Module-6

Dislocations and Strengthening Mechanisms

Contents

1) Dislocations & Plastic deformation and Mechanisms of plastic deformation in metals
2) Strengthening mechanisms in metals
3) Recovery, Recrystallization and Grain growth

Plastic deformation – Dislocations

- Permanent plastic deformation is due to shear process – atoms change their neighbors.
- Inter-atomic forces and crystal structure plays an important role during plastic deformation.
- Cumulative movement of dislocations leads to gross plastic deformation.
- Edge dislocation move by slip and climb, while screw dislocation move by slip and cross-slip.
- During their movement, dislocations tend to interact. The interaction is very complex because of number of dislocations moving over many slip systems in different directions.

Plastic deformation – Dislocations (contd…)

- Dislocations moving on parallel planes may annihilate each other, resulting in either vacancies or interstitials.
- Dislocations moving on non-parallel planes hinder each other's movement by producing sharp breaks – jog (break out of slip plane), kink (break in slip plane)
- Other hindrances to dislocation motion – interstitial and substitutional atoms, foreign particles, grain boundaries, external grain surface, and change in structure due to phase change.
- Material strength can be increased by arresting dislocation motion.

Plastic deformation mechanisms - Slip

- Mainly two kinds: slip and twinning.
- Slip is prominent among the two. It involves sliding of blocks of crystal over other along slip planes.
- Slip occurs when shear stress applied exceeds a critical value.
- Slip occurs most readily in specific directions (slip directions) on certain crystallographic planes.
- Feasible combination of a slip plane together with a slip direction is considered as a slip system.
- During slip each atom usually moves same integral number of atomic distances along the slip plane.

Plastic deformation mechanisms – Slip (contd…)

- Extent of slip depends on many factors - external load and the corresponding value of shear stress produced by it, crystal structure, orientation of active slip planes with the direction of shearing stresses generated.
- Slip occurs when shear stress applied exceeds a critical value.
- For single crystal, Schmid defined critical shear stress as

$$\tau_R = \frac{P\cos\lambda}{A/\cos\phi} = \frac{P}{A}\cos\phi\cos\lambda = \sigma\cos\phi\cos\lambda$$

$$\Rightarrow m = \cos\phi\cos\lambda$$

Plastic deformation mechanisms – Slip (contd…)

- In a polycrystalline aggregate, individual grains provide a mutual geometrical constraint on one other, and this precludes plastic deformation at low applied stresses.
- Slip in polycrystalline material involves generation, movement and (re-)arrangement of dislocations.
- During deformation, mechanical integrity and coherency are maintained along the grain boundaries.
- A minimum of five independent slip systems must be operative for a polycrystalline solid to exhibit ductility and maintain grain boundary integrity – von Mises.
- On the other hand, crystal deform by twinning.

Slip systems

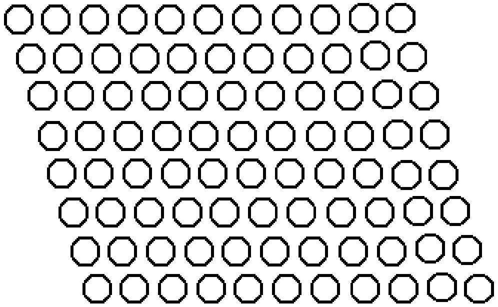
Crystal	**Occurrence**	**Slip planes**	**Slip directions**
FCC		{111}	<110>
BCC	More common Less common	{110} {112},{123}	<111>
HCP	More common Less common	Basal plane Prismatic & Pyramidal planes	Close packed directions
NaCl		{110}	<110>

Plastic deformation mechanisms – Twinning

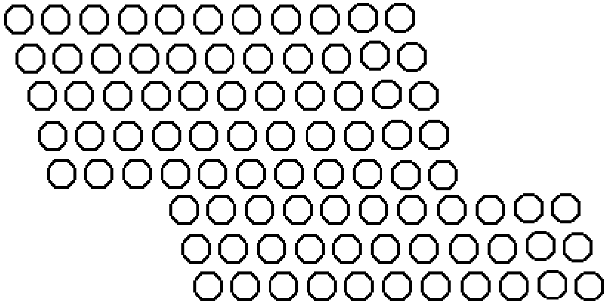
- It results when a portion of crystal takes up an orientation that is related to the orientation of the rest of the untwined lattice in a definite, symmetrical way.
- The important role of twinning in plastic deformation is that it causes changes in plane orientation so that further slip can occur.
- Twinning also occurs in a definite direction on a specific plane for each crystal structure.

Crystal	**Example**	**Twin plane**	**Twin direction**
FCC	Ag, Au, Cu	(111)	[112]
BCC	α-Fe, Ta	(112)	[111]
HCP	Zn, Cd, Mg, Ti	$(10\bar{1}2)$	$[\bar{1}011]$

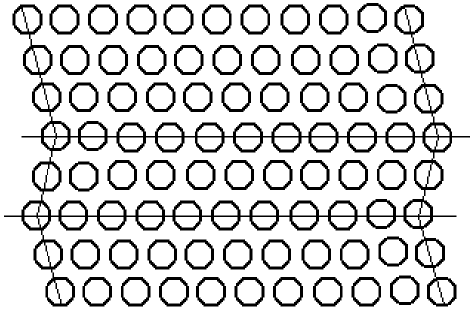
Slip Vs. Twinning



Undeformed Crystal



After Slip



After Twinning

	during/in slip	**during/in twinning**
Crystal orientation	Same above and below the slip plane	Differ across the twin plane
Size (in terms of inter-atomic distance)	Multiples	Fractions
Occurs on	Widely spread planes	Every plane of region involved
Time required	Milli seconds	Micro seconds
Occurrence	On many slip systems simultaneously	On a particular plane for each crystal

Strengthening mechanisms

- Material can be increased by hindering dislocation, which is responsible for plastic deformation.
- Different ways to hinder dislocation motion / Strengthening mechanisms:

in single-phase materials

- Grain size reduction
- Solid solution strengthening
- Strain hardening

in multi-phase materials

- Precipitation strengthening
- Dispersion strengthening
- Fiber strengthening
- Martensite strengthening

Strengthening by Grain size reduction

- It is based on the fact that dislocations will experience hindrances while trying to move from a grain into the next because of abrupt change in orientation of planes.
- Hindrances can be two types: forcible change of slip direction, and discontinuous slip plane.
- Smaller the grain size, often a dislocation encounters a hindrance. Yield strength of material will be increased.
- Yield strength is related to grain size (diameter, *d*) as Hall-Petch relation:

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

- Grain size can be tailored by controlled cooling or by plastic deformation followed by appropriate heat treatment.

Strengthening by Grain size reduction (contd…)

- Grain size reduction improves not only strength, but also the toughness of many alloys.
- If d is average grain diameter, S_v is grain boundary area per unit volume, N_L is mean number of intercepts of grain boundaries per unit length of test line, N_A is number of grains per unit area on a polished surface:

$$S_v = 2N_L \qquad d = \frac{3}{S_v} = \frac{3}{2N_L} \qquad d = \sqrt{\frac{6}{\pi N_A}}$$

- Grain size can also be measured by comparing the grains at a fixed magnification with standard grain size charts.
- Other method: Use of ASTM grain size number (Z). It is related to grain diameter, D (in mm) as follows:

$$D = \frac{1}{100}\sqrt{\frac{645}{2^{G-1}}}$$

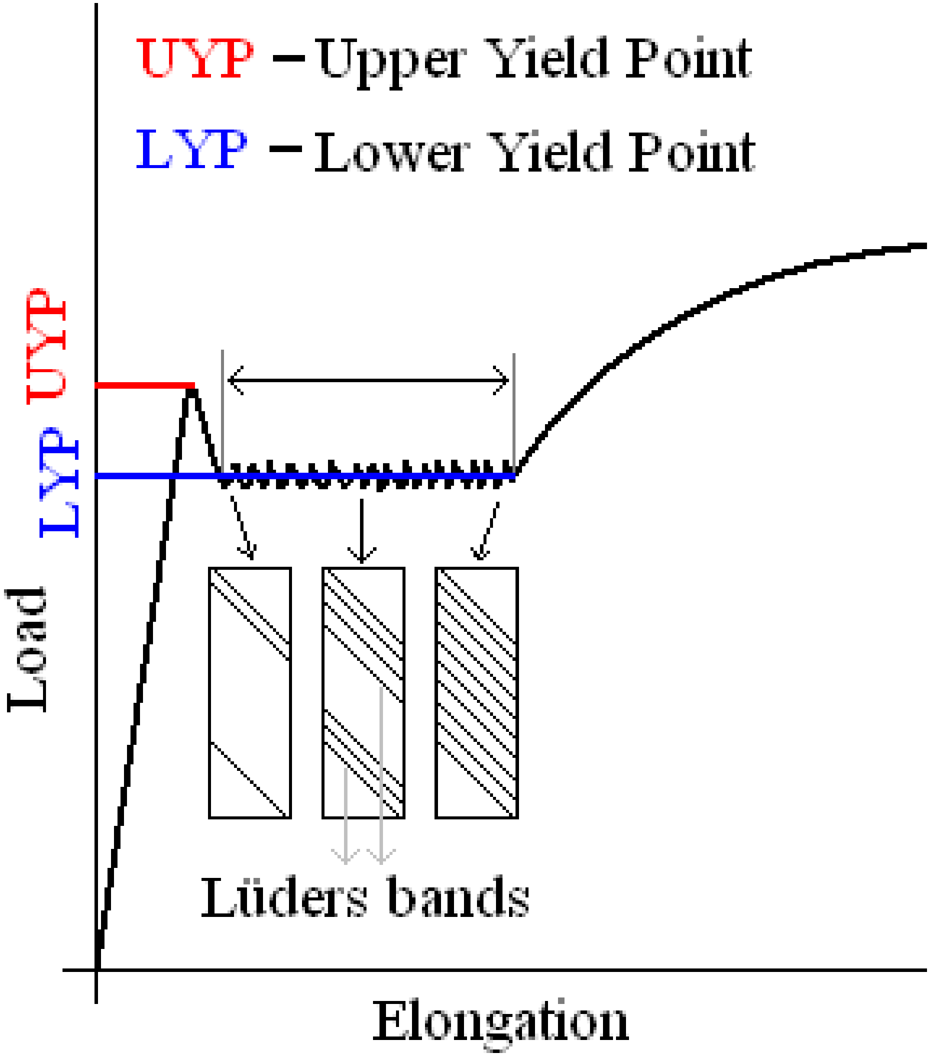
Solid solution strengthening

- Impure foreign atoms in a single phase material produces lattice strains which can anchor the dislocations.
- Effectiveness of this strengthening depends on two factors – size difference and volume fraction of solute.
- Solute atoms interact with dislocations in many ways:
  - elastic interaction
  - modulus interaction
  - stacking-fault interaction
  - electrical interaction
  - short-range order interaction
  - long-range order interaction
- Elastic, modulus, and long-range order interactions are of long-range i.e. they are relatively insensitive to temperature and continue to act about 0.6 *Tm*.

Yield point phenomenon

- Localized, heterogeneous type of transition from elastic to plastic deformation marked by abrupt elastic-plastic transition – Yield point phenomenon.

- It characterizes that material needs higher stress to initiate plastic flow than to continue it.



Yield point phenomenon (contd…)

- The bands are called Lüders bands / Hartmann lines / stretcher stains, and generally are approximately 45 to the tensile axis.

- Occurrence of yield point is associated with presence of small amounts of interstitial or substitutional impurities. It’s been found that either unlocking of dislocations by a high stress for the case of strong pinning or generation of new dislocations are the reasons for yield-point phenomenon.

- Magnitude of yield-point effect will depend on energy of interaction between solute atoms and dislocations and on the concentration of solute atoms at the dislocations.

Strain hardening

- Phenomenon where ductile metals become stronger and harder when they are deformed plastically is called strain hardening *or* work hardening.
- Increasing temperature lowers the rate of strain hardening. Hence materials are strain hardened at low temperatures, thus also called cold working.
- During plastic deformation, dislocation density increases. And thus their interaction with each other resulting in increase in yield stress.
- Dislocation density (ρ) and shear stress (τ) are related as follows:

$$\tau = \tau_0 + A\sqrt{\rho}$$

Strain hardening (contd…)

- During strain hardening, in addition to mechanical properties physical properties also changes:
  - a small decrease in density
  - an appreciable decrease in electrical conductivity
  - small increase in thermal coefficient of expansion
  - increased chemical reactivity (decrease in corrosion resistance).
- Deleterious effects of cold work can be removed by heating the material to suitable temperatures – Annealing. It restores the original properties into material. It consists of three stages – recovery, recrystallization and grain growth.
- In industry, alternate cycles of strain hardening and annealing are used to deform most metals to a very great extent.

Precipitation & Dispersion hardening

- Foreign particles can also obstructs movement of dislocations i.e. increases the strength of the material.
- Foreign particles can be introduced in two ways – precipitation and mixing-and-consolidation technique.
- Precipitation hardening is also called age hardening because strength increases with time.
- Requisite for precipitation hardening is that second phase must be soluble at an elevated temperature but precipitates upon quenching and aging at a lower temperature.

  E.g.: Al-alloys, Cu-Be alloys, Mg-Al alloys, Cu-Sn alloys

- If aging occurs at room temperature – Natural aging
- If material need to be heated during aging – Artificial aging.

Precipitation & Dispersion hardening (contd…)

- In dispersion hardening, fine second particles are mixed with matrix powder, consolidated, and pressed in powder metallurgy techniques.
- For dispersion hardening, second phase need to have very low solubility at all temperatures.

  E.g.: oxides, carbides, nitrides, borides, etc.

- Dislocation moving through matrix embedded with foreign particles can either cut through the particles *or* bend around and bypass them.
- Cutting of particles is easier for small particles which can be considered as segregated solute atoms. Effective strengthening is achieved in the bending process, when the particles are submicroscopic in size.

Precipitation & Dispersion hardening (contd…)

- Stress (τ) required to bend a dislocation is inversely proportional to the average interspacing (λ) of particles:

$$\tau = {Gb}/{\lambda}$$

- Interspacing (λ) of spherical particles:
  where *r* - particle radius, *f* - volume fraction

$$\lambda = \frac{4(1-f)r}{3f}$$

- Optimum strengthening occurs during aging once the right interspacing of particles is achieved.

  - Smaller the particles, dislocations can cut through them at lower stresses

  - larger the particles they will be distributed at wider distances.

Fiber strengthening

- Second phase can be introduced into matrix in fiber form too.
- Requisite for fiber strengthening:

  Fiber material – high strength and high modulus

  Matrix material – ductile and non-reactive with fiber material

  E.g.: fiber material – Al_2O_3, boron, graphite, metal, glass, etc.
  matrix material – metals, polymers
- Mechanism of strengthening is different from other methods.
- Higher modulus fibers carry load, ductile matrix distributes load to fibers. Interface between matrix and fibers thus plays an important role.
- Strengthening analysis involves application of continuum, not dislocation concepts as in other methods of strengthening.

Fiber strengthening (contd…)

- To achieve any benefit from presence of fibers, critical fiber volume which must be exceeded for fiber strengthening to occur:

$$f_{critical} = \frac{\sigma_{mu} - \sigma_m^{'}}{\sigma_{fu} - \sigma_m^{'}}$$

where σ_{mu} – strength of strain hardened matrix, σ'_m – flow stress of matrix at a strain equal to fiber breaking stress, σ_{fu} – ultimate tensile strength of the fiber.

- Minimum volume fraction of fiber which must be exceeded to have real reinforcement:

$$f_{\min} = \frac{\sigma_{mu} - \sigma_m^{'}}{\sigma_{fu} + \sigma_{mu} - \sigma_m^{'}}$$

Martensite strengthening

- This strengthening method is based on formation of martensitic phase from the retained high temperature phase at temperatures lower then the equilibrium invariant transformation temperature.
- Martensite forms as a result of shearing of lattices.
- Martensite platelets assumes characteristic lenticular shape that minimizes the elastic distortion in the matrix. These platelets divide and subdivide the grains of the parent phase. Always touching but never crossing one another.
- Martensite platelets grow at very high speeds (1/3rd of sound speed) i.e. activation energy for growth is less. Thus volume fraction of martensite exist is controlled by its nucleation rate.

Martensite strengthening (contd…)

- Martensite platelets attain their shape by two successive shear displacements - *first* displacement is a homogeneous shear throughout the plate which occurs parallel to a specific plane in the parent phase known as the habit plane, *second* displacement, the lesser of the two, can take place by one of two mechanisms: slip as in Fe-C Martensite or twinning as in Fe-Ni Martensite.
- Martensite formation occurs in many systems.

  E.g.: Fe-C, Fe-Ni, Fe-Ni-C, Cu-Zn, Au-Cd, and even in pure metals like Li, Zr and Co. However, only the alloys based on Fe and C show a pronounced strengthening effect.
- High strength of Martensite is attributed to its characteristic twin structure and to high dislocation density. In Fe-C system, carbon atoms are also involved in strengthening.

Recovery

- Annealing relieves the stresses from cold working – three stages: recovery, recrystallization and grain growth.
- Recovery involves annihilation of point defects.
- Driving force for recovery is decrease in stored energy from cold work.
- During recovery, physical properties of the cold-worked material are restored without any observable change in microstructure.
- Recovery is first stage of annealing which takes place at low temperatures of annealing.
- There is some reduction, though not substantial, in dislocation density as well apart from formation of dislocation configurations with low strain energies.

Recrystallization

- This follows recovery during annealing of cold worked material. Driving force is stored energy during cold work.
- It involves replacement of cold-worked structure by a new set of strain-free, approximately equi-axed grains to replace all the deformed crystals.
- This is process is characterized by recrystallization temperature which is defined as the temperature at which 50% of material recrystallizes in one hour time.
- The recrystallization temperature is strongly dependent on the purity of a material.
- Pure materials may recrystallizes around 0.3 T_m, while impure materials may recrystallizes around 0.5-0.7 T_m, where T_m is absolute melting temperature of the material.

Recrystallization laws

- A minimum amount of deformation is needed to cause recrystallization (Rx).
- Smaller the degree of deformation, higher will be the Rx temperature.
- The finer is the initial grain size; lower will be the Rx temperature.
- The larger the initial grain size, the greater degree of deformation is required to produce an equivalent Rx temperature.
- Greater the degree of deformation and lower the annealing temperature, the smaller will be the recrystallized grain size.
- The higher is the temperature of cold working, the less is the strain energy stored and thus Rx temperature is correspondingly higher.
- The Rx rate increases exponentially with temperature.

Grain growth

- Grain growth follows complete crystallization if the material is left at elevated temperatures.
- Grain growth does not need to be preceded by recovery and recrystallization; it may occur in all polycrystalline materials.
- In contrary to recovery and recrystallization, driving force for this process is reduction in grain boundary energy.
- Tendency for larger grains to grow at the expense of smaller grains is based on physics.
- In practical applications, grain growth is not desirable.
- Incorporation of impurity atoms and insoluble second phase particles are effective in retarding grain growth.
- Grain growth is very strongly dependent on temperature.

Material Strengthening Mechanisms

Academic Resource Center

Agenda

- Definition of strengthening
- Strengthening mechanisms
- Grain size reduction
- Solid solution alloying
- Cold Working (strain hardening)
- Three steps of Annealing: Recovery, Recrystallization & Grain Growth

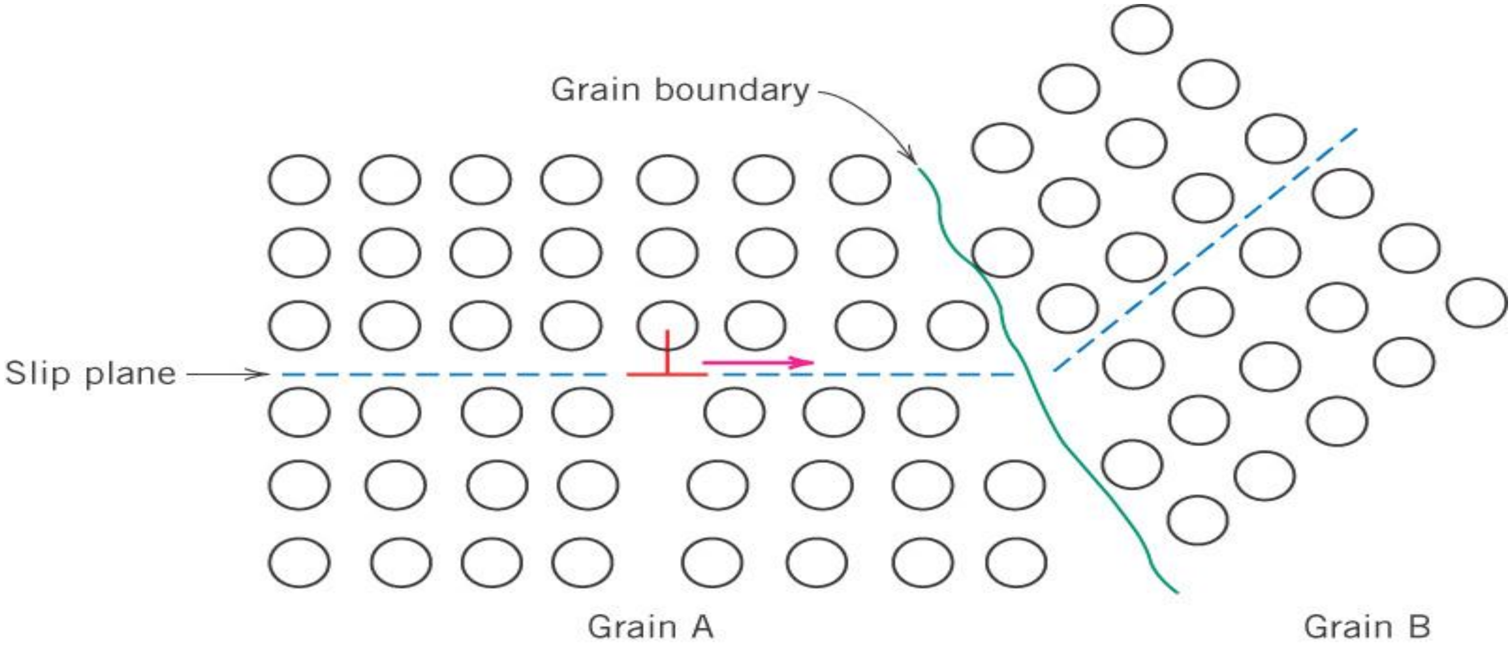
Strengthening

- The ability of a metal to deform plastically depends on the ability of dislocations to move.
- Hardness and strength are related to how easily a metal plastically deforms, so, by reducing dislocation movement, the mechanical strength can be improved.
- To the contrary, if dislocation movement is easy (unhindered), the metal will be soft, easy to deform.

Strengthening Mechanisms

1. Grain Size Reduction
2. Solid Solution Alloying
3. Strain Hardening (Cold Working)
4. Annealing

1. Grain Size Reduction



- Grain boundaries are barriers to slip.
- Barrier "strength “ increases with misorientation.
- Smaller grain size: more barriers to slip.

Hall Petch Relation

- This equation indicates that the yield strength has an inverse square root relation with grain size (d).

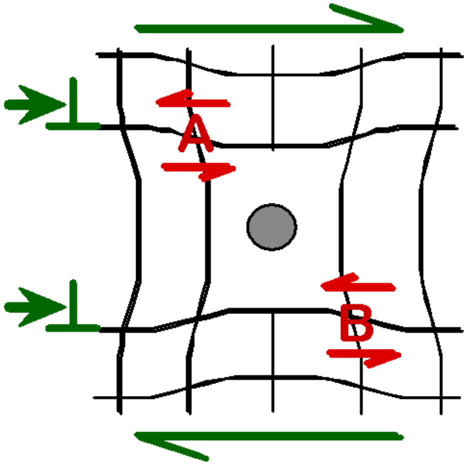
- Theoretically, a ong if the grains are made

$$s_{yield} = s_o + k_y d^{-1/2}$$

2. Solid Solutions

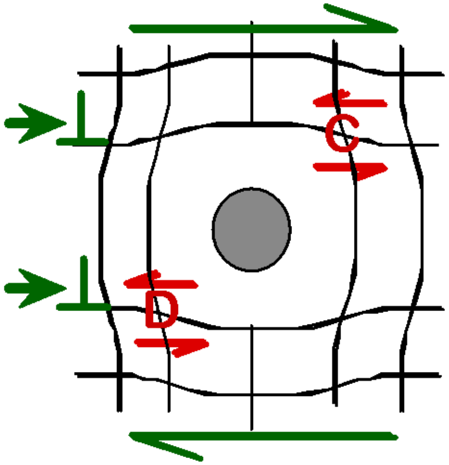
- Impurity atoms distort the lattice & generate stress.
- Stress can produce a barrier to dislocation motion.

Small substitutional impurity



Impurity generates local shear at A and B that opposes dislocation motion to the right.

Large substitutional impurity

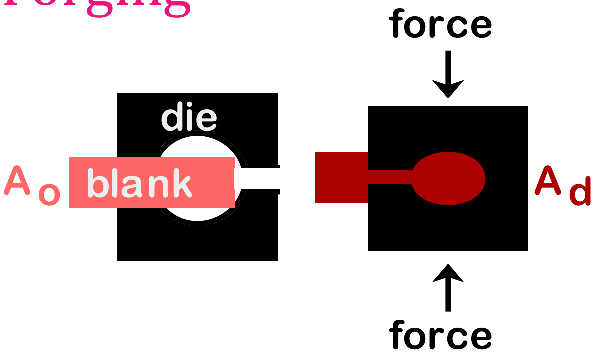


Impurity generates local shear at C and D that opposes dislocation motion to the right.

