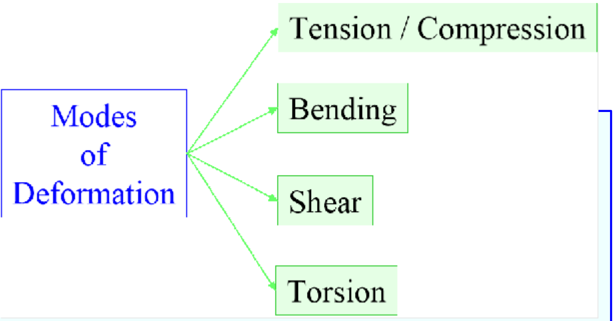
Deformation of metal

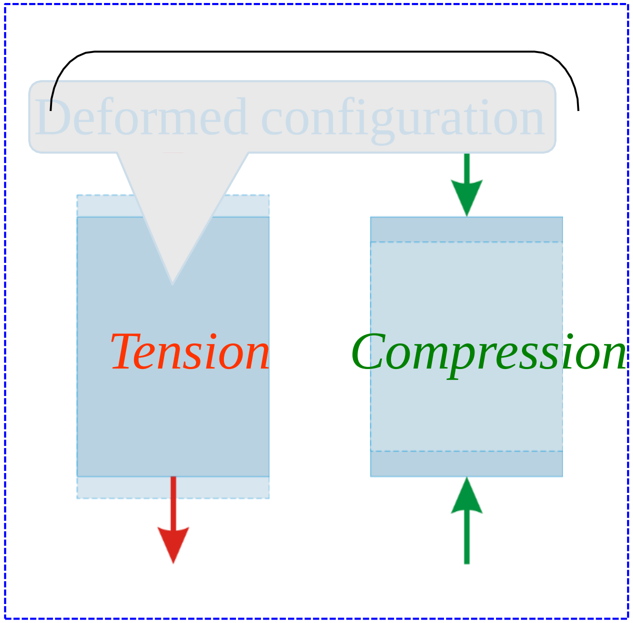
Common types of deformation

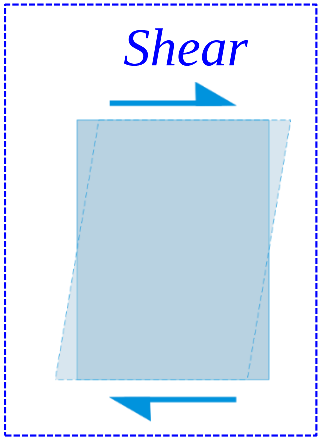

Modes of Deformation

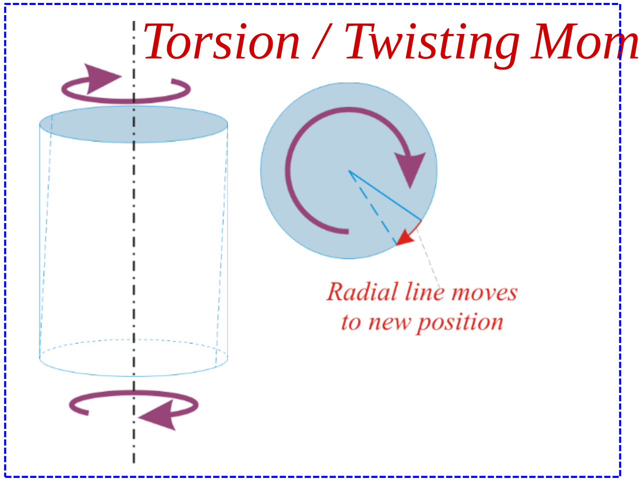
- Tension / Compression
- Bending
- Shear
- Torsion

A body can be deformed using many modes:

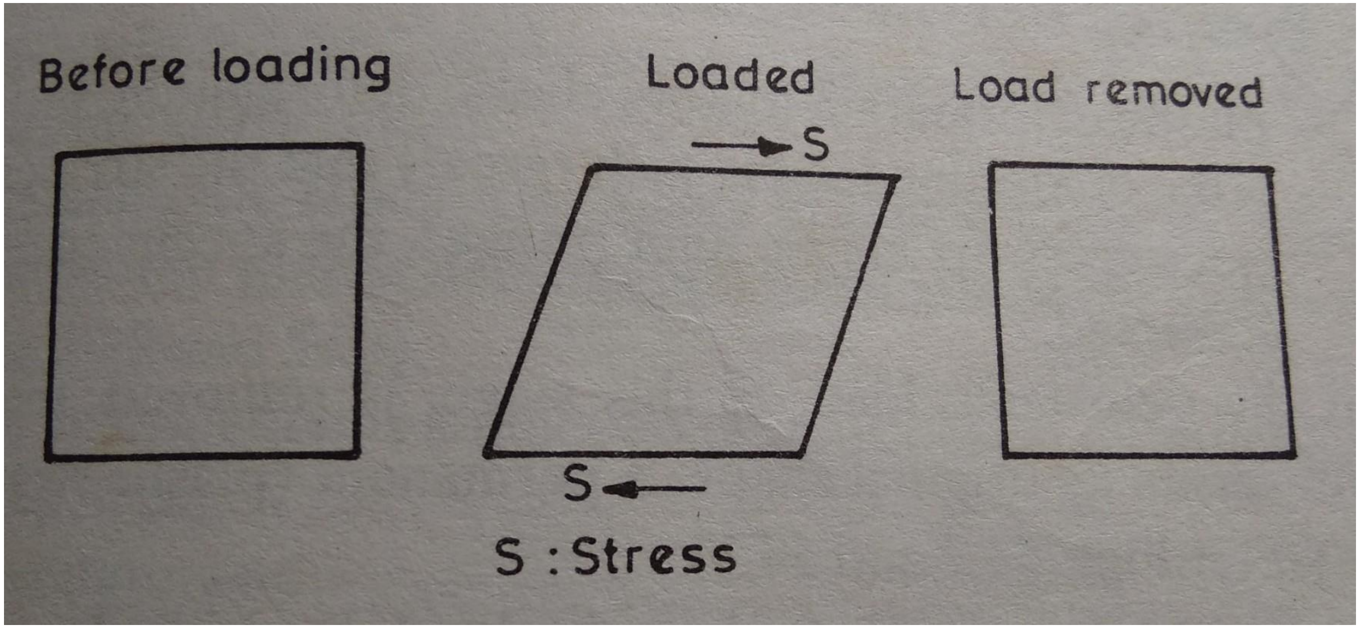
- Tension/Compression
- Bending
- Shear
- Torsion





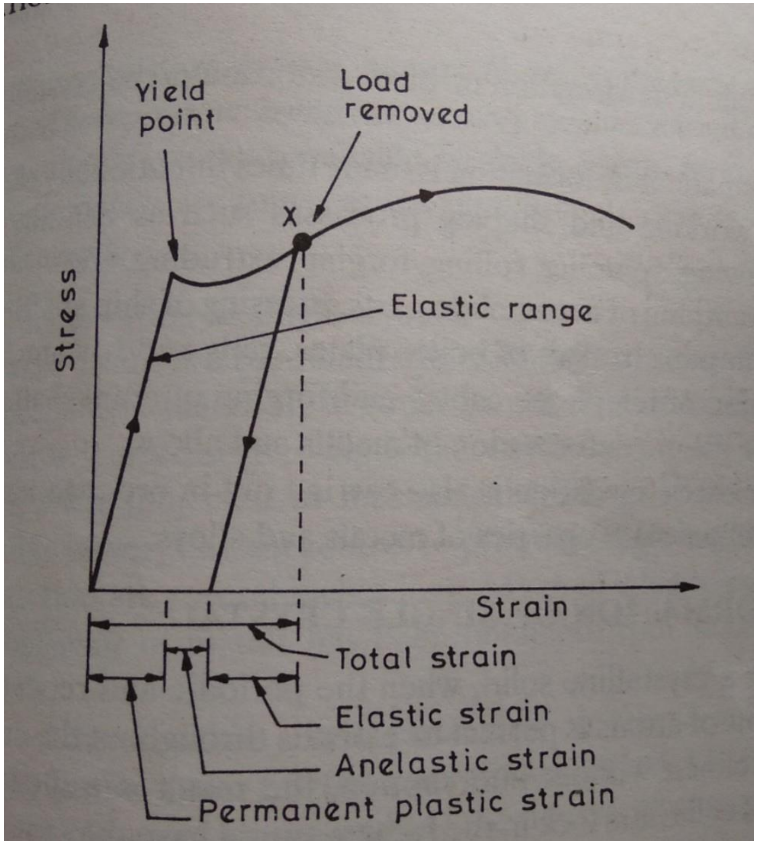


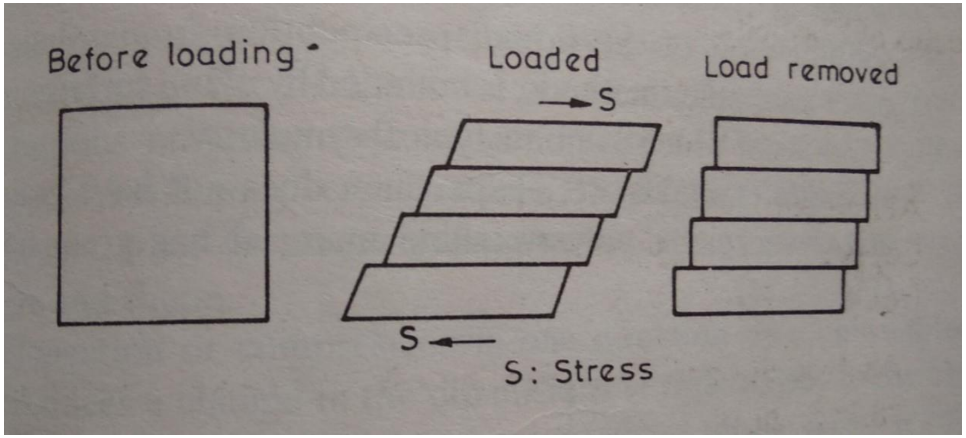
Elastic deformation

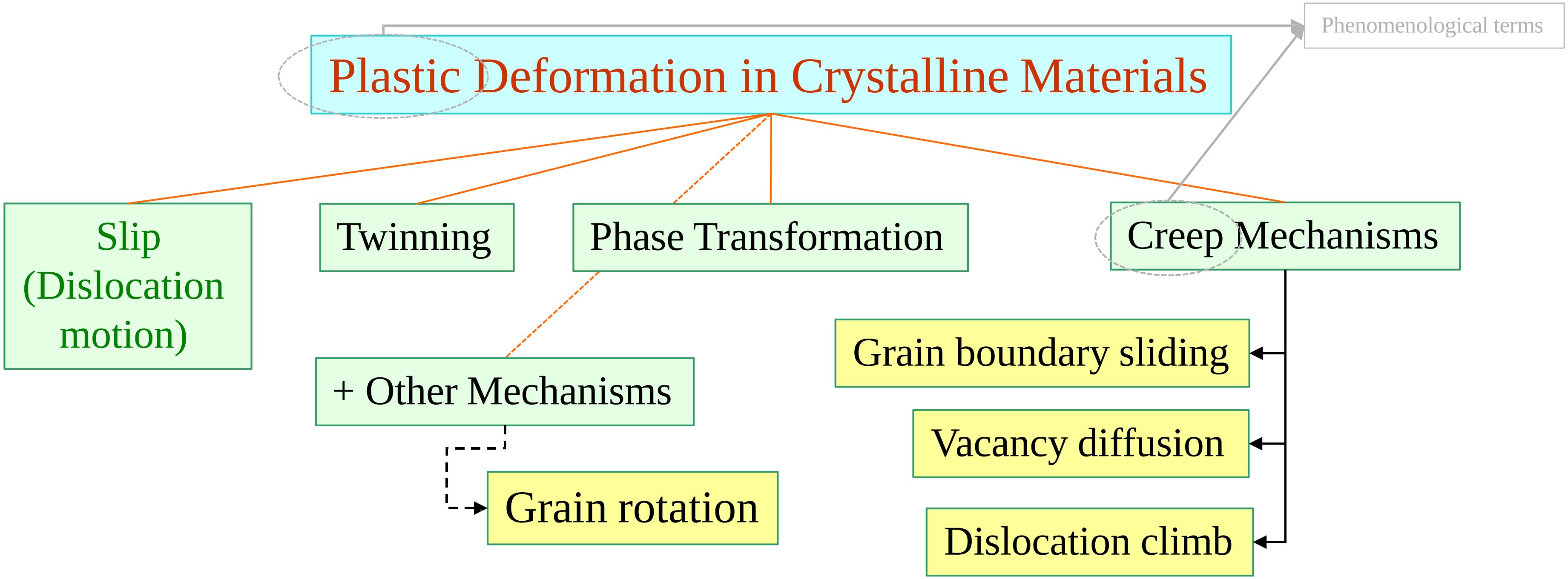


Deformation follows Hook’s law

Plastic deformation







Phenomenological terms

Plastic Deformation in Crystalline Materials

Slip (Dislocation motion)

Twinning

Phase Transformation

Creep Mechanisms

+ Other Mechanisms

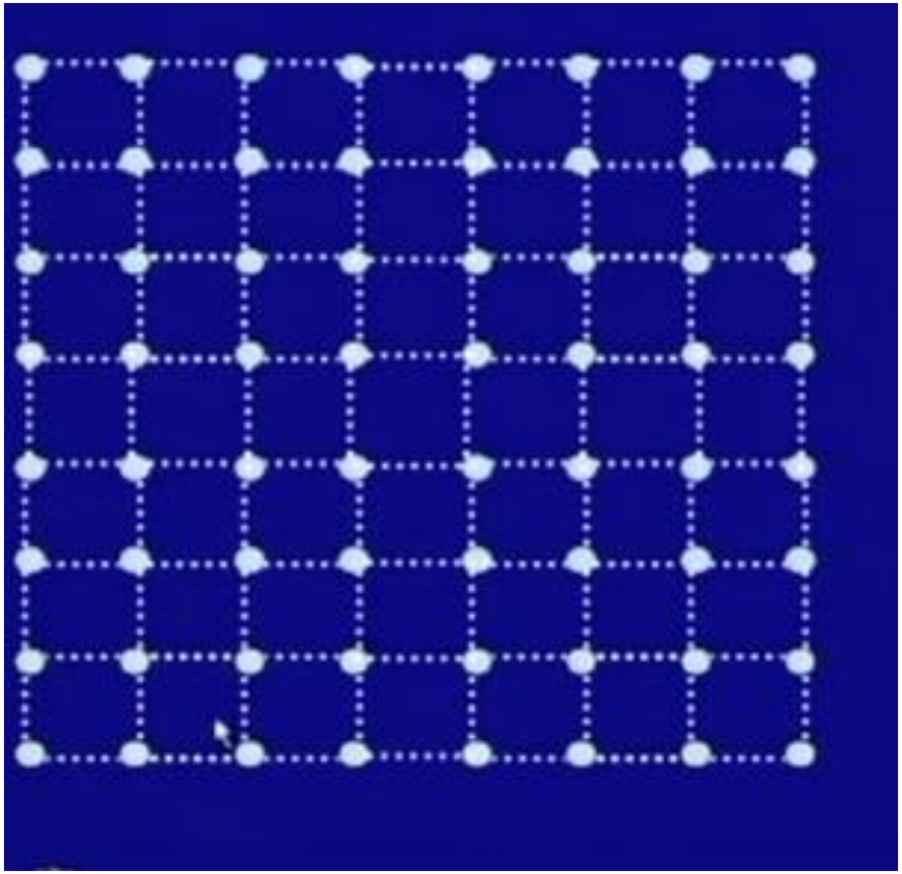
Grain rotation

Grain boundary sliding

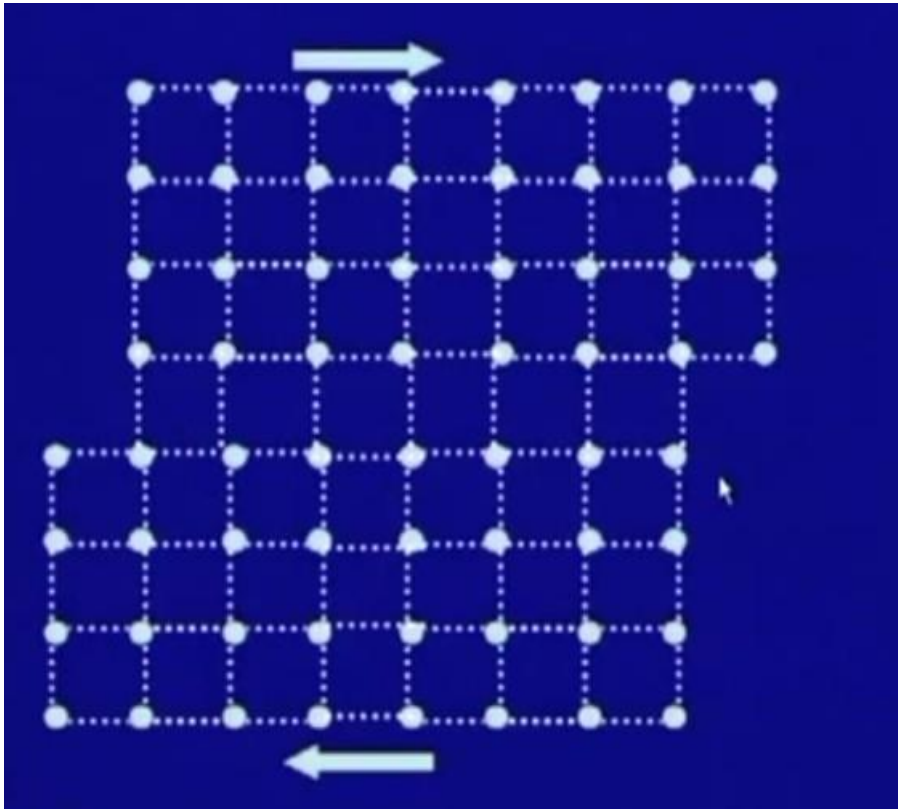
Vacancy diffusion

Dislocation climb

Plastic deformation mechanism: Slip

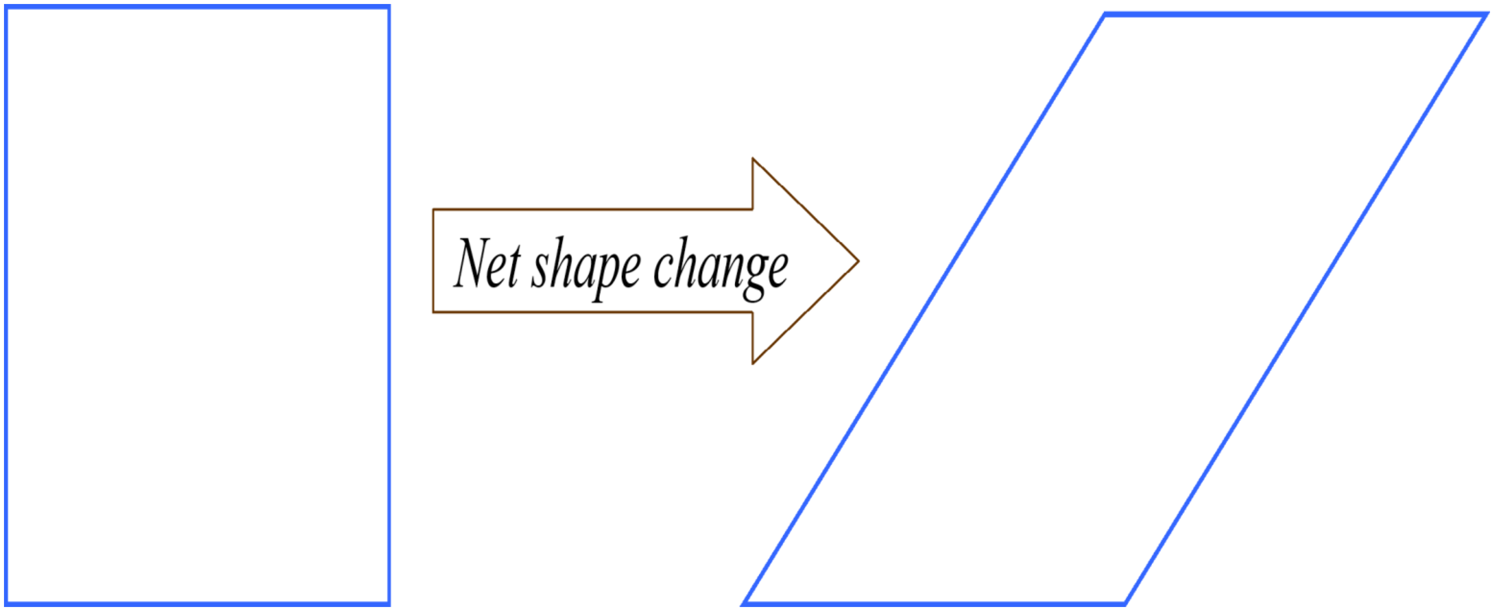


Plastic deformation mechanism: Slip



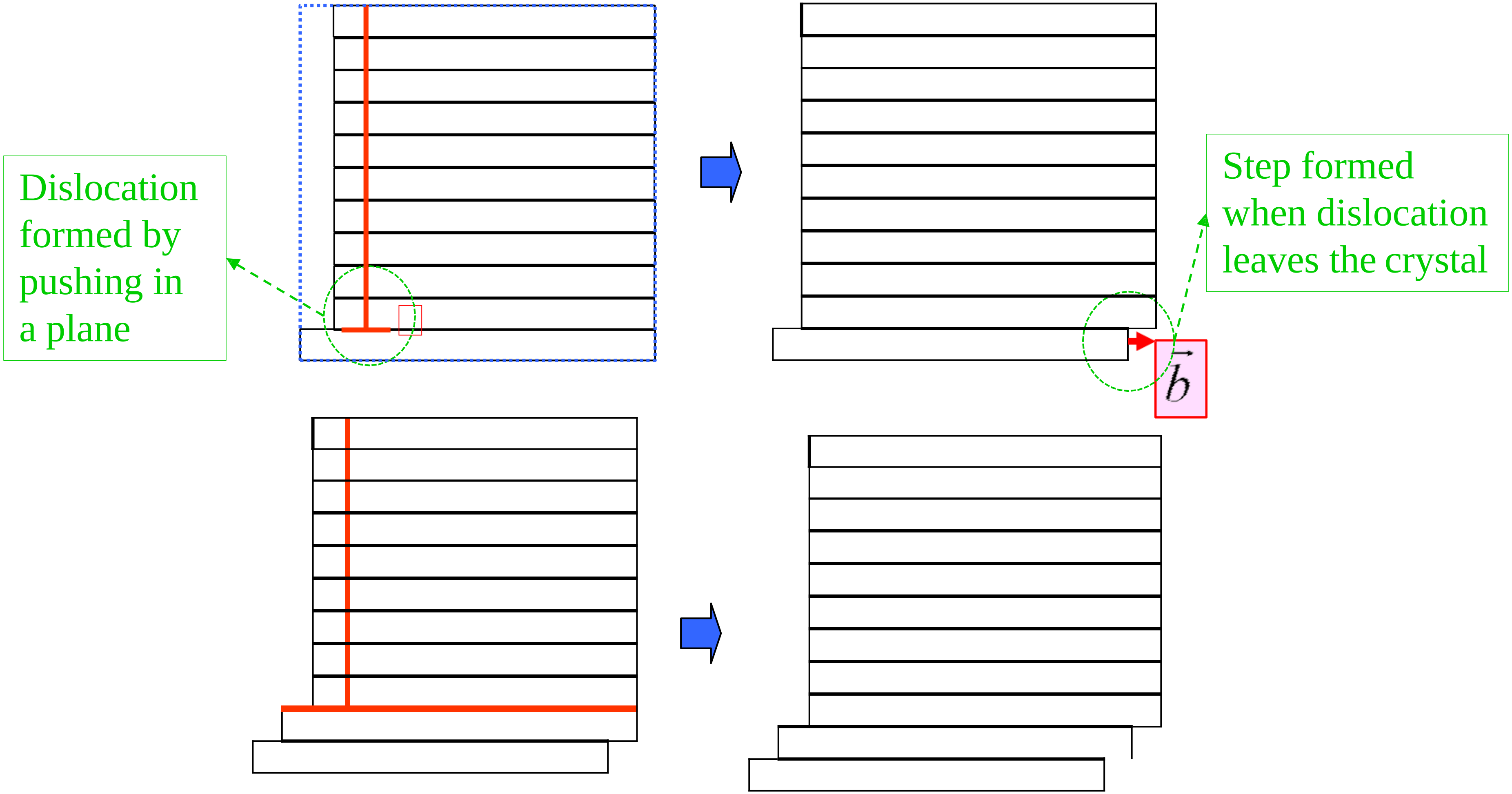
- **No change in crystal structure**
- **No change in orientation**
- **No change in lattice parameter/volume**
- **All atoms undergo identical deformation**

Plastic deformation mechanism: Slip (Cont..)



