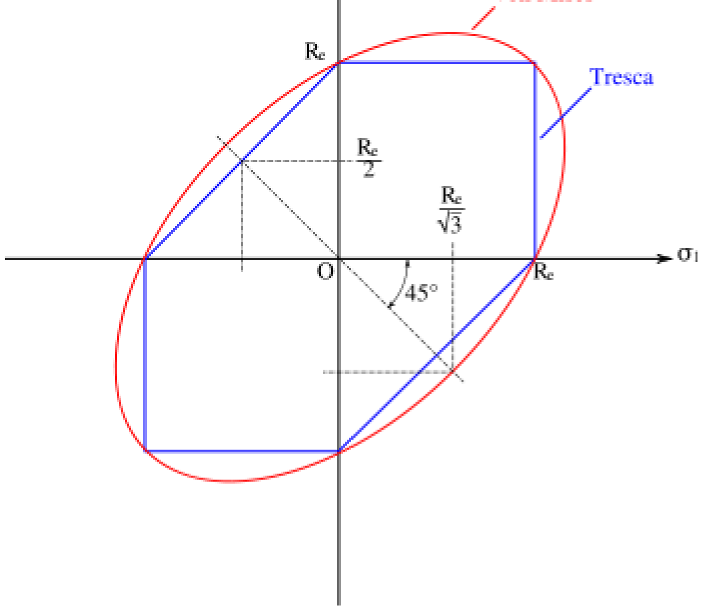
$$c = 2\sigma_f^2$$

The **yield strength** or **yield point** of a material is defined as the stress at which a material begins to deform plastically. Prior to the yield point the material will deform elastically and will return to its original shape when the applied stress is removed. Once the yield point is passed, some fraction of the deformation will be permanent and non-reversible.
In the three-dimensional space of the principal stresses: ***σ1, σ2, σ3,*** an infinite number of yield points form together a yield surface.



The von Mises yield surfaces in principal stress coordinates circumscribes a cylinder around the hydrostatic axis. Also shown is Tresca's hexagonal yield surface.

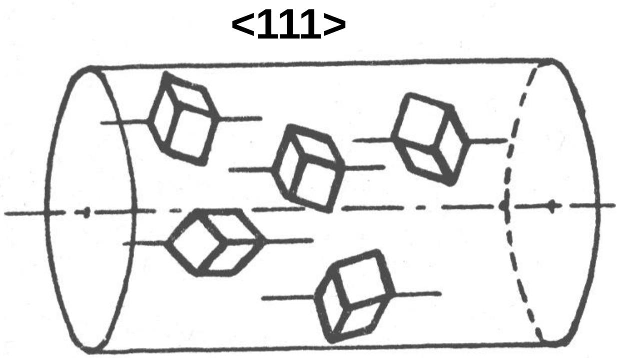
$\sigma_3 = 0$



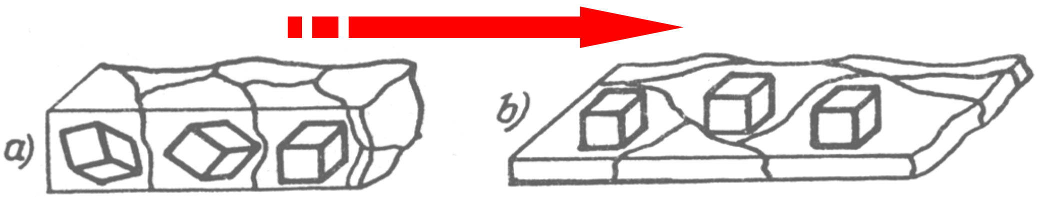
Comparison of Tresca criterion to Von Mises criterion (*plane state of stress*)

Crystallographic texture influence

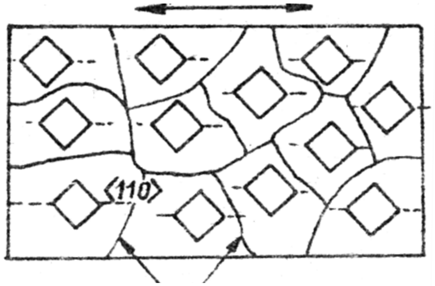
Fibre texture, e.g. Al wire)



Rolling direction

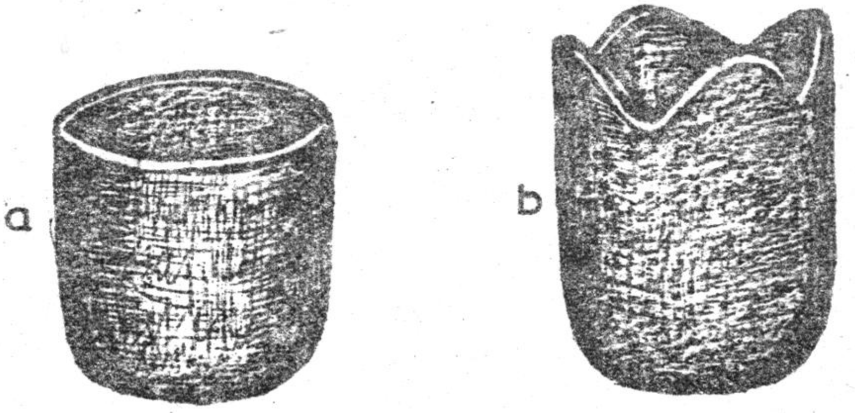


Rolling direction



Grain boundaries

Strong Goss **{100}<011>** texture component in rolled sheets

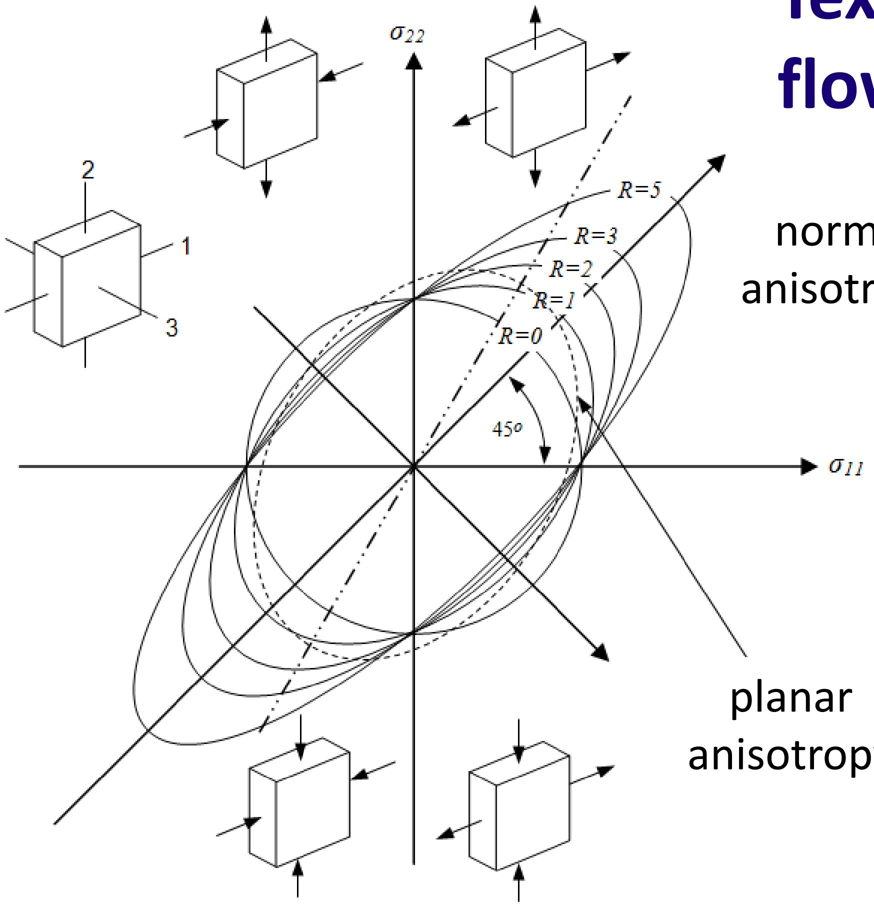


Deep drawing

(a) isotropic sheet,

(b) strong anisotropy (strong cube – {100}<001> texture component in rolled sheets)

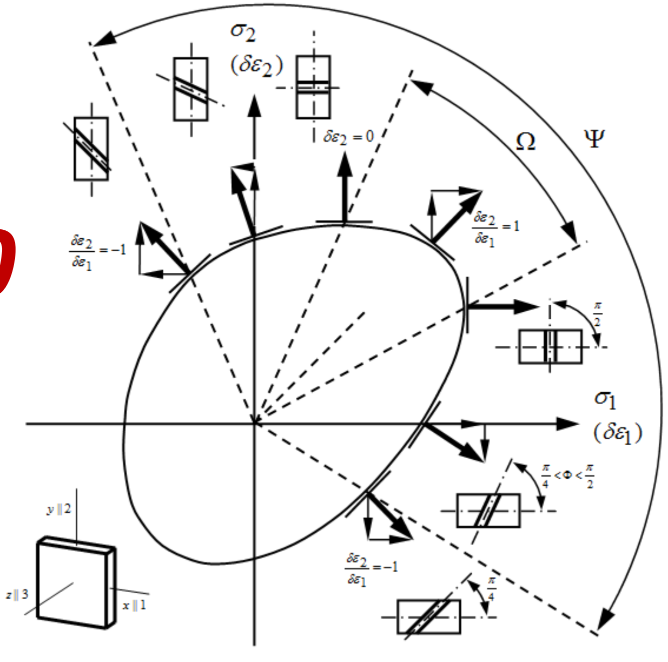
Textured materials – plastic flow anisotropy



normal anisotropy

planar anisotropy

$\sigma_3 = 0$

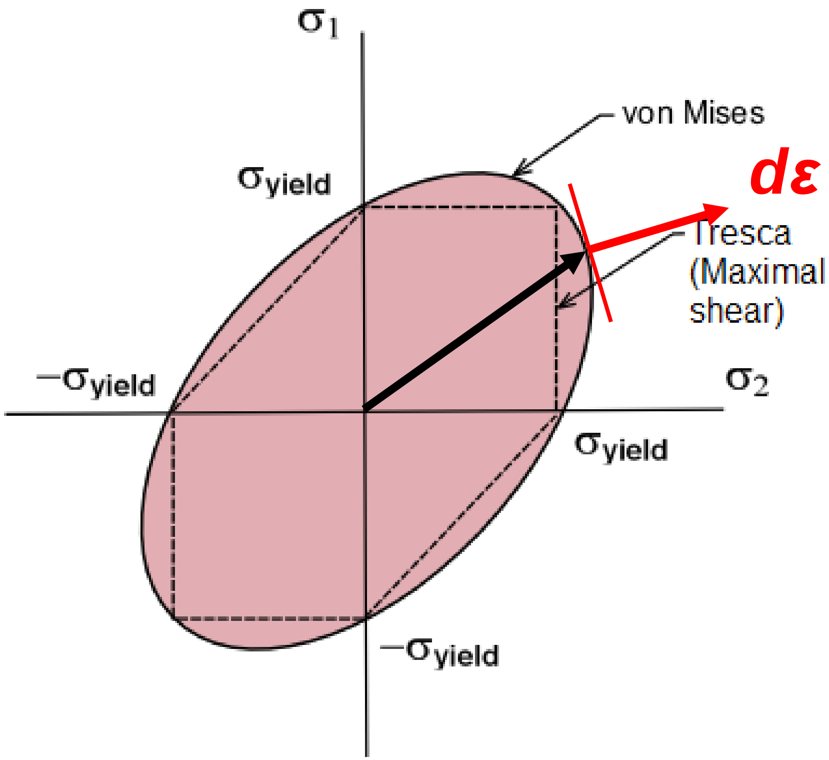


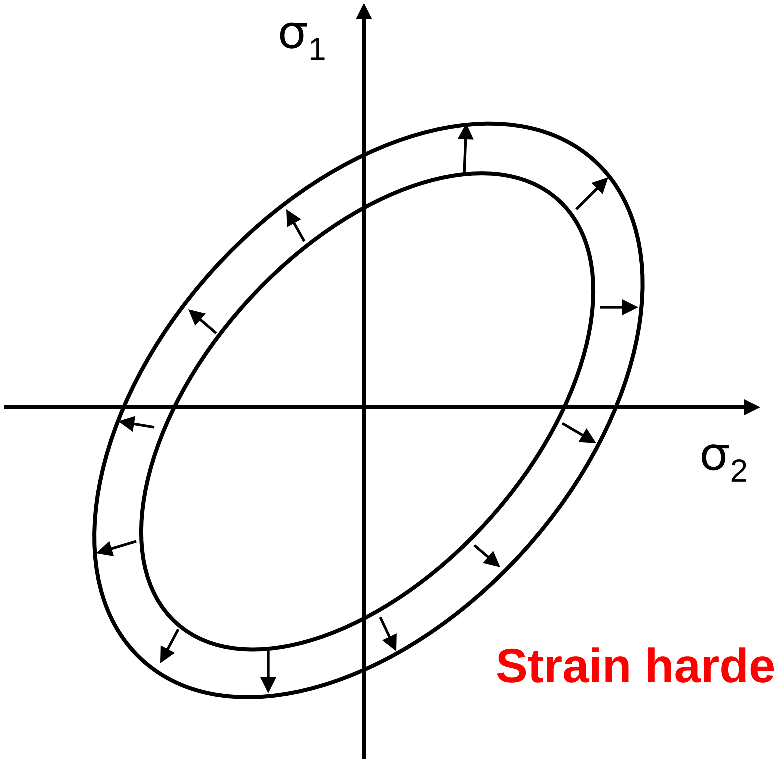
accidental anisotropy

$$\bar{\sigma}_p = \left[\frac{3/2}{F+G+H}\right]^{1/2}\left[F(\sigma_2-\sigma_3)^2+G(\sigma_3-\sigma_1)^2+H(\sigma_1-\sigma_2)^2\right]^{1/2}$$

$$\bar{\sigma}_p = (\sigma_1^2+\sigma_2^2-\frac{2r}{1+r}\sigma_1\sigma_2)^{1/2}$$

Plasticity vs. strain hardening case of plane state of stress $\sigma_3 = 0$



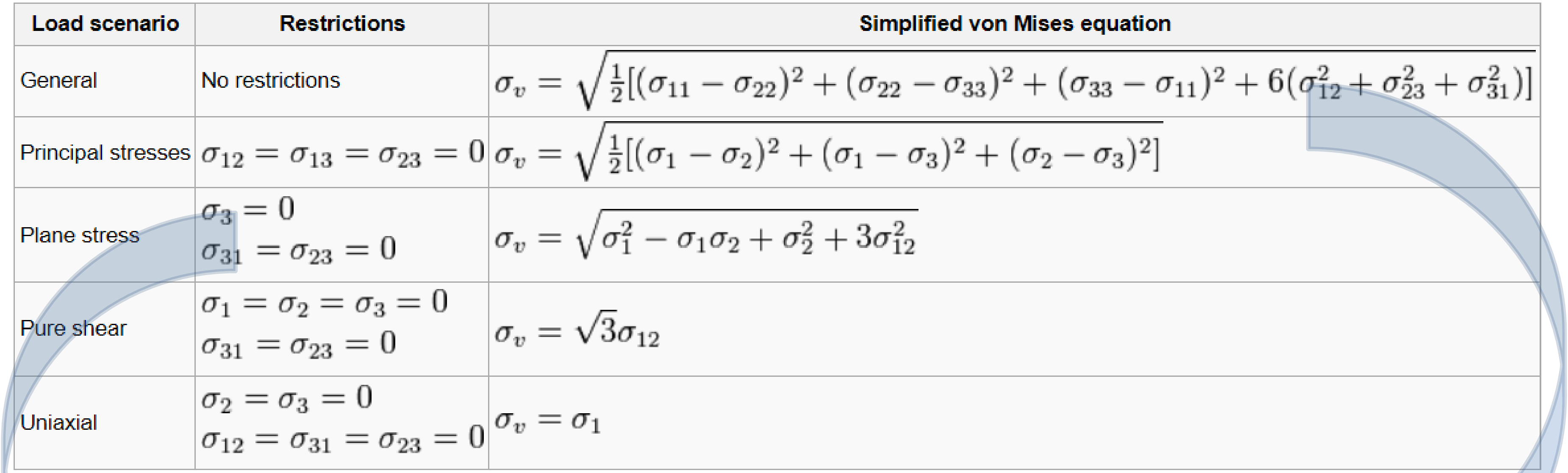


Strain hardening

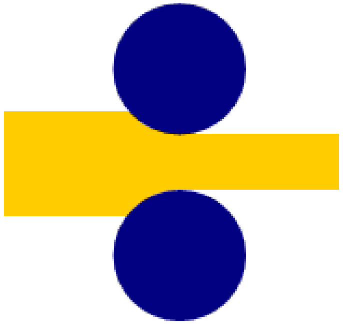
For any stress state within the yield surface, deformation is purely elastic but when the stress attains this surface (arrow from the origin) plastic defromation occurrs with an incremental amount ***dε***.

The strain vector normality rulr states that *the incremental strain vector, dε is perpendicular to the yield surface* at the point corresponding to the stress state on the surface giving rise to plastic flow.