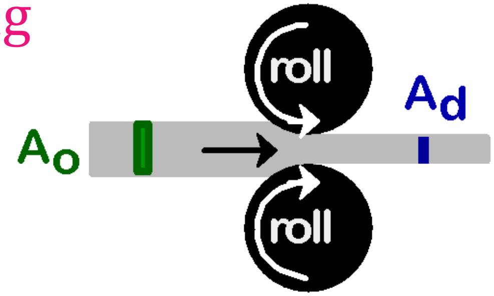
3. Strain Hardening (Cold Work)

- Room temperature deformation.
- Common forming techniques used to change the cross sectional area:

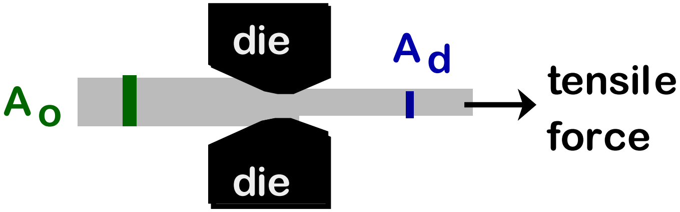
-Forging



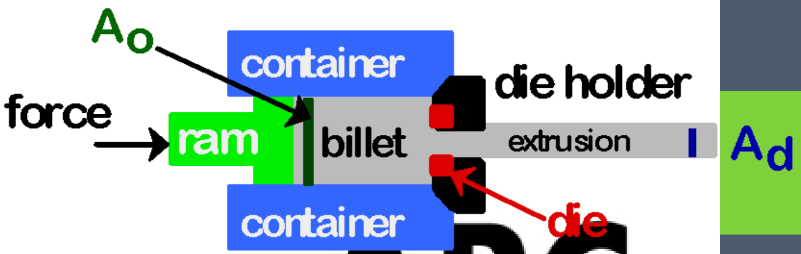
-Rolling



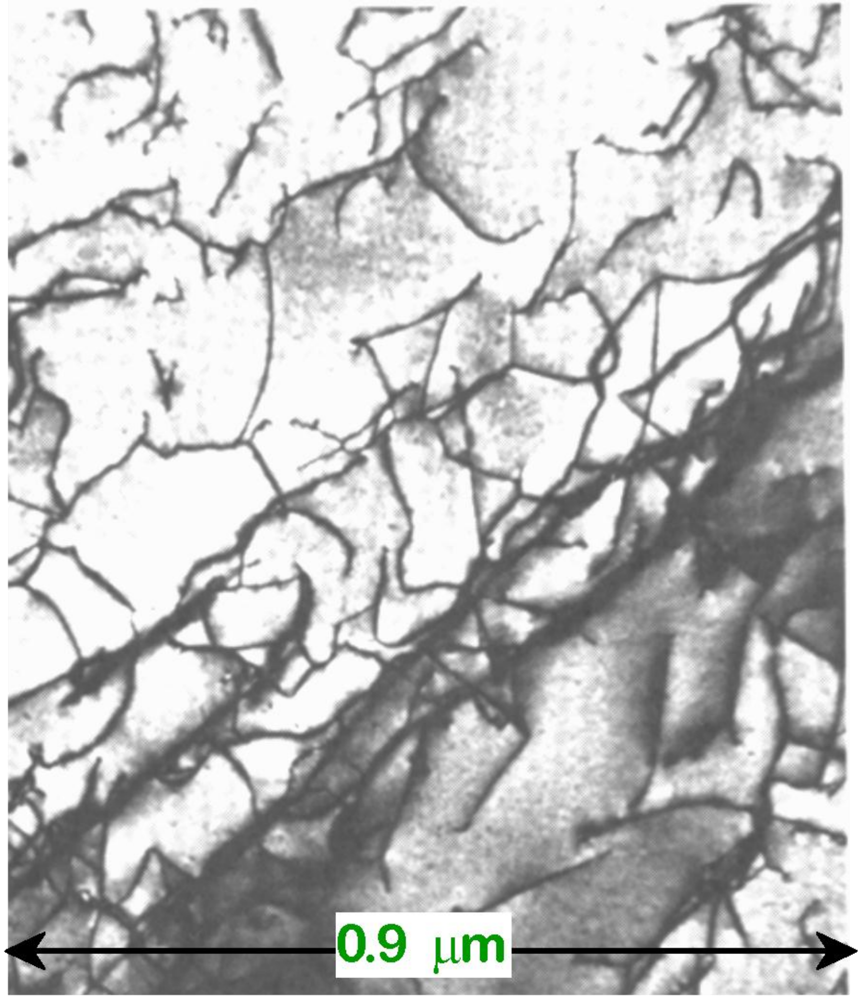
-Drawing



-Extrusion



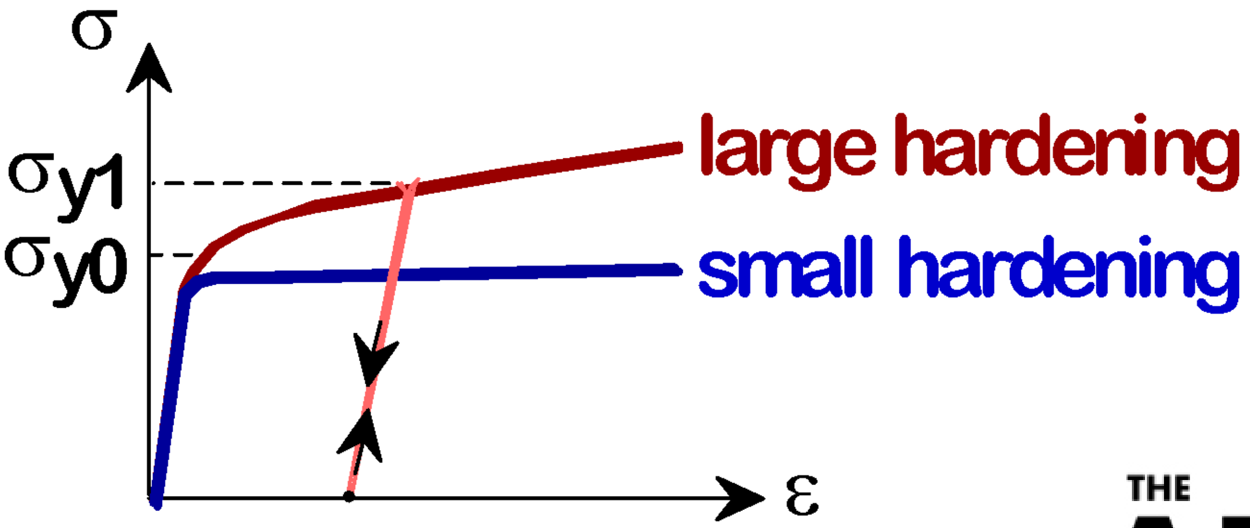
Dislocations during Cold Work



- Dislocations entangle one another during cold work.
- Dislocation motion becomes more difficult, which makes the material stronger overall.

Result of Cold Work

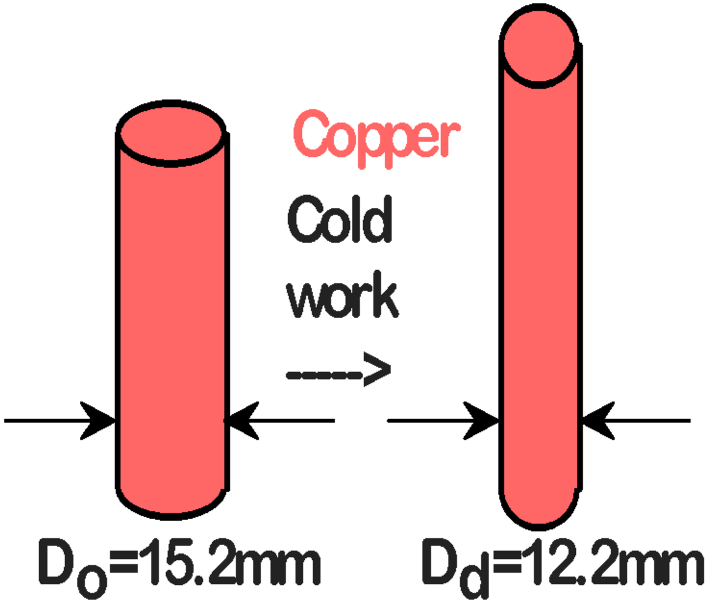
- Dislocation density increases, which leads to a increase in yield strength: Materials becomes harder.
- Ductility and tensile strength also increases.



Percentage Cold Work - Definition

$$\%CW = \frac{A_o - A_d}{A_o} x100$$

$$\%CW = \frac{\pi r_o^2 - \pi r_d^2}{\pi r_o^2} x100 = 35.6\%$$

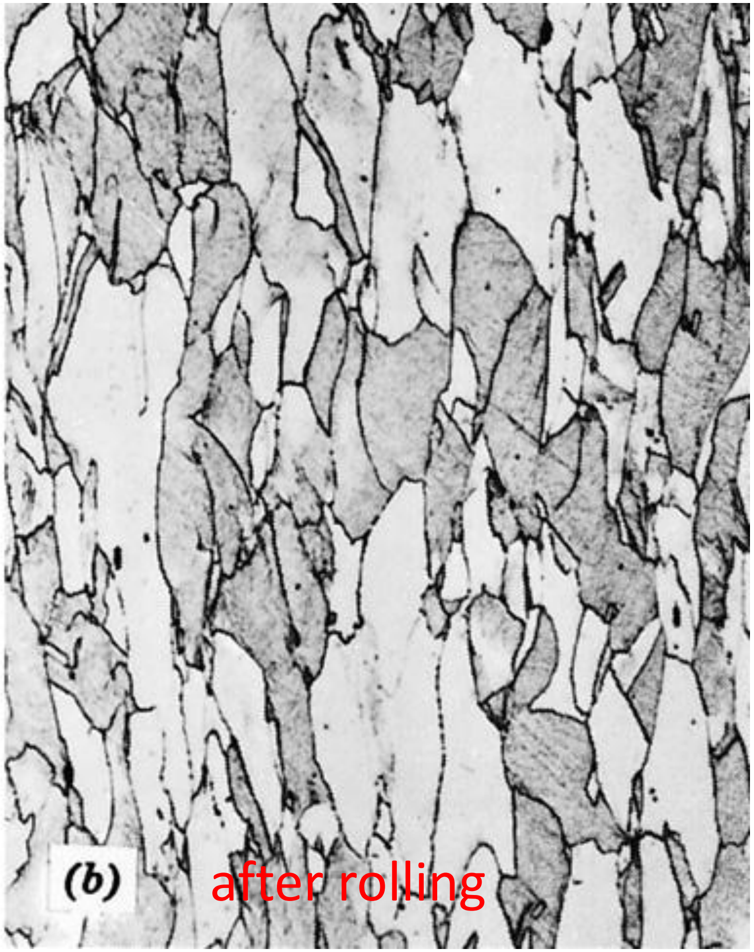


THE ARC.

Cold Rolling Illustration

<u>Isotropic</u>

grains are approx. spherical, equiaxed & randomly oriented.



<u>Anisotropic (directional)</u>

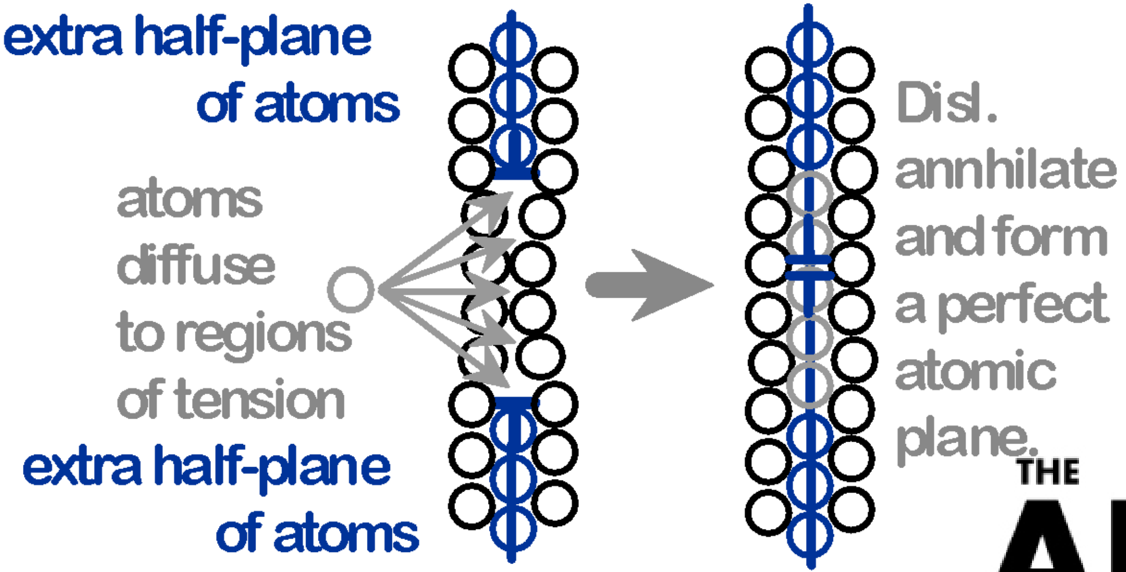
since rolling affects grain orientation and shape

Annealing

- Process where material is heated to above the recrystallization temperature of the sample and then cooled down.
- Main purpose is to improve Cold work properties by increasing ductility and retaining most of the hardness.
- There are 3 steps involved with annealing: recovery, recrystallization and grain growth.

Recovery

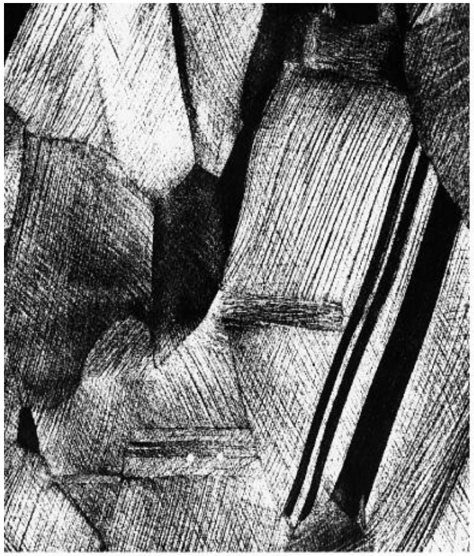
- During recovery, some of the stored internal strain energy is relieved through dislocation motion due to enhanced atomic diffusion at the elevated temperatures.
- Leads to reduction in the number of dislocations.



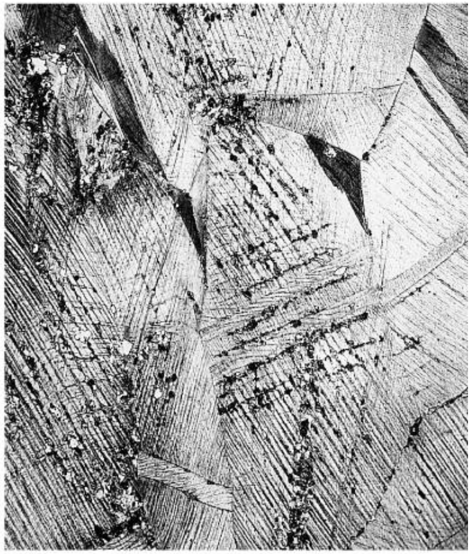
Recrystallization

- After recovery is complete, the grains are still in a relatively high strain energy state.
- Recrystallization is the formation of a new set of strain-free and uniaxial grains that have low dislocation densities.
- The driving force to produce the new grain structure is the internal energy difference between strained and unstrained material.
- The new grains form as very small nuclei and grow until they consume the parent material.

Recrystallization Illustration

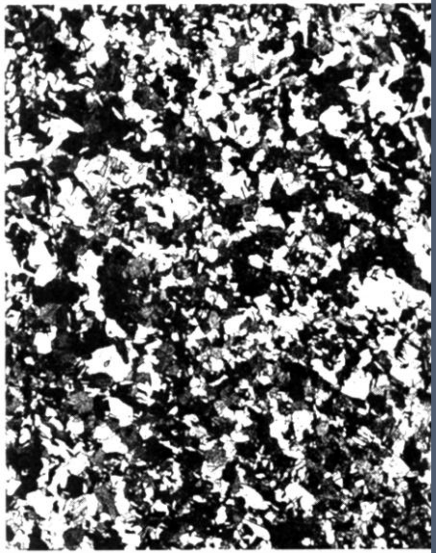


Cold Worked grains. Not annealed.



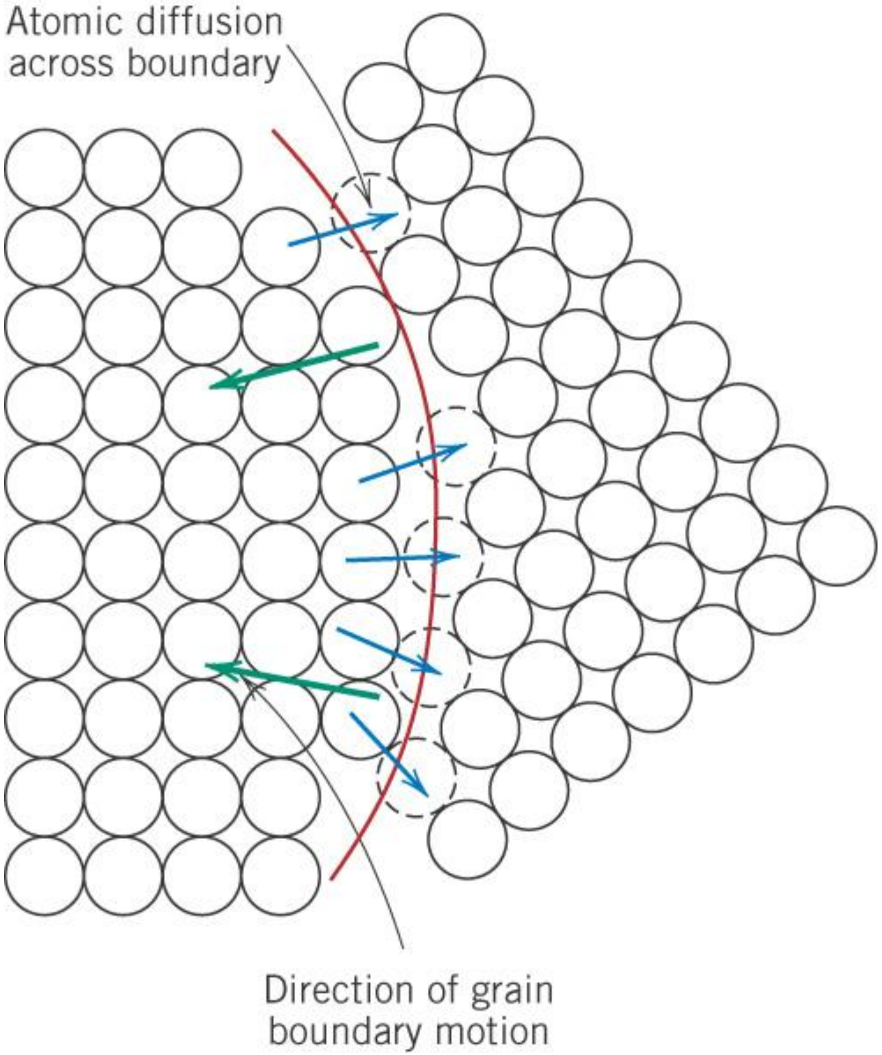
Initial recrystallization after 3 seconds @ 580˚C

Partial replacement of grains, after 4 seconds



Complete recryst. after 8 seconds

Grain Growth



- After recrystallization, the strain-free grains will continue to grow if the metal specimen is left at elevated temperatures.
- As grains increase in size, the total boundary area decreases, as does the total energy.
- Large grains grow at the expense of smaller grains.

References

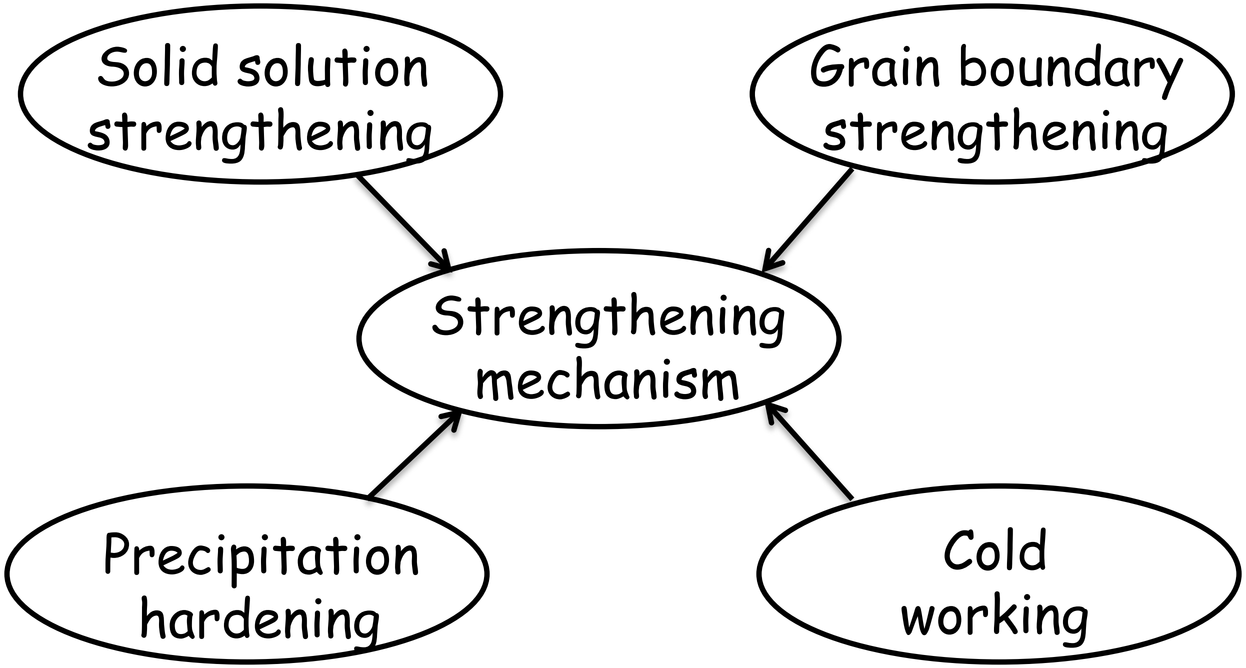
- Abbaschian, Reed-Hill. *“Physical Metallurgy Principles”*. 4th edition. 2009
- Beer & Johnston (2006). Mechanics of Materials (5th edition). McGraw Hill.

Strengthening Mechanisms

The ability of a metal/ alloy to plastically deform depends on the ability of dislocations to move.

→

Strengthening techniques rely on restricting dislocation motion to render a harder and stronger material.



Solid solution strengthening

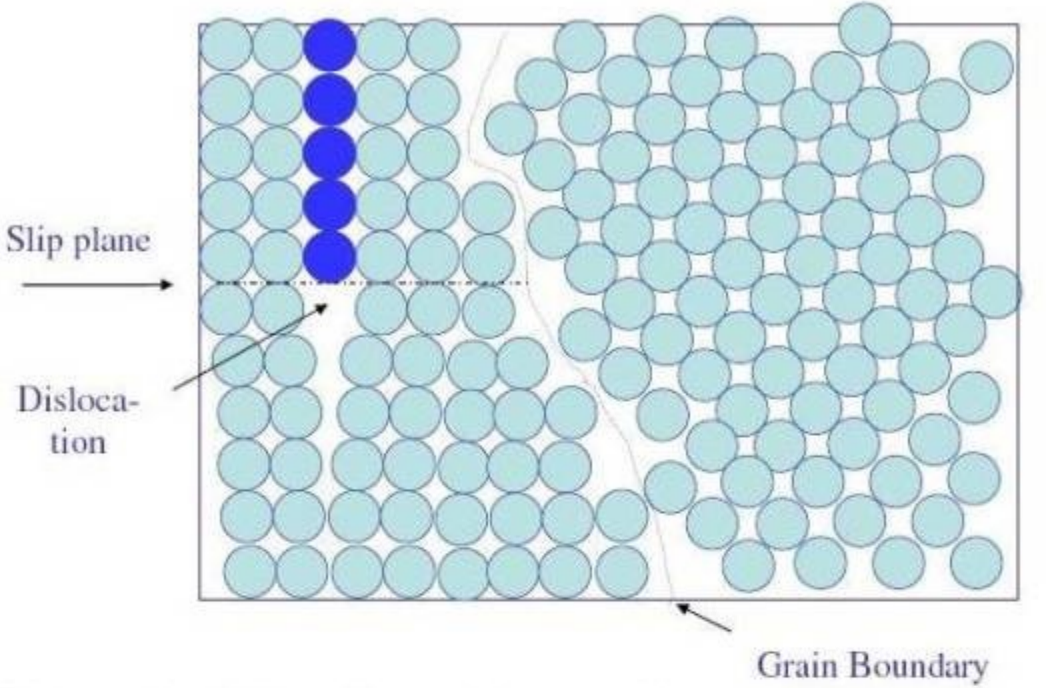
Grain boundary strengthening

Strengthening mechanism

Precipitation hardening

Cold working

Grain Boundary Strengthening



Motion of a dislocation as it encounters a grain boundary

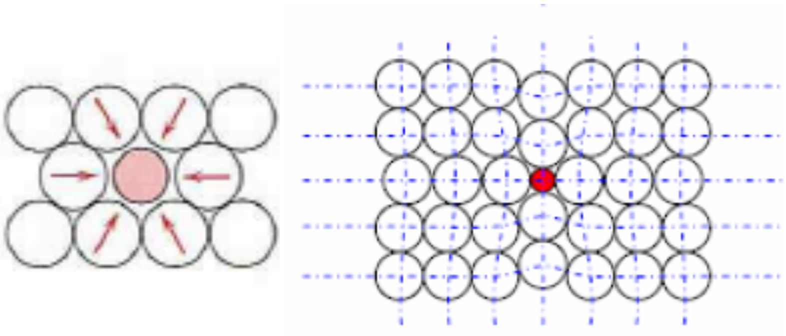
Smaller grain size:
more barriers to slip,
higher strength.

Hall-Petch Equation:

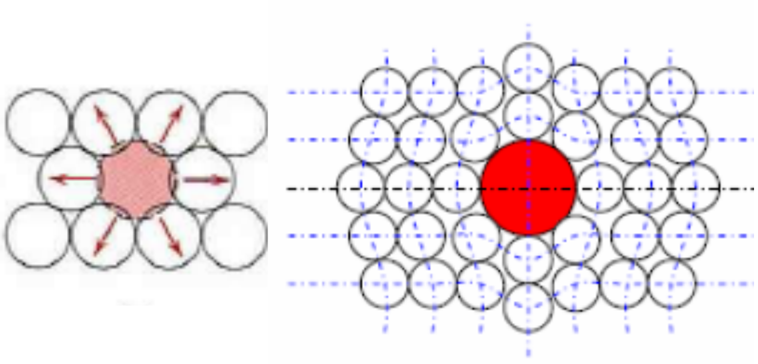
$$\sigma_y = \sigma_i + \frac{k}{\sqrt{D}}$$

Solid Solution Strengthening

- The presence of solute atoms produces lattice strain, either tensile or compressive, depending on the relative size of the solute atom.
- Solute atom generates local shear that opposes dislocation motion.



Smaller substitutional atom creates tensile lattice strain to the host atom.



Bigger substitutional atom creates compressive lattice strain to the host atom.