Net shape change

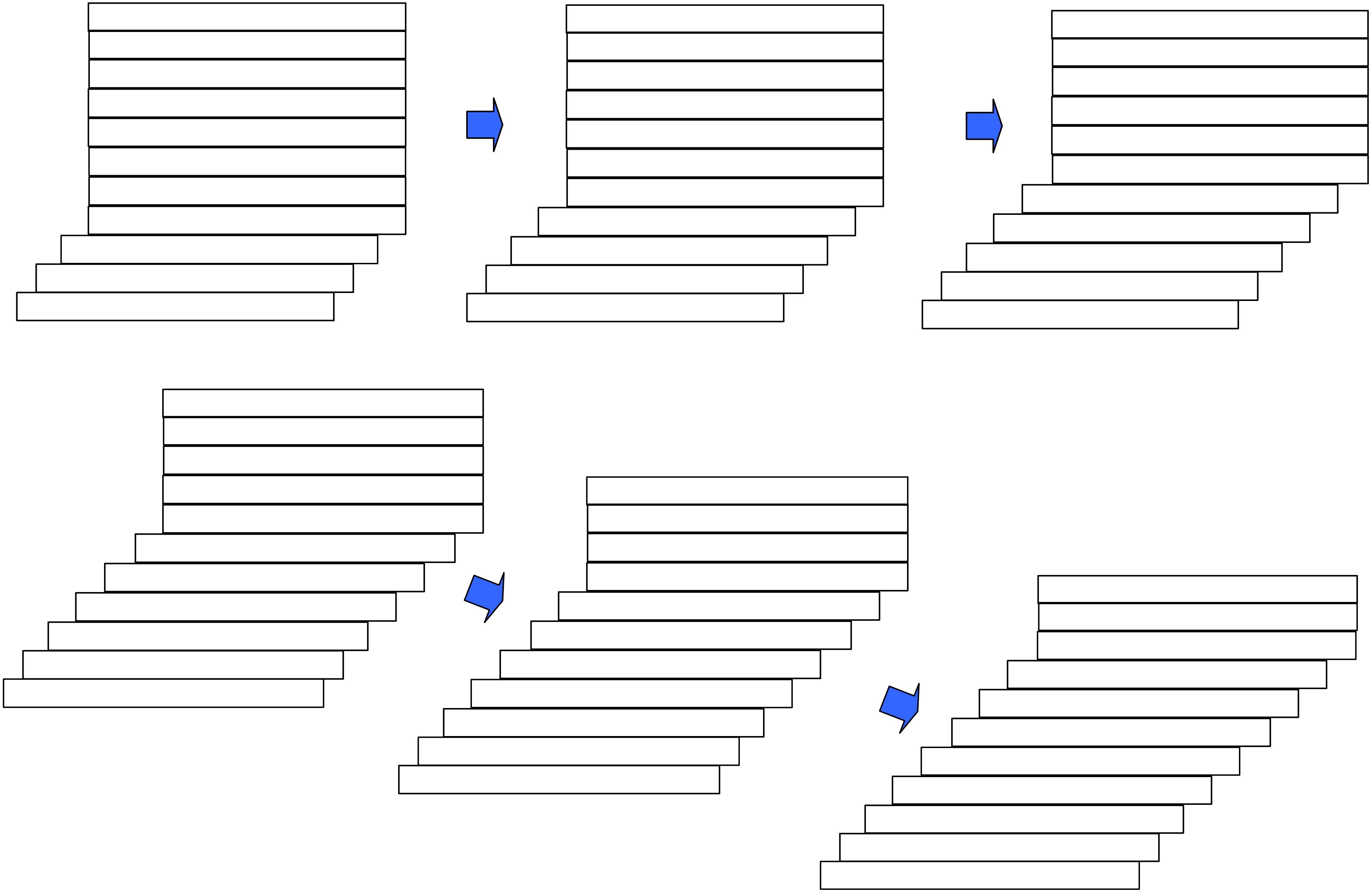
Plastic deformation mechanism: Slip (Cont..)

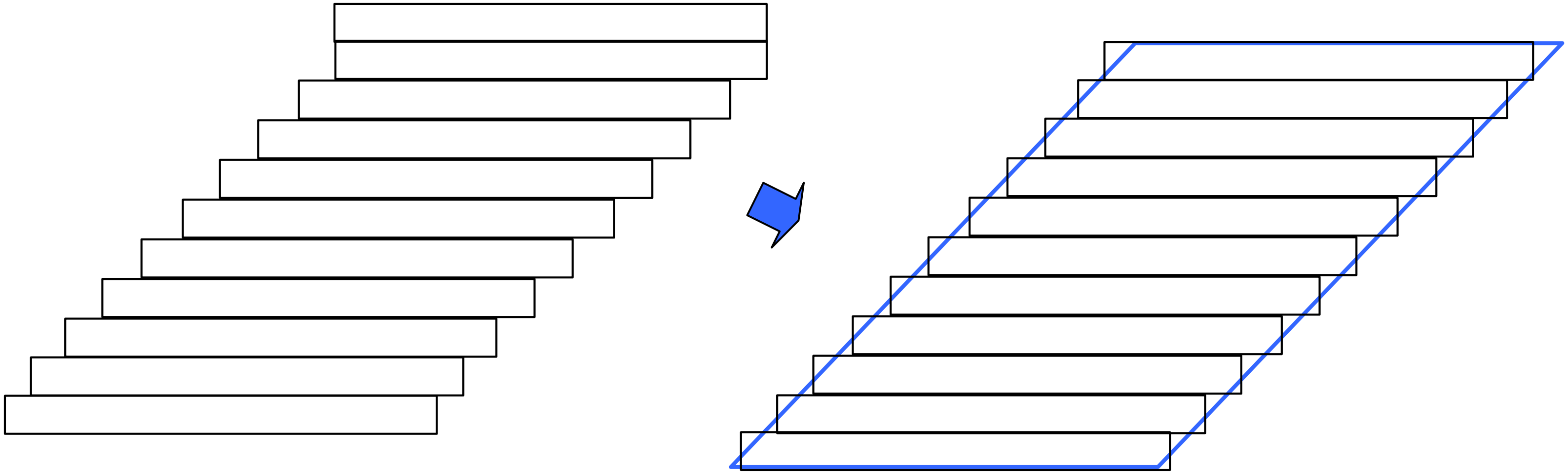


Dislocation formed by pushing in a plane

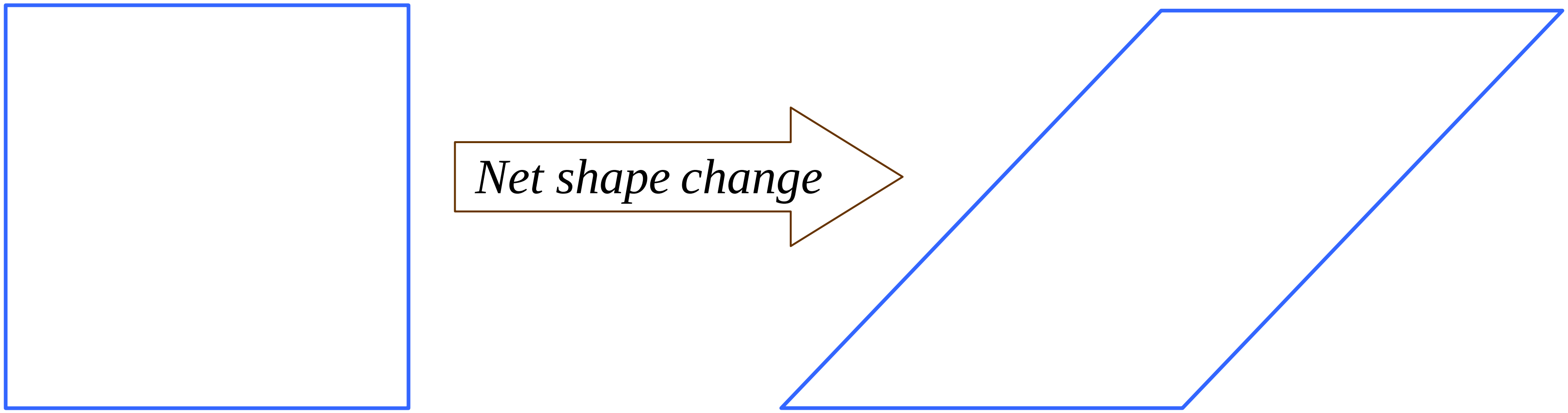
Step formed when dislocation leaves the crystal

Now visualize dislocations being punched in on successive planes → moving and finally leaving the crystal

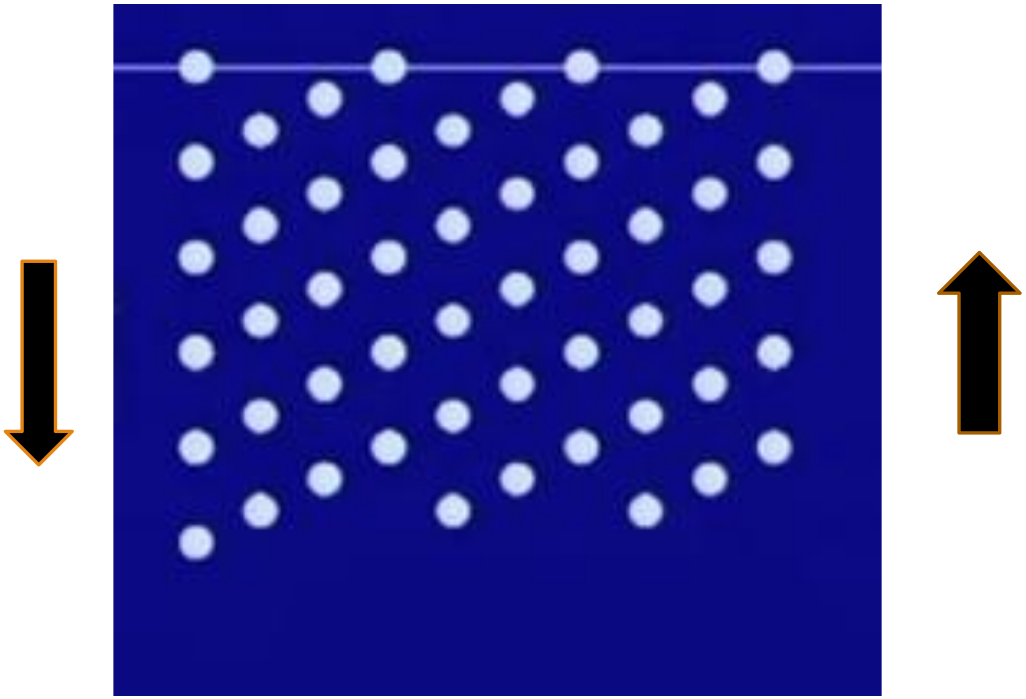




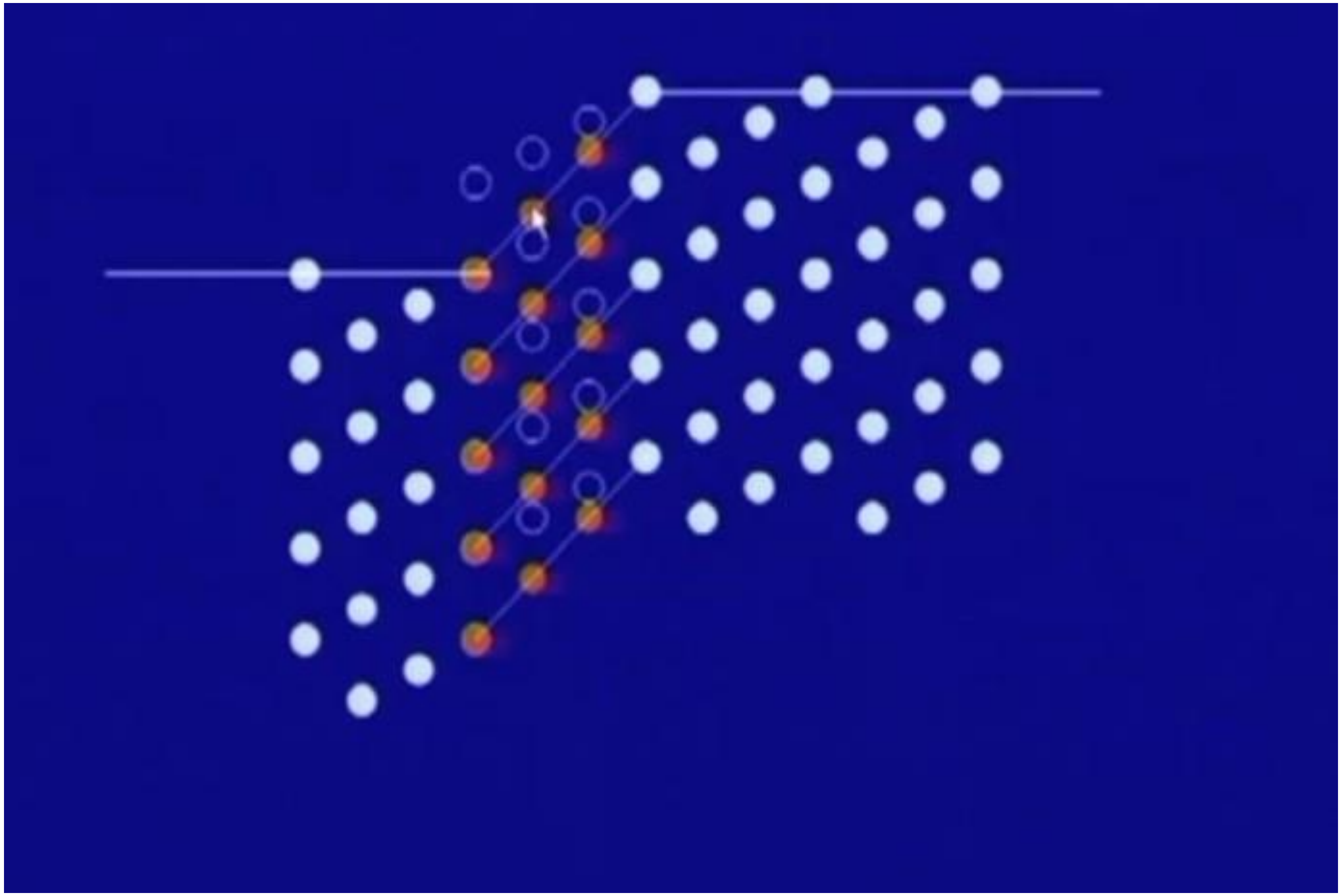
This sequence of events finally leads to deformed shape which can be approximated to a rhombus


Net shape change

Deformation by twinning

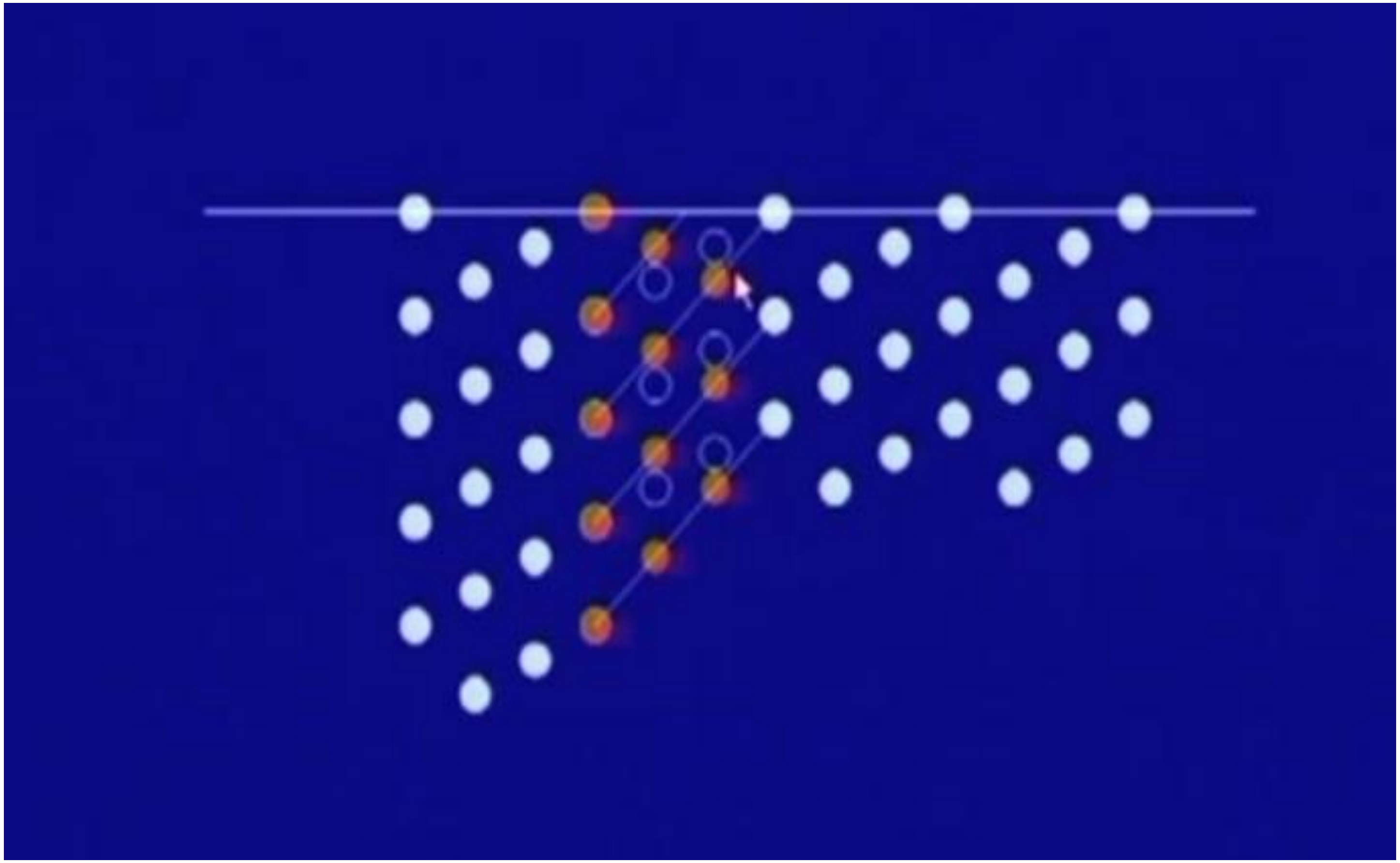


Deformation by twinning



Twin has a different orientation and displacement is proportional to the distance from the twin plane

Deformation by twinning



Plastic deformation mechanism

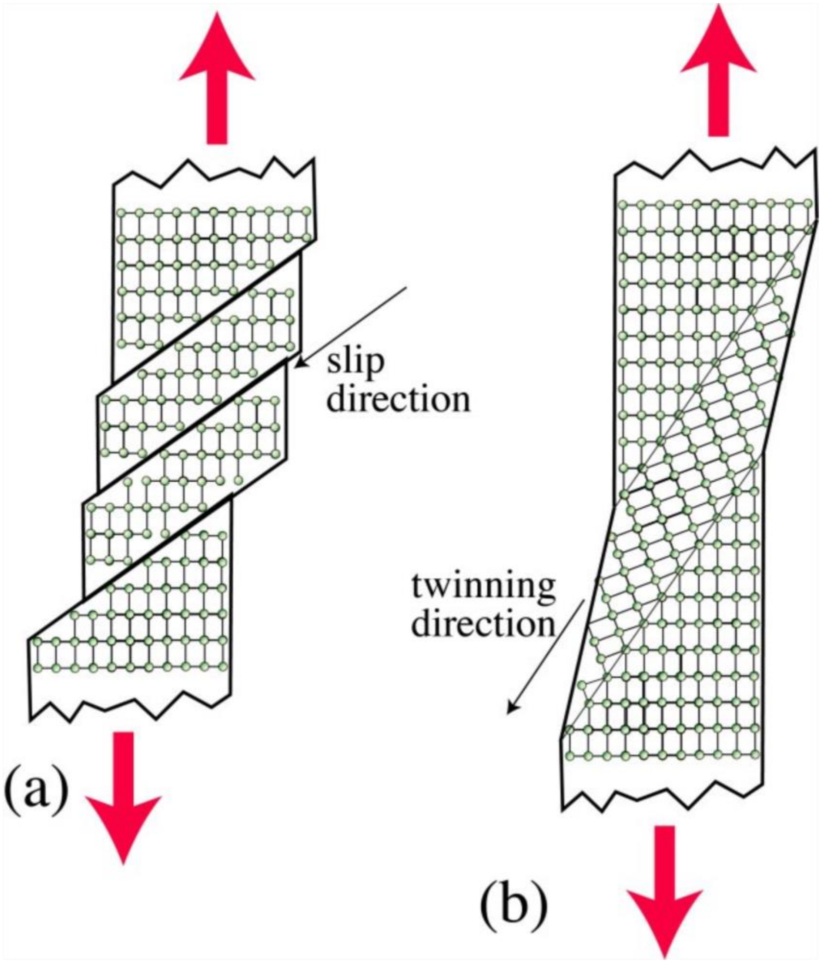


FIGURE 7.10 Slip lines on the surface of a polycrystalline specimen of copper that was polished and subsequently deformed. 173×. [Photomicrograph courtesy of C. Brady, National Bureau of Standards (now the National Institute of Standards and Technology, Gaithersburg, MD.)]

Callister

Slip lines in the microstructure of plastically deformed Cu

Experiment 5

Twin Bands In Zinc

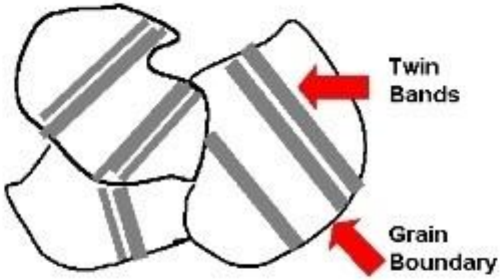


Figure : Twin bands

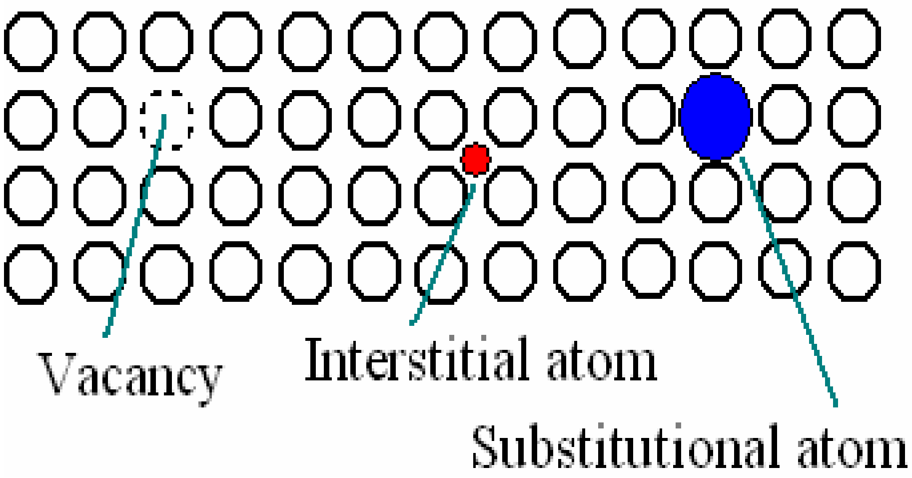
Figure : Twin bands in zinc.