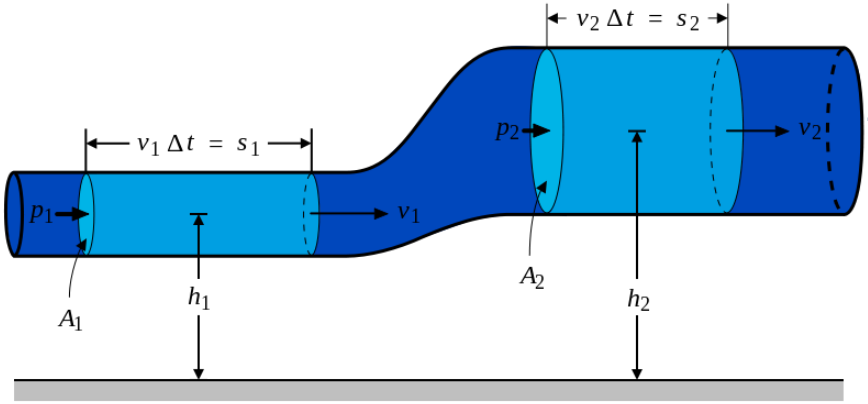
The following table summarises von Mises yield criterion for the different stress conditions



Load scenario	Restrictions	Simplified von Mises equation
General	No restrictions	$\sigma_v = \sqrt{\frac{1}{2}[(\sigma_{11}-\sigma_{22})^2+(\sigma_{22}-\sigma_{33})^2+(\sigma_{33}-\sigma_{11})^2+6(\sigma_{12}^2+\sigma_{23}^2+\sigma_{31}^2)]}$
Principal stresses	$\sigma_{12}=\sigma_{13}=\sigma_{23}=0$	$\sigma_v = \sqrt{\frac{1}{2}[(\sigma_1-\sigma_2)^2+(\sigma_1-\sigma_3)^2+(\sigma_2-\sigma_3)^2]}$
Plane stress	$\sigma_3=0$ $\sigma_{31}=\sigma_{23}=0$	$\sigma_v = \sqrt{\sigma_1^2-\sigma_1\sigma_2+\sigma_2^2+3\sigma_{12}^2}$
Pure shear	$\sigma_1=\sigma_2=\sigma_3=0$ $\sigma_{31}=\sigma_{23}=0$	$\sigma_v = \sqrt{3}\sigma_{12}$
Uniaxial	$\sigma_2=\sigma_3=0$ $\sigma_{12}=\sigma_{31}=\sigma_{23}=0$	$\sigma_v = \sigma_1$



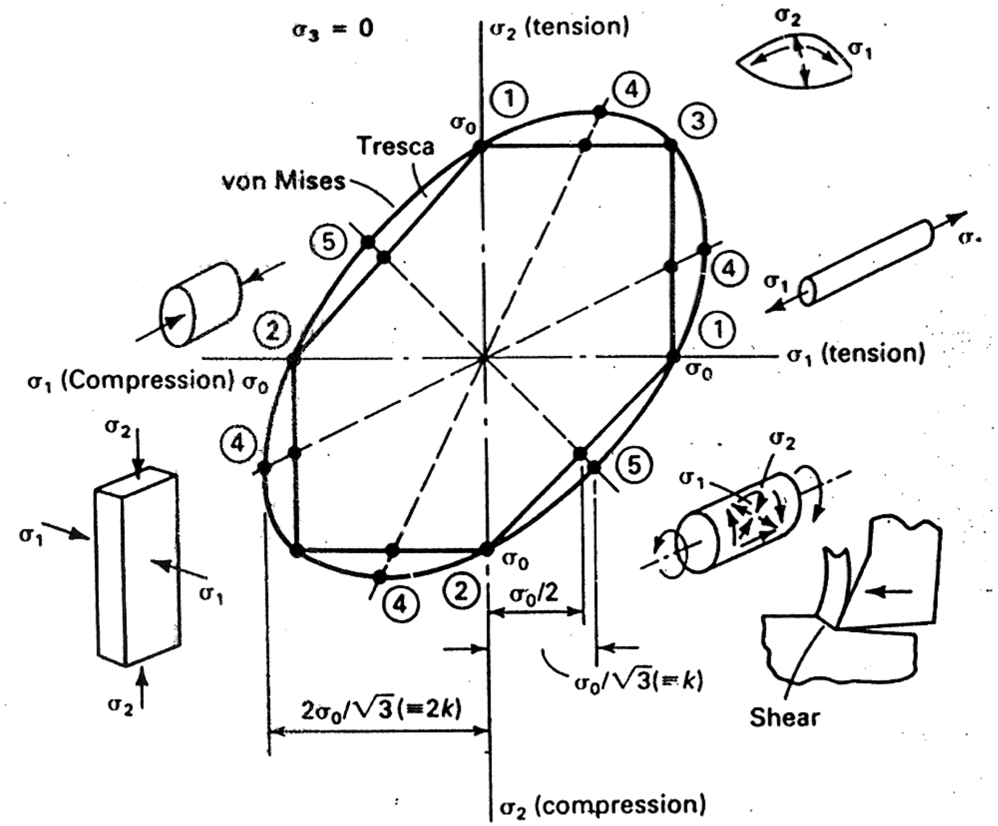
Case 3

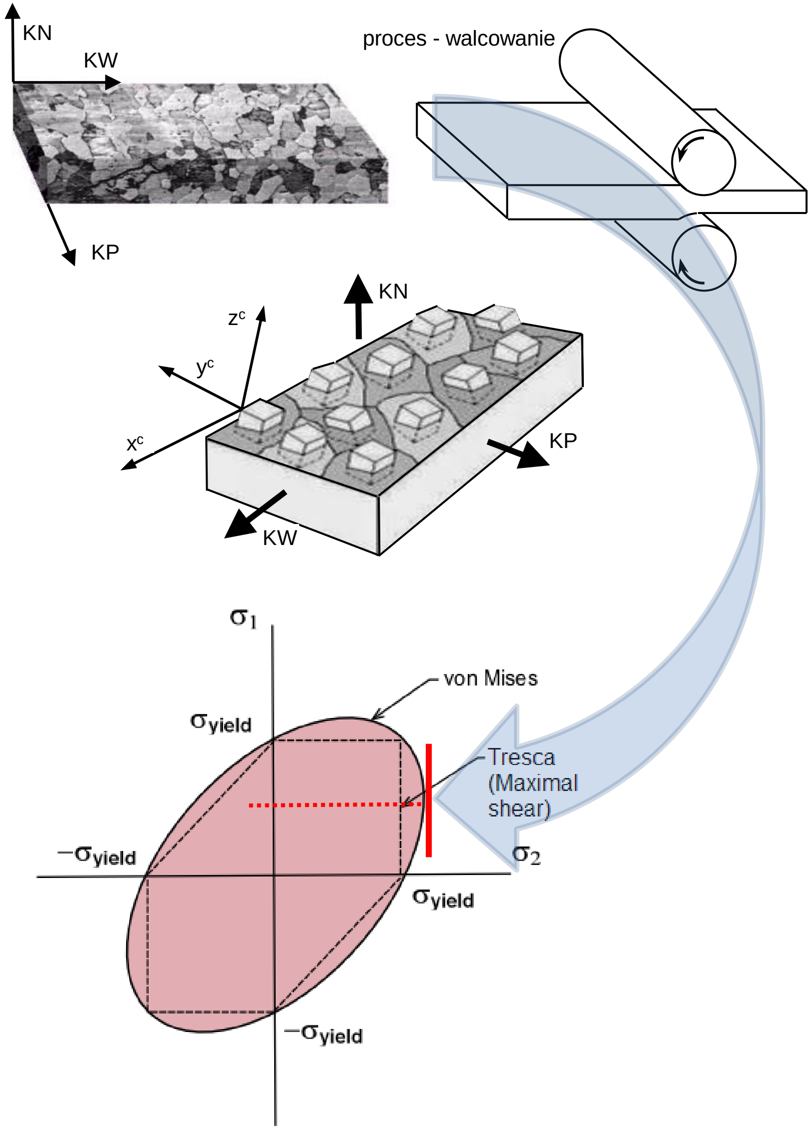


Case 1,2

Different processes – different states of stress

$\sigma_3 = 0$

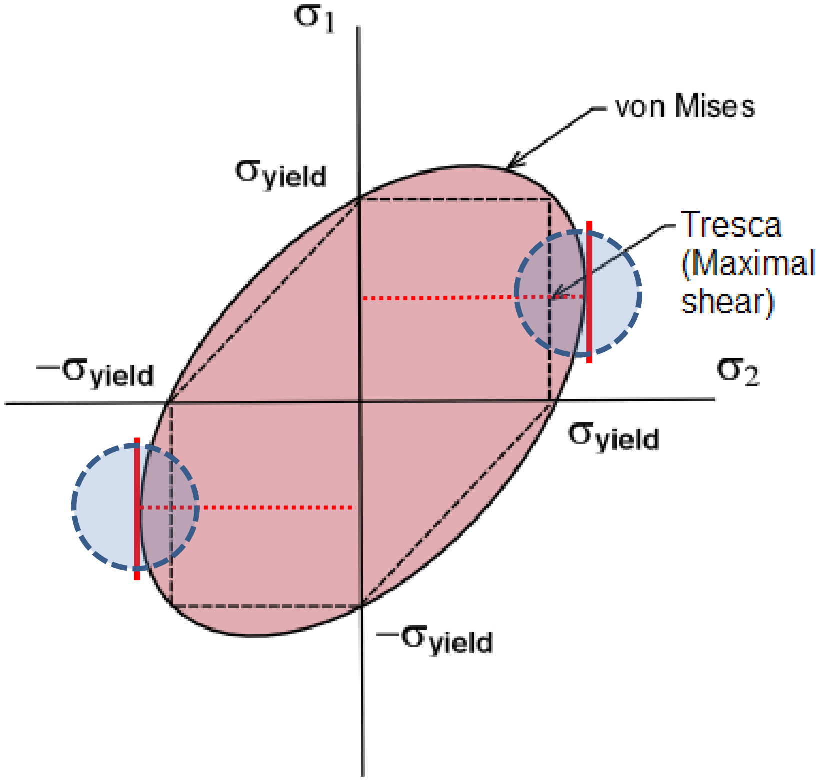




Case of plane state of stress $\sigma_3 = 0$ and plane state of strain

The condition of strain vector normality applied to the von Mises yield function gives some useful stress conditions for different strain paths. If the flow stress is σ_f:

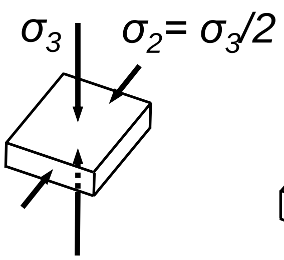
Different processes – the same states of stress

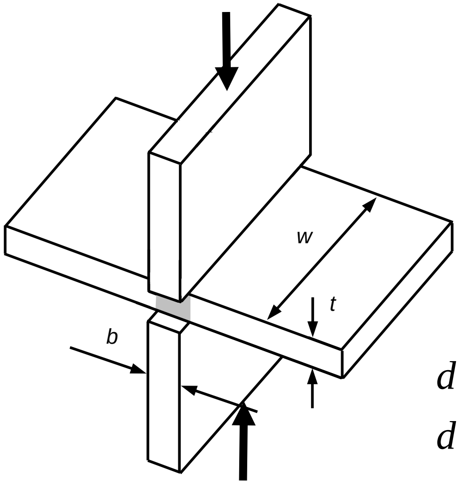


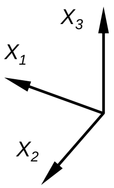
$$Plane\,strain:(\varepsilon_2 = 0, \varepsilon_2 = -\varepsilon_1) \quad \sigma_1 = \frac{2}{\sqrt{3}}\sigma_f\,;\sigma_2 = \frac{1}{\sqrt{3}}\sigma_f$$

$$Drawing:(\varepsilon_2 = 0, \varepsilon_2 = -\varepsilon_1) \quad \sigma_1 = \frac{1}{\sqrt{3}}\sigma_f\,;\sigma_2 = \frac{1}{\sqrt{3}}\sigma_f$$

Case of plane state of strain $\varepsilon_2 = 0$



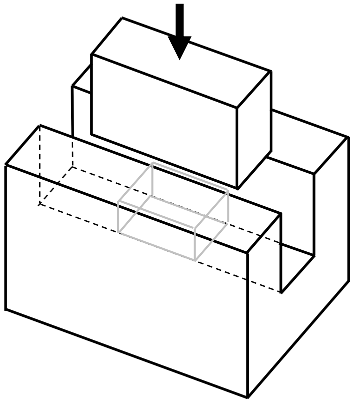


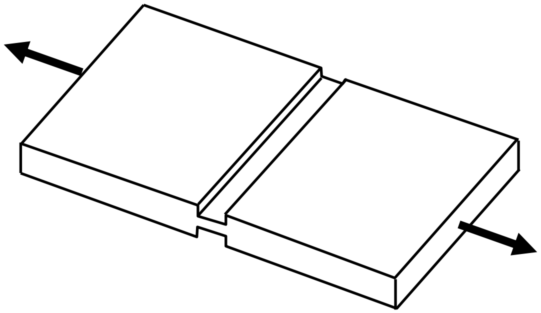


Plane strain indentation

$$d\varepsilon_2 = 0$$

$$d\varepsilon_1 = -d\varepsilon_3$$





Channel-die **Plane strain in tension**

Work hardening - analytical description of plastic flow, i.e. stress-strain curve *(after yielding)*

Analytical description

Ludwik $\sigma = \sigma_y + k_1 \left(\bar{\varepsilon}\right)^n$

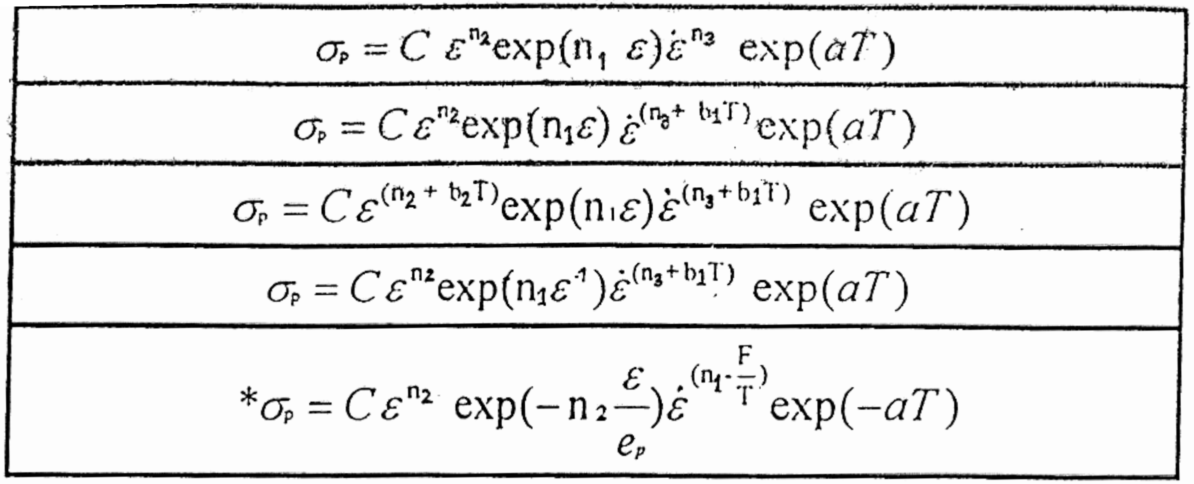
Hollomon $\sigma = k_2 \left(\bar{\varepsilon}\right)^{n'}$

Krupkowski $\sigma = k z_i^m$

Voce'a $\sigma = \sigma_s - \left(\sigma_s - \sigma_y\right) \exp\left(-\alpha \bar{\varepsilon}\right)$

Hocket & Sherby $\sigma = \sigma_s - \left(\sigma_s - \sigma_y\right) \exp\left(-\alpha \bar{\varepsilon}^p\right)$

Equations for numerical analysis



$$\sigma_p = C\,\varepsilon^{n_2} \exp(n_1\,\varepsilon)\,\dot{\varepsilon}^{n_3} \exp(aT)$$

$$\sigma_p = C\,\varepsilon^{n_2} \exp(n_1\varepsilon)\,\dot{\varepsilon}^{(n_3 + b_1 T)} \exp(aT)$$

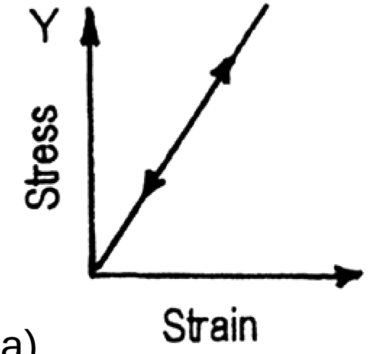
$$\sigma_p = C\,\varepsilon^{(n_2 + b_2 T)} \exp(n_1\varepsilon)\,\dot{\varepsilon}^{(n_3 + b_1 T)} \exp(aT)$$

$$\sigma_p = C\,\varepsilon^{n_2} \exp(n_1\varepsilon^{-1})\,\dot{\varepsilon}^{(n_3 + b_1 T)} \exp(aT)$$

$$*\sigma_p = C\,\varepsilon^{n_2} \exp\left(-n_2 \frac{\varepsilon}{e_p}\right)\dot{\varepsilon}^{\left(n_1 \cdot \frac{F}{T}\right)} \exp(-aT)$$

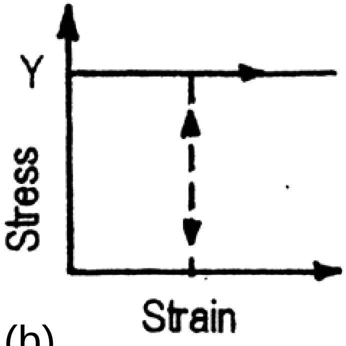
Work hardening – modelling of material behaviour

Perfectly elastic material

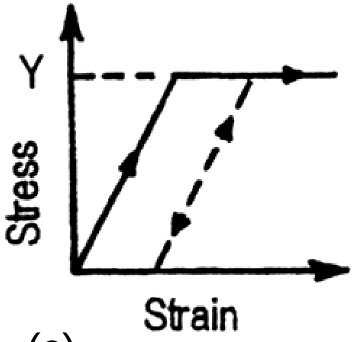


(a)

Rigid, perfectly plastic material

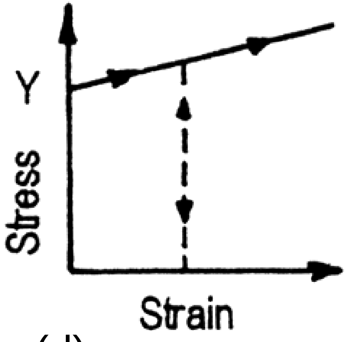


(b)



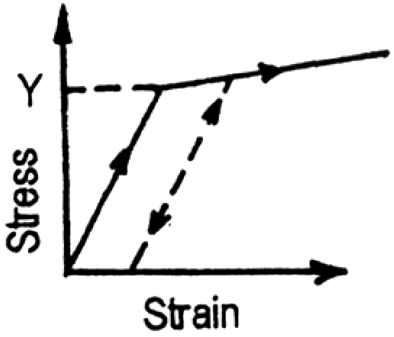
(c)

