Strengthening Mechanism

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Contents

- Strain- hardening of polycrystalline metals, Strain hardening of single crystals, Relation between single and polycrystalline stress-strain curve,
- Solid – Solution hardening.
- Strengthening due to second phase particles,
- Strain – ageing behavior,
- Annealing of cold-worked metals, Recovery, Recrystallization and grain growth.
- All types of tests, Modes of Failure, Theory of ductile-brittle transition temperature (DBTT).

Cold Working / Strain Hardening

Definition: A crystalline material is plastically deformed below or equal to $0.3T_m$ (T_m is melting point in Kelvin scale), is called as cold working.

Cold working or strain hardening, increases the stress required to cause slip compare to previous plastic deformation.

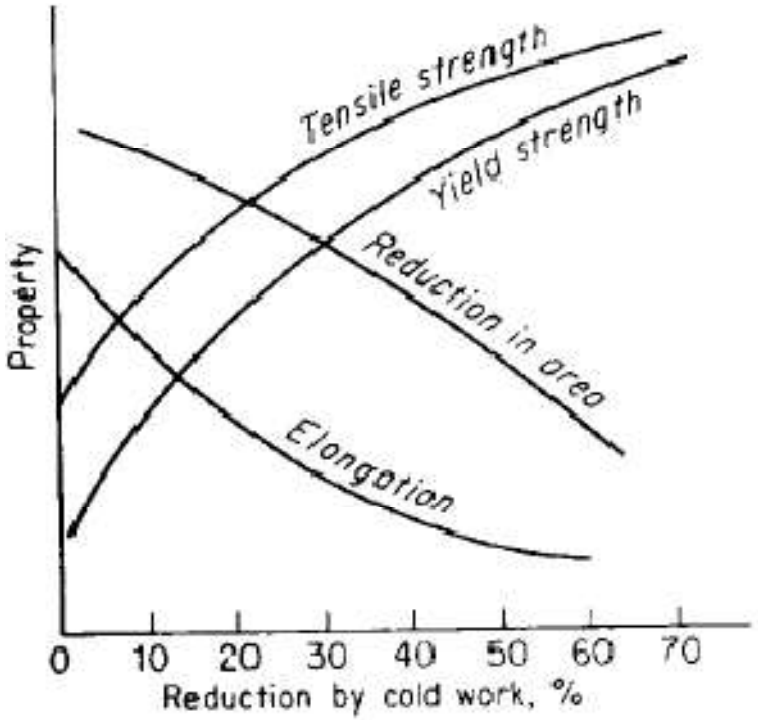
Due to cold working

- hardness ↑
- tensile strength ↑
- electrical resistance ↑ and
- Ductility ↓

Effect of cold working on properties

During cold working,

- It generates dislocation and interaction of dislocation take places
- It generates vacancies
- It produces stacking faults and twin
- It reduces short range order of structure
- It reduces elastic strain energy



Structure of cold work materials depends on the materials, strain, strain rate and temperature of deformation. Change in structure due to cold work affects the properties the materials. They are ,

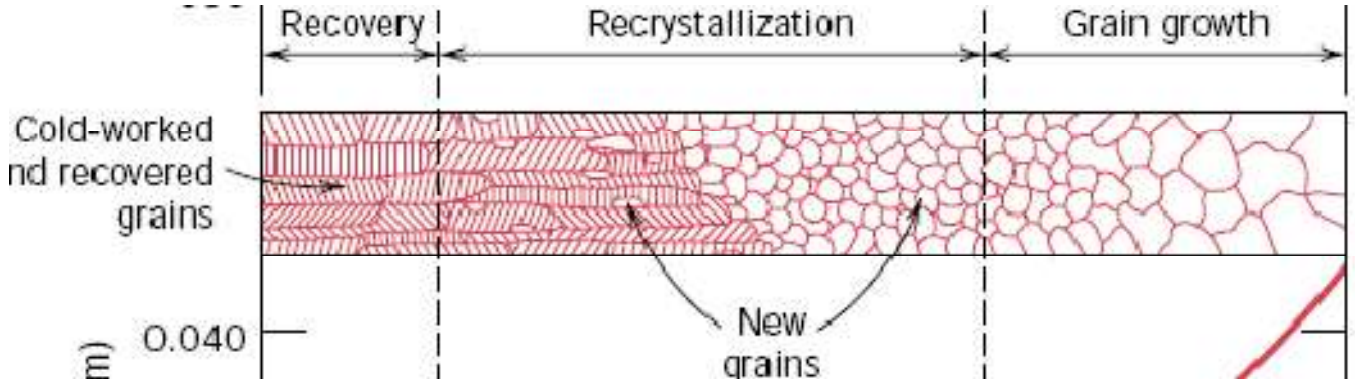
- Reduces the density
- Reduces the electrical conductivity
- Small increase in thermal coefficient of expansion
- Increases the chemical reactivity due to stored energy
- Decreases the corrosion resistance
- introduces the stress corrosion cracking
- Increase tensile strength and yield strength
- Decrease the ductility

Annealing

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

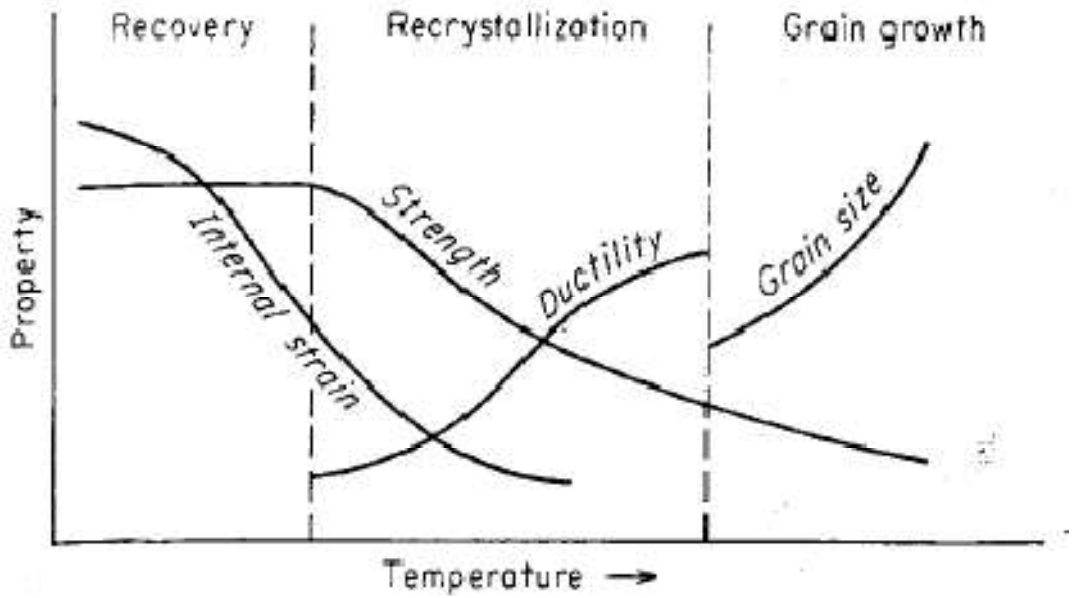
<u>Stages of Annealing</u>

- Recovery
- Recrystallisation
- Grain growth



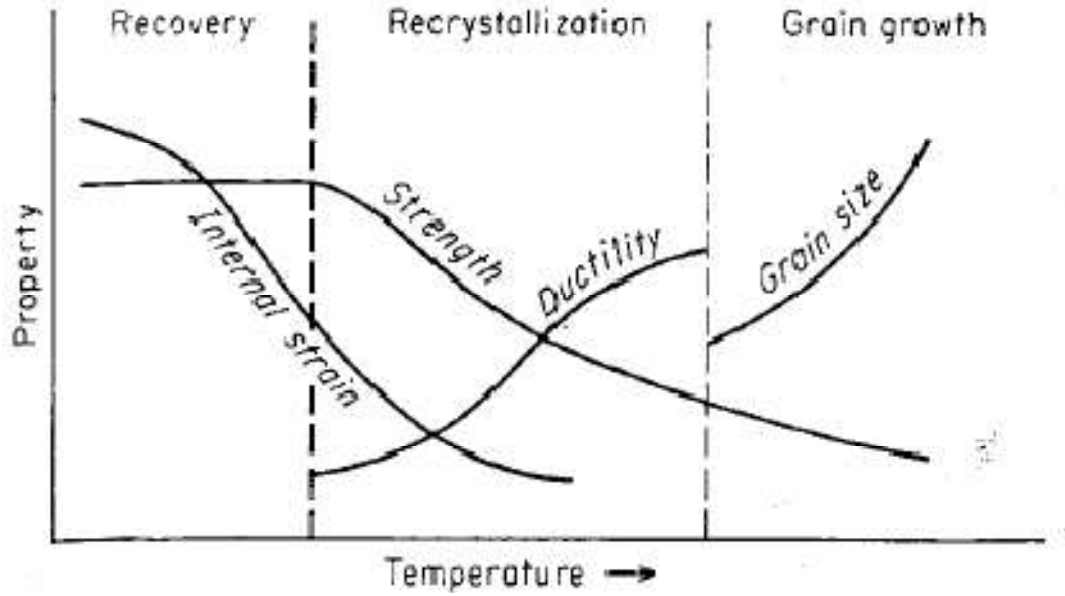
Recovery

- 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.