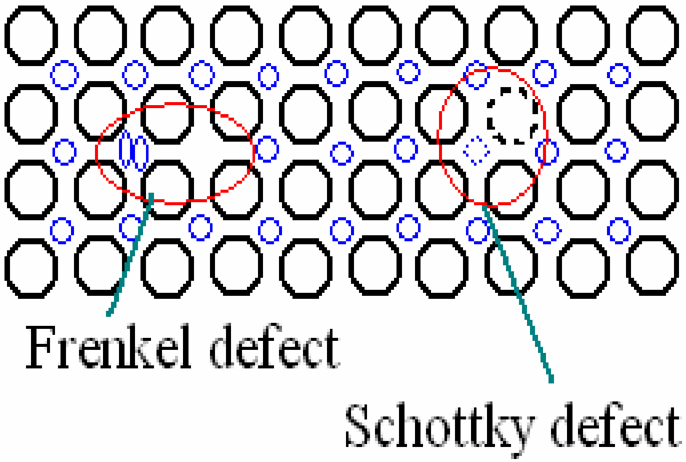
Crystal defects in metal

- **Point defect:** Vacancy, interstitial, substitutional
- **Line defect:** Dislocation (edge/screw)
- **Surface defect:** Stacking fault, twin boundary, grain boundary

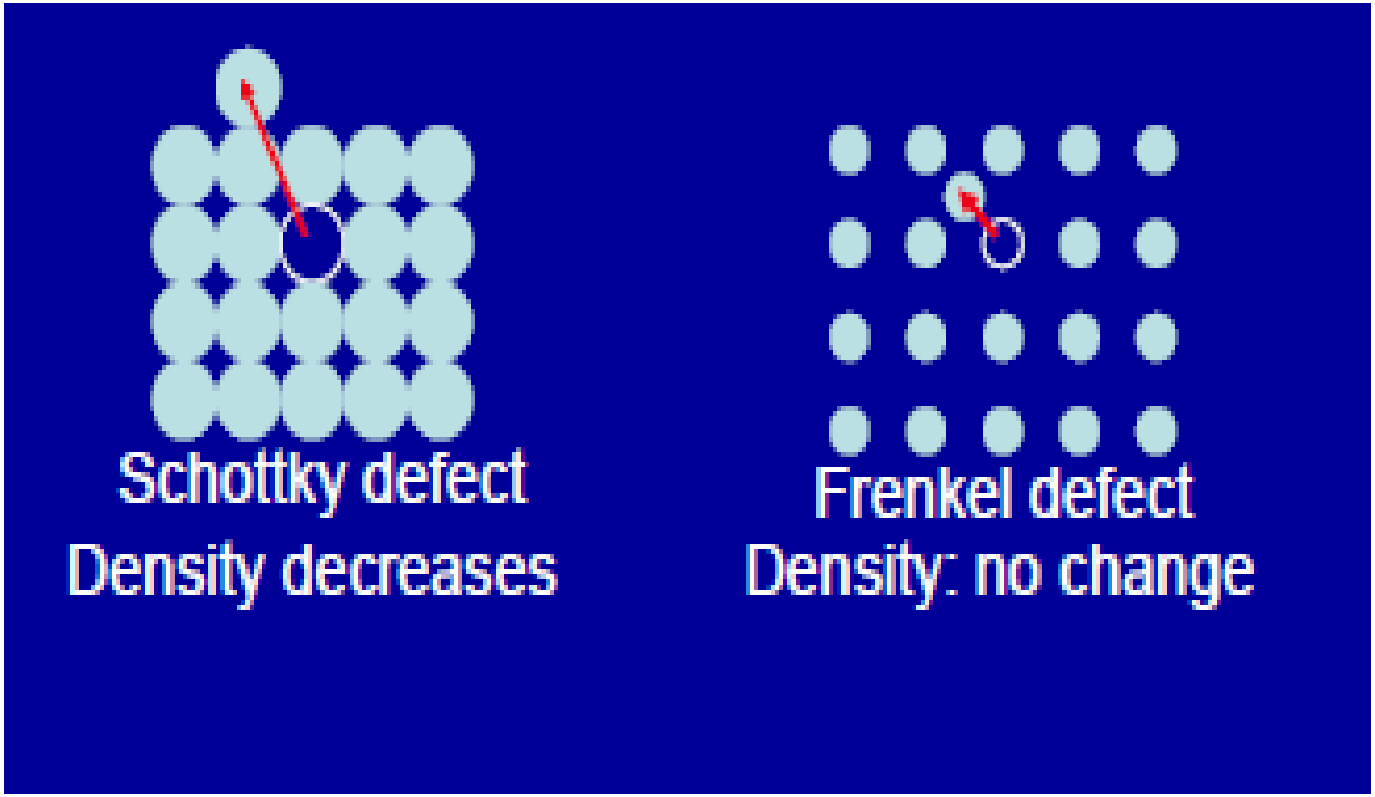
Point defect: Vacancy

- Point defects are of zero dimensional i.e. atomic disorder is restricted to point like regions

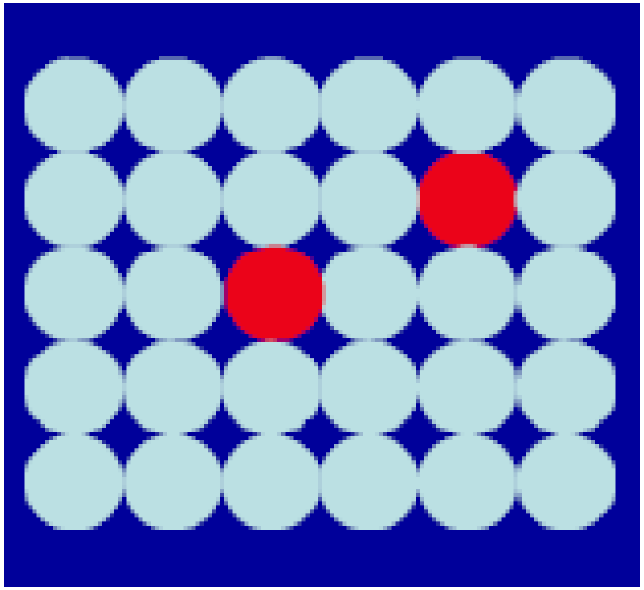




Point defect: Vacancy (Conted…)

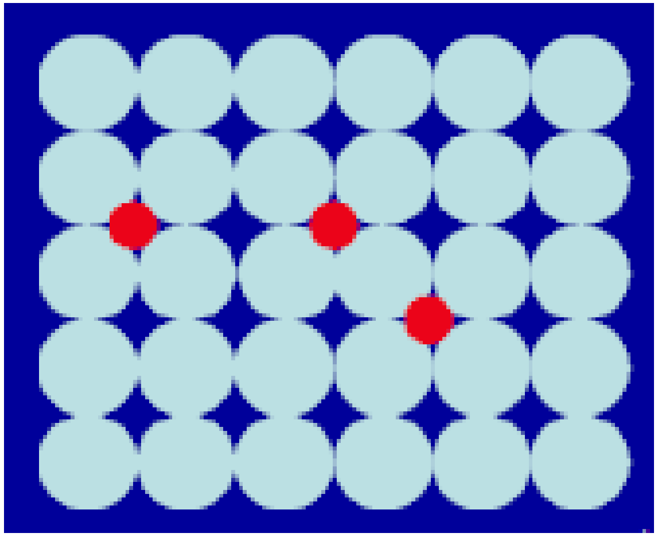


Point defect: Substitutional solid solution

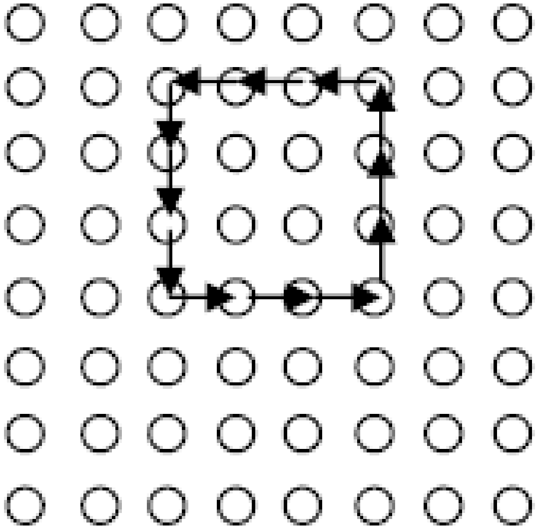


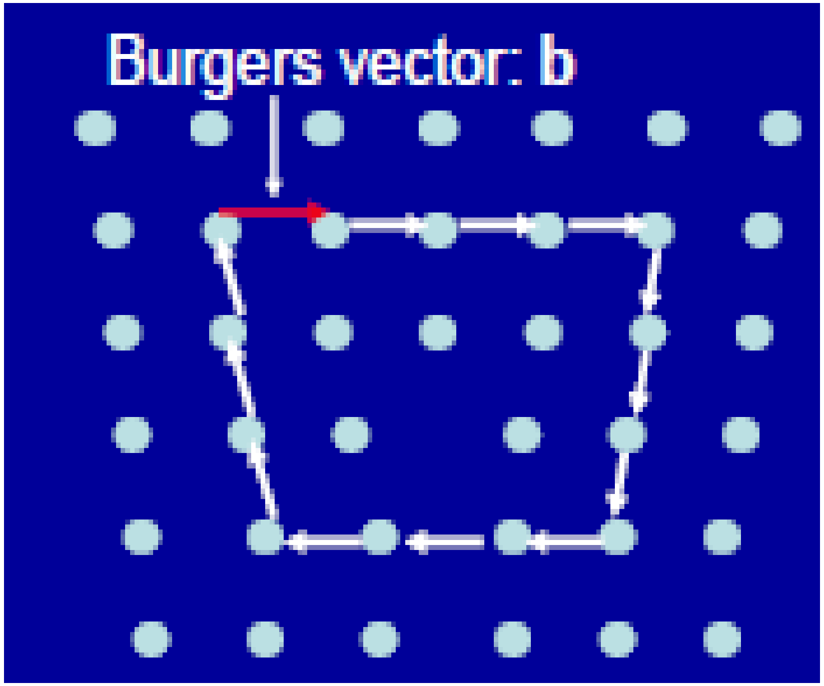
- Pure metal is soft addition of alloy element makes it hard: Sterling Silver (AgCu)

Point defect: Interstitial solid solution



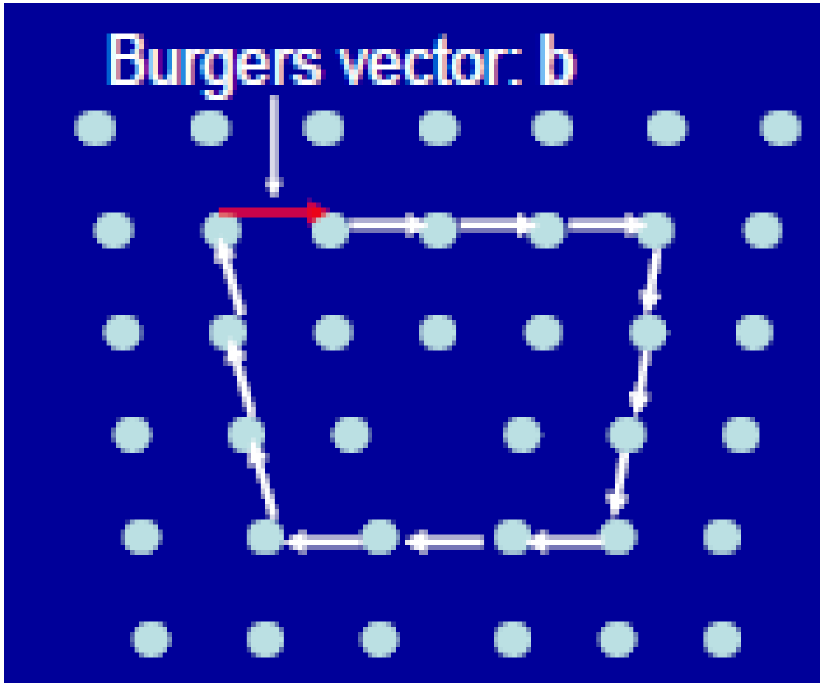
Line defect: Edge dislocation





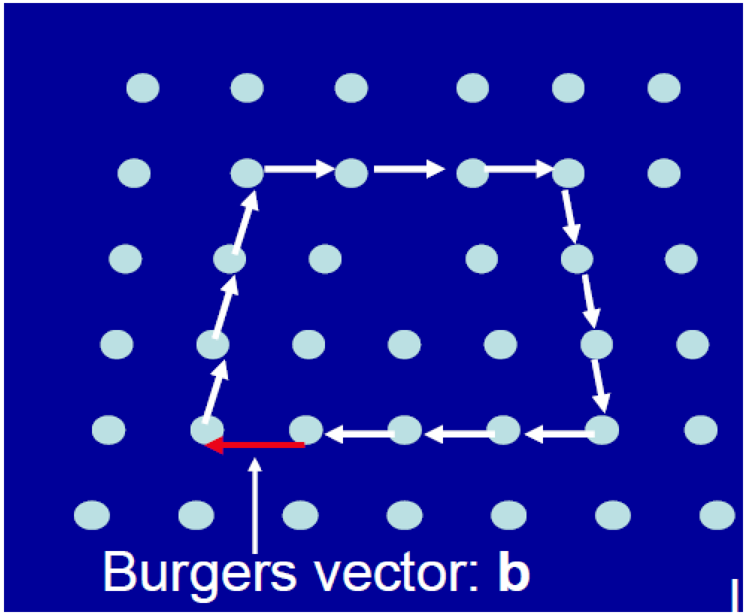
A dislocation may be defined as a defined as a disturbed region between two substantially perfect parts of a crystal

Edge dislocation is a localized distortion of the crystal lattice due to the presence of extra half plane



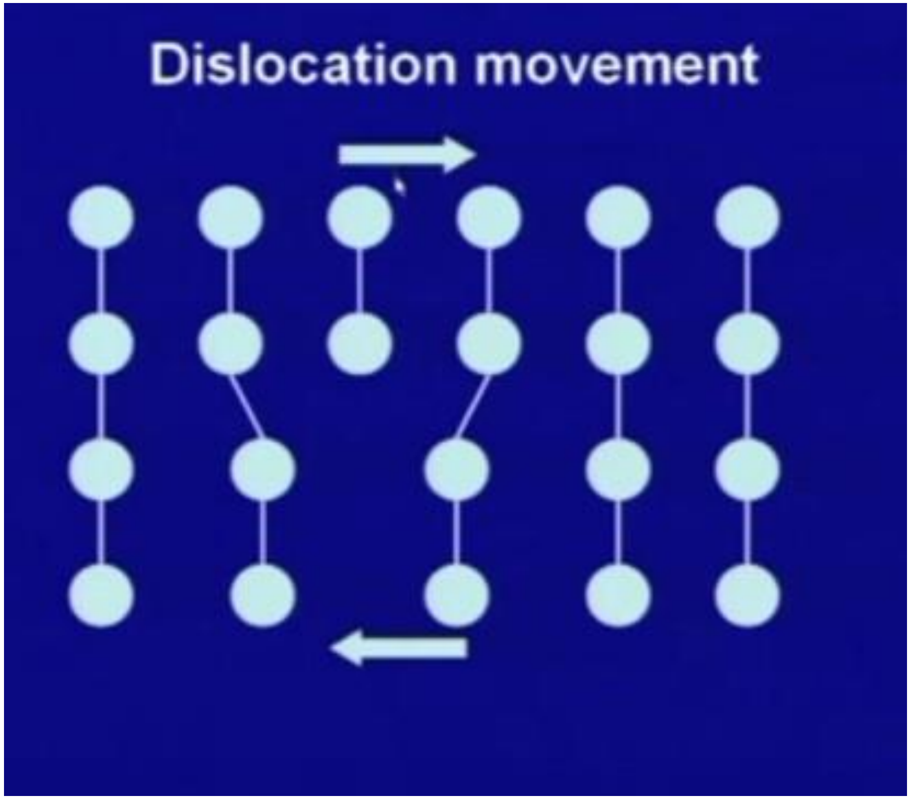
- Positive edge dislocation
- Extra half plane lies in the upper half of slip plane

- Stress field:
- Upper half compressive
- Lower half tensile



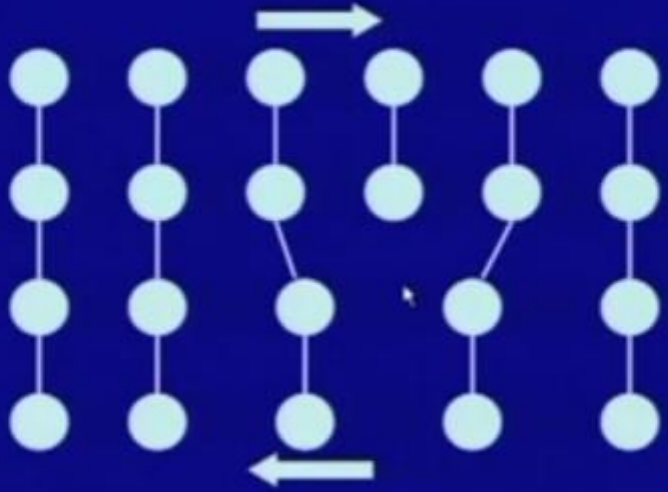
- Negative edge dislocation
- Extra half plane lies in the lower half of slip plane

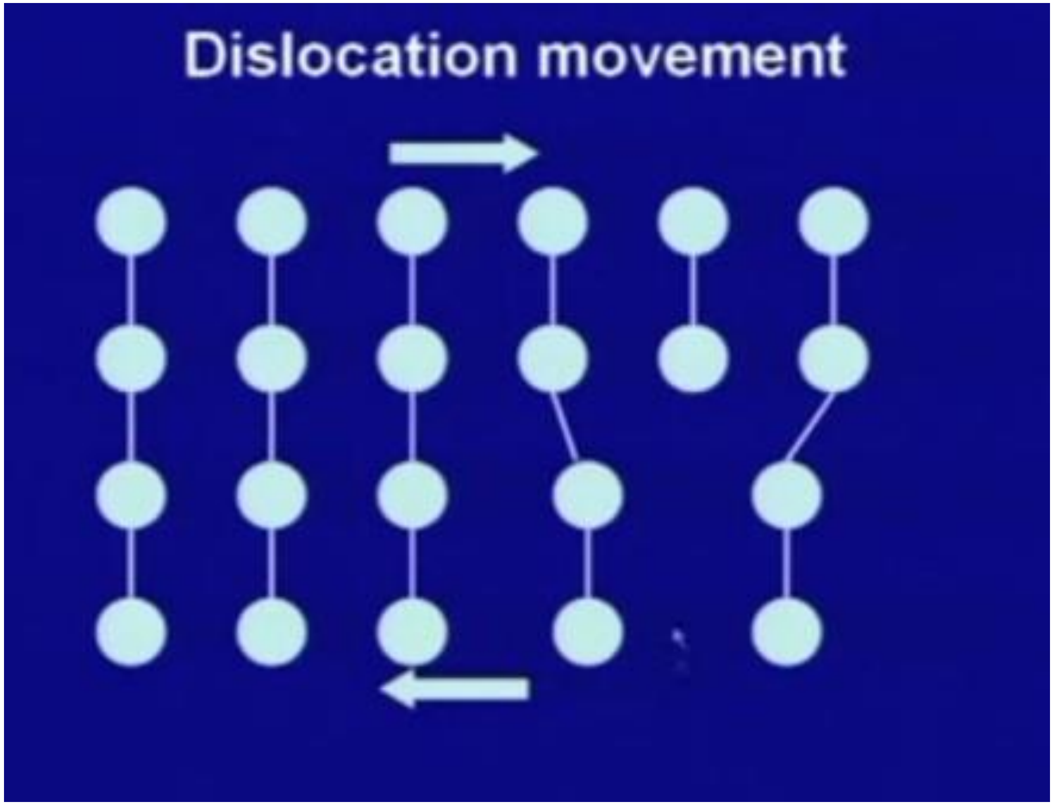
- Stress field:
- Upper half tensile
- Lower half compressive