Perfectly elastic & plasic material



(d)

Rigid, lineary strain-hardening material



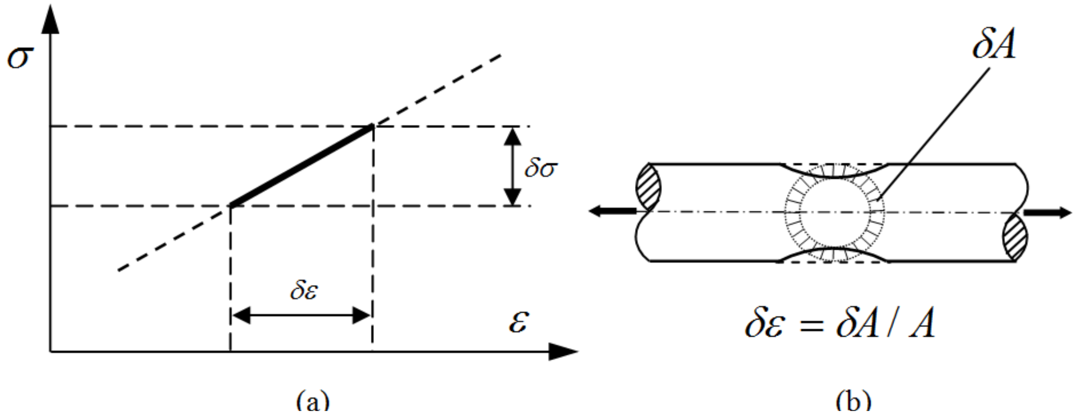
(e)

Elastic, lineary strain–hardening material

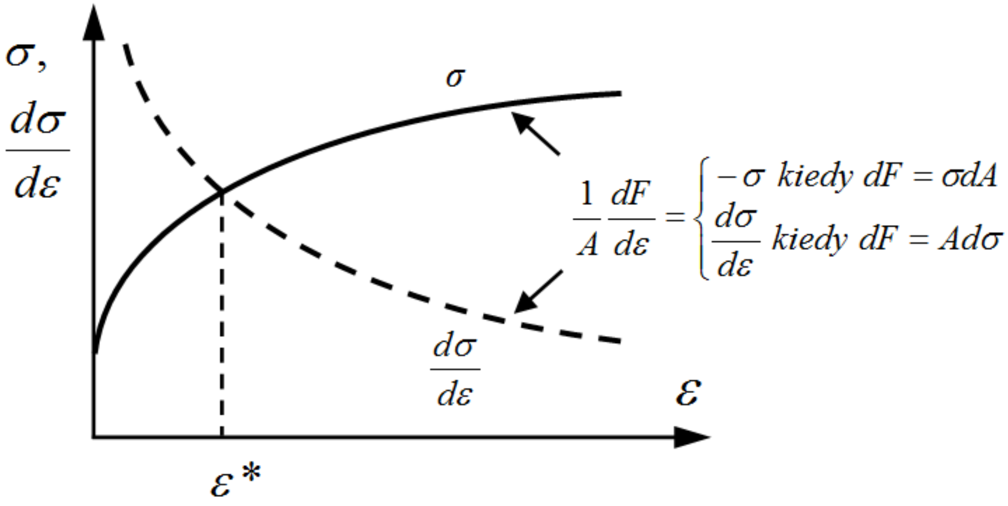
Idealized stress-strain diagrams

Lost of stability and fracture

Geometrical instability



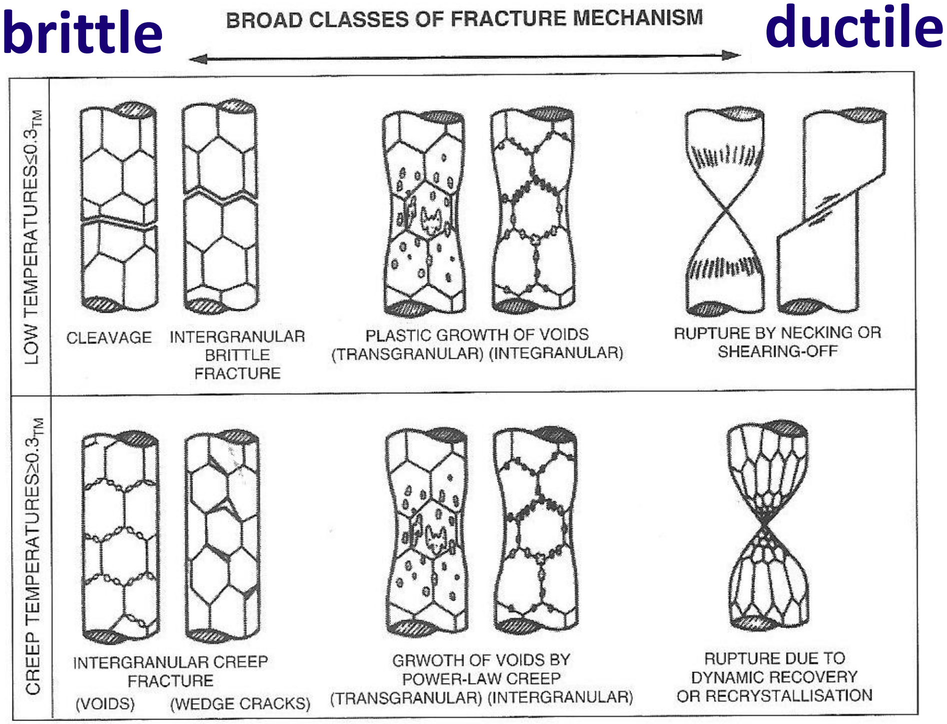
Two concurent processes: (a) hardening), (b) geometrical softening



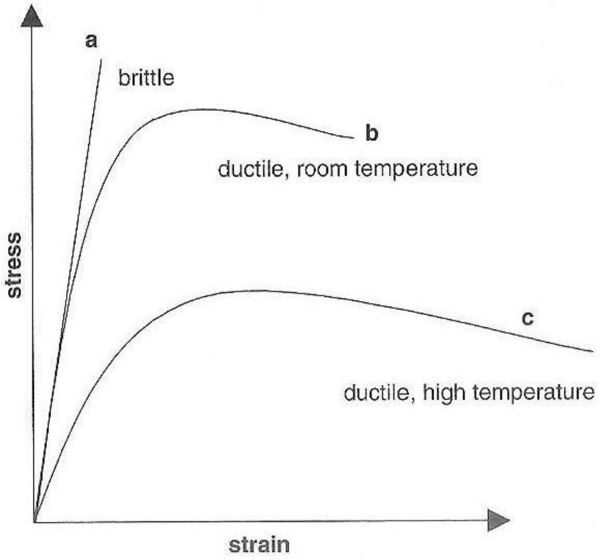
Lost of stability during uniaxial straining

Rupture & failure mechanisms

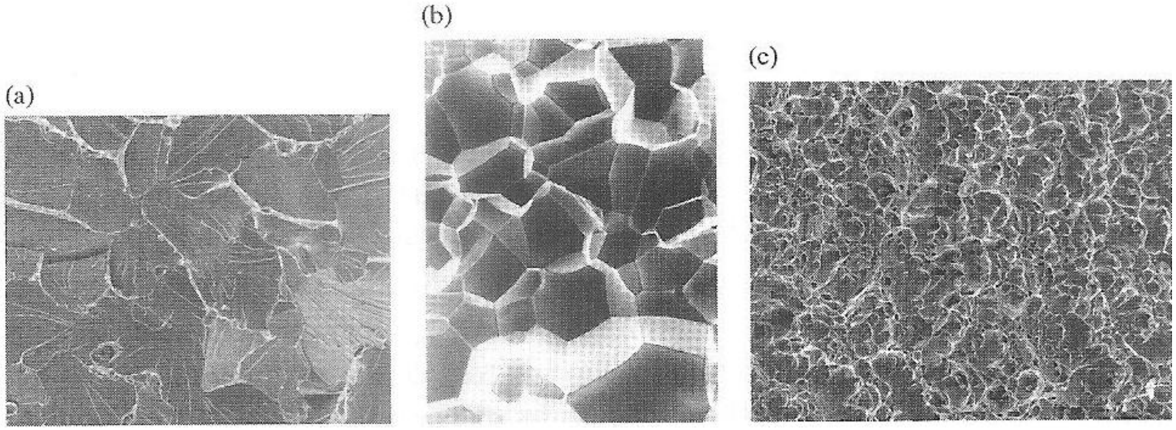
brittle **ductile**



Classes of fracture mechanisms, after Ashby et al. (1979)



Schematic stress-strain curves for common failure modes: (a) brittle, (b) ductile at RT and (c) high temperature



Typical SEM fracture surfaces:

(a) brittle cleavage of martensitic 0.38%C steel,
(b) brittle intergranular fracture of W at room temperature, and
(c) ductile rupture fracture showing cusps formed by void growth around particles.

Plasticity – ability of metals to strain accomodation without decomposition of grain cohesion

Range of plasticity = ultimate strenght - yield stress

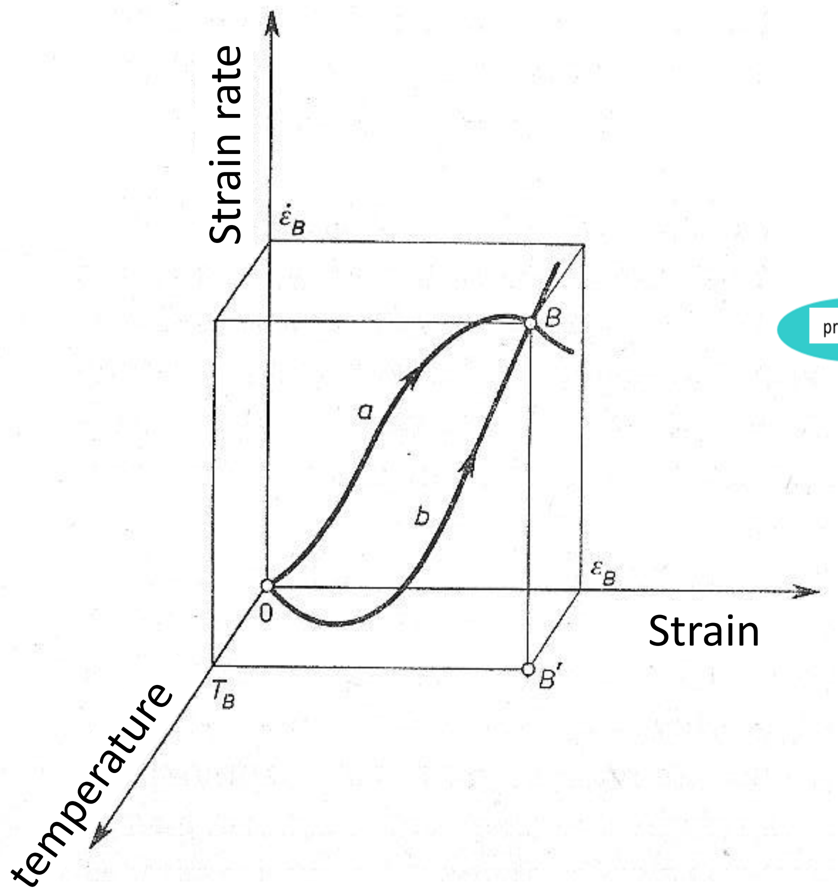
Factors that controls plasticity of metals:

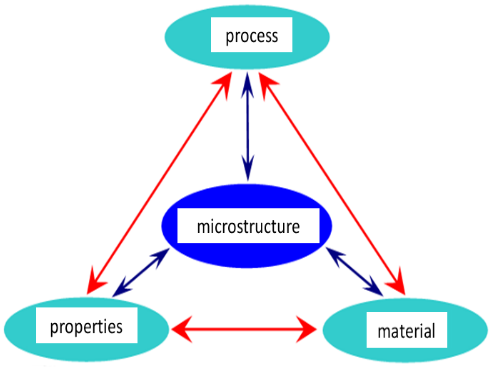
Technological terms of plastic deformation (forming): deformation temperature, deformation degree, strain rate, processes of recovery and recrystallization, mechanical state of strain,

Structure of metals: crystallographic lattice, chemical composition (and impurities), phase composition,

Values of plasticity indexes: uniform elongation, deformation after necking, range of plasticity,

State of material after processing vs. TMP path





process

microstructure

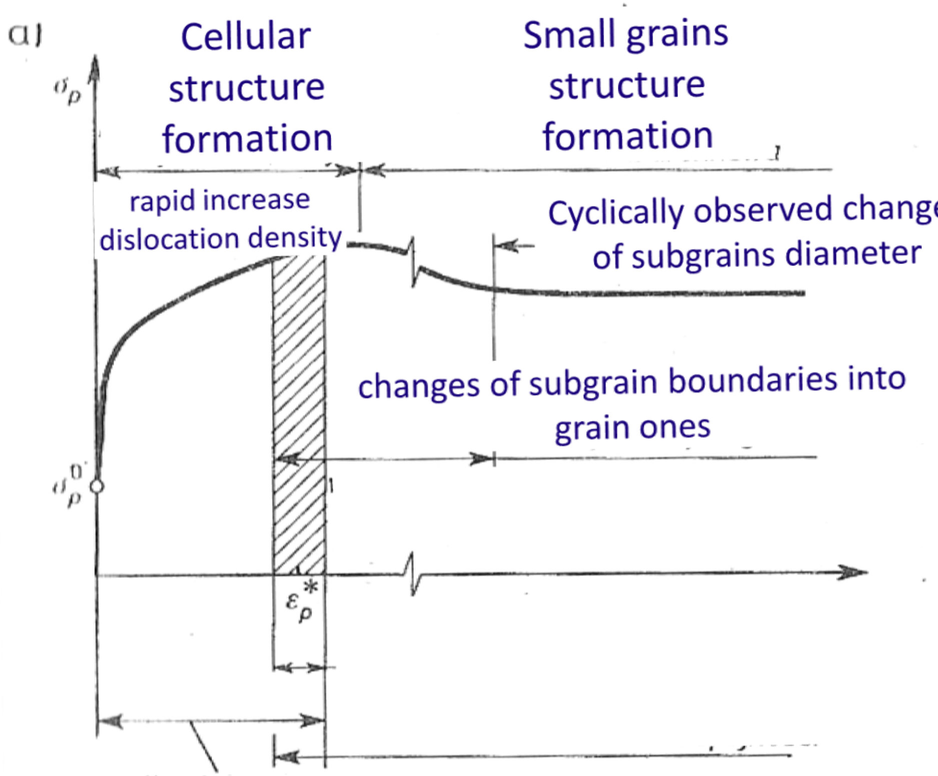
properties

material

σ = f(strain, strain rate, temperature)