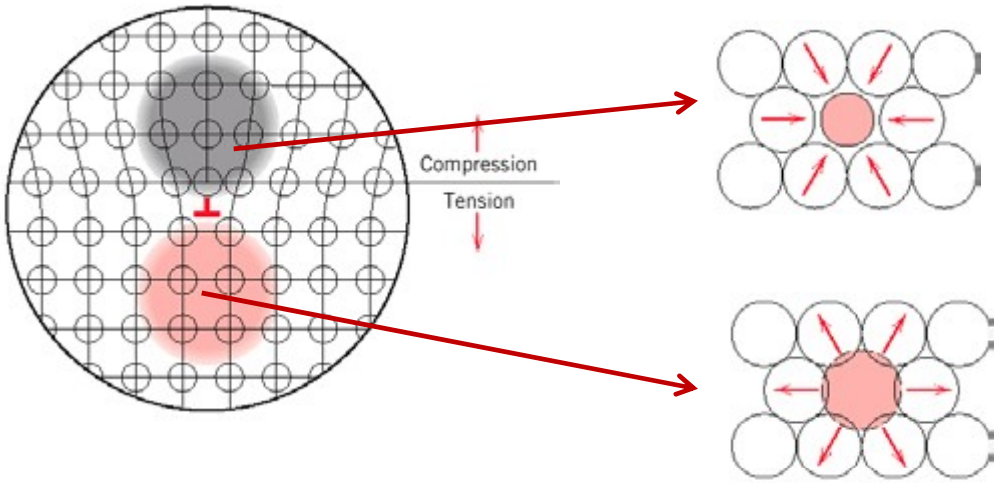


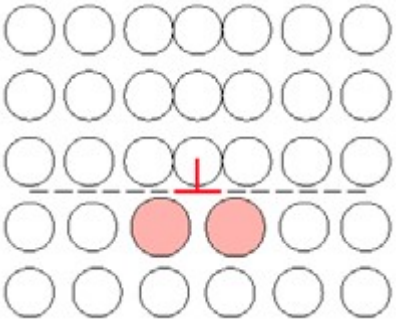
Grain Growth

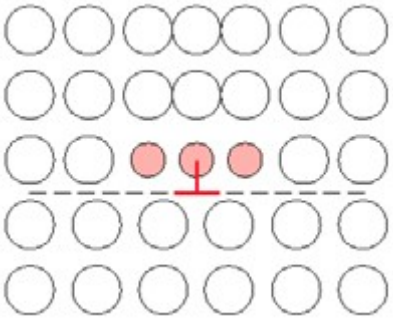
- After recrystallization is complete, the strain free grain continues to grow during grain growth.
- Grain growth does no need to be preceded by recovery and recrystallization.
- Grain growth occurs by the migration of grain boundaries.

Solid solution strengthening

- Homogeneous mixture of two or more kinds of atoms occurs in the solid state is called as solid solution.
- Types of solid solution:
  - substitutional solid solution
  - interstitial solid solution.
- Hume Ruthery rules gives the various factors affecting solid solution.
- Alloys are stronger than pure metals
- Impurity atoms that go into solid solution ordinarily impose lattice strains on the surrounding host atoms.
- Lattice strain field interactions between dislocations and these impurity atoms result, restrict the movement of dislocation.

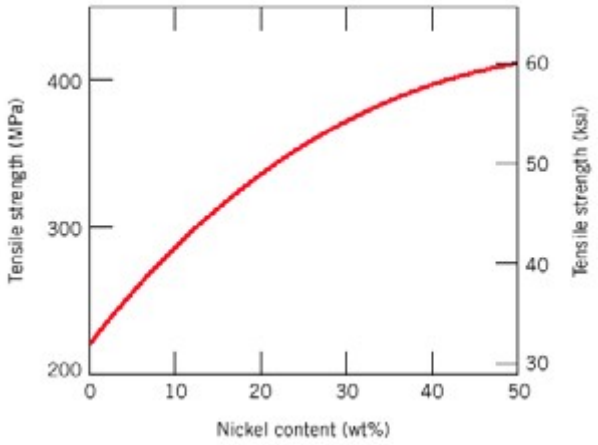

Compression
Tension

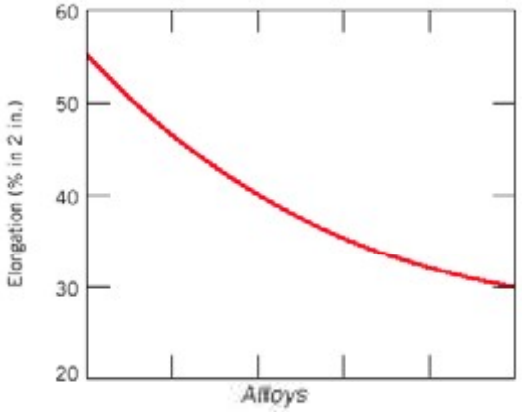


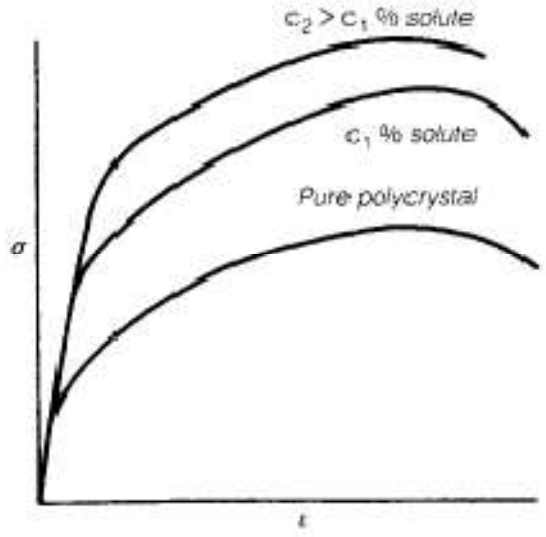


Effect of solid-solutions strengthening on properties

- The yield strength, tensile strength and hardness of the alloy are greater than the pure metals.
- The ductility of the alloy is less than that of the pure metal.
- Electrical conductivity of the alloys is much lower than that of the pure mental.
- The resistance to creep or loss of strength at elevated temperatures is improved by solid-solution strengthening.

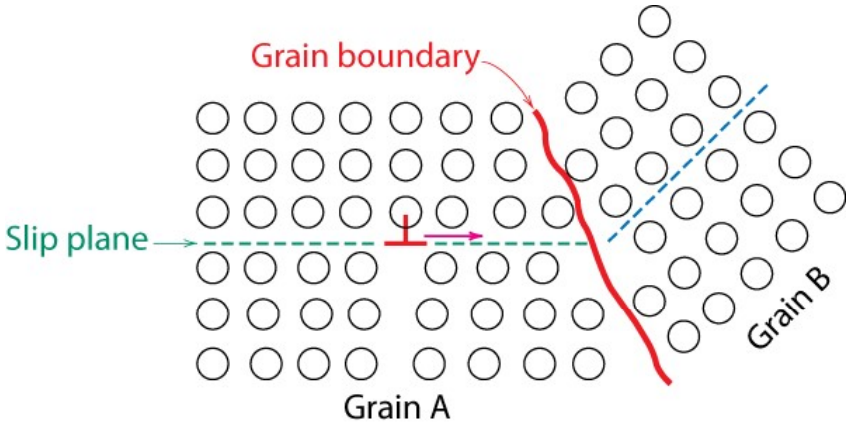






Grain size Strengthenging

- Grain boundary act as barrier for dislocation motion: slip plane discontinues or change orientation.
- Dislocations gliding on a slip plane are unable to cross the boundary but get piled up against it. This happens more often in a fine grained material.
- Small angle grain boundaries are not very effective in blocking dislocations.



- High-angle grain boundaries block slip and increase strength of the material.