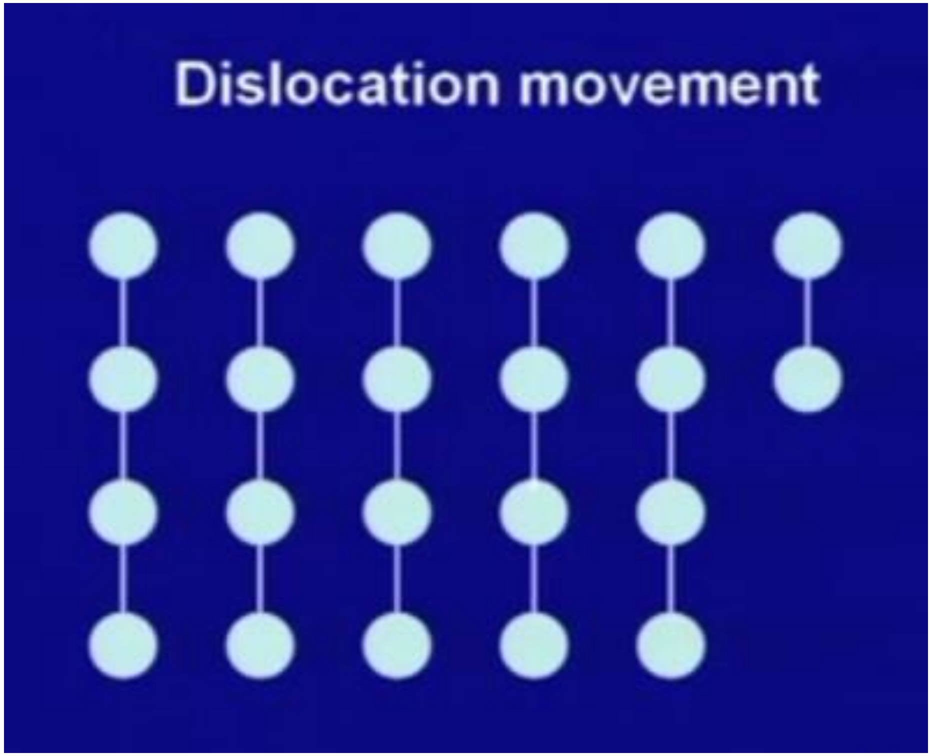
Dislocation movement

Dislocation movement



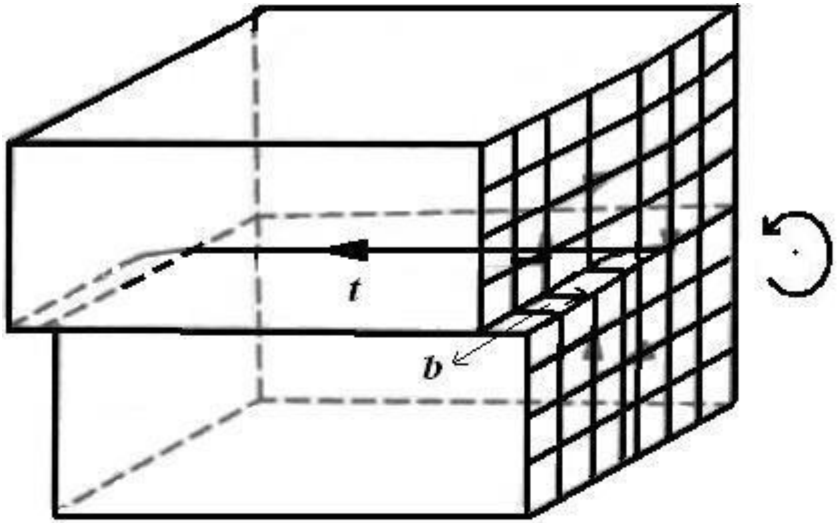


Dislocation movement

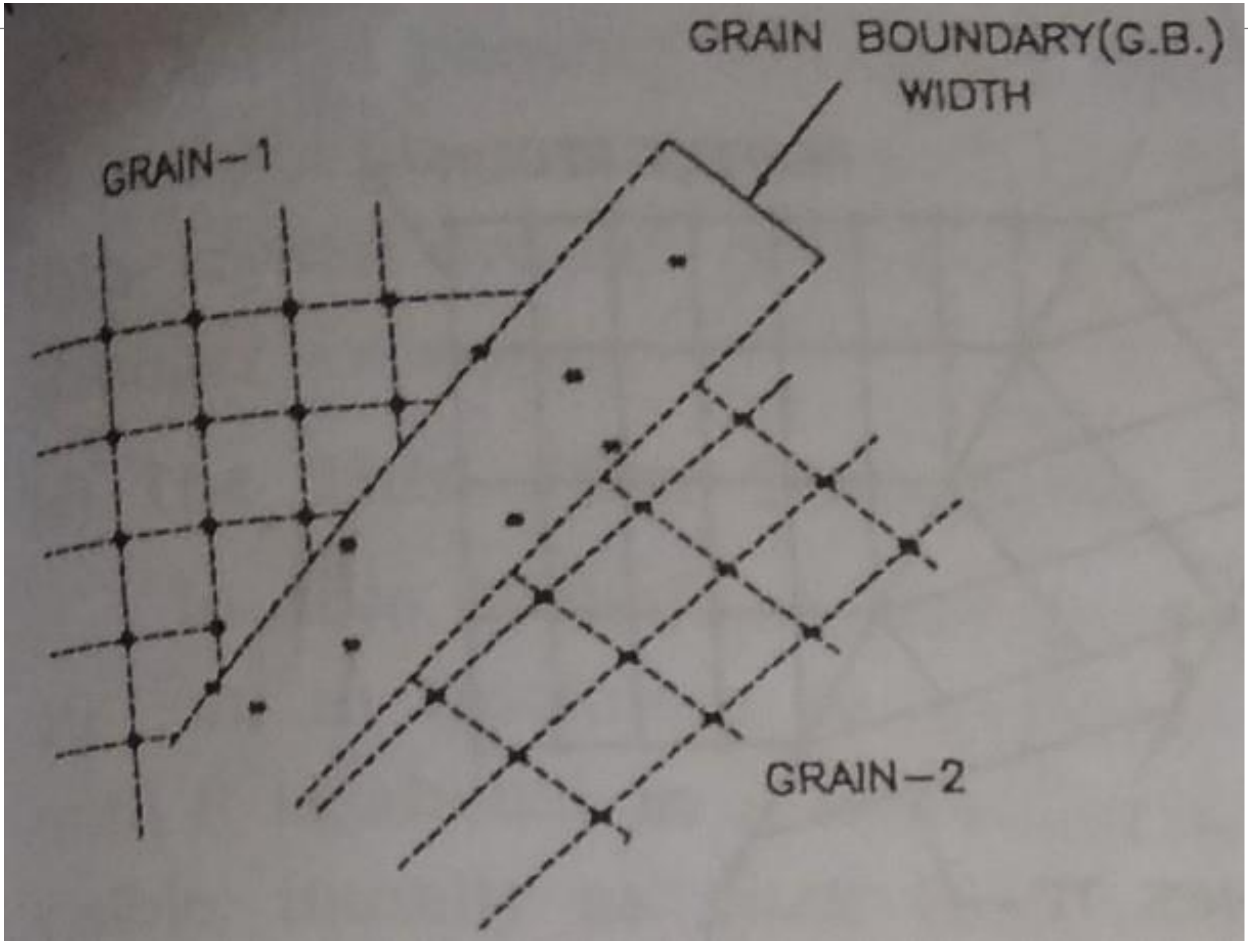


- As the dislocation moves out it leaves behind a slip step. Its magnitude is b

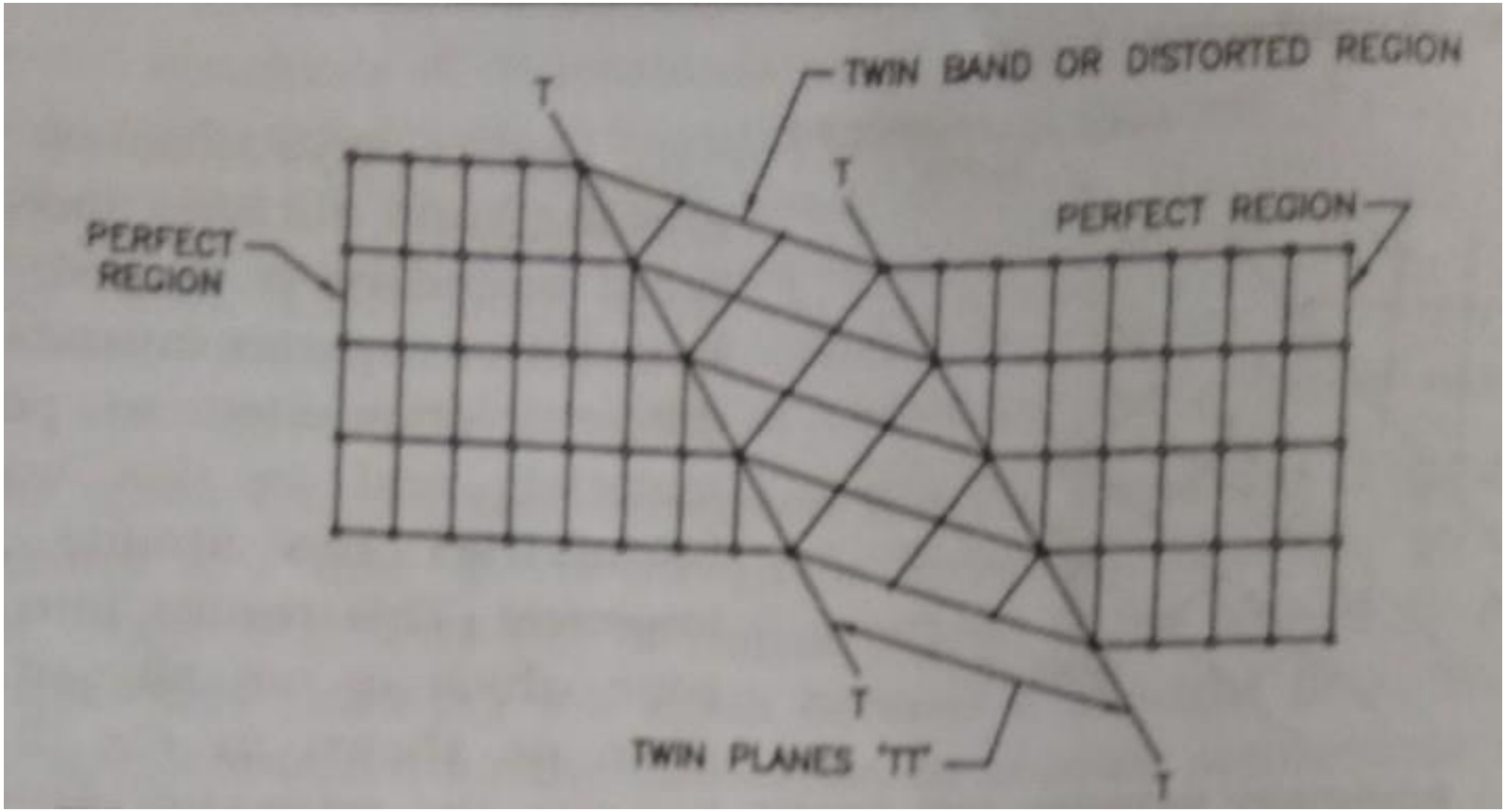
Screw Dislocation

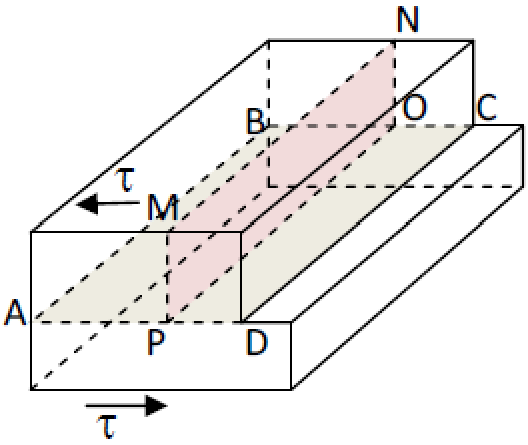


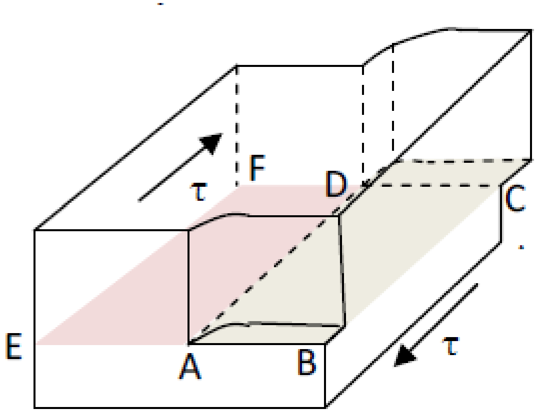
Surface defect: Grain boundary



Surface defect: Twin boundary

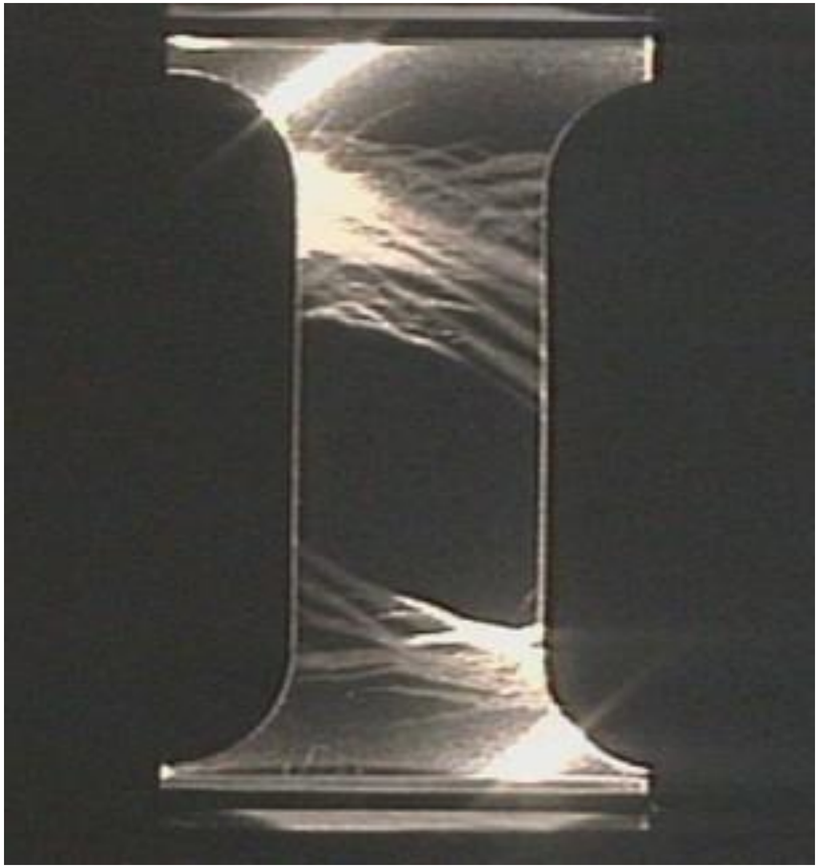



N
B
O
C
τ
M
A
P
D
τ


F
τ
D
C
E
A
B
τ

Edge dislocation	Screw dislocation
1. An edge dislocation lies perpendicular of its Burgers vector	1. An screw dislocation lies perpendicular of its Burgers vector
2. An edge dislocation moves in the direction of the Burgers vector	2. An screw dislocation moves in the direction perpendicular to the Burgers vector
3. Force required to initiate an edge dislocation is less	3. Force required to initiate an screw dislocation is more
4. Speed of movement of edge dislocation is less	4. Speed of movement of screw dislocation is more
5. Region of lattice distribution in edge dislocation extends along an edge inside a crystal	5. Region of lattice distribution extends in two separate planes perpendicular to each other

Discontinuous and Inhomogeneous Deformation



C1 Precipitation hardening

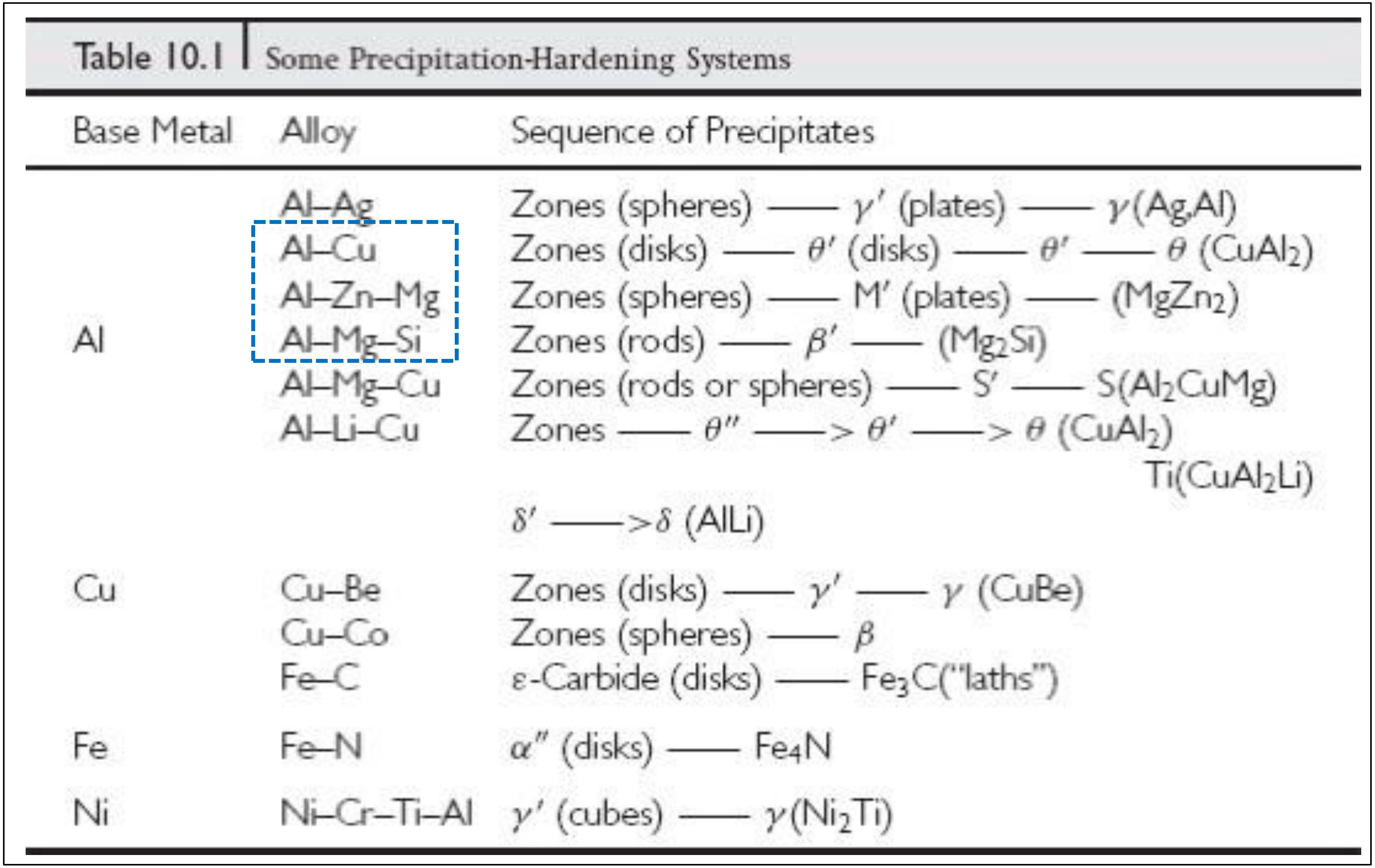


Table 10.1 Some Precipitation-Hardening Systems

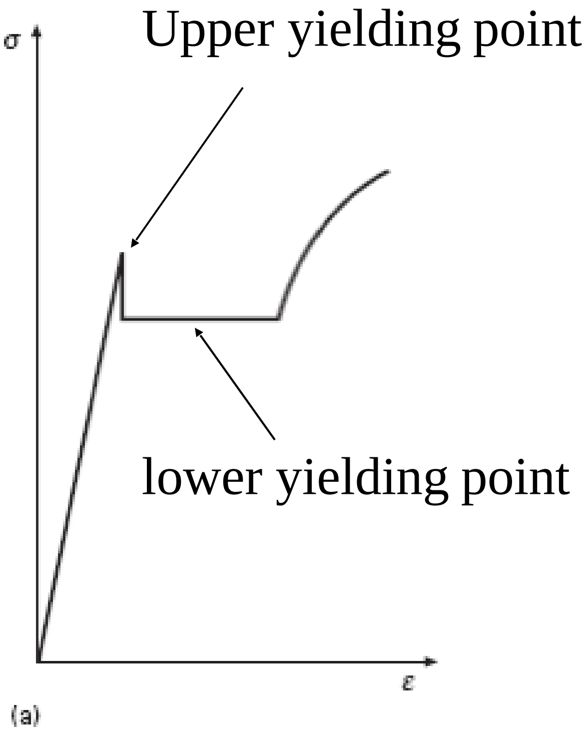
Base Metal	Alloy	Sequence of Precipitates
Al	Al–Ag	Zones (spheres) —— γ' (plates) —— γ(Ag,Al)
	Al–Cu	Zones (disks) —— θ' (disks) —— θ' —— θ ($CuAl_2$)
	Al–Zn–Mg	Zones (spheres) —— M′ (plates) —— ($MgZn_2$)
	Al–Mg–Si	Zones (rods) —— β' —— (Mg_2Si)
	Al–Mg–Cu	Zones (rods or spheres) —— S′ —— S(Al_2CuMg)
	Al–Li–Cu	Zones —— θ'' ——> θ' ——> θ ($CuAl_2$) Ti($CuAl_2Li$) δ' ——> δ (AlLi)
Cu	Cu–Be	Zones (disks) —— γ' —— γ (CuBe)
	Cu–Co	Zones (spheres) —— β
	Fe–C	ε-Carbide (disks) —— Fe_3C("laths")
Fe	Fe–N	α'' (disks) —— Fe_4N
Ni	Ni–Cr–Ti–Al	γ' (cubes) —— γ(Ni_3Ti)

C1 Precipitation hardening

The International Alloy Designation System is the most widely accepted naming scheme for wrought alloys. Each alloy is given a four-digit number, where the first digit indicates the major alloying elements.

- **1XXX** series: pure Al, work hardening, non-heat treatable alloys
- **2XXX** series: Al- Cu, precipitation hardening (Al-Cu), heat treatable alloys
- **3XXX** series: Al- Mn, work hardening (0.62%Mn), non-heat treatable alloys
- **4XXX** series: Al- Si (1.5%Si), non-heat treatable alloys
- **5XXX** series: Al- Mg (17.1%Mg), non-heat treatable alloys
- **6XXX** series: Al- Mg- Si, precipitation hardening (Al-Mg-Si), heat treatable alloys
- **7XXX** series: Al- Zn-Mg, precipitation hardening (Al-Zn-Mg), heat treatable alloys
- **8XXX** series: Miscellaneous alloys eg. Al-Li alloys

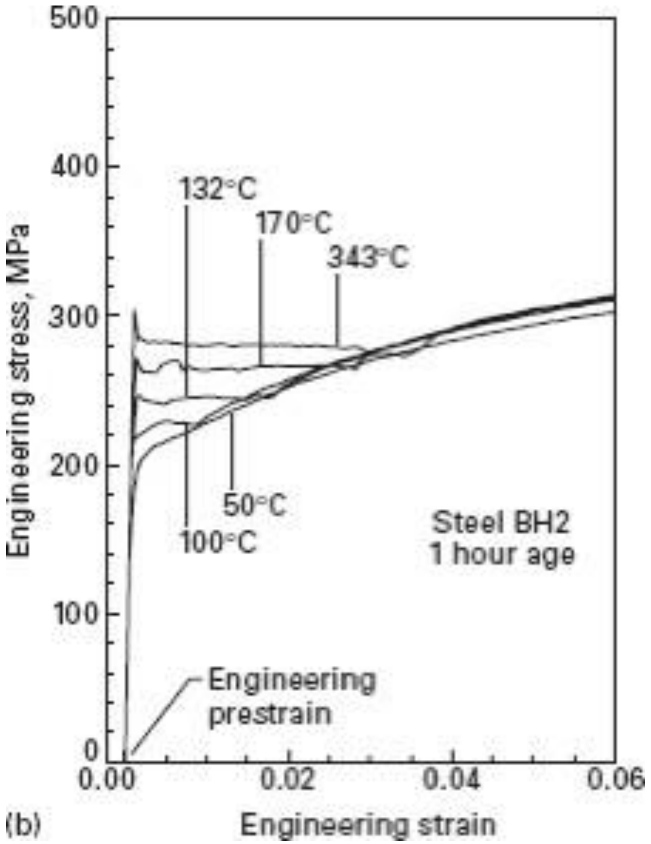
C2: Upper yield points caused by Solutes



Upper yielding point

lower yielding point

Low carbon steel



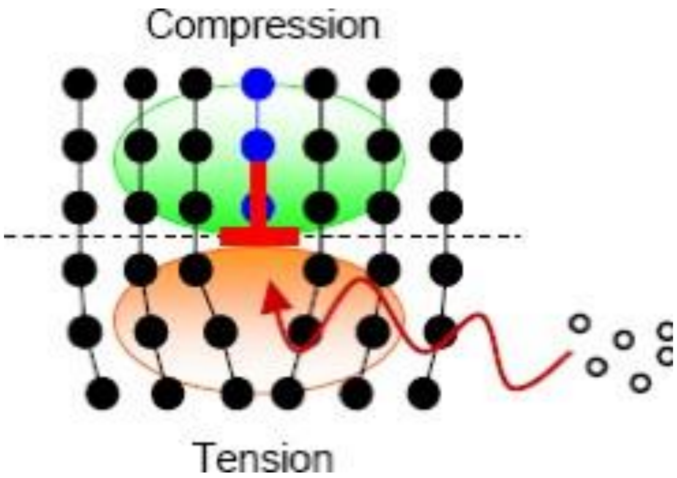
Low-carbon steel in a temper-rolled condition and annealed for one hour between 100 ◦C and 34.3 ◦C

Upper yield points caused by Solutes: Mechanism

- Solute atoms will preferentially segregate to the distorted regions near the dislocations such that the total elastic strain can be minimized (i.e., solutes will move to locations that **minimize the distortion of the lattice caused by their presence**).

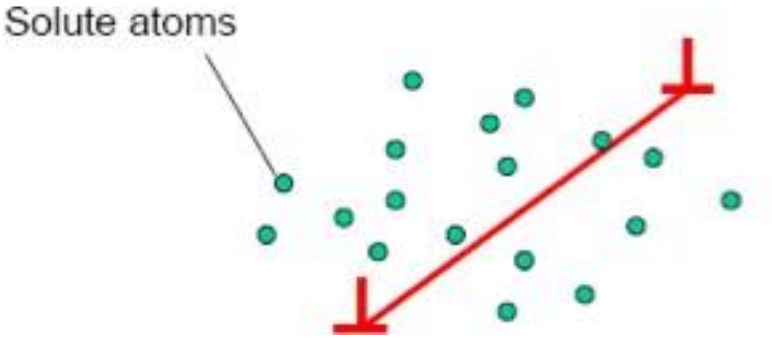
- This segregation of solutes results in the formation of solute atmospheres wherein solute atoms will tend **to accumulate in the stress field of the dislocation**.

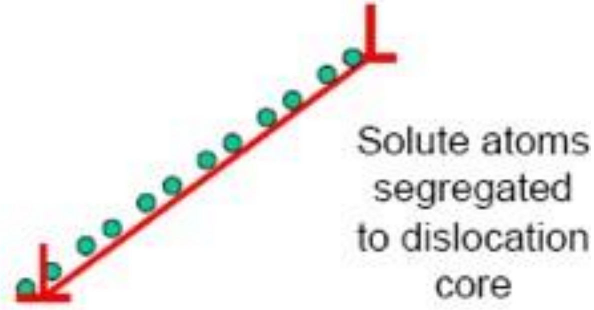
Cottrell-Bilby Model



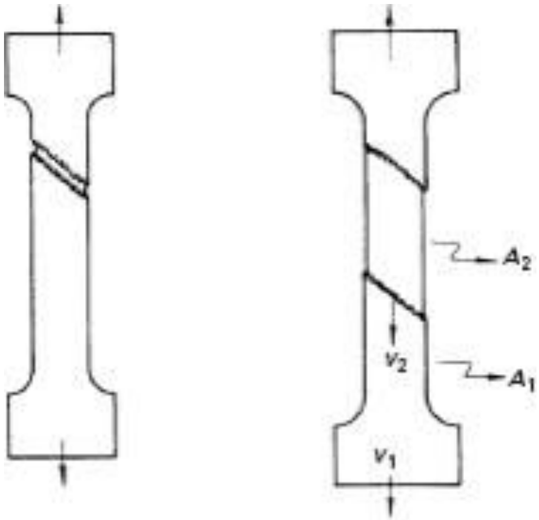
Upper yield points caused by Solutes: Mechanism

- At elevated temperatures, diffusion processes increase mobility for the solute atoms. Solute atmospheres can move along with the dislocation line in order to maintain a minimum energy state.
- Diffusion of solutes, within a specific temperature-strain rate range, restricts dislocation motion because the dislocations must “drag” the solute atmospheres along with them.
- Dislocation motion will be restricted until the applied stress is becomes large enough to “break the dislocations free” from the solute atmospheres.





C3 Strain Localization of Lueders Band



(a) (b)

After the upper yield point, there follows a plateau region called as the lower yield point where dislocations are free of the solute atmospheres.

Nonhomogeneous deformation, such as Lueders bands appears and propagates through the sample. This is known as Lueders band along the stress-concentrated zones, i.e., along 45 degrees to the tensile direction.

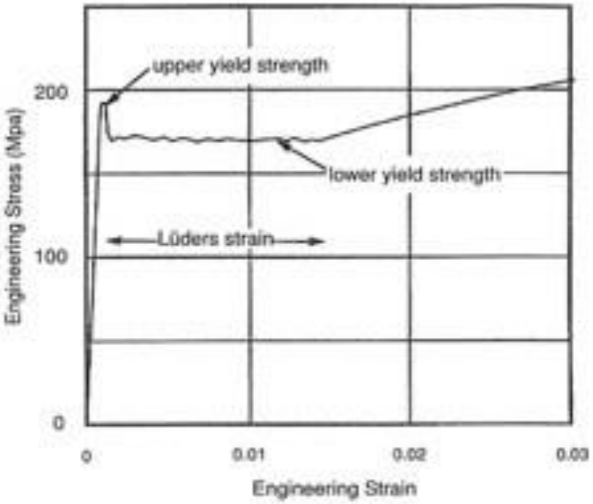
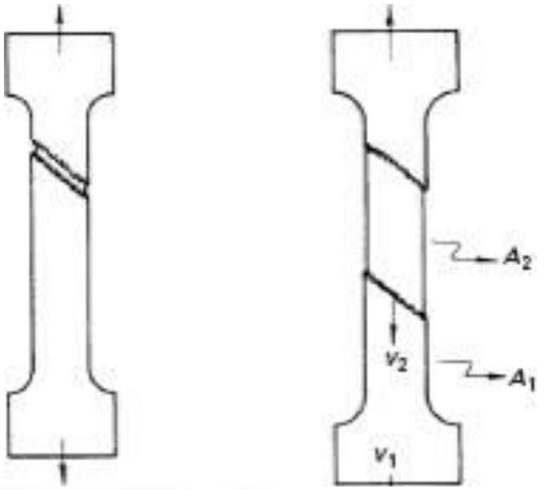
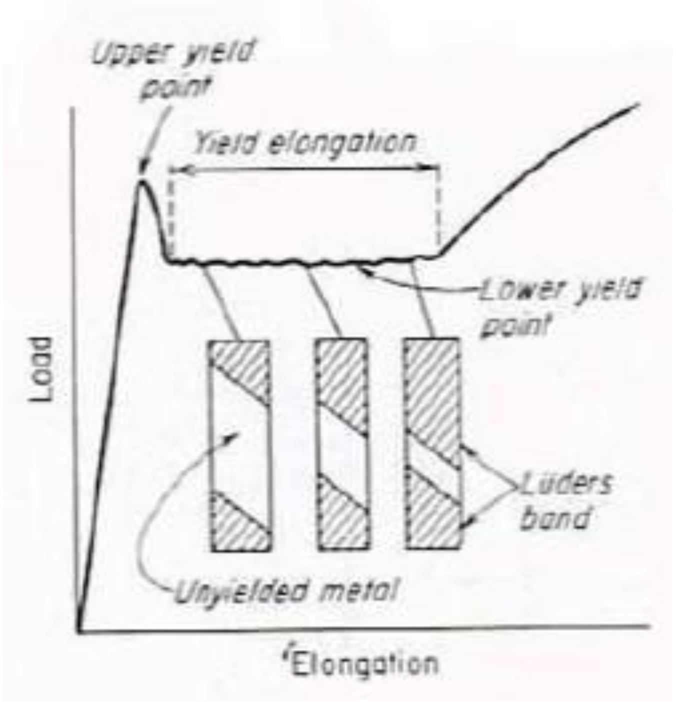


Figure 12.18. Lüder's bands on a low carbon steel tensile specimen. From S. Kalpakjian, *Mechanical Processing of Materials*, Van Nostrand, 1967, p. 194. Courtesy of J. F. Butler, Jones and Laughlin Steel Corp.