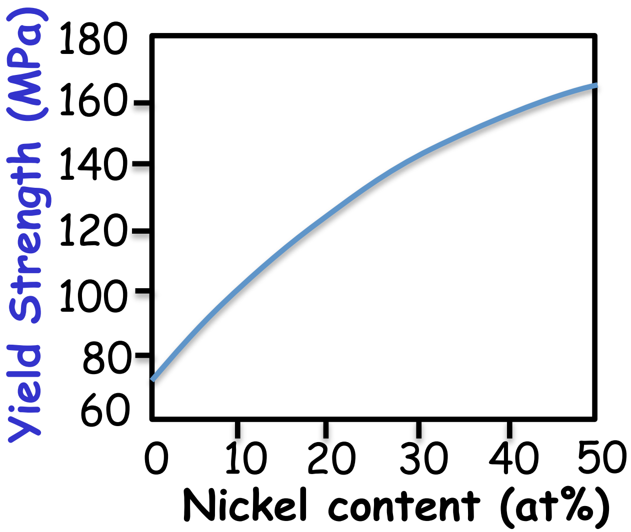
Solid Solution Strengthening

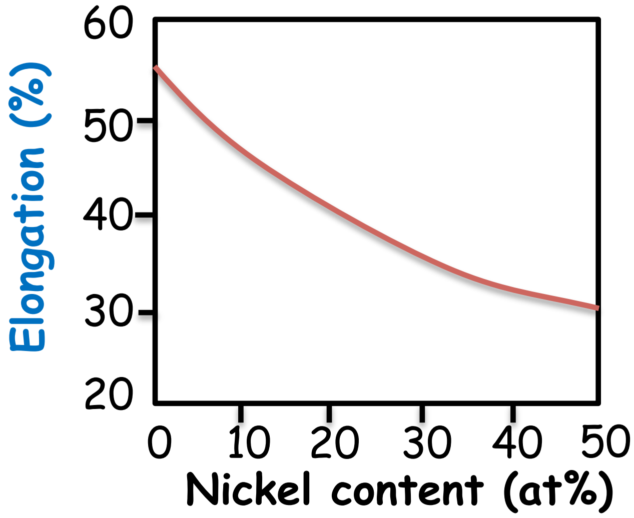
Impurity atom content increase:

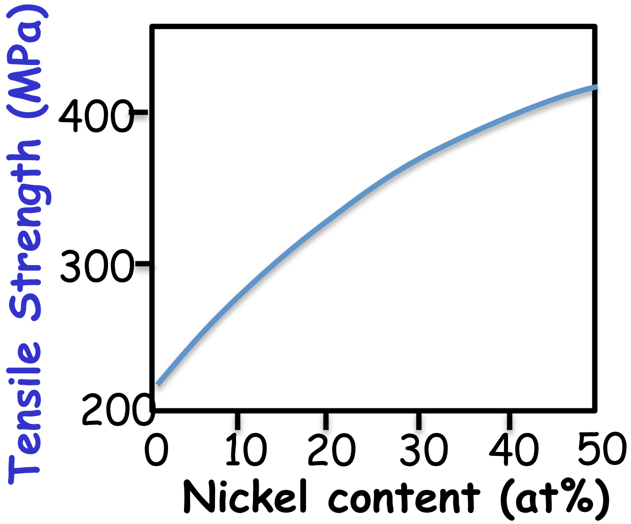
Tensile and yield strength ⬆

Ductility ⬇

Example: Cu-Ni Alloy





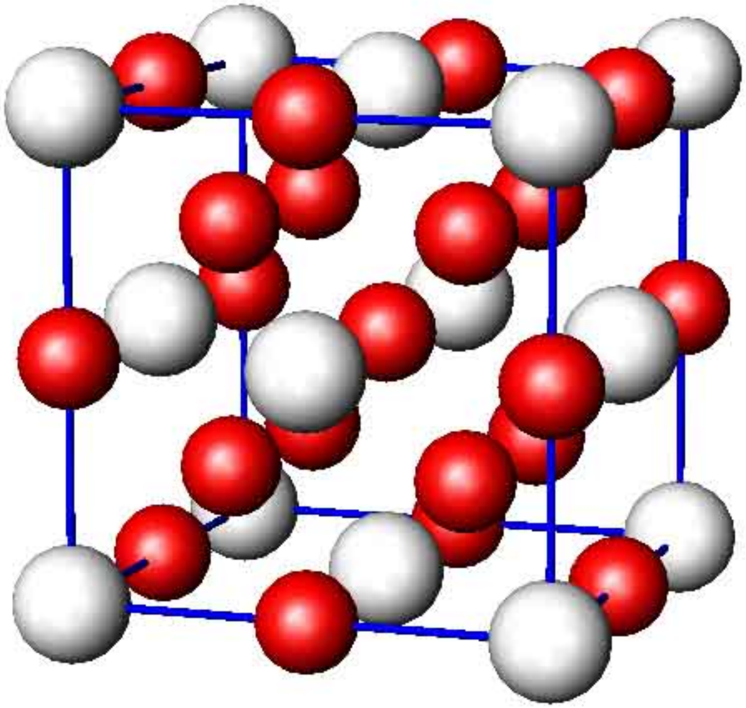


Solid Solution Strengthening

In ordered condition:

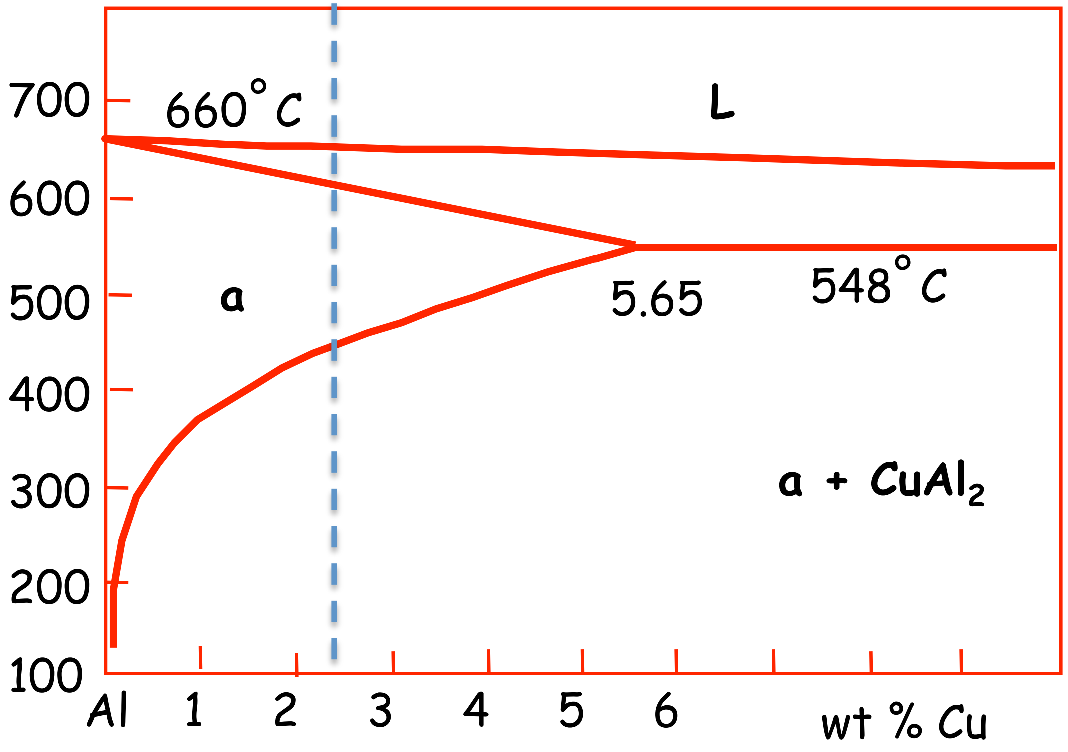
burgers vector is large

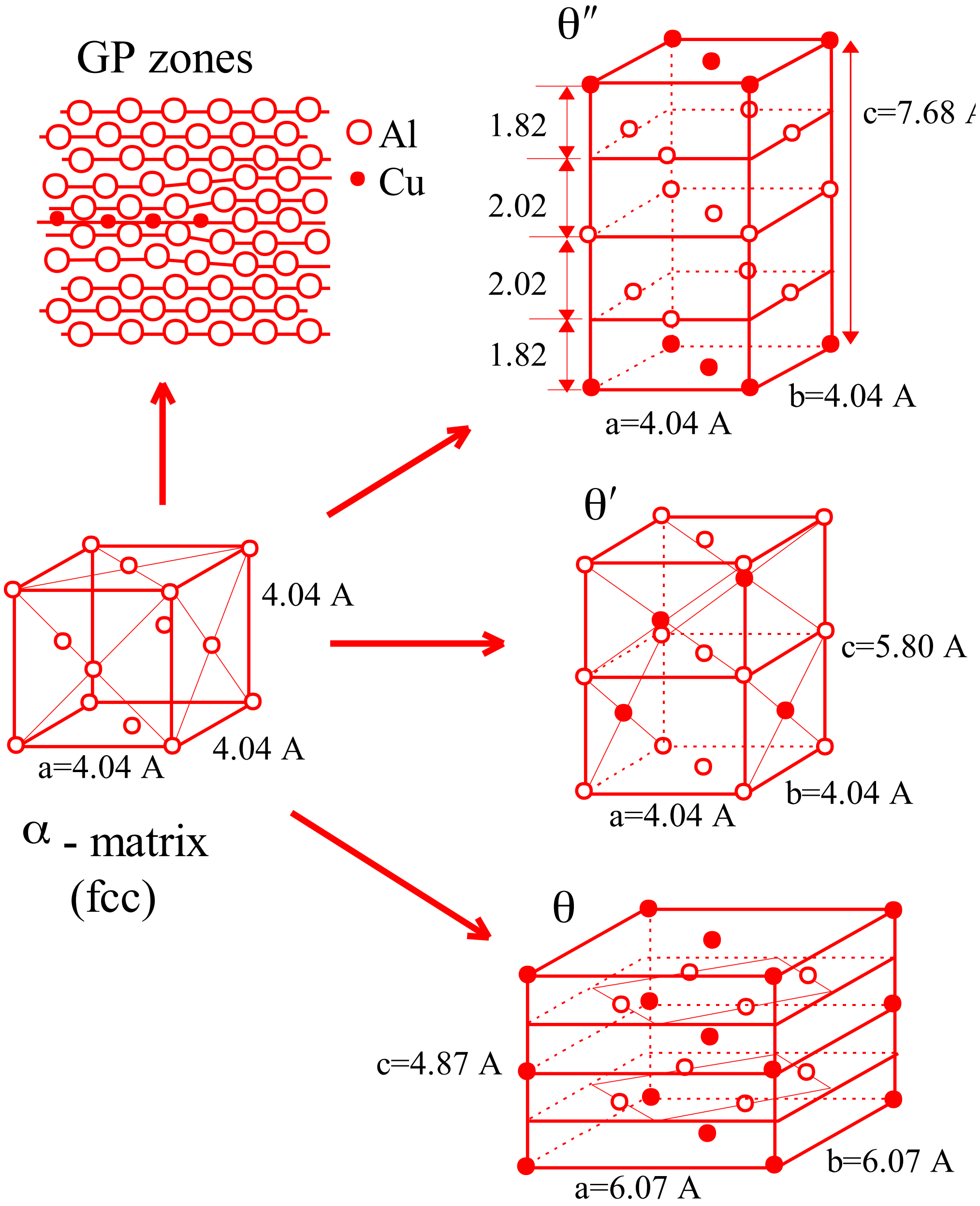
➔strain hardening rate is higher

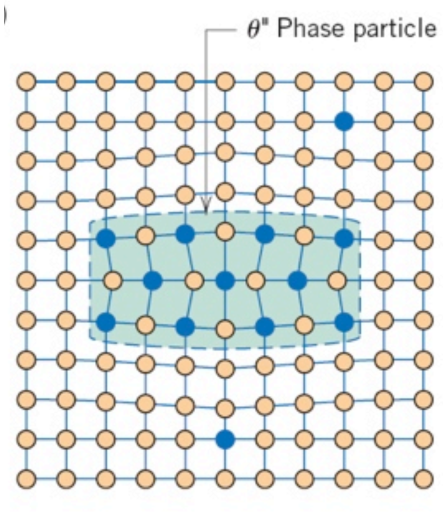


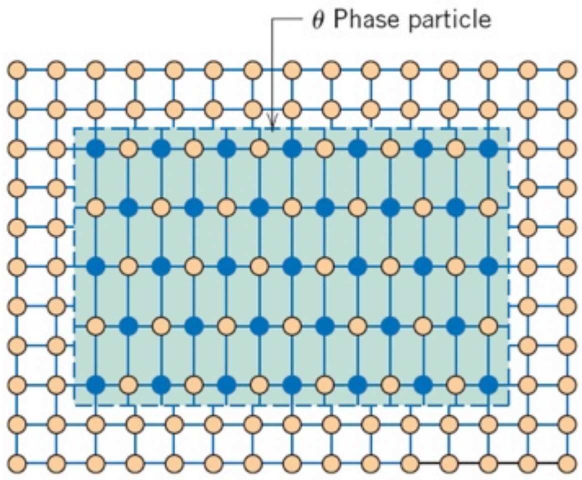
Precipitation Hardening

Precipitation hardening or age hardening requires the second phase, which is soluble at high temperature, has a limited solubility at lower temperatures.



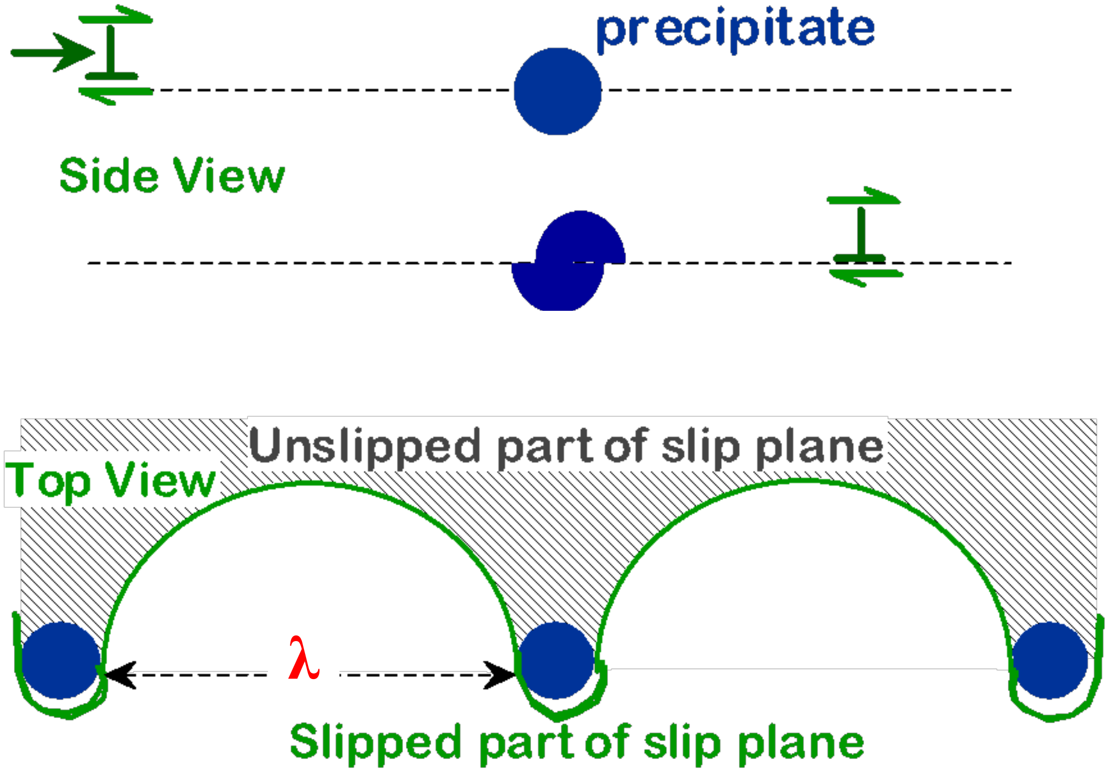

GP zones
Al
Cu
θ″
1.82
2.02
2.02
1.82
c=7.68
b=4.04 A
a=4.04 A
θ′
c=5.80 A
b=4.04 A
a=4.04 A
4.04 A
4.04 A
a=4.04 A
α - matrix
(fcc)
θ
c=4.87 A
b=6.07 A
a=6.07 A


θ" Phase particle


θ Phase particle

Interaction of Dislocations with Precipitates

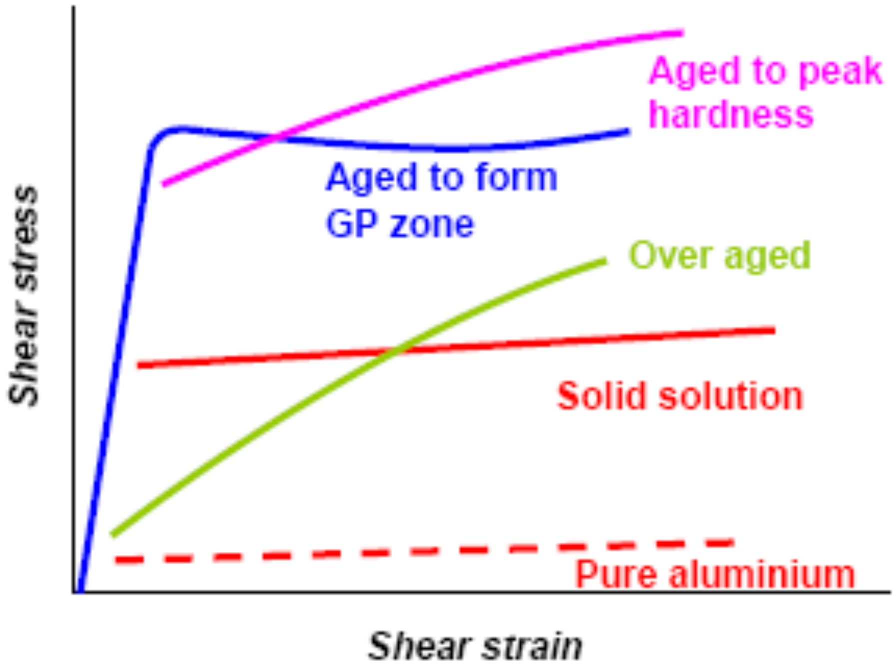
Second phase particles act in two distinct ways to retard the motion of dislocations.



Stress required to force dislocation between particles: $\tau = \dfrac{Gb}{\lambda}$

Precipitation Hardening

- The yield stress increases when the crystal is aged to form coherent GP zone. Yield drop and low strain hardening suggest that dislocations cut through the zone once the stress reaches a high enough value.
- Strain hardening significantly increase when the crystal is aged to peak hardness. Dislocations are short and move around particles.



- Over-aged condition produces coarse incoherent particles, giving low yield stress, high strain hardening.

Precipitation vs. Dispersion Hardening

- In dispersion hardening, hard particles are mixed with matrix powder and processed by powder metallurgy techniques.

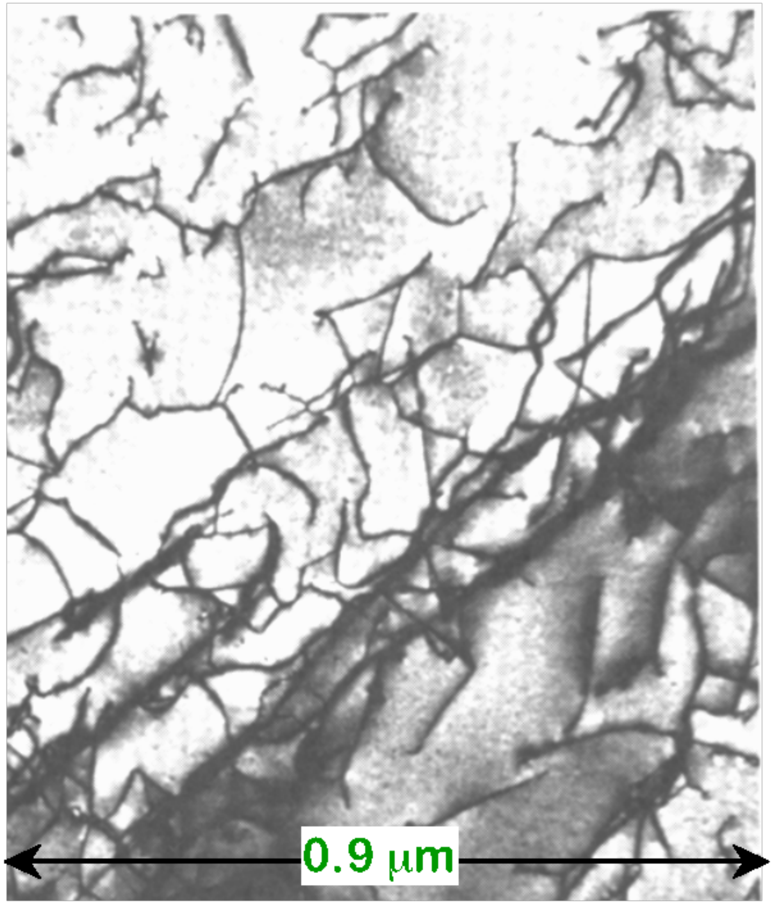
- In dispersion hardening, there is no coherency between second phase and matrix.

- In dispersion-hardening, the second phase has very little solubility in the matrix, even at elevated temperatures.

- Dispersion hardening systems have more temperature stability.

Cold Working

- Cold-work structure occurs when plastic deformation is applied in a temperature region such that the strain hardening is not relieved (0.3 - 0.5 T_m).



- ➢ Cold worked structure contains dislocation ~10^8-10^{10} mm^{-2}, while annealed structure possesses ~10^3-10^4 mm^{-2}.
- ➢ Dislocations entangle with one another during cold work. Hence dislocation motion becomes more difficult.

As T ↓, strain rate ↑
stored energy ↑

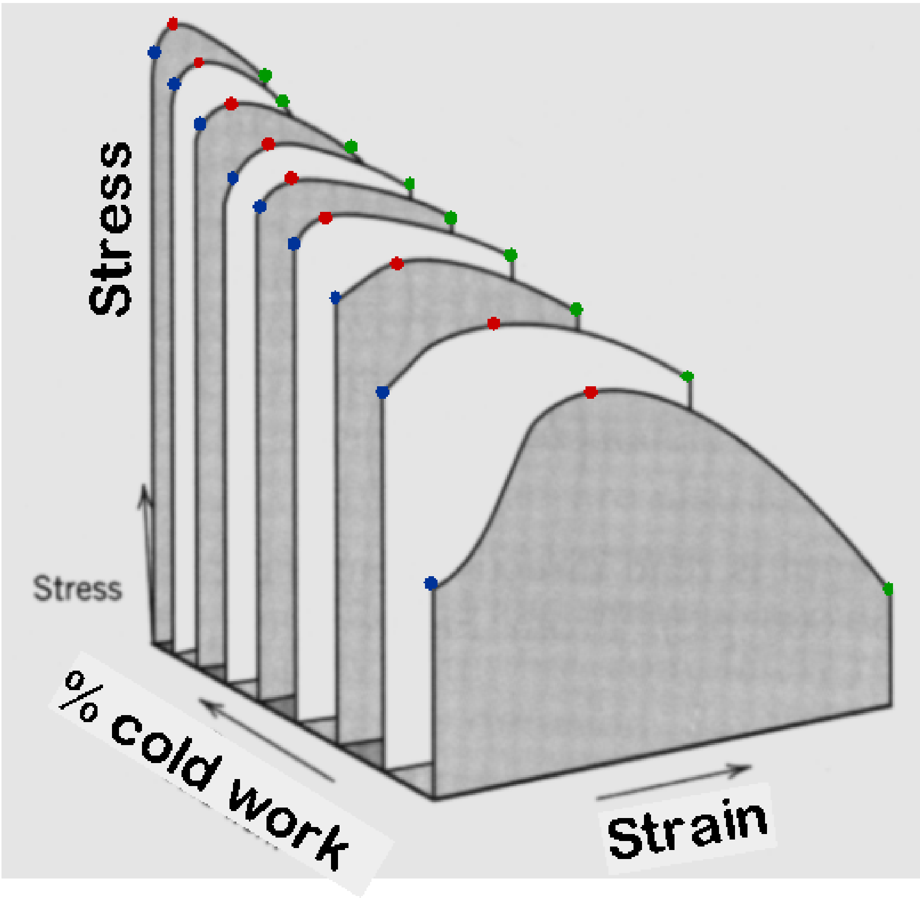
Strain Hardening

- Strain hardening or cold working is esp. used to harden alloys that do not respond to heat treatment.
- The rate of strain hardening is lower in HCP than in cubic metals.

Cold work ⇧

Strength ⇧

Ductility ⇩



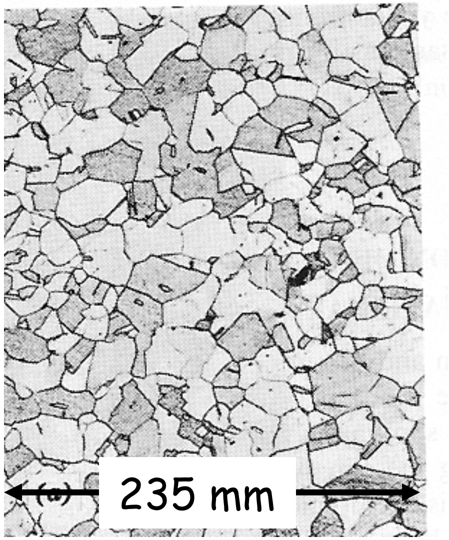
Texture Formation

- Severe deformation produces a reorientation of the grains into a preferred orientation. Certain crystallographic planes tend to orient themselves in a preferred manner with respect to the maximum strain direction.
- The preferred orientation resulting from plastic deformation is strongly dependent on the available slip and twining systems, but not affected by processing variable such as die angle, roll diameter, roll speed, etc.

Anisotropy in σ_{yield}

Can be induced by rolling a polycrystalline metal

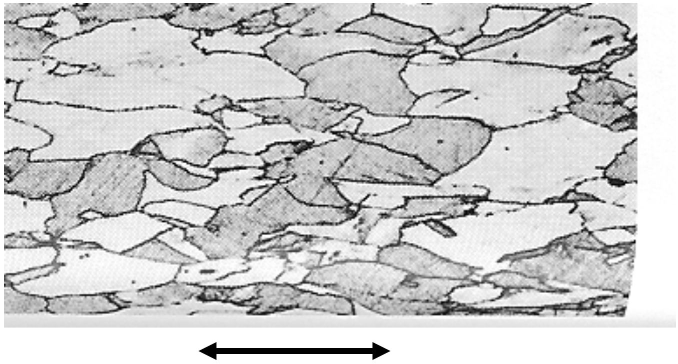
-before rolling



isotropic

since grains are approx. spherical & randomly oriented.

-after rolling



rolling direction

anisotropic

since rolling affects grain orientation and shape.