this function – no exists

Deformation degree vs. plasticity



Cellular structure formation

Small grains structure formation

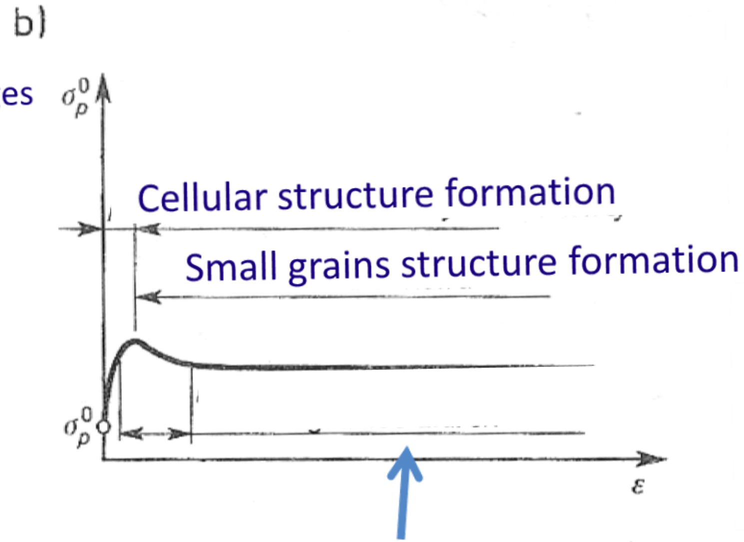
rapid increase dislocation density

Cyclically observed changes of subgrains diameter

changes of subgrain boundaries into grain ones

range of deformations in most shaping processing

Cold working



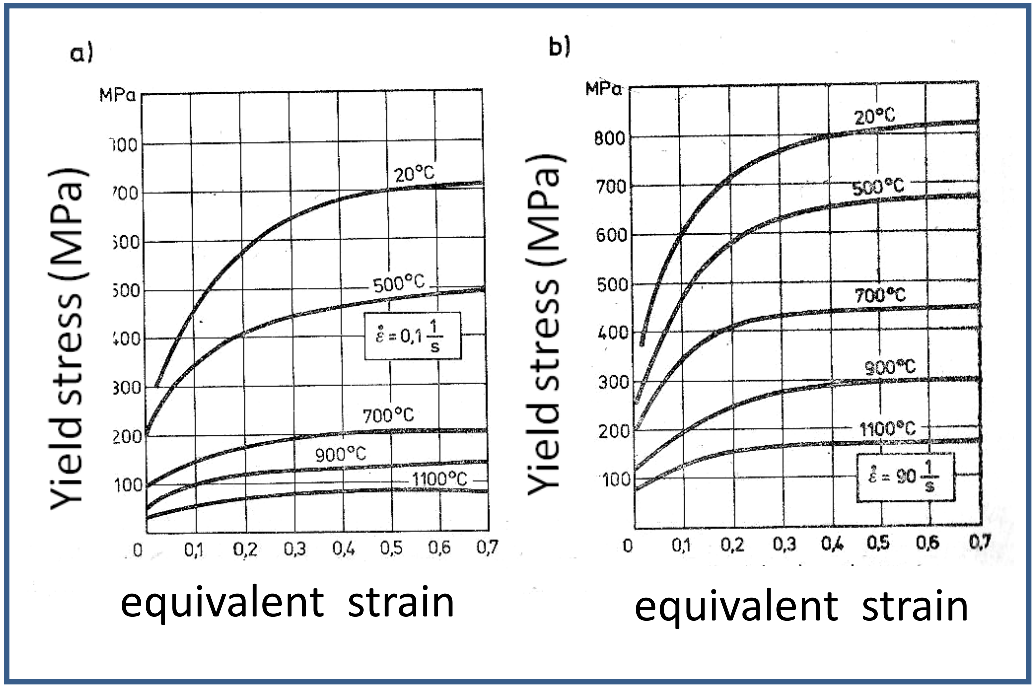
Cellular structure formation

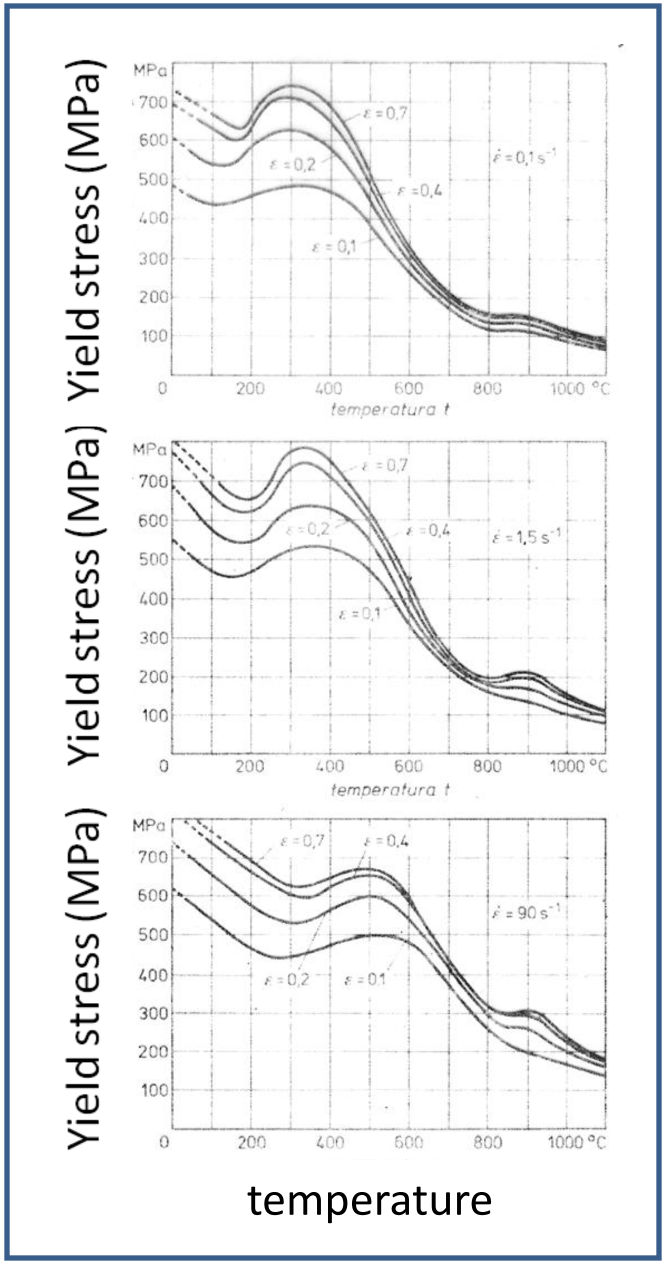
Small grains structure formation

Changes of subgrain boundaries into grain boundaries

Hot working

Plasticity vs. temperature

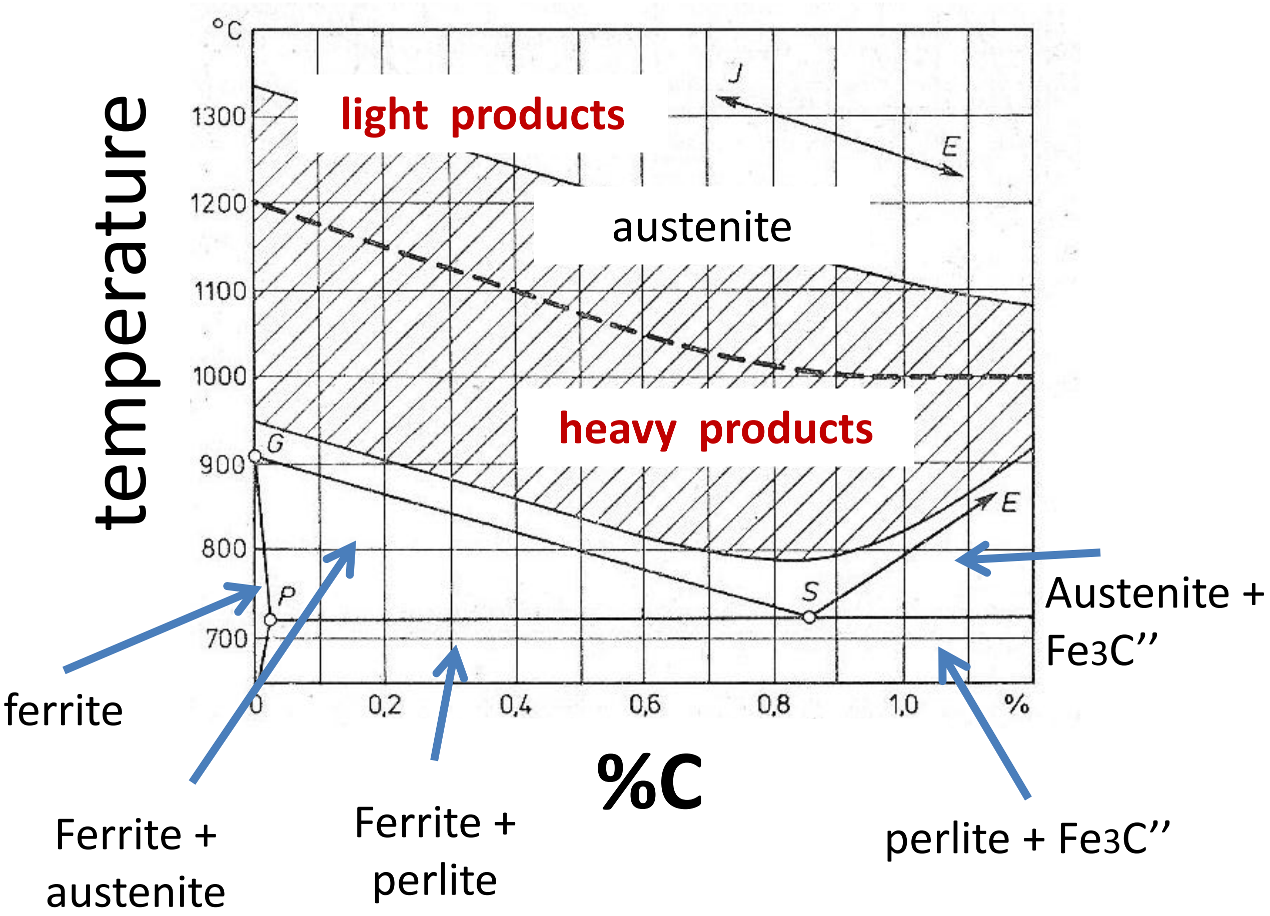




$$\sigma_p = \sigma_{po} \exp(-aT)$$

hot working $T = (0.6\text{-}0.9)T_t$

Hot working – temperature of heating (steels)



temperature

light products

austenite

heavy products

Austenite + Fe_3C''

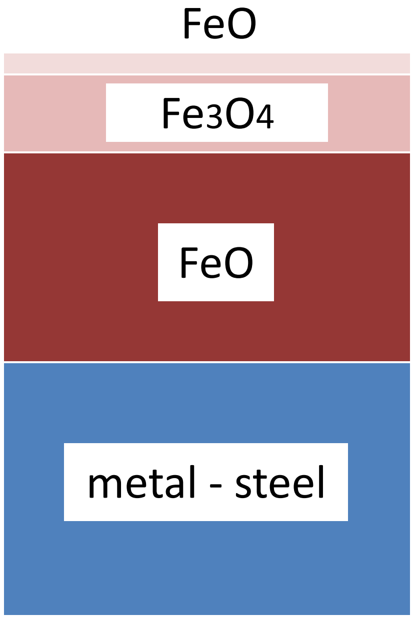
ferrite

Ferrite + austenite

Ferrite + perlite

%C

perlite + Fe_3C''



FeO

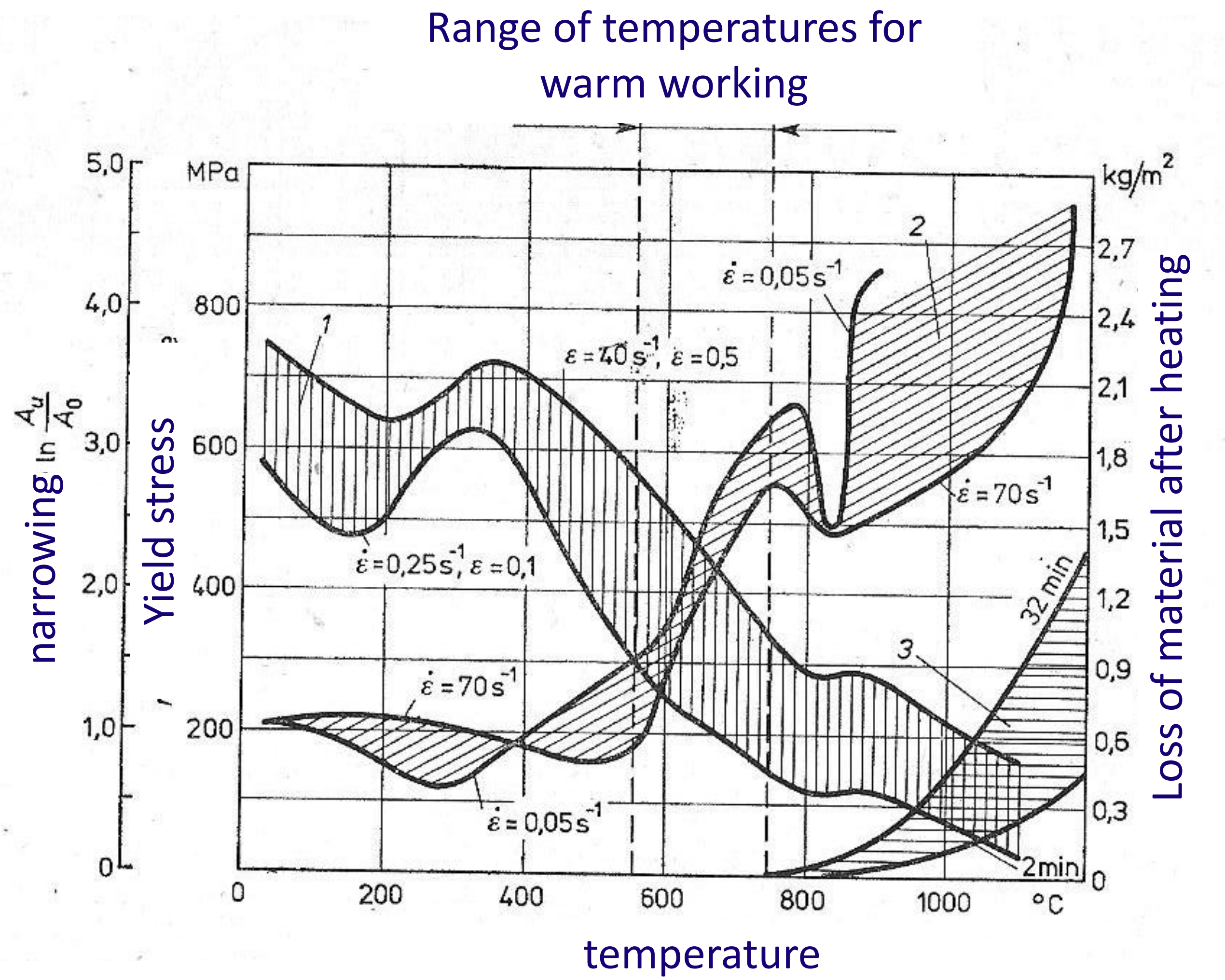
Fe_3O_4

FeO

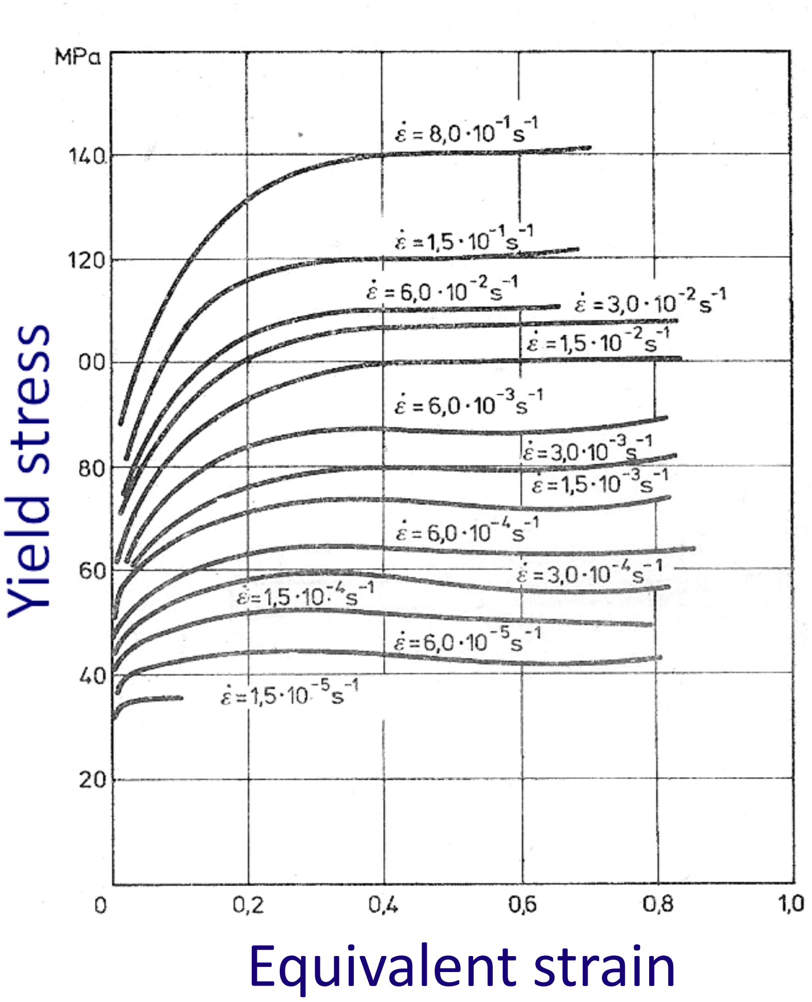
metal - steel

Range of temperatures applied for hot working of carbon steels

Temperature range of warm working



Plasticity vs. strain rate



$$\sigma = C(d\varepsilon/dt)^m$$

$$\lg\sigma = \lg C + m \lg\varepsilon$$

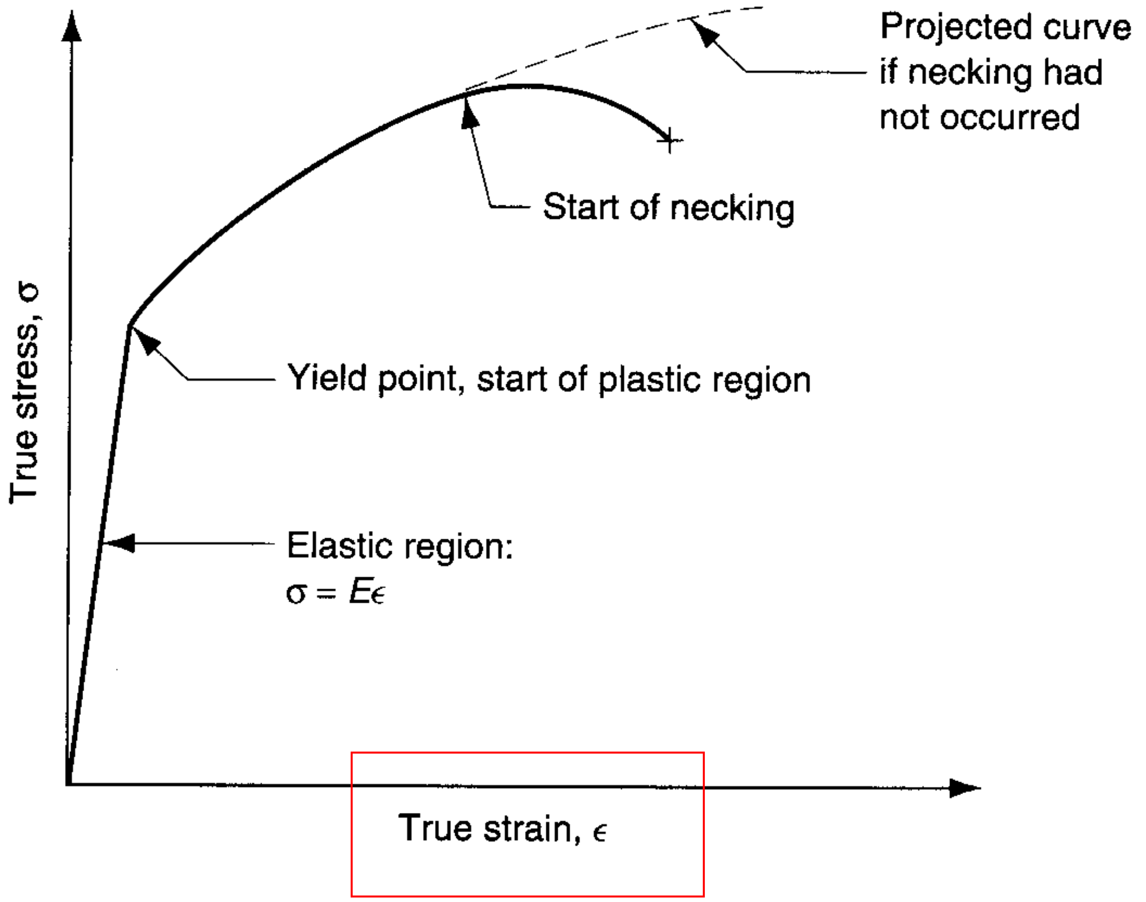
$$m = \frac{\partial \sigma_p}{\sigma_p}\left(\frac{\partial \dot{\varepsilon}}{\dot{\varepsilon}}\right)^{-1}$$

or

$$m = \frac{\partial \sigma_p}{\partial \dot{\varepsilon}}\,\frac{\dot{\varepsilon}}{\sigma_p}$$

1. General mechanics principle

- The underlying mechanics principle for metal forming is the stress-strain relationship; see Figure 1.