Phenomenon II: Strain Localization of Lueders Band





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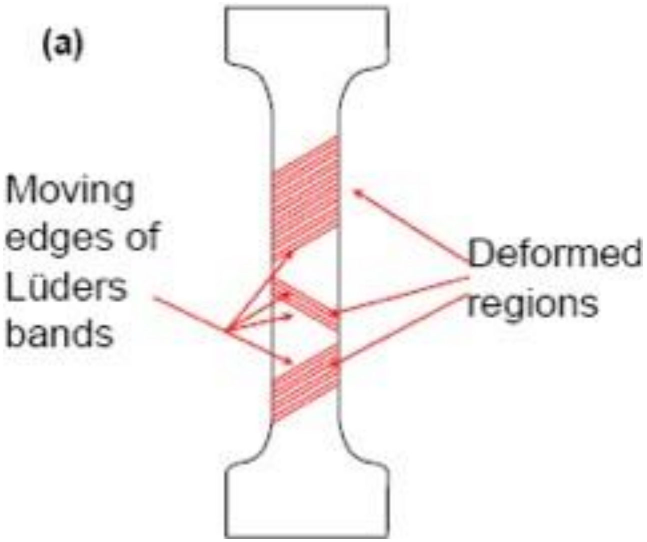
Phenomenon II: Strain Localization of Lueders Band

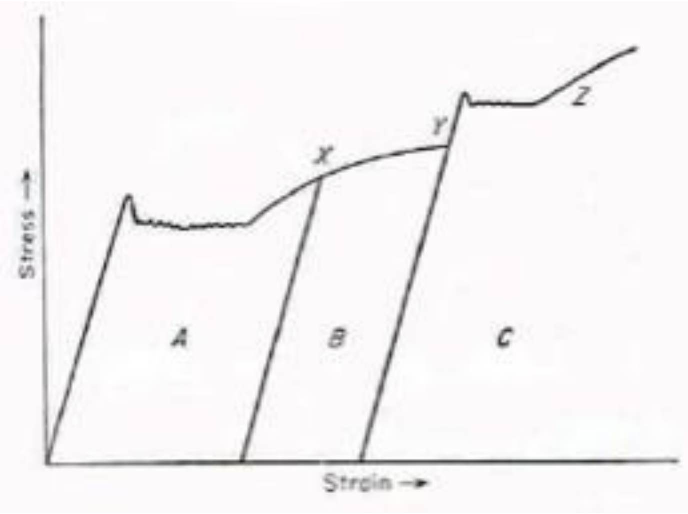


To reduce the formation of Lueders band:

1. Adding Al, V, Ti and Nb or B to steel
2. Prestraining the sheet to a strain larger than the yield point

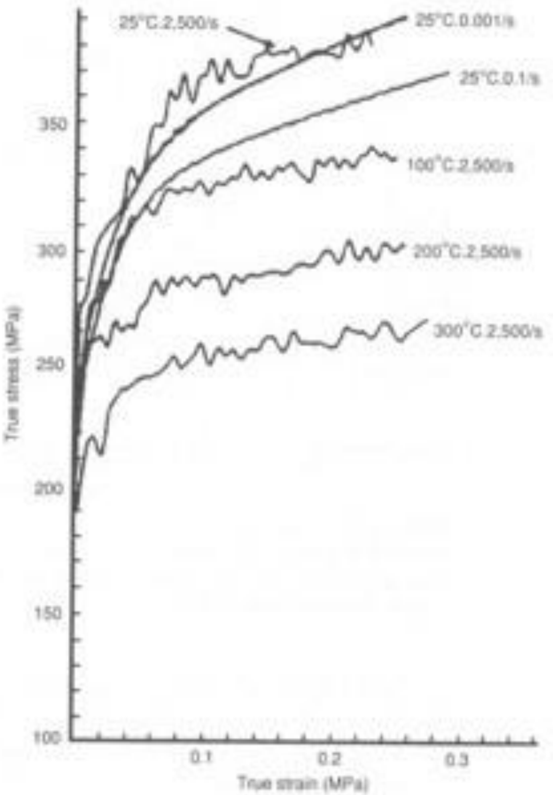
C4 Phenomenon III: Strain aging

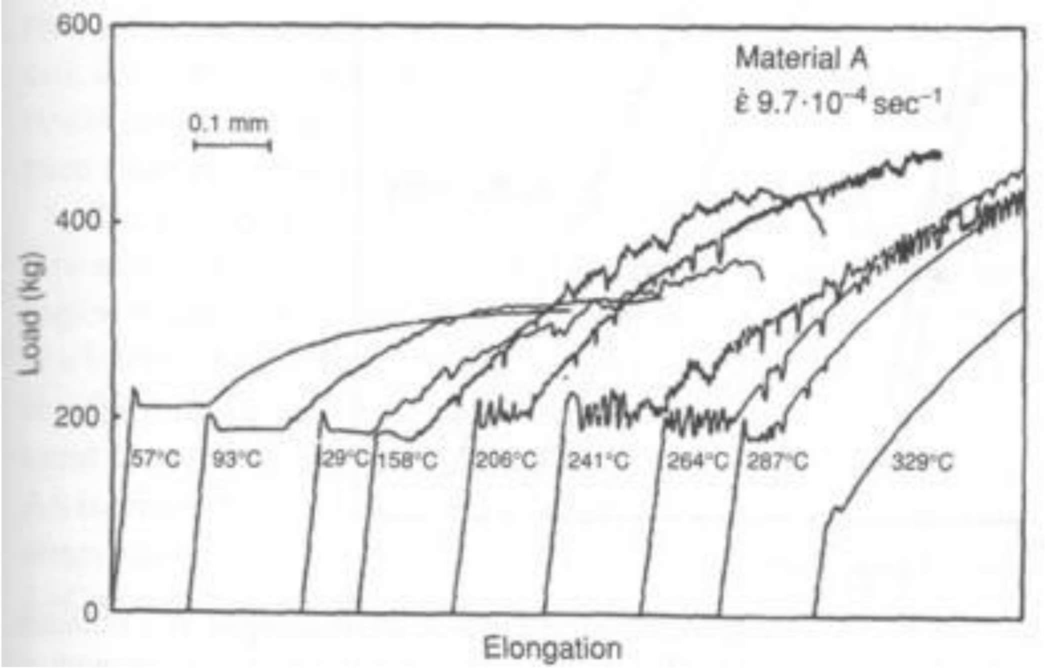
Strain ageing is a phenomenon in which the metal increase in strength while losing ductility after being heated at relatively low temperature or cold-working.



- Reloading at X and straining to Y does not produce yield point.
- After this point if the specimen is reloading after ageing (RT or ageing temp) the yield point will reappear at a higher value.
- This reappearance of the yield point is due to the diffusion of C and N atoms to anchor the dislocations.
- N has more strain ageing effect in iron than C due to a higher solubility and diffusion coefficient.

C5 Phenomenon IV: Dynamic Strain Aging





- Strain ageing is also associated with serrated stress-strain curves or repeated yielding, due to high speed of diffusion of solute atoms to catch and lock dislocations.
- This dynamic strain ageing is also called Portevin-LeChatelier effect.

Phenomenon IV: Dynamic Strain Aging

- Serrated stress-strain curves are observed and serrated yielding is also known as the Portevin-LeChatelier (PLC) effect.
- PLC occurs when the solutes are mobile enough to continuously diffuse to and pin dislocations during deformation.
- Each serration represents repeated pinning and breakaway of dislocations from solute atmospheres.

Phenomenon IV: Dynamic Strain Aging

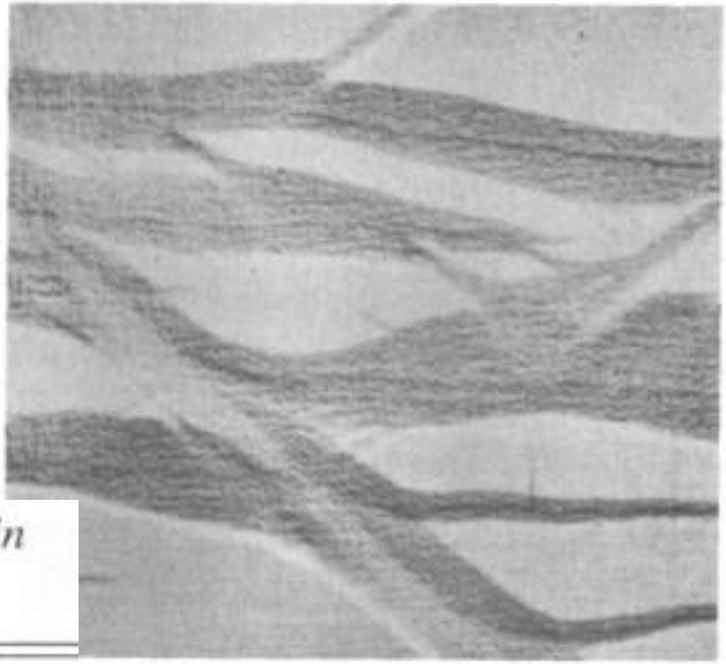
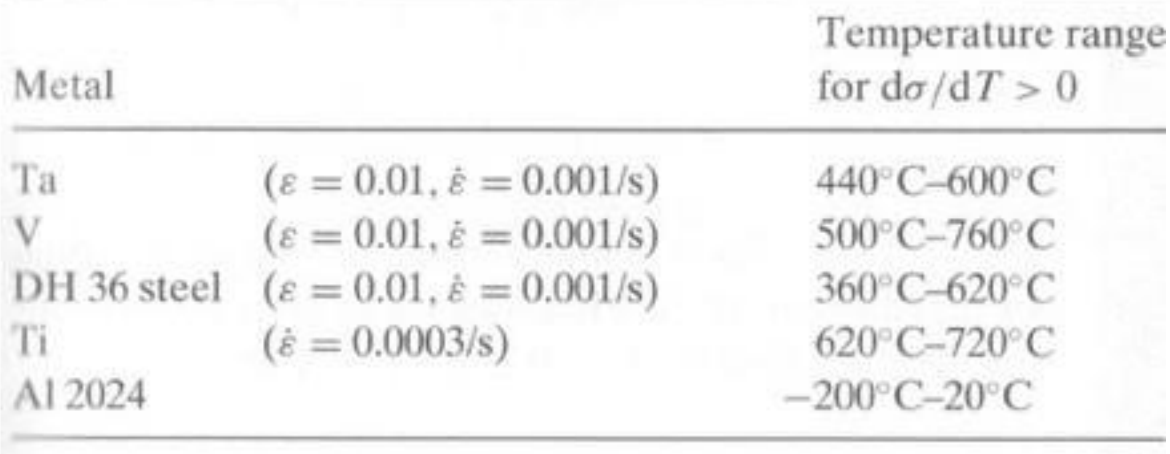


Table 12.1. *Temperature range for dynamic strain aging in several metals*



Metal		Temperature range for $d\sigma/dT > 0$
Ta	$(\varepsilon = 0.01, \dot{\varepsilon} = 0.001/\text{s})$	440°C–600°C
V	$(\varepsilon = 0.01, \dot{\varepsilon} = 0.001/\text{s})$	500°C–760°C
DH 36 steel	$(\varepsilon = 0.01, \dot{\varepsilon} = 0.001/\text{s})$	360°C–620°C
Ti	$(\dot{\varepsilon} = 0.0003/\text{s})$	620°C–720°C
Al 2024		−200°C–20°C

C6 : Bake-hardened (BH) steel

Bake-hardening process:

Cold forming (auto-body) → Painting →

Heat-treating (at 170 ºC for 20 min) → Increasing of Y.S. due to aging effect (~ 40-50 MPa)

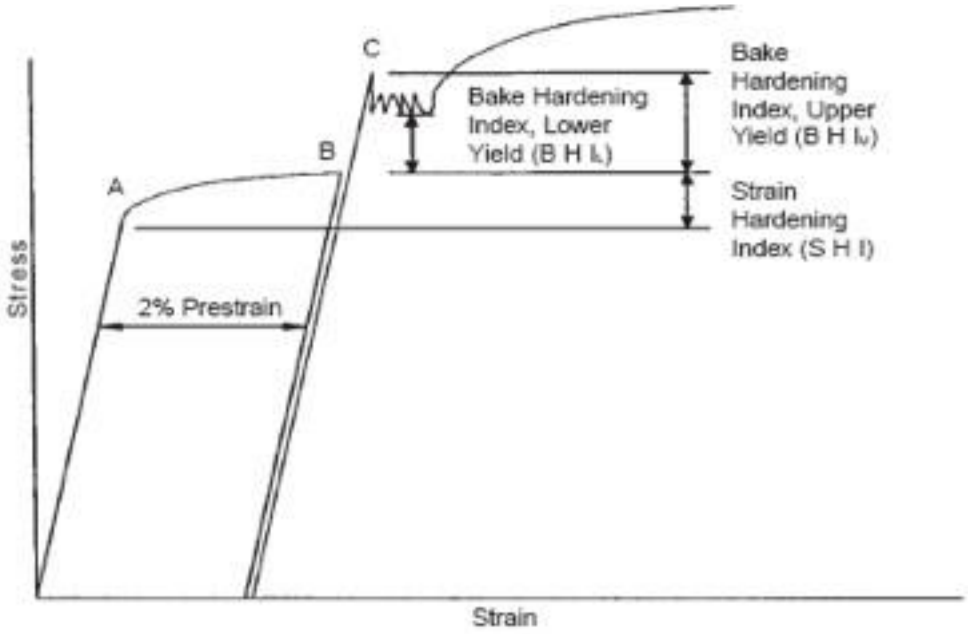
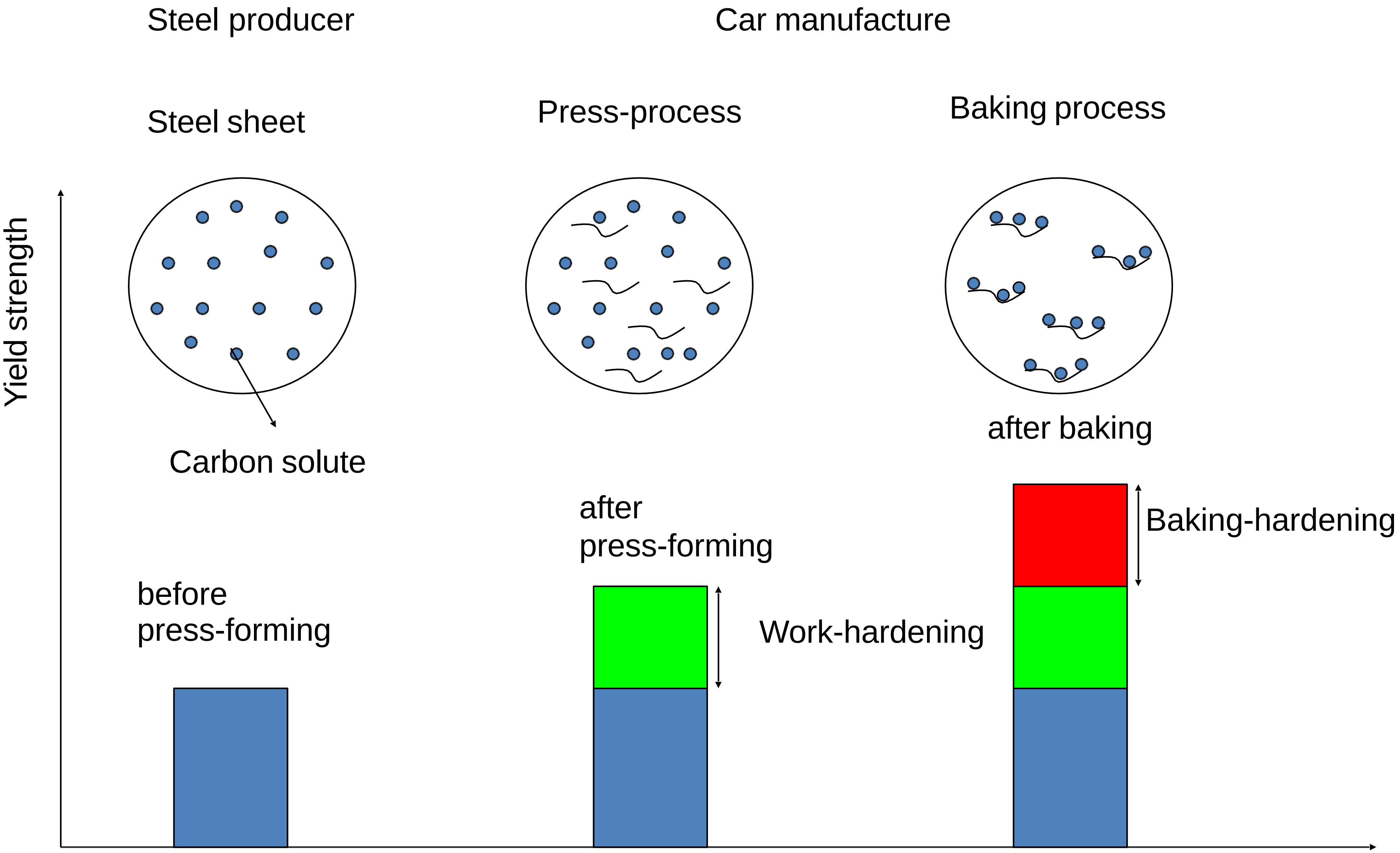


Figure 1 Schematic Illustration Showing Strain Hardening and Bake Hardening Index and the Increase in Yield Strength that Occurs During The Bake Cycle.

Schematic of Bake-hardened (BH) steel



Steel producer

Car manufacture

Steel sheet

Press-process

Baking process

Carbon solute

after baking

after
press-forming

Baking-hardening

before
press-forming

Work-hardening

C7 High Strength Low Alloy Steel (HSLA)

- Addition of micro-alloy (carbide, nitride or carbo-nitride forming elements) such as Nb, V, Ti in structural steel and strip steel grades, the materials are known as “High Strength Low Alloy (HSLA) steel”

- At slab soaking temperature ~ 1200 ºC

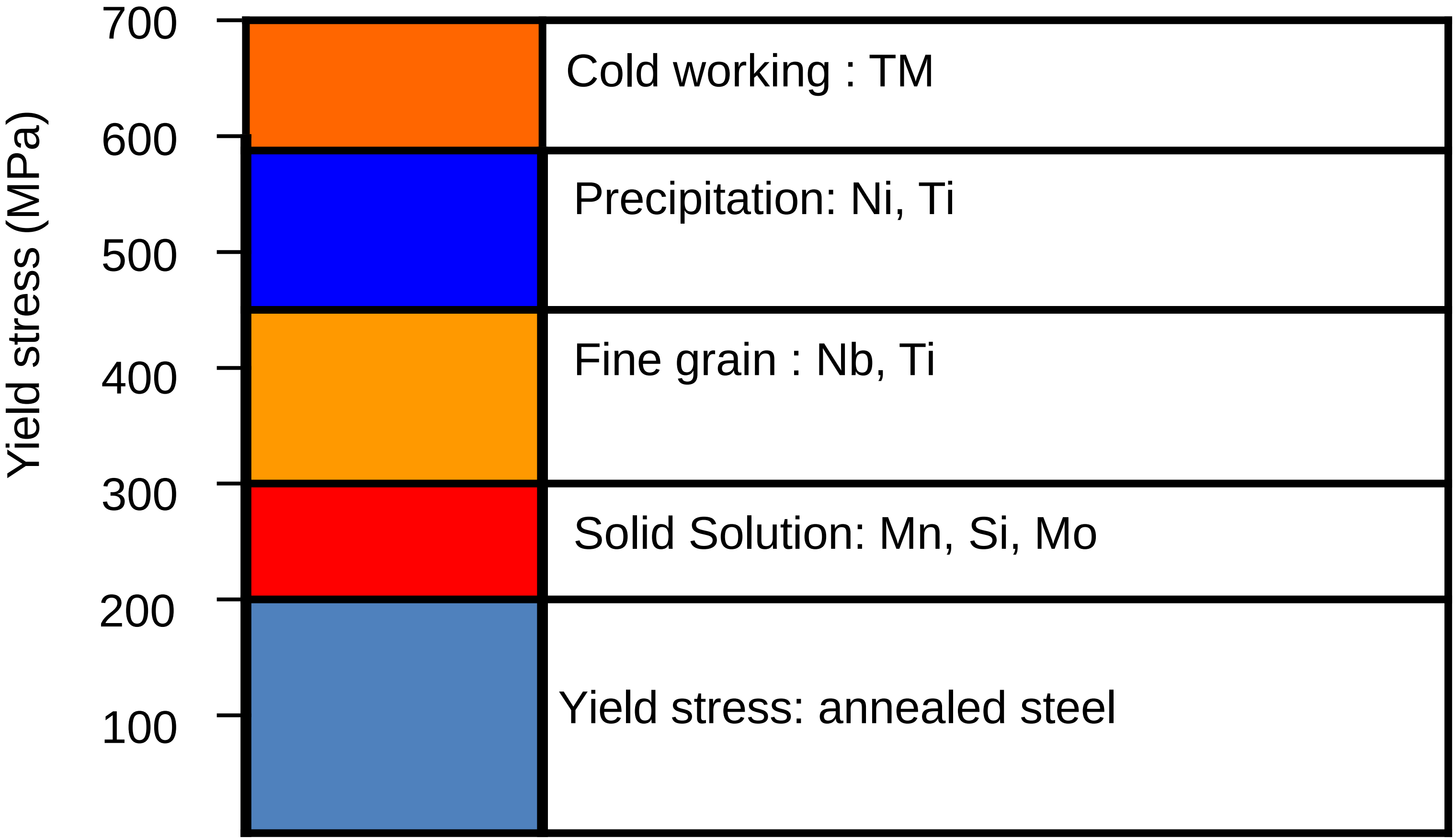
- undissolved particles (such as TiN, NbC and AlN) restricts the size of austenite grain (affect to inhibit recrystallization during hot rolling
  → produces fine austenite grain size → induces fine ferrite grain size)

- a proportion of micro-alloys are dissolved to solid solution (affect to precipitate in later process in form of fine carbide/ carbonitride/ nitride at austenite-ferrite interface on cooling to room temperature)

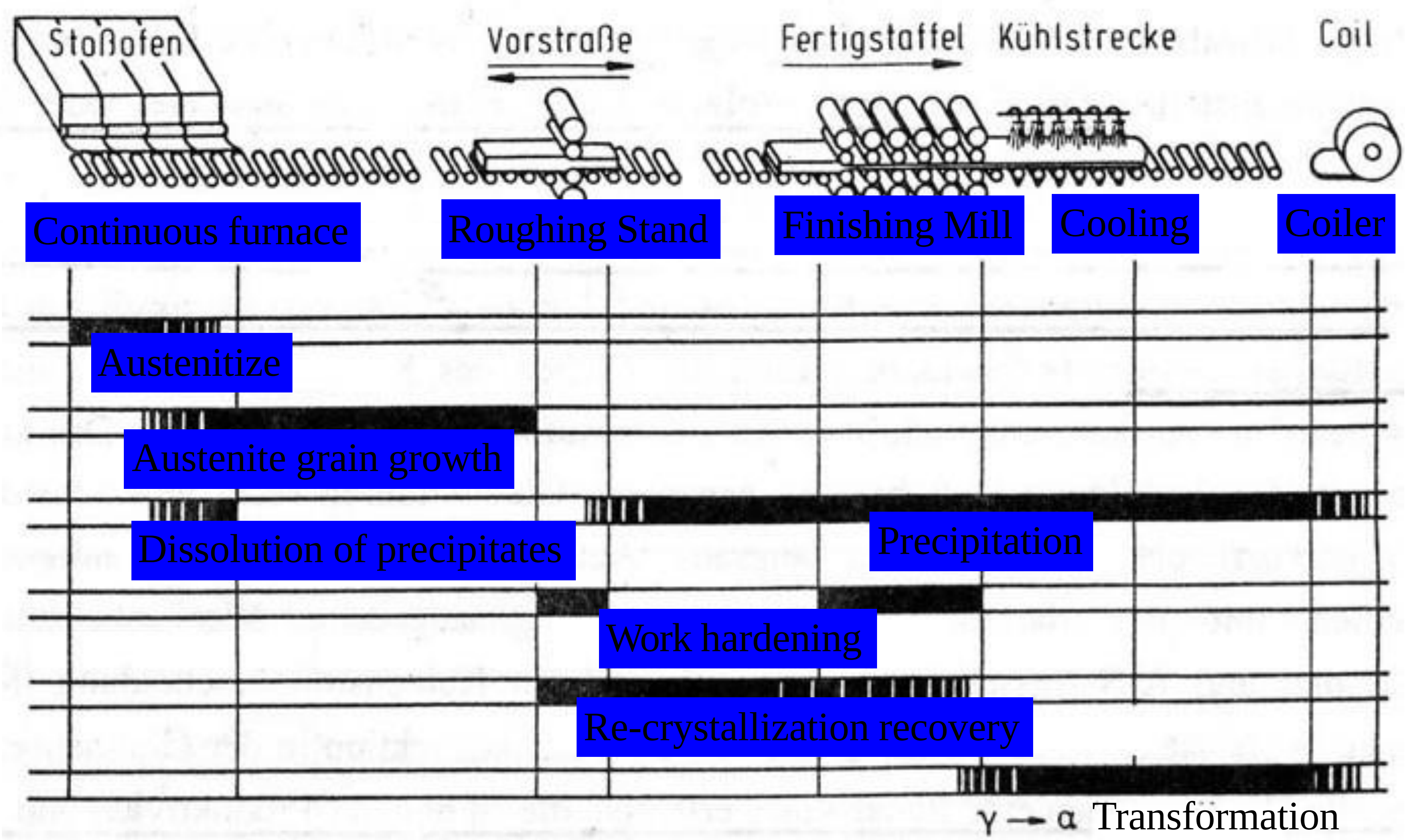
Table 10.2 Important Precipitates in High-Strength Low-Alloy (HSLA) Steels

Element(s)	Main Precipitates
Niobium	Nb(C,N), Nb_4C_3
Vanadium	V (C,N), V_4C_3
Niobium + molybdenum	(Nb,Mo)C
Vanadium + nitrogen	VN
Copper + niobium	Cu,Nb(C,N)
Titanium	Ti(C,N), TiC
Aluminum + nitrogen	AlN