Importance of Anisotropy

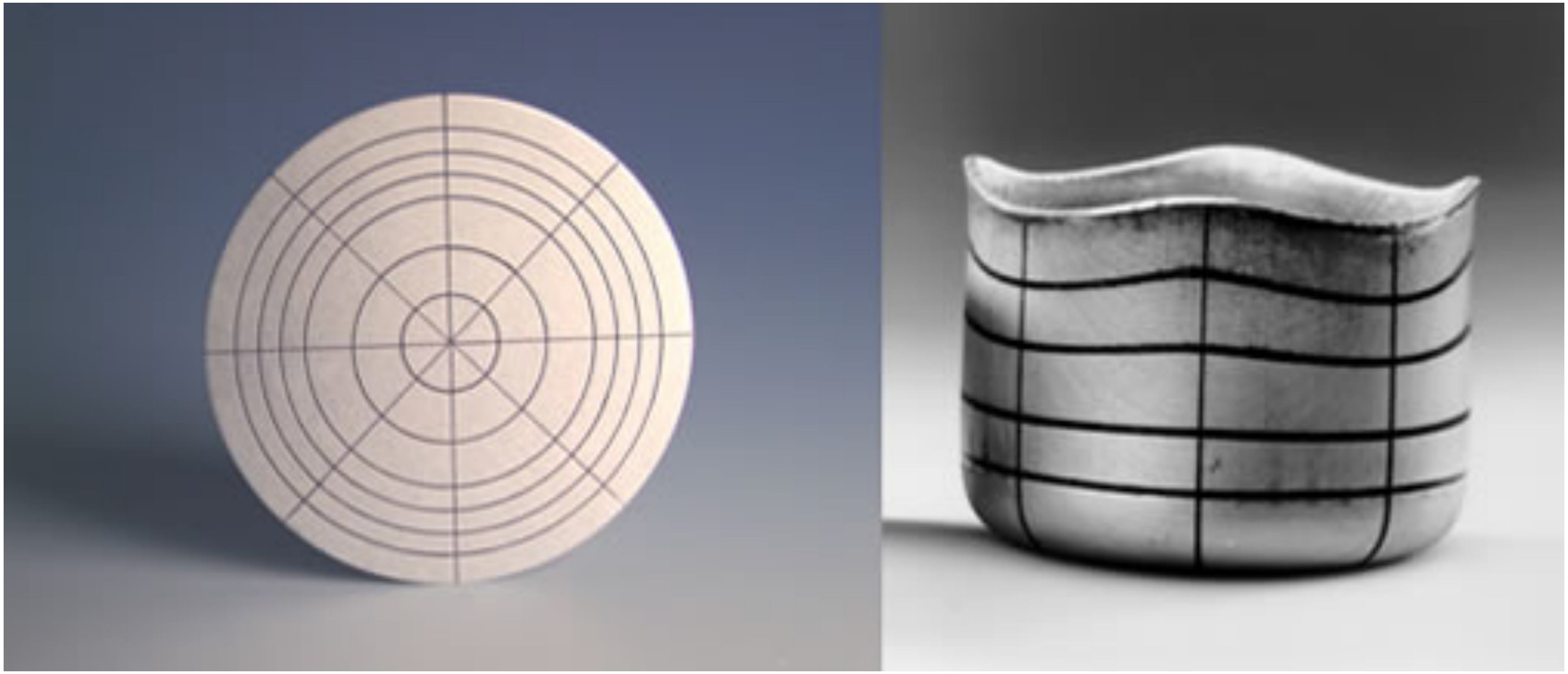
- Normal Anisotropy, R:

$$R = \frac{\varepsilon_w}{\varepsilon_t}$$

- Planar Anisotropy, ΔR:

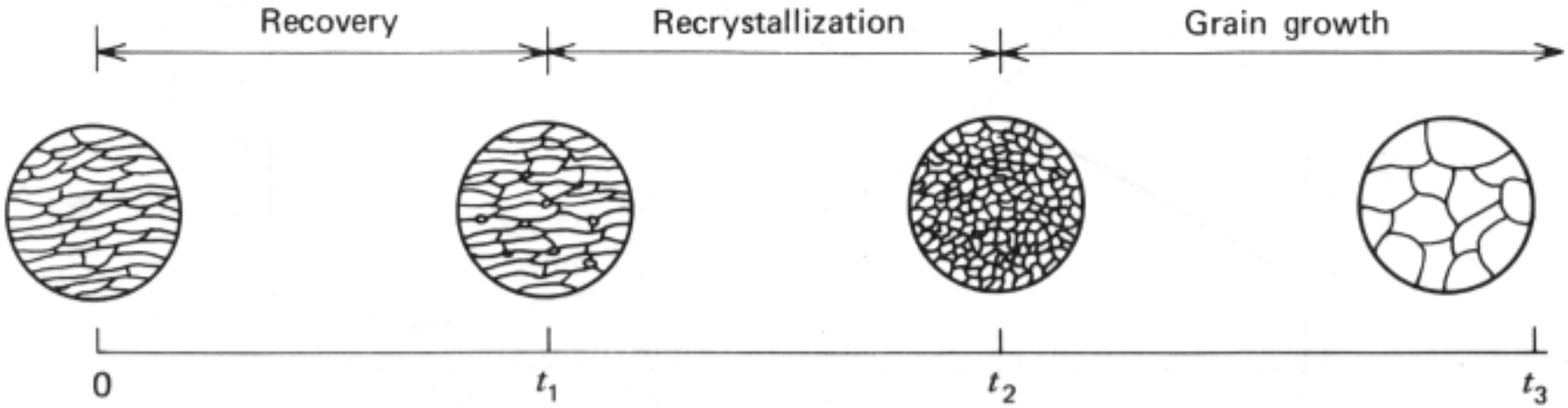
$$\Delta R = \frac{R_0 + R_{90} - 2R_{45}}{2}$$

Earing



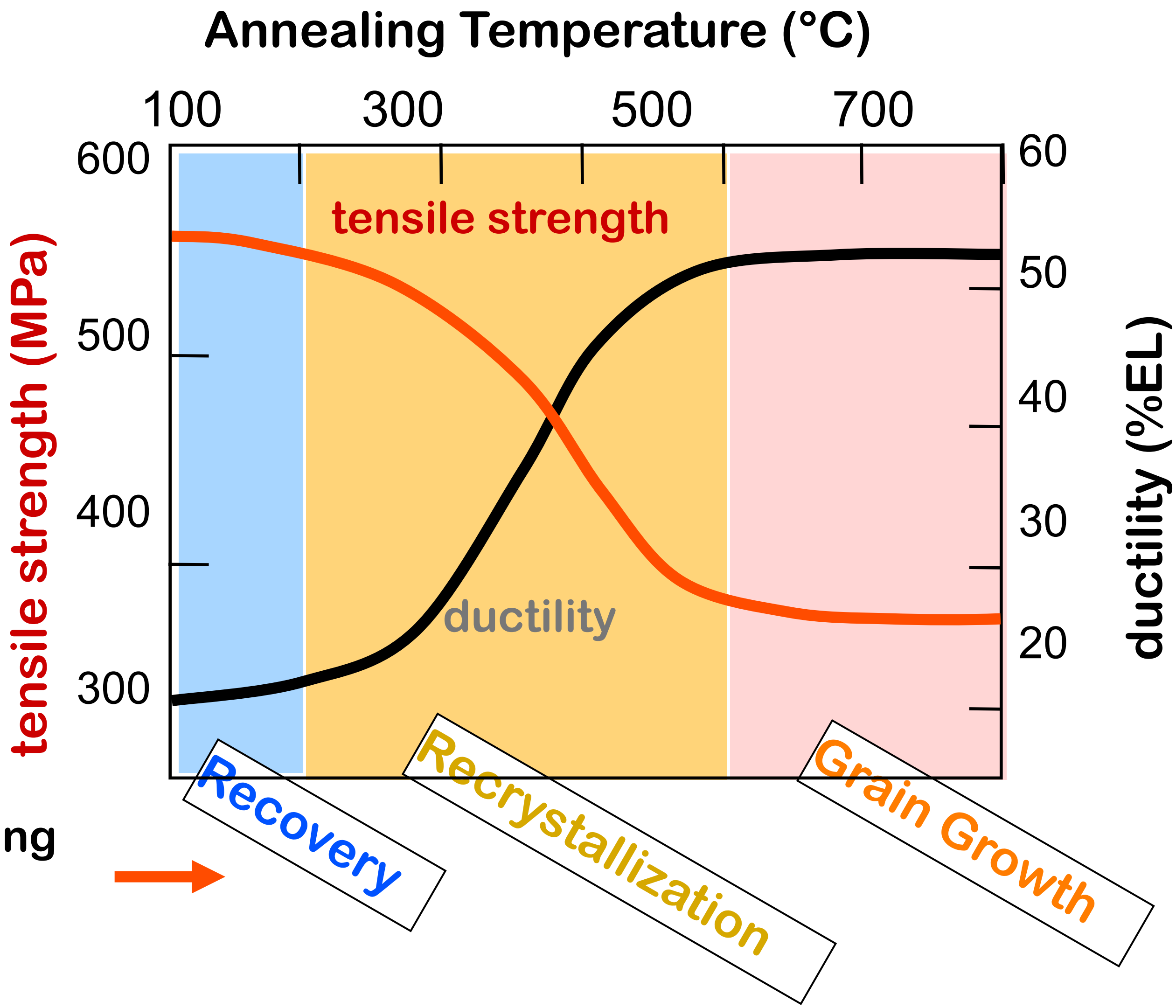
Annealing of Cold-Worked Metal

- Annealing of the cold worked structure at high temperature softens the metal and reverts to a strain-free condition.
- The transformations that take place during annealing are recovery, recrystallization and grain growth, respectively.
- The driving force for recovery and recrystallization is the energy of the defects introduced during cold working (stored energy of the deformed matrix).
- The driving force for grain growth is the boundary curvature.



Annealing of Cold-Worked Metal

3 Annealing stages



Effect of 1 hour heating on mechanical properties

Recovery

Recrystallization
nucleation and
growth of strain
free grains

Grain growth

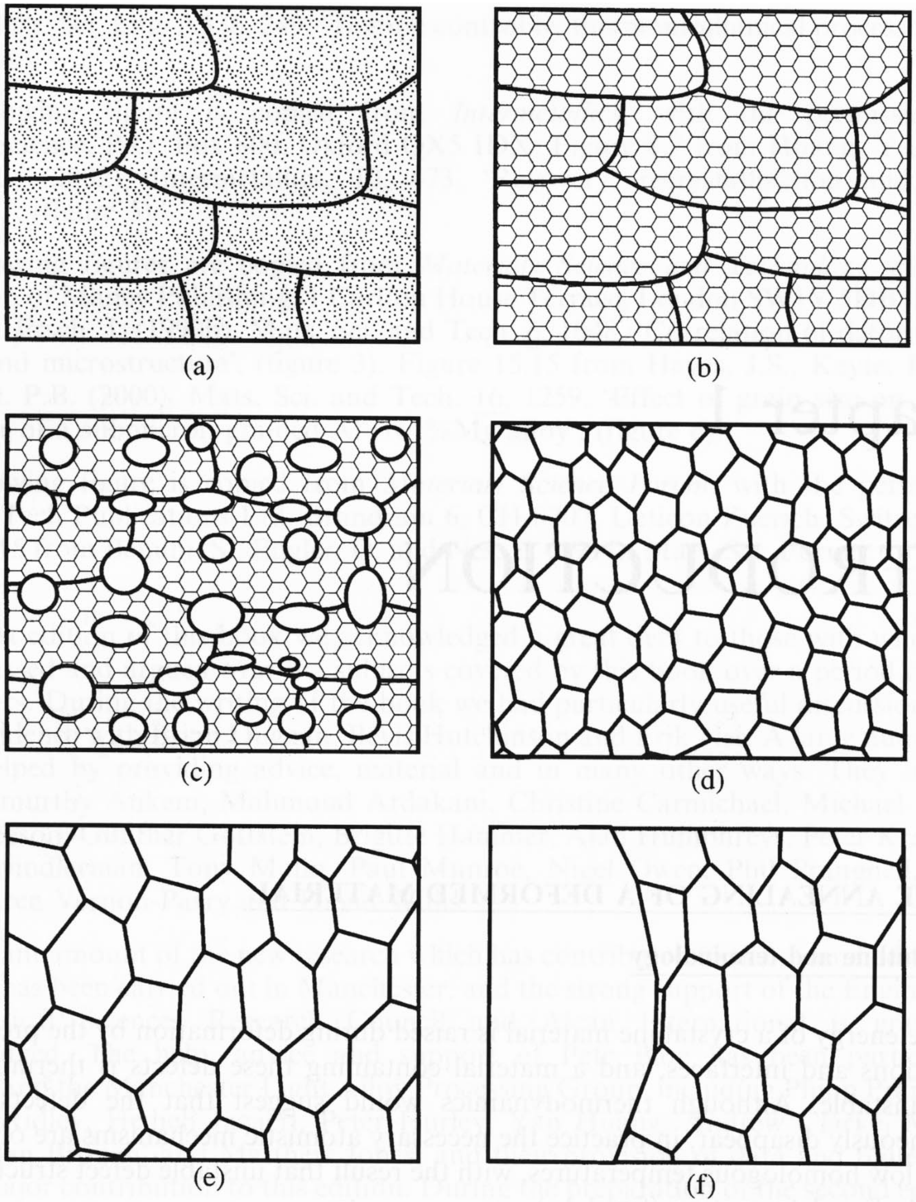
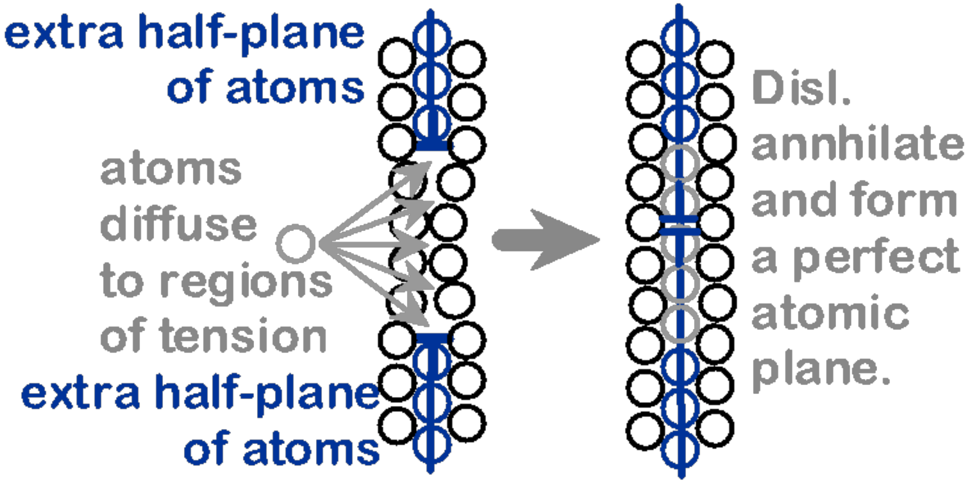


Fig. 1.1. Schematic diagram of the main annealing processes; (a) Deformed state, (b) Recovered, (c) Partially recrystallized, (d) Fully recrystallized, (e) Grain growth and (f) Abnormal grain growth.

Recovery

Annihilation reduces dislocation density.

Scenario 1



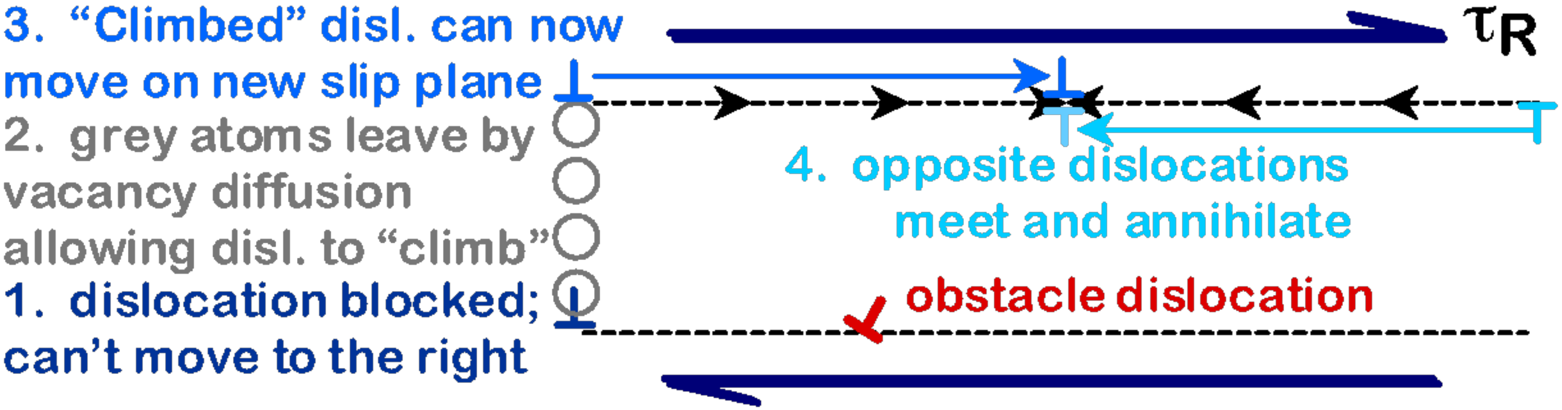
extra half-plane of atoms

atoms diffuse to regions of tension

extra half-plane of atoms

Disl. annhilate and form a perfect atomic plane.

Scenario 2



3. "Climbed" disl. can now move on new slip plane

2. grey atoms leave by vacancy diffusion allowing disl. to "climb"

1. dislocation blocked; can't move to the right

τ_R

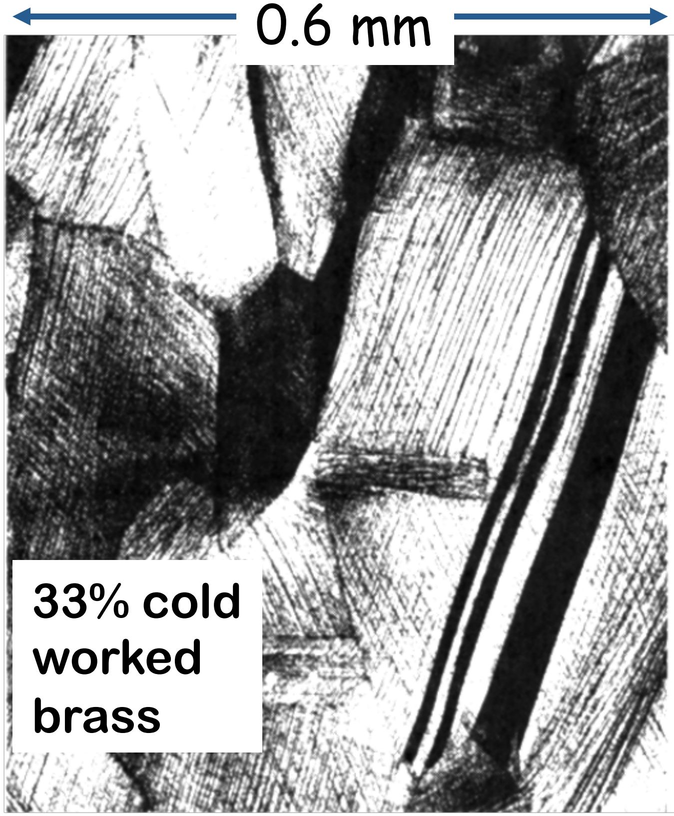
4. opposite dislocations meet and annihilate

obstacle dislocation

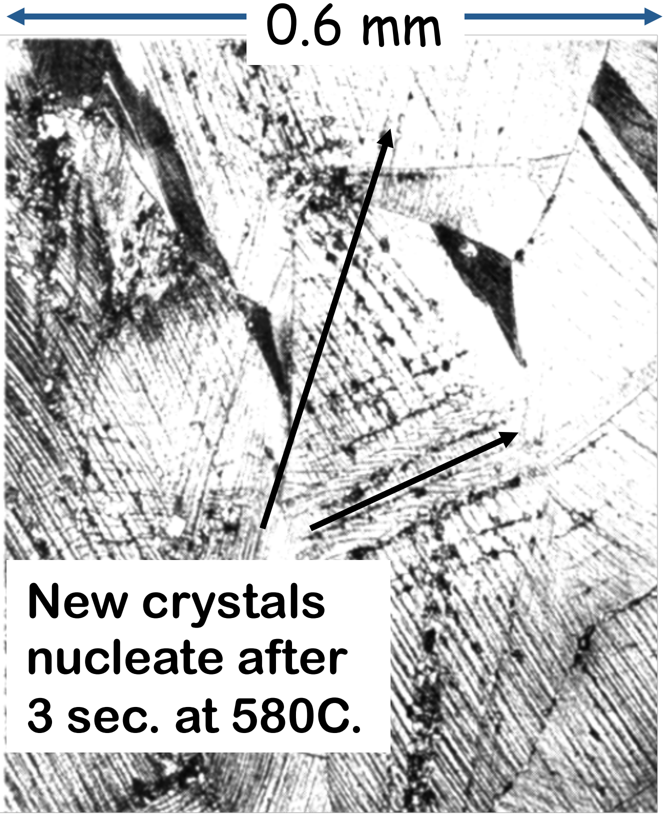
Recrystallization

New crystals are formed that:

- have a small dislocation density
- are small
- consume cold-worked crystals.



33% cold worked brass

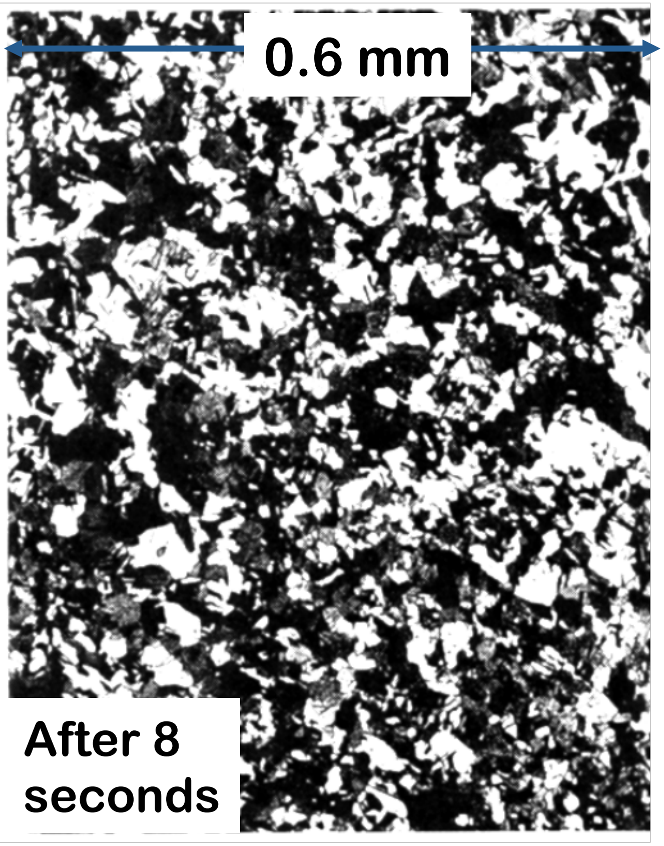


New crystals nucleate after 3 sec. at 580C.

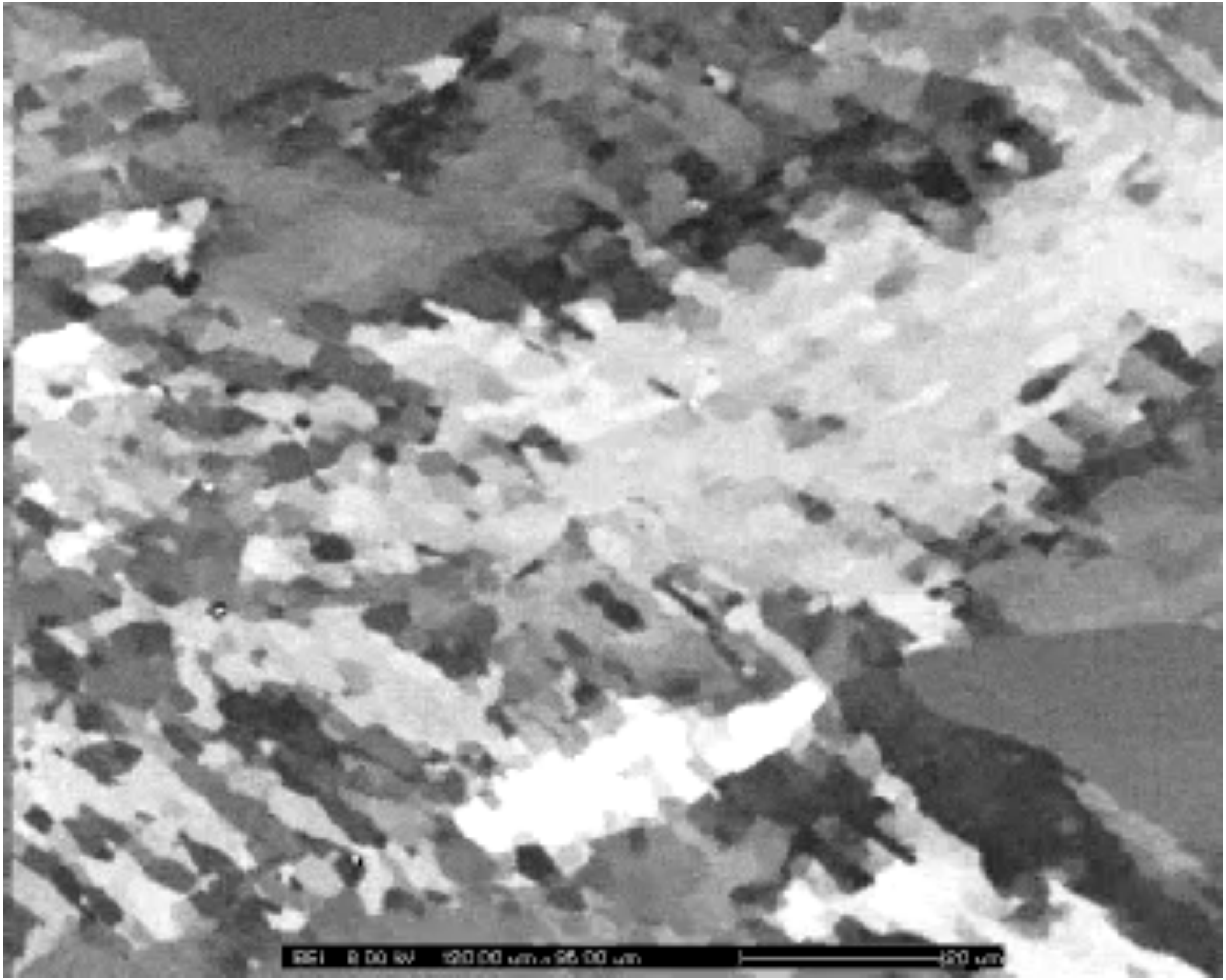
Further Recrystallization

All cold-worked crystals are consumed.

After 4 seconds



After 8 seconds


BSI 8.00 kV 120.00 um x 96.00 um
20 um

Variables Affecting Recrystallization

1) The amount of prior deformation
2) Temperature
3) Time
4) Initial grain size
5) Composition
6) Amount of recovery prior to start the recrystallisation.

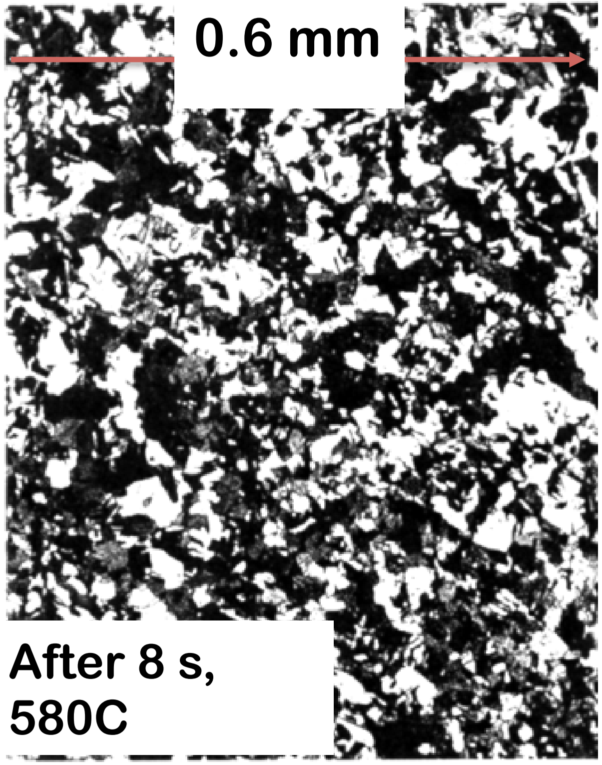
Recrystallization temperature can be defined as the temperature at which a given alloy in a highly cold-worked state completely recrystallizes in 1 h.

Degree of Deformation ⇧ T_{recrys} ⇩ T_{anneal} ⇩ GS_{recrys} ⇩

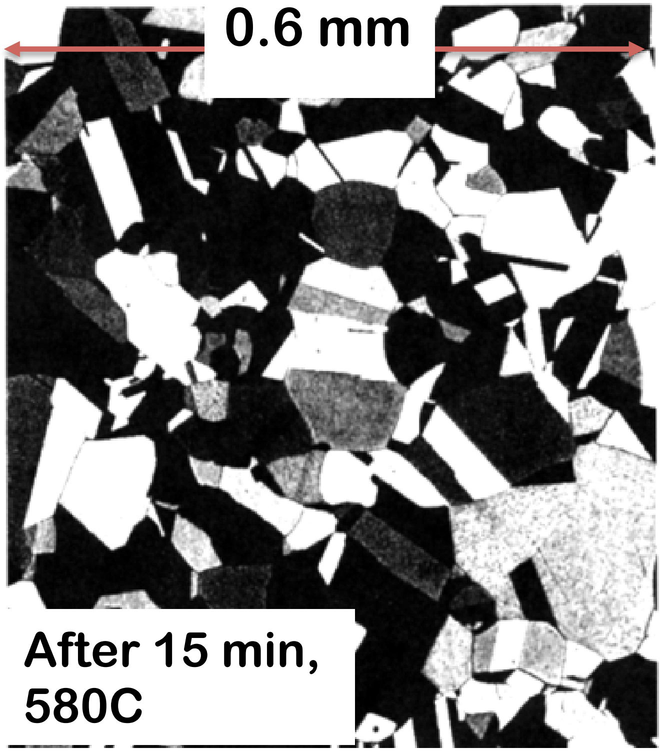
Impurity ⇧ T_{recrys} ⇧

Grain Growth

- At longer times, larger grains consume smaller ones.
- Grain boundary area (and therefore energy) is reduced.