The yield strength of a poly crystalline material is a function of its grain size as given by the Hall petch equation

$$\sigma_y = \sigma_i + kd^{-1/2}$$

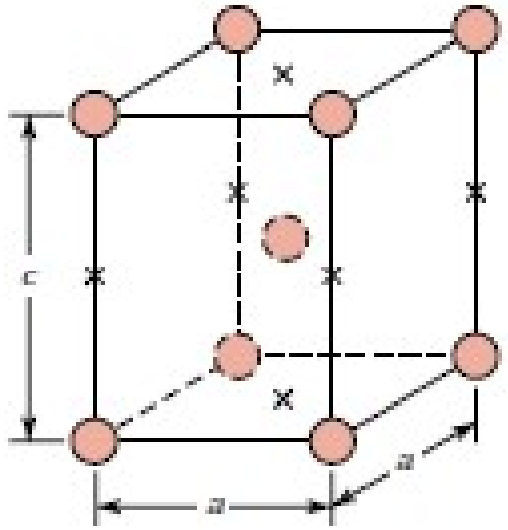
σ_i the yield strength of the material where there are no grain boundaries (single crystal),

k is the relative hardening contribution of the grain boundaries or the Hall Petch constant

d is the grain diameter, which can be derived from the ASTM grain size number.

Martensite strengthening

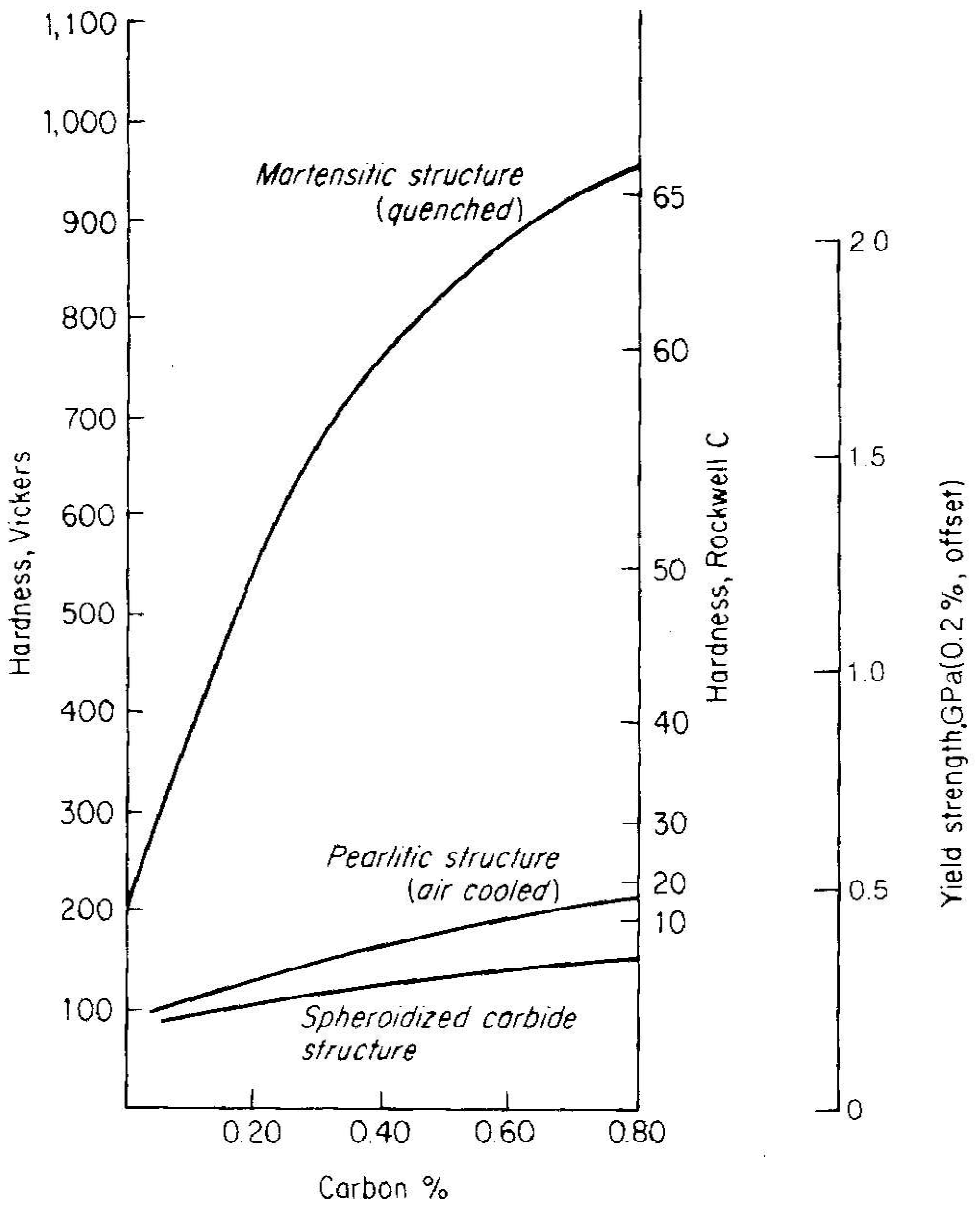
- Martensite is a metastable phase formed in steel
- Occurs by diffusionless /shear type transformation.
- Shear process coverts the FCC structure of austenite to the BCT structure of matrensite.
- During the transformation, the vertical ‘c’ axis of the BCT cell compressed by about 20% and the horizontal ‘a’ axes expand by about 12 % each.
- The iron atoms move only a fraction of the interatomic distance.
- As the carbon atoms are all situated at the middle of the c axis which induces strain in the crystal.



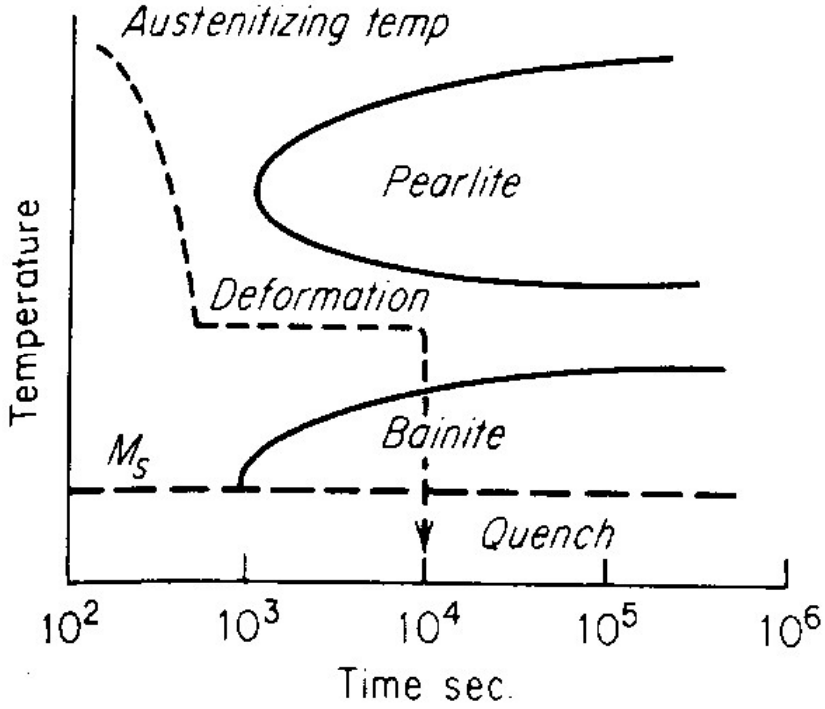
- Types of Martensite:
  - Conventional Martensite
  - Ausforming Martensite