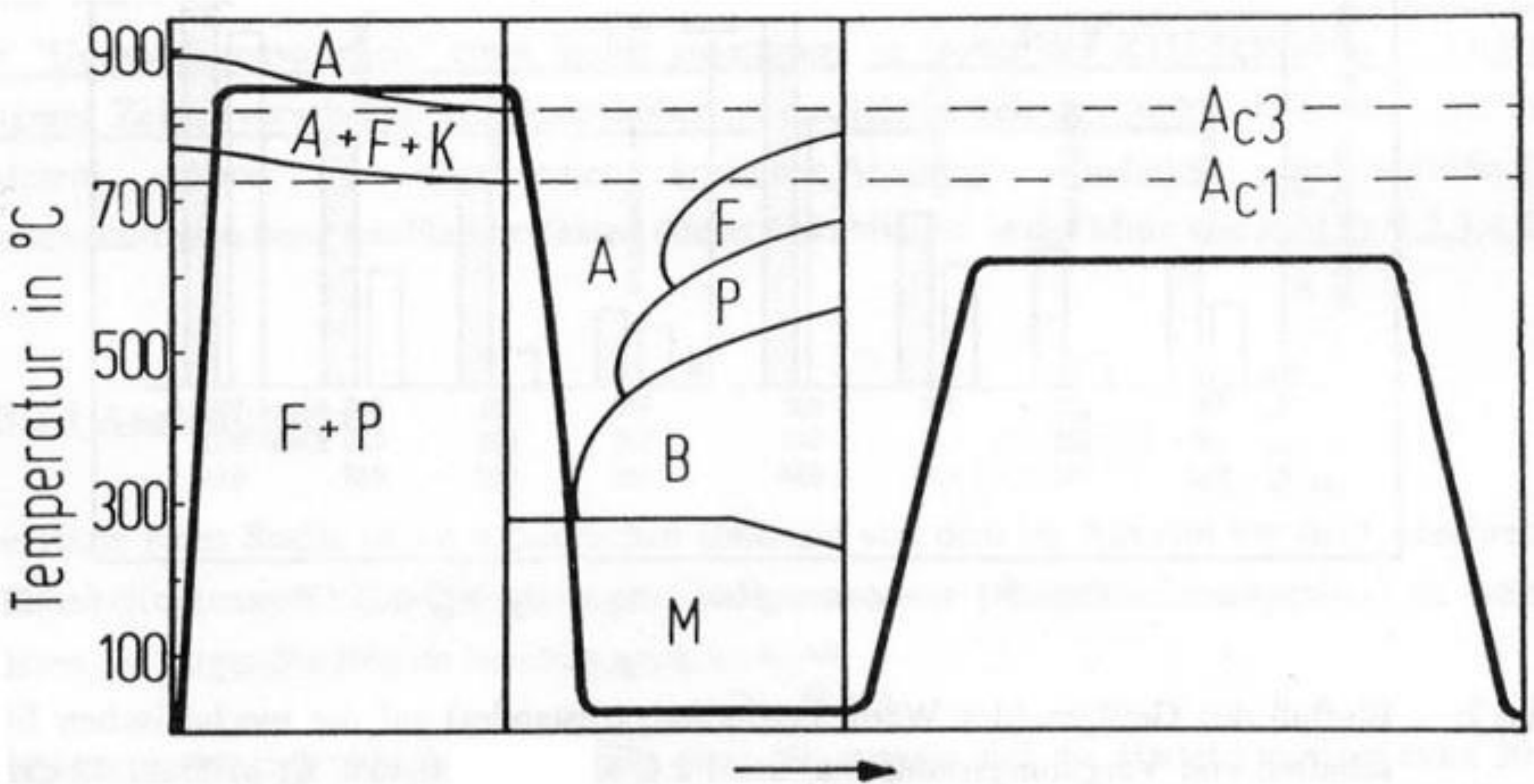
Hardening mechanism of high Strength Low Alloy Steel (HSLA)



C8 Hot-Rolled Strip



C8 Heat Treatment of Steel

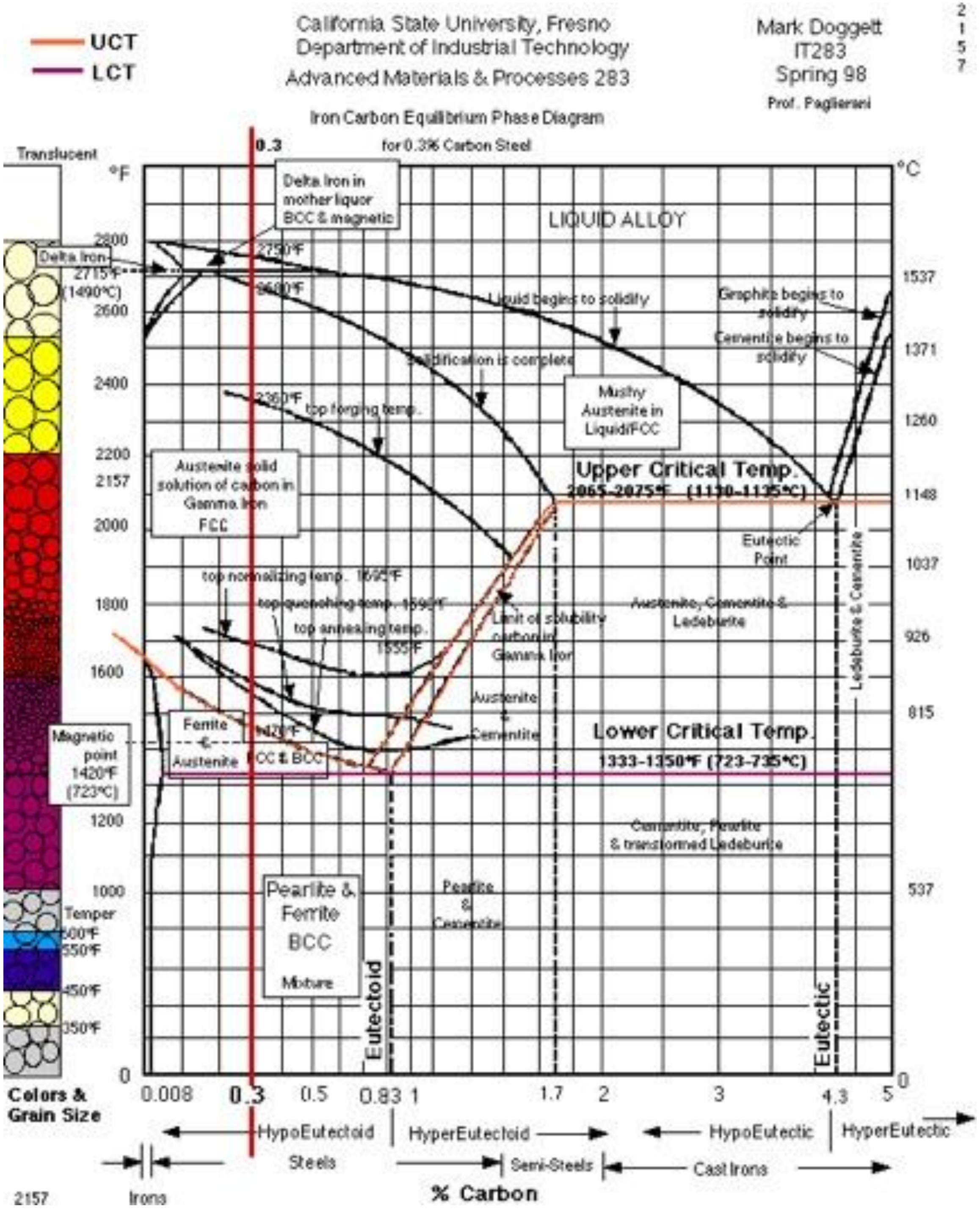


Austenitize + Quenching

Hardening

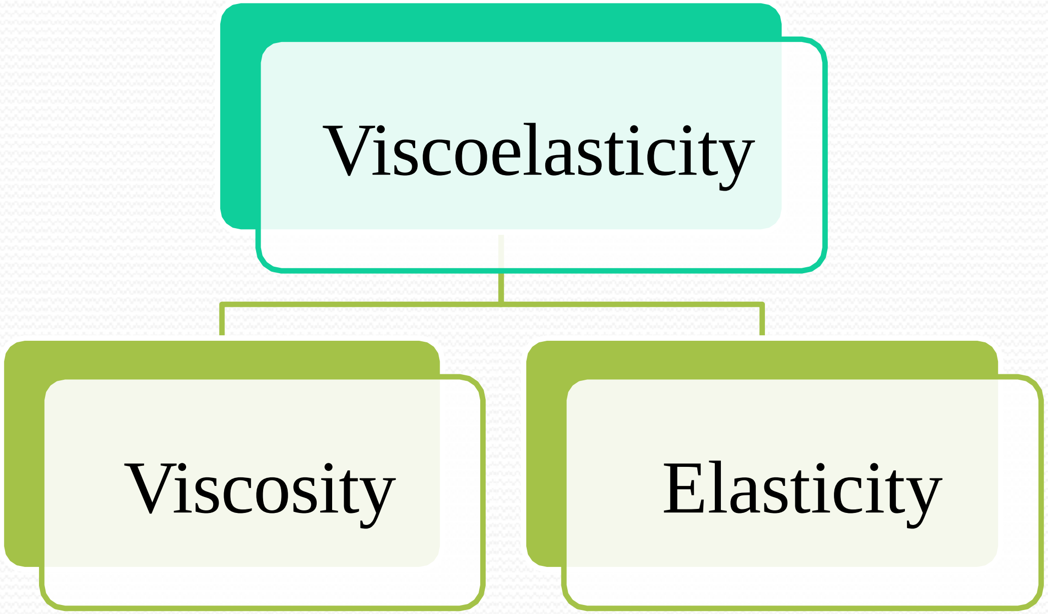
Tempering

Fe-C Diagram


UCT
LCT
California State University, Fresno
Department of Industrial Technology
Advanced Materials & Processes 283
Mark Doggett
IT283
Spring 98
Prof. Paglierani
2157
Iron Carbon Equilibrium Phase Diagram
for 0.3% Carbon Steel
0.3
Translucent
°F
°C
Delta Iron in mother liquor BCC & magnetic
LIQUID ALLOY
Delta Iron
2715°F (1490°C)
2750°F
2600°F
Liquid begins to solidify
Graphite begins to solidify
Cementite begins to solidify
Solidification is complete
2360°F
top forging temp.
Mushy Austenite in Liquid/FCC
Austenite solid solution of carbon in Gamma Iron FCC
Upper Critical Temp.
2065-2075°F (1130-1135°C)
Eutectic Point
top normalizing temp. 1695°F
top quenching temp. 1595°F
top annealing temp. 1555°F
Limit of solubility carbon in Gamma Iron
Austenite, Cementite & Ledeburite
Ledeburite & Cementite
Austenite + Cementite
Ferrite + Austenite
1420°F
FCC & BCC
Magnetic point 1420°F (723°C)
Lower Critical Temp.
1333-1350°F (723-735°C)
Cementite, Pearlite & transformed Ledeburite
Pearlite & Ferrite BCC Mixture
Pearlite & Cementite
Temper
600°F
550°F
450°F
350°F
Eutectoid
Eutectic
2800
2600
2400
2200
2157
2000
1800
1600
1200
1000
0
1537
1371
1260
1148
1037
926
815
537
0
0.008
0.3
0.5
0.83
1
1.7
2
3
4.3
5
Colors & Grain Size
HypoEutectoid
HyperEutectoid
HypoEutectic
HyperEutectic
Irons
Steels
Semi-Steels
Cast Irons
% Carbon
2157

Viscoelasticity

VISCOELASTICITY


Viscoelasticity

Viscosity

Elasticity

- It is the property of materials that exhibits both viscous properties of liquid & elastic property of solids.

CREEP

- It can be defined as the slow & progressive (increasingly continuing) deformation of a material with time under a constant stress.
- Creep being defined as time-dependent inelastic strain under sustained load and elevated temperature.
- The meaning of elevated temperature must be determined individually for each material on the basis of its behavior, for example, at 205°C (400°F) for aluminum alloys, 315°C (600°F) for titanium alloys, 370°C (700°F) for low-alloy steels.
- Viscoelastic materials when subjected to stress for short period of time undergo slight deformation & exhibit elasticity up on removal of stress & when subjected for longer period of time , deformation increases & becomes more permanent.

CREEP VISCOMETER

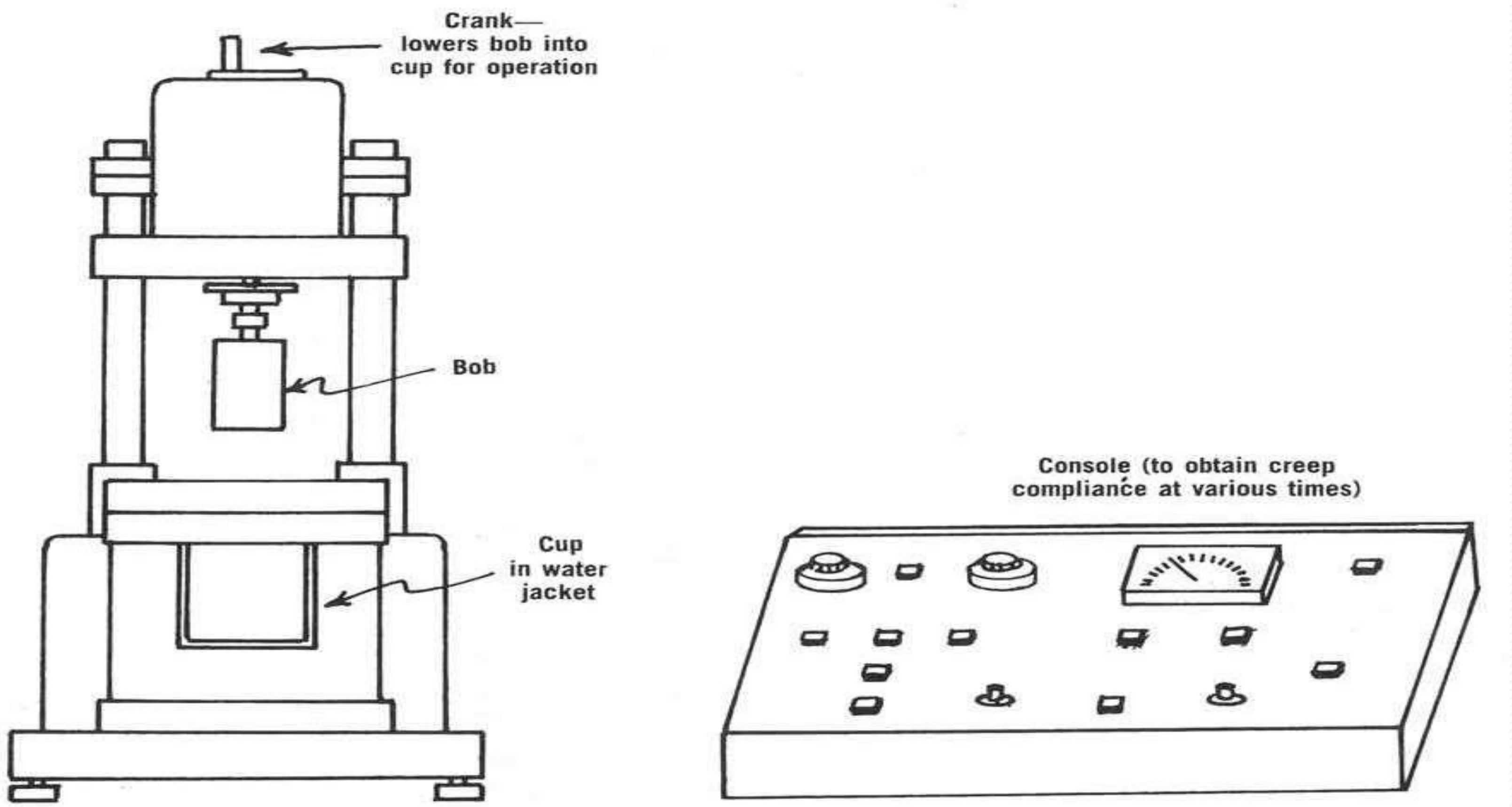


Figure 1 Creep Viscometer

□ The main type of creep testing machine that is most commonly used is a constant load creep testing machine. It consists of

- **Load platform** or sometimes called load hanger is where the object will endure pressure at a constant rate.
- **Grips** are used to hold the material you are testing in a certain position.
- **Dial Gauge** is used to measure the strain. It is the object that captures the movement of the object in the machine. The load beam transfers the movement from the grip to the dial gauge.
- **Heating Chamber** is what surrounds the object and maintain the temperature that the object is subjected to.

CREEP CURVE

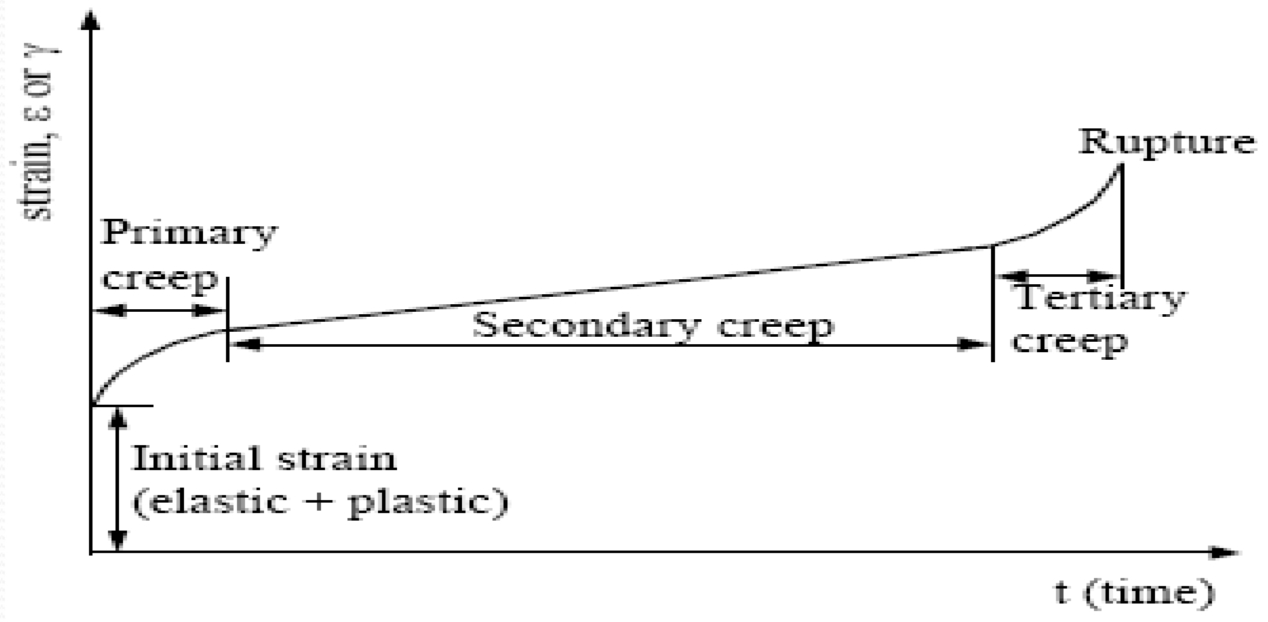


Figure 2 Creep Curve

- Primary creep, the strain rate is relatively high, but slows with increasing time. This is due to work hardening

- Secondary or steady-state creep. The strain rate eventually reaches a minimum and becomes near constant. This is due to the balance between work hardening and annealing (thermal softening).

- In tertiary creep, the strain rate exponentially increases with stress because of necking phenomena or internal voiding decreases the effective area of the specimen. Fracture always occurs at the tertiary stage.

- The creep curve is consists of three parts, first a sharply rising portion ABcorresponding to the elastic behaviour of the material ; second, a curved portion BC represents viscoelastic behaviour ; and third linear portion CD represents viscous flow of the material.

GENERAL CREEP EQUATION

$$\frac{d\varepsilon}{dt} = \frac{C\sigma^{m}}{d^{b}} e^{\frac{-Q}{KT}}$$

- Where ε is the creep strain, *C* is a constant dependent on the material and the particular creep mechanism, *m* and *b* are exponents dependent on the creep mechanism, *Q* is the activation energy of the creep mechanism, σ is the applied stress, *d* is the grain size of the material, *k* is Boltzmann's constant, and *T* is the absolute temperature.

MECHANISMS OF CREEP IN METALS

DISLOCATION CREEP

- At high stresses (relative to the shear modulus), creep is controlled by the movement of dislocations. For dislocation creep, *Q = Q(self diffusion)*, *m* = 4–6, and *b* = 0. Therefore, dislocation creep has a strong dependence on the applied stress and no grain size dependence.
- Dislocations are line defects that slip through a crystal lattice when a minimum shear stress is applied. Dislocations initially slip along the closest packed planes in the closest packed directions since this requires the least energy or applied stress.
- Some alloys exhibit a very large stress exponent ($n > 10$), and this has typically been explained by introducing a "threshold stress," σ_{th}, below which creep can't be measured. The modified power law equation then becomes:

$$\frac{d\varepsilon}{dt} = A(\sigma - \sigma_{th})^n e^{\frac{-Q}{RT}}$$

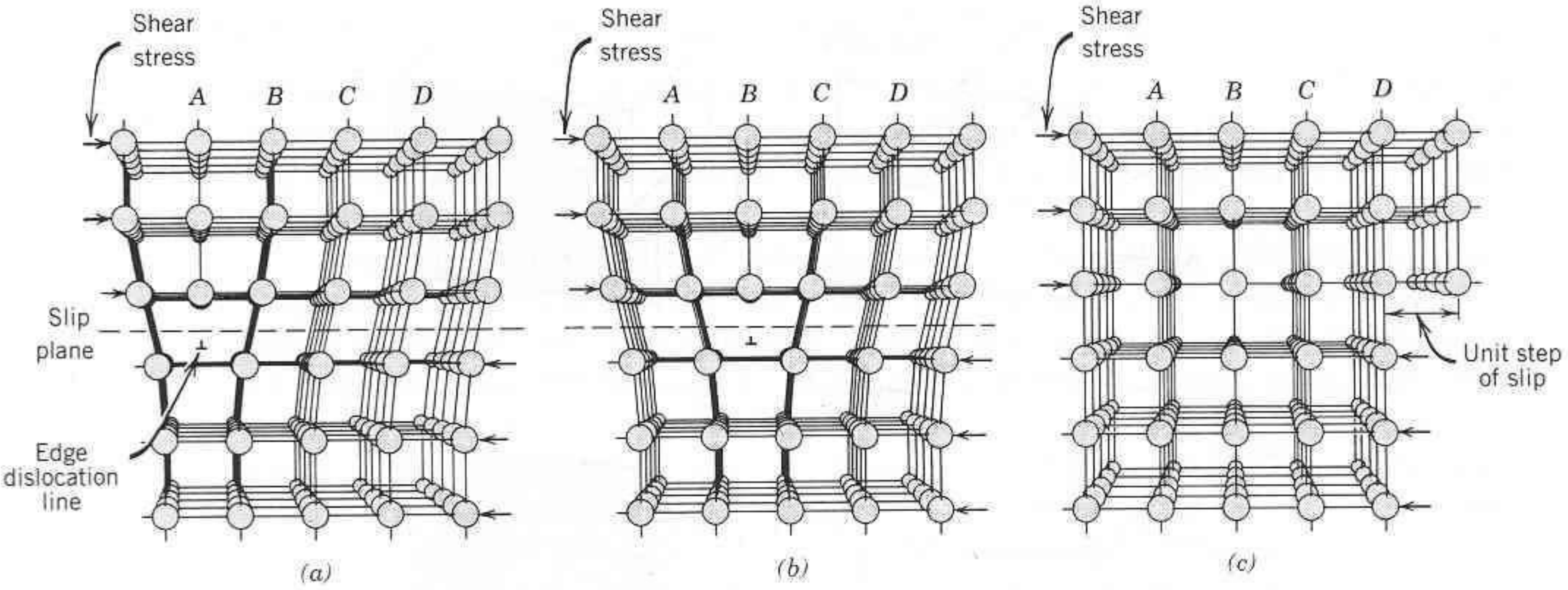


Figure 3 shows an **edge dislocation** slipping through a crystal lattice (simple cubic for simplicity) and producing a unit of slip called a **slip step, on the surface of the crystal**

NABARRO-HERRING CREEP

- Nabarro-Herring creep is a form of diffusion creep.
- In Nabarro-Herring creep, atoms diffuse through the lattice causing grains to elongate along the stress axis
- *Q* = *Q(self diffusion)*, *m* = 1, and *b* = 2. Therefore, Nabarro-Herring creep has a weak stress dependence and a moderate grain size dependence, with the creep rate decreasing as grain size is increased.
- For lattice diffusion of atoms to occur in a material, neighboring lattice sites or interstitial sites in the crystal structure must be free. A given atom must also overcome the energy barrier to move from its current site to the nearby vacant site

- The general form of the diffusion equation is
- $D = D_0 exp(E/KT)$ where D_0 has a dependence on both the attempted jump frequency and the number of nearest neighbor sites and the probability of the sites being vacant.
- At higher temperatures the diffusivity increases due to the direct temperature dependence of the equation
- The increase in vacancies through Schottky defectformation
- Nabarro-Herring creep dominates at very high temperatures relative to a material's melting temperature.

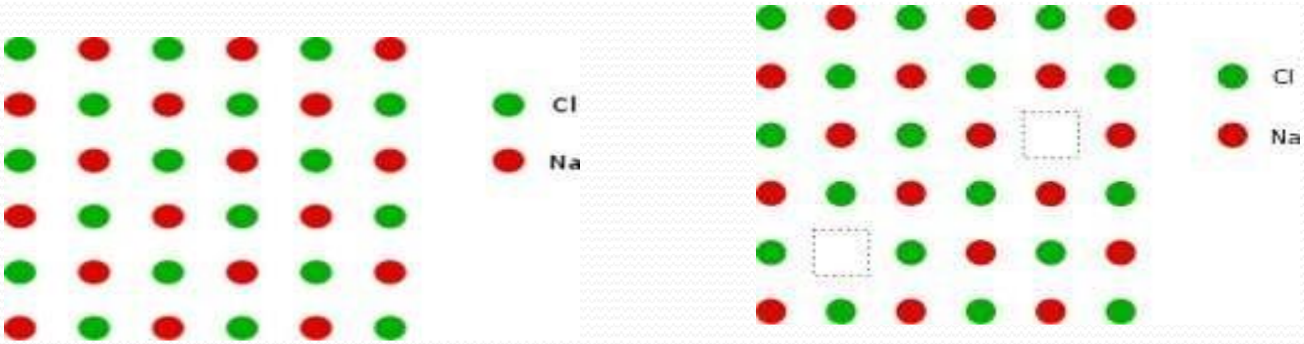


Figure 4 Schottky Defect

COBLE CREEP

- Coble creep is a second form of diffusion controlled creep.
- In Coble creep the atoms diffuse along grain boundaries to elongate the grains along the stress axis. This causes Coble creep to have a stronger grain size dependence than Nabarro-Herring creep.
- For Coble creep *k* is related to the diffusion coefficient of atoms along the grain boundary, $Q = Q(\textit{grain boundary diffusion})$, $m = 1$, and $b = 3$.
- Because $Q(\textit{grain boundary diffusion}) < Q(\textit{self diffusion})$, Coble creep occurs at lower temperatures than Nabarro-Herring creep.
- Coble creep is still temperature dependent, as the temperature increases so does the grain boundary diffusion. However, since the number of nearest neighbors is effectively limited along the interface of the grains, and thermal generation of vacancies along the boundaries is less prevalent, the temperature dependence is not as strong as in Nabarro-Herring creep.
- It also exhibits the same linear dependence on stress as Nabarro-Herring creep.