After 8 s,
580C

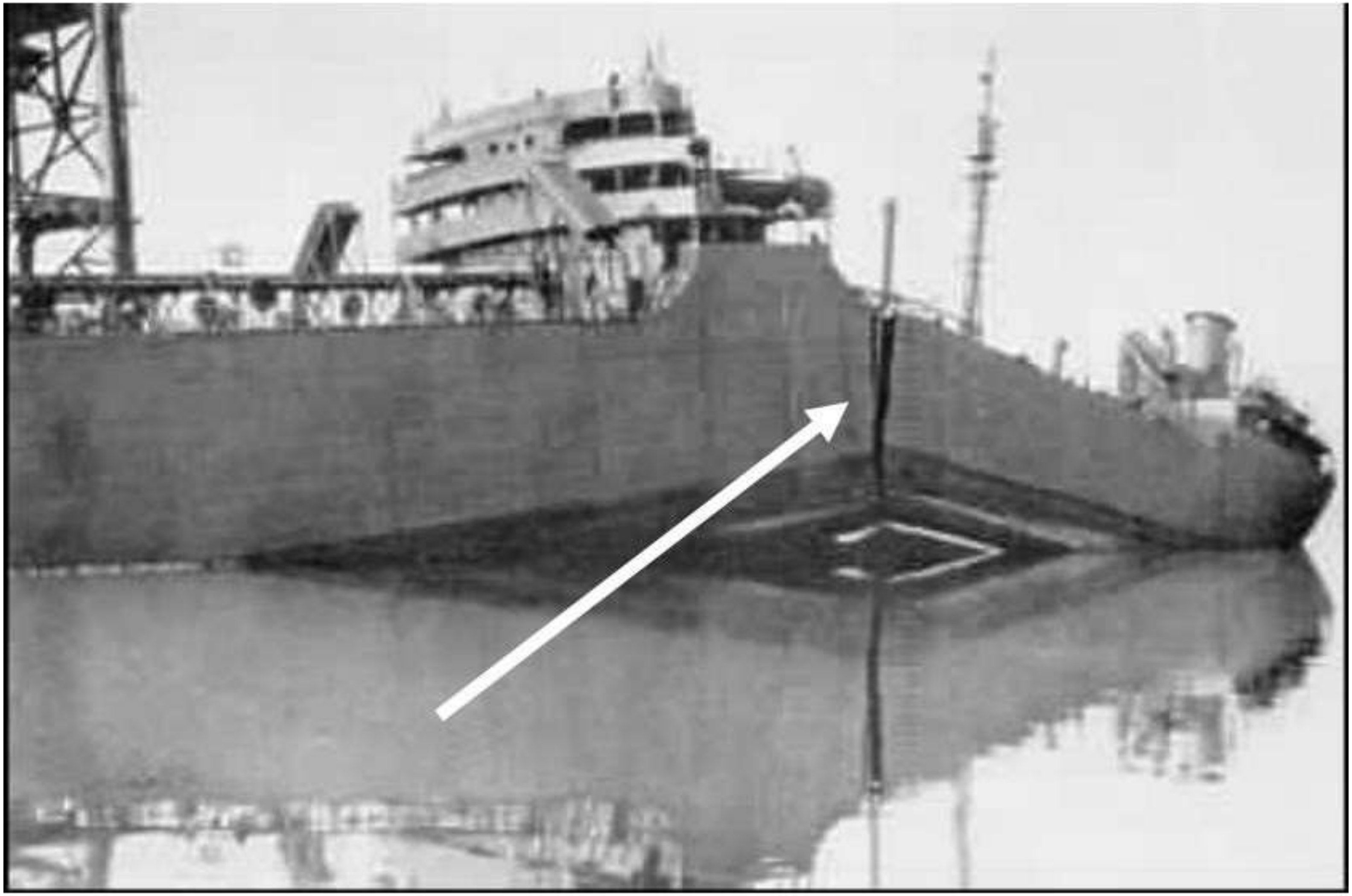


After 15 min,
580C

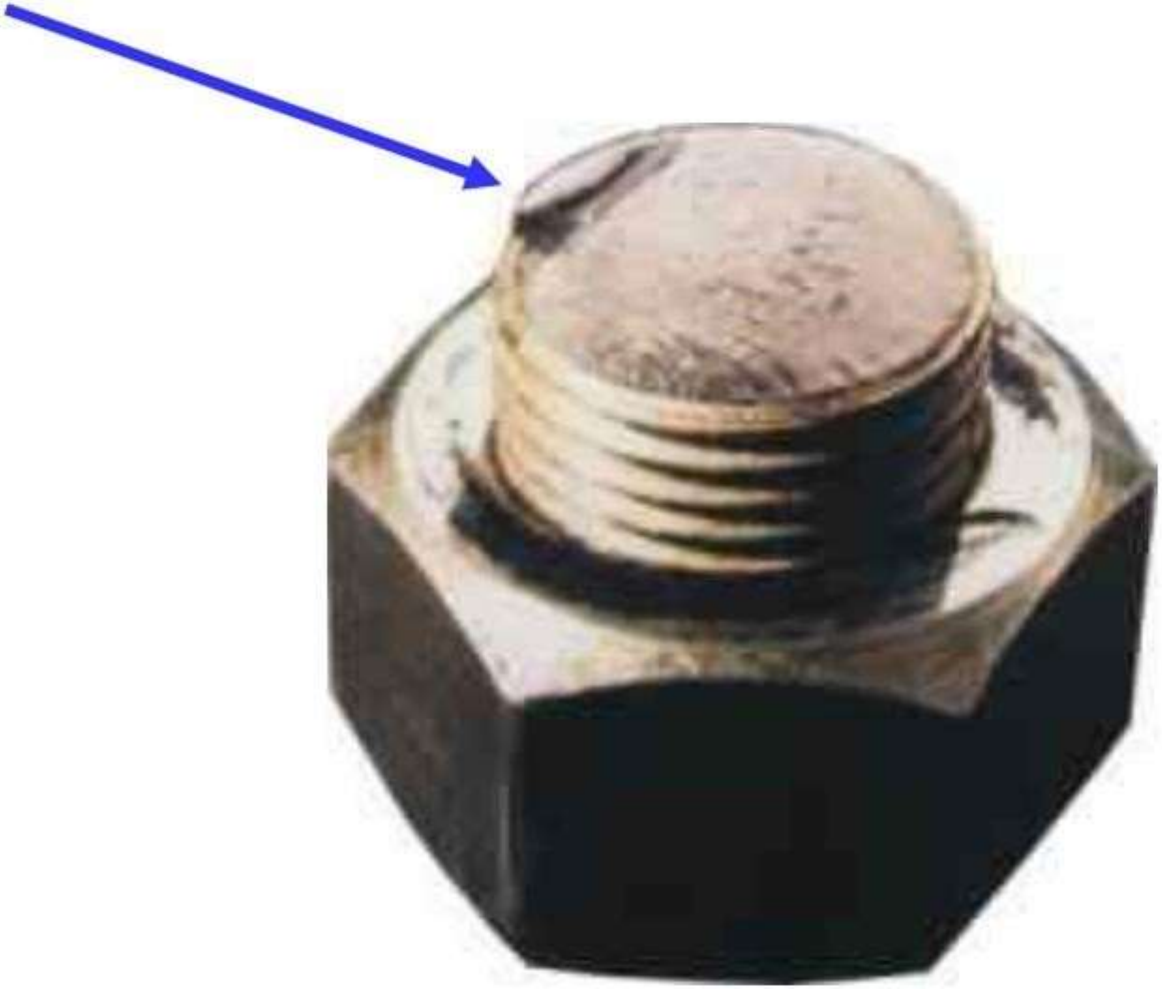
UNIT-4

FATIGUE BEHAVIOUR
AND
TESTING

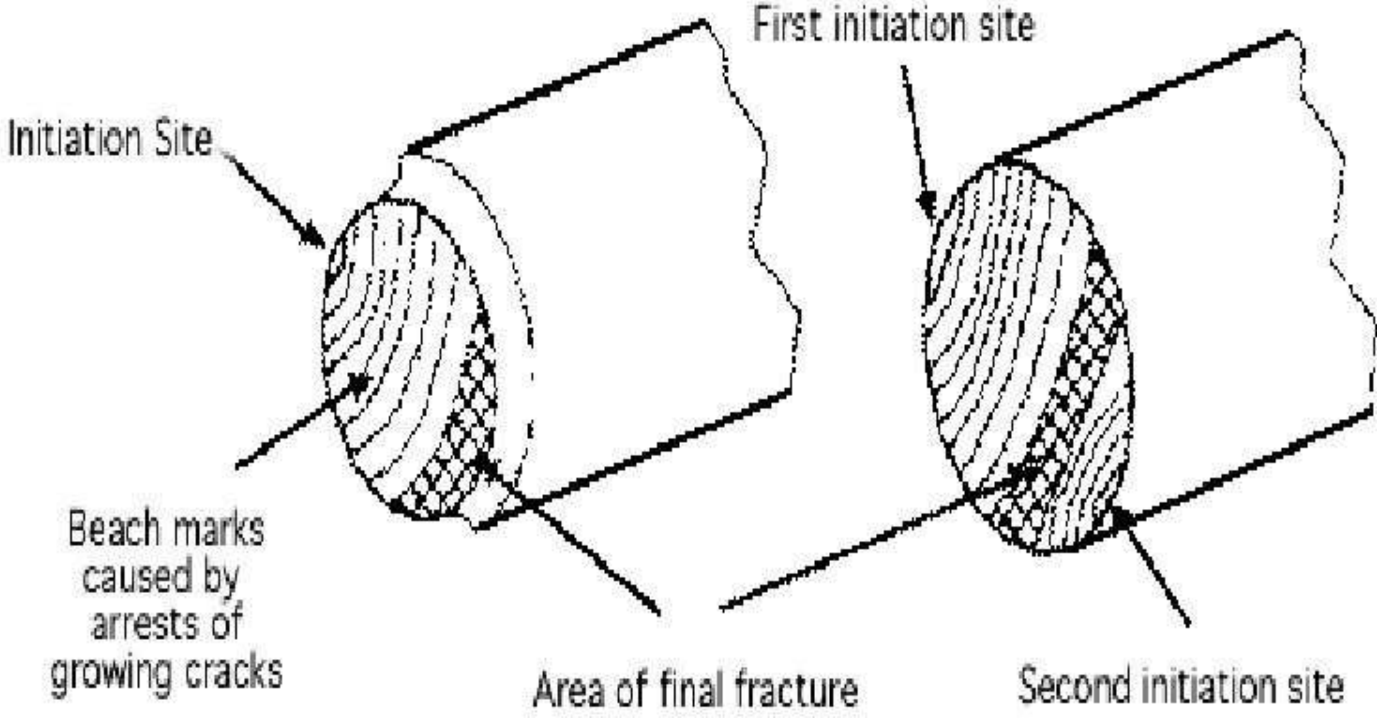
Ship Break



BOLT FAILURE

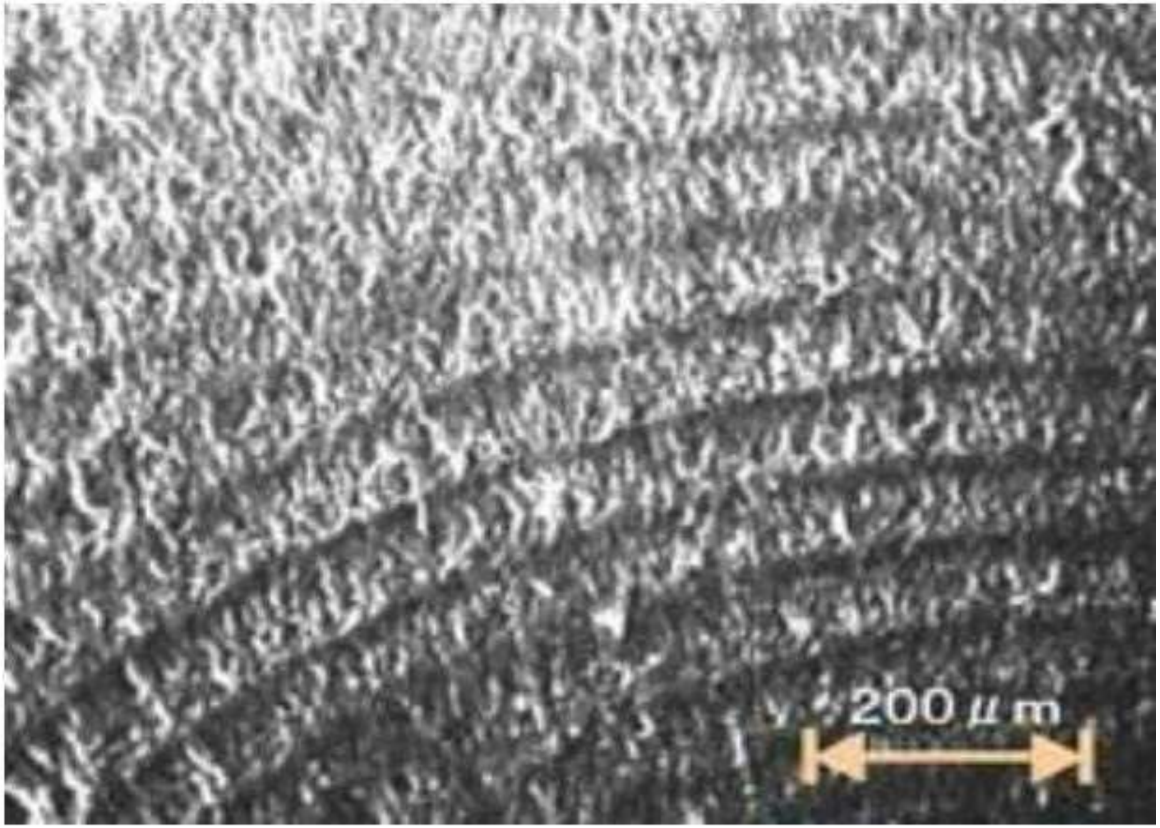


BEACH MARKS


First initiation site
Initiation Site
Beach marks caused by arrests of growing cracks
Area of final fracture
Second initiation site

Beach Marks of FATIGUE

-



Examples of Bolt Failures
M24 Engine Mounting Bolt Failure

Failure due to repeatedly applied load is known *as Fatigue.*

- The physical effect of a repeated load on a material is different from the static load.
- Failure always being brittle fracture regardless of whether the material is brittle or ductile.
- Mostly fatigue failure occur at stress well below the static elastic strength of the material.

- Fatigue
- It has long been known that a component subjected to fluctuating stresses may fail at stress levels much lower than its monotonic fracture strength, due to a process called *Fatigue*.
- Fatigue is an insidious time-dependent type of failure which can occur without any obvious warning.

It is believed that more than 95 % of all mechanical failures can be attributed to fatigue.

There are normally three distinct stages in the fatigue failure of a component,

namely: *Crack Initiation,*

Incremental Crack Growth,

and the *Final Fracture.*

Fatigue

- Introduction :
- In several applications, components have to withstand different kinds of load at different times .

- Materials subjected to these fluctuating or repeated load tends to show a behavior which is different from what they show under steady loads.

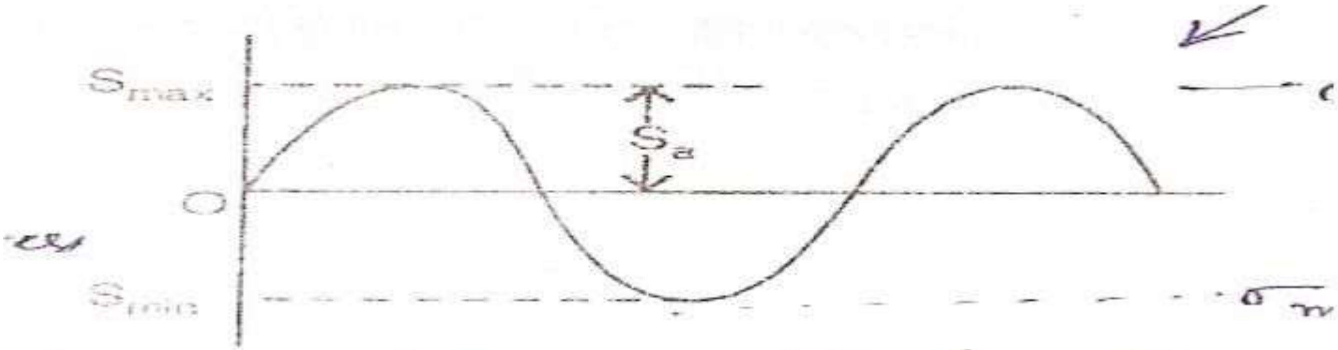
- Fatigue occurs at stress well within the ordinary elastic range as measured in the static tension test.

- Fracture resulting from fatigue is very difficult to predict and hence a good understanding of fatgue behavior is very important.

- **Types of fatigue loading:**

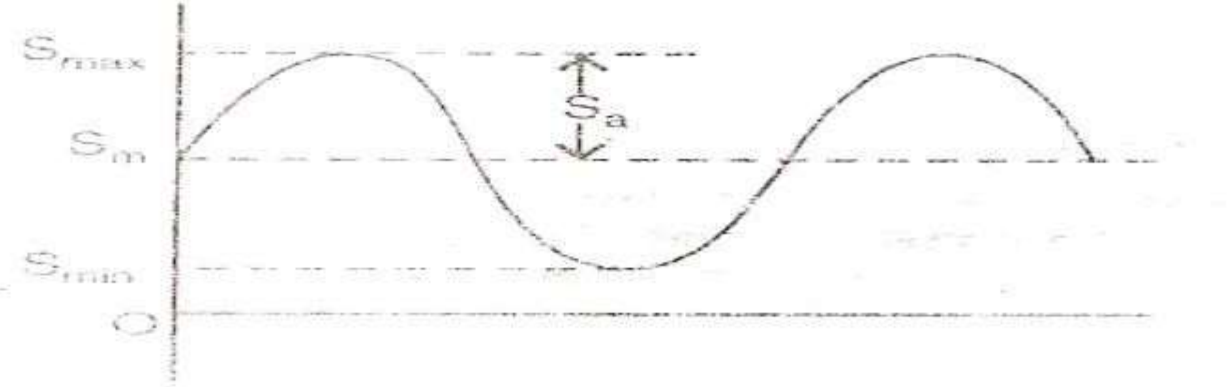
- **1.Completely reversed cycle of stress:**
- **2. repeated stress cycles**

- **3. irregular or random stress cycle:**



Here stress amplitude = σ_{max}

Fig. 7.1 Simple fatigue



- Completely reversed cycle of stress:
- Illustrates the type of fatigue loading where a member is subjected to opposite loads alternately with a means of zero.
- For example bending of steel wire continuously in either direction leads to alternate tensile and compressive stresses on its surface layers and failure fatigue.

- **If the applied load changes from any magnitude in one direction to the same magnitude in the opposite direction, the loading is termed *completely reversed,***

- Repeated stress cycles:
- Type of fatigue loading where a member is subjected to only tension but to various degrees.

- A spring subjected to repeated tension as in a toy would lead to fatigue failure.

- **Irregular or random stress cycle:**
- **This type of fatigue loading where a member could be subjected to irregular loads just as in**
- **the case of an aircraft wing subjected to wind loads.**

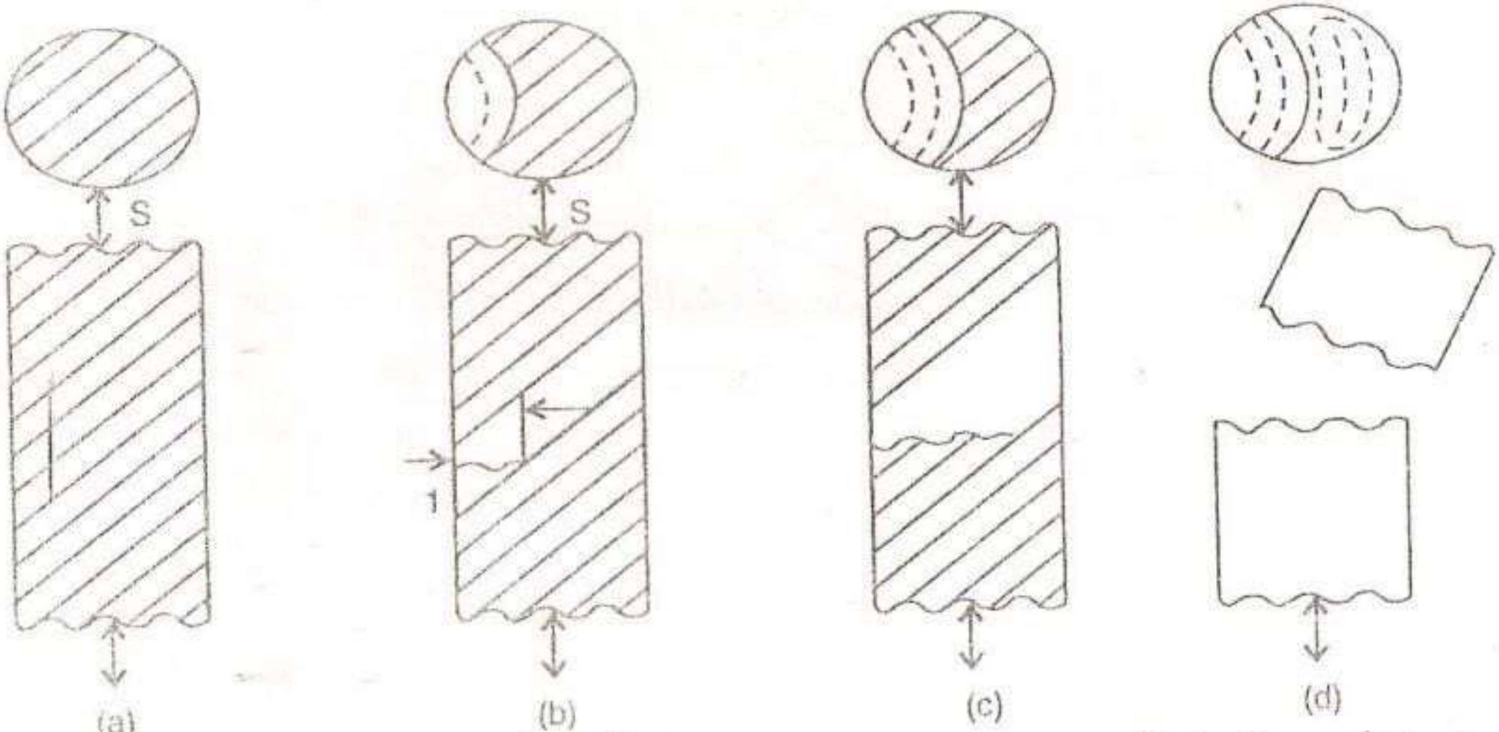
- **i.e if the load changes from one magnitude to another (the direction does not necessarily change), the load is said to be *fluctuating load.***

- **Stages** of fatigue failure
- consider a ductile material which is subjected to simple alternating tensile and compressive stresses.
- Failure by fatigue is found to take place in three stages:
- i) **Crack nucleation**
- **ii) Crack growth**
- **iii) Fracture**

ation

1
ned

cells



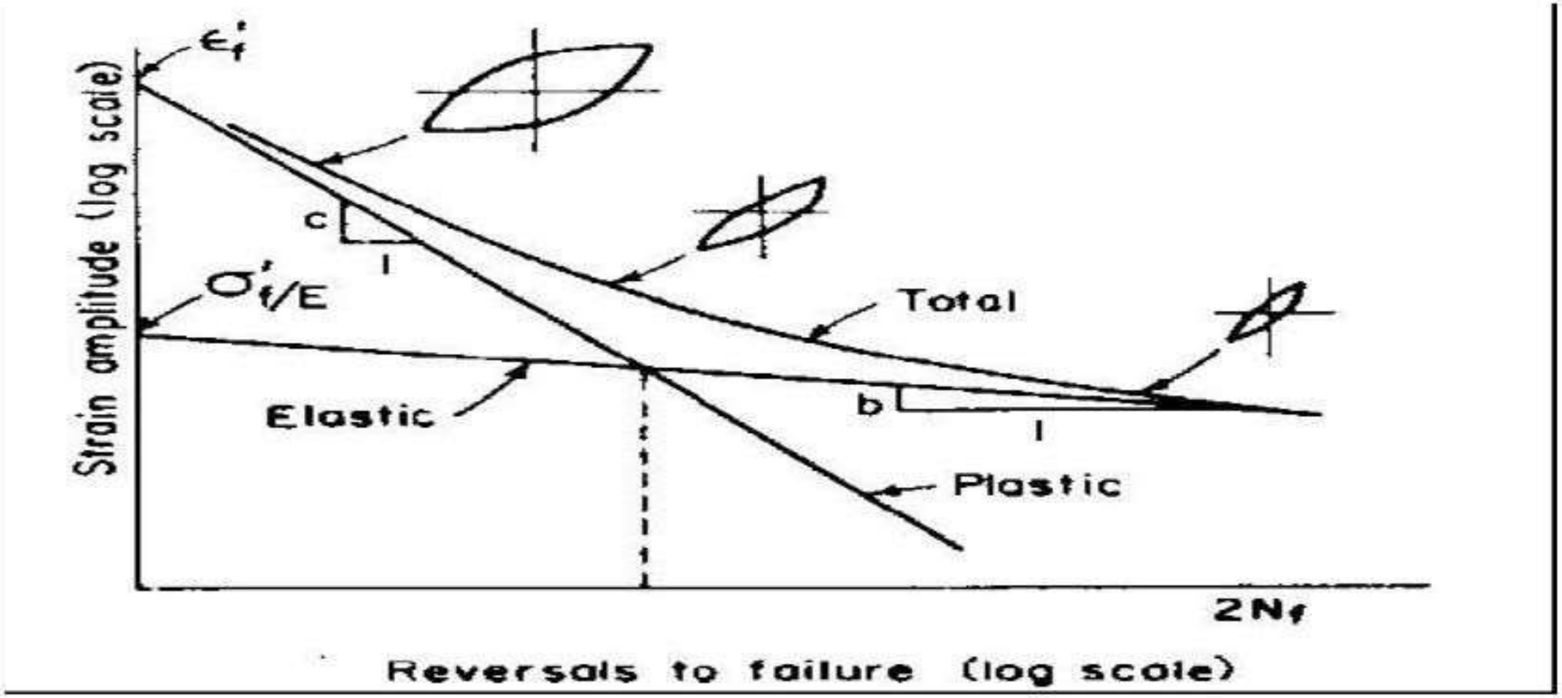
[illegible]

- **Crack nucleation:**

During the first few cycles of loading, localized changes take place in the structure at various places within the material.

These changes lead to the formation of submicroscopic cracks.

- **Low Cycle Fatigue**
- **Based on the LCF *local strain philosophy*, fatigue cracks initiate as a result of repeated plastic strain cycling at the locations of maximum strain concentration.**



These cracks are usually formed at the surface of the specimen.

There are several theories like

orowans theory,

cottell & hull theory etc,

which explain the mechanism of crack nucleation.

- **Crack growth:**

- The submicroscopic cracks formed grow as the cycles of loading continue
- and become microscopic cracks.