Conventional Martensite

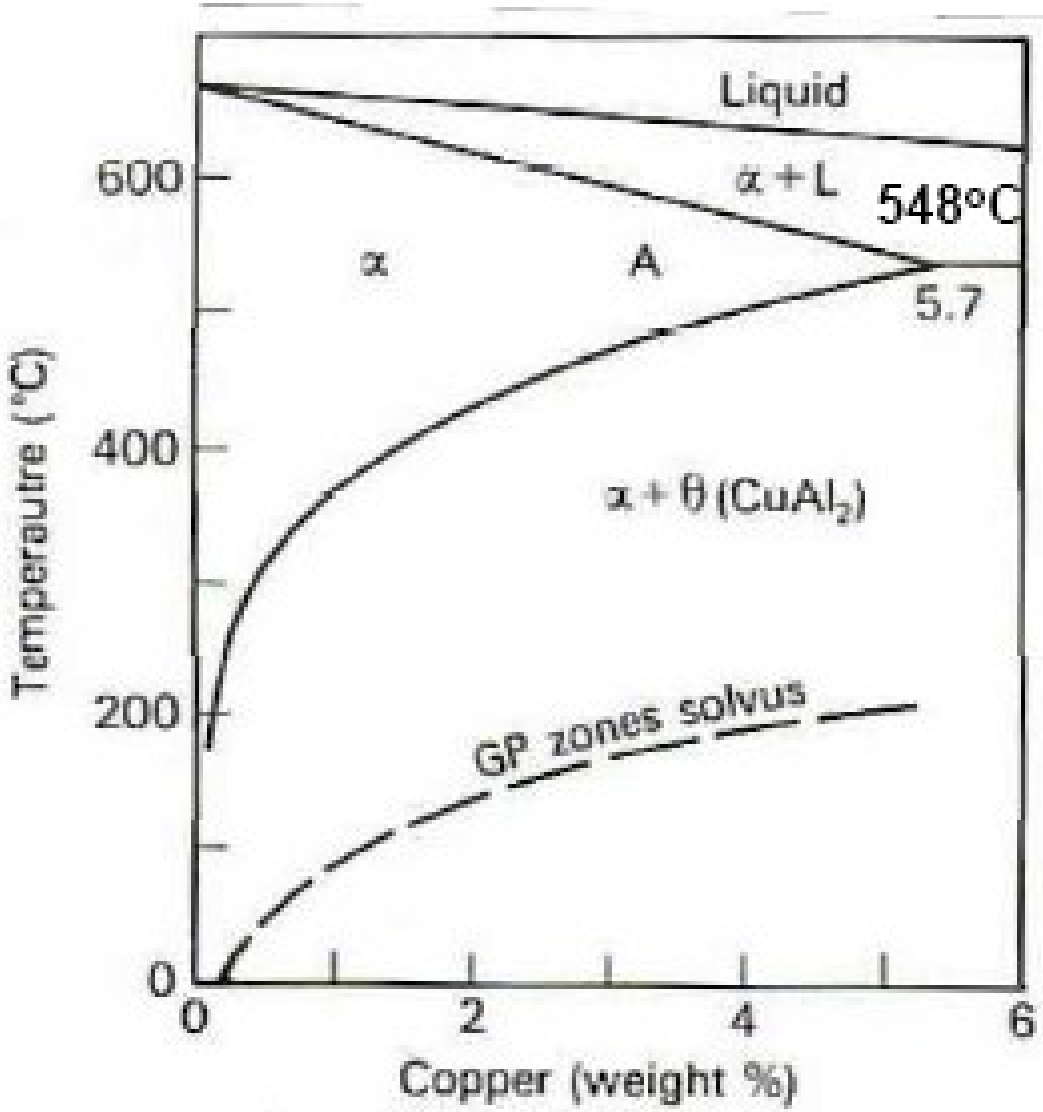
- Plate structure with a unique habit plane and internal structure of parallel twins of 0.1µm thick within the plates
  - Block martensite – high dislocation density (10^9 to 10^{10} mm^{-2})
  - High strength
    - Effective barriers to slip provided by the fine twin structure or the high dislocation density.
    - Carbon atoms strains the ferrite lattice
    - Formation of carbon atom clusters on {011} planes


1,100
1,000
900
800
700
600
500
400
300
200
100
Hardness, Vickers
Martensitic structure
(quenched)
Pearlitic structure
(air cooled)
Spheroidized carbide
structure
65
60
50
40
30
20
10
Hardness, Rockwell C
2.0
1.5
1.0
0.5
0
Yield strength,GPa(0.2%, offset)
0.20
0.40
0.60
0.80
Carbon %

- Ausforming Martensite :
- Martensite phase obtained by Thermo Mechanical process
- High dislocation density ($10^{11}mm^{-2}$)
- Precipitates which provides additional sites for dislocation multiplication and pinning.
- High yield strength



Precipitation Hardening



Al-Cu system

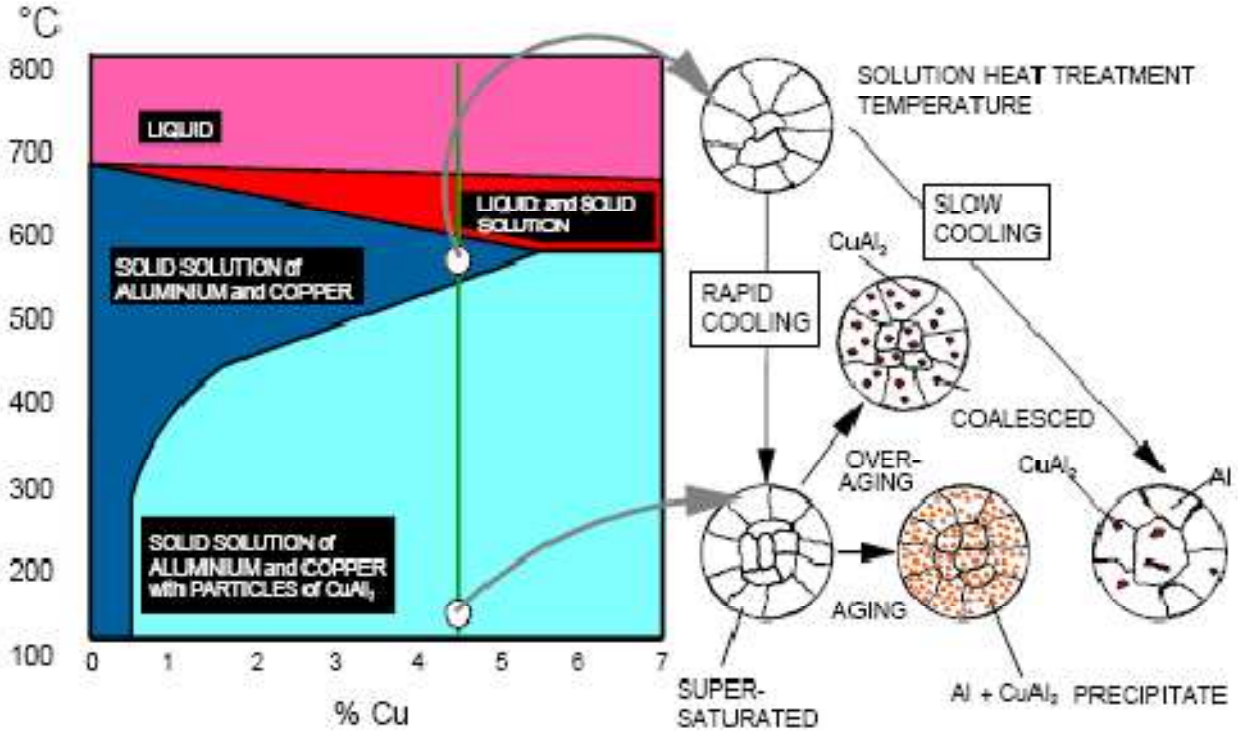
Precipitation Strengthening of Al-Cu alloy

- **Solution heat treatment:** The Al-4%Cu alloy first heated to about 515°C to form uniform solid solution α. This step is also called as solutionizing.
- **Quenching:** After the solutionizing, the alloy quenched to room temperature in water. This treatment produces a supersaturated solid solution (SSSS) of copper in aluminum.
- **Aging:**

  1. Natural Aging: Give sufficient time with out heating
  2. Artificial Aging: Heated between 130 to 190°C.

  Due to the limited diffusion, very fine precipitate particles are obtained. The finely distributed particles effectively hinder the motion of dislocations in the Al matrix and increase the strength of the alloy.

Al-Cu system


°C
800
700
600
500
400
300
200
100
0
1
2
3
4
5
6
7
% Cu
LIQUID
LIQUID and SOLID SOLUTION
SOLID SOLUTION of ALUMINIUM and COPPER
SOLID SOLUTION of ALUMINIUM and COPPER with PARTICLES of $CuAl_2$
SOLUTION HEAT TREATMENT TEMPERATURE
SLOW COOLING
RAPID COOLING
$CuAl_2$
COALESCED
OVER-AGING
AGING
$CuAl_2$
Al
SUPER-SATURATED
Al + $CuAl_2$ PRECIPITATE

Al-Cu precipitation sequence

- In precipitation-strengthened Al-Cu alloys, four intermediated structure are identified:
    1. Gp_1 (Guiner – Preston) zones
    2. GP_2 zone (θ’’)
    3. θ’ and
    4. θ ($CuAl_2$)

Al-Cu precipitation sequence

- The sequence is:

  $\alpha_0 \rightarrow \alpha_1 + \text{GP-zones} \rightarrow \alpha_2 + \theta'' \rightarrow \alpha_3 + \theta' \rightarrow \alpha_4 + \theta$

- The phase are:

  α_n – fcc solid solution of aluminum; n^{th} subscript denotes each equilibrium

  GP zones - mono-atomic layers of Cu on $(001)_{Al}$

  θ“ - thin discs, fully coherent precipitate with matrix

  θ’ - disc-shaped, semi-coherent precipitate.

  θ - incoherent interface, ~spherical, complex body-centered tetragonal (bct) precipitate.