HARPER-DORN CREEP

- Harper-Dorn creep is a climb-controlled dislocation mechanism at low stresses that has been observed in aluminum, lead, and tin systems, in addition to nonmetal systems such as ceramics and ice.
- It is characterized by two principal phenomena: a linear relationship between the steady-state strain rate and applied stress at a constant temperature, and an independent relationship between the steady-state strain rate and grain size for a provided temperature and applied stress.

$$\frac{d\varepsilon}{dt} = \rho_0 \frac{D_v G b^3}{k_B T}\left(\frac{\sigma_s}{G}\right)$$

- Where: ρ_0 is dislocation density (constant for Harper-Dorn creep), D_v is the diffusivity through the volume of the material, G is the shear modulus, b is the Burger's vector, σ_s is the applied stress, B is Boltzmann's constant, and T is temperature.

- Harper-Dorn creep is controlled by dislocation movement

- The volumetric activation energy indicates that the rate of Harper-Dorn creep is controlled by vacancy diffusion to and from dislocations, resulting in climb-controlled dislocation motion

- The dislocation density here is constant and independent of the applied stress. Moreover, the dislocation density must be low for Harper-Dorn creep to dominate.

OSCILLATORY TESTING

- Oscillatory shear testing is a general term covering a range of techniques that can be deployed to characterize and quantify the presence, rigidity and integrity of a material's internal structure.
- For example, flocculation and interaction of dispersed particles or droplets, or cross-linking and entanglement of dissolved polymers.
- Oscillatory rheology testing is almost always performed at very low applied stresses and strains, often significantly below the yield point of a sample.
- Typically measured parameters include: Complex modulus (G*), Elastic (or storage) modulus (G') and viscous (or loss) modulus (G"), Phase angle (δ) and tangent of the phase angle (tan δ).

- Phase angle and complex modulus together can define a viscoelastic map (see graphic) differentiating between elastic solids and viscous liquids (left to right) and high to low rigidity or viscosity (top to bottom).

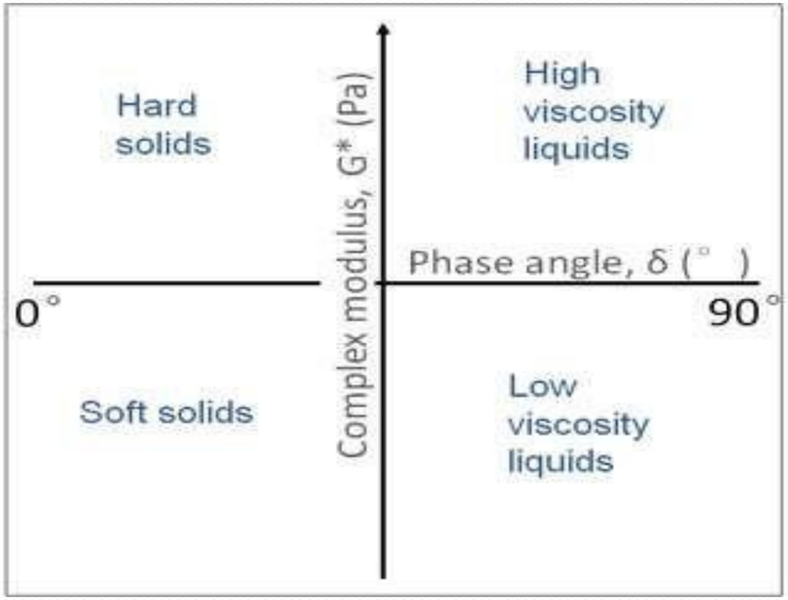


Figure 5 Viscoelastic Map

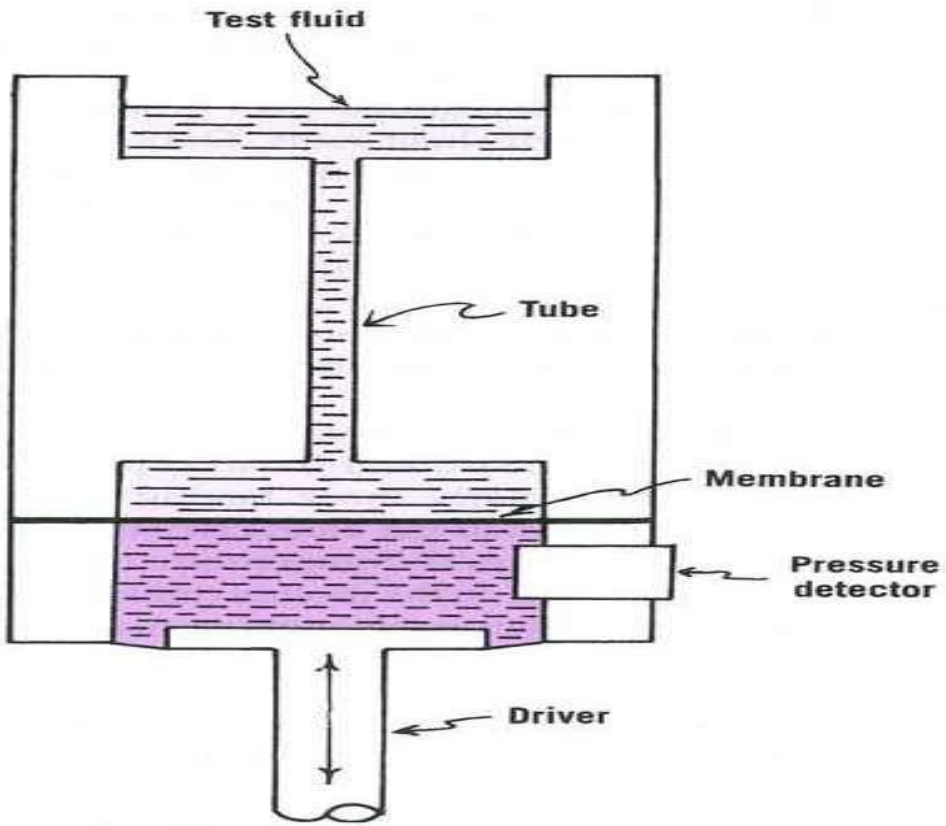


Figure 6 Apparatus for oscillatory testing of viscoelastic material

- The basic principle of an oscillatory rheometer is to induce a sinusoidal shear deformation in the sample and measure the resultant stress response; the time scale probed is determined by the frequency of oscillation, ω.

- In a typical experiment, the sample is placed between two plates, While the top plate remains stationary, a motor rotates the bottom plate, thereby imposing a time dependent strain $\gamma(t)=\gamma\cdot\sin(\omega t)$ on the sample.

- Simultaneously, the time dependent stress $\sigma(t)$ is quantified by measuring the torque that the sample imposes on the top plate.

- Measuring this time dependent stress response at a single frequency immediately reveals key differences between materials.

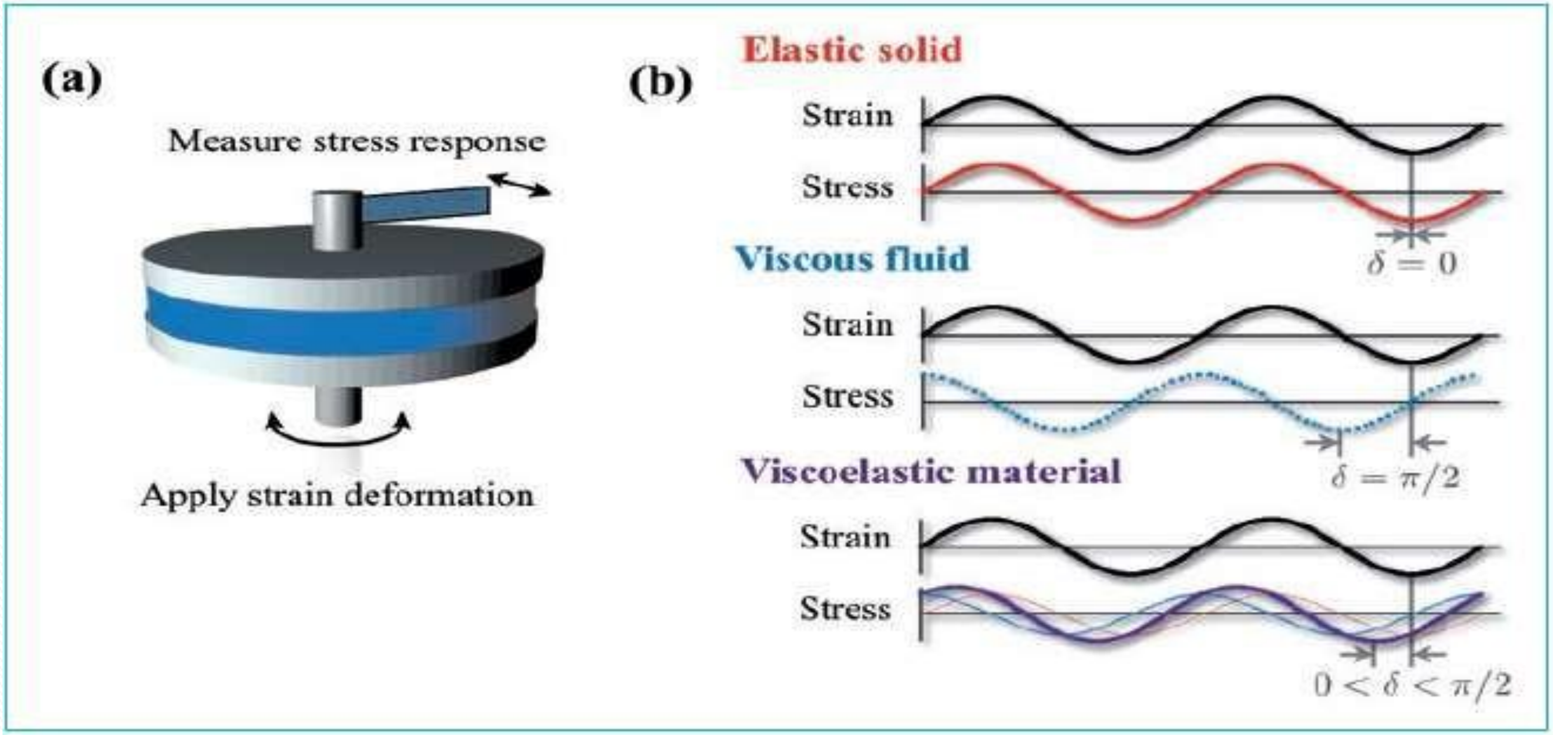


Figure 7 Schematic stress response to oscillatory strain deformation for an elastic solid, a viscous fluid and a viscoelastic material

- If the material is an ideal elastic solid, then the sample stress is proportional to the strain deformation, and the proportionality constant is the shear modulus of the material. The stress is always exactly in phase with the applied sinusoidal strain deformation.

- In contrast, if the material is a purely viscous fluid, the stress in the sample is proportional to the rate of strain deformation, where the proportionality constant is the viscosity of the fluid. The applied strain and the measured stress are out of phase, with a phase angle $\delta=\pi/2$.

- Viscoelastic materials show a response that contains both in-phase and out-of-phase contributions, & shows a phase shift δ with respect to the applied strain deformation that lies between that of solids and liquids, $0<\delta<\pi/2$.

- The viscoelastic behaviour of the system at ω is characterised by the storage modulus, $G'(\omega)$, and the loss modulus, $G''(\omega)$,

- The storage modulus measures the stored energy, representing the elastic portion, and the loss modulus measures the energy dissipated as heat, representing the viscous portion

- For a sinusoidal strain deformation $\gamma(t)=\gamma 0 \sin(\omega t)$, the stress response of a viscoelastic material is given by $\sigma(t)=G'(\omega)\gamma 0 \sin(\omega t)+ G''(\omega)\gamma 0 \cos(\omega t)$.

- A typical example is shown in figure 8 where we plot G’(ω) and G”(ω) for a suspension of hydrogel particles; at the lowest accessible frequencies the response is viscous-like, with a loss modulus that is much larger than the storage modulus while at the highest frequencies accessed the storage modulus dominates the response, indicating solid-like behaviour.

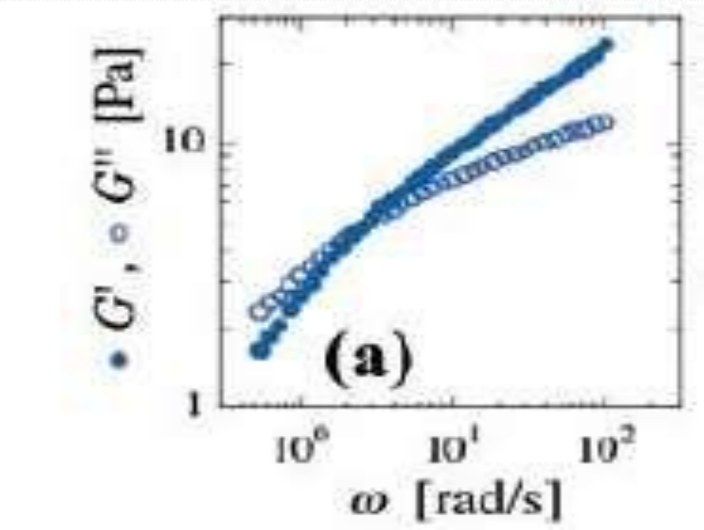


Figure 8 A suspension of hydrogel particles

Work hardening & strain hardening

INTRODUCTION

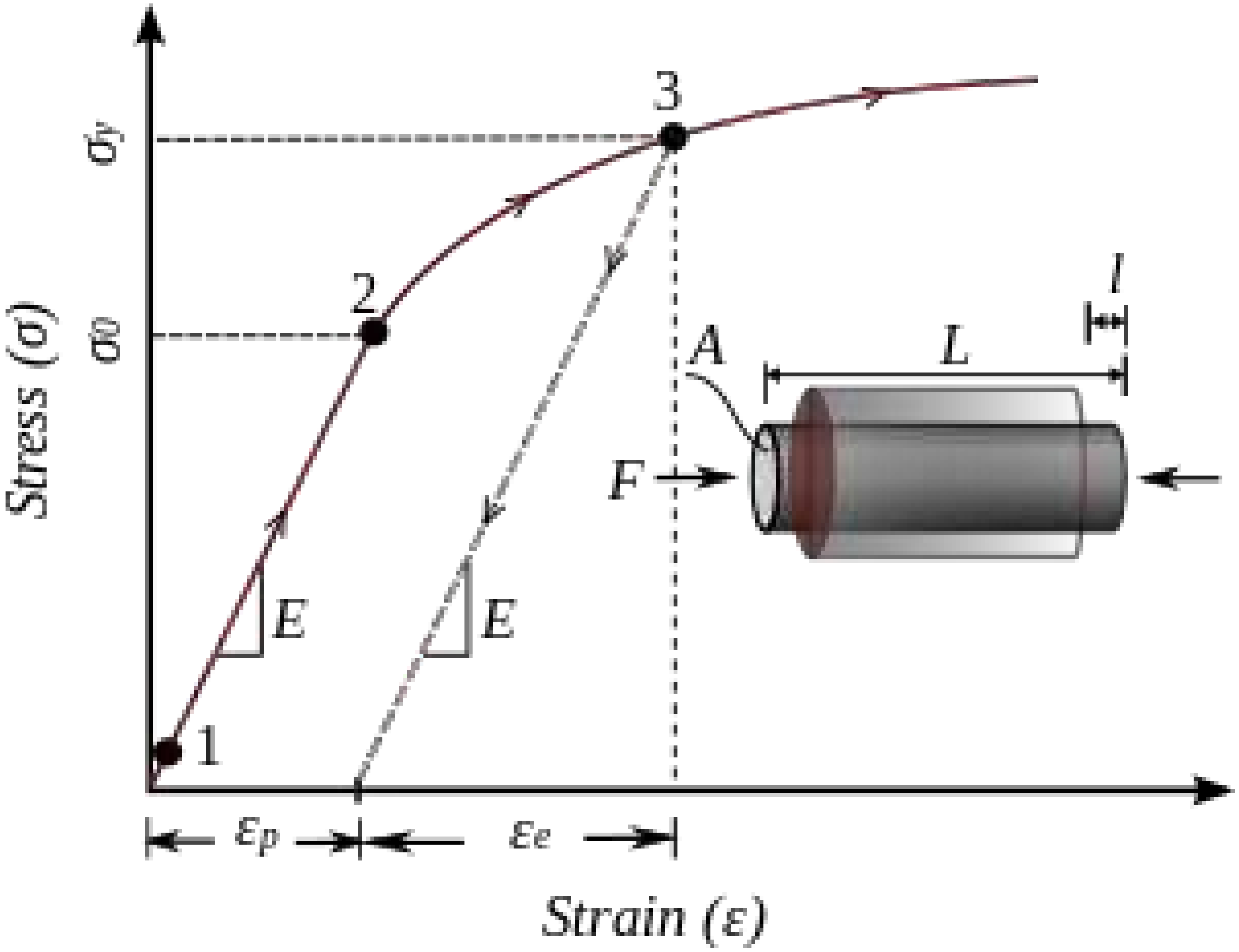
- With increasing stress on a material ,i.e. ,by applying load there are possibilities that a material may fail before reaching the desired stress value.
- To improve the hardness of a substance so that it is able to sustain more load in the elastic region process of strain hardening is done
- Here ductility is compromised to get hardness and strength

- PRINCIPLE
- The ability of a metal to plastically deform depends on the ability of dislocation to move

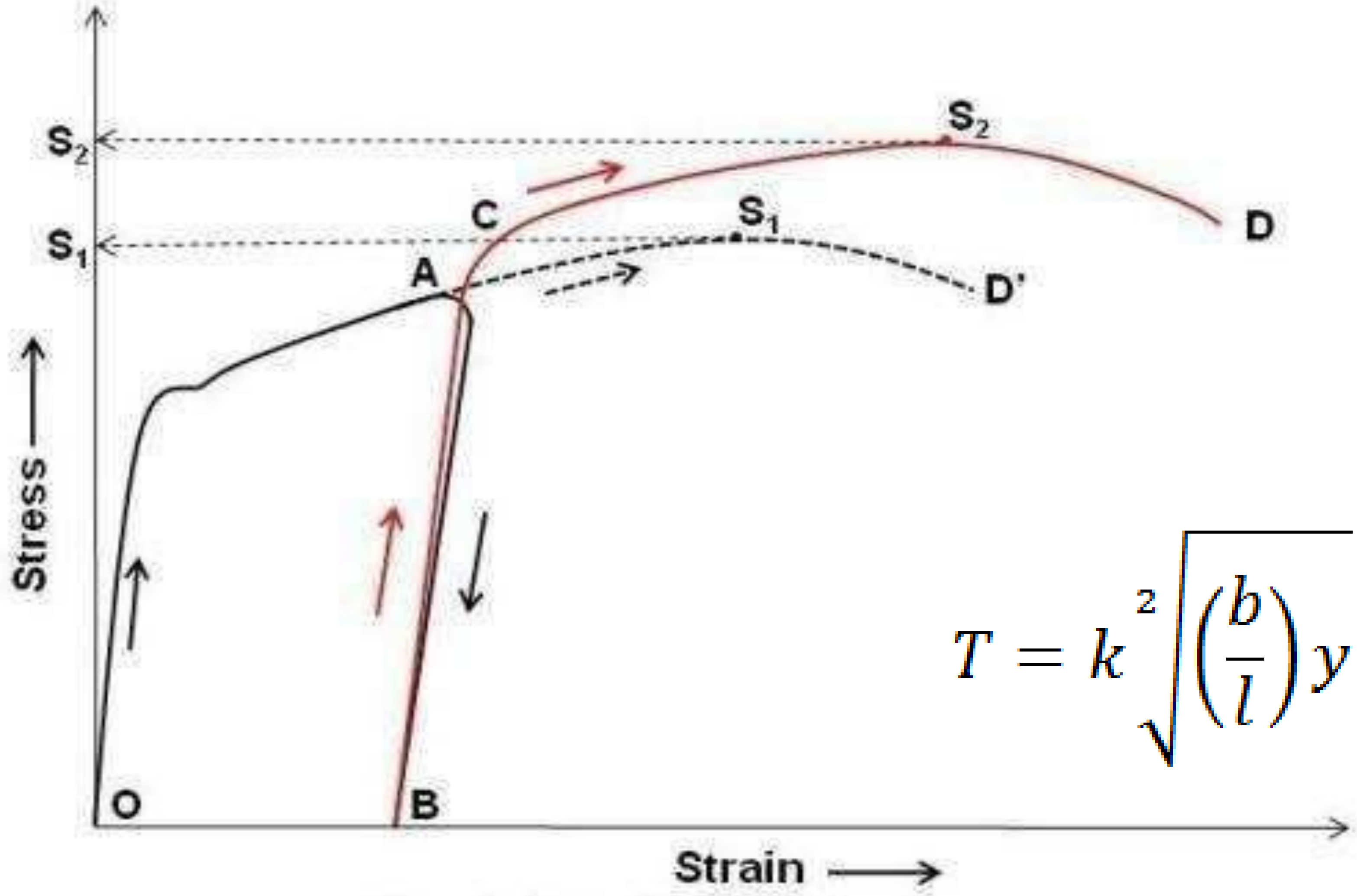
THEORY OF WORK HARDENING

- Before work hardening, the lattice of the material exhibits a regular, nearly defect-free pattern
- As the material is work hardened it becomes increasingly saturated with new dislocations, and more dislocations are prevented from nucleating (a resistance to dislocation-formation develops).
- This resistance to dislocation-formation manifests itself as a resistance to plastic deformation hence, the observed strengthening.

STRAIN HARDENING



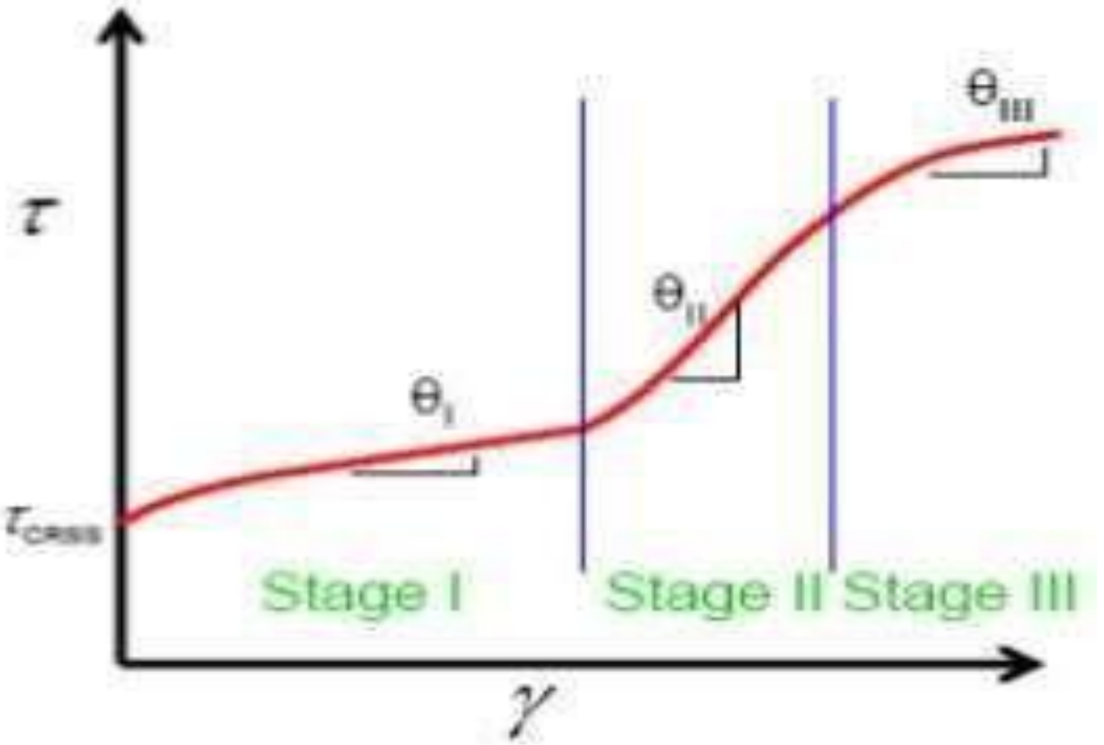
STRAIN HARDENING



$$T = k\sqrt[2]{\left(\frac{b}{l}\right)y}$$

Work (Strain) Hardening

STAGES OF WORK HARDENING



- STAGE I : <u>Easy Glide Region</u>
- STAGE II : <u>Linear Hardening Region</u>
- STAGE III : <u>Parabolic Hardening Region</u>

EASY GLIDE REGION

- Shear stress is almost constant.
- Very low work hardening rate.
- BCC system do not exhibit an easy glide.

PARABOLIC HARDENING REGION :

- Increase in degree of cross slip.
- Low hardening rate.
- Shape is parabolic.

ADVANTAGES

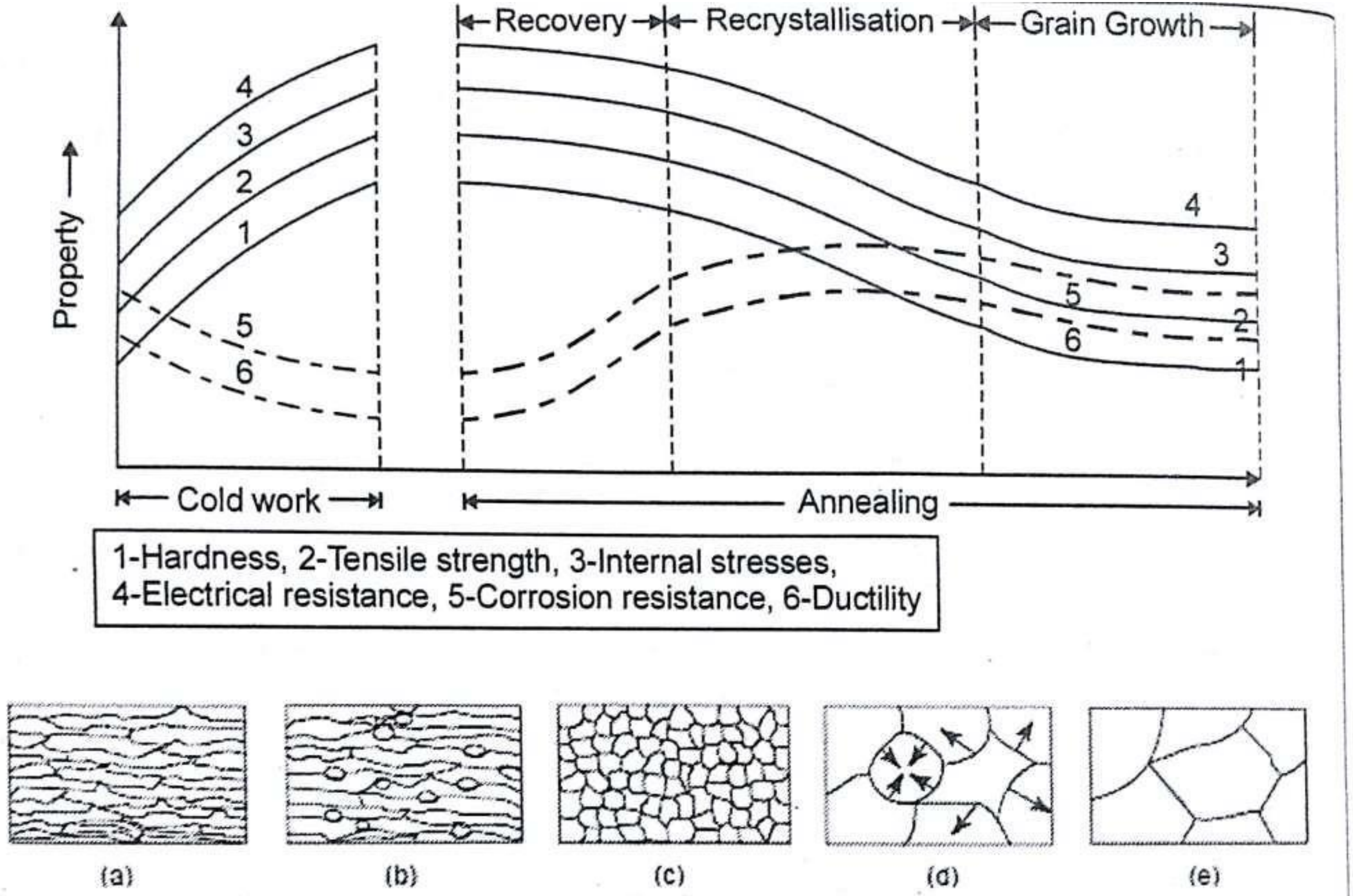
- No heating required.
- Better surface finish.
- Superior dimensional control.
- Better reproducibility and interchange ability.
- Directional properties can be imparted into the metal.
- Contamination problems are minimized.

ANNEALING

Annealing is done when strain hardened materials are exposed to heat above recrystallization temperature for definite time and then it is cooled at room temperature.

- It has 3 basic stages :

⑩ RECOVERY
⑩ RECRYSTALLIZATION
⑩ GRAIN GROWTH


Recovery
Recrystallisation
Grain Growth
Property
4
3
2
1
5
6
Cold work
Annealing
1-Hardness, 2-Tensile strength, 3-Internal stresses,
4-Electrical resistance, 5-Corrosion resistance, 6-Ductility
(a)
(b)
(c)
(d)
(e)

RECOVERY

- The relief of some of the internal strain energy of a previously cold-worked material.
- Relieves the stresses from cold working
- 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 process ocurs above recrystallisation temperature which is defined as the temperature at which 50% of material recrystallises in one hour time.
- The recrystallization temperature is strongly dependent on the purity of a material.
- Pure materials may recrystallize around 0.3Tm, while impure materials may recrystallise around 0.4Tm, where Tm is absolute melting temperature of the material.

RECRYSTALLIZATION

- The nucleation of new grains happens in regions of high dislocation density.
- Nucleation begins in a jumble of dislocations. The recrystallised grain will essentially be free from dislocations.
- A greater nucleation rate leads to a finer ultimate grain size.
- There is a critical level of deformation below which there will be no recrystallisation at all.
- A critical strain anneal can lead to a single crystal recrystallisation.

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

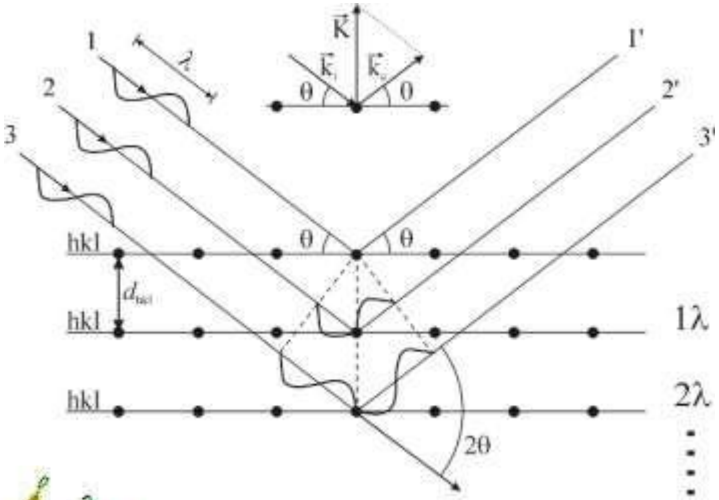
INDUSTRIAL APPLICATIONS

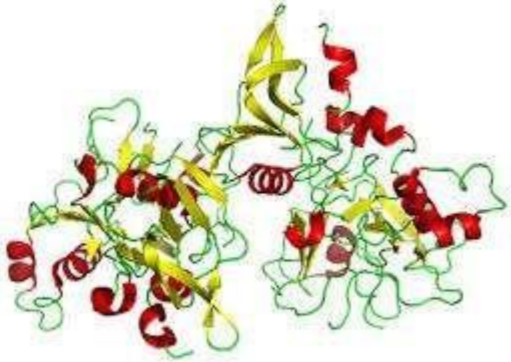
- Construction materials - High strength reduces the need for material thickness which generally saves weight and cost.
- Machine cutting tools (drill bits, taps, lathe tools) need be much harder than the material they are operating on in order to be effective.
- Knife blades – a high hardness blade keeps a sharp edge.
- Anti-fatigue - Hardening can drastically improve the service life of mechanical components with repeated loading/unloading, such as axles and cogs.

S.No.	Cold working	Hot working
1	It is done at a temperature below the recrystallization temperature.	Hot working is done at a temperature above recrystallization temperature.
2.	It is done below recrystallization temperature so it is accomplished by strain hardening.	Hardening due to plastic deformation is completely eliminated.
3.	Cold working decreases mechanical properties of metal like elongation, reduction of area and impact values.	It increases mechanical properties.
4.	Crystallization does not take place.	Crystallization takes place.
5.	Material is not uniform after this working.	Material is uniform thought.
6.	There is more risk of cracks.	There is less risk of cracks.
7.	Cold working increases ultimate tensile strength, yield point hardness and fatigue strength but decreases resistance to corrosion.	In hot working, ultimate tensile strength, yield point, corrosion resistance are unaffected.

S.No.	Cold working	Hot working
8.	Internal and residual stresses are produced.	Internal and residual stresses are not produced.
9.	Cold working required more energy for plastic deformation.	It requires less energy for plastic deformation because at higher temperature metal become more ductile and soft.
10.	More stress is required.	Less stress required.
11.	It does not require pickling because no oxidation of metal takes place.	Heavy oxidation occurs during hot working so pickling is required to remove oxide.
12.	Embrittlement does not occur in cold working due to no reaction with oxygen at lower temperature.	There is chance of embrittlement by oxygen in hot working hence metal working is done at inert atmosphere for reactive metals.

X-Ray Diffraction



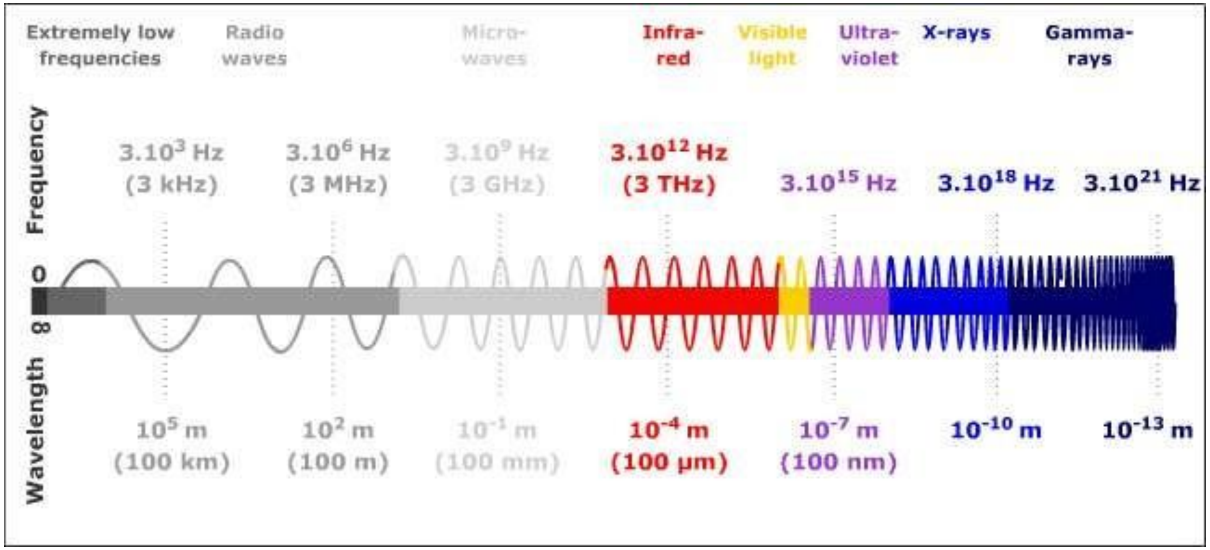


X Ray

An electromagnetic wave of high energy and very short wavelength (between ultraviolet light and gamma rays), which is able to pass through many materials opaque to light.

Why are x-rays used?

$\lambda \sim$ Å

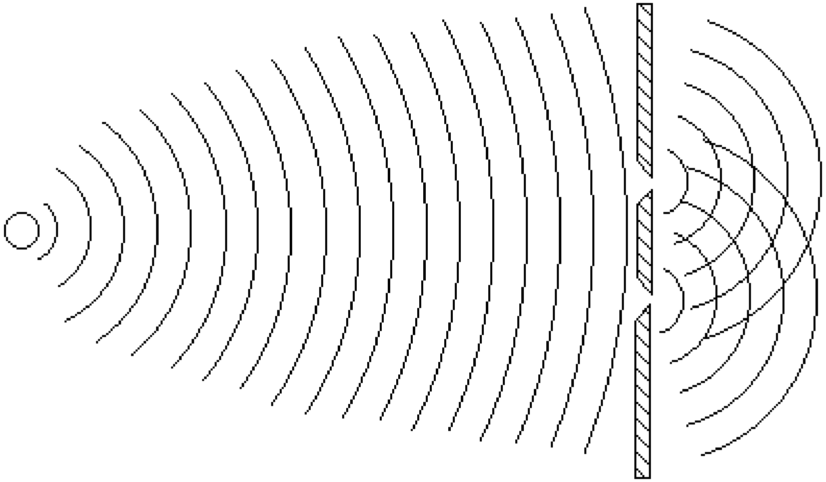


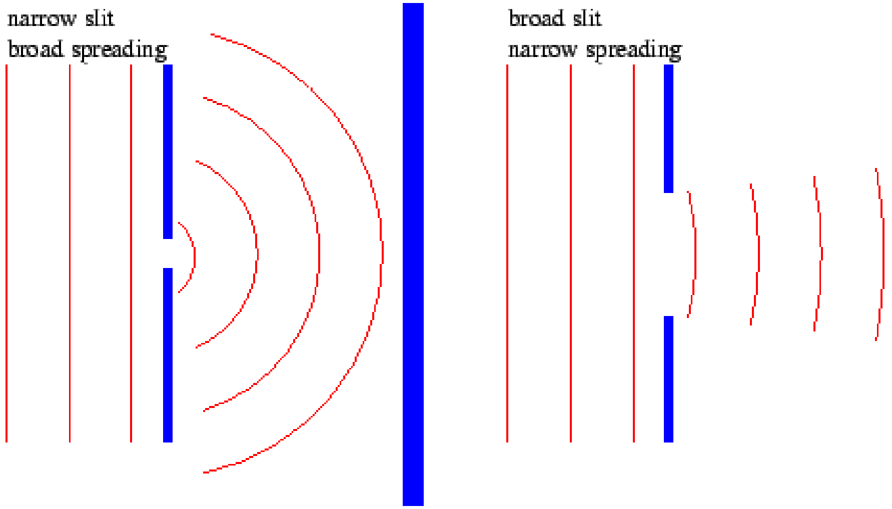
Energy : 100 eV to 100keV

Wavelength : 0.01 to 10 nanometer

Diffraction

The process by which a beam of light or other system of waves is spread out as a result of passing through a narrow aperture or across an edge, typically accompanied by interference between the wave forms produced.





X Ray Diffraction

A technique used to determine the atomic and molecular structure of a crystal, in which the crystalline atoms cause a beam of incident X-rays to diffract into many specific directions.

The atomic planes of a crystal cause an incident beam of X-rays to interfere with one another as they leave the crystal. The phenomenon is called X-ray diffraction.

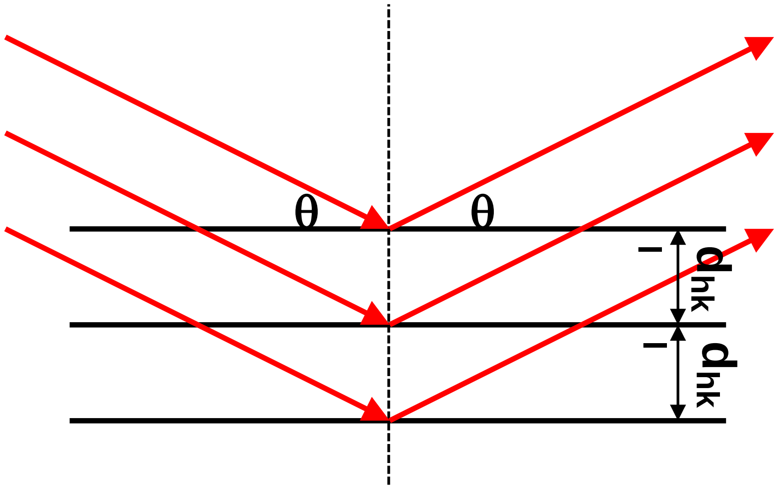
A stream of X-rays directed at a crystal diffract and scatter as they encounter atoms. The scattered rays interfere with each other and produce spots of different intensities that can be recorded on film.

Working Principle

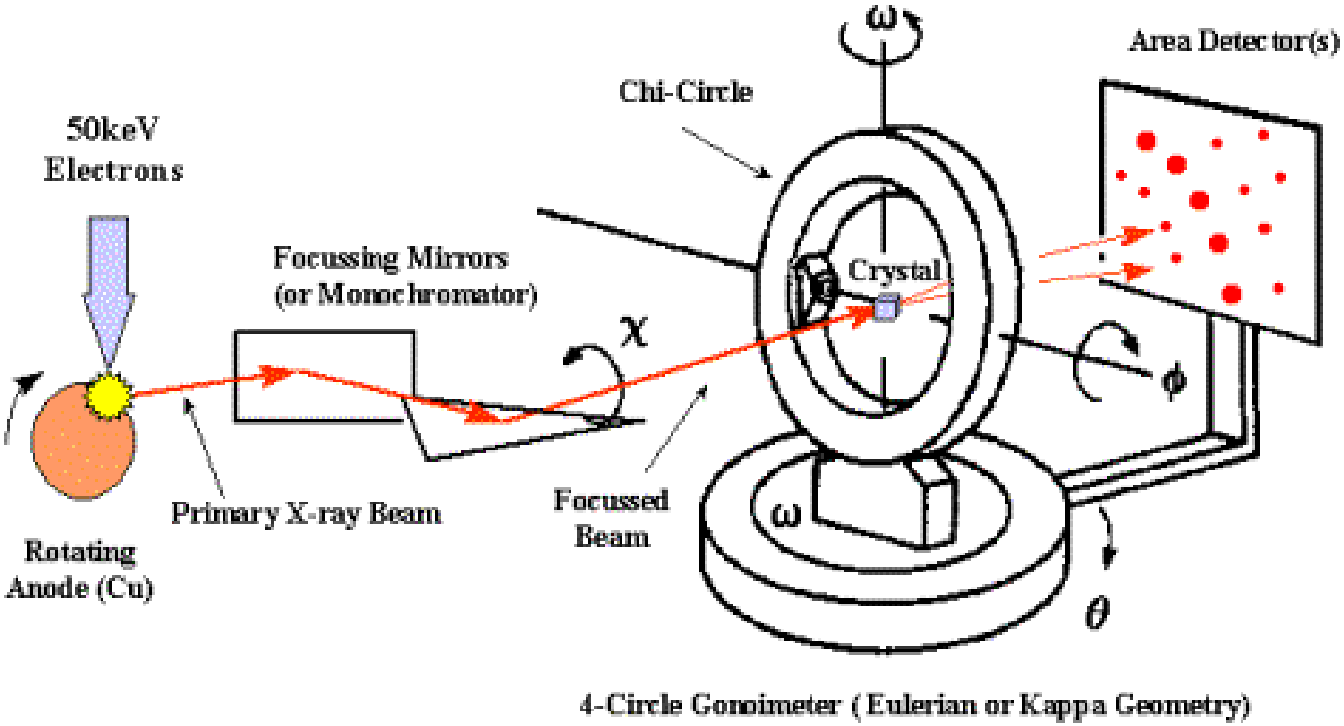
Bragg’s Law

Bragg's law was used to explain the interference pattern of X-rays scattered by crystals

$$N\lambda = 2d\sin\theta$$

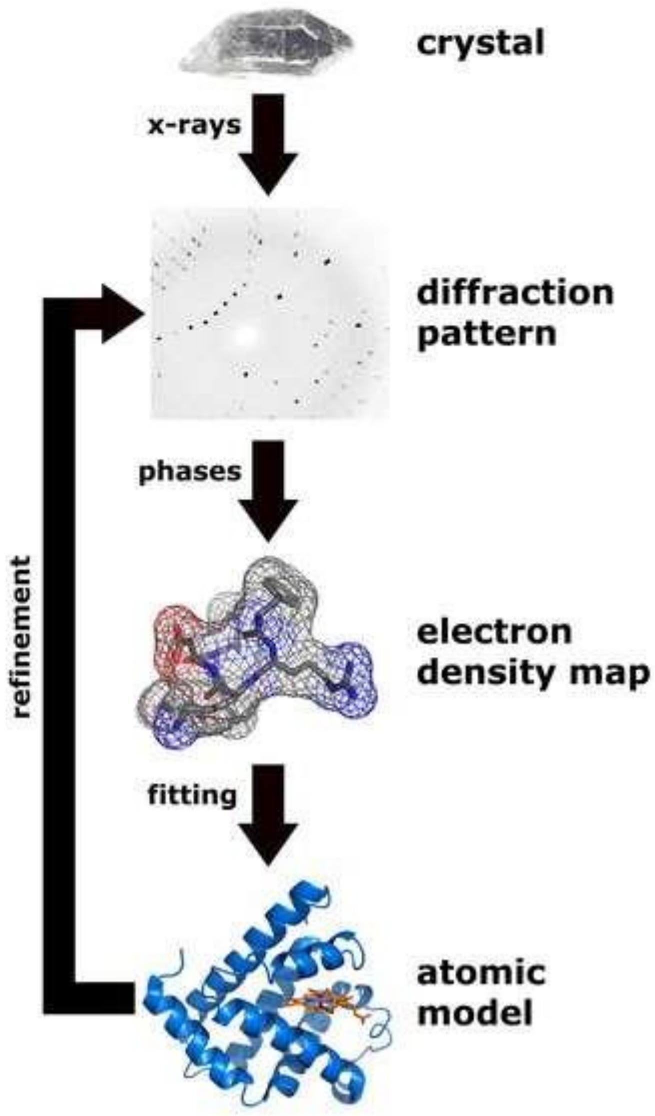


Experimental Setup



Source:
http://pruffle.mit.edu/atomiccontrol/education/xray/xray_diff.php

How Does It Work



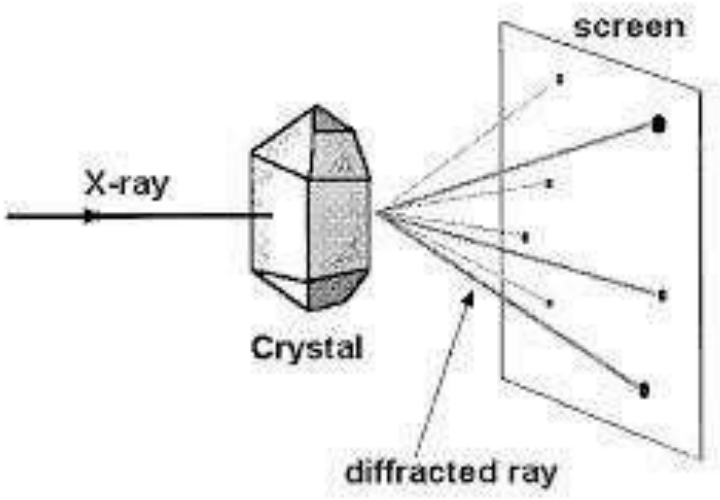
Source: http://en.wikipedia.org/wiki/File:X_ray_diffraction.png

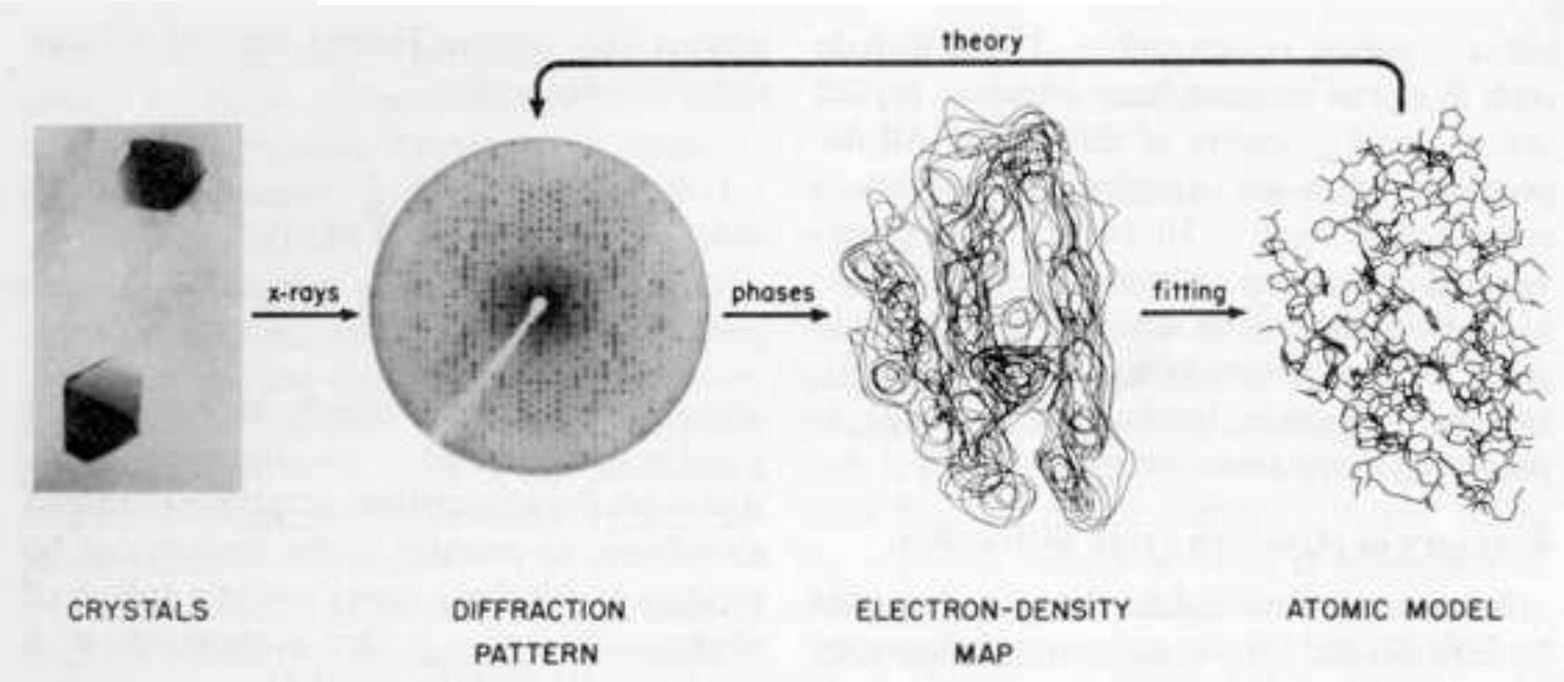
Crystal (regular array of atoms) is mounted on a Goniometer

Bombarded with X-Ray while rotating

Production of diffraction pattern of regularly spaced spots

The 2-D images taken at different rotation are converted to 3-D models of the electron density map by the method of Fourier Transform



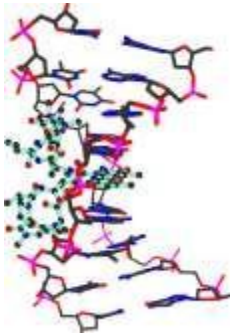


Some Example Images

Uses

- XRD is a non-destructive technique.

- To determine structural properties such as Lattice parameters (10-4Å), strain, grain size



- **Biological macromolecular crystallography**

- To determine atomic arrangement.

- To measure thickness of thin films and multi-layers.