- Fatigue Crack Propagation
- If a crack exists in the component *before* it goes into service, for example due to weld

  fabrication or from some other cause, the ‘initiation’ stage is by-passed and the fatigue

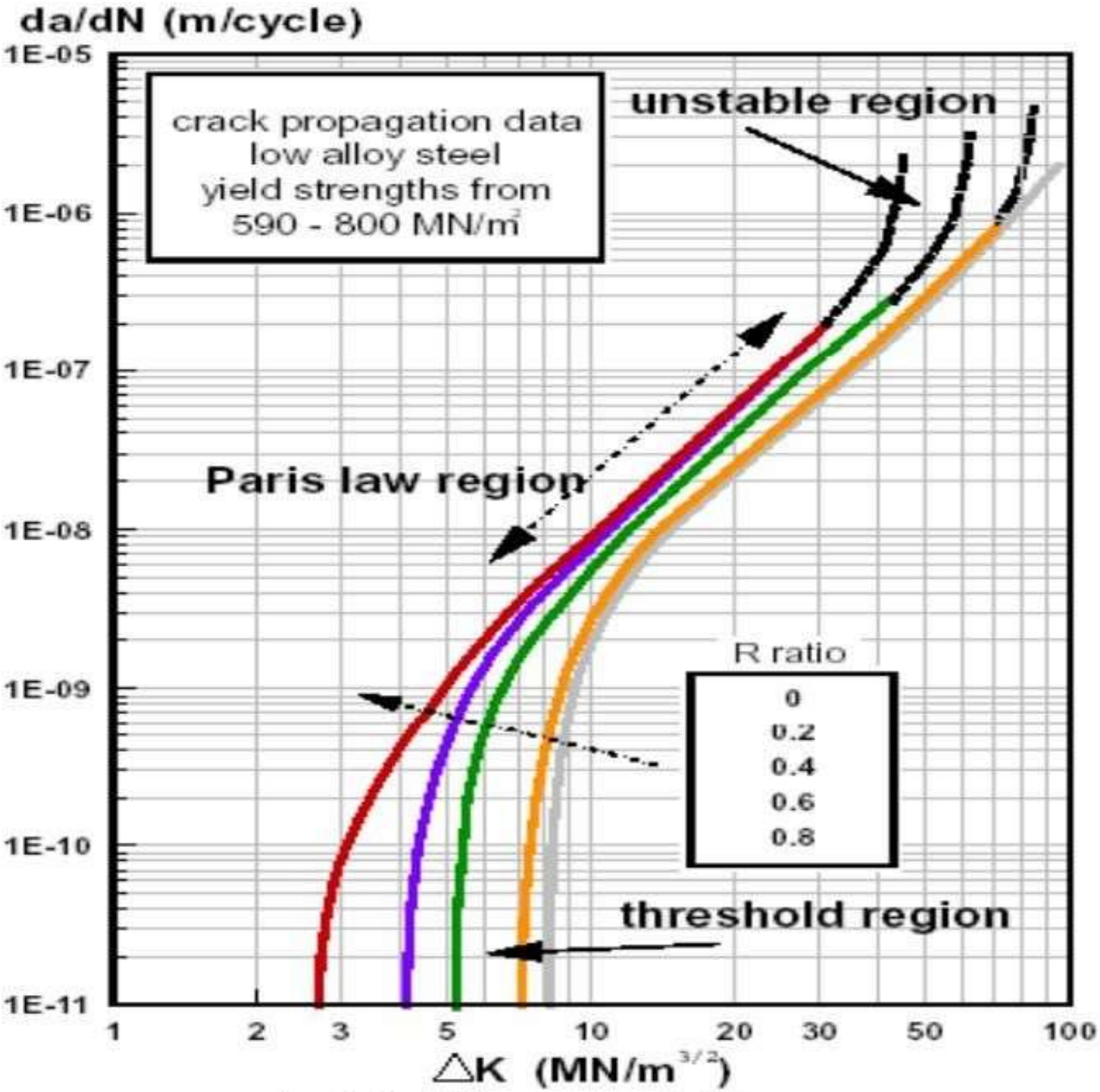
  failure process is taken up entirely with incremental growth and final fracture.

Most fatigue failures in practice are in the low stress region, much less than the yield stress,

where the LEFM is likely to be valid.

Hence, the LEFM principles can be applied to

predict incremental fatigue crack propagation

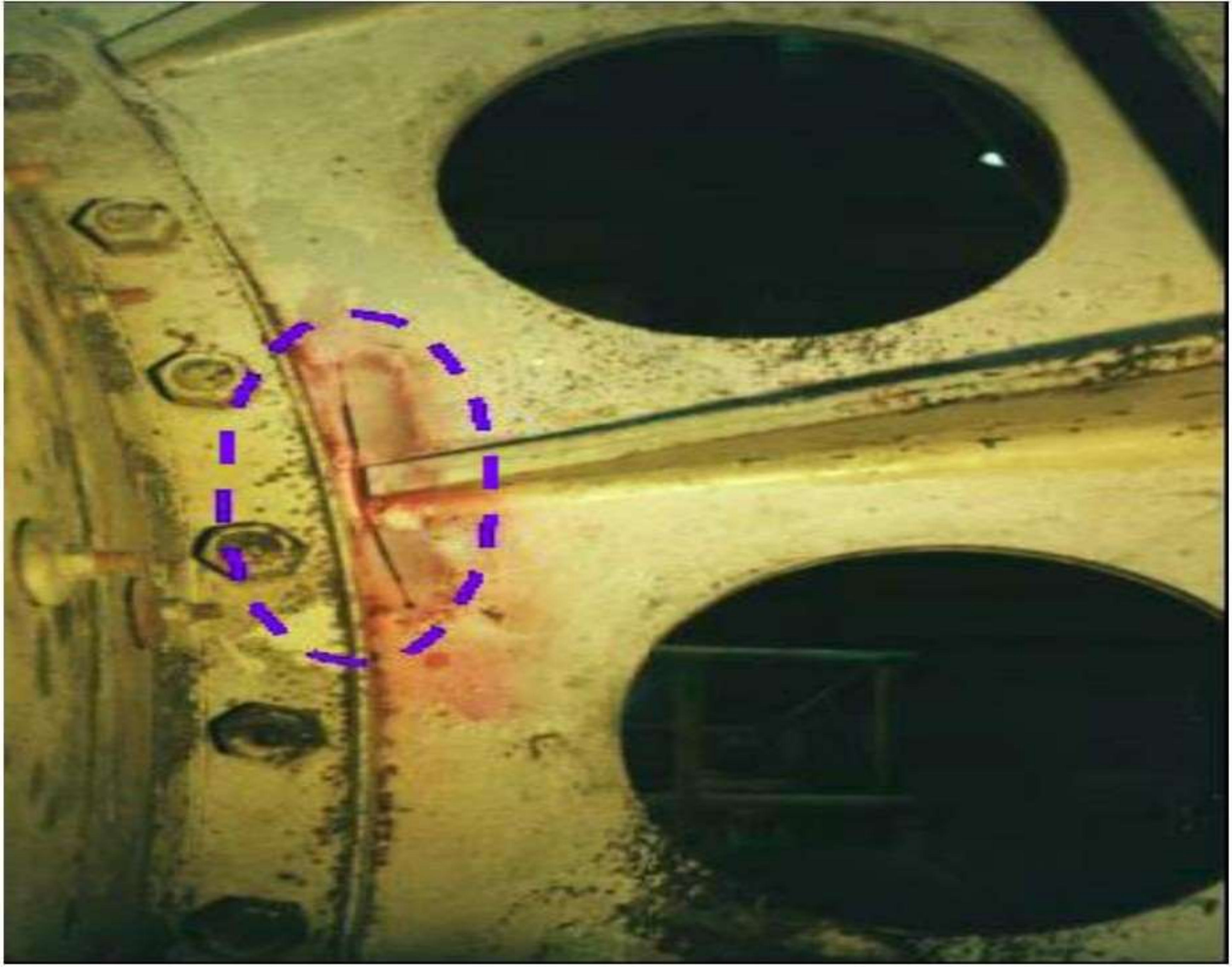


typical da/dN versus ΔK curve

- **Fracture:**

When critical size is reached, the cark propagates. →

The are of cross-section supporting the load gets reduced thus increasing the stress value and finally occurs.



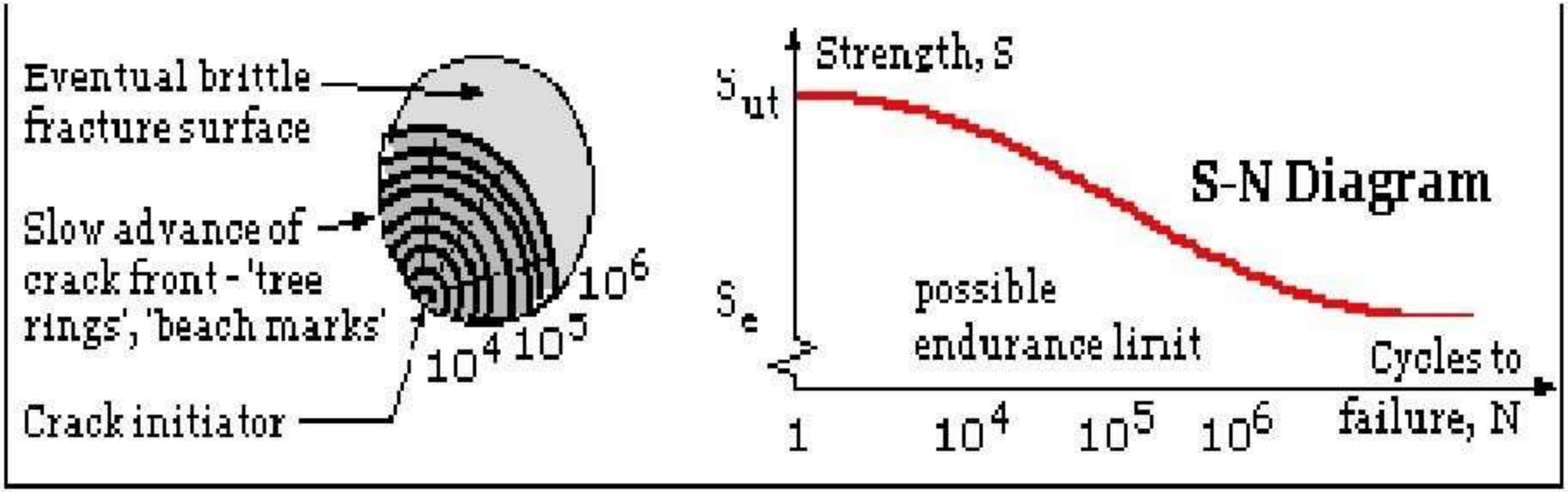
- Classical Fatigue
- The classical approach to fatigue, also referred to as *Stress Controlled Fatigue or High Cycle Fatigue (HCF),* through S/N or Wöhler diagrams,
- .

- **In order to determine the strength of materials under the action of fatigue loads, specimens with polished surfaces are subjected to repeated or varying loads of specified magnitude while the stress reversals are counted up to the destruction point.**

- **The number of the stress cycles to failure can be approximated by the**

  WOHLER or S-N DIAGRAM,

WOHLER or S-N DIAGRAM,



- **Fatigue properties :**
- **Fatigue life (N):** it is total number of cycles are required to bring about final fracture in a specimen at a given stress.
- Fatigue life for a given condition is a property of the individual specimen
- and is arrived at after testing a number of specimens at the same stress.

- Fatigue life for P % survival (N_p)

  It is fatigue life for which P percent of samples tested have a longer life than the rest.

- For example, N_{90} is the fatigue life for which 90% of the samples would be expected to survive and 10% to fail at a particular stress.

- **Median fatigue life:**

- it is fatigue life for which 50 % of the population of samples fail
- and the other 50 % survive at a particular stress.

- **Fatigue strength (σ_n)**

- It is stress at which a material can withstand repeatedly N number of cycles before failure.

- OR it is the strength of a material for a particular fatigue life.

- Fatigue limit or Endurance limit (σ_E):
- it is stress below which a material will not fail for any number of cycles.
- For ferrous materials it is approximately half of the ultimate tensile strength.
- For non-ferrous metal since there is no fatigue limit.

- **Endurance limit**

  is taken to be the stress at which it endures, N number of cycles without failure .N is usually taken as

  5×10^8 cycles for

  non-ferrous metals.

Factors affecting fatigue:

1) Effect of stress concentration
2) Size effect:
3) Surface Roughness:
4) Surface Residual Stress:
5) Effect of temperature:
6) Effect of metallurgical variables;

- Factors affecting fatigue:
- 1) EFFECT OF STRESS CONCENTRATION
- It is most responsible for the majority of fatigue failures
- All m/c elements contain stress raisers like fillets, key ways, screw threads, porosity etc. fatigue cracks are nucleated in the region of such geometrical irregularities.

- The actual effectiveness of stress concentration is measured by the fatigue strength reduction factor K_f

$$K_f = \sigma_n / \sigma_n'$$

σ_n = the fatigue strength of a member without any stress concentration

σ_n' = the fatigue strength of the same member with the specified stress concentration.

- fatigue failure by stress concentration can be minimized by
- reducing the avoidable stress-raisers
- careful design and
- the prevention of stress raisers by careful machining and fabrication.

2) SIZE EFFECT:

The strength of large members is lower than that of small specimens.

This may be due to two reasons.

The larger member will have a larger distribution of weak points than the smaller one and on an average, fails at a lower stress.

Larger members have larger surface Ares. This is important because the imperfections that cause fatigue failure are usually at the surface.

Effect of size:

Increasing the size (especially section thickness) results in larger surface area and creation of stresses.

This factor leads to increase in the probability of crack initiation.

This factor must be kept in mind while designing large sized components.

3) SURFACE ROUGHNESS:

- almost all fatigue cracks nucleate at the surface of the members.
- The conditions of the surface roughness and surface oxidation or corrosion are very important.
- Experiments have shown that different surface finishes of the same material will show different fatigue strength.

- Methods which Improve the surface finish and those which introduce compressive stresses on the surface will improve the fatigue strength.
- Smoothly polished specimens have higher fatigue strength.

Surface treatments. Fatigue cracks initiate at free surface, treatments can be significant

Plating, thermal or mechanical means to induce residual stress

- **4) SURFACE RESIDUAL STRESS:**
- Residual stresses are nothing but locked up stresses which are present in a part even when it is not subjected to an external force.

- Residual stresses arise during casting or during cold working when the plastic deformation would not be uniform throughout the cross section of the part.

Compressive residual stresses are beneficial, tension is detrimental

Residual stresses not permanent, can be relaxed (temp., overload)

Shot Peening

- **Surface of component blasted with high velocity steel or glass beads**
- **Core of material in residual tension, surface in residual compression**
- **Easily used on odd shaped parts, but leaves surface dimpling**

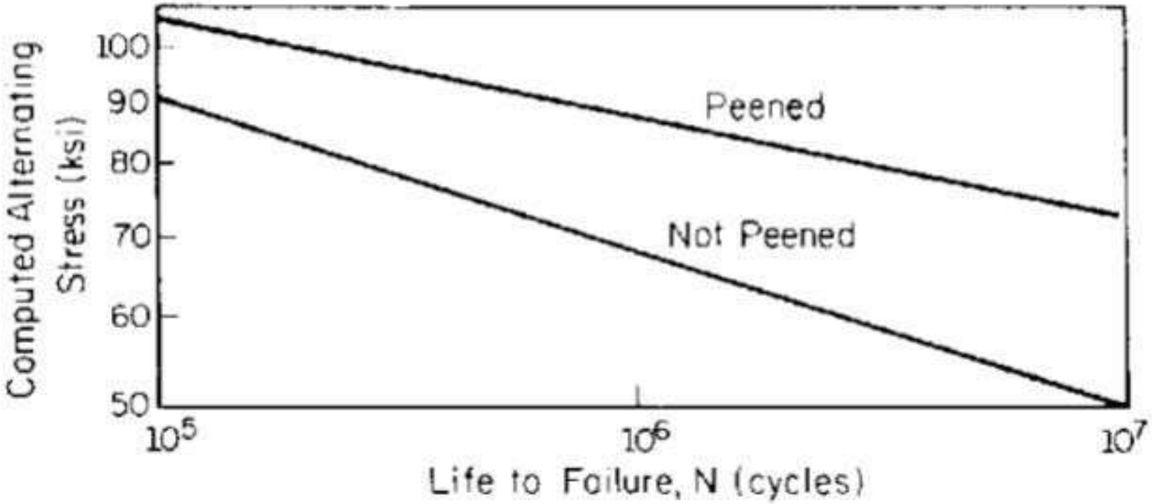


Figure 1.23 *S*–*N* curve of carburized gears in peened and unpeened conditions. (From Ref. 12.)

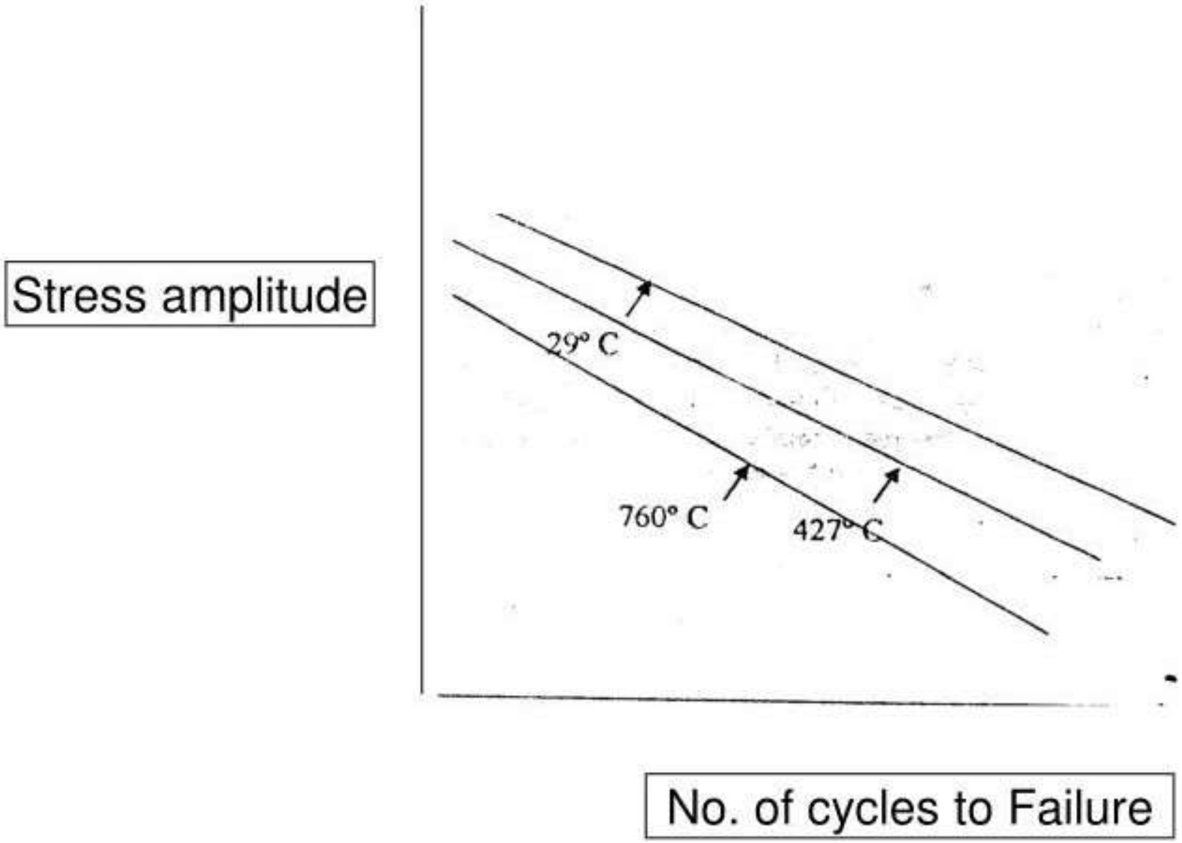
- **Residual stresses can be either tensile or compressive when plastically deformed.**

- **Those residual stresses help in the nucleation of cracks and their further propagation.**

5) EFFECT OF TEMPERATURE:

- Fatigue tests on metals carried out at below room temperature shows that fatigue strength increases with decreasing temperature.
- F.S ↑ as Temperature ↓

Higher the temperature, lower the fatigue strength.



Temperature. Endurance limits increase at low temperature (but fracture toughness decreases significantly)

Endurance limits disappear at high temperature

Creep is important above 0.5Tm (plastic, stress-life not valid)

- **Effect of metallurgical variables;**
- Fatigue strength generally increases with increase in UTS
- Fatigue strength of quenched & tempered steels (tempered martensitic structure) have better fatigue strength
- Finer grain size show better fatigue strength than coarser grain size.
- Non-metallic inclusions either at surface or sub-surface reduces' the fatigue strength

Environmental Effects

Environment. Corrosion has complex interactive effect with fatigue (attacks surface and creates brittle oxide film, which cracks and pits to cause stress concentrations)

Often in practice, there are modifying factors for the above applied to the equation for the endurance limit.

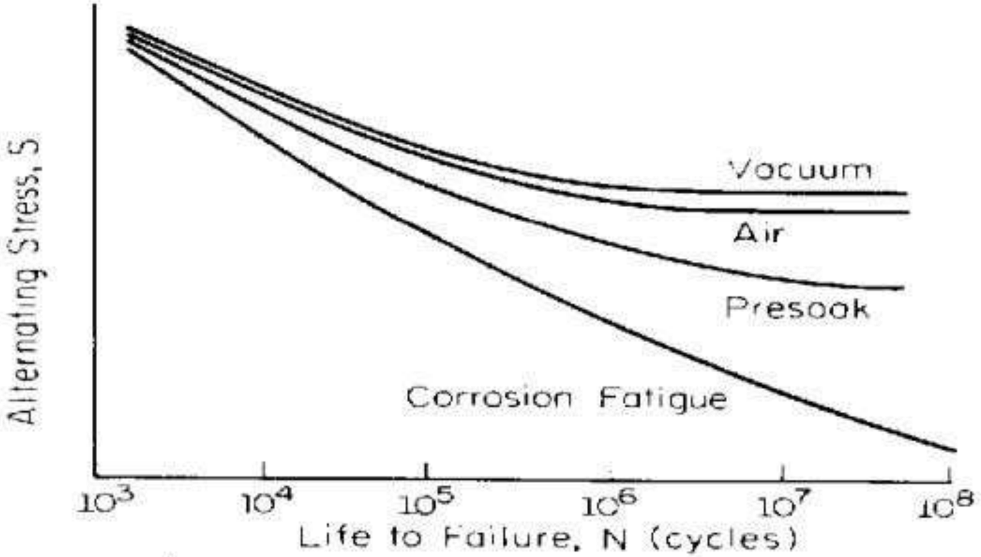


Figure 1.25 Effect of various environments on the $S-N$ curve of steel. (H. O. Fuchs and R. I. Stephens, *Metal Fatigue in Engineering*, John Wiley and Sons, New York, 1980. Reprinted with permission.)

- **Mechanisms of fatigue failure**
- Some of the theories which explain the mechanism of crank nucleation leading to fatigue fracture are mentioned below,
- **Wood's theory**
- **Orowan's theory**
- **Cottrell and Hull theory**

- **Wood’s theory:** ‘slip’ takes place along certain crystallographic planes due to shear stresses acting along those planes.

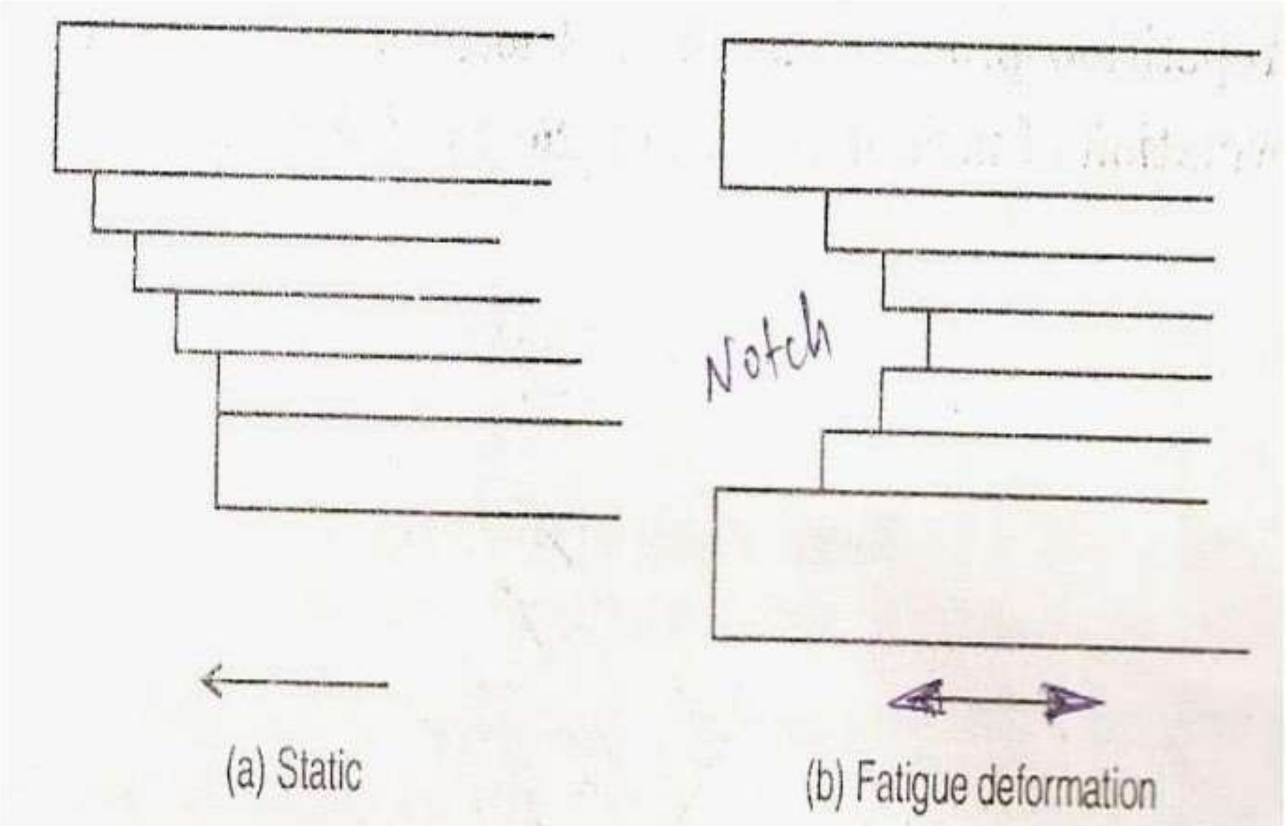
- When an alternate load is applied, the direction of the shear stresses also changes alternately.

Wood's theory:

- These causes back and forth slip moments in opposite directions.

- Slip bands are produced due to this systematic buildup of fine slip movements in either direction.

- **Wood's theory:**



(a) Static

(b) Fatigue deformation

STATIC

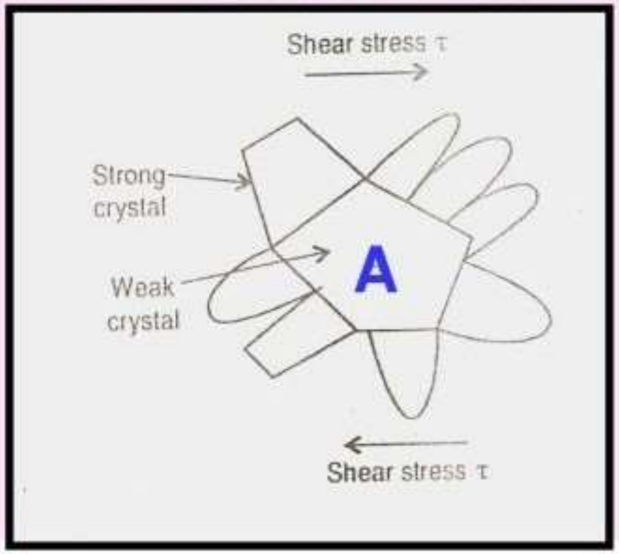
FATIGUE DEFORMATION

- **Wood's theory:**

- These slip movements are in the order of 1 nanometer, these slip bands are nothing but intrusions and extrusions formed on the surface of the specimen to form surface irregularities which are initiated as cracks.

- **Wood's theory:**
- Once the cracks are nucleated, growth of these cracks takes place continuously due to stress concentration before fracture occurs.
- Typical , the crack growth period accounts for 75-90% of the fatigue life in the part.

- **Orowans Polycrystalline Model theory:**
- Consider a polycrystalline sample consisting of a number of grains. Let A be one of the grains which is weaker then the surrounding grains.



- Orowans Polycrystalline Model theory:
- When load is applied to this sample, grain A being weaker than the rest, yields in the directions of loading.