Al-Cu ppt. structures

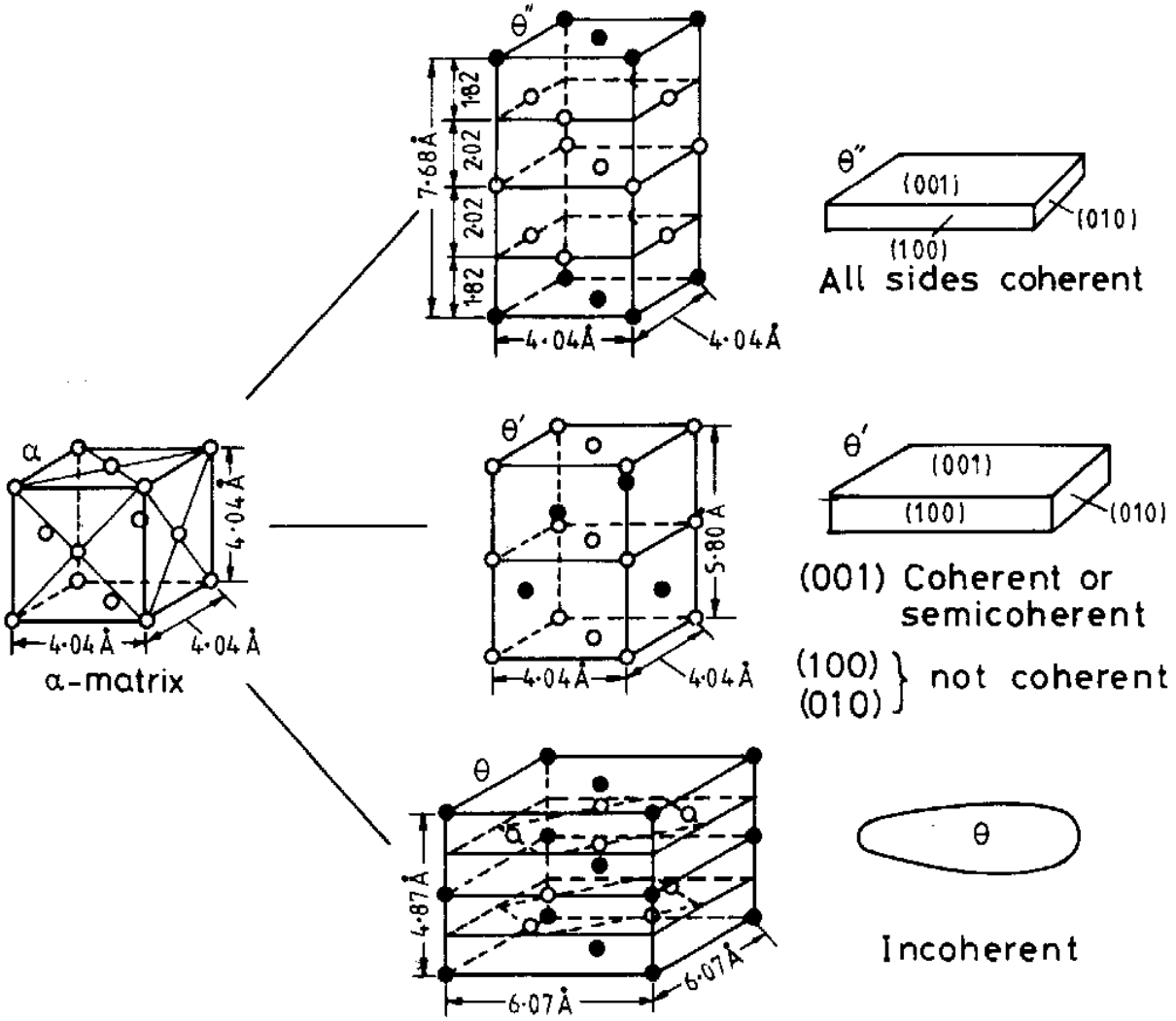


Fig. 5.29 Structure and morphology of θ″, θ′ and θ in Al–Cu (○ Al, ● Cu).

Age Hardening Curves

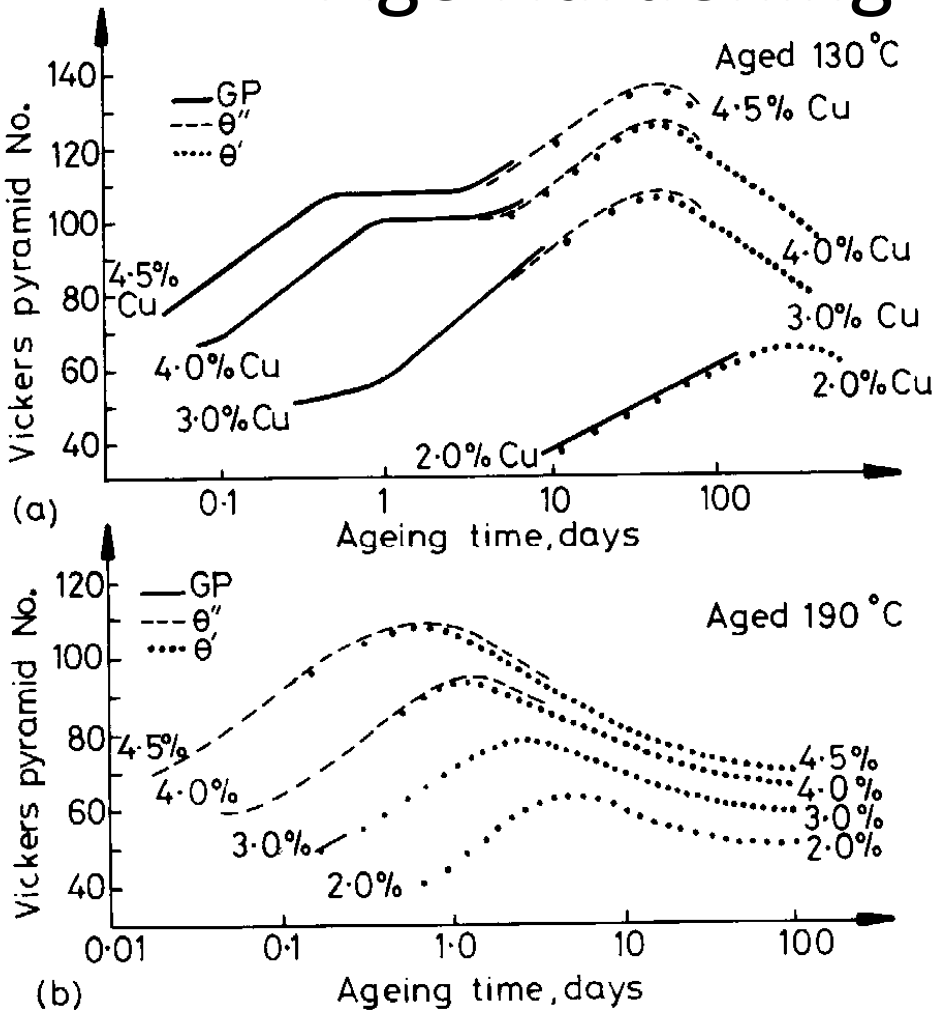


Fig. 5.37 Hardness v. time for various Al–Cu alloys at (a) 130 °C (b) 190 °C. (After J.M. Silcock. T.J. Heal and H.K. Hardy, *Journal of the Institute of Metals* **82** (1953–1954) 239.

Overaging: . After the peak hardness, further ageing tends to decrease the hardness.

Al-Cu phase relationships

The explanation of age hardening depends on understanding the metastable phases that can appear.

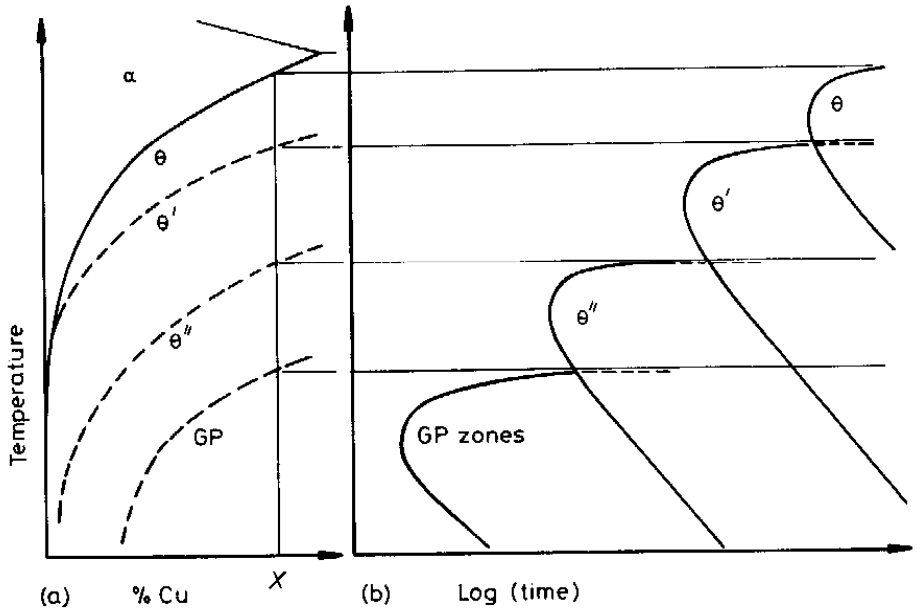


Fig. 5.32 (a) Metastable solvus lines in Al–Cu (schematic). (b) Time for start of precipitation at different temperatures for alloy X in (a).