- The true stress is defined as instantaneous elongation per unit length of the material, and can be expressed by

$$\varepsilon = \int_{L0}^{L} \frac{dL}{L} = \ln \frac{L}{L0}$$

L0: the initial length of a specimen

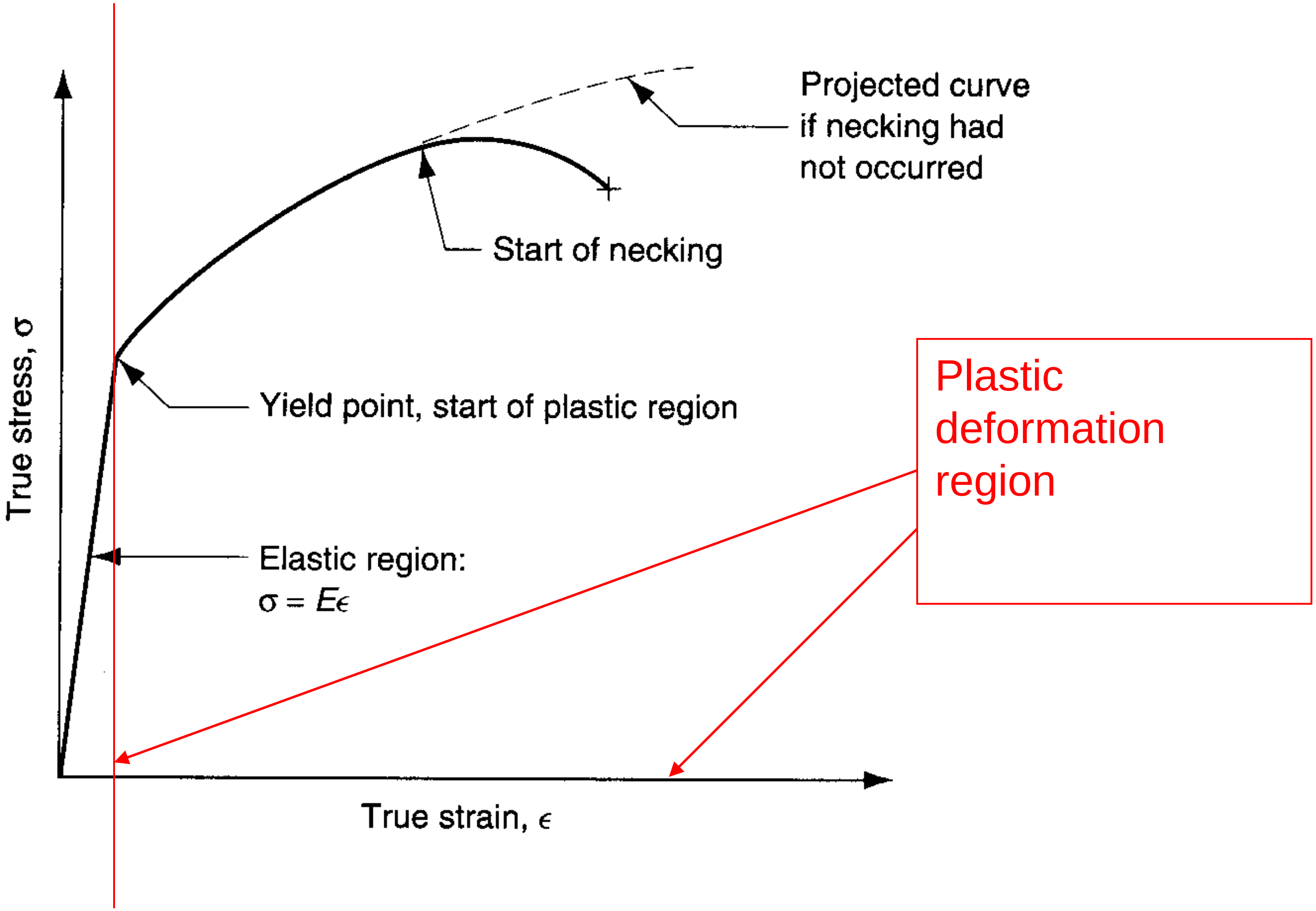
L: the length of the specimen at time t

ε the true strain at time t

In the case of compression, we have

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

- In the forming process we are more interested in the plastic deformation region (Figure 1)



- The stress-strain relationship in the plastic deformation region is described by

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

Where

K= the strength coefficient, (MPa)
ε = the true strain, σ=the true stress
n= the strain hardening exponent,

The **flow stress** (Y_f) is used for the above stress (which is the stress beyond yield)

- For many bulk deforming processes, rather than the instantaneous stress is used, a so-called average stress is used, for example in the case of extrusion.

- The average flow stress can be obtained by integrating the flow stress along the trajectory of straining, from zero to the final strain value defining the range of interest, i.e.,

$$\bar{Y}_f = \frac{\left(\int_0^{\varepsilon} Y_f \, d\varepsilon\right)}{\varepsilon} = \frac{k\varepsilon^n}{1+n}$$

Example 1:

Determine the value of the strain-hardening exponent for a metal that will cause the average flow stress to be three-quarters of the final flow stress after deformation.

Solution:

- The above analysis is generally applicable to the cold working, where the temperature factor is not considered.

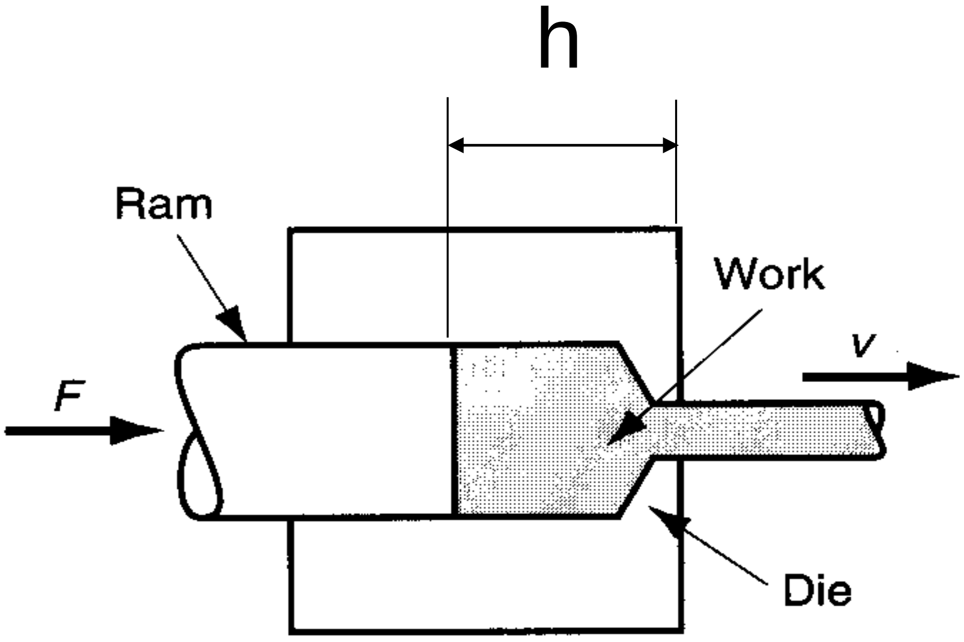
- The metal forming process has three kinds in terms of temperature: (1) cold, (2) warm, (3) hot

- In the case of warm and hot forming, the temperature factor needs to be considered, in particular

Temperature **up** → The strength **down** and ductility **up**

- **Strain rate (related to elevated temperatures)**

In the hot forming or warm forming, the strain rate can affect the flow stress. The strain rate is defined below



(c)

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

$$\downarrow$$

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

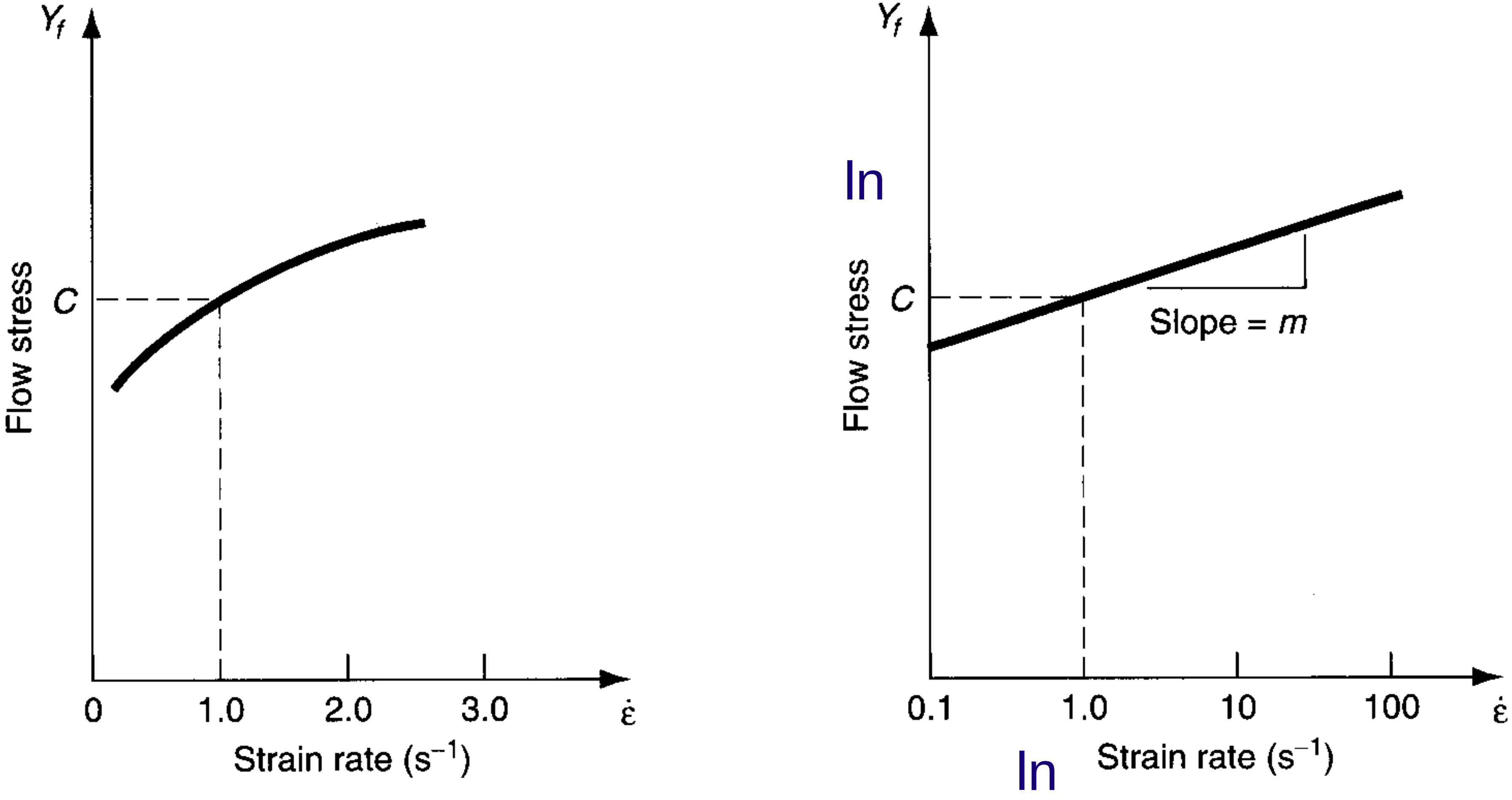
$$Y_f = C\dot{\varepsilon}^m$$

Strength coefficient but not the same as K

where:

C is the strength constant
m is the strain-rate sensitivity exponent.

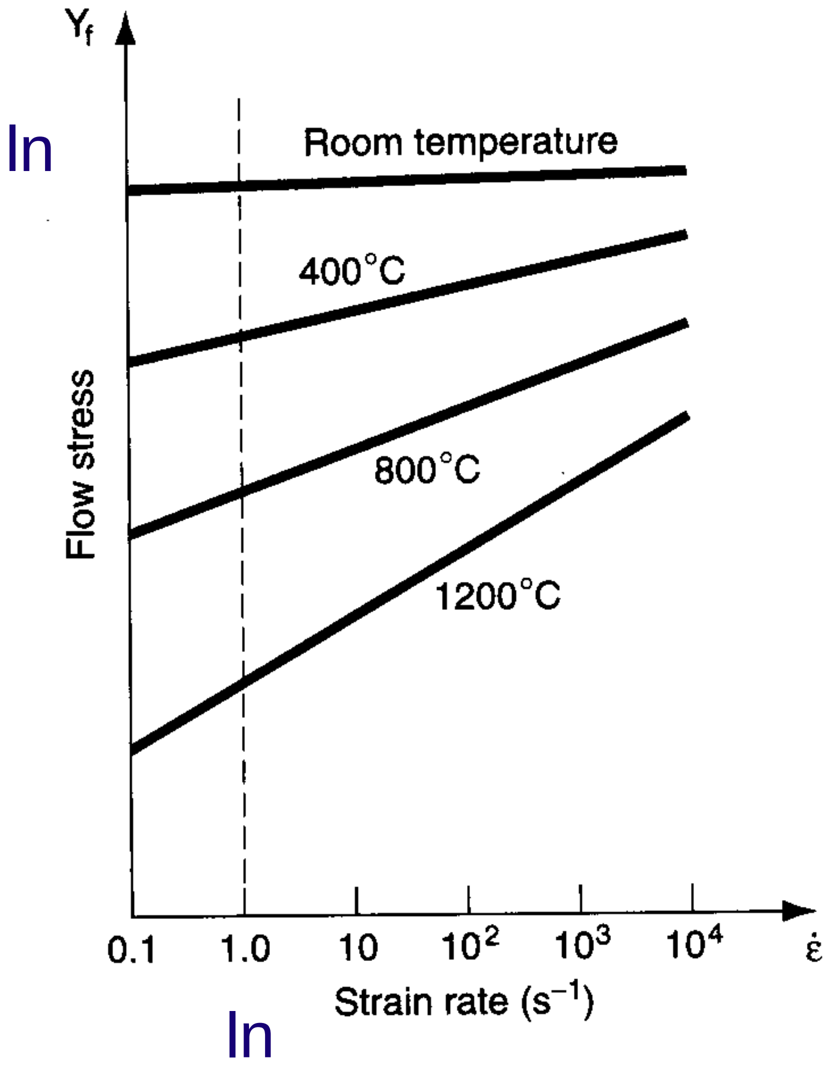
C and m are determined by the following figure which is generated from the experiment


Y_f
Flow stress
C
0
1.0
2.0
3.0
$\dot{\varepsilon}$
Strain rate (s^{-1})
Y_f
ln
Flow stress
C
Slope = m
0.1
1.0
10
100
$\dot{\varepsilon}$
ln
Strain rate (s^{-1})

(a)

(b)

C and m are affected by temperature



Temperature Up

C Down

m Up

Integrated effects are shown in the left figure

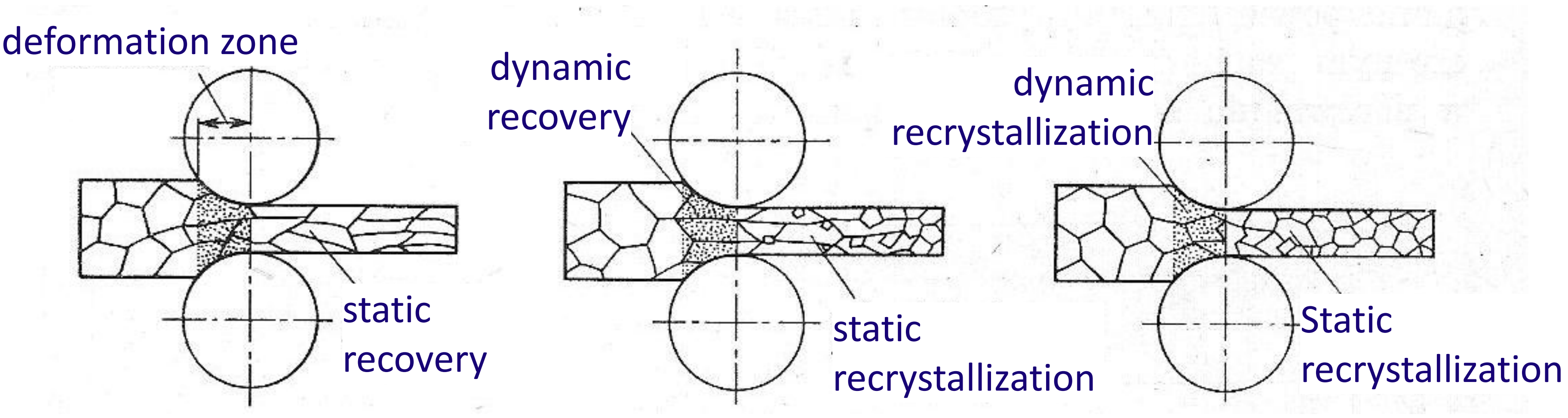
Even in the cold work, the strain rate could affect the flow stress. A more general expression of the flow stress with consideration of the strain rate and strain is presented as follows:

$$Y_f = A\varepsilon^n \dot{\varepsilon}^m$$

A is a strength coefficient, a combined effect of K, C

All these coefficients, A, n, m, are functions of temperature

The influence of temperature on plastic defromation - Hot working (steels)



deformation zone

static recovery

dynamic recovery

static recrystallization

dynamic recrystallization

Static recrystallization

$T<T_R$

$T>T_R$
Strain rate - large

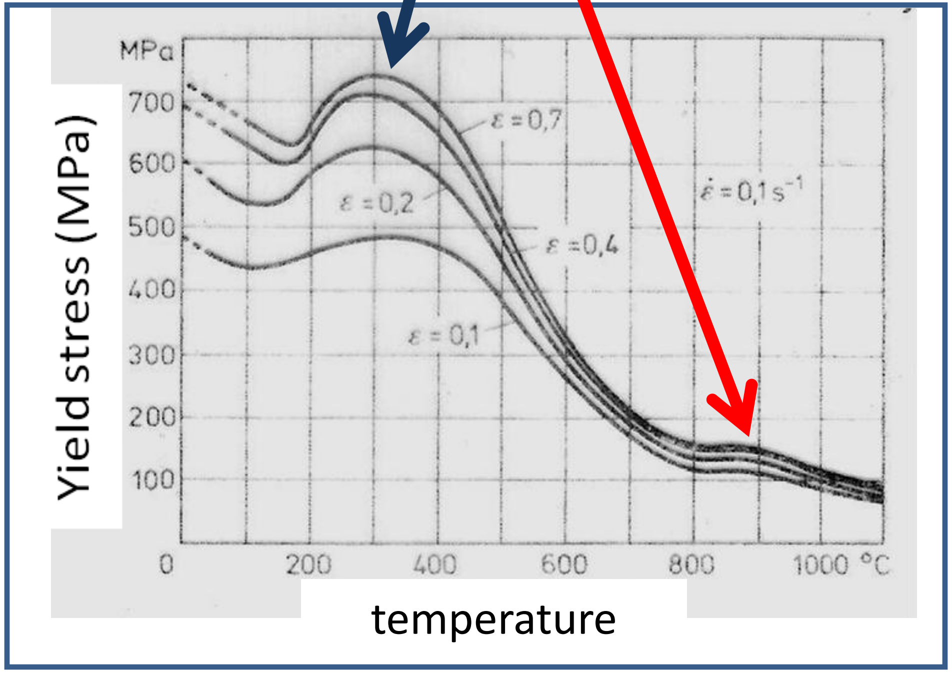
$T>>T_R$
Strain rate - low

hardening *vs*. recovery and recrystallization during rolling

Chemical composition (of the steel) *vs.* plasticity

C - the larger contents the lower plasticity

The influence of impurities on steel properties (all decreases plasticity): **P**, **S, Cu, H_2, O_2, N_2**