- When the load is reversed, grain A tries to yield in the opposite direction.

- Orowans Polycrystalline Model theory:

- As the loads are continuously alternated.
- Grain A continuously yields in opposite direction and faster than the rest of grains.
- This causes a relative movement between grains A and the surrounding grains and leads to the formation of fine submicroscopic cracks at the grain boundary of grain A.

- **Orowans Polycrystalline Model theory:**

In a polycrystalline sample, there may be a number of such grains which may be weaker than their surrounding grains.

Hence a number of submicroscopic cracks may be expected to form at their boundaries.

Subsequent cycles of stresses helps in the coalescence of a number of submicroscopic cracks to form a bigger crack which may grow and result in fracture.

- Orowans Polycrystalline Model theory:
- In general fatigue cracks begins at the surface of the specimen, probably because the grains adjacent to the surface are less restricted than the surrounding grains. Therefore weak grains like grain A can be to be found next to the surface.

- **Cottrell and Hull Theory:**
- This theory is based on a model; involving interaction of edge dislocations on two slip systems.
- When two different slip systems work with different directions and planes then they produce slip at the surface forming intrusion and extrusion.
- These intrusions act as starting point of fatigue cracks.

- Fatigue Design Guideline (minimize stress concentrations)

1. Consider actual stresses, including stress concentrations, rather than to nominal average stresses.

2. Visualize load transfer from one part or section to another and the distortions that occur during loading to locate points of high stress

3. Avoid adding secondary brackets, fittings, handles, steps, bosses, grooves, and openings at locations of high stress

4. Use gradual changes in section and symmetry of design to reduce secondary flexure
5. Consider location and types of joints (frequent cause of fatigue problems)
6. Use double shear joints when possible
7. Do not use rivets for carrying repeated tensile loads (bolts superior)
8. Avoid open and loosely filled holes

9. Consider fabrication methods, specify strict requirements when needed
10. Choose proper surface finishes, but not overly severe (rivet holes, welds, openings etc. may be larger drivers)
11. Provide suitable protection against corrosion
12. Avoid metallic plating with widely different properties than underlying material

13. Consider prestressing when feasible, to include shot peening and cold working
14. Consider maintenance, to include inspections, and protection against corrosion, wear, abuse, overheating, and repeated overloading
15. Avoid use of structures at critical or fundamental frequency of individual parts or of the structure as a whole (induces many cycles of relatively high stress)
16. Consider temperature effects.

- **Fatigue test -** Fatigue testing machine:
- In the simplest type of machine for fatigue testing, the load applied is of **bending type**.
- The test specimen may be of

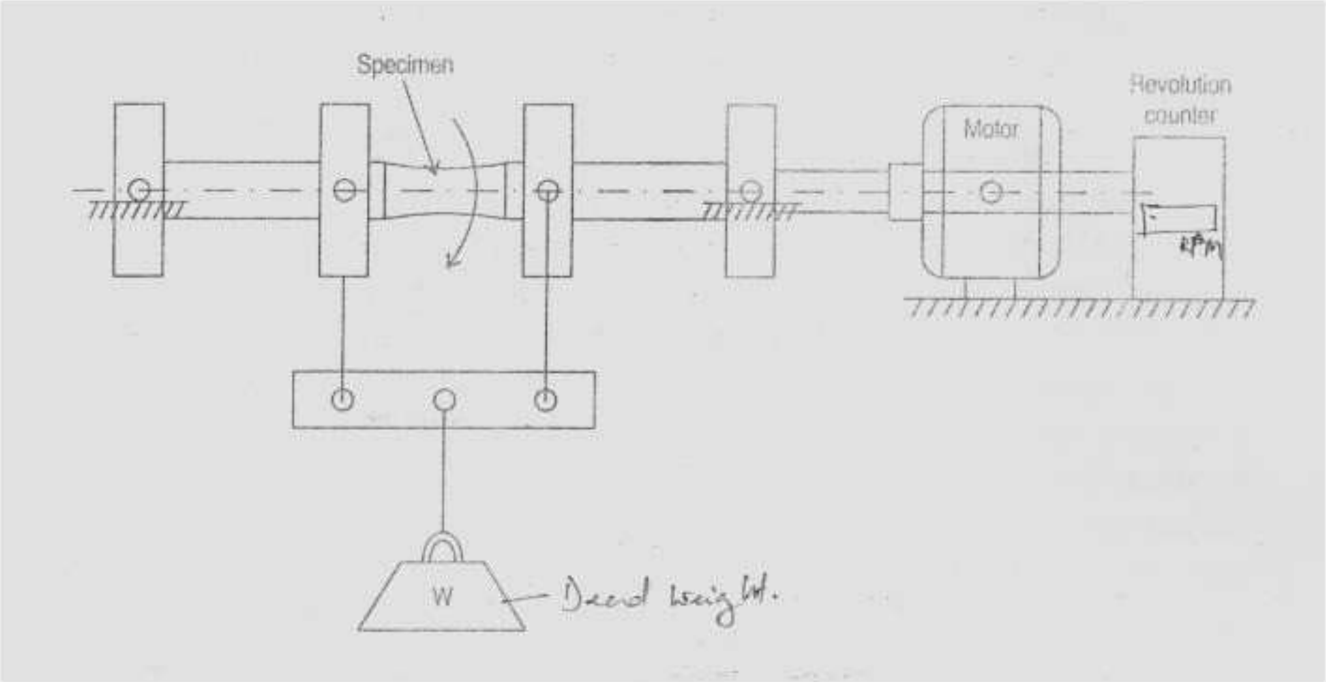
simply supported beam or a **cantilever**.

- In a R.R.Moore rotating beam type machine for a simply supported beam a specimen of circular cross-section is held at its ends in special holders and loaded through two bearings equidistant from the center of the span.

- **R R Moore reversed- bending fatigue test:**
- Fatigue failure in engineering materials are observed by conducting the fatigue test which involves the plotting of an S-N diagram.

- **Equal loads on these bearings are applied by means of weights that produce a uniform bending moment in the specimen between the loaded bearings.**
- **A motor rotates the specimen.**

R R Moore reversed- bending fatigue test:



One such test is the RR Moore reversed- bending fatigue testing machine.

- **Since the upper fibers of the rotating beam are always in compression while the lower fibers are in tension, it is apparent that a complete cycle of reversed stress in all fibers of the beam is produced during each revolution.**
- **A revolution counter is used to find- the number of cycles the specimen is repeatedly subjected to the load. For simply supported beam, maximum bending moment is at the center.**

- Specimens subjected to fatigue test are made to undergo fluctuating or opposite stresses.
- One such test arranged is shown in fig. where specimen is bent with the help of weights as well as rotated.
- By this alternate tensile and compressive stresses are imposed on the various layers of the specimen.

- **A counter coupled to the motor counts the number of cycles to failure. The experiment could be conducted for different loads, and different number of cycles to fracture are noted to draw the S-N diagram.**

- Bending momentMb = *FL* and bending stress S = *M b*
- 4 z
- Where *L* is the length of the specimen and z is the sectional modulus.
- In rotating cantilever beam type, the specimen is rotated while a gravity load is applied to the free end by means of a bearing.
- For cantilever specimen the maximum bending moment is at the fixed end.
- *.* *M*
- :. *Mb* = *FL* and S *=_b*
- Z

CREEP

FAILURE

- Definition:
- When materials under severe service conditions are required to sustain steady loads for long periods of time, they undergo

a time dependent deformation.

- This is known as creep

CREEP

- **can also be defined as**

‘ the slow and progressive deformation of a material with time at constant stress.’

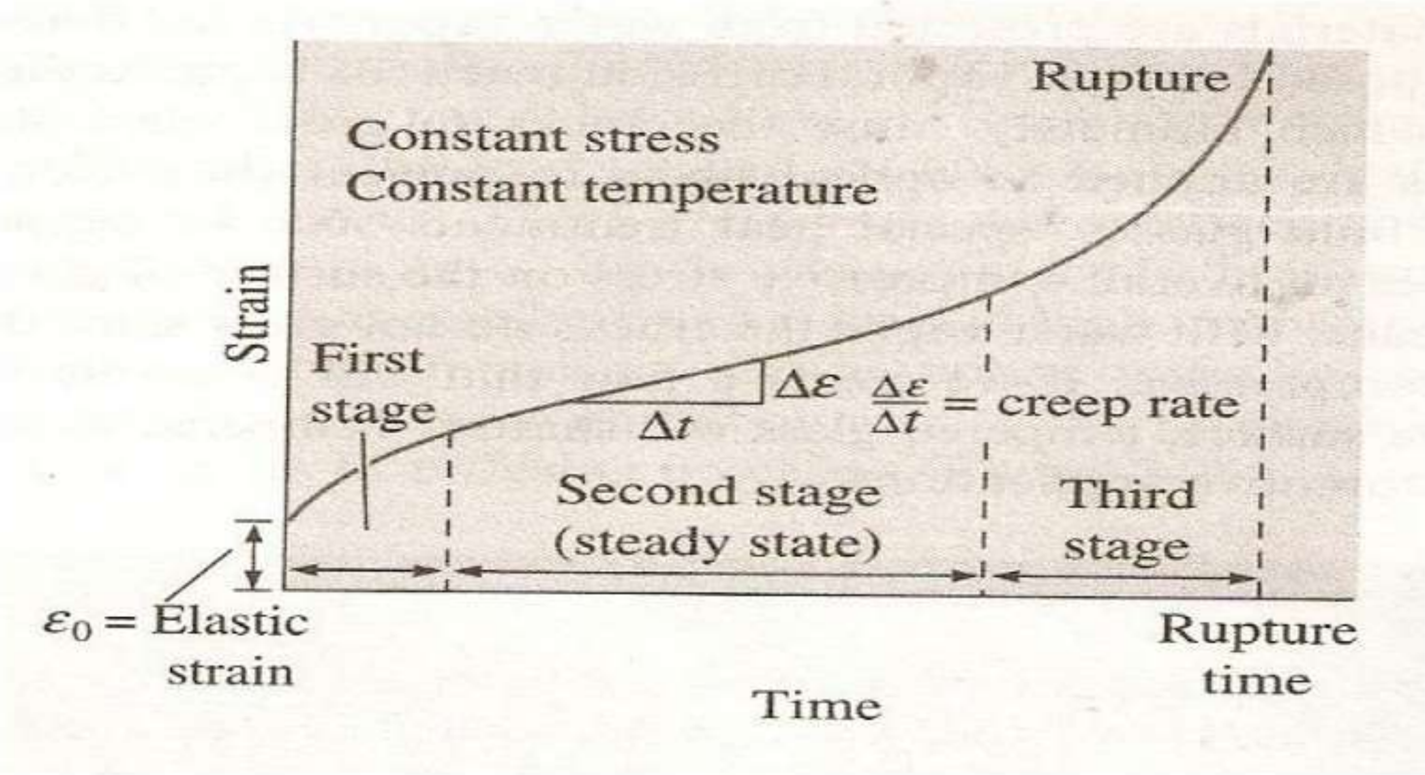
Creep is found to occur at higher temperature than at lower temp.

Therefore the study of creep is very important for those materials which are used at high temp like components of gas turbines, furnaces, rockets, missiles etc

- Creep curve:

- **The creep curve is obtained by applying a constant tensile load below the yield point to a specimen maintained at constant temp.**

CREEP CURVE

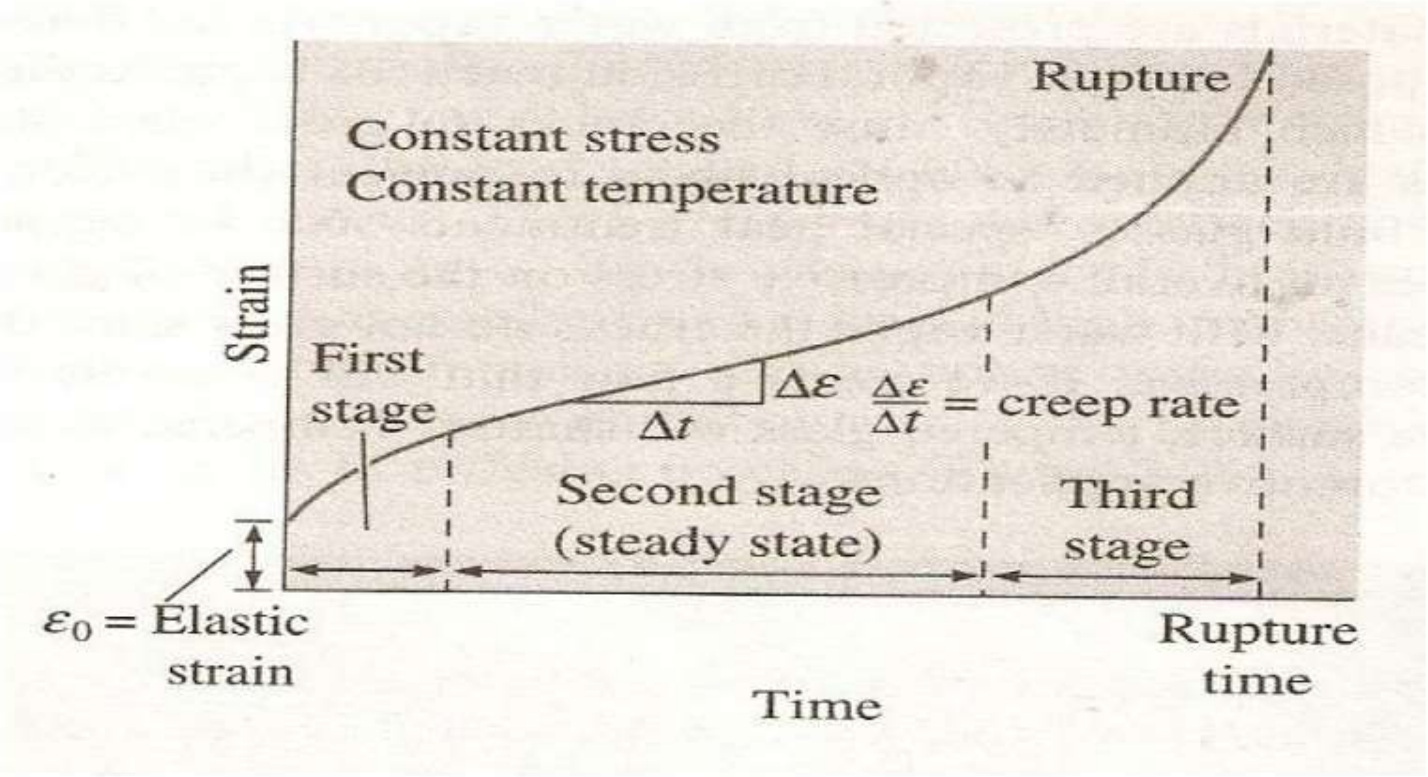

Rupture
Constant stress
Constant temperature
Strain
First stage
$\Delta\varepsilon$
Δt
$\frac{\Delta\varepsilon}{\Delta t}$ = creep rate
Second stage (steady state)
Third stage
ε_0 = Elastic strain
Rupture time
Time

- As soon as the specimen is loaded, there will be an instantaneous strain which is denoted by ε_o on the creep curve.

- **Further deformation of the metal only after the instantaneous strain is considered as**
- **‘creep deformation’.**

- Creep deformation of materials up to failure are divided into 3 stages
- i) primary creep
- ii) secondary creep
- iii) tertiary creep.

CREEP CURVE


Rupture
Constant stress
Constant temperature
Strain
First stage
$\Delta\varepsilon$
Δt
$\frac{\Delta\varepsilon}{\Delta t}$ = creep rate
Second stage (steady state)
Third stage
ε_0 = Elastic strain
Rupture time
Time

Primary creep: OR TRANSIENT CREEP

This is the first stage of the creep which represents a region of decreasing creep rate.

- In this region the rate at which the material deforms decreases with time until it reaches a constant value.

- The creep rate goes on reducing because as the metal deforms it undergoes strain hardening and offers more and more resistance to further elongation.

- **Transient creep:**
- The principle characteristic of transient creep is the decreasing rate in deformation.
- Deformation is rapid at first but gradually becomes slower and slower as the rate approaches some fixed value.
- Transient creep in metals is observed at all temp, even near absolute zero. Hence it is some times referred to as ‘cold creep’

Secondary creep: [steady state creep]

Nearly constant creep rate,

because strain-hardening and recovery effects

balance each other.

Creep in this region takes place by the viscous flow in the materials.

- Viscous creep: SECONDARY CREEP]
- **It is characterized by the viscous flow of the material means that there is a constant or a steady increase in deformation at constant stress.**

- Although strain hardening is present, its effect is just balanced by the ‘recovery’ process which has the opposite effect
- i.e softening the metal.

- viscous creep is stopped when there is considerable reduction in cross sectional area and enters the tertiary stage .
-
- The rate of deformation increases rapidly in this 3rd stage and fracture occurs at the end of this stage.

- Viscous creep also known as ‘hot creep', since it is observed only at higher temperature.

- **Tertiary creep :**

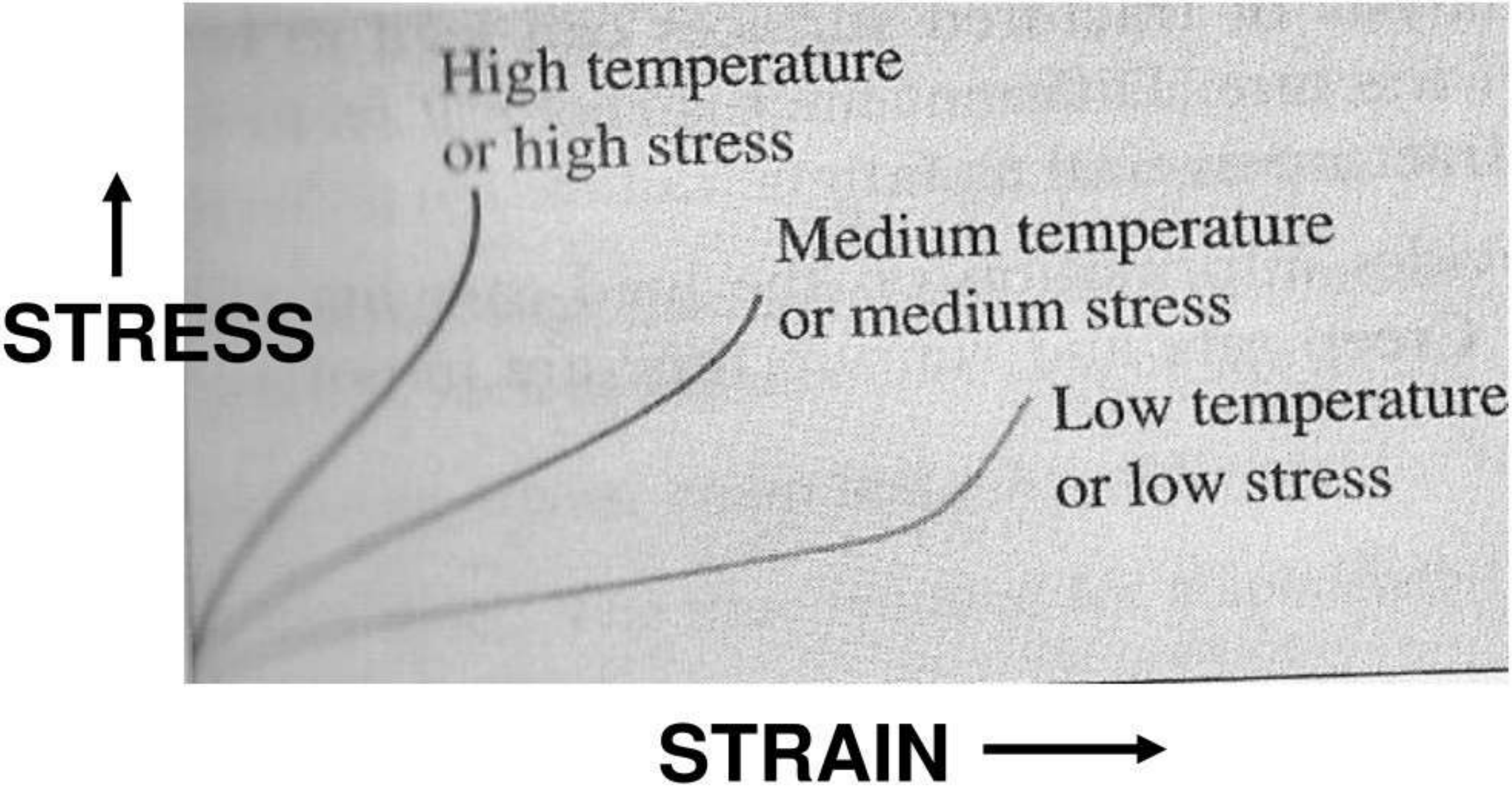
This stage is period of increasing strain rate.

Tertiary creep occurs when there is an effective reduction in cross-sectional area due to necking or internal void formation.

- If the stress is kept constant of the load or if true strain is taken into consideration

then the resulting fracture due to creep would be at ‘B’.

- Effect of low temperature :
- Temperature below $T_m/4$ are called as LOWER TEMP.
- lower temp have an effect of decreasing the creep rate. ↓
- This is because strain hardening effects will be more and recovery process is negligible.


High temperature or high stress
Medium temperature or medium stress
Low temperature or low stress
STRESS
STRAIN

- Creep occurring at lower temp is known as ‘logarithmic creep’
-

$$\varepsilon = \alpha \ln t$$

where ε - strain ,

α – a constant

t – time .

- low temp. logarithmic creep obeys a mechanical equation of state i.e the rate of strain at a given time depends only on the instantaneous values of stress and strain and not on the previous strain history.

- **Effect of high temperature:**

At Higher temp. the creep rate increases. ↑

- **‘ structural changes’ takes place.**

- **Mobility of atoms increases ↑ with temp and**
- **occupy lower energy positions.**

- **Mobility of dislocation also increases ↑ and they overcome the obstacles by the mechanism of climb.**

- The concentration of vacancies increases with temp ↑
- and the rate of diffusion increases. ↑
- Recrystallization takes place as a result of increased rate of diffusion.

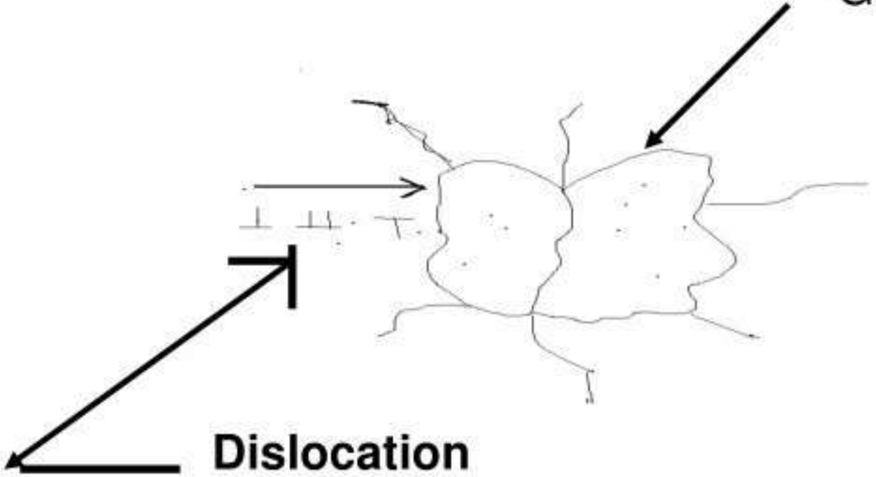
- Grains in polycrystalline materials move relative to each other .
- This grain- boundary sliding is a shear process which occurs in the direction of the grain boundary and leads to intergranular cracks.

- **Mechanism of creep:** The chief mechanism responsible for creep deformation are ,
- Dislocation glide
- Dislocation creep or dislocation climb
- Diffusion creep
- Grain boundary sliding.

- 1) **Dislocation glide :**

- **The creep rate is established by the ease with which the dislocation move across obstacles such as precipitates, GB etc.**

- **Dislocation glide**



- This may include cross-slip of dislocations with the aid of thermal energy.

- Dislocation glide results in increase in plastic strain during creep deformation

- 2) **Dislocation creep or dislocation climb:**

- **This is caused due to mutual movement of dislocations & vacancies.**

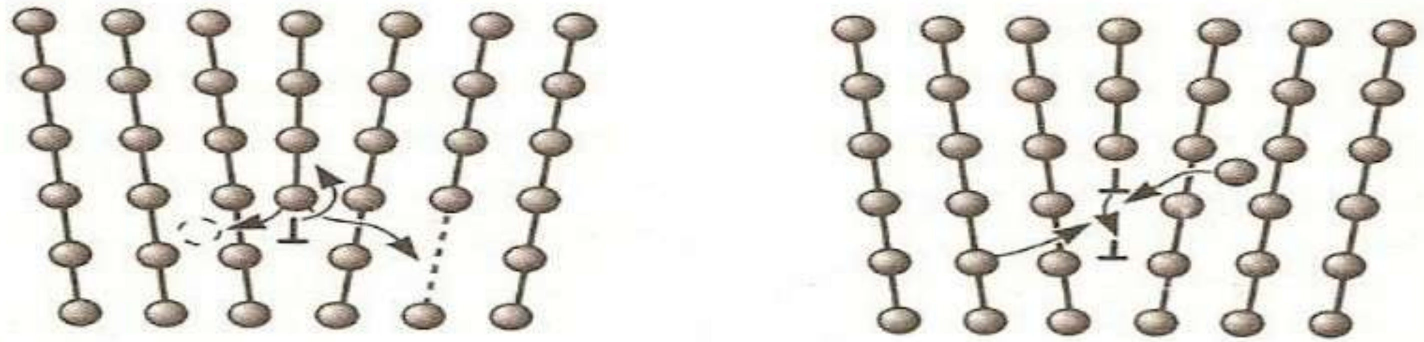
- At high temp the diffusion rate of vacancies is more which make the dislocations to glide & climb,
- edge dislocation can move end of a slip plane
- OR to a plane above or below the slip Plane.

This is called dislocation climb.

⊥ Dislocation

◌ Vacancy

Mutual movement of dislocations & vacancies.



(a) (b)

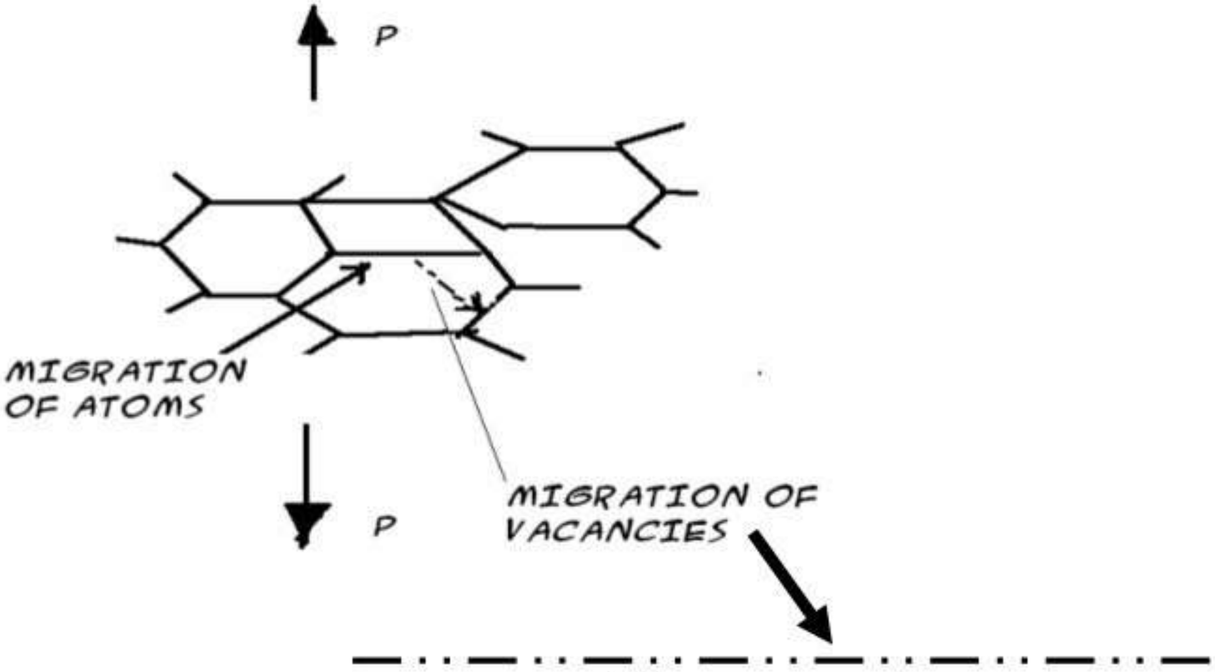
- This occurs at high temperature $(T>0.4T_m)$ &

- When dislocation cause across obstacles,
- they use vacancies/or interstitial atoms to climb and go around them for slip &
- hence plastic deformation continues.