Dispersion Strengthening

Strengthening by the introduction of a second phase in matrix is known as dispersion strengthening.

Matrix: The soft continuous phase present in large amount

Precipitate: hard strengthening phase is called dispersion phase or precipitate

The strengthening of second phase particle in matrix:

- the size, shape, quantity and distribution of the second phase particles,
- the strength, ductility and strain hardening behavior depends on the matrix and second phase and crystallographic fit between the phases, the interfacial energy and interfacial bonding between the phases

S. No.	Matrix	Second phase	Remark
1	Soft and ductile	Hard and strong	Matrix –ductility Ppt. strength
2	Continuous	Discontinuous	Crack can be avoided
3	Continuous	Small and numerous	Strength will be more
4		Round	Needle or sharp edge produce crack
5		Higher concentration	

- When the particles are small and/or soft, dislocation can cut and deform the particles.
- Cutting through will not be possible, if there is an interface between the precipitate and the matrix and if the orientation changes abruptly at the interface. Under such circumstances, the dislocations bend around and bypass the precipitate particles

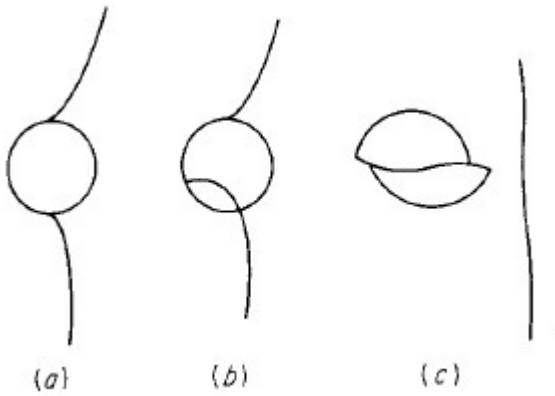
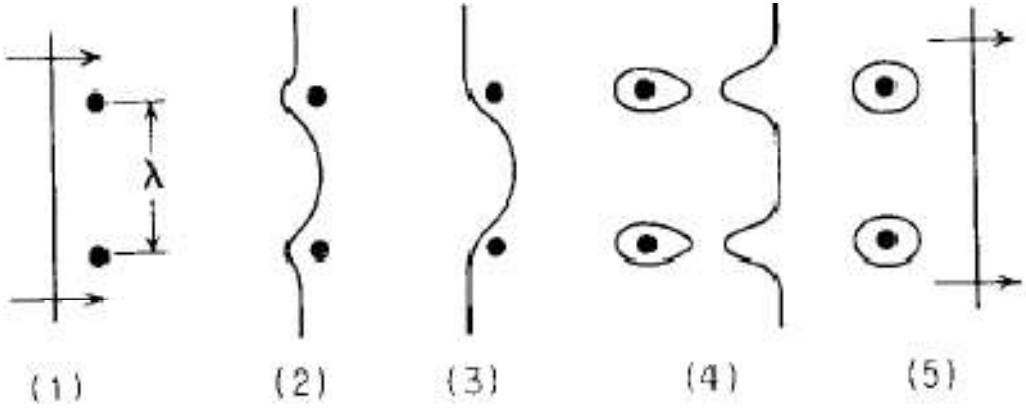


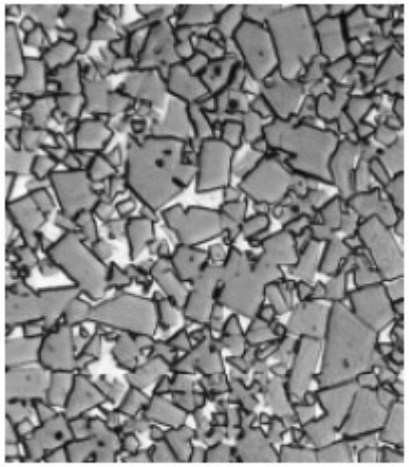
Figure : A dislocation cutting a particle.



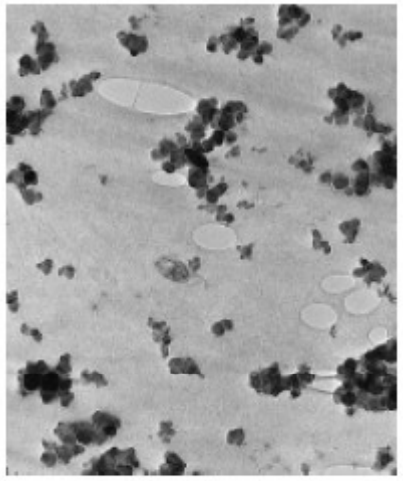
Advantages of Dispersion Strengthening

- Thermally stable at very high temperatures. Because of the finely dispersed second-phase particles are resistant to recrystallization and grain growth than single phase alloys.
- There is very little solubility of the second phase constituent in the matrix, the particles resist growth or overageing to greater extent than the second phase particles in a precipitation-hardening system.

Dispersion strengthening	Precipitation hardening
The second phase in dispersion-hardening system has very little solubility in the matrix even at elevated temperatures.	The second phase must be soluble at an elevated temperature and exhibit decreasing solubility with decreasing temperature.
Precipitates are formed by alloying element and/ or added purposely like oxides, carbides, nitrides and borides etc.	Precipitates form by alloying element.
There is no coherency between precipitate and the matrix	There is coherency between precipitate and the matrix
At high temperature, the dispersed particles resist growth or overageing.	At high temperature, overageing takes place.
Example: ThO_2 dispersed Ni, WC dispersed Co	Example: Al-Cu system



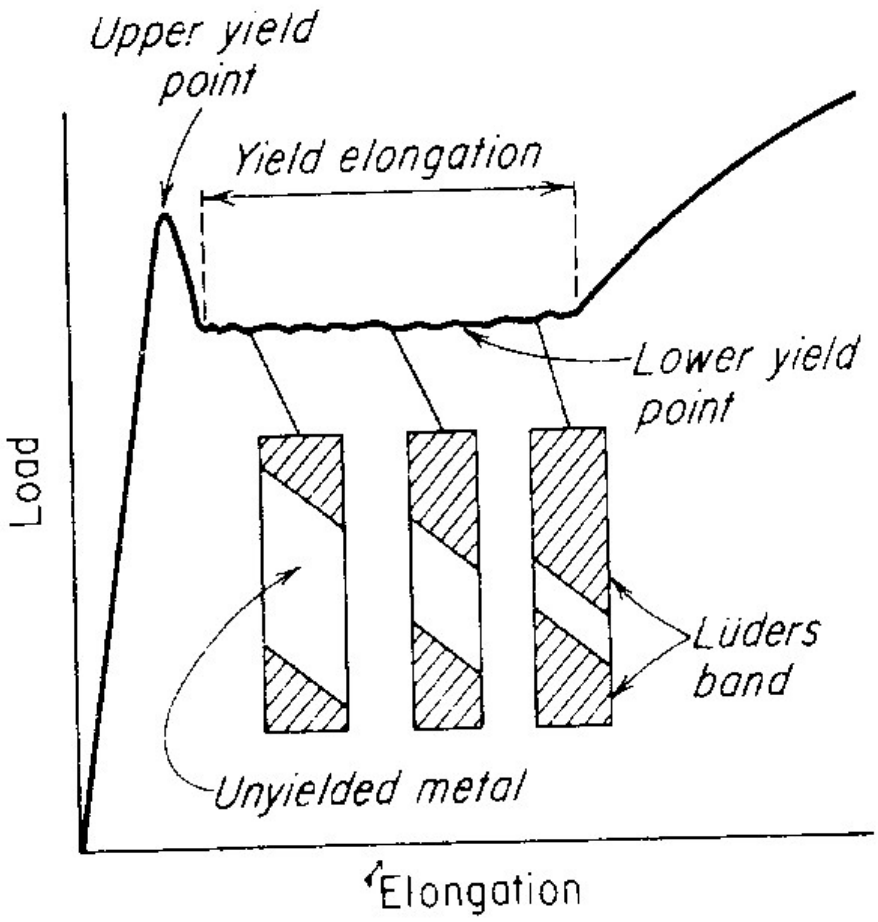
WC in Co matrix



Spherical reinforcing C in
Synthetic rupper

Yield Point Phenomenon

- The load at which sudden drop occurs – Upper Yield Point
- The average constant load – Lower yield point
- The elongation which occurs at constant load – yield point elongation
- Discrete band formation in the material during yield – Luders bond



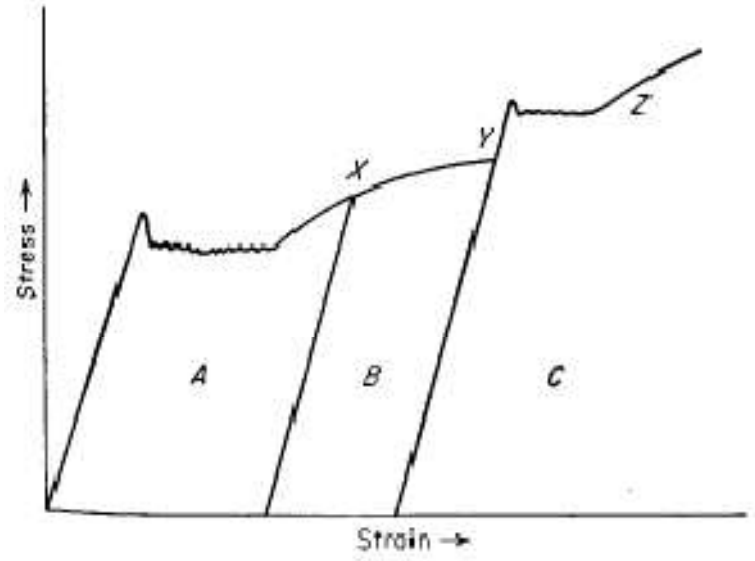
Due to interstitial or substitutional impurities

Yield point phenomena observed in

- Steel
- Mo, Ti and Al alloys
- Single crystals of Fe, Cd, Zn, brass, Al

Strain Ageing

- A metal hardens as a result of ageing after plastic deformation is called strain ageing.



To control the strain ageing,

- Lower the amount of carbon and nitrogen.
- Alloying element Al, V, Ti, and boron are added to convert carbon and nitrogen as stable carbides or nitrides.
- Deform the metals immediately before it can age.

Dynamic strain-ageing

- Strain ageing is associated with the occurrence of serrations in the stress-strain curve
- Dynamic strain-ageing behaviour or Portevin-LeChatelier effect

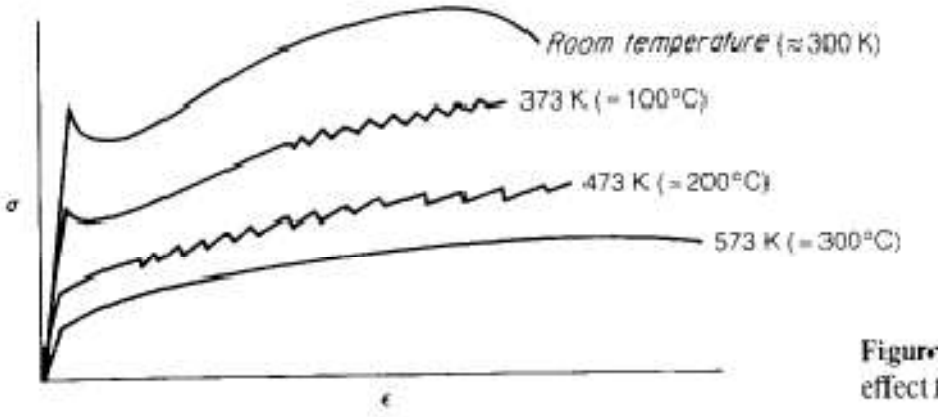


Figure
effect

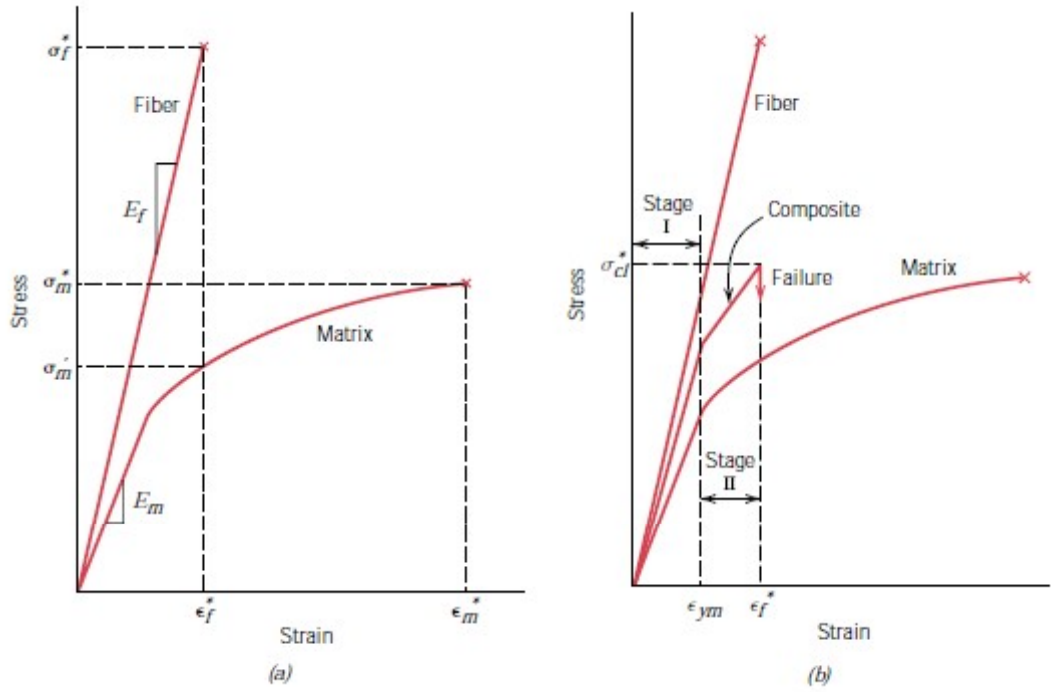
For plain C steel

- The solute atoms are diffuse in the specimen at a rate faster than the speed of the dislocations and arrest the dislocations
- Due to mechanical twinning during deformation or stress assisted martensitic transformations

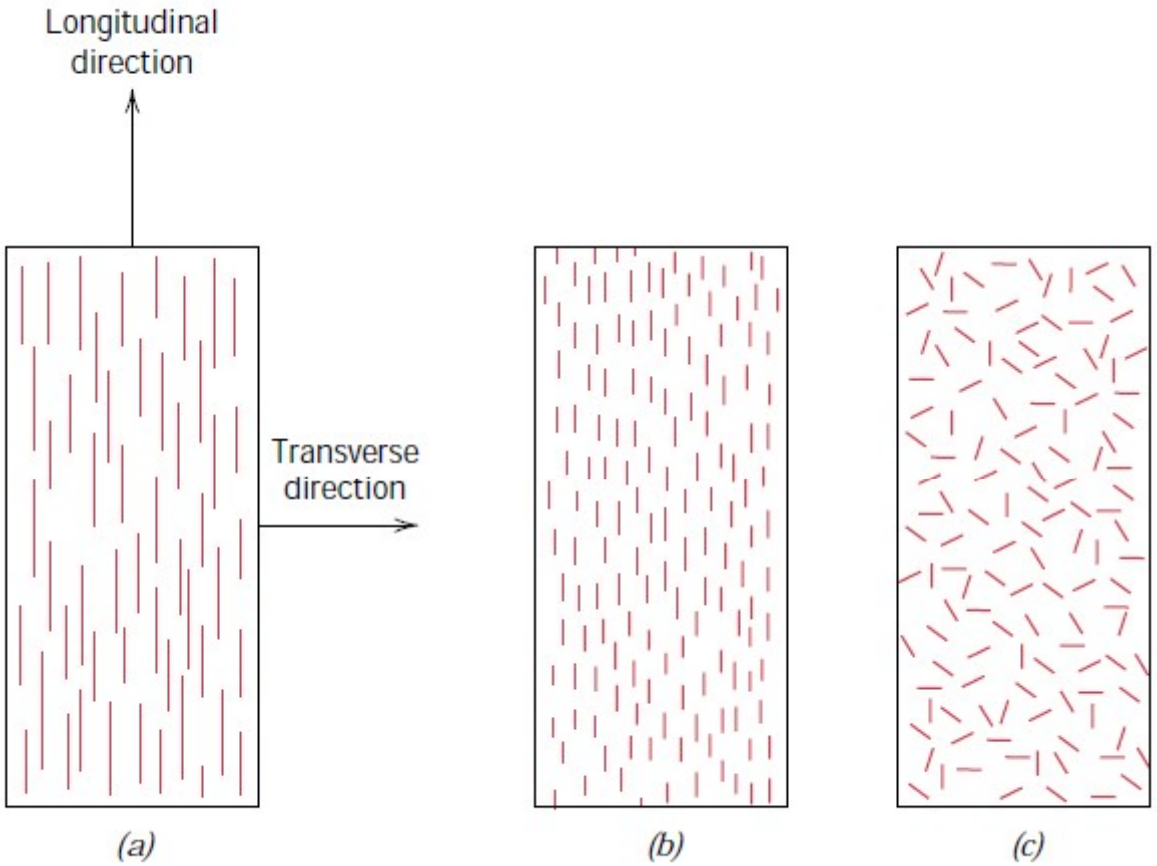
- PCS discontinuous yielding / dynamic strain-ageing occurs in the temperature region of 500 to 650 K. This temperature region is known as ***blue brittle region***

Fiber Strengthening

- Materials with high strength to weight ratio is produced by incorporating fine fibers in a ductile matrix.
- Fiber
  - high strength and high elastic modulus
  - long and continuous or discontinuous
  - Ceramics like carbides and glass wool, boron or graphite or metal wires
- Matrix
  - ductile and non reactive with the fibers.
  - Metals or polymers



In fiber strengthening, the matrix transmits load to the high modulus fibers and protect fibers from surface damage. The fibers and the matrix have different elastic modulus; a complex stress distribution is developed during loading.



Continuous and aligned

Discontinuous and aligned

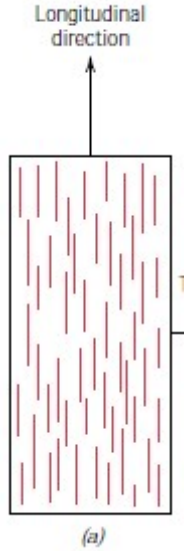
Discontinuous and random

Elastic Behaviour

Longitudinal loading: Continuous and aligned fiber

Assumption: deformation of matrix and fiber same.

$$e_c = e_f = e_m = e$$



Total load applied to composite – F_c

$$F_c = F_m + F_f$$

F=σA. Therefore

$$\sigma_c A_c = \sigma_m A_m + \sigma_f A_f$$

$$\sigma_c = \sigma_m \frac{A_m}{A_c} + \sigma_f \frac{A_f}{A_c}$$

A_m/A_c and A_f/A_c are the area fractions of the matrix and fiber phases

In terms of volume fraction

$$\sigma_c = \sigma_m V_m + \sigma_f V_f$$

If the above equation is divided by its respective strain,

$$\frac{\sigma_c}{e_c} = \frac{\sigma_m}{e_m} V_m + \frac{\sigma_f}{e_f} V_f$$

if composite, matrix and fiber deformation are all elastic, then ,

$$\frac{\sigma_c}{e_c} = E_c \qquad \frac{\sigma_m}{e_m} = E_m \qquad \frac{\sigma_f}{e_f} = E_f$$

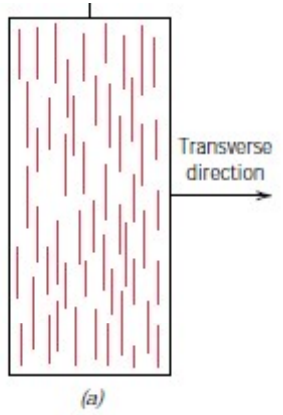
E- Elastic Modulus of respective phase.

$$E_c = E_m V_m + E_f V_f \qquad E_c = E_m(1 - V_f) + E_f V_f$$

Since $V_m + V_f = 1$

Elastic behavior-Transverse loading:

A continuous and oriented fiber composite loaded in the transverse directions.



Isostress state

$$\sigma_c = \sigma_f = \sigma_m = \sigma$$

Strain or deformation of the entire composite e_c is

$$e_c = e_m V_m + e_f V_f$$

Since $e = {}^{\upsilon}/_{E}$

$$\frac{\sigma}{E_c} = \frac{\sigma}{E_m} V_m + \frac{\sigma}{E_f} V_f$$

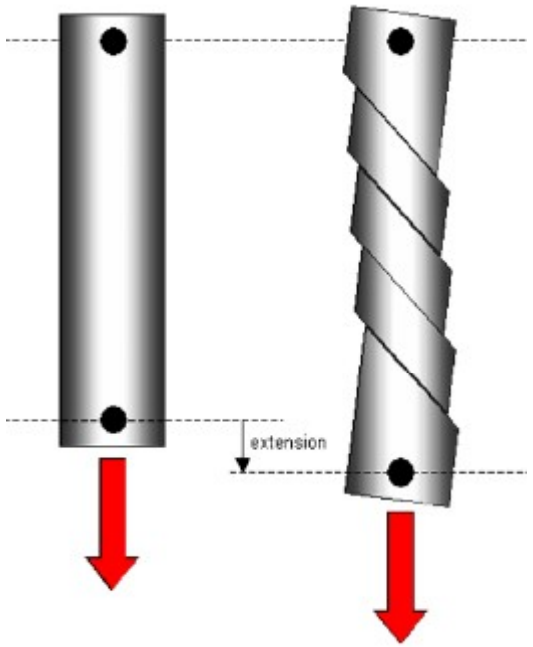
And dividing through by σ.

$$\frac{1}{E_c} = \frac{V_m}{E_m} + \frac{V_f}{E_f}$$

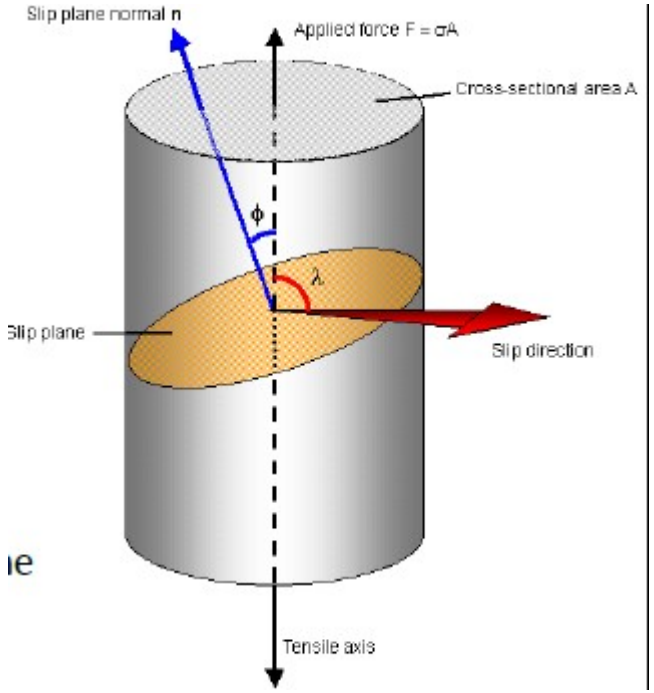
$$E_c = \frac{E_m E_f}{E_f V_m + E_m V_f} = \frac{E_m E_f}{E_f(1 - V_f) + E_m V_f}$$

Deformation of Single Crystals

- When a single crystal deformed under a tensile stress, it observed that plastic deformation occurs by slip.
- Section of the crystal slide relative to one another, changing the geometry of the sample

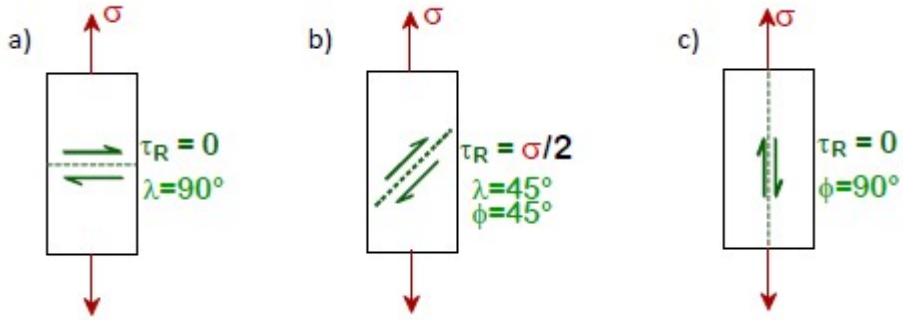


Slip occurs when the shear stress acting in the slip direction on the slip plane reaches the critical values.



$$\tau_C = \sigma_Y \cos\phi \cos\lambda$$

$$\sigma_y = \frac{\tau_{crss}}{(\cos\phi \cos\lambda)_{\max}}$$



Example

A tensile stress of 5kPa is applied parallel to the [432] direction in a cubic crystal. Find the shear stresses, τ, on the (11-1) plane in the [011] direction.

Solution

Find the Schmidt's factor for the slip system

$$Cos\phi = \frac{[432]\cdot[1\bar{1}\bar{1}]}{\sqrt{4^2+3^2+2^2}\cdot\sqrt{1^2+1^2+1^2}} = \frac{5}{\sqrt{29}\cdot\sqrt{3}} = 0.536$$

$$Cos\lambda = \frac{[432]\cdot[011]}{\sqrt{4^2+3^2+2^2}\cdot\sqrt{1^2+1^2+0^2}} = \frac{5}{\sqrt{29}\cdot\sqrt{2}} = 0.6565$$

$$M = Cos\phi \times Cos\lambda = 0.352$$

$$\tau = M\sigma = 0.352 \times 5kPa = 1.76kPa$$