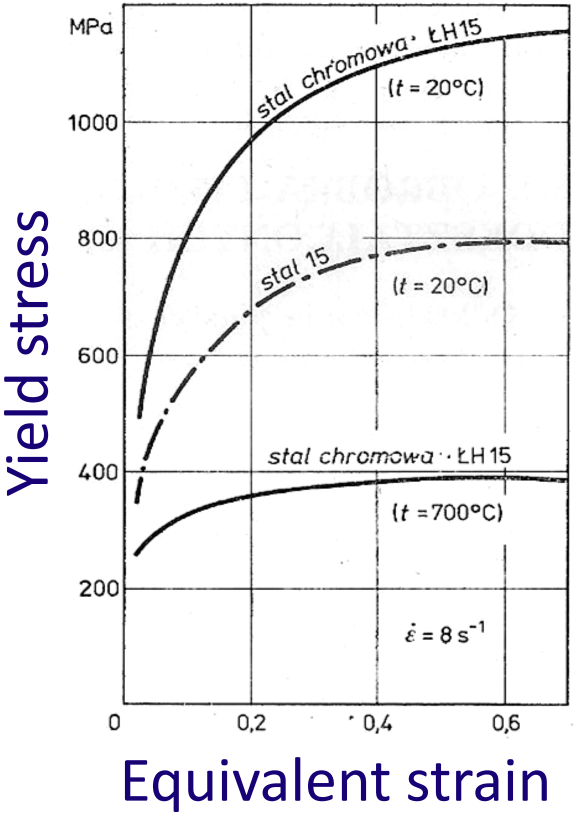
Phases in metals:

A phase is a distinct and physically, chemically or crystallographically homogeneous portion of an alloy. The following three phases are considered:

- pure metals
- Intermetallic compounds
- Solid solution

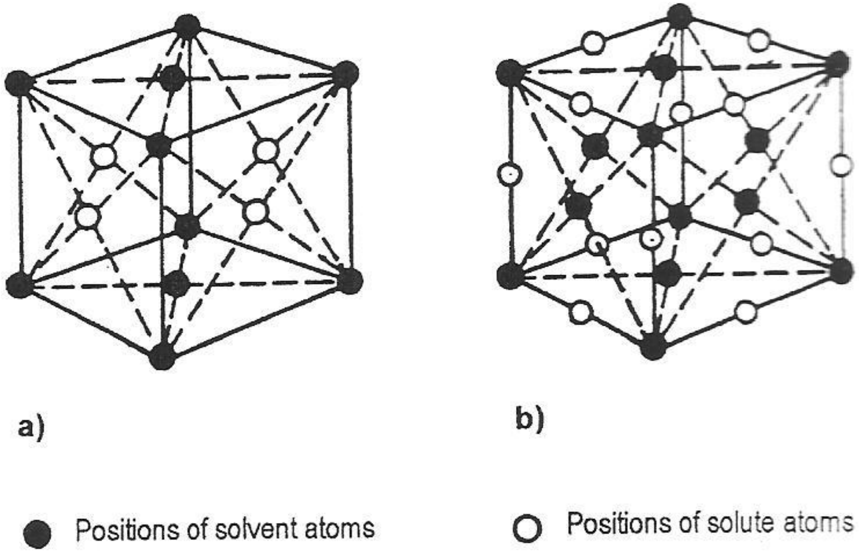
Phase composition *vs*. plasticity :

Ferrite and perlite – high plasticity
Austenite – average plasticity
Cementite – very low plasticity



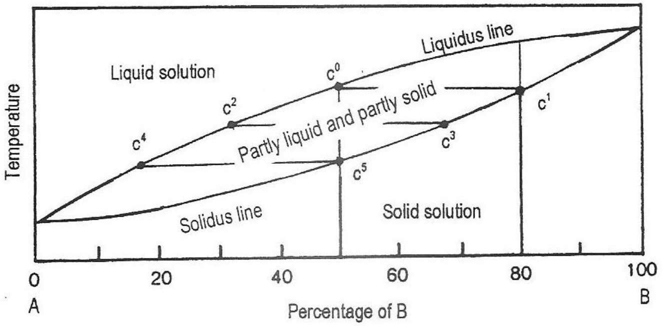
Solid solution

A complete merging in the solid state of the two phases, pure metals and intermetallic compounds, is know as a solid solution

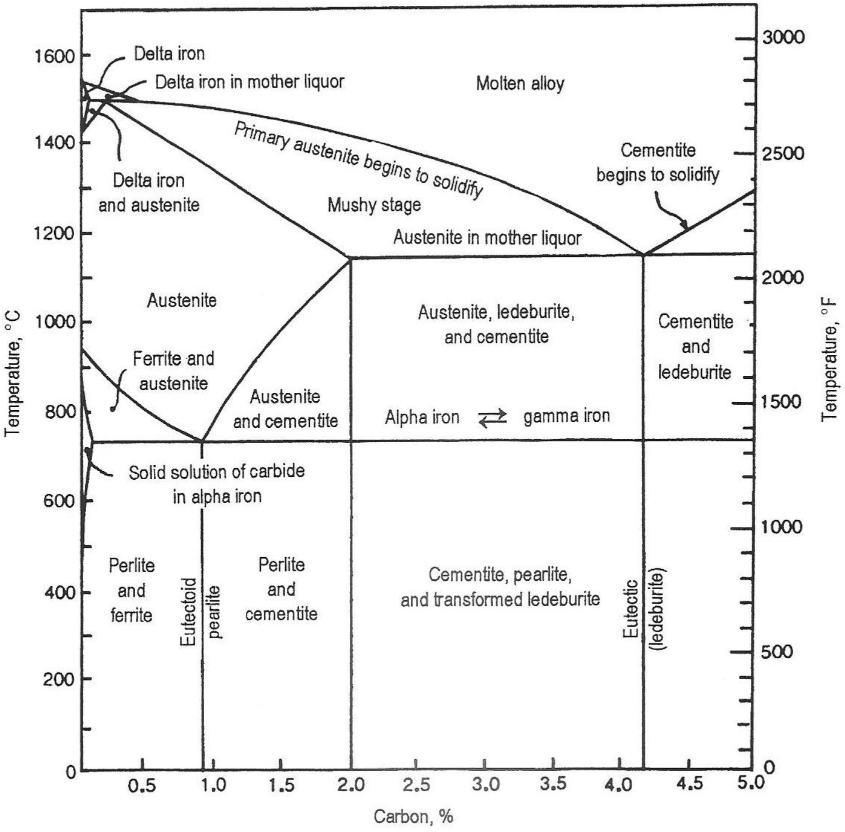


Space lattices of: (a) substitutional solid solution, (b) interstitial solid solution

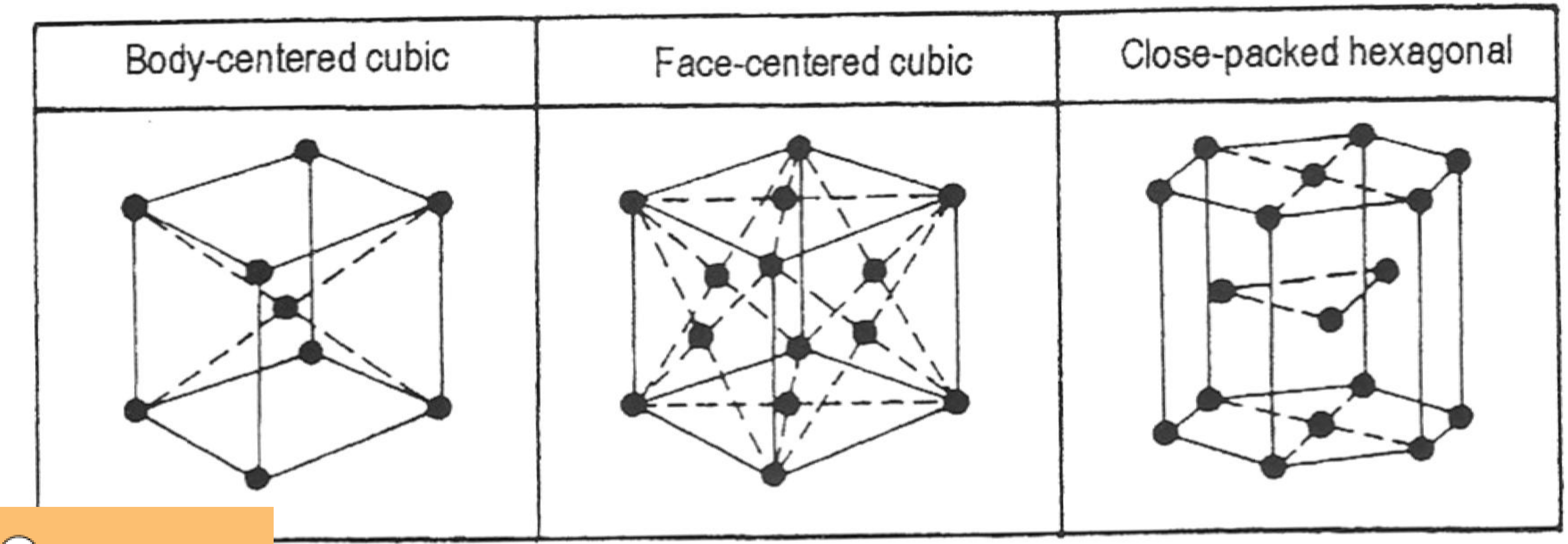
Phase diagram



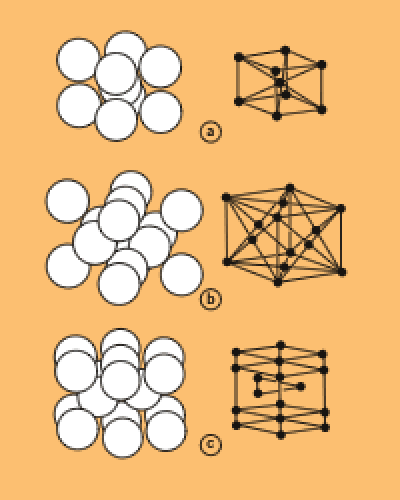
Fe-Fe$_3$C



Microstructural characteristics of metals

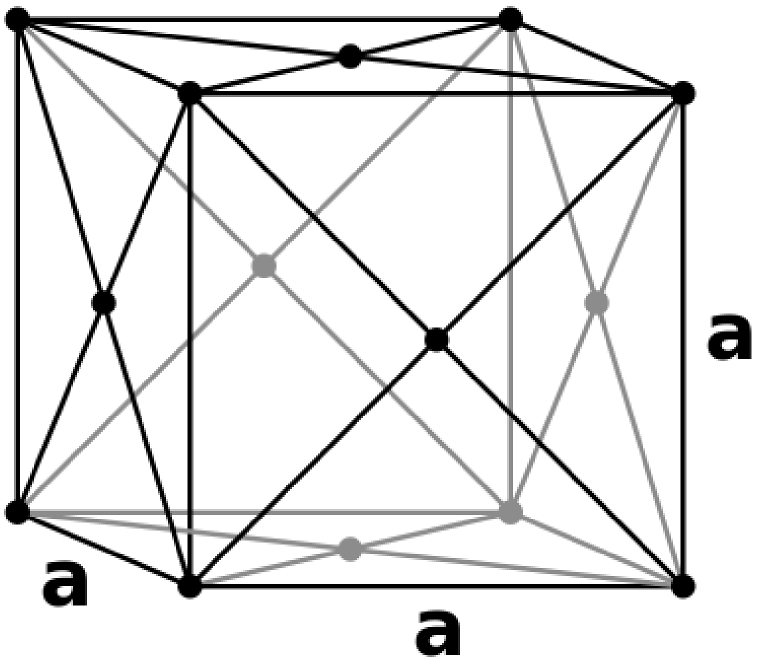


Principal types of crystal lattices

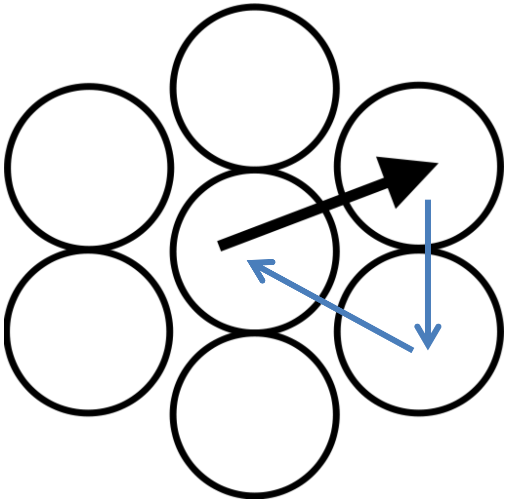


All metals are crystalline in nature

The crystallization of metals during solidification when the atoms of a liquid metal assemble themselves in an orderly arrangement and form a defrinite space pattern known as a ***space lattice***



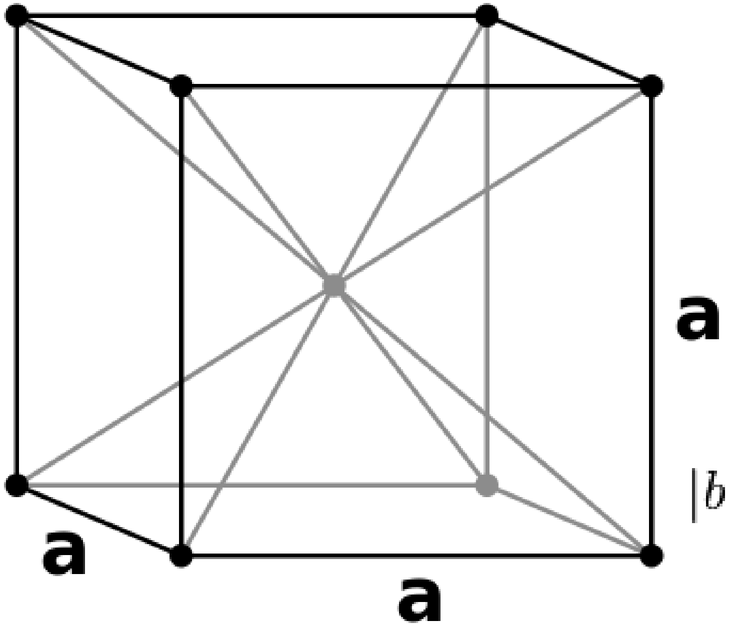
Lattice configuration of the close packed slip plane in an fcc material. The arrow represents the burgers vector in this dislocation glide system



Slip in fcc crystals occurs along the *close packed plane*. Specifically, the slip plane is of type {111}, and the direction is of type <110>. In the diagram, the specific plane and direction are (111) and [110], respectively. Given the permutations of the slip plane types and direction types, fcc crystals have 12 slip systems. In the fcc lattice, the norm of the Burgers vector, b, can be calculated using the following equation:

$$|b| = \frac{a}{2}| < 110 > | = \frac{a}{\sqrt{2}}$$

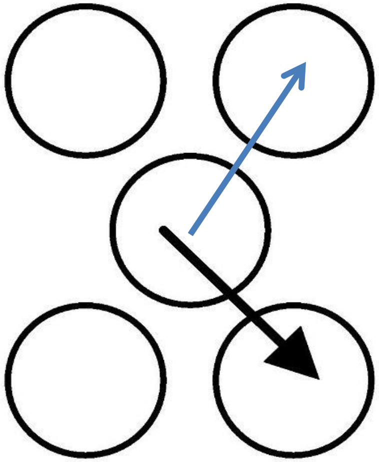
where ‘a’ is the lattice constant of the unit cell. (Al, Cu, Ni, Fe-γ, Ag, Au, Cr-α, Ta, etc.)



Lattice configuration of the slip plane in a bcc material. The arrow represents the burgers vector in this dislocation glide system.

{110} – main slip planes

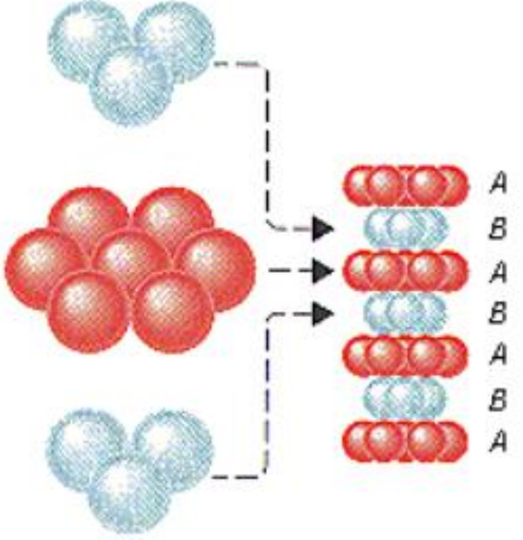
$$|b| = \frac{a}{2}|<111>| = \frac{\sqrt{3}a}{2}$$



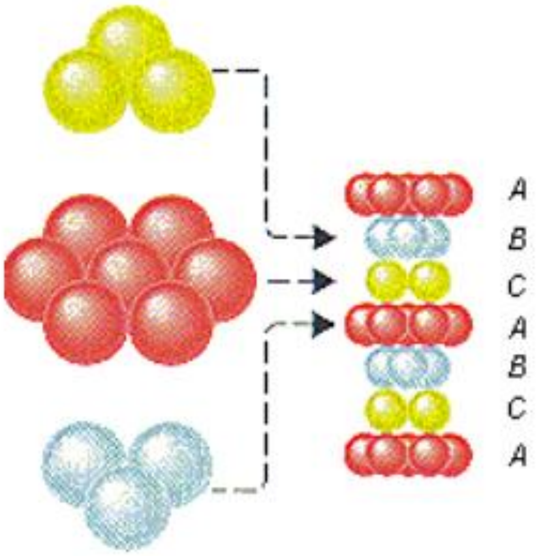
Slip in bcc crystals occurs along the plane of shortest Burgers vector as well; however, unlike fcc, there are no truly close-packed planes in the bcc crystal structure. Thus, a slip system in bcc requires heat to activate. Some bcc materials (e.g. *α-Fe*) can contain up to 48 slip systems. There are six slip planes of type {110}, each with two <111> directions (12 systems). There are 24 {123} and 12 {112} planes each with one <111> direction (36 systems, for a total of 48). While the {123} and {112} planes are not exactly identical in activation energy to {110}, they are so close in energy that for all intents and purposes they can be treated as identical. The specific slip plane and direction are (110) and [111], respectively.

Elemental metals in the bcc crystal structure include: Li, Na, K, V, Cr, Mn, Fe-α, Ru, Ta, W, Mo, etc.

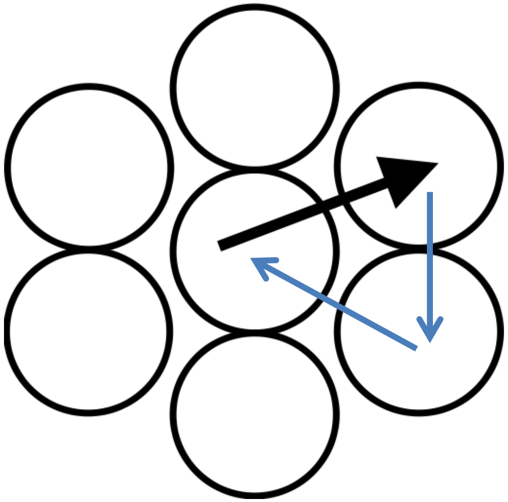
hps vs. fcc



Hexagonal closest packed structure



Cubic closest packed structure



Hcp

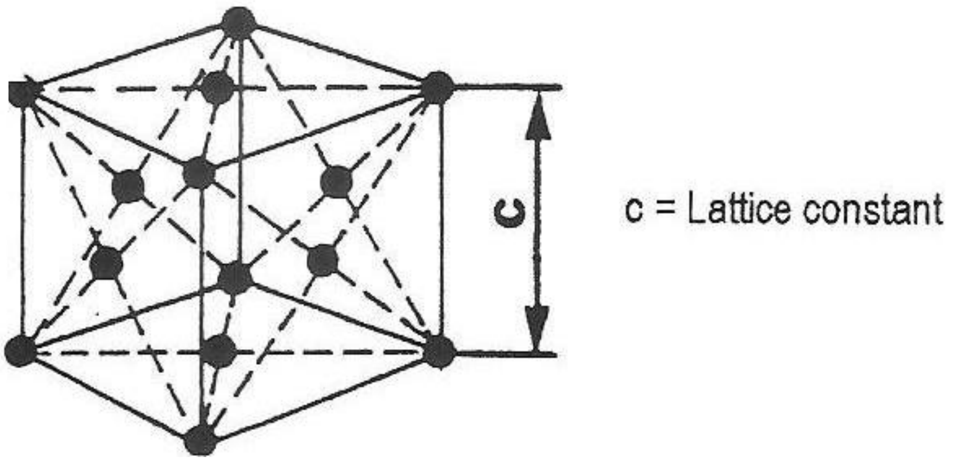
Slip in hcp metals is much more limited than in bcc and fcc crystal structures. This is because few active slip systems exist in hcp metals. The result of the small number of slip systems is the metal is generally brittle.

Cd, Zn, Mg, Ti and Be have a slip plane at {0001} and a slip direction of <1120>. ***This creates a total of three slip systems***, depending on orientation. Other combinations are also possible.

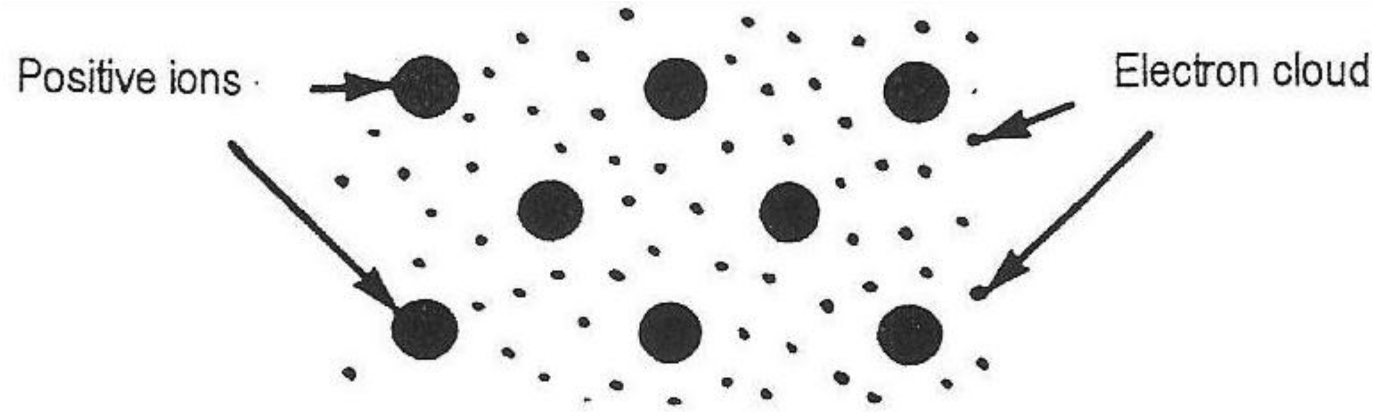
Lattice constant:

Cr – 2.878 A

Pb – 4.941 A



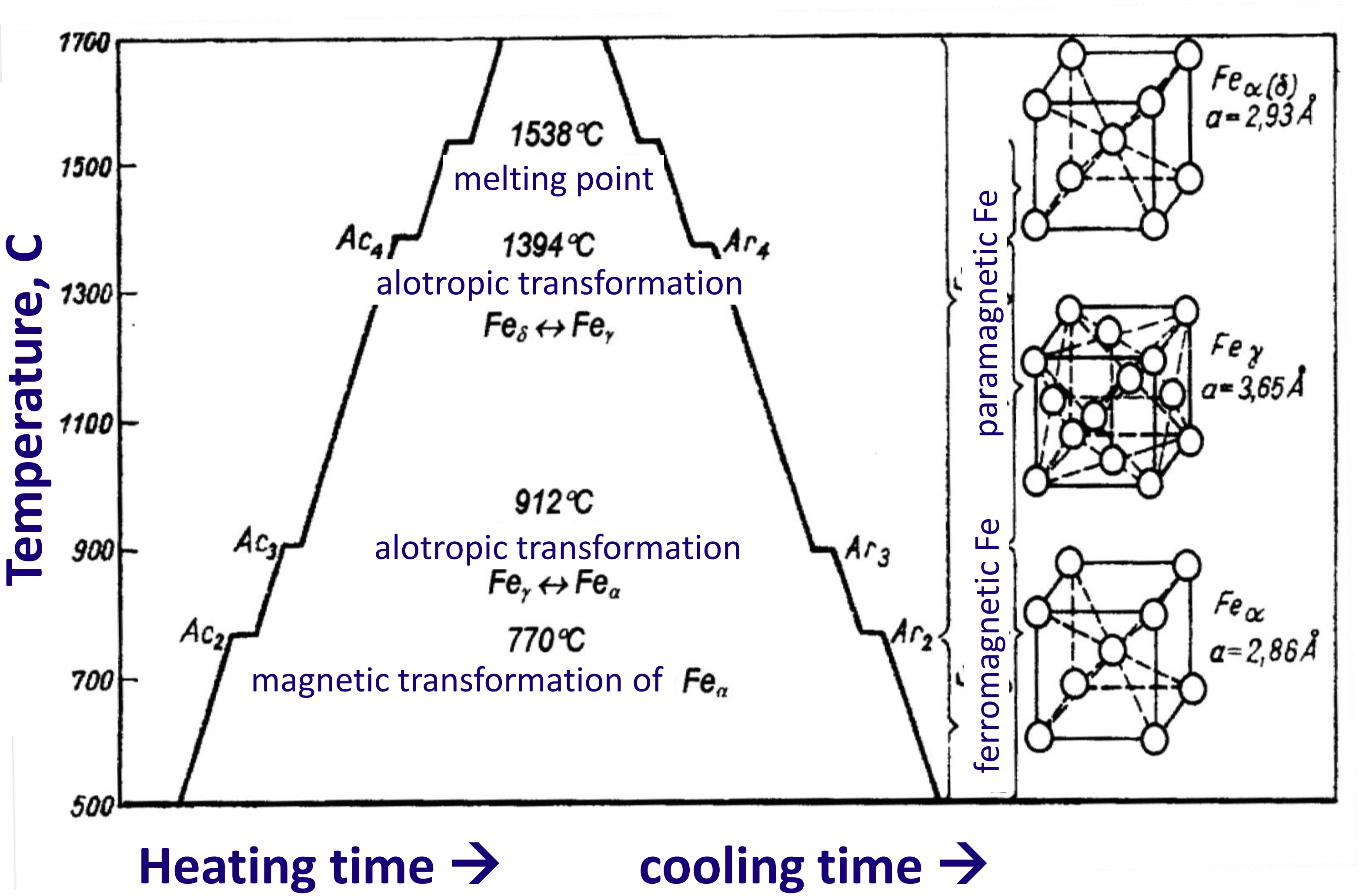
Metallic bond



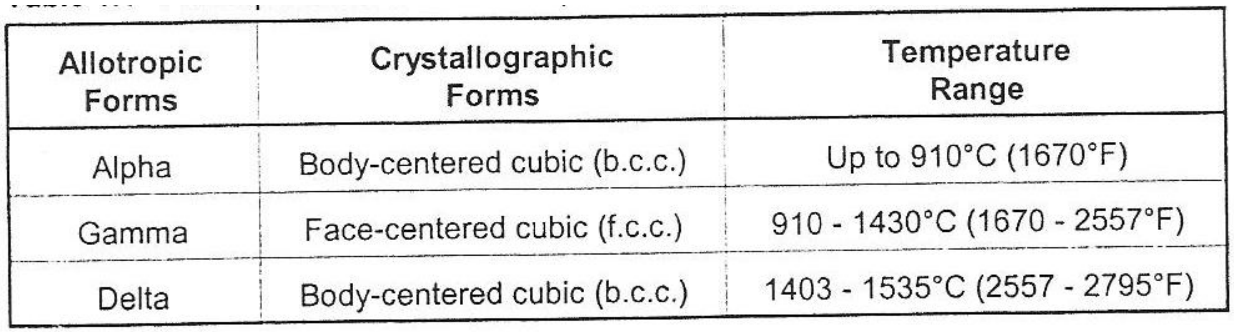
Diagrammatic representation of a metallic bond

Alotropic transformations in pure Fe

When a metal undergoes a transformation from one crystal pattern to another, it is know as an allotropic change. The allotropic forms of iron are temperature dependent

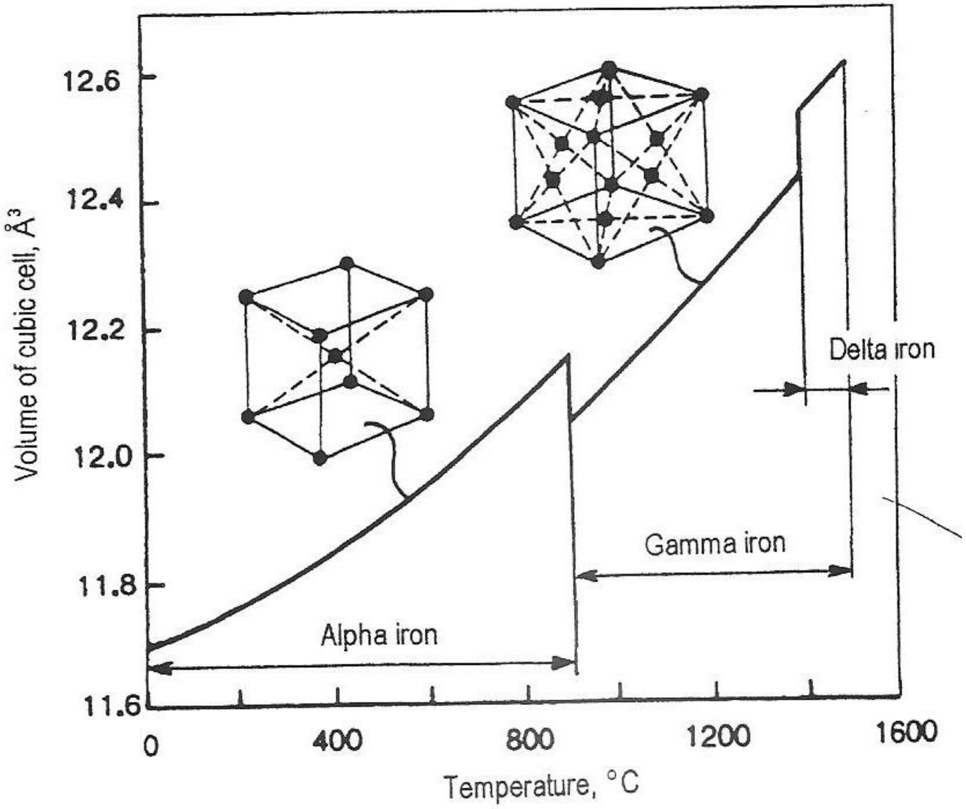


Allotropic changes



Allotropic Forms	Crystallographic Forms	Temperature Range
Alpha	Body-centered cubic (b.c.c.)	Up to 910°C (1670°F)
Gamma	Face-centered cubic (f.c.c.)	910 - 1430°C (1670 - 2557°F)
Delta	Body-centered cubic (b.c.c.)	1403 - 1535°C (2557 - 2795°F)

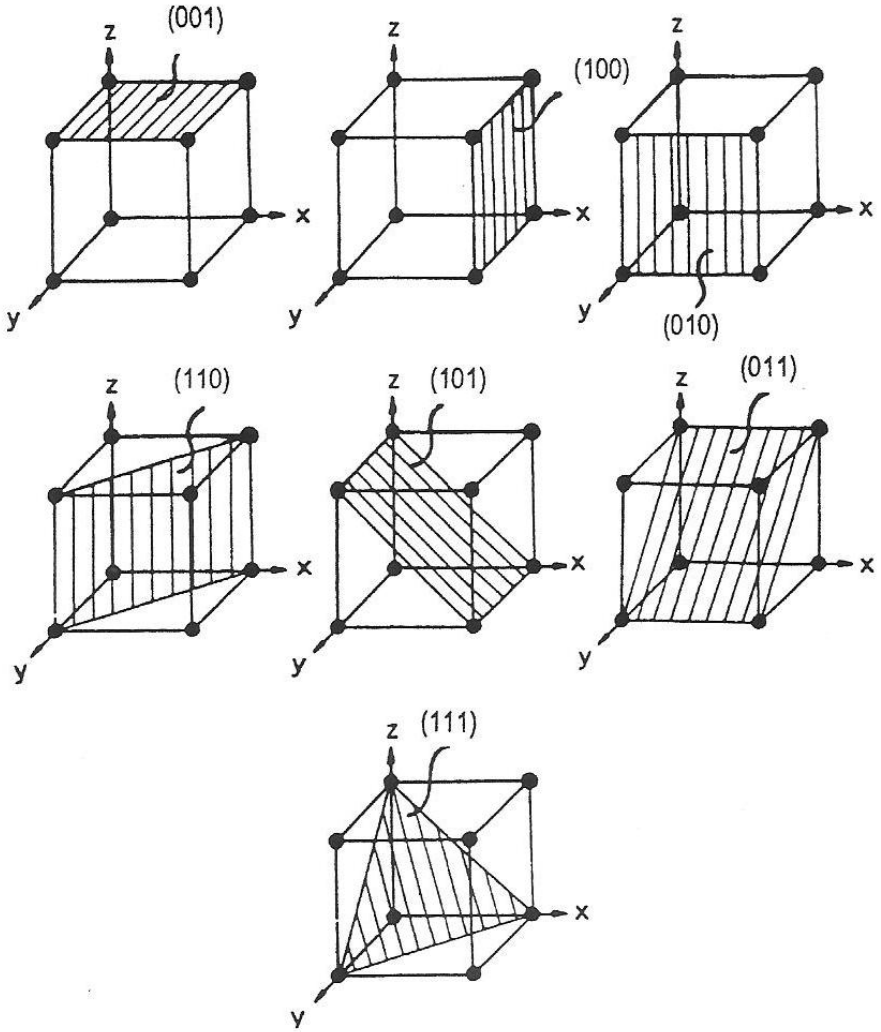
Allotropic forms in iron



Allotropic changes in the density of iron

Atomic planes → crystallographic anisotropy

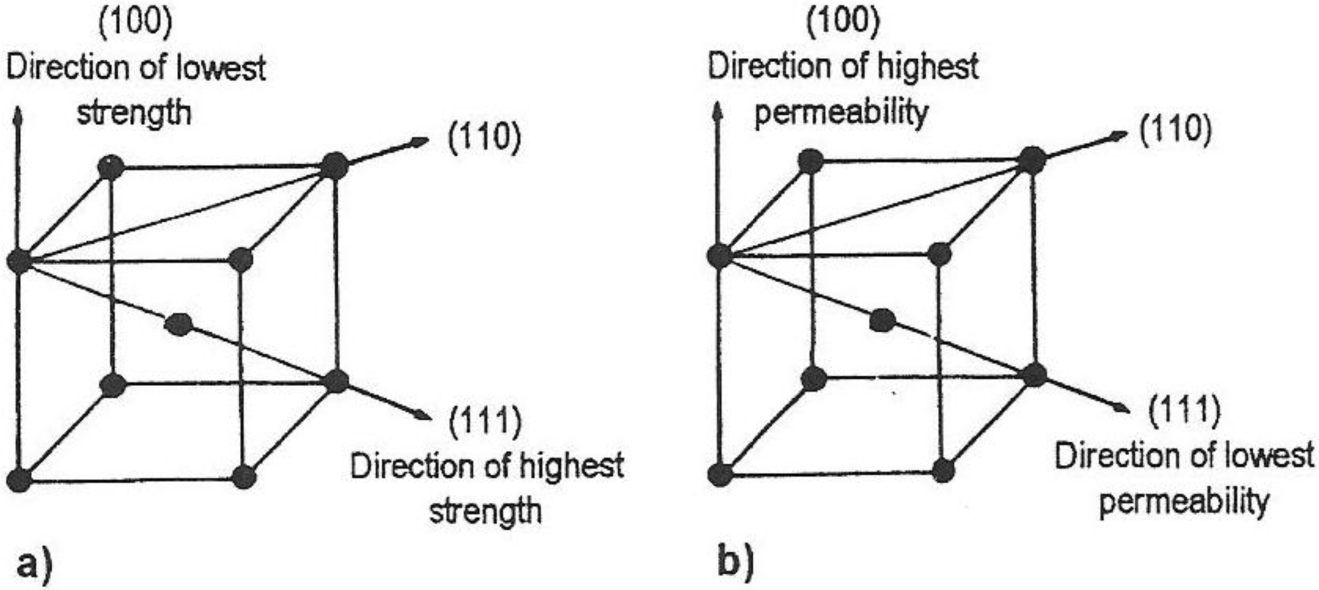
Slip systems



anisotropy

Atomic planes in cubic cells

Anisotropy of physical properties in a cubic crystal

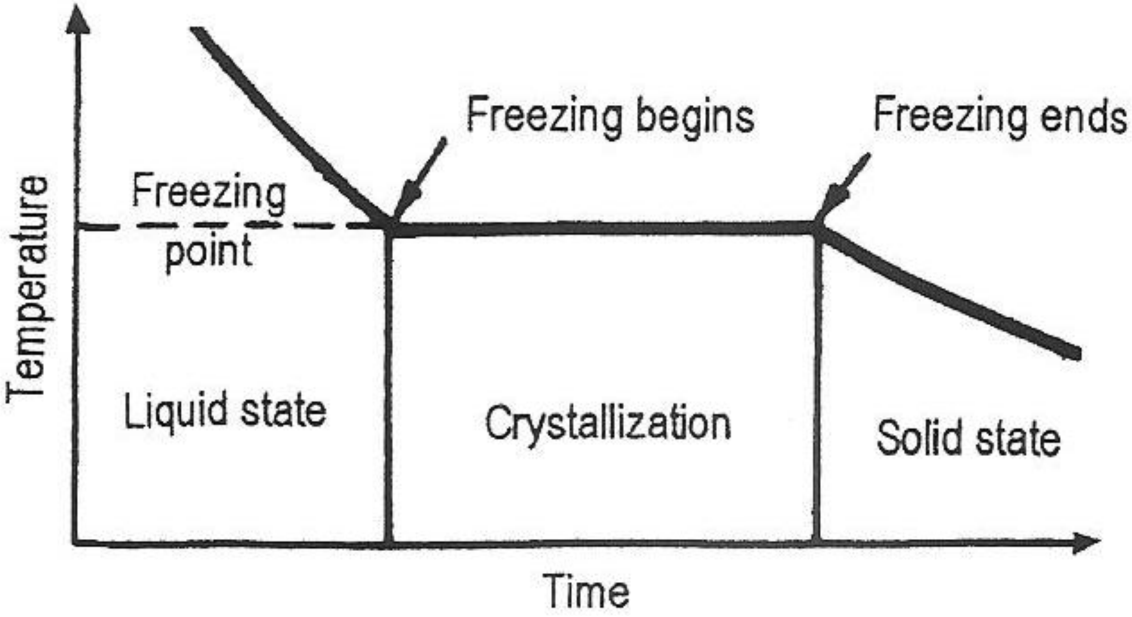


The physical properties of a crystal depend on the direction of their measurement with respect to their crystallographic axis.

In bcc structures of Fe the highest strenght lies in the direction of the atomic plane (111) and the lowest along the atomic plane (100). Any deviation from a perfectly random orientation of many crystals in metallic material will therefore result in anisotropy of the mechanical properties of the material.

Young modulus.
Magnetic properties (in silicon steels)
In Al-alloys plasic properties (due to cube texture formation)

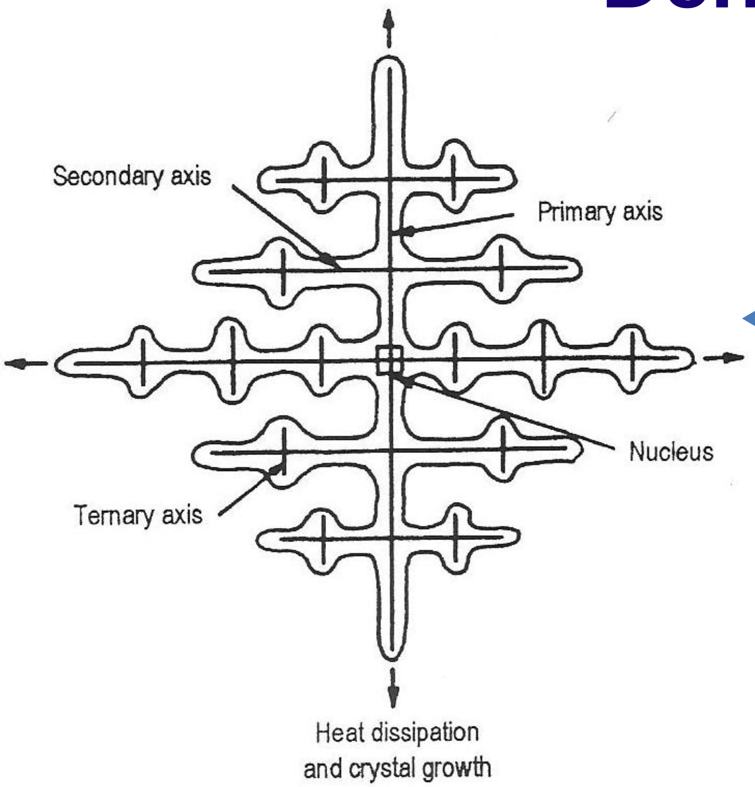
A pure liquid metal solidifies into a crystalline solid at a fixed temperature called the ***freezing point***.



Typical cooling curve of a pure metal

This is due to the fact that the amount of internal heat relieved during the crystallization process is equal to the amount of heat given up by the material. The later is know as the ***latent heat of solidification***

Dendrite growth

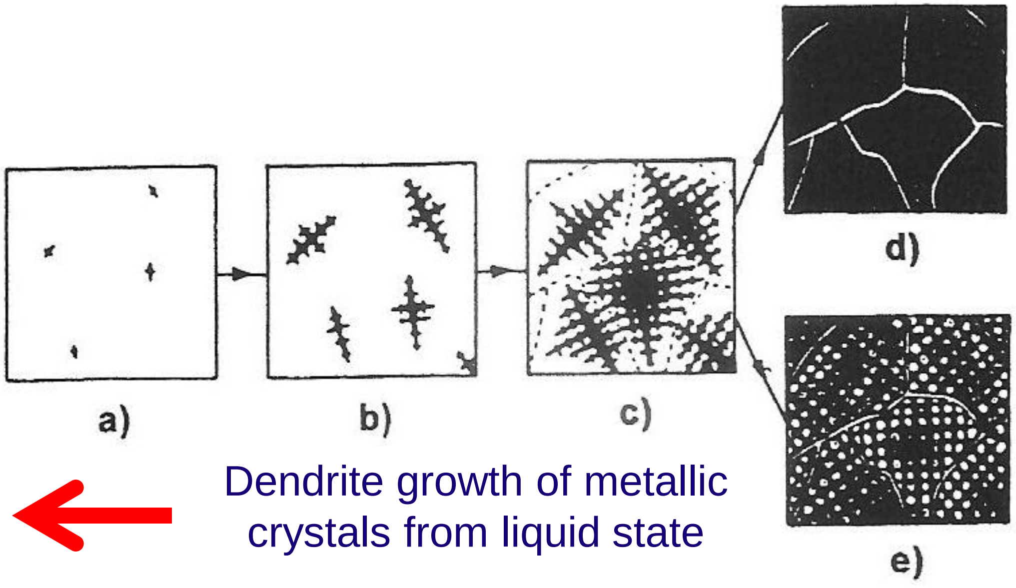


Early stages in the growth of a metallic dendrite

- When a pure metal solidifies, each crystal begins to grow independently from a nucleus or center of crystallization.

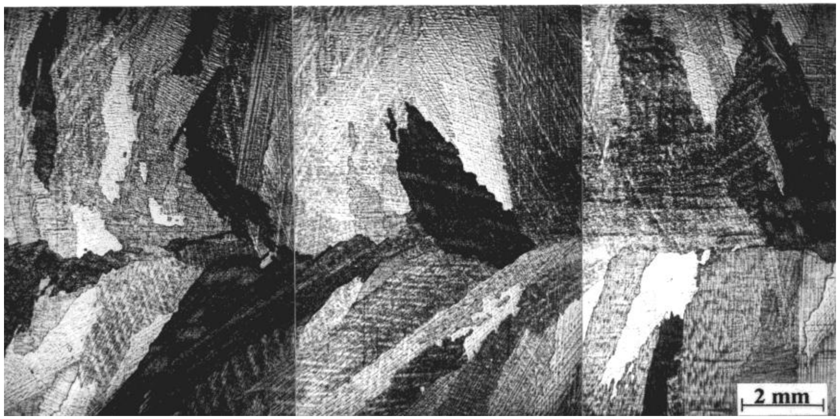
- A metallic crystal grows by dendrite formation because heat is dissipated more quickly from a point where the temperature decreases at the highest rate leading to the formation of rather elongated skeleton.

The dendrite arms continue to grow and thicken until ultimately the space between them becomes completey silid

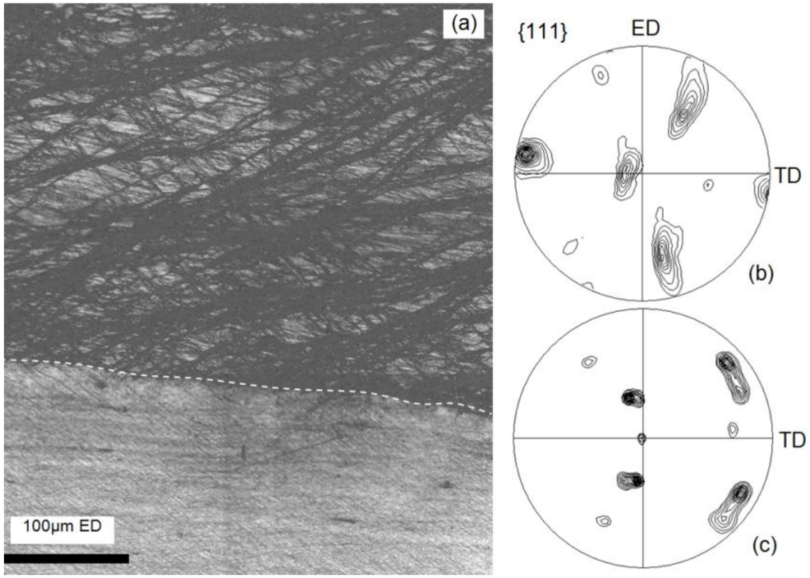


Dendrite growth of metallic crystals from liquid state

Structure after semi- continuous casting (copper alloys)

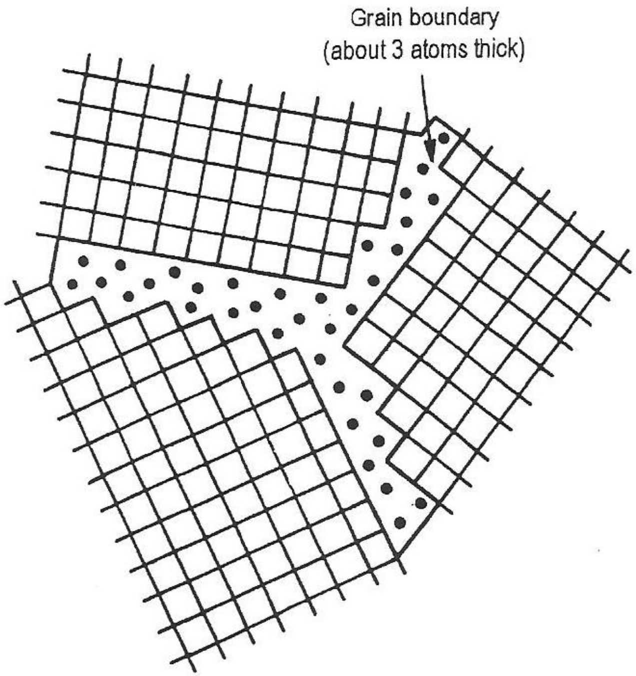


Large grains in CuZn30 alloy (semi- continuous casting)

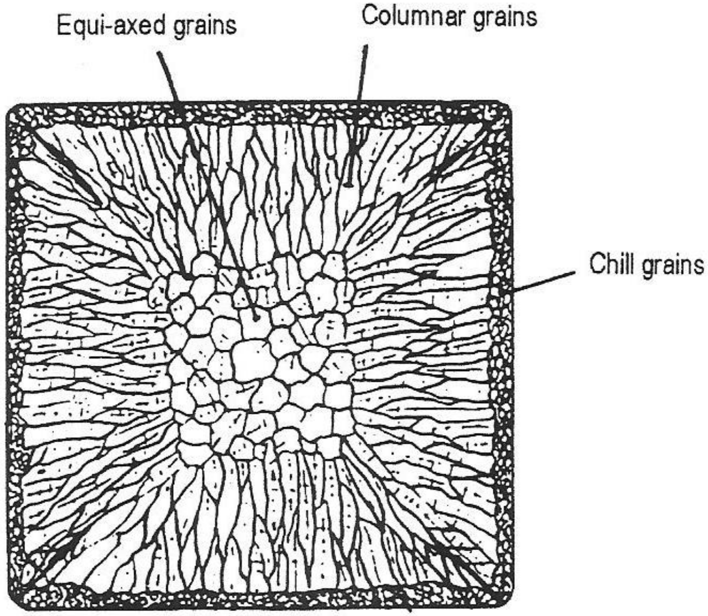


Textural changes during plane strain deformation (rolling)

Crystals boundary



Diagrammatic representation of a grain boundary. Adapted from Wusatowski and Higgins



Grain structure in a section of a ingot

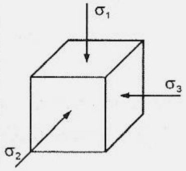
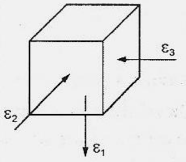
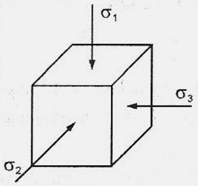
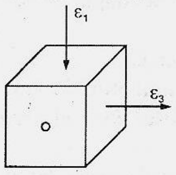
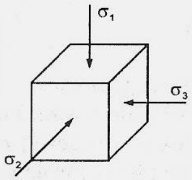
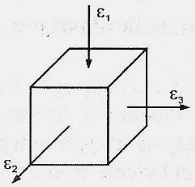
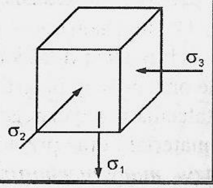
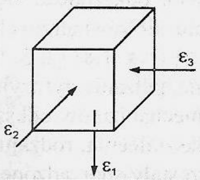
A solidified metal consists of a mass of separate crystals that are irregular in shape but interlocking with each other like a three-dimensional jigsaw puzzle

- Small chill grains located at the surface of an ingot,
- Colummnar grains located in the intermediate zone,
- Large equi-axed grains located at the center of an ingot

Morphology vs. texture

Plasticity vs. mechanical state of stress & strain

(+)σ tensile stress, (-)σ compression stress | **(+)ε increase dimension, (-)ε decrease dimension**

process	Stress state	Strain state	force	plasticity
Exstrusion round bars	$\sigma_1 < \sigma_2 = \sigma_3 << 0$  	$\varepsilon_3 = \varepsilon_2 < 0 < \varepsilon_1$  	Very high	Very high
Flat rolling b/h>6	$\sigma_1 < \sigma_2 < \sigma_3 < 0$  	$\varepsilon_1 < \varepsilon_2 = 0 < \varepsilon_3$  	high	high
Forging round bars	$\sigma_1 < \sigma_2 = \sigma_3 < 0$  	$\varepsilon_1 < 0 < \varepsilon_2 = \varepsilon_3$  	average	average
Drawing round bars	$\sigma_2 = \sigma_3 < 0 < \sigma_1$  	$\varepsilon_3 = \varepsilon_2 < 0 < \varepsilon_1$  	low	low