- 3) Diffusion creep: -
- It occurs when temp. is high & at relatively low stresses.

- diffusion of vacancies controls the creep rate.
- But edge dislocation is not involved in them.

vacancies move from the surface of the specimen towards the stress axis



Stress axis

- i.e when load is applied & kept constant ,the vertical boundaries are subjected to compression & the horizontal grain boundaries are subjected to tensile stress.

- so vacancies migrate from tensile region to compression region &

  atoms migrate in opposite direction to vacancies.
- i.e causing the creep strain along tensile axis,

- the mechanism is called **Nabarro-herring creep** because the flux of atoms is through the bulk of atoms.

- **4) Grain boundary sliding:-**
- **At low temp the Grain boundaries will not flow viscously & provide obstacles to dislocation motion.**
-

- At elevated temp , the grains in polycrystalline materials are able to move relative to each other, this is called grain boundary sliding and is an shear process which occurs in the direction of grain boundary [GB] .

- a large no. of grains sliding with each other results in plastic deformation due to creep .

- GB sliding is promoted by increases the temp. T & or decreasing the strain rate.

- In fine grained materials because of large no. of grains this type of creep is more ,so to avoid it large-coarse grained materials are to be used.

- Ex :
- Ni-based super alloy with single crystals in jet engine blades, eliminates the possibility of creep at high temp aided by grain boundary sliding

- **Stress relaxation :-**
- Stress relaxation is the time dependent decrease in stress acting on a body which is constrained to a certain fixed deformation.

- In other words it is the reduction in the value of stress in those compounds which are not allowed to elongate.

- Ex :
- stress relaxation in bolts which hold rigid bodies in tight contact , stress will reduce in such numbers after a long period.

- Expression for stress relaxation :
- Consider a tensile specimen which is subjected to a constant initial stress σ_i at elevated temp.
- The total strain of the specimen is given
- $\varepsilon = \varepsilon_e + \varepsilon_P$

- This eqn. is the expression for stress relaxation this gives the value of stress (σ) at any instant of time t with initial stress being σ_i.
- It is seen form the relation that ($\sigma \alpha 1/t$)
- i.e σ is inversely propotional to it.
- i.e stress σ goes on decreasing with time with other quantities being constant temp ,T1,T2,T3 , T1< T2< T3.
- Fig stress relaxation curves.

Expression for stress relaxation

Consider a tensile specimen which is subjected to a constant initial load σ_i at elevated temperatures.

The total strain $\in$ of the specimen is given by,

$$\in \; = \; \in_e + \in_P \quad \text{where}$$

$\in_e =$ elastic strain

$$\in \; = \; \frac{\sigma}{E} + \in_P \qquad \text{---- (1)}$$

$\in_P =$ plastic (creep) strain

Due to creep, the specimen tries to increase in length. But if its is constrained at it's two ends, the total strain remains constant at any point of time. However whatever strain the specimen has undergone will become plastic while the elastic strain goes on decreasing. In other words all the elastic deformation is converted to plastic deformation with the passage of time.

Since the total strain does not change with respect to time, differentiate $\in$ with respect to t and equate it to zero.

$$\frac{d(\in)}{dt} = \frac{d}{dt}(\in_e + \in_P) = 0$$

$$\frac{d\in_e}{dt} = \frac{-d\in_P}{dt} \qquad \text{---- (2)}$$

But

$$\in_e = \frac{\sigma}{E} \quad \text{and} \quad \frac{d\in_P}{dt} = B\sigma^n$$

where

$\sigma =$ stress

$E =$ Young's modulus

$B, n =$ constants $(n > 1)$

Substituting these values in (2)

$$\frac{d}{dt}\left(\frac{\sigma}{E}\right) = -B\sigma^n$$

$$\frac{1}{E}\frac{d\sigma}{dt} = -B\sigma^n$$

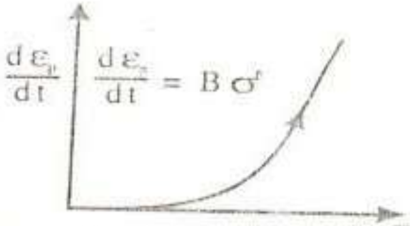


Fig. : Minimum Creep rate

Integrating both sides,

$$\frac{1}{E}\int\frac{d\sigma}{dt} = -\int B\sigma^{n}$$

$$\int\frac{d\sigma}{\sigma^{n}} = -BE\int dt$$

$$\frac{-1}{(n-1)\sigma^{(n-1)}} = -BEt + C \qquad ---- (3)$$

To find the value of C

At $t = 0$, $\sigma = \sigma_i$ where σ_i = initial stress

$$\frac{-1}{(n-1)\sigma_i^{(n-1)}} = -BE \times 0 + C$$

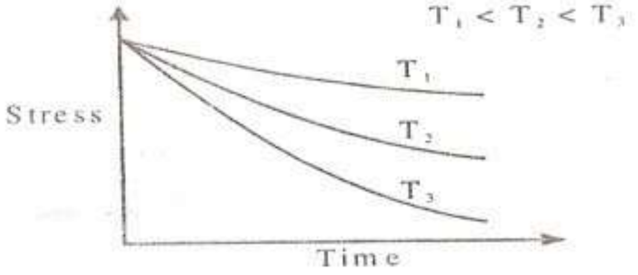
$$\therefore \quad C = \frac{-1}{(n-1)\sigma_i^{(n-1)}} \qquad ---- (4)$$

Substituting (4) in (3)

$$\frac{-1}{(n-1)\sigma^{(n-1)}} = -BEt - \frac{1}{(n-1)\sigma_i^{(n-1)}}$$

$$\therefore \quad \boxed{\frac{1}{\sigma^{(n-1)}} = \frac{1}{\sigma_i^{(n-1)}} + BE\,(n-1)t}$$

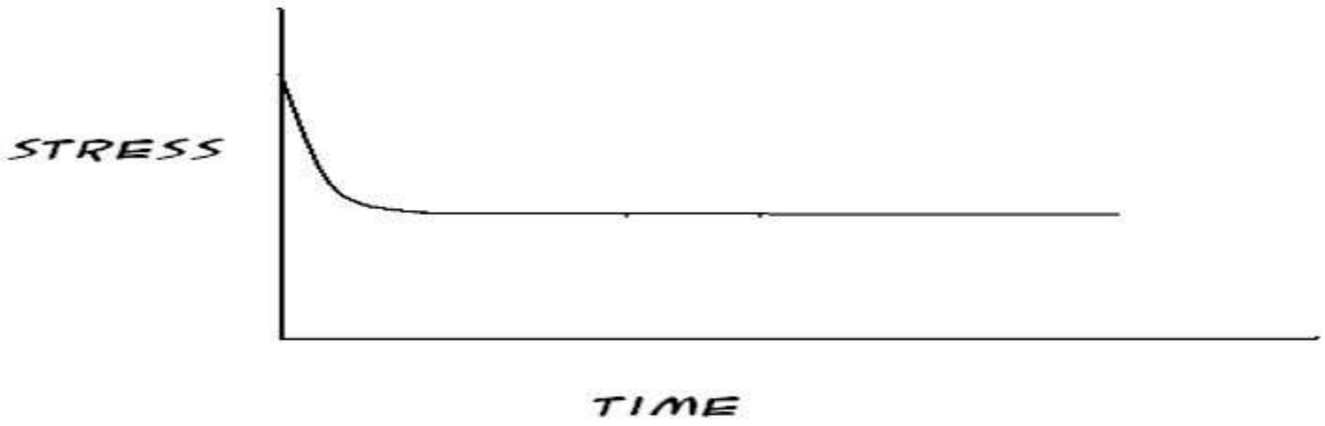
The above equation is the expression for stress - relaxation. This equation gives the value of stress σ at any point of time 't' with the initial stress being σ_i. It is seen from the relation that σ is inversely proportional to 't' i.e., stress goes on decreasing with time with the other quantities being constant.



- Creep properties :-
- 1) creep strength/ or creep limit:

- It is defined as the highest stress that material can withstand without excessive deformation for a specified length of time.

- Ex :- **creep strength for a steam turbine blade may be that stress which will produce just 0.2% creep for 10,000 hours of working at 800°C.**



- Creep strength can also be defined as the stress at given temperature which produces steady state creep rate of fixed amount say 10^{-11} to 10^{-8} /sec.

OR

It is the stress to cause a creep strain of 1% in fixed time say 10^5 hours.

- 2) **Creep rupture strength**:- it is defined as the highest stress that a material can withstand without rupture for a specified length of time.

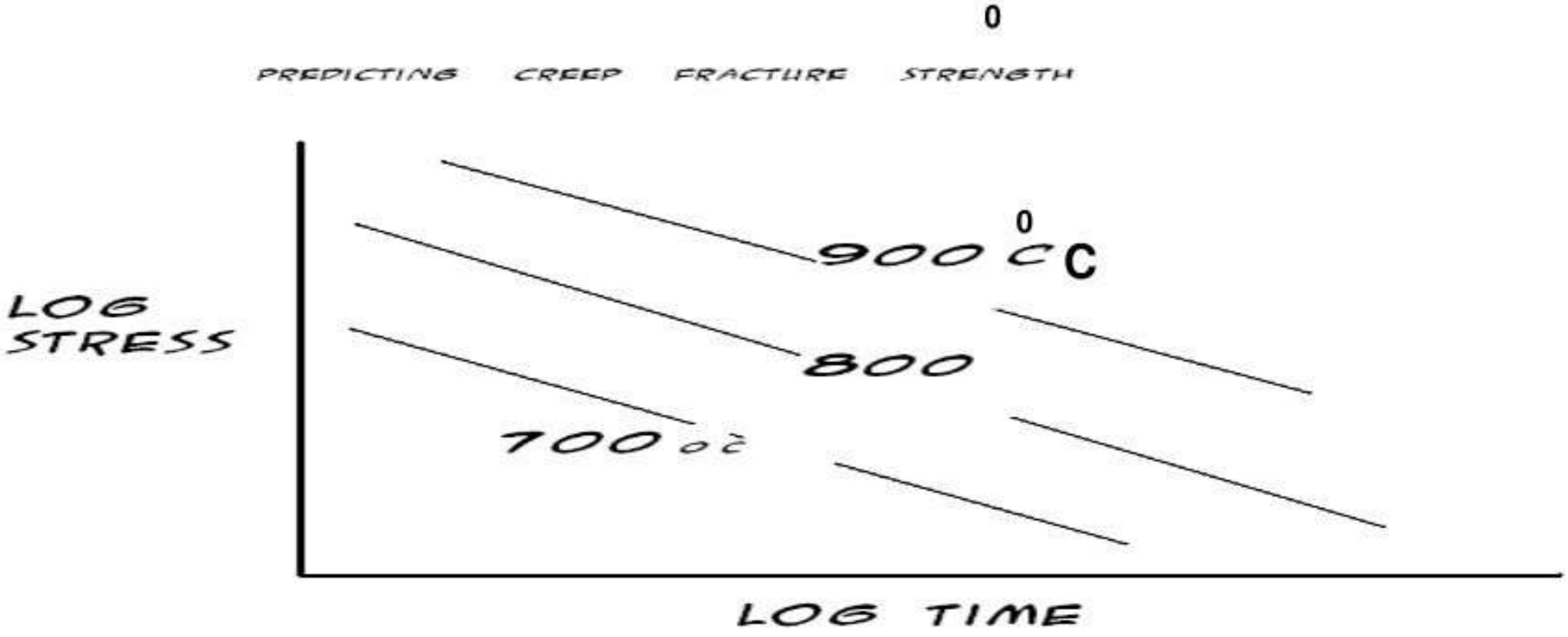
- Ex : For the same turbine blade . the rupture strength is that stress which produces a fracture in 1000HR OR 10000HR OR 100 000 hrs at 800°C.

- Thus creep rupture strength is also defined as the limiting stress below which creep is so slow that will not result in fracture within any finite length of time.

- It is also called as" stress ruptures strength".

- 3) **Creep life:**

it is defined as the TIME to fracture under a given static load.



- **Factors affecting Creep:**

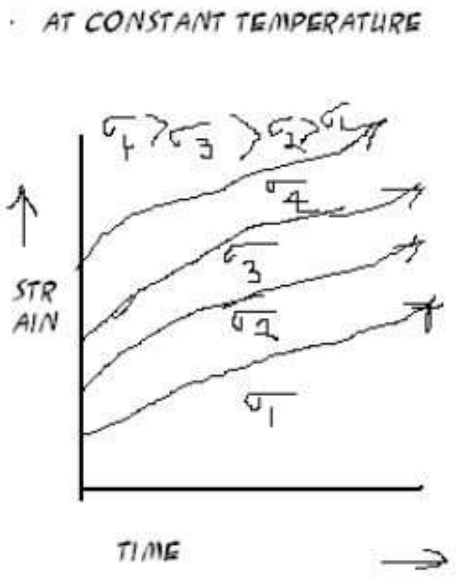
- **Load :**
- **Temperature:**
- **Composition:**
- **Grain size**
- **Heat treatment**

- **Load :** Creep rate increases as load increases.
- **Temperature:** Creep rate increases as T increases.
- **Composition:** Pure metals are softer than alloys , the different phases present stops the dislocation glide .

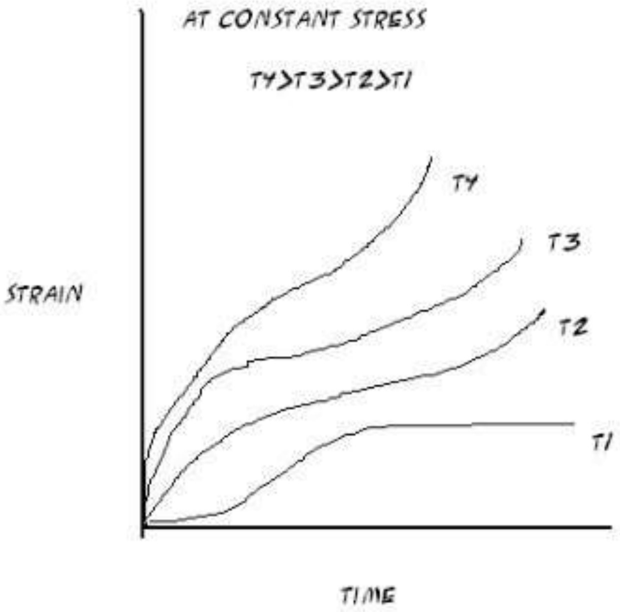
  Hence creep is more in pure metals.

- <u>Grain size:</u> “Smaller the grain, stronger the material.”
- But above Equicohessive temp. this effect will be reversed one.
- Equicohessive temp. (Kelvin) $T_{e} > T_{m/2}$

Heat Treatment: This changes the structure,Obviously the materials property changes, creep resistance also changes.

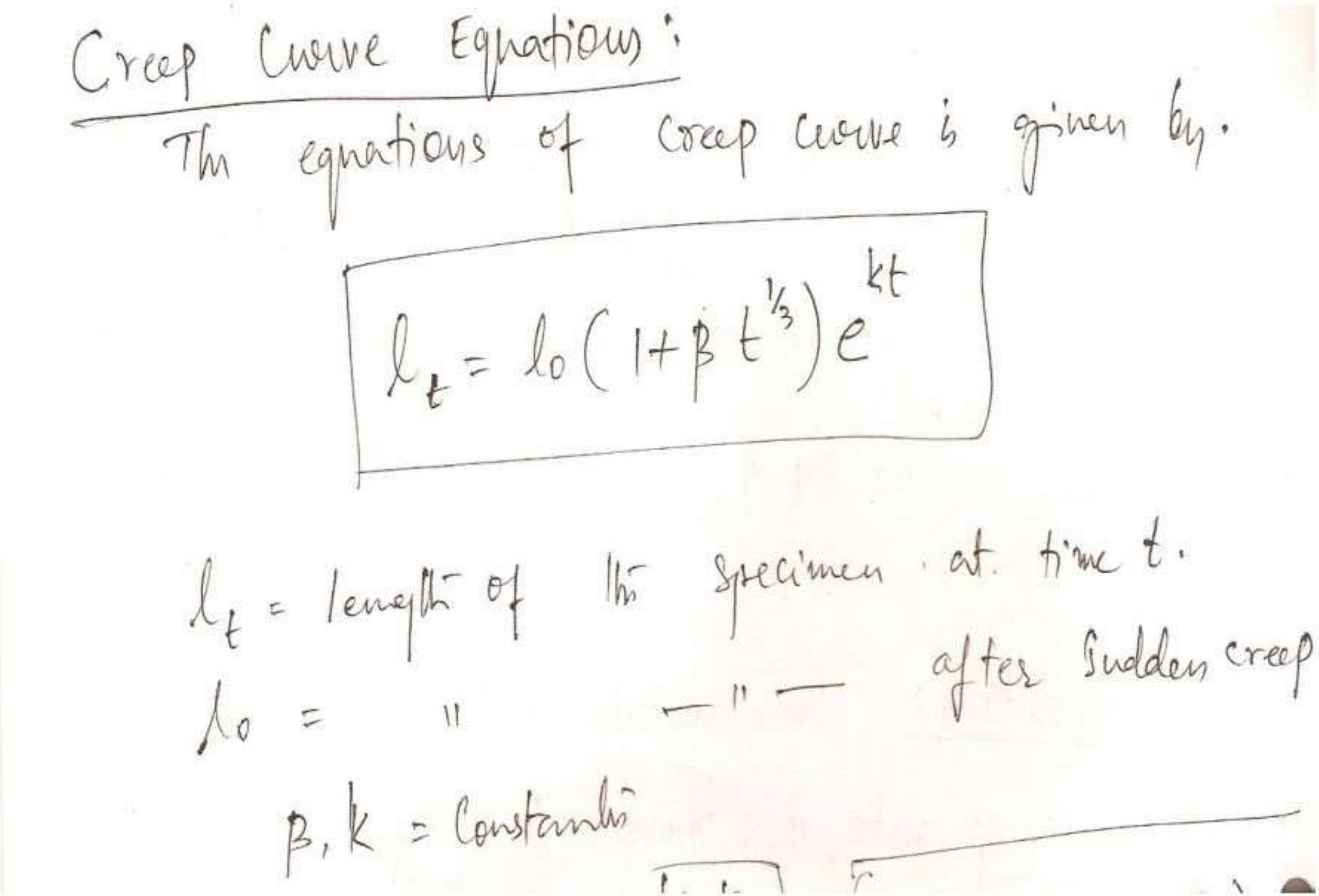


EFFECT OF STRESS ON CREEP CURVE



EFFECT OF TEMPERATURE ON CREEP CURVE.

Creep curve equations:



Creep Curve Equations:

The equations of creep curve is given by.

$$\boxed{l_t = l_0 \left(1 + \beta t^{1/3}\right) e^{kt}}$$

l_t = length of the specimen at time t.

l_0 = " — " — after sudden creep

β, k = Constants

I) For transient creep, $\boxed{\text{set } k=0} \Rightarrow l_t = l_0\left(1+\beta t^{1/3}\right)$

change in length / unit time $= \frac{dl_t}{dt} = \frac{1}{3} l_0 \beta t^{-2/3}$

II) For viscous Creep, $\boxed{\text{set } \beta=0}$.

$$\therefore \boxed{l_t = l_0 \cdot e^{k\cdot t}}$$

$\frac{\text{change in length}}{\text{unit time}} \Rightarrow \frac{dl_t}{dt} = k\cdot\left(l_0 \cdot e^{kt}\right)$

$$= \underline{\underline{k \cdot l_t}}$$

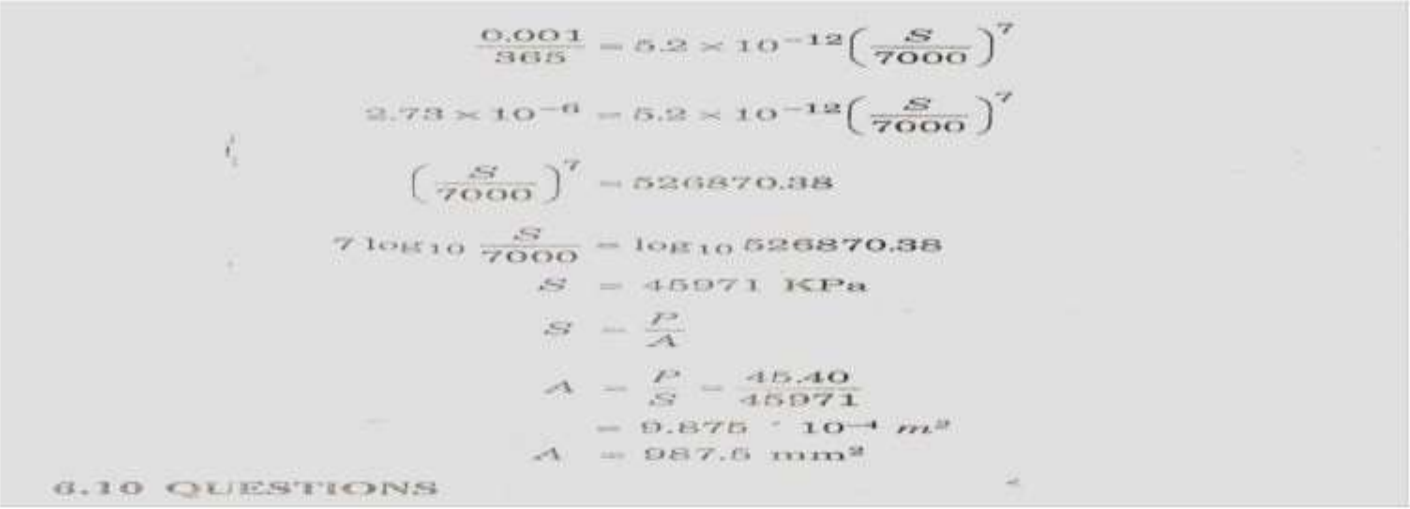
or $k = \frac{1}{l_t}\cdot\frac{dl_t}{dt} = \left(\frac{dl_t}{l_t}\right)\frac{1}{dt} = \frac{d\varepsilon}{dt}$.

Strain Rate = increment of strain / increment in time

i) **A steel member 3m long is subjected to an axial tensile load of 45.4 KN at an operating temperature of 400°C. Determine the cross-sectional area required for an estimated life of 20 years based on an allowable creep rate of 0.001 mm per mm per year using creep relation $C = \frac{\epsilon}{t} = B\left(\frac{S}{S_0}\right)^n$, where $n = 7$, $S_0 = 7$ Mpa and $B = 5.2 \times 10^{-12}$ mm per mm per day.**

olution:

$$\frac{\epsilon}{t} = B\left(\frac{S}{S_0}\right)^n$$



$$\frac{0.001}{365} = 5.2 \times 10^{-12}\left(\frac{S}{7000}\right)^7$$

$$2.73 \times 10^{-6} = 5.2 \times 10^{-12}\left(\frac{S}{7000}\right)^7$$

$$\left(\frac{S}{7000}\right)^7 = 526870.38$$

$$7 \log_{10} \frac{S}{7000} = \log_{10} 526870.38$$

$$S = 45971 \text{ KPa}$$

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

$$A = \frac{P}{S} = \frac{45.40}{45971}$$

$$= 9.875 \times 10^{-4}\ m^2$$

$$A = 987.5 \text{ mm}^2$$

6.10 QUESTIONS

2. A steel bolt is subjected to an axial tensile load between two rigid plates so that the length of the bolt remains constant. The bolt is subjected to an elevated temperature so that creep is produced. What must be the initial stress so that 70% of the stress is retained after ten years? Use the relaxation relation. Values of n = 6.0, $S_0 = 7$ Mpa, $V_0 = 4.2 \times 10^{-8}$ mm/mm per day and $E = 210$ Gpa.

Solution: $V_0 = B\,S^n{}_0$

$$\log_{10} V_0 = \log_{10} B + n \log_{10} S$$

$$\log_{10} B = \log_{10} (4.2 \times 10^{-8}) - 6 \log_{10} 7000$$

$$B = 3.56 \times 10^{-31}$$

$$\frac{1}{S^{n-1}} = \frac{1}{S_i^{n-1}} + B\,E\,(n-1)t$$

$$S = 0.7\,S_i$$

$$\frac{1}{0.7S_i^{n-1}} = \frac{1}{S_i^{n-1}} + 3.56 \times 10^{31} \times 210 \times 10^{6}\,(6-1)\;10 \times 365$$

$$S_i^{6-1} = 3.23 \times 10^{17}$$

Solving $S_i = 3.145$ Mpa

3) **A member is subjected to an initial tension of 14 Mpa and relaxation of the stress occurs since it is subjected to an elevated temperature and the length of the member is maintained constant. Find the time required for the stress to become 12.6 Mpa. Take n = 8.0.**

$B = 7.2 \times 10^{-9}$ mm/mm per day and $S_0 = 7$ Mpa

$E = 210$ GPa.

Solution:

$$V_0 = B\, S_0^{\,n}$$

$$\log_{10} V_0 = \log B + n \log S_0$$

$$\log_{10} B = \log (7.2 \times 10^{-9}) - 8 \log_{10} 7000$$

$$B = 1.248 \times 10^{-39}$$

$$\frac{1}{S^{n-1}} = \frac{1}{S_i^{n-1}} + BE(n-1)t$$

$$\frac{1}{(12600)^{8-1}} = \frac{1}{(14000)^{8-1}} + 1.248 \times 10^{-39} \times 210 \times 10^{6} (8-1)t$$

$$t = 5.638 \text{ days}$$

6.9 PROBLEMS

1. A steel bolt clamping two rigid plates together is held at a temperature of 540°C. Tests at this temperature gives $n = 3.0$ and $V_0 = 2.8 \times 10^{-8}$ (mm/mm) / hr at a stress of 28 Mpa. If the bolt is initially tightened to a stress of 70 Mpa, determine the stress remaining after 1 year has elapsed. Take E for steel as 210 Gpa.

Solution:

$$V_0 = B\,S^n$$

$$\log_{10} V_0 = \log_{10} B + n \log S$$

$$\log_{10} B = \log_{10} (2.8 \times 10^{-8}) - 3 \log_{10} \underline{28000}$$

?

$$B = 1.275 \times 10^{-21}$$

Given.

$S = 28$ KPa

$= 28000$ Pa

$E = 210$ GPa

$= 210 \times 10^9$ Pa

Stress relaxation equation is

$$\frac{1}{S^{n-1}} = \frac{1}{S_i^{n-1}} + BE(n-1)t$$

$S_i = 70$ Mpa, $E = 210$GPa

$t = 1$ year $= 8760$ hrs, $n = 3$.

?

$$\therefore \quad \frac{1}{S^{3-1}} = \frac{1}{(70000)^{3-1}} + 1.275 \times 10^{-21} \times 210 \times \underline{10^6}(3-1)8760$$

$$S = 14.287 \text{ Mpa}$$

CREEP RESISTANCE MATERIALS: