Deformation Behavior of Materials (B.Tech, 5th Semester)

Course Instructor

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Department of Metallurgical & Materials Engineering

LESSON PLAN- Deformation Behavior of Materials

Subject Name : Deformation Behavior of Materials
Credits : 3-0-0
Department : Metallurgical & Materials Engineering
Session : 2024-25 (Odd Semester)
Level : Undergraduate (5th Semester)
Course Instructor : Dr. Dinesh Kumar Mishra
Category : Compulsory course for all B.Tech 5th Semester students of MME Department.

Marks Distribution		
End Term	Mid Term	Assignments + Quiz Test + Attendance
50	30	20
Total -100 Marks		

Required Text book

1. Mechanical Metallurgy, 3rd Ed., McGraw Hill Book Company, New Delhi, 1986 - G.E Dieter
2. Mechanical Behavior of Materials, McGraw Hill Book Company, New Delhi, 1990 - T.H. Courtney

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(Course Coordinator)

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Deformation Behavior of Materials

Module I (8 Hours)

Introduction: Scope of the subject, elastic, plastic and visco-elastic deformation. Deformation behavior: Tensile and compression testing, effect of temperature and strain rate Continuum mechanics: Concepts of stress and strain in 3D stress and strain tensor,

Module II (8 Hours)

Principal stresses and strains and principal axes, mean stress, stress deviator, maximum shear, equilibrium of stresses, equations of compatibility. Elastic behavior of materials: Constitutive equations in elasticity for isotropic and anisotropic materials, strain energy, elastic stiffness and compliance tensor,

Module III (8 Hours)

Effect of crystal structure on elastic constants. Plastic response of materials-a continuum approach: classification of stress-strain curves, yield criteria. Microscopic basis of plastic deformation: Elements of dislocation theory, movement of dislocation, elastic properties of dislocation.

Module IV (8 Hours)

Intersection of dislocation, dislocation reactions in different crystal structures, origin and multiplication of dislocations. Plastic deformation of single crystals: Critical resolved shear stress, deformation by twinning, deformation band and kink band, strain hardening of single crystal; stress-strain curves of fcc, bcc and hcp materials.

Module V (8 Hours)

Plastic deformation of polycrystalline materials: Role of grain boundaries in deformation, strengthening by grain boundaries, yield point phenomenon, strain ageing, strengthening by solutes, precipitates, dispersoids and fibres. Deformation in non-metallic materials: structure and deformation of polymers, concept Super lattice dislocations in inter metallics, and concept of charge associated with dislocations in ceramics.

LECTURE-1

Mechanical metallurgy is the area of knowledge which deals with the behavior and response of metals to applied forces. It will mean different things to different persons

- Mechanical properties of metals or mechanical testing
- The plastic working and shaping of metals
- Theoretical aspects of the field, which merge with metal physics and physical metallurgy
- Mechanical metallurgy is closely allied with applied mathematics and applied mechanics

Continued…

Mechanical metallurgy is the area of metallurgy which is concerned primarily with the response of metals to forces or loads. It is necessary to know something about the limiting values which can be withstood without failure.

- A ***continuous body*** is one which does not contain voids or empty spaces of any kind.
- A body is ***homogeneous*** if it has identical properties at all points.
- A body is considered to be ***isotropic*** with respect to some property when that property does not vary with direction or orientation.
- A property which varies with orientation with respect to some system of axes is said to be ***anisotropic****.*

Continued…

ELASTIC AND PLASTIC BEHAVIOR

- The recovery of the original dimensions of a deformed body when the load is removed is known as ***elastic behavior****.*
- The limiting load beyond which the material no longer behaves elastically is the ***elastic limit****.*
- If the elastic limit is exceeded, the body will experience a permanent set or deformation when the load is removed. A body which is permanently deformed is said to have undergone ***plastic deformation.***
- ***Viscoelastic materials*** refers those materials which show the material behavior in between both solid and liquid phase.

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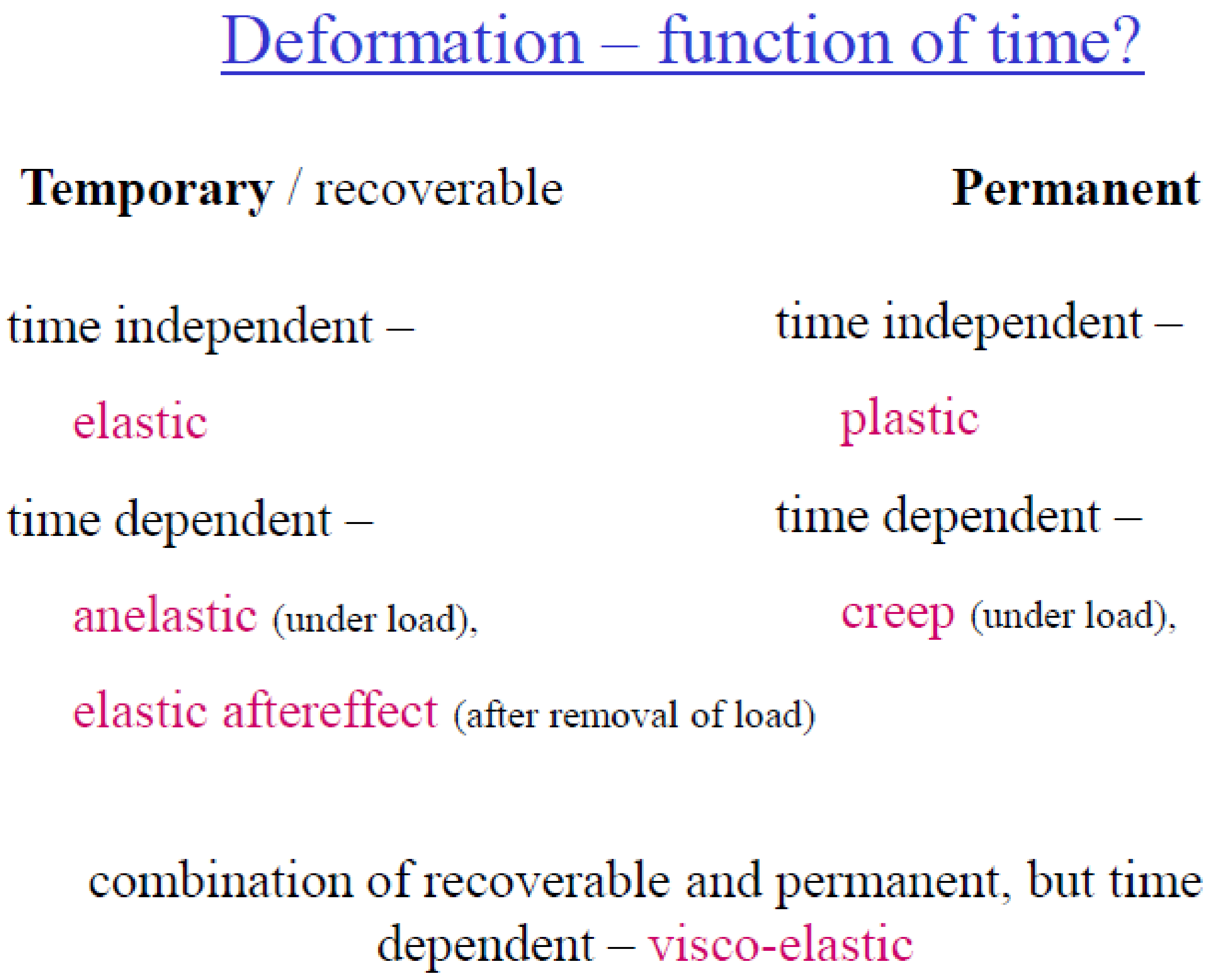

Deformation – function of time?

Temporary / recoverable	**Permanent**
time independent –	time independent –
elastic	plastic
time dependent –	time dependent –
anelastic (under load),	creep (under load),
elastic aftereffect (after removal of load)	

combination of recoverable and permanent, but time dependent – visco-elastic

Ref: https://nptel.ac.in/content/storage2/courses/112108150/pdf/PPTs/MTS_04_m.pdf

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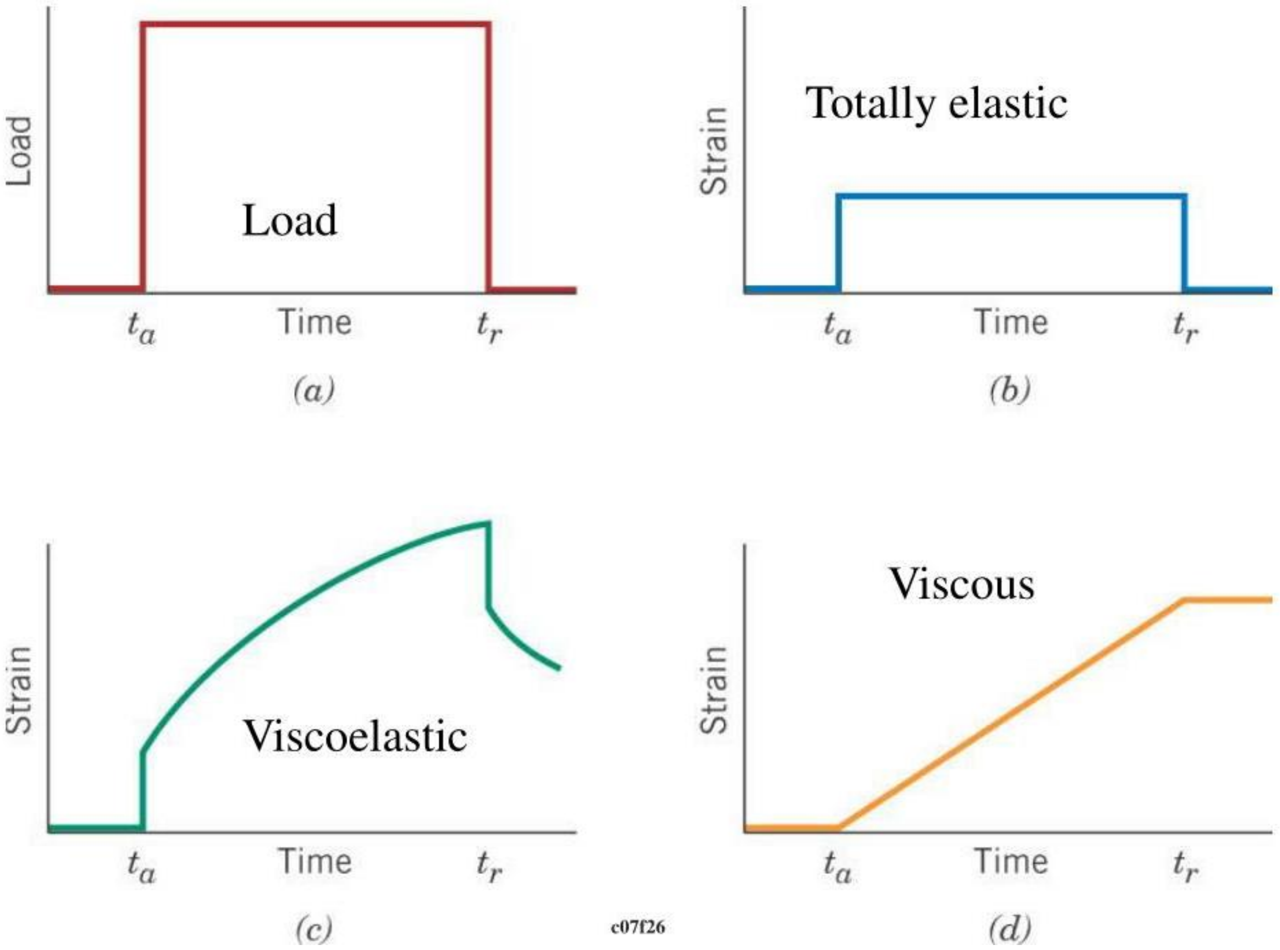
7.15 Viscoelasticity Deformation



Ref- https://www.slideserve.com/Albert_Lan/c07f01

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Hooke's law:

For most materials, as long as the load does not exceed the elastic limit, the deformation is proportional to the load. This relationship is known as Hooke's law; it is more frequently stated as $\boldsymbol{\sigma}$ *.*

- However, it does not necessarily follow that all materials which behave elastically will have a linear stress-strain relationship. Rubber is an example of a material with a nonlinear stress-strain relationship that still satisfies the definition of an elastic material.

AVERAGE STRESS AND STRAIN

A load P is applied to one end of the bar, and the gage length undergoes a slight increase in length and decrease in diameter. The distance between the gage marks has increased by an amount δ, called the deformation. The ***average linear strain e*** is the ratio of the change in length to the original length.

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- Strain is a **dimensionless** quantity.

$$e = \frac{\delta}{L_0} = \frac{\Delta L}{L_0} = \frac{L-L_a}{L_0}$$

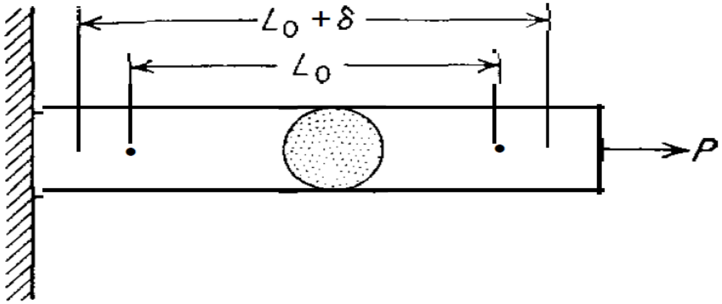

Figure I-I Cylindrical bar subjected to axial load.

- The external load *P* is balanced by the internal resisting force $\sigma.dA$, where σ is the stress normal to the cutting plane and *A* is the cross-sectional area of the bar. The equilibrium equation is

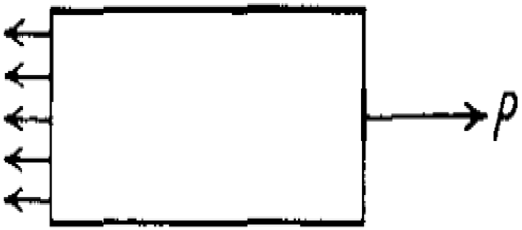

Figure 1-2 Free-body diagram for Fig. 1-1.

$$P = \sigma.dA$$

$$P = \int \sigma.dA = \sigma.A$$

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

Continued…

The elastic limit Hooke's law can be considered valid, so that the average stress is proportional to the average strain,

$$\frac{\sigma}{e} = E = Constant$$

The constant *E* is the ***modulus of elasticity***, or ***Young's modulus***.

Elastic modulus vs Stiffness

Elastic modulus:

- It is a material property, so varies from material to material.
- It is obtained as the slope of stress-strain plot.

Stiffness:

- It is material property that depends on geometry and modulus of material.
- It is obtained as the slope of force-displacement plot.

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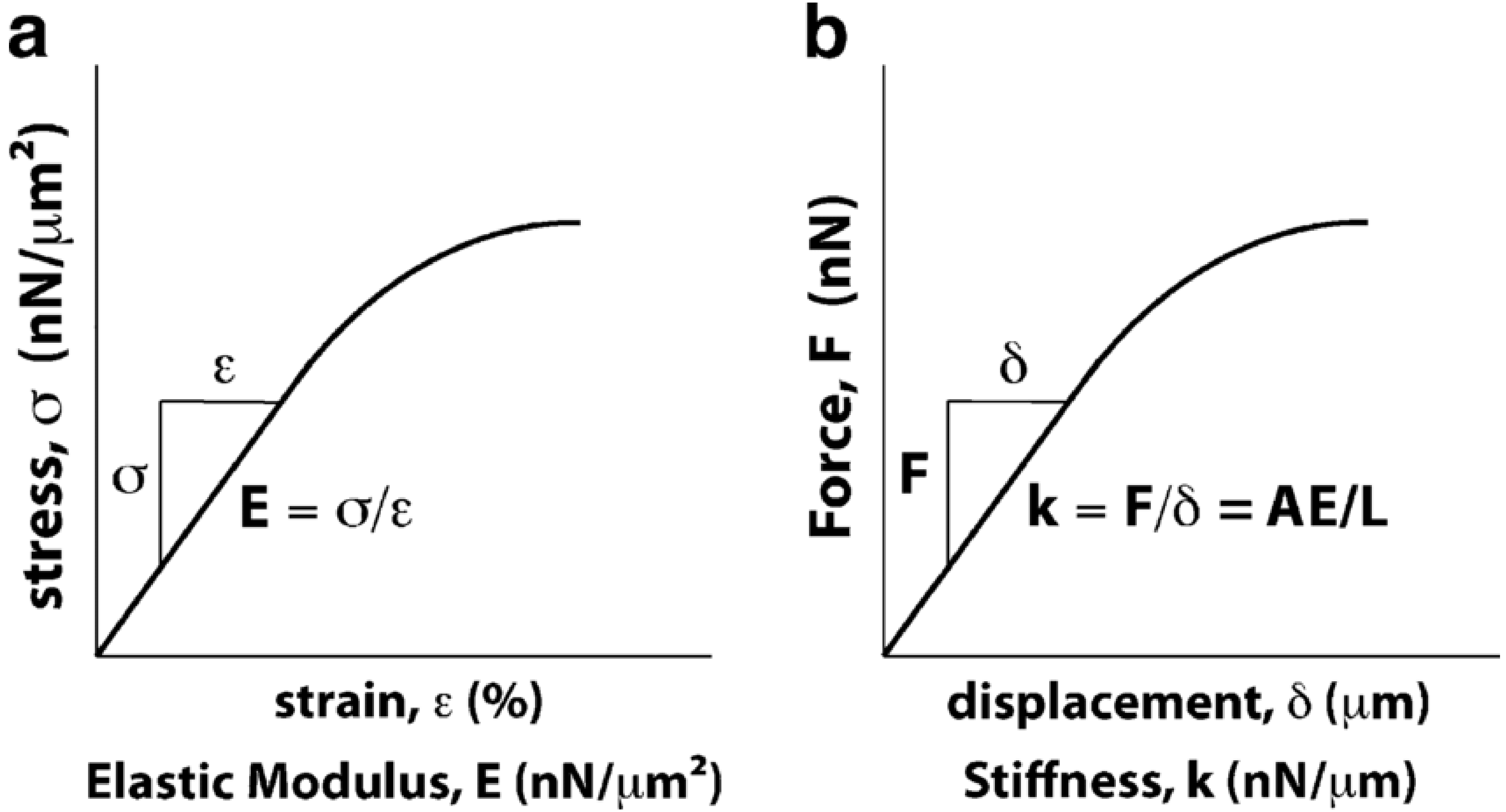

Ref- Guelcher, S. A., & Sterling, J. A. (2011). Contribution of bone tissue modulus to breast cancer metastasis to bone. *Cancer Microenvironment*, *4*(3), 247-259.

LECTURE-2

TENSILE DEFORMATION OF DUCTILE METAL

- The data obtained from the tension test are generally plotted as a stress-strain diagram.
- It shows a typical stress-strain curve for a metal such as aluminum or copper.
- The initial linear portion of the curve ***OA*** is the elastic region within which Hooke's law is obeyed.
- Point ***A*** is the elastic limit, defined as the greatest stress that the metal can withstand without experiencing a permanent strain when the load is removed.
- The determination of the elastic limit is quite tedious, not at all routine, and dependent on the sensitivity of the strain-measuring instrument.
- For these reasons it is often replaced by the ***proportional limit,*** point ***A'.***

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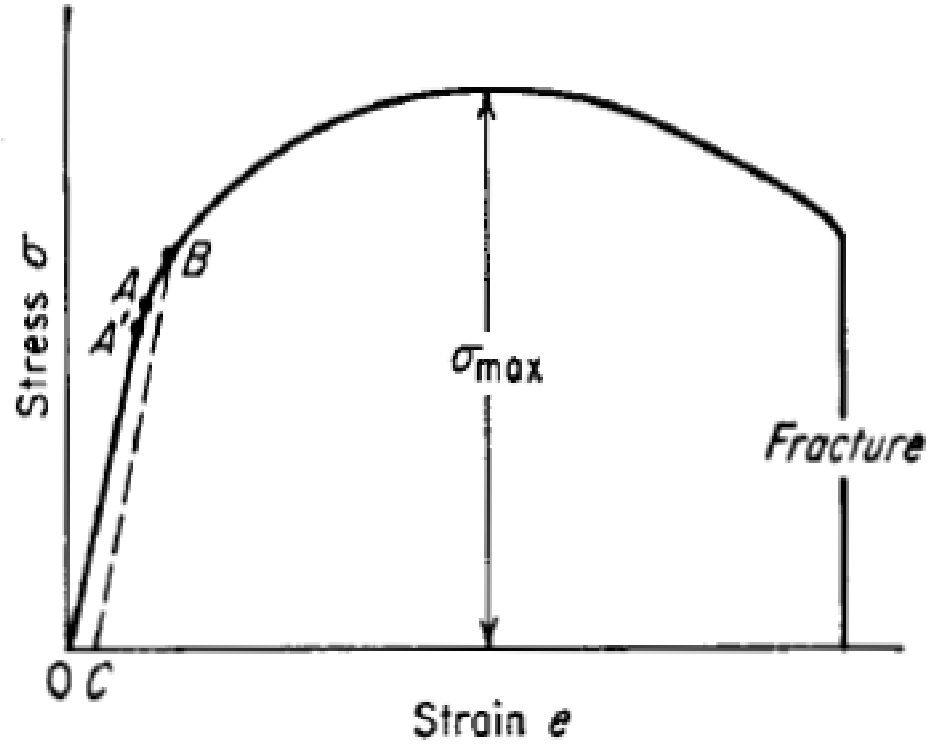

Fig. 1.3 Typical tension stress-strain curve

- The proportional limit is the stress at which the stress-strain curve deviates from linearity.
- The slope of the stress-strain curve in this region is the modulus of elasticity.
- For engineering purposes the limit of usable elastic behavior is described by **the *yield strength*,** point ***B***.

Continued…

- The yield strength is defined as the stress which will produce a small amount of permanent deformation, generally equal to a strain of 0.002. This permanent strain, or offset, is **OC**.
- Plastic deformation begins when the elastic limit is exceeded.
- As the plastic deformation of the specimen increases, the metal becomes stronger (strain hardening), so that the load required extending the specimen increases with further straining.
- Eventually the load reaches a maximum value. The maximum load divided by the original area of the specimen is the ***ultimate tensile strength***.
- For a ductile metal the diameter of the specimen begins to decrease rapidly beyond maximum load, so that the load required continuing deformation drops off until the specimen fractures.

Continued…

DUCTILE vs BRITTLE BEHAVIOR

- **Brittle Materials:** A completely brittle material would fracture almost at the elastic limit
- **Ductile Materials:** A brittle metal, such as white cast iron, shows some slight measure of plasticity before fracture.

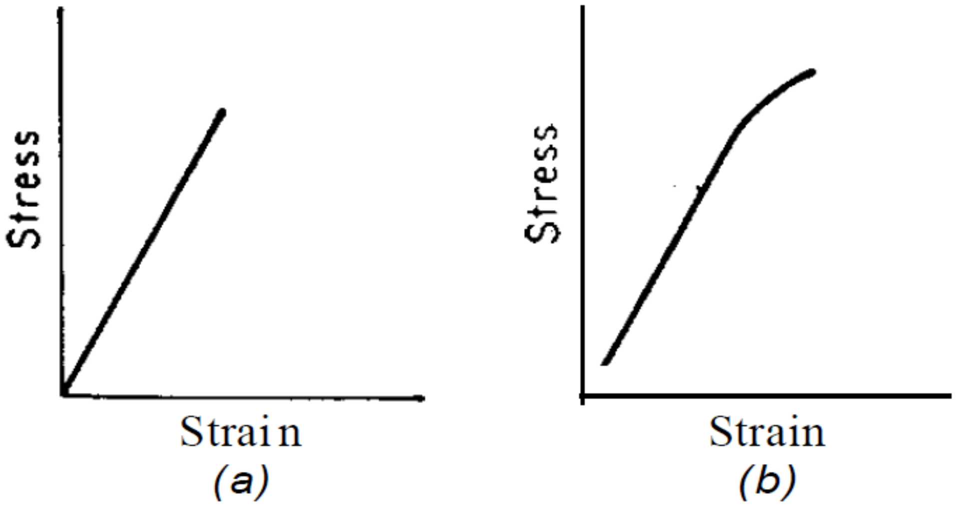

Figure 1-4 *(a)* Stress-strain curve for completely brittle material (ideal behavior); *(b)* stress-strain curve for brittle metal with slight amount of ductility.

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- Adequate ductility is an important engineering consideration, because it allows the material to redistribute localized stresses.
- It is important to note that brittleness is not an absolute property of a metal.
- A metal such as tungsten, which is brittle at room temperature, is ductile at an elevated temperature.
- A metal which is brittle in tension may be ductile under hydrostatic compression.
- Furthermore, a metal which is ductile in tension at room temperature can become brittle in the presence of notches, low temperature, high rates of loading, or embrittling agents such as hydrogen.

Continued…

CONCEPT OF STRAIN AND THE TYPES OF STRAIN

- The average linear strain **(engineering strain)** was defined as the ratio of the change in length to the original length of the same dimension.

$$e = \frac{\delta}{L_0} = \frac{\Delta L}{L_0} = \frac{L - L_a}{L_0}$$

[Where, *e* = average linear strain, δ= deformation]

- Rather than referring the change in length to the original gage length, it often is more useful to define the strain as the change in linear dimension divided by the instantaneous value of the dimension. The above equation defines the ***natural*** **or** ***true strain.***

Continued…

True Stress – True Strain

- *True* or *Natural* stress and strain are defined to give true picture of the instantaneous conditions.

- True strain:

$$\varepsilon = \sum \frac{L_1 - L_0}{L_0} + \frac{L_2 - L_1}{L_1} + \frac{L_3 - L_2}{L_2} + \ldots \qquad \varepsilon = \int_{L_0}^{L} \frac{dL}{L} = \ln \frac{L}{L_0}$$

- True stress:

$$\sigma = \frac{P}{A} = \frac{P}{A_0}\frac{A_0}{A} = s(e+1)$$

Ref: https://nptel.ac.in/content/storage2/courses/112108150/pdf/PPTs/MTS_04_m.pdf

Continued…

- Not only will the elastic deformation of a body result in a change in length of a linear element in the body, but it may also result in a change in the initial angle between any two lines. The angular change in a right angle is known as ***shear strain.***

- **Poisson's ratio:** While a tensile force in the *x* direction produces an extension along that axis, it also produces a contraction in the transverse *y* and *z* directions. The transverse strain has been found by experience to be a constant fraction of the strain in the longitudinal direction. This is known as ***Poisson's ratio,*** denoted by the symbol *v.*

$$\nu = \frac{Transverse\ strain}{Longitudinal\ strain} = -\frac{\varepsilon_t}{\varepsilon_l}$$

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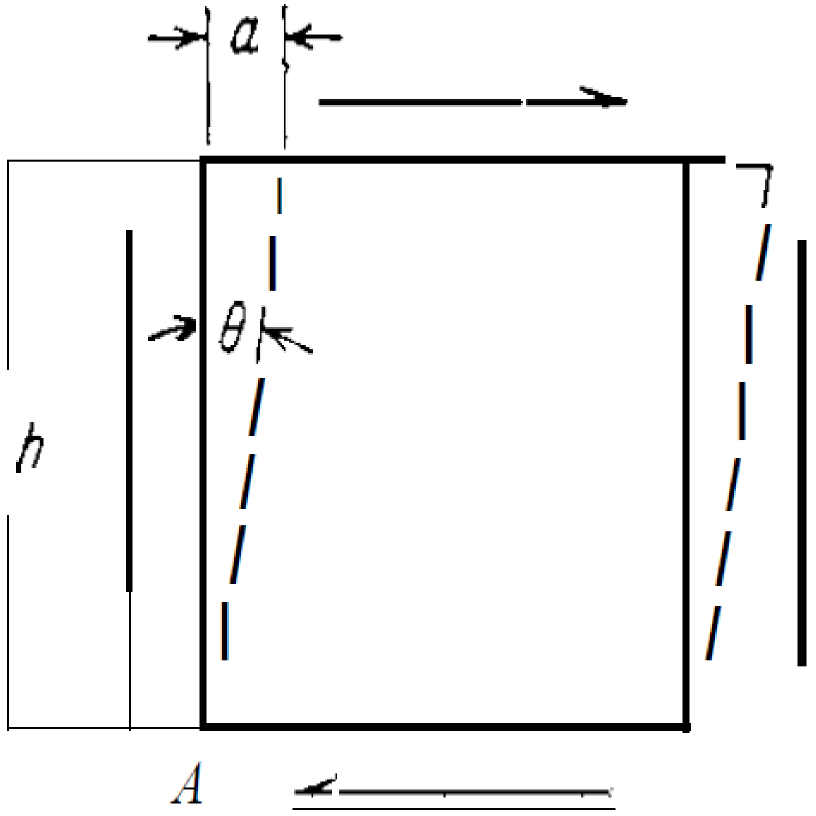

Figure 1-7 Shear strain.

- For most metals the values of ν are close to 0.33.

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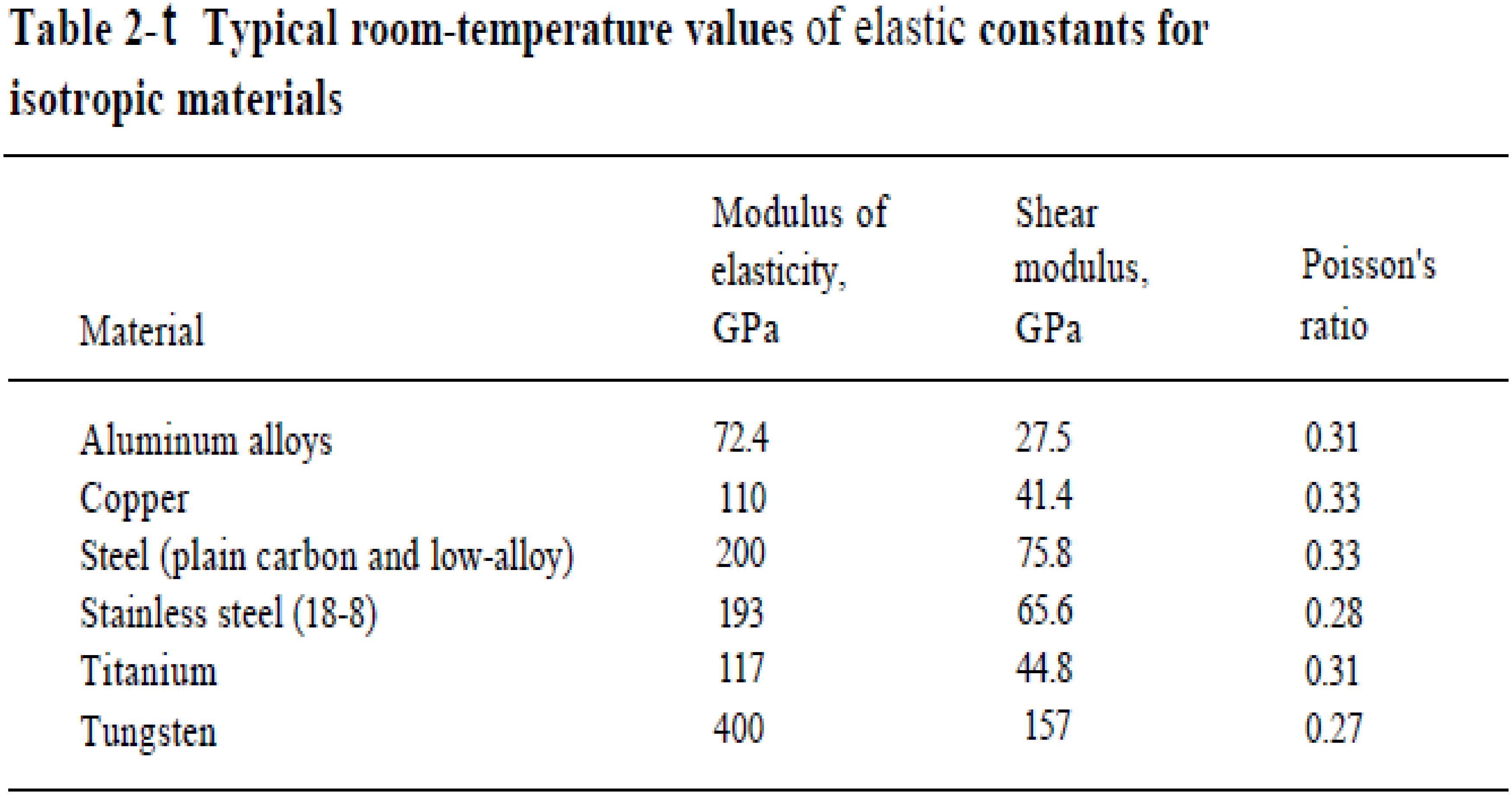

Table 2-t Typical room-temperature values of elastic constants for isotropic materials

Material	Modulus of elasticity, GPa	Shear modulus, GPa	Poisson's ratio
Aluminum alloys	72.4	27.5	0.31
Copper	110	41.4	0.33
Steel (plain carbon and low-alloy)	200	75.8	0.33
Stainless steel (18-8)	193	65.6	0.28
Titanium	117	44.8	0.31
Tungsten	400	157	0.27

LECTURE-3

ELEMENTS OF THE THEORY OF PLASTICITY

- The theory of plasticity deals with the behavior of materials at strains where Hooke's law is no longer valid.
- Elastic deformation depends only on the initial and final states of stress and strain. The plastic strain depends on the loading path by which the final state is achieved.
- Moreover, in plastic deformation there is no easily measured constant relating stress to strain as with Young's modulus for elastic deformation.
- The phenomenon of **strain hardening** is difficult to accommodate within the theory of plasticity without introducing considerable mathematical complexity.
- Also, several aspects of real material behavior, such as plastic anisotropy, elastic hysteresis, and the Bauschinger effect cannot be treated easily by plasticity theory.

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THE FLOW CURVE

- The stress-strain curve obtained by uniaxial loading, as in the ordinary tension test, is of fundamental interest in plasticity when the curve is plotted in terms of true stress and true strain.
- A true stress-strain curve is frequently called a ***flow curve*** because it gives the stress required to cause the metal to flow plastically to any given strain.
- Many attempts have been made to fit mathematical equations to this curve.
- The most common is a power expression of the form

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

Were K is the stress at $\varepsilon = 1.0$ and n *is* the strain-hardening coefficient or the slope of a log-log plot of above Eq.

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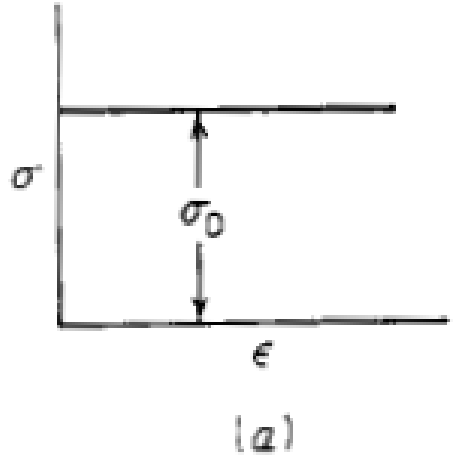
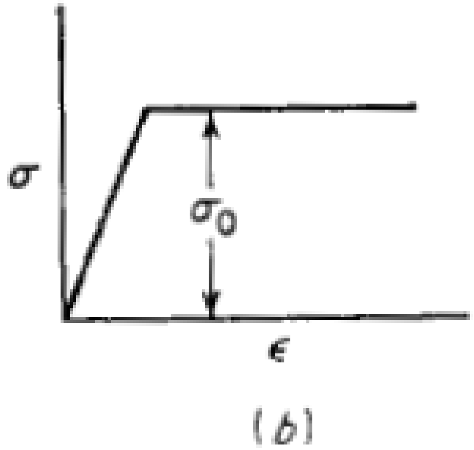
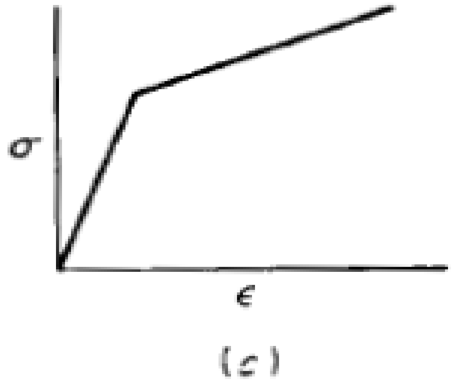
- This equation can be ***valid only from the beginning of plastic flow to the maximum load*** at which the specimen begins to neck down.



(a) Rigid ideal plastic material



(b) ideal plastic material with



(c) piecewise linear (strain-hardening) material

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TRUE STRESS AND TRUE STRAIN

STRESS

Stress, σ, is defined as the intensity of force at a point:

$$\boldsymbol{\sigma = \partial F/\partial A \text{ as } \partial A \rightarrow 0.}$$

If the state of stress is the same everywhere in a body,

$$\boldsymbol{\sigma = F/A.}$$

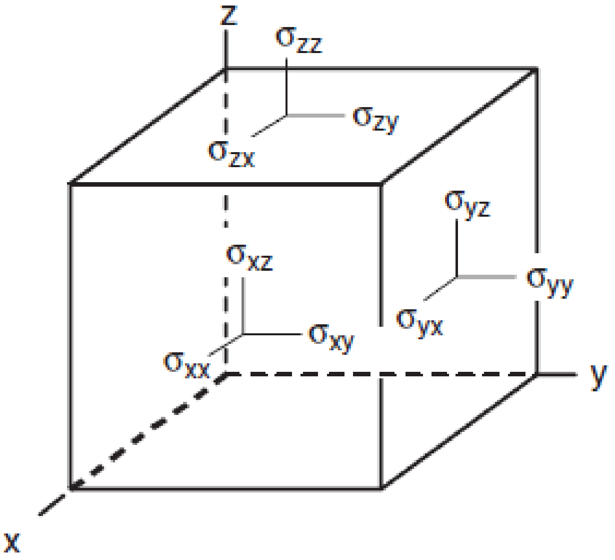

Figure 1.1. The nine components of stress acting on an infinitesimal element. The normal stress components are σ_{xx}, σ_{yy}, and σ_{zz}. The shear stress components are σ_{yz}, σ_{zx}, σ_{xy}, σ_{zy}, σ_{xz}, and σ_{yx}.

Continued…

- A *normal stress* (compressive or tensile) is one in which the force is normal to the area on which it acts. With a *shear stress,* the force is parallel to the area on which it acts.
- Two subscripts are required to define a stress. The first subscript denotes the normal to the plane on which the force acts and the second subscript identifies the direction of the force. For example, a tensile stress in the x-direction is denoted by σ_{xx} , indicating that the force is in the x-direction and it acts on a plane normal to x. For a shear stress, σ_{xy}, a force in the y-direction acts on a plane normal to x.
- Because stresses involve both forces and areas, they are not vector quantities. Nine components of stress are needed to describe a state of stressfully at a point, as shown in Figure 1.1.

Continued…

- The stress component $\sigma_{yy} = F_y/A_y$ describes the tensile stress in the *y*-direction. The stress component $\sigma_{zy} = F_y/A_z$ is the shear stress caused by a shear force in the *y*-direction acting on a plane normal to *z*. Repeated subscripts denote normal stresses (e.g., σ_{xx}, σ_{yy}, . . .) whereas mixed subscripts denote shear stresses (e.g., σ_{xy}, σ_{zx}, . . .). In *tensor* notation the state of stress is expressed as

$$\sigma_{ij} = \begin{vmatrix} \sigma_{xx} & \sigma_{yx} & \sigma_{zx} \\ \sigma_{xy} & \sigma_{yy} & \sigma_{zy} \\ \sigma_{xz} & \sigma_{yz} & \sigma_{zz} \end{vmatrix},$$

Where *i* and *j* are iterated over *x*, *y*, and *z*. Except where tensor notation is required, it is often simpler to use a single subscript for a normal stress and to denote a shear stress by τ .

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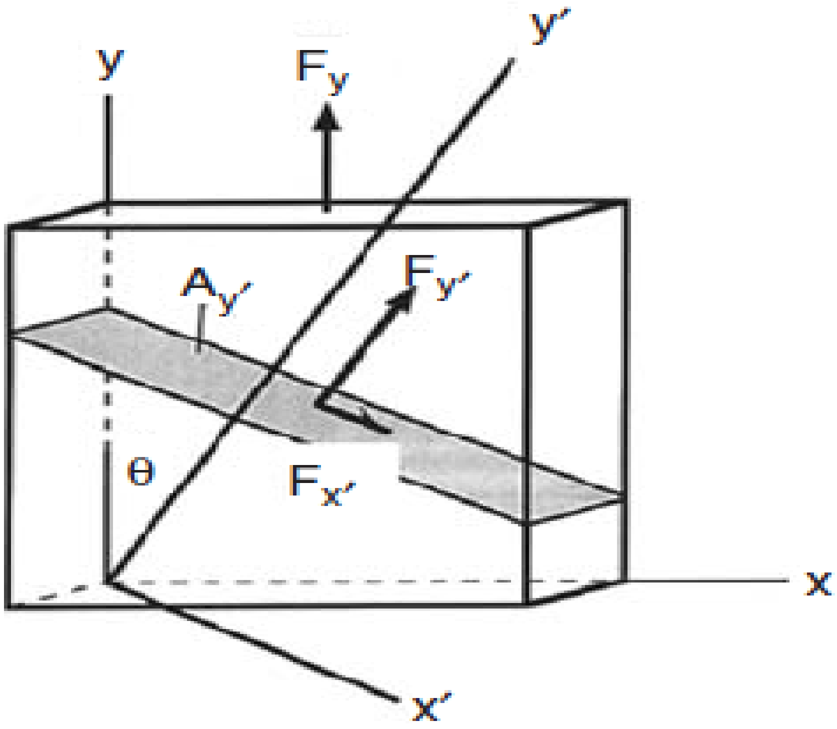

Figure 1.2. Stresses acting on an area, A', under a normal force, F_y. The normal stress $\sigma_{y'y'} = F_{y'}/A_{y'} = F_y \cos\theta/(A_y/\cos\theta) = \sigma_{yy}\cos^2\theta$. The shear stress $\tau_{y'x'} = F_x/A_{y'} = F_y \sin\theta/(A_{yx}/\cos\theta) = \sigma_{yy}\cos\theta\ \sin\theta$.

$$\sigma_x \equiv \sigma_{xx} \quad \text{and} \quad \tau_{xy} \equiv \sigma_{xy}.$$

LECTURE-4

STRAINS

- An infinitesimal normal strain is defined by the change of length, *L*, of a line:

$$d\varepsilon = dL/L.$$

- Integrating from the initial length, *L*o, to the current length, *L*,

$$\varepsilon = \int dL/L = \ln(L/L_o).$$

- This finite form is called *true strain* (or *natural strain, logarithmic strain*). Alternatively, *engineering* or *nominal strain*, *e*, is defined as

$$e = \Delta L/L_o.$$

Continued…

- If the strains are small, then engineering and true strains are nearly equal. Expressing $\varepsilon = \ln(L/L_o) = \ln(1 + e)$ as a series expansion, $\varepsilon = e - e^2/2 + e^3/3! - \cdot$, so as $e \rightarrow 0$, $\varepsilon \rightarrow e$. This is illustrated in the following example.

Example problem: Calculate the ratio e/ε for several values of e.

Solution: $e/\varepsilon = e/\ln(1 + e)$. Evaluating:

For $e = 0.001$, $e/\varepsilon = 1.0005$; For $e = 0.01$, $e/\varepsilon = 1.005$;

For $e = 0.02$, $e/\varepsilon = 1.010$; For $e = 0.05$, $e/\varepsilon = 1.025$;

For $e = 0.10$, $e/\varepsilon = 1.049$; For $e = 0.20$, $e/\varepsilon = 1.097$;

For $e = 0.50$, $e/\varepsilon = 1.233$.

Continued…

Note that the difference between e and ε is less than 1% for $e < 0.02$. There are several reasons that true strains are more convenient than engineering strains.

- True strains for equivalent amounts of deformation in tension and compression are equal except for sign.
- True strains are additive. For a deformation consisting of several steps, the overall strain is the sum of the strains in each step.
- The volume change is related to the sum of the three normal strains. For constant volume, $\varepsilon x + \varepsilon y + \varepsilon z = 0$.

These statements are not true for engineering strains, as illustrated in the following examples.

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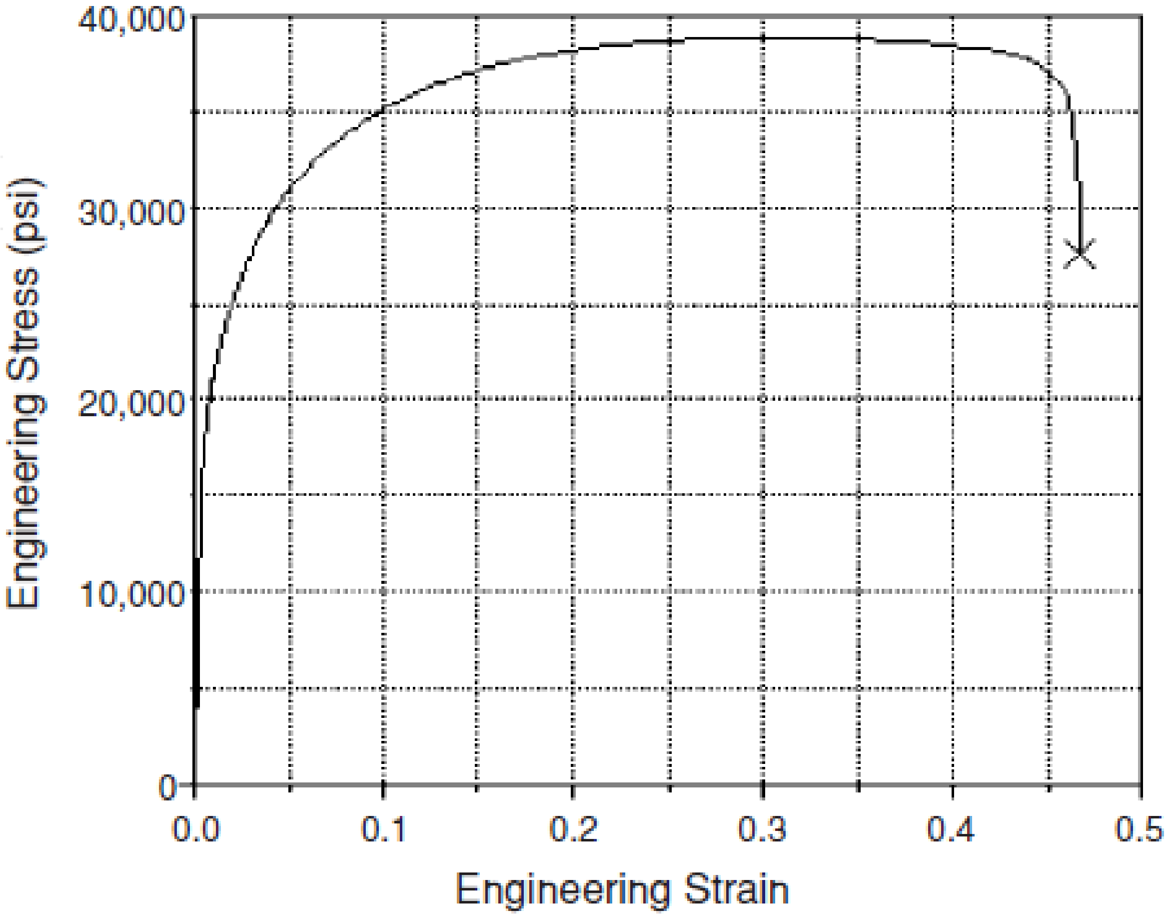
STRESS-STRAIN CURVES:



Typical engineering stress– strain curve for a ductile material

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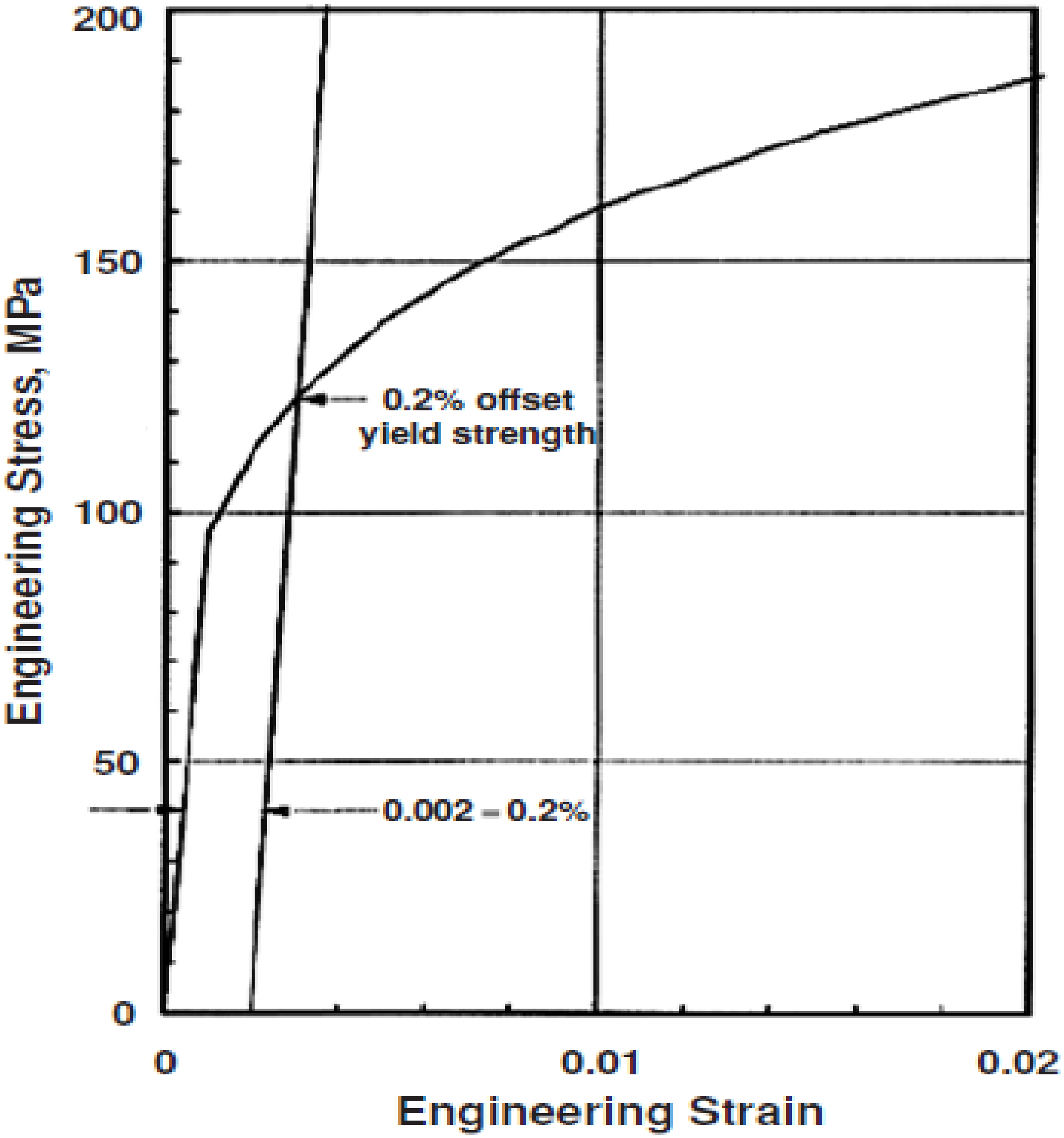

The low-strain region of the stress–strain curve for a ductile material

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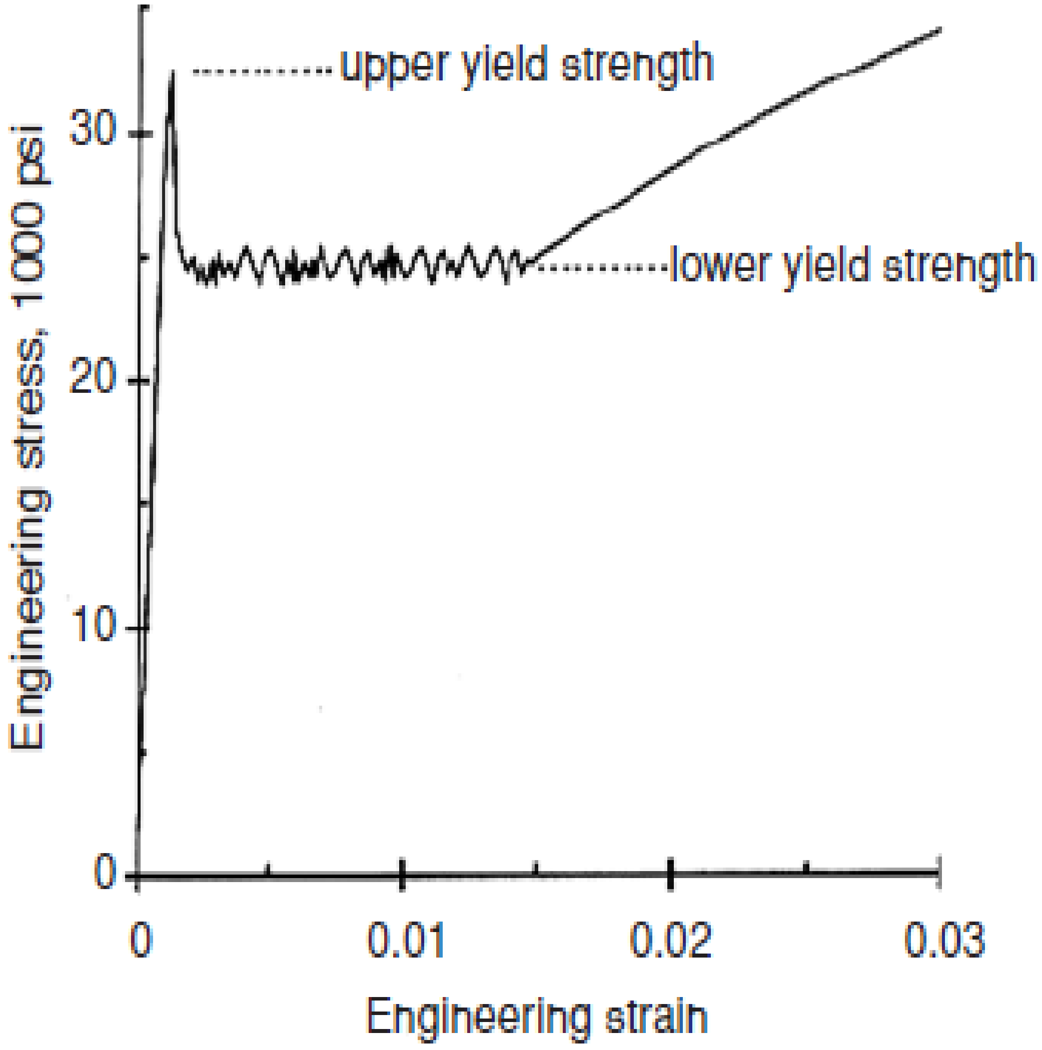

Inhomogeneous yielding of low carbon steel

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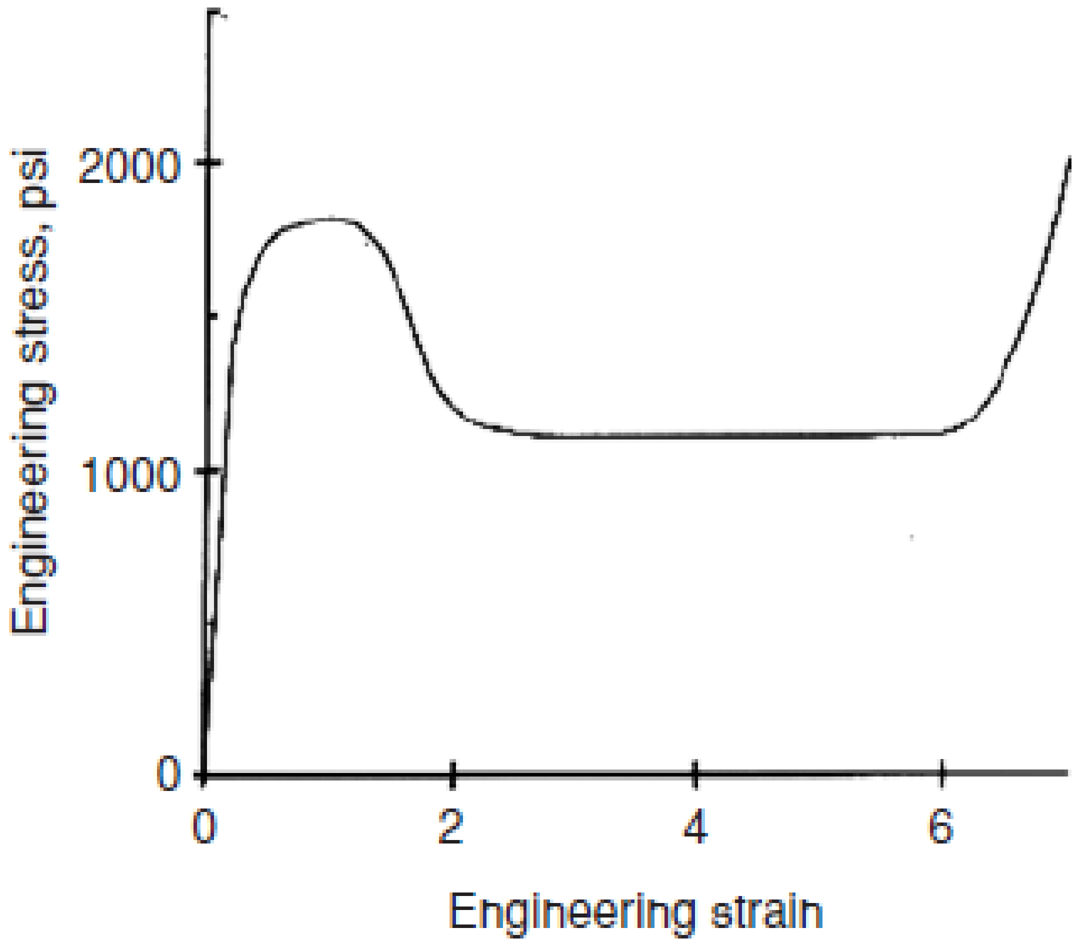

Inhomogeneous yielding of a linear polymer

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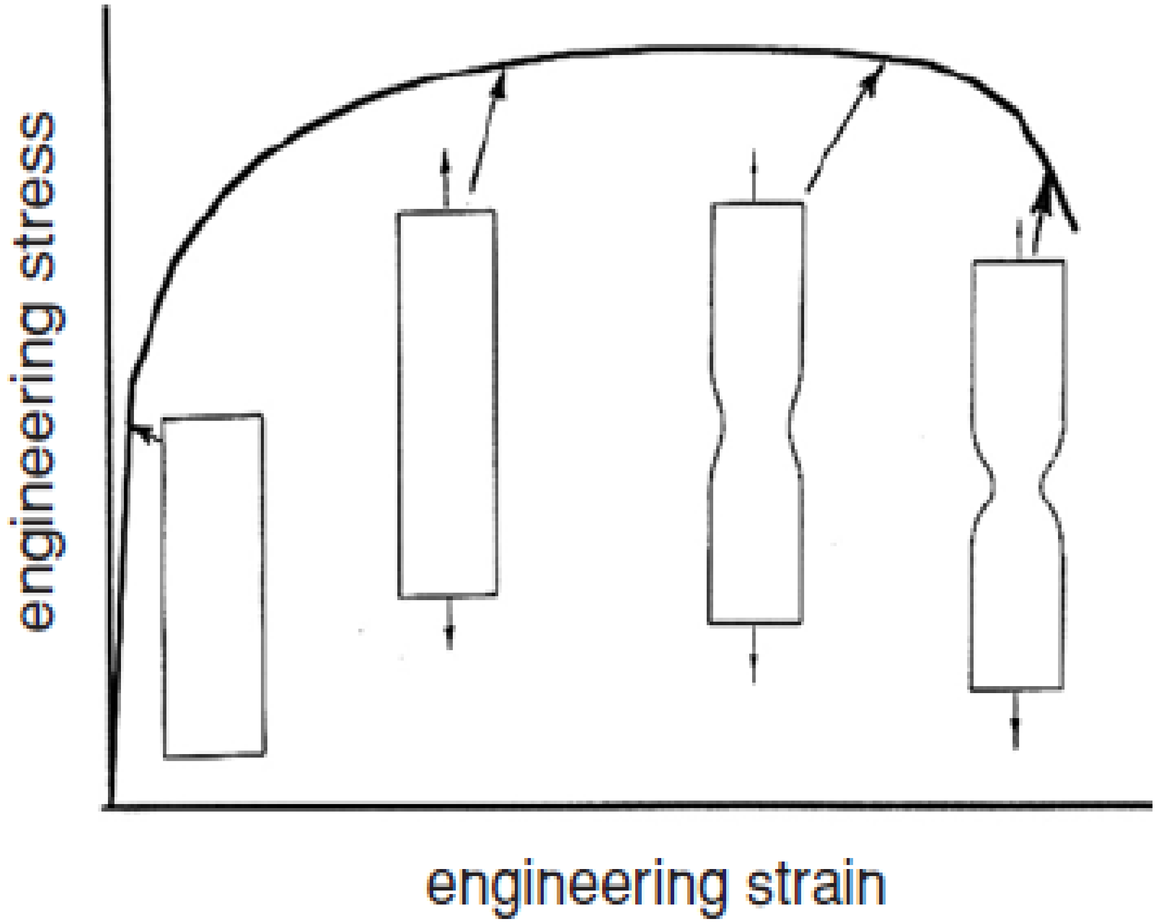


After a maximum on the stress–strain curve, deformation localizes to form a neck.

LECTURE-5

TRUE STRESS AND STRAIN

TENSION TEST:

The true stress is defined as

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

Where, *A* is the instantaneous cross-sectional area corresponding to the force *F*. Before necking begins, the true strain is given by

$$\varepsilon = ln(L/L_0)$$

The engineering stress is defined as the force divided by the original area, $s=F/A$o, and the engineering strain is defined as the change in length divided by the original length, $e=\Delta L/L$o.

Continued…

As long as the deformation is uniform along the gauge length, the true stress and true strain can be calculated from the engineering quantities. With constant volume, *LA*=*L*o *A*o, so that

$$\frac{A_0}{A} = \frac{L}{L_0}$$

and thus *A*o/*A*=1+*e* Rewriting above Equation as *σ* =(*F*/*A*o)(*A*o/*A*) and substituting *A*o/*A*=1+*e* and *s*=*F*/*A*o,

$$\sigma = s(1 + e)$$

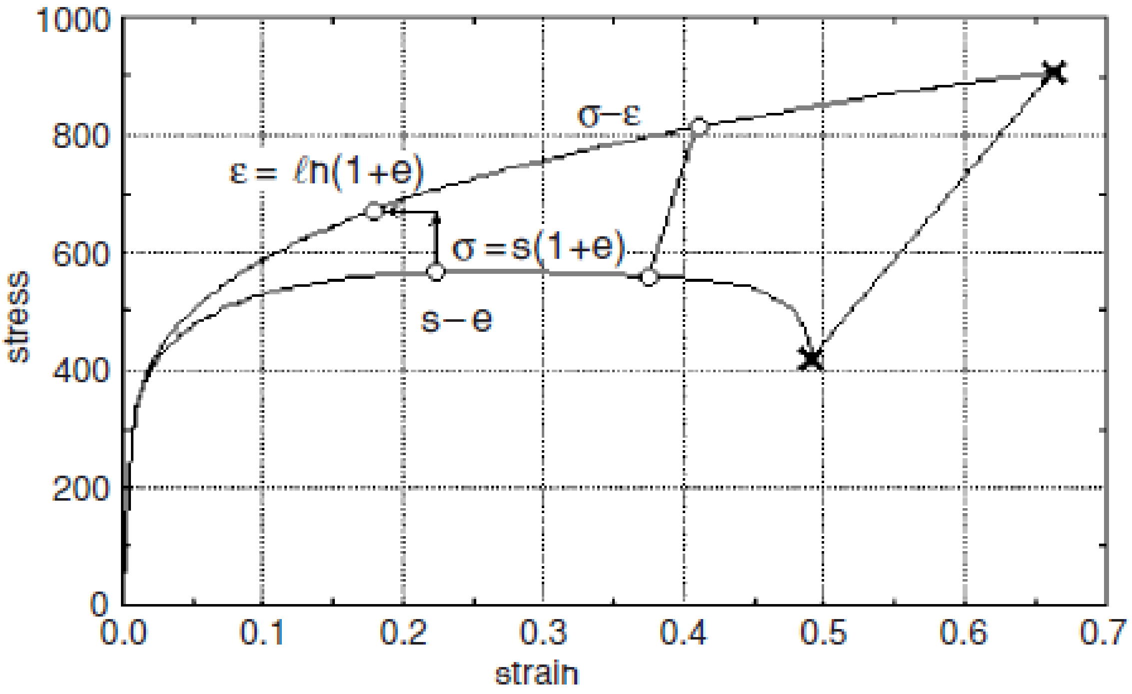
Substitution of *L*/*L*o =1+*e, true strain becomes*

$$\varepsilon = ln(1 + e)$$

Continued…

COMPRESSION TEST:

The shape of the engineering stress–strain curve in compression can be predicted from the true stress–strain curve in tension, assuming that absolute values of true stress in tension and compression are the same at the same absolute strain values.



Comparison of engineering and true stress–strain curves.

Continued…

It must be remembered that both the stress and strain are negative in compression. The engineering stress and strain for compression test becomes,

$$e_{comp} = exp(\varepsilon) - 1$$

$$s_{comp} = \sigma/(1 + e)$$

Before necking, a point on the true stress–strain curve (*σ*–*ε*) can be constructed from a point on the engineering stress–strain curve (*s*–*e*). After necking, the cross-sectional area at the neck must be measured to find the true stress and strain.

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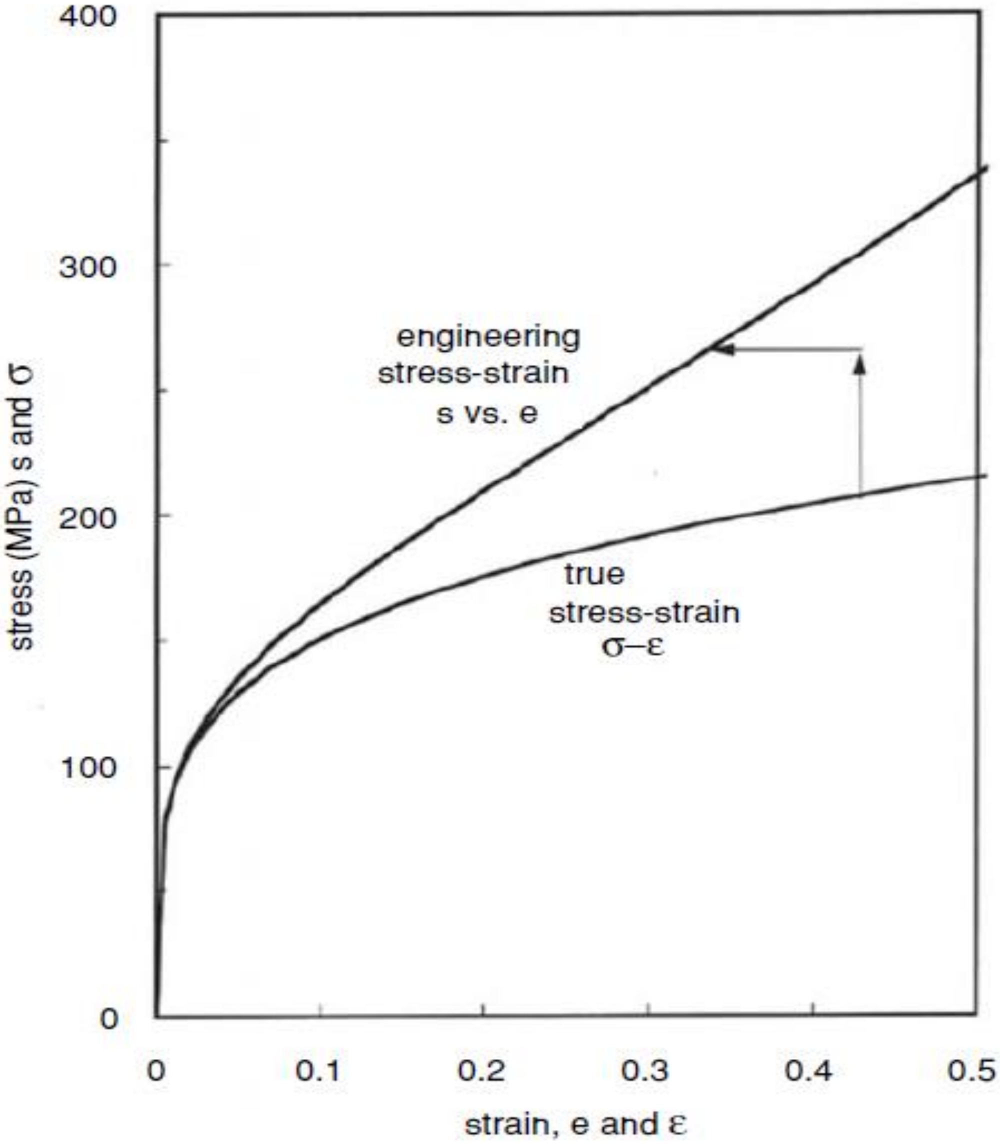

Stress–strain relations in compression for a ductile material.

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- Each point σ, ε on the true stress–true strain curve corresponds to a point s, e on the engineering stress–strain curve. The arrows connect these points.
- The engineering stress-strain curve does not give a true indication of the deformation characteristics of a material because it is based entirely on the original dimensions of the specimen, and these dimensions change continuously during the test.

$$e = \frac{\Delta L}{L_0} = \frac{1}{L_0}\int_{L_0}^{L} dL$$

- This definition of strain is satisfactory for elastic strains where ΔL is very small.

Continued…

- However, in plastic deformation the strains are frequently large, and during the extension the gage length changes considerably.
- Ludwik first proposed the definition of true strain, or natural strain, ε, which obviates this difficulty.
- In this definition of strain the change in length is referred ·to the instantaneous gage length, rather than to the original gage length.

$$\varepsilon = \sum \frac{L_1 - L_0}{L_0} + \frac{L_2 - L_1}{L_1} + \frac{L_3 - L_2}{L_2} + \cdots$$

Or

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

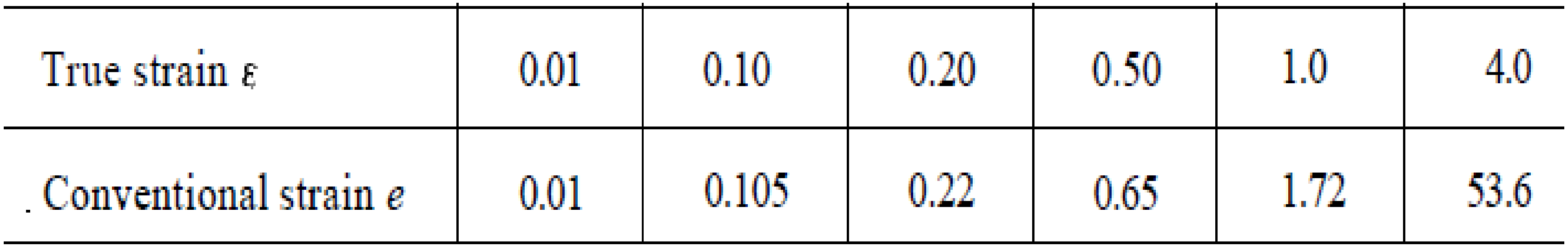
Continued…

- The relationship between true strain and conventional linear strain follows from previous relationship.

$$e = \frac{\Delta L}{L_0} = \frac{L - L_0}{L_0} = \frac{L}{L_0} - 1 \Rightarrow e + 1 = \frac{L}{L_0}$$

$$\varepsilon = ln\frac{L}{L_0} = \ln(e+1)$$

- Values of true strain and conventional linear strain are given for comparison:



True strain ε	0.01	0.10	0.20	0.50	1.0	4.0
Conventional strain e	0.01	0.105	0.22	0.65	1.72	53.6

- ***True stress*** is the load at any instant divided by the cross-sectional area over which it acts.

Continued…

- The ***engineering stress**,* or conventional stress, is the load divided by the original area.
- True stress will be denoted by the familiar symbol *σ,* while engineering stress will be denoted by s.
- True stress $\sigma = \frac{P}{A}$
- Engineering stress $S = \frac{P}{A_0}$
- The true stress may be determined from the engineering stress as follows:

$$\sigma = \frac{P}{A} = \frac{P}{A_0} \times \frac{A_0}{A}$$

Continued…

But, by the constancy-of-volume relationships

$$\frac{A_0}{A} = \frac{L}{L_0} = e + 1$$

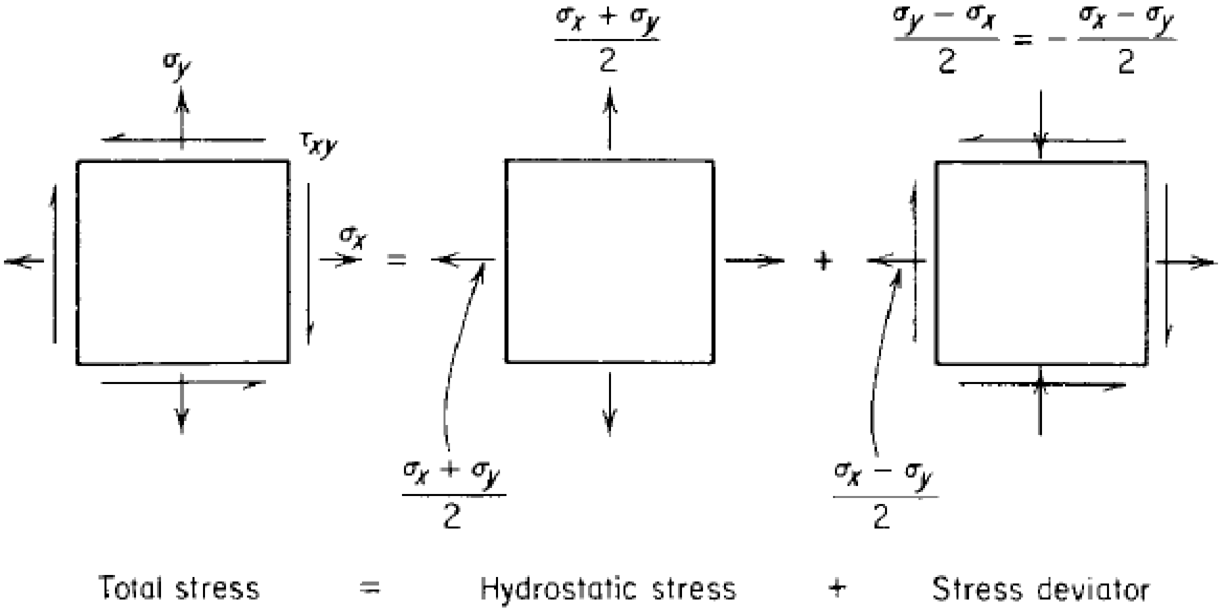
From above eq.:

$$\sigma = \frac{P}{A_0} \times \frac{A_0}{A} = S(e + 1)$$

LECTURE-6

HYDROSTATIC AND DEVIATOR COMPONENTS OF STRESS:

The total stress tensor can be divided into a hydrostatic or mean stress tensor σ_m, which involves only pure tension or compression, and a deviator stress tensor σ'_{IJ}, which represents the shear stresses in the total state of stress.



Resolution of total stress into hydrostatic stress and stress deviator

Continued…

- The hydrostatic component of the stress tensor produces ***only elastic volume changes and does not cause plastic deformation***. Experiment shows that ***the yield stress of metals*** *is* ***independent of hydrostatic stress***, although the ***fracture strain is strongly influenced by hydrostatic stress.***
- Because the ***stress deviator involves the shearing stresses, it is important in causing plastic deformation***

$$\sigma_{ij} = \sigma_{ij}{}' + \frac{1}{3}\delta_{ij}\sigma_{kk}$$

- We shall see that the stress deviator is useful in formulating theories of yielding.

$$\sigma_m = \frac{\sigma_{kk}}{3} = \frac{\sigma_x + \sigma_y + \sigma_z}{3} = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3}$$

Continued…

The decomposition of the stress tensor is given by

$$\sigma'_{ij} = \sigma_{ij} - \sigma_m \delta_{ij}$$

$$\sigma'_{ij} = \begin{vmatrix} \dfrac{2\sigma_x - \sigma_y - \sigma_z}{3} & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \dfrac{2\sigma_y - \sigma_z - \sigma_x}{3} & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \dfrac{2\sigma_z - \sigma_x - \sigma_y}{3} \end{vmatrix}$$

ELASTIC STRESS-STRAIN RELATIONS

- Equations of this nature are called **constitutive equations**. In this chapter we shall consider only constitutive equations for elastic solids. Moreover, initially we shall only consider isotropic elastic solids.

Continued…

- The elastic stress is linearly related to elastic strain by means of the modulus of elasticity (Hooke's law).

$$\sigma_x = E\varepsilon_x$$

Where E is the modulus of elasticity in tension or compression

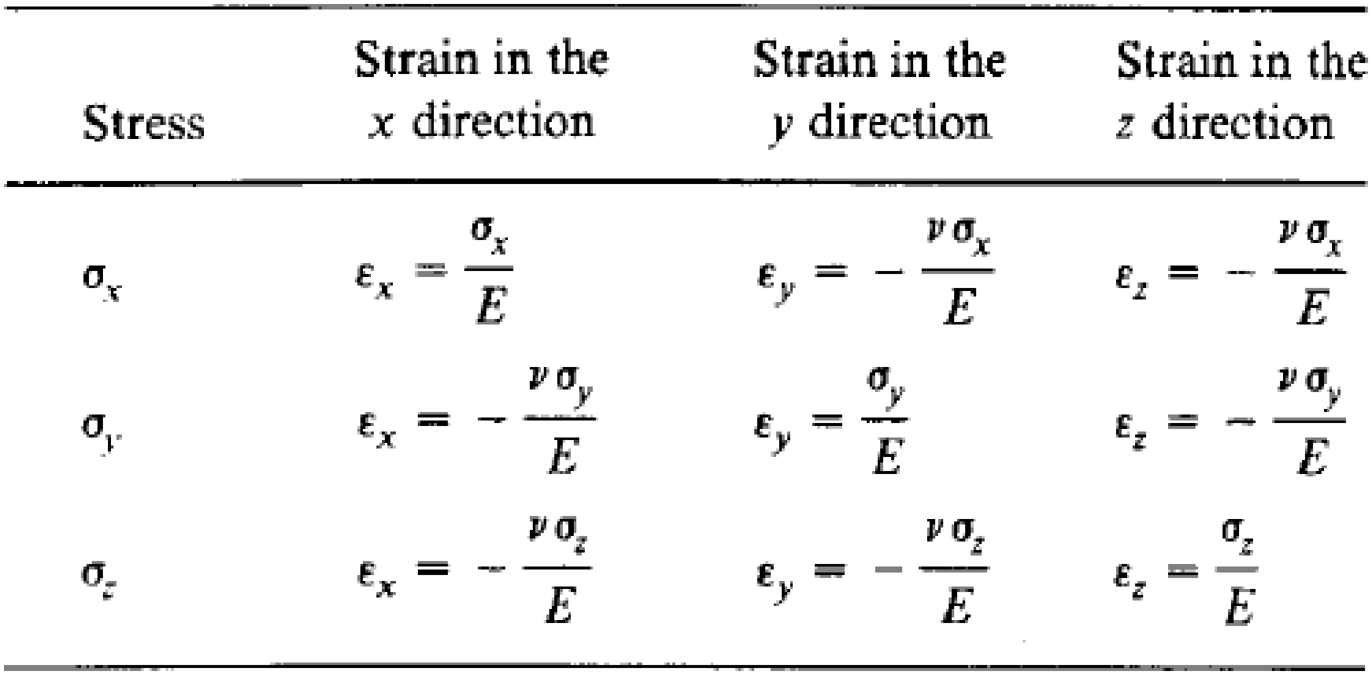
Poisson's ratio

- While a tensile force in the x direction produces an extension along that axis, it also produces a contraction in the transverse y and z directions.
- The transverse strain has been found by experience to be a constant fraction of the strain in the longitudinal direction. This is known as **Poisson's ratio**, denoted by the symbol ν.
- Only the absolute value of ν is used in calculations. For **most metals** the values of v are close to **0.33**.

Continued…

Stress-strain relations for a 3D state of stress

- The elastic stresses are small and the material is isotropic, we can assume that normal stress ox does not produce shear strain on the x, y, or z planes and that a shear stress t does not produce normal strains on the x, y, or z planes. So



Stress	Strain in the x direction	Strain in the y direction	Strain in the z direction
σ_x	$\varepsilon_x = \frac{\sigma_x}{E}$	$\varepsilon_y = -\frac{\nu\sigma_x}{E}$	$\varepsilon_z = -\frac{\nu\sigma_x}{E}$
σ_y	$\varepsilon_x = -\frac{\nu\sigma_y}{E}$	$\varepsilon_y = \frac{\sigma_y}{E}$	$\varepsilon_z = -\frac{\nu\sigma_y}{E}$
σ_z	$\varepsilon_x = -\frac{\nu\sigma_z}{E}$	$\varepsilon_y = -\frac{\nu\sigma_z}{E}$	$\varepsilon_z = \frac{\sigma_z}{E}$

Continued…

By superposition of the components of strain in the x, y, and z directions

$$\varepsilon_x = \frac{1}{E}\left[\sigma_x - \nu(\sigma_y + \sigma_z)\right]$$

$$\varepsilon_y = \frac{1}{E}\left[\sigma_y - \nu(\sigma_z + \sigma_x)\right]$$

$$\varepsilon_z = \frac{1}{E}\left[\sigma_z - \nu(\sigma_x + \sigma_y)\right]$$

- The shearing stresses acting on the unit cube produce shearing strains

$$\tau_{xy} = G\gamma_{xy} \qquad \tau_{yz} = G\gamma_{yz} \qquad \tau_{xz} = G\gamma_{xz}$$

- The proportionality **constant G is the modulus of elasticity** in shear, or **the modulus of rigidity**. Values of G are usually determined from a **torsion test**.

Continued…

- Still another elastic constant is **the bulk modulus** or **the volumetric modulus of elasticity K**. The bulk modulus is the ratio of the hydrostatic pressure to the dilatation that it produces

$$K = \frac{\sigma_m}{\Delta} = \frac{-p}{\Delta} = \frac{1}{\beta}$$

Where -p is the hydrostatic pressure and $\frac{1}{\beta}$ is the compressibility.

- Many useful relationships may be derived between the elastic constants E, G, γ, K. For example, if we add up the three equations

$$\varepsilon_x + \varepsilon_y + \varepsilon_z = \frac{1-2\nu}{E}(\sigma_x + \sigma_y + \sigma_z)$$

- The term on the left is the volume strain Δ, and the term on the right is $3\sigma_m$.

$$\Delta = \frac{1-2\nu}{E} 3\sigma_m \qquad \text{Or} \qquad K = \frac{\sigma_m}{\Delta} = \frac{E}{3(1-2\nu)}$$

Continued…

- Another important relationship is the expression relating E, G, and γ

$$G = \frac{E}{2(1+\nu)}$$

- Many other relationships can be developed between these four isotropic elastic constants

$$E = \frac{9K}{1 + 3K/G} \qquad \nu = \frac{1 - 2G/3K}{2 + 2G/3K}$$

$$G = \frac{3(1-2\nu)K}{2(1+\nu)} \qquad K = \frac{E}{9 - 3E/G}$$

STRAIN ENERGY

- The *elastic strain energy U* is the energy expended by the action of external forces in deforming an elastic body.
- Essentially all the work performed during elastic deformation is stored as elastic energy, and this energy is recovered on the release of the applied forces.

Continued…

- Energy (or work) is equal to a force multiplied by the distance over which it acts.
- In the deformation of an elastic body, the force and deformation increase linearly from initial values of zero so that the average energy is equal to one-half of their product.
- This is also equal to the area under the load-deformation curve.

$$U = \frac{1}{2} P\delta$$

- For an elemental cube that is subjected to only a tensile stress along the x axis, the elastic strain energy is given by

$$dU = \tfrac{1}{2} P\,du = \tfrac{1}{2}(\sigma_x A)(\varepsilon_x\,dx)$$
$$= \tfrac{1}{2}(\sigma_x \varepsilon_x)(A\,dx)$$

Continued…

- The strain energy per unit volume or strain energy density U_0 is given by

$$U_0 = \frac{1}{2}\sigma_x \varepsilon_x = \frac{1}{2}\frac{\sigma_x^2}{E} = \frac{1}{2}\varepsilon_x^2 E$$

- By the same type of reasoning, the strain energy per unit volume of an element subjected to pure shear is given by

$$U_0 = \frac{1}{2}\tau_{xy}\gamma_{xy} = \frac{1}{2}\frac{\tau_{xy}^2}{G} = \frac{1}{2}\gamma_{xy}^2 G$$

LECTURE-7

CONTINUUM MECHANICS

It should be recognized that the equations describing the state of stress or strain in a body are applicable to any solid continuum, whether it be an elastic or plastic solid or a viscous fluid. Indeed, this body of knowledge is often called ***continuum mechanics***. The equations relating stress and strain are called ***constitutive equations*** because they depend on the material behavior.

For example,

- In a thin plate loaded in the plane of the plate there will be no stress acting perpendicular to the surface of the plate. The stress system will consist of two normal stresses σ_x and σ_y and a shear stress τ_{xy}. A stress condition in which the stresses are zero in one of the primary directions is called ***plane stress.***

Continued…

- For any state of stress it is always possible to define a new coordinate system which has axes perpendicular to the planes on which the maximum normal stresses act and on which no shearing stresses act. These planes are called the ***principal planes***, and the stresses normal to these planes are the ***principal stresses***.
- For two-dimensional plane stress there will be two principal stresses $\sigma_1$and σ_2 which occur at angles that are 90° apart. For the general case of stress in three dimensions there will be three principal stressesσ_1, σ_2 and σ_3.
- According to convention, a1 is the algebraically greatest principal stress, while is the algebraically smallest stress.

Continued…

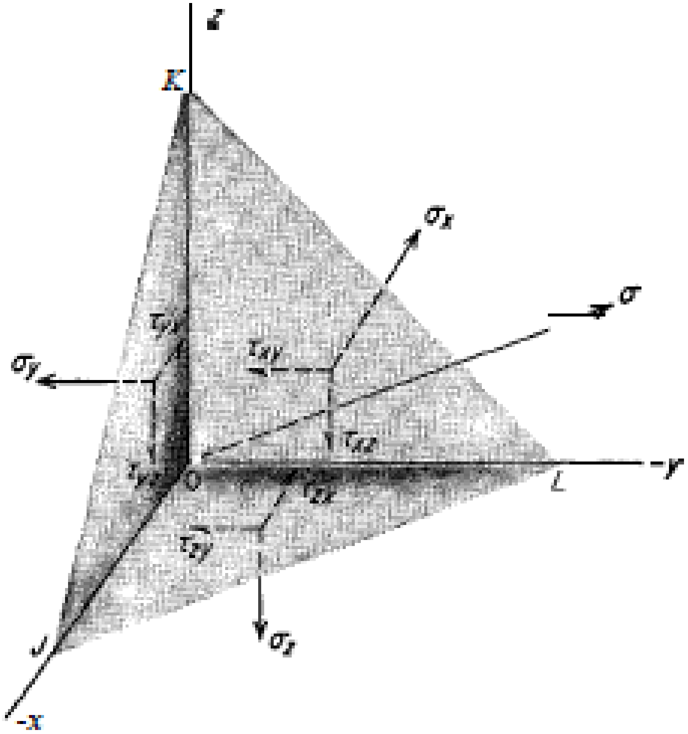
- The directions of the principal stresses are the principal axes 1, 2, and 3. Although in general the principal axes 1, 2, and 3 do not coincide with the Cartesian-coordinate axes x, y, z, for many situations that are encountered in practice the two systems of axes coincide because of symmetry of loading and deformation.
- The specification of the principal stresses and their direction provides a convenient way of describing the state of stress at a point.

State of Stress in Three Dimensions

- The general three-dimensional state of stress consists of three unequal principal stresses acting at a point. This is called a tri-axial state of stress.
- If two of the three principal stresses are equal, the state of stress is known as cylindrical.

Continued…

- While if all three principal stresses are equal, the state of stress is said to be hydrostatic or spherical.
- The determination of the principal stresses for a three-dimensional state of stress in terms of the stresses acting on an arbitrary Cartesian-coordinate system is an extension of the method described for the two-dimensional case.



- The schematic is an elemental free body with a diagonal plane JKL of area A.
- The plane JKL is assumed to be a principal plane cutting through the unit cube; σ is the principal stress acting normal to the plane JKL.

Continued…

- Let *l, m, n* be the direction cosines of σ, that is, the cosines of the angles between σ and the x, y, and z axes. Since the free body is in equilibrium, the forces acting on each of its faces must balance.
- The components of σ along each of the axes are S_x, S_y and S_z

$$S_x = \sigma l, \qquad S_y = \sigma m \qquad S_z = \sigma n$$

Area KOL = Al

Area JOK = Am

Area JOL = An

- Taking the summation of the forces in the x direction results in

$$\sigma A l - \sigma_x A l - \tau_{yx} A m - \tau_{zx} A n = 0$$

- This reduces to, $(\sigma - \sigma_x) l - \tau_{yx} m - \tau_{zx} = 0$
- Summing the forces along the other two axes results in

$$-\tau_{yx} l + (\sigma - \sigma_y) m - \tau_{zy} n = 0$$

$$-\tau_{xz} - \tau_{yz} + (\sigma - \sigma_z) n = 0$$

Continued…

- The only nontrivial solution of the force equations along three axes can be obtained by setting the determinant of the coefficients of l, m, and n equal to zero, since l, w, and n cannot all be zero.

$$\begin{vmatrix} \sigma - \sigma_x & -\tau_{yx} & -\tau_{zx} \\ -\tau_{xy} & \sigma - \sigma_y & -\tau_{zy} \\ -\tau_{xz} & -\tau_{yz} & \sigma - \sigma_z \end{vmatrix} = 0$$

- Solution of the determinant results in a cubic equation in σ.

$$\sigma^3 - (\sigma_x + \sigma_y + \sigma_z)\sigma^2 + (\sigma_x\sigma_y + \sigma_y\sigma_z + \sigma_x\sigma_z - \tau_{xy}^2 - \tau_{yz}^2 - \tau_{xz}^2)\,\sigma$$
$$- (\sigma_x\sigma_y\sigma_z + 2\tau_{xy}\tau_{yz}\tau_{xz} - \sigma_x\tau_{yz}^2 - \sigma_y\tau_{xz}^2 - \sigma_z\tau_{xy}^2) = 0$$

- The three roots of the above cubic equations are the three principal stresses σ_1, σ_2, and σ_3.

Continued…

- To determine the direction with respect to the original x, y, z axes in which the principal stresses act, it is necessary to substitute σ_1, σ_2, and σ_3 each in turn into the three equations force equations.
- The resulting equations must be solved simultaneously for l, m, and n with the help of the auxiliary relationship $l^2 + m^2 + n^2 = 1$. Note that there are three combinations of stress components in previous cubic equation that make up the coefficients of the cubic equation. Since the values of these Coefficients determine the principal stresses, they obviously do not vary with Changes in the coordinate axes. Therefore, they are invariant coefficients.

$$\sigma_x + \sigma_y + \sigma_z = I_1$$

$$\sigma_x\sigma_y + \sigma_y\sigma_z + \sigma_x\sigma_z - \tau_{xy}^2 - \tau_{yz}^2 - \tau_{xz}^2 = I_2$$

$$\sigma_x\sigma_y\sigma_z + 2\tau_{xy}\tau_{yz}\tau_{xz} - \sigma_x\tau_{yz}^2 - \sigma_y\tau_{xz}^2 - \sigma_z\tau_{xy}^2 = I_3$$

Continued…

- The first invariant of stress I_1 has been seen before for the two-dimensional state of stress. It states the useful relationship that the sum of the normal stresses for any orientation in the coordinate system is equal to the sum of the normal stresses for any other orientation.

For example

$$\sigma_x + \sigma_y + \sigma_z = \sigma_{x'} + \sigma_{y'} + \sigma_{z'} = \sigma_1 + \sigma_2 + \sigma_3$$

LECTURE-8

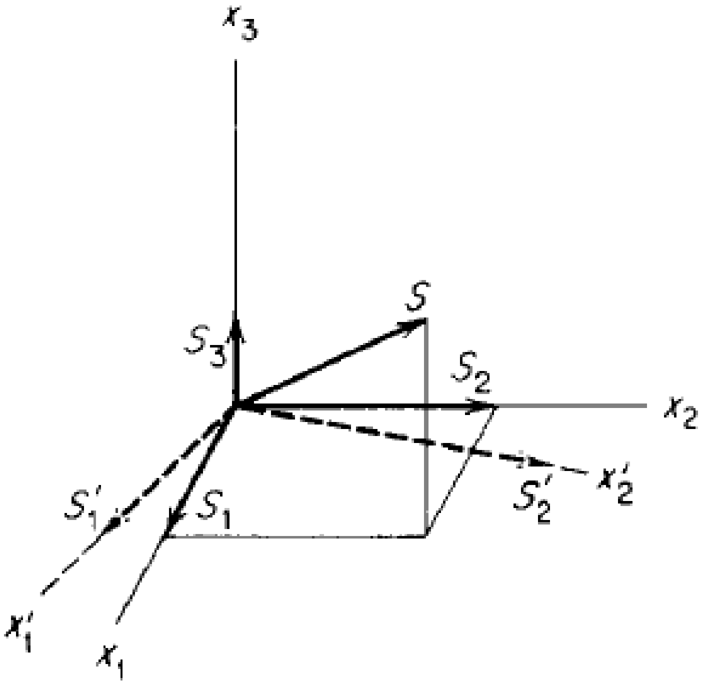
Stress Tensor

- Many aspects of the analysis of stress, such as the equations for the transformation of the stress components from one set of coordinate axes to another coordinate system or the existence of principal stresses, become simpler when it is realized that stress is a second-rank tensor quantity. Many of the techniques for manipulating second-rank tensors do not require a deep understanding of tensor calculus, so it is advantageous to learn something about the properties of tensors.
- We shall start with the consideration of the transformation of a vector (a first-rank tensor) from one coordinate system to another.
- Consider the vector

$$S = S_1 i_1 + S_2 i_2 + S_3 i_3$$

Continued…

When the unit vectors i_1, i_2, i_3 are in the directions S_1, S_2, S_3 (In accordance with convention and convenience in working with tensor quantities, the coordinate axes will be designated x_1, x_2, etc., where x_1 is equivalent to our previous designation x, x_2 is equivalent to the old y, etc.)



Transformation of axes for a vector

Continued…

S_1, S_2, S_3 are the components of S referred to the axes x1, x2, x3. We now want to find the components of S referred to the x_1', x_2', x_3' axes, refer above Figure. S is obtained by resolving S_1, S_2, S_3 along the new directionx_1'.

$$S_1' = S_1 \, cos(x_1 x_1') + S_2 \, cos(x_2 x_1') + S_3 \, cos(x_3 x_1')$$

Or

$$S_1' = a_{11} S_1 + a_{12} S_2 + a_{13} S_3$$

Where a_{11} is the direction cosine between x_1' andx_1, a_{12} is the direction cosine between x_1' and x_2 etc., similarly

$$S_2' = a_{21} S_1 + a_{22} S_1 + a_{23} S_3$$

$$S_3' = a_{31} S_1 + a_{32} S_2 + a_{33} S_3$$

- We note that the leading suffix for each direction cosine in each equation is the same, so we could write these equations as

$$S_1' = \sum_{j=1}^{3} a_{1,j} S_j \, , \; S_2' = \sum_{j=1}^{3} a_{2,j} S_j \, , S_3' = \sum_{j=1}^{3} a_{3,j} S_j$$

Continued…

- These three equations could be combined by writing

$$S_i' = \sum_{j=1}^{3} a_{i,j} S_j \; (i = 1, 2, 3) = \; a_{i1} S_1 + \; a_{i2} S_2 + \; a_{i\,3} S_3$$

- Still greater brevity is obtained by writing the above equation in the Einstein suffix notation as

$$S_i' = \; a_{ij} S_j$$

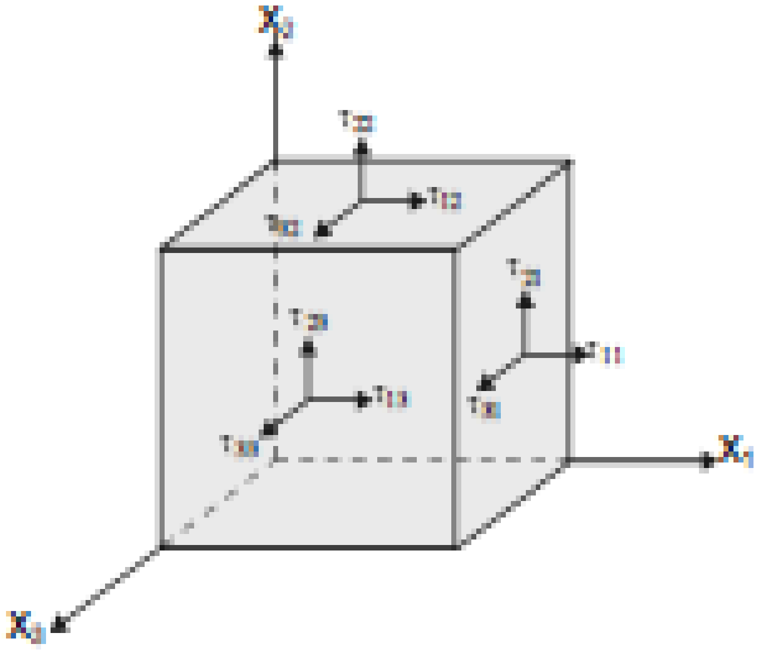
- The suffix notation is a very useful way of compactly expressing the systems of equations usually found in continuum mechanics. In the above equation, it is understood that when a suffix occurs twice in the same term (in this case the suffix j), it indicates summation with respect to that suffix. Unless otherwise indicated, the summation of the other index is from 1 to 3.

Continued…

- In the above example, I is a free suffix and it is understood that in the expanded form there is one equation for each value of i. The repeated index is called a dummy suffix. Its only purpose is to indicate summation.
- Exactly the same three equations would be produced if some other letter were used for the dummy suffix, for example, $S_i' = a_{ir} S_j$ would mean the same thing as previous equation.
- The complete determination of the state of stress at a point in a solid requires the specification of nine components of stress on the orthogonal faces of the element at the point.
- A vector quantity only requires the specification of three components. Obviously, stress is more complicated than a vector.

Continued…

- Stress Tensor $\tau_{i,j}$: The stress (force per unit area) at a point in fluid needs nine components to be completely specified, since each component of the stress must be depend not only by the direction in which it acts but also the orientation of the surface upon which it is acting.



Shear stresses on an infinitesimal cube whose surface are parallel to the coordinate system

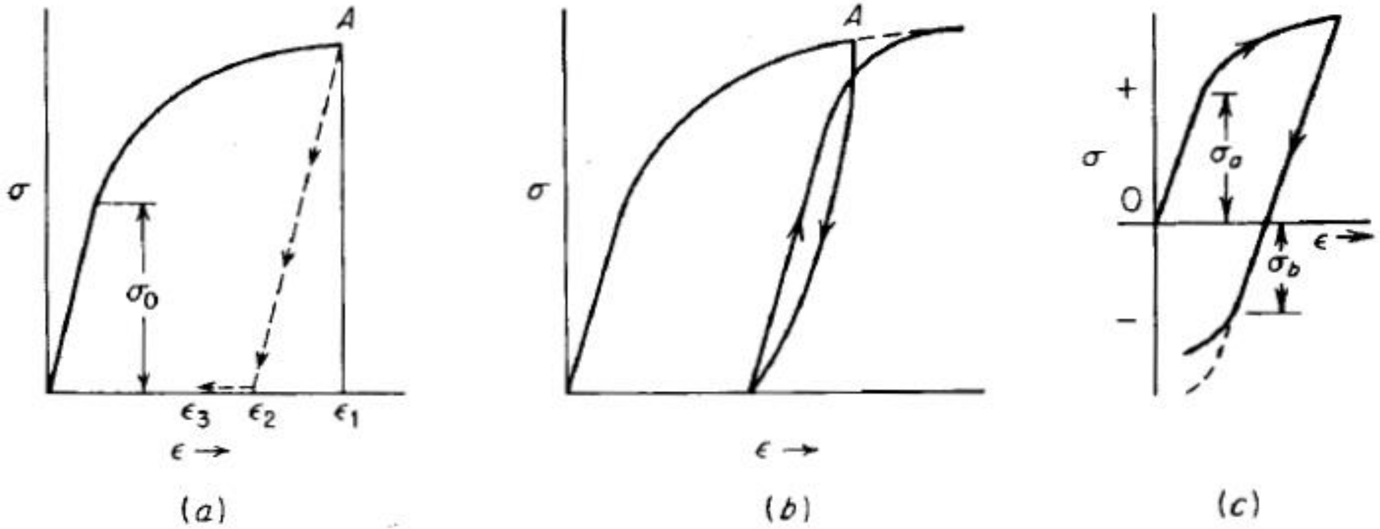
Continued…

- The first index specifies the direction in which the stress component acts, and the second identifies the orientation of the surface upon which it is acting. Therefore, the i^{th} component of the force acting on a surface whose outward normal points in the j^{th} direction is $\tau_{i,j}$.
- An example of surface forces is the shear force and an example of volumetric forces is the gravity force. At equilibrium, the surface forces and volumetric forces are in balance.
- As the body gets smaller, the mass of the body goes to zero, which makes the volumetric forces equal to zero and leaving the sum of the surface forces equal zero. So, as $\delta \rightarrow 0$; $\sum_{all\ 4\ faces} F_i = 0$ for *i* = 1, 2, 3.

Continued…

FLOW CURVES IN DUCTILE MATERIALS:

- The true stress-strain curve for a typical ductile metal, such as aluminum, is illustrated in below schematic (a).



Typical true stress-strain curve for ductile materials

- Hooke's law is followed up to some yield stress σ_0 (The value of σ_0 will depend upon the accuracy with which strain is measured). Beyond σ_0, the metal deforms plastically.

Continued…

- Most metals strain-harden in this region, so that increases in strain require higher values of stress than the initial yield stress σ_0.
- However, unlike the situation in the elastic region, the stress and strain are not related by any simple constant of proportionality. If the metal is strained to point A, when the load is released the total strain will immediately decrease from ϵ_1 to ϵ_2 by an amount σ_0/E.
- The strain decrease ϵ_1- ϵ_2 is the recoverable elastic strain. However, the strain remaining is not all permanent plastic strain.
- Depending upon the metal and the temperature, a small amount of the plastic strain ϵ_2- ϵ_3 will disappear with time. This is known as anelastic behavior. Generally, the anelastic strain is neglected in mathematical theories of plasticity.

Continued…

- Usually the stress-strain curve on unloading from a plastic strain will not be exactly linear and parallel to the elastic portion of the stress-strain curve (b).
- Moreover, on reloading the curve will generally bend over as the stress approaches the original value of stress from which it was unloaded. With a little additional plastic strain the stress-strain curve becomes a continuation of what it would have been had no unloading taken place. The hysteresis behavior resulting from unloading and loading from a plastic strain is generally neglected in plasticity theories.
- If a specimen is deformed plastically beyond the yield stress in one direction, e.g., in tension, and then after unloading to zero stress it is reloaded in the opposite direction, e.g., in compression, it is found that the yield stress on reloading is less than the original yield stress.

Continued…

- Referring to True stress-strain curve (c), σ_b <σ_a. This dependence of the yield stress on loading path and direction is called the ***Bauschinger effect***.
- The Bauschinger effect is commonly ignored in plasticity theory, and it is usual to assume that the yield stress in tension and compression are the same.

LECTURE-9

YIELDING CRITERIA FOR DUCTILE MATERIALS:

- The problem of deducing mathematical relationships for predicting the conditions at which plastic yielding begins when a material is subjected to any possible combination of stresses is an important consideration in the field of plasticity.
- The yielding criteria are essentially empirical relationships. However, a yield criterion must be consistent with a number of experimental observations, the chief of which is that pure hydrostatic pressure does not cause yielding in a continuous solid.
- As a result of this, the hydrostatic component of a complex state of stress does not influence the stress at which yielding occurs.

Continued…

- Therefore, we look for the stress deviator to be involved with yielding. Moreover, for an isotropic material, the yield criterion must be independent of the choice of axes, i.e., it must be an invariant function.
- These considerations lead to the conclusion that the yield criteria must be some function of the invariants of the stress deviator. At present there are two generally accepted criteria for predicting the onset of yielding in ductile metals.
  I. Von Mises' or Distortion-Energy Criterion
  II. Maximum-Shear-Stress or Tresca Criterion

VON MISES' OR DISTORTION-ENERGY CRITERION:

Von Mises (1913) proposed that yielding would occur when the second invariant of the stress deviator J_2 exceeded some critical value.

$$J_2 = k^2$$

Continued…

Where, $J_2 = \frac{1}{6}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right]$

- To evaluate the constant k and relate it to yielding in the tension test, we realize that at yielding in uniaxial tension $\sigma_1 = \sigma_0$, $\sigma_2 = \sigma_3 = 0$

$$\boldsymbol{\sigma_0^2 + \sigma_0^2 = 6k^2}$$

$$\boldsymbol{\sigma_0 = \sqrt{3}\,k} \Rightarrow k = \sigma_0/\sqrt{3}$$

Substituting J_2 and k in stress deviator equation in previous page results in the usual form of the Von Mises' yield criterion

$$\boldsymbol{\sigma_0 = \frac{1}{\sqrt{2}}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right]^{1/2}}$$

Continued…

Or, by considering both normal and shear stress as follows the equation (2-61) in [***Dieter G. E., Mechanical metallurgy***]

$$\boldsymbol{\sigma_0 = \frac{1}{\sqrt{2}}\left[\left(\sigma_x - \sigma_y\right)^2 + \left(\sigma_y - \sigma_z\right)^2 + \left(\sigma_z - \sigma_x\right)^2 + \left(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{xz}^2\right)\right]^{1/2}}$$

So the above two Equations predicts that yielding will occur when the differences of stresses on the right side of the equation exceed the yield stress in uniaxial tension σ_0.

To identify the constant k can be identified by considering the state of stress in pure shear, as is produced in a torsion test.

$$\sigma_1 = -\sigma_3 = \tau, \; \sigma_2 = 0$$

At yielding, $$\sigma_1^2 + \sigma_1^2 + 4\,\sigma_1^2 = 6\,k^2$$

$$\sigma_1 = k$$

Continued…

- So that k represents the yield stress in pure shear (torsion). Therefore, the Von Mises' criterion predicts that the yield stress in torsion will be less than in uniaxial tension according to

$$k = \frac{1}{\sqrt{3}} \sigma_0 = 0.577\sigma_0$$

- To summarized, note that the Von Mises’ yield criterion implies that is not depend on any particular normal stress or shear stress, but instead, yielding depend on a function of all three values of principal shearing stress. Since the yield criterion is based on differences of normal stresses, σ_1 - σ_2, etc., the criterion is independent of the component of hydrostatic stress.
- Since the von Mises' yield criterion involves squared terms, the result is independent of the sign of the individual stresses.

Continued…

This is an important advantage since it is not necessary to know which are the largest and smallest principal stresses in order to use this yield criterion.

MAXIMUM-SHEAR-STRESS OR TRESCA CRITERION

This yield criterion assumes that yielding occurs when the maximum shear stress reaches the value of the shear stress in the uniaxial-tension test. From Eq. (2-21), in [***Dieter G. E., Mechanical metallurgy***] the maximum shear stress is given by

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

Where σ_1 is the algebraically largest and σ_3 is the algebraically smallest principal stress

- For uniaxial tension, σ_1=σ_0, σ_2=σ_3= 0, and the shearing yield stress τ_0 is equal to$^{\sigma_0}/_2$. Substituting all the maximum shear stress becomes

$$\tau_{max} = \frac{\sigma_1 - \sigma_3}{2} = \tau_0 = \frac{\sigma_0}{2}$$

Continued…

Therefore, the maximum-shear-stress criterion is given by

$$\sigma_1 - \sigma_3 = \sigma_0$$

For a state of pure shear, σ_1 = -σ_3 = k, σ_2 = 0, the maximum-shear-stress criterion predicts that yielding will occur when

$$\sigma_1 - \sigma_3 = 2k = \sigma_0$$

$$k = \frac{\sigma_0}{2}$$

So that the maximum-shear-stress criterion may be written

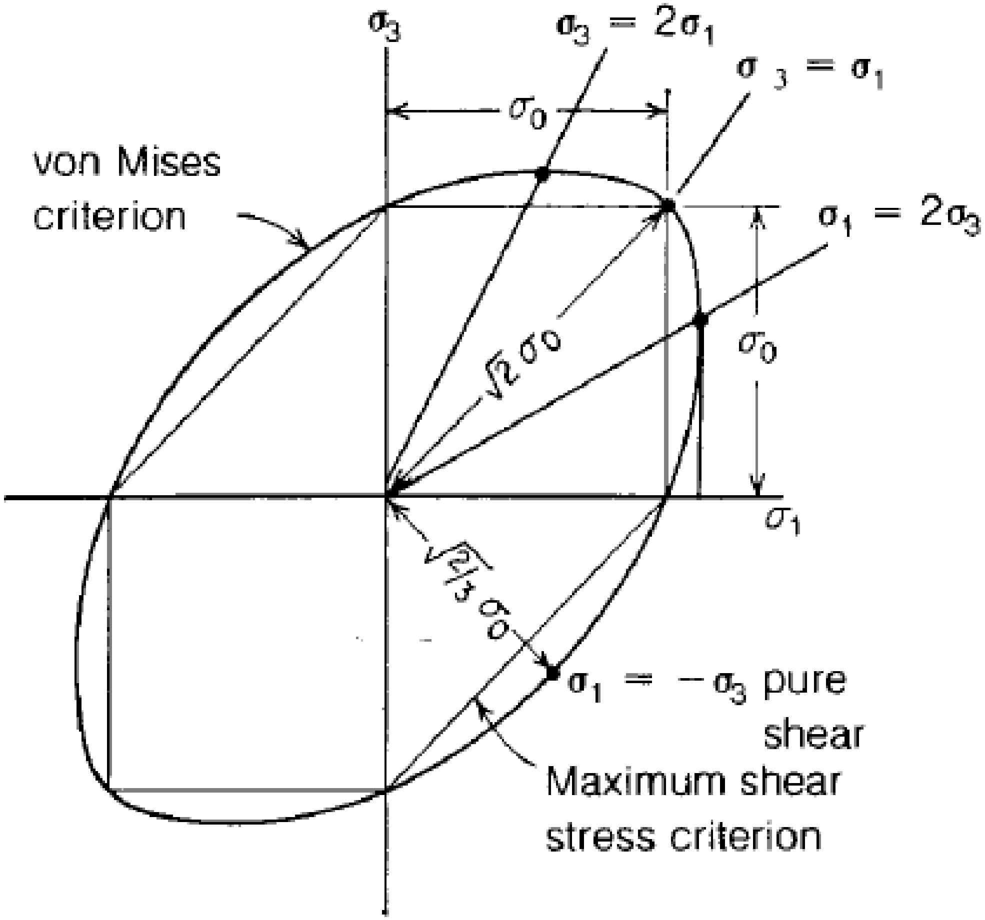
$$\sigma_1 - \sigma_3 = \sigma_1' - \sigma_3' = 2k$$

Note that the maximum shear stress criterion is lass complicated mathematically than the von Mises' criterion and for this reason it is often used in engineering design. However, the maximum shear criterion does not take into consideration the intermediate principal stress.

Continued…

For simplicity, the von Mises' criterion for most of the theoretical work is usually preferred as

$$4j_2^3 - 27\, j_3^2 - 36\, k^2\, j_2^2 + 96\, k^4\, j_2 - 64\, k^6 = 0$$



Comparison of yield criteria for plane stress.

LECTURE-10

PLASTIC DEFORMATION OF SINGLE CRYSTALS

- ☐ Following the discovery of the diffraction of x-rays by metallic crystals by Von Laue in 1912 and the realization that metals were fundamentally composed of atoms arranged in specific geometric lattices there have been a great many investigations of the relationships between atomic structure and the plastic behavior of metals.
- ☐ The dislocation theory, which plays such an important part in modem concepts of plastic deformation.

CONCEPTS OF CRYSTAL GEOMETRY

X-ray diffraction analysis shows that the atoms in a metal crystal are arranged in a regular, repeated three-dimensional pattern. The atom arrangement of metals is most simply portrayed by a crystal lattice in which the atoms are visualized as hard balls located at particular locations in a geometrical arrangement.

Continued…

- The most elementary crystal structure is the **simple cubic lattice**. This is the type of structure cell found for ionic crystals, such as **NaCl and LiF**.
- Three mutually perpendicular axes are arbitrarily placed one of the comers of the cell.
- Crystallographic planes and directions will be specified with respect to these axes in terms of ***Miller indices.***

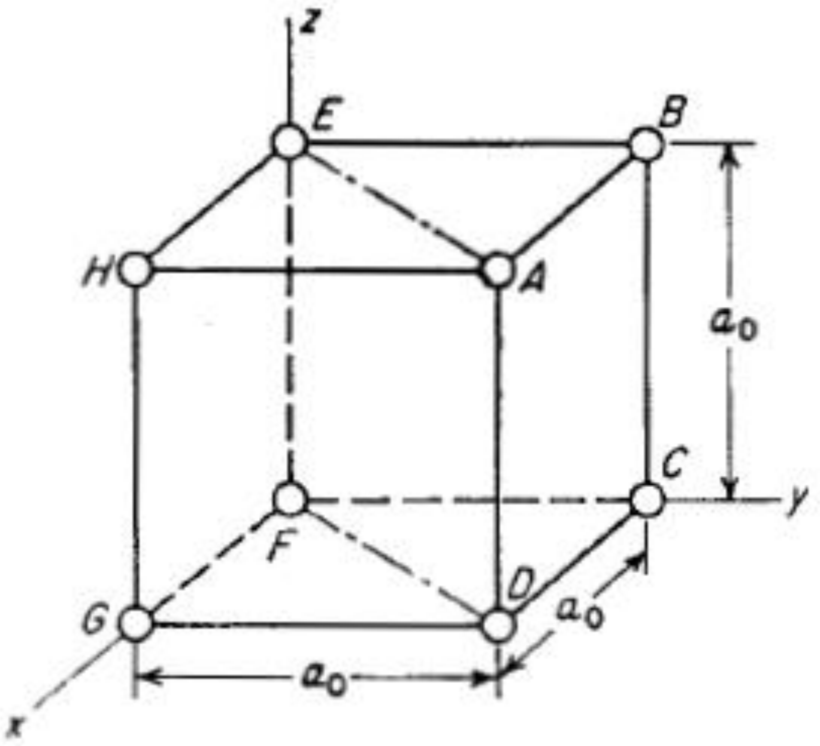
a) A crystallographic plane is specified in terms of the length of its intercepts on the three axes, measured from the origin of the coordinate axes.

b) To simplify the crystallographic formulas, the reciprocals of these intercepts are used.

c) They are reduced to a lowest common denominator to give the Miller indices ***(hkl)*** of the plane.

Continued…

- For example, the plane *ABCD* in Fig. 4-1 is parallel to the *x* and *z* axes and intersects the *y* axis at one interatomic distance $a_{0.}$ Therefore, the indices of the plane are $1/\infty$, $1/1$, $1/\infty$ or *(hkl)* = (010).



Simple cubic structure

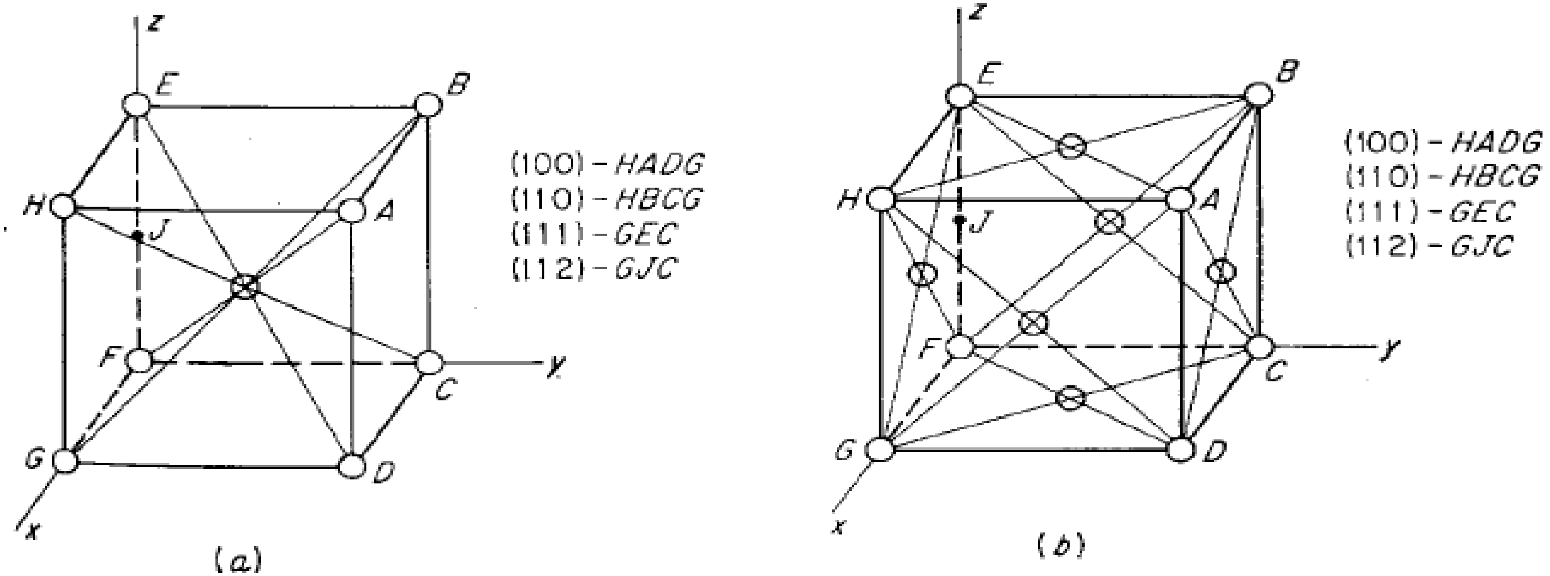
- Plane *EBCF* would be designated as the $(\bar{1}00)$ plane, since the origin of the coordinate system can be moved to G because every point in a space lattice has the same arrangement of points as every other point.

Continued…

- The bar over one of the integers indicates that the plane intersects one of the axes in a negative direction.
- There are six crystallographically equivalent planes of the type (100), anyone of which can have the indices (100), (010), (001), (100), (010), (001) depending upon the choice of axes.
- The notation {100} is used when they are to be considered as a group, or *family of planes.* Crystallographic directions are indicated by integers in brackets: *[uvw].*
- Reciprocals are not used in determining directions. As an example, the direction of the line *FD* is obtained by moving out from the origin a distance a_o along the x axis and moving an equal distance in the positive y direction.
- The indices of this direction are then [110]. A family of crystallographically equivalent directions would be designated <*uvw*>*.*

Continued…

- For the cubic lattice only, a direction is always perpendicular to the plane having the same indices.
- Many of the common metals have either a **body-centered cubic (bcc)** or **face-centered cubic (fcc)** crystal structure.
- Below schematic (*a)* shows a body-centered cubic structure cell with an atom at each corner and another atom at the body center of the cube.



(a) body-centered cubic (bcc) (b) face-centered cubic (fcc) crystal structure

Continued…

- Each corner atom is surrounded by eight adjacent atoms, as is the atom located at the center of the cell. Therefore, there are two atoms ***per structure cell*** for the body-centered cubic structure $(\frac{8}{8}+1)$. Typical metals which have this crystal structure are **alpha iron, columbium, tantalum, chromium, molybdenum, and tungsten.**
- Figure (*b)* shows the structure cell for a face-centered cubic crystal structure. In addition to an atom at each corner, there is an atom at the center of each of the cube faces. Since these latter atoms belong to two unit cells, there are four atoms per structure cell in the face-centered cubic structure$(\frac{8}{8}+\frac{6}{2})$. **Al, Cu, Au, Ag, and Ni** are common face centered cubic metals.

Continued…

For cubic systems there is a set of simple relationships between a direction ***[uvw]*** and a plane ***(hkl)*** which are very useful.

a. *[uvw]* is normal to *(hkl)* when $u = h; v = k; w = l$. [111] is normal to (111).

b. *[uvw]* is parallel to *(hkl),* i.e., *[uvw]* lies in *(hkl),* when $hu + kv + lw = 0$. [112] is a direction in (111).

c. Two planes $(h_1k_1l_1)$ and $(h_2k_2l_2)$ are normal if $h_1h_2 + k_1k_2 + l_1l_2 = 0$. (001) is perpendicular to (100) and (010). (110) is perpendicular to (110).

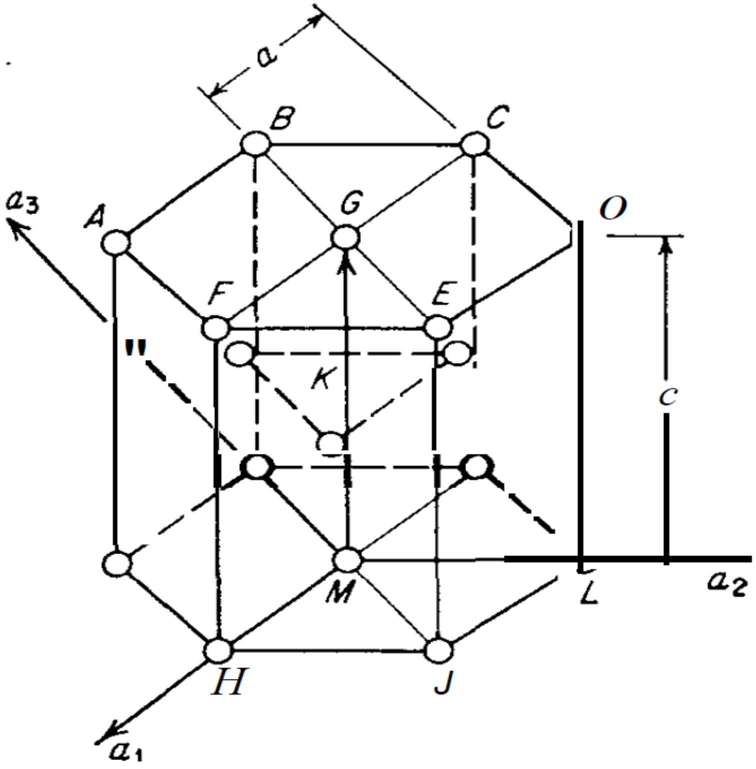
d. Two directions $u_1v_1w_1$ and $u_2v_2w_2$ are normal if $u_1u_2 + v_1v_2 + w_1w_2 = 0$. [100] is perpendicular to [001]. [111] is perpendicular to [112].

e. Angles between planes $(h_1k_1l_1)$ and $(h_2k_2l_2)$ are given by

$$cos\theta = \frac{h_1h_2 + k_1k_2 + l_1l_2}{\left[\sqrt{h_1^2 + k_1^2 + l_1^2}\right]\left[\sqrt{h_2^2 + k_2^2 + l_2^2}\right]}$$

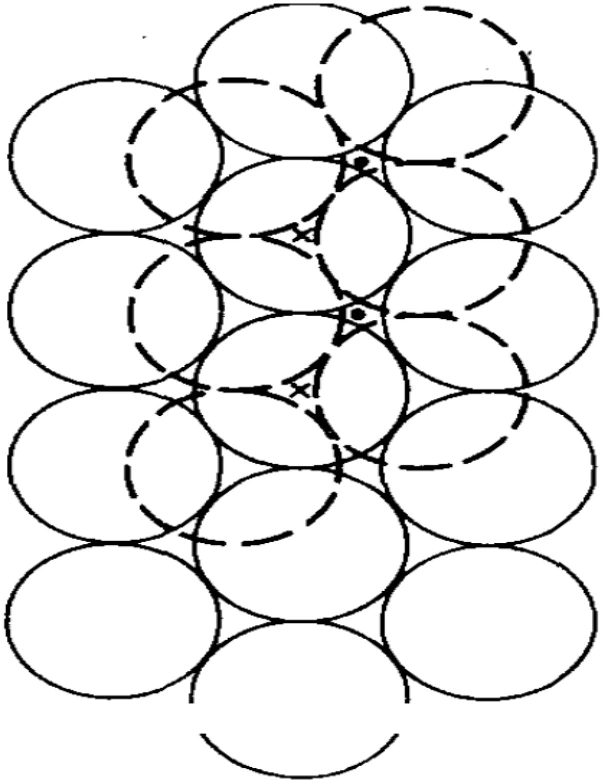
Continued…

- The third common metallic crystal structure is the **hexagonal close-packed (hcp)** structure.
- In order to specify planes and directions in the hcp structure, it is convenient to use the Miller-Bravais system with four indices of the type *(hkil).*
- These indices are based on four axes; the three axes a_1, a_2, a_3 are 120^0 apart in the basal plane, and the vertical c axis is normal to the basal plane.
- The third index is related to the first two by the relation ***i* = - *(h + k).***



HCP Structure

Continued…



Stacking of close-packed structure

- The face-centered cubic and hexagonal close-packed structures can both be built up from a stacking of close-packed planes of spheres.
- The schematic of stacking of close-packed structure is shown that the atomic arrangement or stacking can be done in two ways in which the spheres can be stacked.
- The first layer of spheres is arranged so that each sphere is surrounded by and just touching six other spheres.. This corresponds to the solid circles in Figure.

Continued…

- A second layer of close-packed spheres can be placed over the bottom layer so that the centers of the atoms in the second plane cover one-half the number of valleys in the bottom layer (dashed circles in Figure).
- There are two ways of adding spheres to give a third close-packed plane. Although the spheres in the third layer must fit into the valleys in the second plane, they may lie either over the valleys not covered in the first plane (the dots in Fig.) or directly above the atoms in the first plane (the crosses in Fig.).
- The first possibility results in a stacking sequence ***ABCABC…..*** which is found for the $\{111\}$ planes of an **fcc structure**.
- The other possibility results in the stacking sequence ***ABAB…..*** which is found for the (0001) basal plane of the **hcp structure**. For the ideal hcp packing, the ratio $\frac{c}{a}$ is $\sqrt{\frac{8}{3}}$ or 1.633.

Continued…

- Table 4-1 shows that actual hcp metals deviate from the ideal $\frac{c}{a}$ ratio.

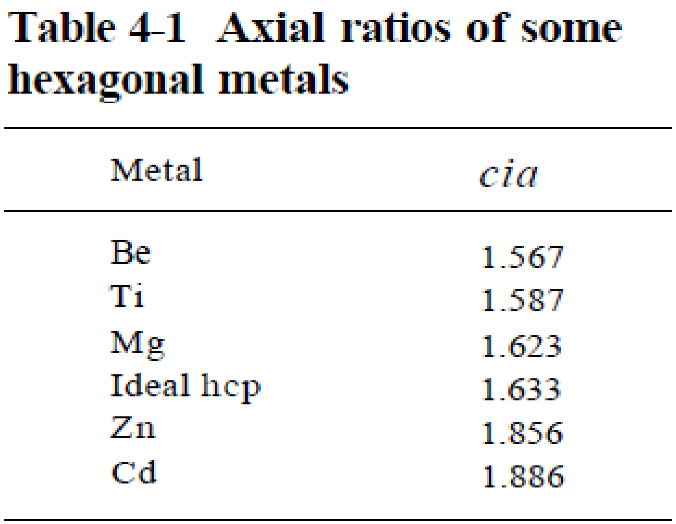


Table 4-1 Axial ratios of some hexagonal metals

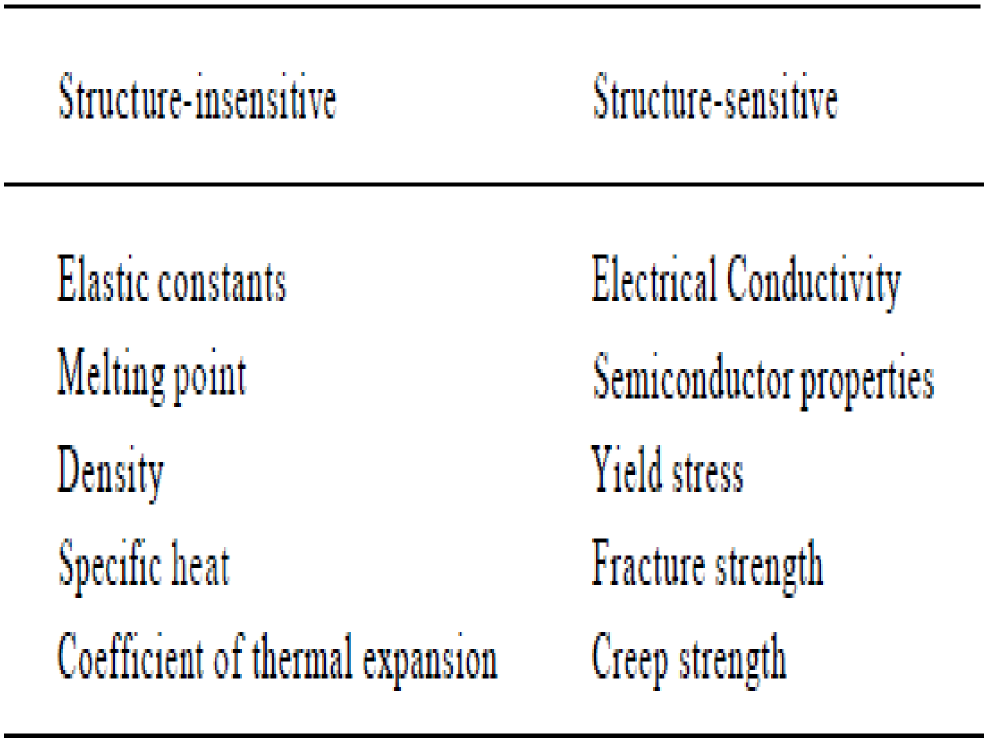
Metal	*cia*
Be	1.567
Ti	1.587
Mg	1.623
Ideal hcp	1.633
Zn	1.856
Cd	1.886

- The fcc and hcp structures are both close-packed structures.
- **74 %** of the volume of the unit cell is occupied by atoms, on a hard sphere model, in the fcc and hcp structures. This is contrasted with **68 %** packing for a bcc unit cell.
- **52 %** of the volume occupied by atoms in the simple cubic unit cell.

LECTURE-11

LATTICE DEFECTS

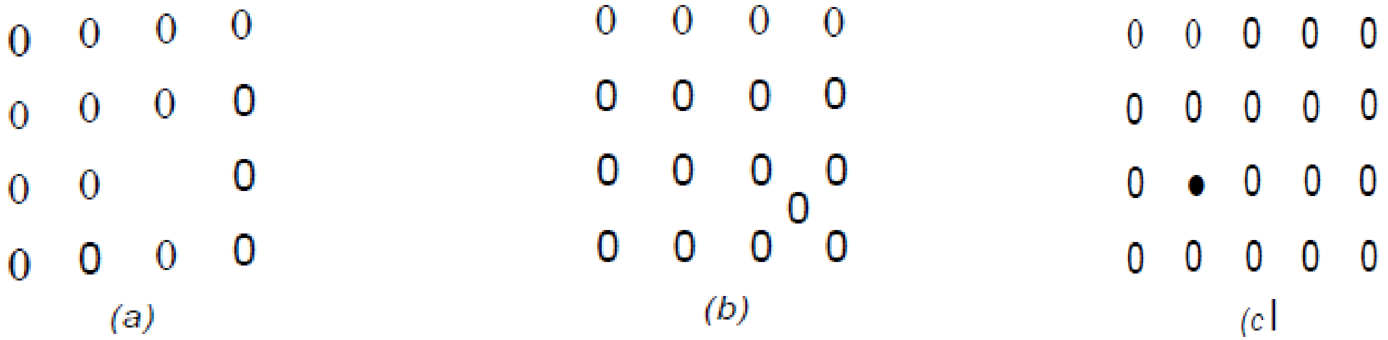
- While the concept of the perfect lattice is adequate for explaining the *structure-insensitive* properties of metals. For a better understanding of the *structure-sensitive* properties it has been necessary to consider a number of types of lattice defects.



Structure-insensitive	Structure-sensitive
Elastic constants	Electrical Conductivity
Melting point	Semiconductor properties
Density	Yield stress
Specific heat	Fracture strength
Coefficient of thermal expansion	Creep strength

Continued…

- The term ***defect* or *imperfection*,** is generally used to describe any deviation from an orderly array of lattice points.



Schematic of Point defects (a) vacancy (b) interstitial (c) impurity atom

- Low-angle boundaries and grain boundaries are surface defects.
- When the deviation from the periodic arrangement of the lattice is localized to the vicinity of only a few atoms it is called a ***point defect* or *point imperfection*.**

Continued…

- However, if the defect extends through microscopic regions of the crystal, it is called a ***lattice imperfection***.
- Lattice imperfections may be divided into ***line defects*** and ***surface* or *plane defects***.
- The **edge and screw dislocations** that are discussed in this section are the common **line defects** encountered in metals.
- The ***stacking fault*** between two close-packed regions of the crystal that have alternate stacking sequences and twinned region of a crystal are other examples of **surface defects.**

POINT DEFECTS

- A ***vacancy* or *vacant lattice site*** exists when an atom is missing from a normal lattice position.

Continued…

- In pure metals, small numbers of vacancies are created by thermal excitation, and these are thermodynamically stable at temperatures greater than absolute zero.
- At equilibrium, the fraction of lattices that are vacant at a given temperature is given approximately by the equation.

$$\frac{n}{N} = e^{-E_s/kT}$$

Where ***n*** is the number of vacant sites in ***N*** sites and ***E_s*** is the energy required to move an atom from the interior of a crystal to its surface.

- An atom that is trapped inside the crystal at a point intermediate between normal lattice positions is called an ***interstitial atom,*** or interstitialcy (Fig. *b).*

Continued…

- The interstitial defect occurs in pure metals as a result of bombardment with high-energy nuclear particles (radiation damage), but it does not occur frequently as a result of thermal activation.
- The presence of an ***impurity atom*** at a lattice position (Fig. *c)* or at an interstitial position results in a local disturbance of the periodicity of the lattice, the same as for vacancies and interstitials.
- It is important to realize that no material is completely pure. Most commercially "pure" materials contain usually 0.01 to 1 percent impurities, While ultra purity materials, such as germanium and silicon crystals for transistors, contain purposely introduced foreign atoms on the order of one part in 10^{10}.

Continued…

LINE DEFECTS-DISLOCATIONS

- The most important two-dimensional, or line, defect is the ***dislocation**.* The dislocation is the defect responsible for the phenomenon of **slip**, by which most metals deform plastically.
- In the schematic, *AB* represents a dislocation lying in the slip plane, which is the plane of the paper. It is assumed that slip is advancing to the right. All the atoms above area C have been displaced one atomic distance in the slip direction; the atoms above *D* have not yet slipped. *AB* is then the boundary between the slipped and unslipped regions.

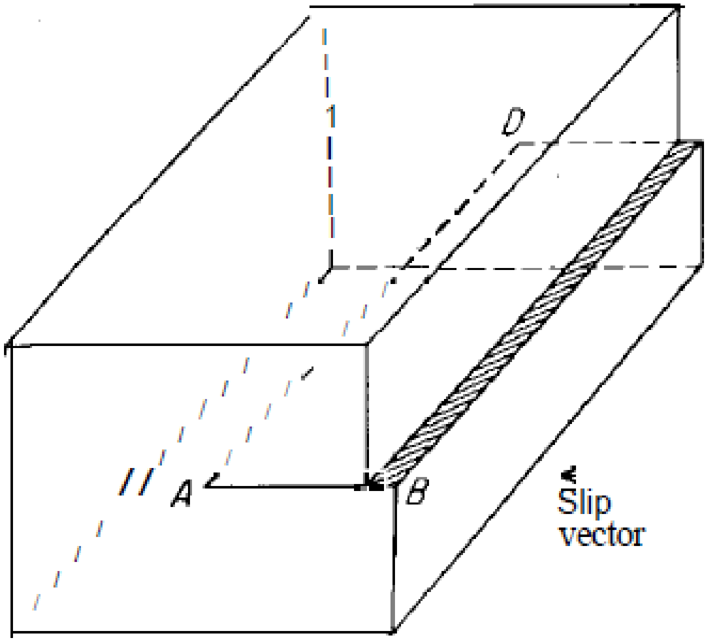


Fig-Edge dislocation produced by slip in a simple cubic lattice. Dislocation lies along *AD,* perpendicular to slip direction. Slip has occurred over area *ABCD*

Continued…

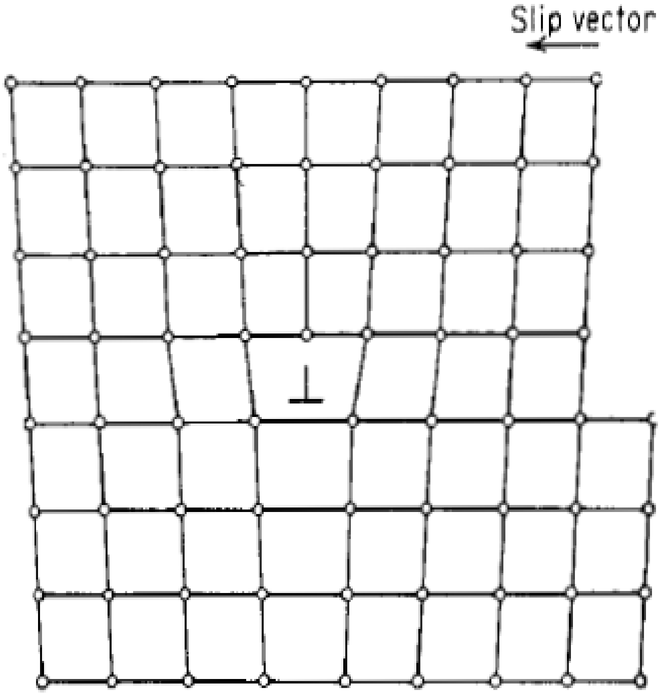
- In the absence of obstacles, a dislocation can move easily on the application of only a small force. This helps explain why real crystals deform much more readily than would be expected for a crystal with a perfect lattice.
- Not only are dislocations important for explaining the slip of crystals, but they are also intimately connected with nearly all other mechanical phenomena such as **strain hardening, the yield point, creep, fatigue, and brittle fracture.**
- The two basic types of dislocations are the edge dislocation and the screw dislocation.
- Figure shows the slip that produces an edge dislocation for an element of crystal having a simple cubic lattice. Slip has occurred in the direction of the slip vector over the area *ABCD.* The boundary between the right-hand slipped part of the crystal and the left-hand part which has not yet slipped is the line *AD,* the edge dislocation.

Continued…

- The amount of displacement is equal to the ***Burgers vector (b)*** of the dislocation. A defining characteristic of an **edge dislocation** is that its Burgers vector is always **perpendicular to the dislocation line**.
- There is one more vertical row of atoms above the slip plane than below it. The atomic arrangement results in a **compressive stress** above the slip plane and a **tensile stress** below the slip plane.
- An edge dislocation with the extra plane of atoms above the slip plane, as in Figure, by convention is called a ***positive edge dislocation*** and is frequently indicated by the symbol ⊥. If the extra plane of atoms lies below the slip plane, the dislocation is a **negative edge dislocation, ⊤.**
- A pure edge dislocation can glide or slip in a direction perpendicular to its length. However, it may move vertically by a process known as ***climb,*** if diffusion of atoms or vacancies can take place at an appreciable rate.

LECTURE-12

- Although the exact arrangement of atoms along AD is not known, it is generally agreed that Fig. closely represents the atomic arrangement in a plane normal to the edge dislocation AD.
- The plane of the paper in this figure corresponds to a (100) plane in a simple cubic lattice and is equivalent to any plane parallel to the front face of previous Figure.



Atomic arrangement in a plane normal to an edge dislocation

- Note that the lattice is distorted in the region of the dislocation. There is one more vertical row of atoms above the slip plane than below it. The atomic arrangement results in a compressive stress above the slip plane and a tensile stress below the slip plane.

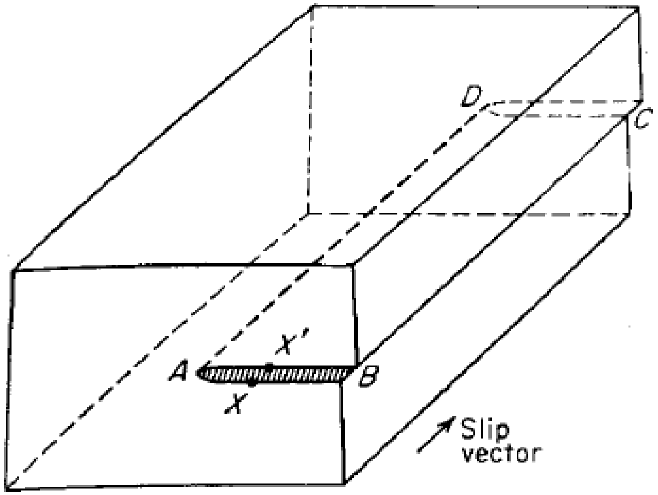
Continued…

- An edge dislocation with the extra plane of atoms above the slip plane, as in Fig., by convention is called a positive edge dislocation and is frequently indicated by the symbol ⊥. If the extra plane of atoms lies below the slip plane, the dislocation is a negative edge dislocation, ⊤.
- A pure edge dislocation can glide or slip in a direction perpendicular to its length. However, it may move vertically by a process known as climb, if diffusion of atoms or vacancies can take place at an appreciable rate.
- Consider Fig., For the edge dislocation to move upward (positive direction of climb), it is necessary to remove the extra atom directly over the symbol ⊥ or to add a vacancy to this spot.
- One such atom would have to be removed for every atomic spacing; which the dislocation climbs.

Continued…

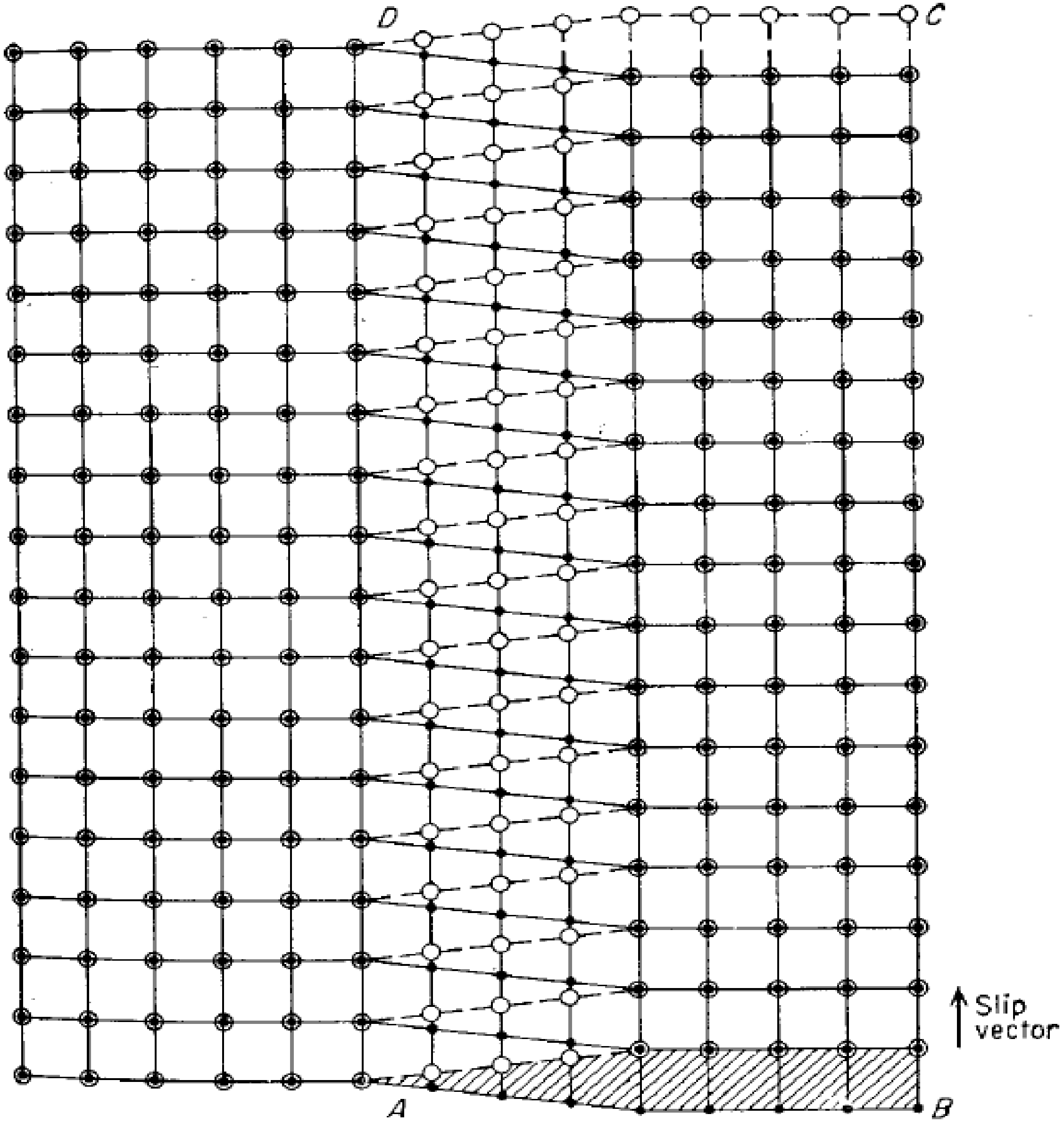
- Conversely, if the dislocation moved down, atoms would have to be added. Atoms could be removed from the extra plane of atoms by the extra atom interacting with a lattice vacancy.
- Atoms are added to the extra plane for negative climb by the diffusion of an atom from the surrounding crystal, creating a vacancy. Since movement by climb is diffusion controlled, motion is much slower than in glide and less likely except at high temperatures.

    - **Figure** Slip that produces a screw dislocation in a simple cubic lattice. Dislocation lies along AD, parallel to slip direction. Slip has occurred over the area ABCD.



Continued…

Figure Atomic arrangement around the screw dislocation shown in previous Fig.. The plane of the figure is parallel to the slip plane. ABCD is the slipped area, and AD is the screw dislocation. Open circles represent atoms in the atomic plane just above the slip plane, and the solid circles are atoms in the plane just below the slip plane.



Continued…

- The second basic type of dislocation is the screw, or Burgers dislocation. Figure shows a simple example of a screw dislocation. The upper part of the crystal to the right of AD has moved relative to the lower part in the direction of the slip vector. No slip has taken place to the left of AD, and therefore AD is a dislocation line.
- Thus, the dislocation line is parallel to its Burgers vector, or slip vector, and by definition this must be a screw dislocation. Consider the trace of a circuit around the dislocation line, on the front face of the crystal.
- Starting at X and completing a counterclockwise circuit, we arrive at X', one atomic plane behind that containing X. In making this circuit we have traced the path of a right-handed screw.
- Every time a circuit is made around the dislocation line, the end point is displaced one plane parallel to the slip plane in the lattice.

Continued…

- Therefore, the atomic planes are arranged around the dislocation in a spiral staircase or screw. The arrangement of atoms (in two dimensions) around a screw dislocation in a simple cubic lattice is shown in Fig.
- In this figure we are looking down on the slip plane in Fig.. The open circles represent atoms just above the slip plane, and the solid circles are atoms just below the slip plane. ***A screw dislocation does not have a preferred slip plane, as an edge dislocation has, and therefore the motion of a screw dislocation is less restricted than the motion of an edge dislocation***.
- However, ***movement by climb is not possible with a screw dislocation***.

DEFORMATION BY SLIP

The usual method of plastic deformation in metals is by the sliding of blocks of the crystal over one another along definite crystallographic planes, called **slip planes.**

Continued…

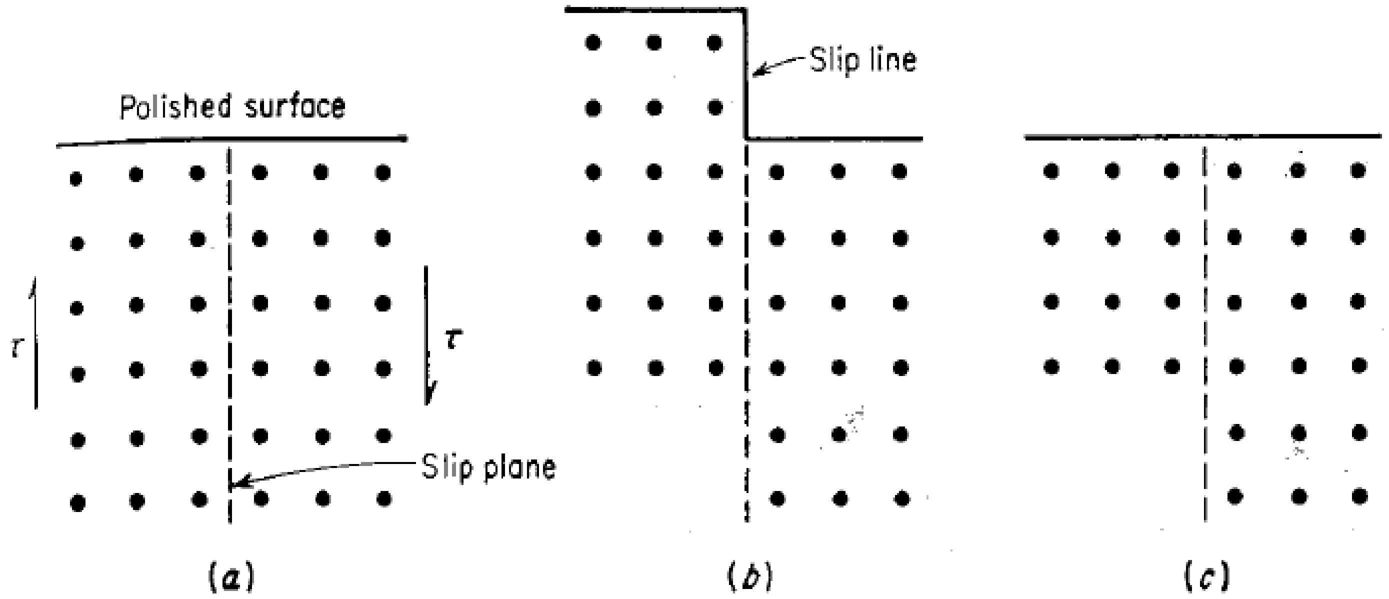


Figure illustrates this classical picture of slip.

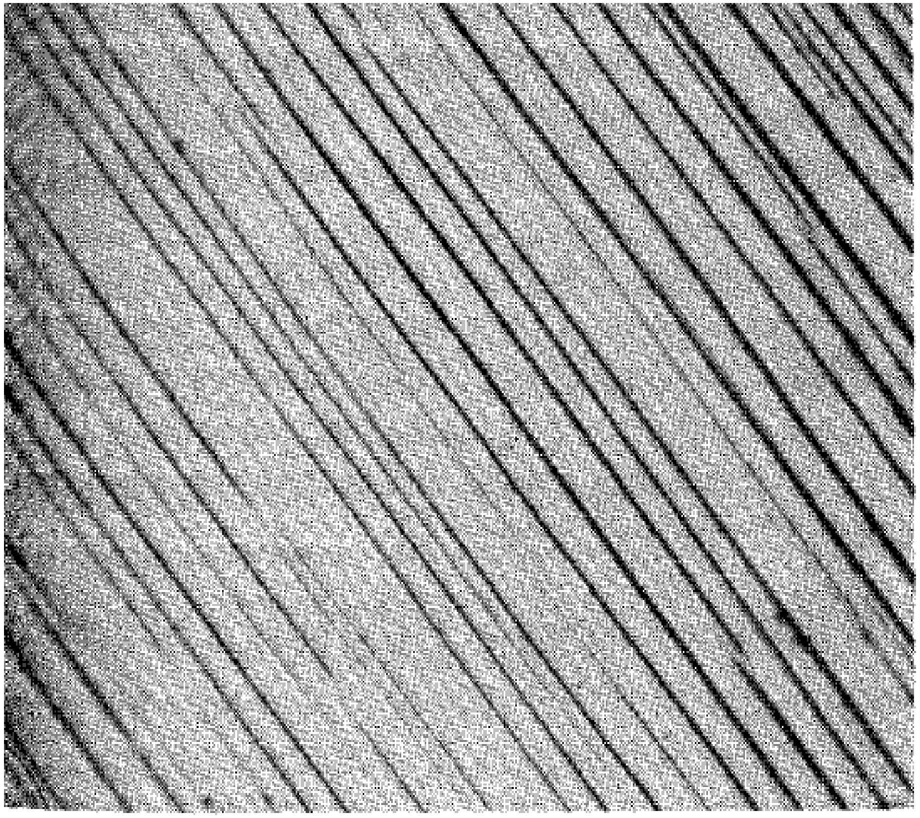
- As a very crude approximation, the ***slip, or glide of a crystal can be considered analogous to the distortion produced in a deck of cards*** when it is pushed from one end.
- In Fig. (a), a shear stress is applied to a metal cube with a top polished surface. Slip occurs when the shear stress exceeds a critical value.

Continued…

- The atoms move an integral number of atomic distances along the slip plane, and a step is produced in the polished surface (Fig. b).
- When we view the polished surface from above with a microscope, the step shows up as a line, which we call a slip line. If the surface is then repolished after slip has occurred, so that the step is removed, the slip line will disappear (Fig. c).
- Because of the translational symmetry of a crystal lattice, the crystal structure is perfectly restored after slip has taken place provided that the deformation was uniform.

Continued…

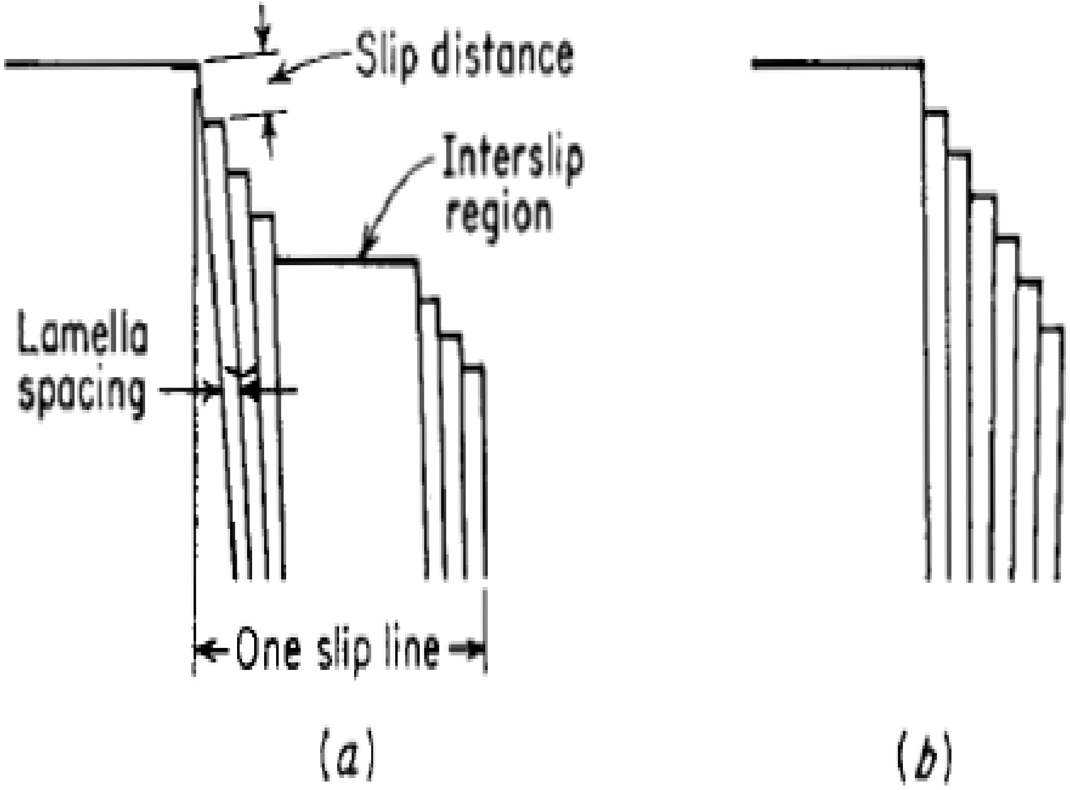
- Note that slip lines are due to changes in surface elevation and that the surface must be suitably prepared for microscopic observation prior to deformation if the slip lines are to be observed. Figure shows straight slip lines in copper.



Straight slip line in Cu

Continued…

The fine structure of slip lines has been studied at high magnification by means of the electron microscope. What appears as a line, or at best a narrow band at 1,500 diameters' magnification in the optical microscope can be resolved by the electron microscope as discrete slip lamellae at 20,000 diameters, shown schematically in Fig.



Schematic drawing of the line structure of a slip band, (a) Small deformation; (b) large deformation

Continued…

- Slip occurs most readily in specific directions on certain crystallographic planes.
- Generally the **slip plane** is **the plane of greatest atomic density** (Table 4-2) and the **slip direction** is **the closest-packed direction within the slip plane.**
- The **slip plane** together with the **slip direction** establishes the **slip system**

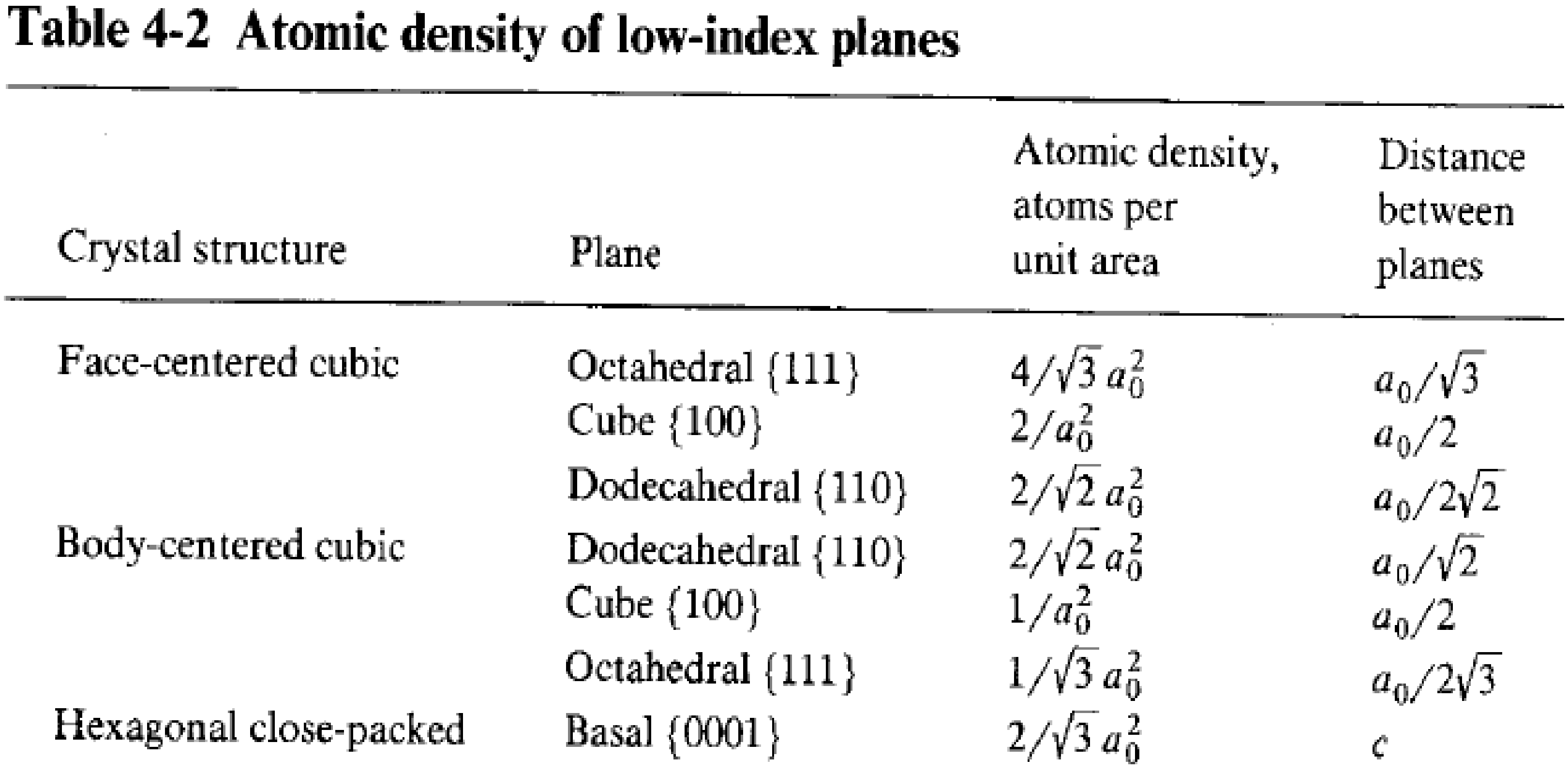


Table 4-2 Atomic density of low-index planes

Crystal structure	Plane	Atomic density, atoms per unit area	Distance between planes
Face-centered cubic	Octahedral {111}	$4/\sqrt{3}\,a_0^2$	$a_0/\sqrt{3}$
	Cube {100}	$2/a_0^2$	$a_0/2$
	Dodecahedral {110}	$2/\sqrt{2}\,a_0^2$	$a_0/2\sqrt{2}$
Body-centered cubic	Dodecahedral {110}	$2/\sqrt{2}\,a_0^2$	$a_0/\sqrt{2}$
	Cube {100}	$1/a_0^2$	$a_0/2$
	Octahedral {111}	$1/\sqrt{3}\,a_0^2$	$a_0/2\sqrt{3}$
Hexagonal close-packed	Basal {0001}	$2/\sqrt{3}\,a_0^2$	c

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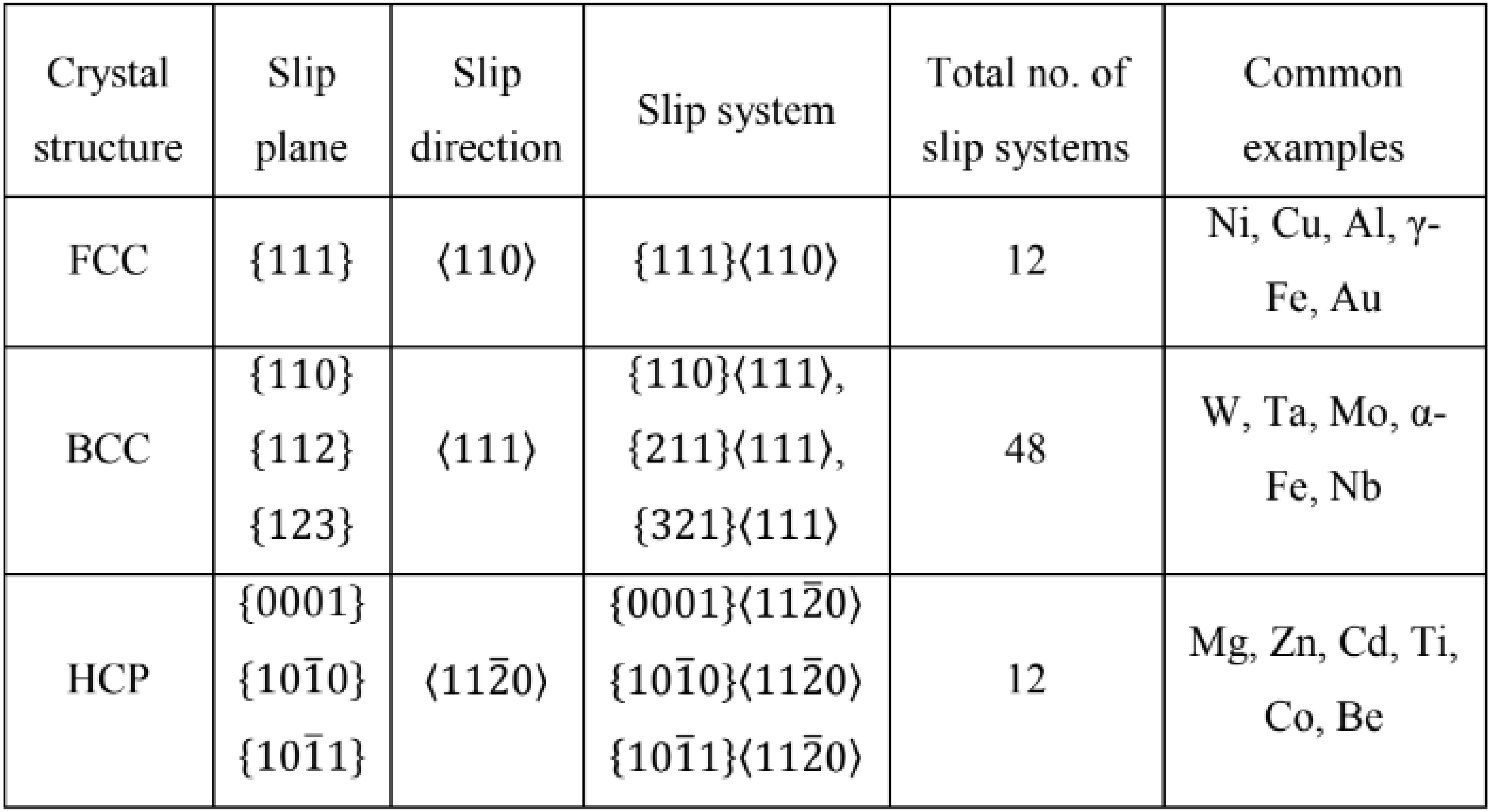


Crystal structure	Slip plane	Slip direction	Slip system	Total no. of slip systems	Common examples
FCC	{111}	⟨110⟩	{111}⟨110⟩	12	Ni, Cu, Al, γ-Fe, Au
BCC	{110} {112} {123}	⟨111⟩	{110}⟨111⟩, {211}⟨111⟩, {321}⟨111⟩	48	W, Ta, Mo, α-Fe, Nb
HCP	{0001} $\{10\bar{1}0\}$ $\{10\bar{1}1\}$	$\langle 11\bar{2}0 \rangle$	$\{0001\}\langle 11\bar{2}0 \rangle$ $\{10\bar{1}0\}\langle 11\bar{2}0 \rangle$ $\{10\bar{1}1\}\langle 11\bar{2}0 \rangle$	12	Mg, Zn, Cd, Ti, Co, Be

LECTURE-13

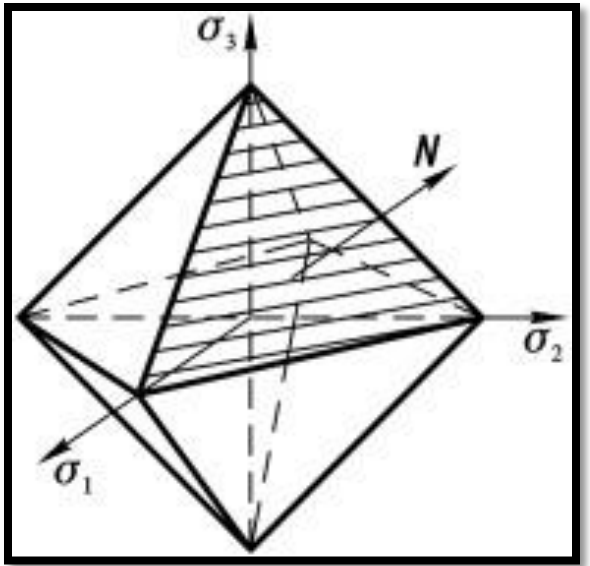
HCP System

- In the **hexagonal close-packed metals**, the only plane with high atomic density is the basal plane (0001). The axes <1120> are the close-packed directions.
- For zinc, cadmium, magnesium, and cobalt slip occurs on the (0001) plane in the <1120> directions. Since there is only one basal plane per unit cell and three <1120> directions.
- The **hcp structure** possesses **three slip** systems.
- The **limited number of slip systems** is the reason for the **extreme orientation dependence and low ductility in hcp crystals.**
- **Zirconium** and **titanium**, which have low **c/a ratios**, slip primarily on the prism and pyramidal planes in the <11$\bar{2}$0> direction.

Continued…

FCC System

- In the face-centered cubic structure, the {111} octahedral planes and the <110> directions are the close-packed systems.
- There are eight {111} planes in the fcc unit cell. However, the planes at opposite faces of the octahedron are parallel to each other, so that there are only four sets of octahedral planes.
- Each {111} plane contains three <110> directions (the reverse directions being neglected).
- Therefore, the fcc lattice has 12 possible slip systems.

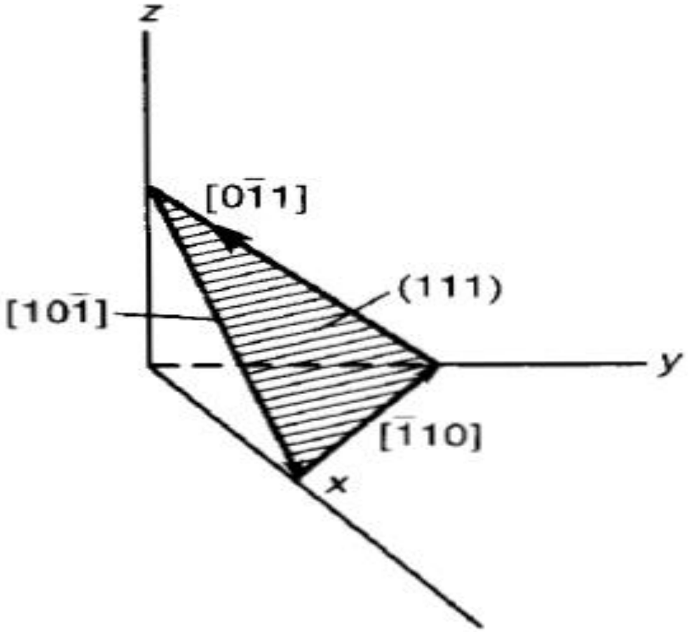


Octahedron represent the 8 nos. of octahedral planes or 4 pair/set of different octahedral planes.

Continued…

Example:

Determine the slip systems for slip on a (111) plane in a fee crystal and sketch the result.



- Slip direction in fee is <110> type direction. Slip directions are most easily established from a sketch of the (111) plane.
- To prove that these slip directions lie in the slip plane **hu + kv + lw = 0**

$$(1)(1) + (1)(0) + (1)(-1) = 0$$

$$(1)(-1) + (1)(1) + (1)(0) = 0$$

$$(1)(0) + (1)(-1) + (1)(1) = 0$$

Continued…

BCC System

- The bcc structure is not a close-packed structure like the fcc or hcp structures.
- Accordingly, there is **no one plane of predominant atomic density**, as (111) in the fcc structure and (0001) in the hcp structure.
- The {110} planes have the **highest atomic density in the bcc structure**, but they are **not greatly superior** in this respect to several other planes.
- However, in the **bcc structure the <111> direction** is just as **close-packed** as the <110> and <1120> directions in the fcc and hcp structures respectively.
- Therefore, the **bcc metals** obey the general rule that **the slip direction is the close-packed direction**, but they differ from most **other metals by not having a definite single slip plane**.

Continued…

- Slip in bcc metals is found to occur on the {110}, {112}, and {123} planes, while the slip direction is always the [111] direction.
- There are 48 possible slip systems, but since the planes are not so close-packed as in the fcc structure, higher shearing stresses are usually required to cause slip.
- Slip lines in bcc metals have a ***wavy appearance***. This is due to the fact that ***slip occurs on several planes, {110}, {112}, {123} but always in the close-packed <111> direction which is common to each of these planes***.
- Dislocations can readily move from one type of plane to another by cross sip, giving rise to the irregular wavy slip bands.

Continued…

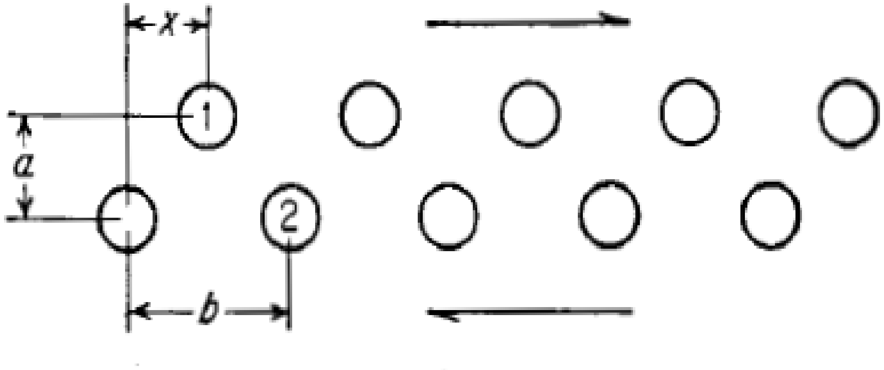
Property at high temp:

- Certain metals show additional slip systems with increased temperature. **Aluminum** deforms on the **{110}** plane at elevated temperature, while in **magnesium** the **{1011}** pyramidal plane plays an important role in deformation by slip above **225 ^{0}C**.
- In all cases the slip direction remains the same when the slip plane changes with temperature.

Slip in a perfect lattice

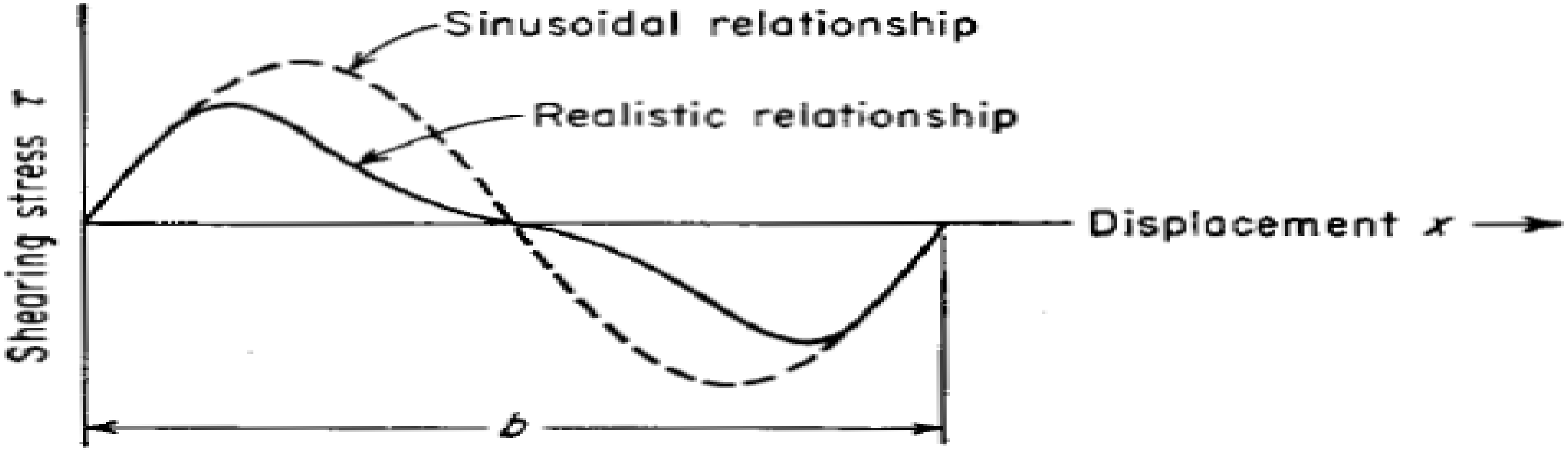
- If slip is assumed to occur by the translation of one plane of atoms over another, it is possible to make a reasonable estimate of the shear stress required for such a movement in a perfect lattice.

Continued…



(a)

Figure (a) Shear displacement of one plane of atoms over another atomic plane; (b) variation of shearing stress with displacement in slip direction.



(b)

Continued…

- Consider two planes of atoms subjected to a homogeneous shear stress as shown in previous figure. The shear stress is assumed to act in the slip plane along the slip direction. The distance between atoms in the slip directions is **b**, and the spacing between adjacent lattice planes is **a**. The shear stress causes a displacement **x** in the slip direction between the pair of adjacent lattice planes.
- The shearing stress is initially zero when the two planes are in coincidence, and it is also zero when the two planes have moved one identity distance b, so that point 1 in the top plane is over point 2 on the bottom plane.
- The shearing stress is also zero when the atoms of the top plane are midway between those of the bottom plane, since this is a symmetry position.
- Between these positions each atom is attracted toward the nearest atom of the other row, so that the shearing stress is a periodic function of the displacement.

Continued…

As a first approximation, the relationship between shear stress and displacement can be expressed by a sine function

$$\tau = \tau_m sin(2\pi x/b)$$

Where $\tau_m$the amplitude of the sine wave and b is is the period. At small values of displacement, Hooke's law should apply.

$$\tau = G\gamma = Gx/a$$

For small values of x/b, the above equation can be written as

$$\tau = \tau_m(2\pi x/b)$$

Combining above two equations provide an expression for the maximum shear stress at which slip should occur.

$$\tau_m = \frac{G}{2\pi}\frac{b}{a}$$

Continued…

- As a rough approximation, b can be taken equal to a, with the result that the theoretical shear strength of a perfect crystal is approximately equal to the shear modulus divided by 2π

$$\boldsymbol{\tau_m = \frac{G}{2\pi}}$$

- The shear modulus for metals is in the range 20 to 150 GPa. So the above Eq. predicts that the theoretical shear stress will be in the range (3 to 30 GPa),
- While actual values of the shear stress required to produce, plastic deformation in metal single crystals are in the range 0.5 to 10 MPa.
- Even if more refined calculations are used to correct the sine-wave assumption, the value of τ_m cannot be made equal to the observed shear stress.

Continued…

- Tyson, using a computer solution of the interatomic force equations, predicted τ_m = G/16 for an fcc metal, G/8 for an NaCl structure, and G/4 for a covalently bonded diamond structure.
- Since the theoretical shear strength of metal crystals is at least 100 times greater than the observed shear strength, it must be concluded that a mechanism other than bodily shearing of planes of atoms is responsible for slip.
- In the next section it is shown that dislocations provide such a mechanism.

LECTURE-14

Slip by Dislocation Movement

The concept of the dislocation was first introduced to explain the discrepancy between the observed and theoretical shear strengths of metals.

- ❑ For the dislocation concept to be valid it is necessary to show

  (1) that the motion of a dislocation through a crystal lattice requires a stress far smaller than the theoretical shear stress, and

  (2) That the movement of the dislocation produces a step, or slip band, at the free surface.

- ❑ In a perfect lattice all atoms above and below the slip plane are in minimum energy positions. When a shear stress is applied to the crystal, the same force opposing the movement acts on all the atoms. this is the model for slip presented in previous figure

Continued…

- When there is a dislocation in the crystal, the atoms well away from the dislocation are still in the minimum energy positions but at the dislocation only a small movement of the atoms is required.

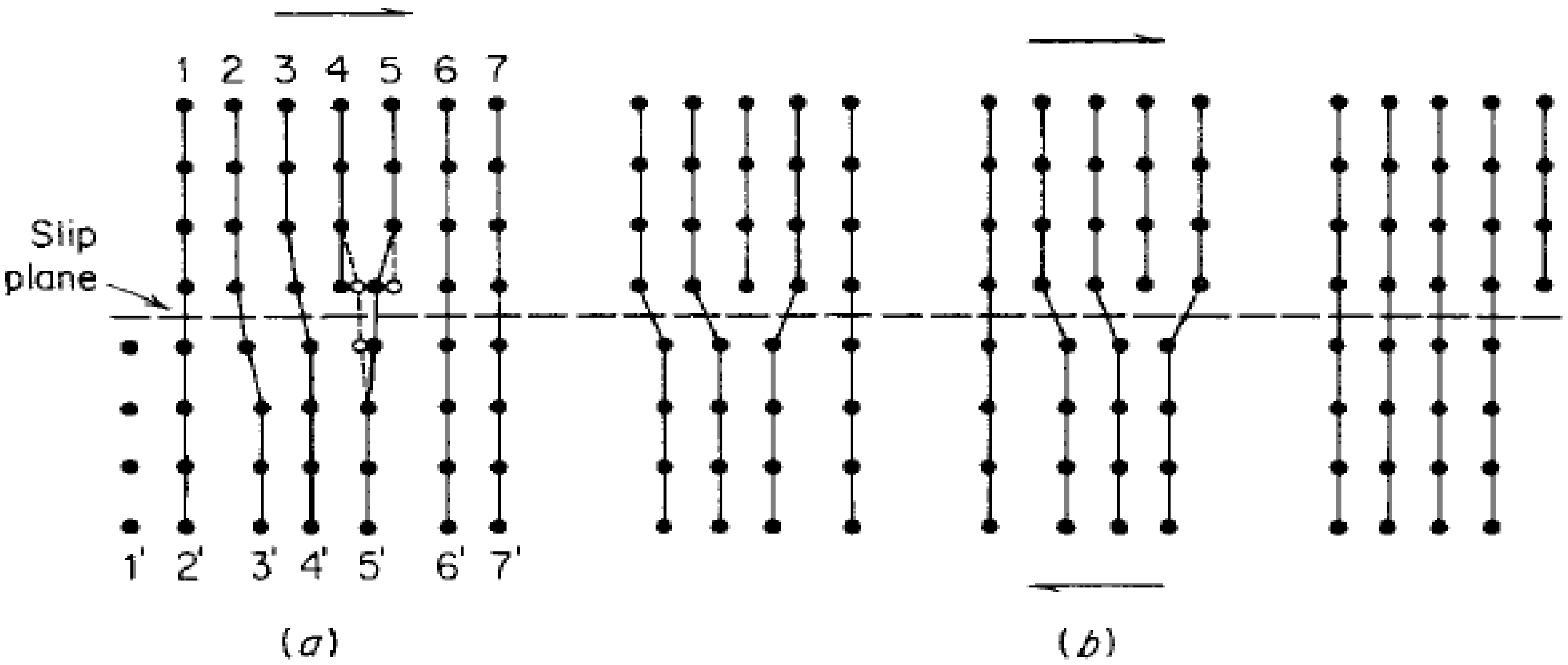


Figure (a) Atom movements near dislocation in slip; (b) movement of an edge dislocation.

Continued…

- Referring to Fig. (a), the extra plane of atoms at the **edge dislocation initially is at 4**. Under the action of the shear stress, **a very small movement of atoms to the right will allow this half plane to line up with the half plane 5'**, at the same time cutting the half plane 5 from its neighbors below the slip plane.

- By this process the **edge dislocation line has moved from its initial position between planes 4' and 5' to a new position between planes 5' and 6'.**

- Since the atoms around the dislocations are symmetrically placed on opposite sides of the extra half plane, equal and opposite forces oppose and assist the motion. Thus, in a first approximation there is no net force on the dislocation and the stress required to move the dislocation is zero.

Continued…

- The continuation of this process under the stresses shown in Fig. moves the dislocation to the right.

- When the extra half plane of atoms reaches a free surface (Fig. (b)), it results in a slip step of one Burgers vector, or one atomic distance for the simple cubic lattice.

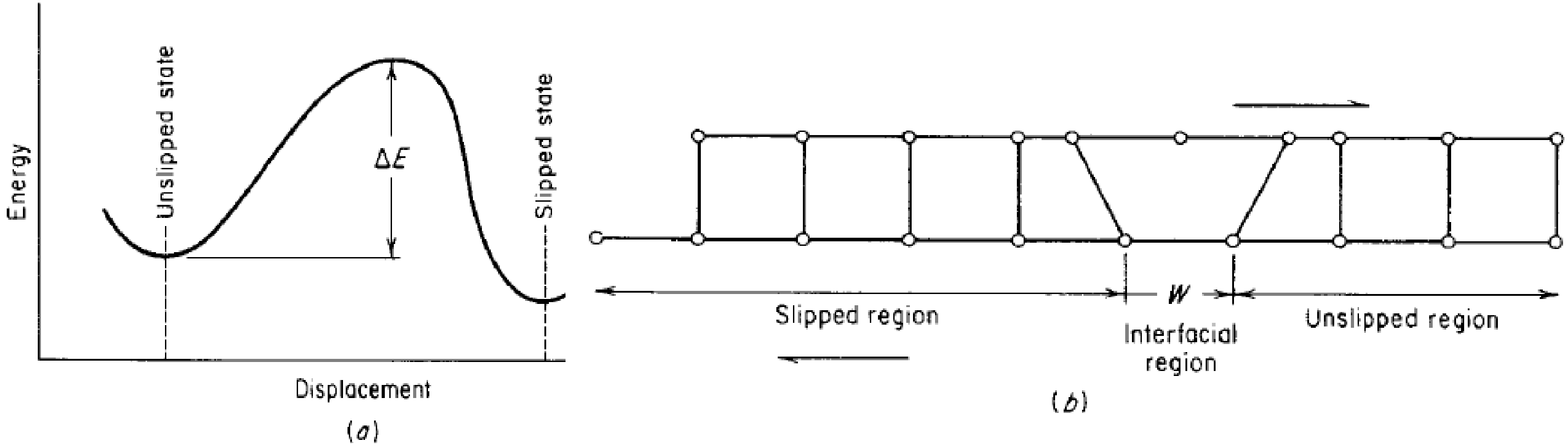


Figure (a) Energy change from unslipped to slipped state; (b) stages in growth of slipped region.

Continued…

- Slip by dislocation motion has been proposed by **Cottrell**. Consider that plastic deformation is the transition from an unslipped to a slipped state (Fig. (a)). Since the process is opposed by an energy barrier, ΔE in order to facilitate the process it is logical to assume that the material will not all make the transition simultaneously.

- To minimize the energetics of the process, the slipped material will grow at the expense of the unslipped region by the advance of an interfacial region (Fig. (b)). The interfacial region is a ***dislocation***.

- To minimize the energy for the transition, we expect the interface thickness ***w*** to be narrow. The distance ***w*** is the width of the dislocation.

- The smaller the width of the dislocation, the lower is the interfacial energy, but the wider the dislocation, the lower is the elastic energy of the crystal because then the atomic spacing in the Slip direction is closer to its equilibrium spacing.

Continued…

- Thus, the equilibrium width of the dislocation is determined by a balance between these two opposing energy changes (one is elastic energy and other one is interfacial energy).

PEIERLS-NABARRO FORCE

- The dislocation width is important because it determines the force required to move a dislocation through the crystal lattice. This force is called Peierls - Nabarro force. The Peierls stress is the shear stress required to move a dislocation through a crystal lattice in a particular direction.

$$\boxed{\tau_p \approx \frac{2G}{1-\nu} e^{-2\pi w/b} \approx \frac{2G}{1-\nu} e^{-[2\pi a/(1-\nu)b]}}$$

Where **a** is the distance between slip planes and **b** is the distance between atoms in the slip direction. Note that the dislocation width appears in the exponential term in Eq., so that the Peierls stress will be very sensitive to the atomic position at the core of a dislocation.

Continued…

- These are not known with any high degree of accuracy and, since above Eq. was derived for the sinusoidal force-distance law that has only limited validity,
- The equation cannot be used for precise calculations. However, it is accurate enough to show that the stress needed to move a dislocation in a metal is quite low.
- In spite of these limitations, the **Peierls equation has important conceptual value. It shows that materials with wide dislocations will require a low stress to move the dislocations**.

CRITICAL RESOLVED SHEAR STRESS FOR SLIP

The extent of slip in a single crystal depends on the magnitude of the shearing stress produced by external loads, the geometry of the crystal structure, and the orientation of the active slip planes with respect to the shearing stresses.

Continued…

- Slip begins when the shearing stress on the slip plane in the slip direction reaches a threshold value called the ***critical resolved shear stress (CRSS)***. This value is really the single-crystal equivalent of the yield stress of an ordinary stress-strain curve.
- The value of the CRSS depends mainly on composition and temperature.
- The fact that different tensile loads are required to produce slip in single crystals of different orientation can be rationalized by a CRSS; this was first recognized by ***Schmid.***
- To calculate the CRSS from a single crystal tested in tension, it is necessary to know, from x-ray diffraction, the orientation with respect to the tensile axis of the plane on which slip first appears and the slip direction.

LECTURE-15

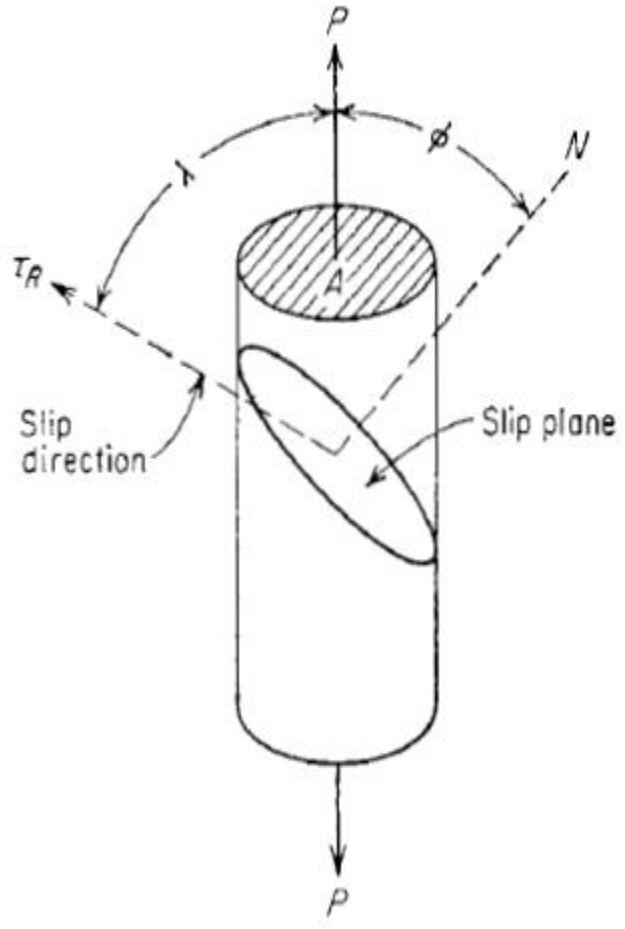


Diagram for calculating critical resolved shear stress.

- ☐ Consider a cylindrical single crystal with cross-sectional area **A**.
- ☐ The angle between the normal to the slip plane and the tensile axis is $\boldsymbol{\phi}$ and the angle which the slip direction makes with the tensile axis is $\boldsymbol{\lambda}$.
- ☐ The area of the slip plane inclined at the angle $\boldsymbol{\phi}$ will be A/cos $\boldsymbol{\phi}$ and the component of the axial load acting in the slip plane in the slip direction is P Cos $\boldsymbol{\lambda}$**.**

Continued…

- Therefore, the CRSS is given by:

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

- The above Equation gives **the shear stress resolved on the slip plane in the slip direction**. This CRSS is a maximum when $\boldsymbol{\phi}$= $\boldsymbol{\lambda}$ = 45°, so that $\tau_R = \frac{1}{2} {}^{P}/_{A}$.

- If the tension axis is normal to the slip plane (λ = 90°) or if it is parallel to the slip plane (ϕ= 90°), the resolved shear stress is zero. Slip will not occur for these extreme orientations since there is no shear stress on the slip plane.

- Crystals close to these orientations tend to fracture rather than slip.

Continued…

Example: Determine the tensile stress that is applied along the $[1\bar{1}0]$ axis of a silver crystal to cause slip on the $(1\bar{1}\bar{1})$ $[0\bar{1}\bar{1}]$ system. The critical resolved shear stress is 6 MPa.

The angle between tensile axis $[1\bar{1}0]$ and normal to $(1\bar{1}\bar{1})$ is

$$\cos\phi = \frac{(1)(1)+(-1)(-1)+(0)(-1)}{\sqrt{(1)^2+(-1)^2+(0)^2}\sqrt{(1)^2+(-1)^2+(-1)^2}} = \frac{2}{\sqrt{2}\sqrt{3}} = \frac{2}{\sqrt{6}}$$

The angle between tensile axis $[1\bar{1}0]$ and slip direction $[0\bar{1}\bar{1}]$ is

$$\cos\lambda = \frac{(1)(0)+(-1)(-1)+(0)(-1)}{\sqrt{2}\sqrt{(0)^2+(-1)^2+(-1)^2}} = \frac{1}{\sqrt{2}\sqrt{2}} = \frac{1}{2}$$

From Eq. for critical resolved shear stress calculation

$$\sigma = \frac{P}{A} = \frac{\tau_R}{\cos\phi\cos\lambda} = \frac{6}{2/\sqrt{6}\times\frac{1}{2}} = 6\sqrt{6} = 14.7\ \text{MPa}$$

Continued…

Property of CRSS

- ❑ The importance of small amounts of impurities in increasing the critical resolved shear stress is shown by the data for silver and copper.
- ❑ Alloying-element additions have even a greater effect, as shown by the data for gold-silver alloys in Figure.

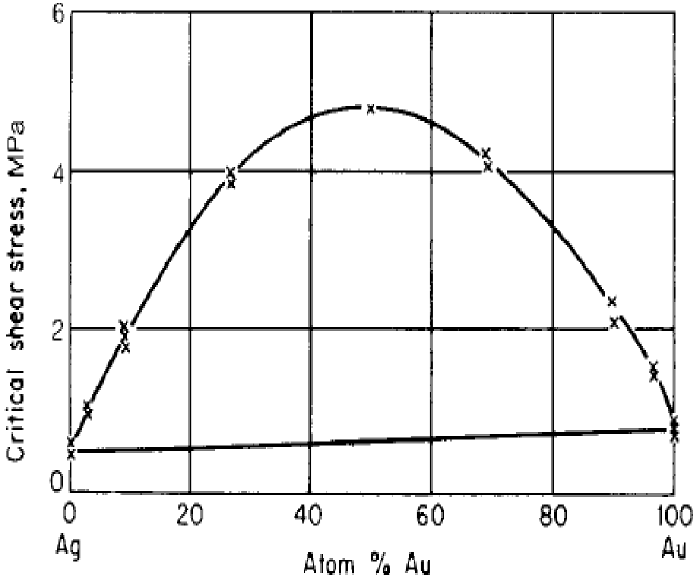


Figure Variation of critical resolved shear stress with composition in silver-gold-alloy single crystals.

Continued…

- Note that a large increase in the resistance to slip is produced by **alloying gold and silver** even though these atoms are very much alike in size and electro negativity, and hence they form a solid solution over the complete range of composition.
- In solid solutions, where the solute atoms differ considerably in size from the solvent atoms, an even greater increase in critical resolved shear stress would be observed.
- The magnitude of the critical resolved shear stress of a crystal is determined by the interaction of its population of dislocations with each other and with defects such as vacancies, interstitials, and impurity atoms. This stress is, of course, greater than the stress required to move a single dislocation, but it is appreciably lower than the stress required to produce slip in a perfect lattice.

Continued…

- ❑ On the basis of this reasoning, the critical resolved shear stress should decrease as the density of defects decreases, provided that the total number of imperfections is not zero.

SCHMID LAW:

- ❑ The ratio of the resolved shear stress to the axial stress is called the Schmid factor m. For a single crystal loaded in tension or compression along its axis, **m = cos ϕ cos λ.**

- ❑ It is observed experimentally that a single crystal will slip when the resolved shear stress on the slip plane reaches a critical value. This behavior, known as **Schmid's law**, is best demonstrated with hcp metals where the limited number of slip systems allows large differences in orientation between the slip plane and the tensile axis.

Continued…

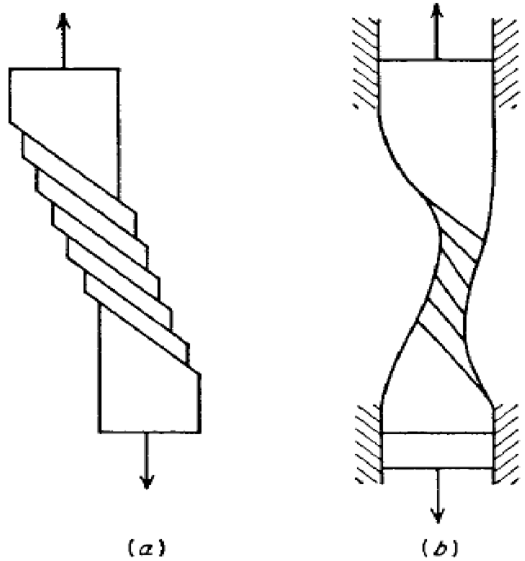
Deformation of Single crystals

- ❑ Most studies of the mechanical properties of single crystals are made by subjecting the crystal to simple uniaxial tension. Therefore, the specimen is not permitted to deform freely by uniform glide on every slip plane along the gage length of the specimen, as is pictured in Fig. (a). Instead, the slip planes rotate toward the tensile axis since the tensile axis of the specimen remains fixed, as in Fig. (b)

- ❑ Since plastic low occurs by slip on certain planes in particular directions, the measured increase in length of the specimen for a given amount of slip will depend on the orientations of the slip plane and direction with the specimen axis.

Continued…

- The fundamental measure of plastic strain in a single crystal is the crystallographic glide strain γ
- Glide strain is the relative displacement of two parallel slip planes separated at a unit distance. The equations relating glide strain with specimen extension can be derived from Fig.
- As the single crystal elongates, the slip direction rotates toward the tensile axis. For simplicity in Fig., the glide elements are kept fixed and the tensile axis is rotated as the crystal elongates from L_0 to L_1



(a) Tensile deformation of single crystal without constraint; (b) rotation of slip planes due to constraint.

Continued…

- The two cases are equivalent geometrically. Moreover, for simplicity the orientation of the slip plane is given by the angle χ between the axis of the glide ellipse and the tensile axis rather than the angle Φ between the normal to the glide ellipse (slip plane) and the tensile axis. With this selection of angles, = P/A sin χ cos Φ. From triangle ABB', using the law of sines, we can see that.

$$\frac{L_0}{\sin \lambda_1} = \frac{L_1}{\sin (180 - \lambda_0)} = \frac{L_1}{\sin \lambda_0}$$

Continued…

- From triangles ABC and AB'C

$$AC = L_0 \sin \chi_0 = L_1 \sin \chi_1$$

- The glide strain is defined as the total amount of slip divided by the thickness of the glide packet

$$\lambda = \frac{BB'}{AC}$$

Again, from the law of sines

$$BB' = \frac{L_1 \sin(\lambda_0 - \lambda_1)}{\sin \lambda_0}$$

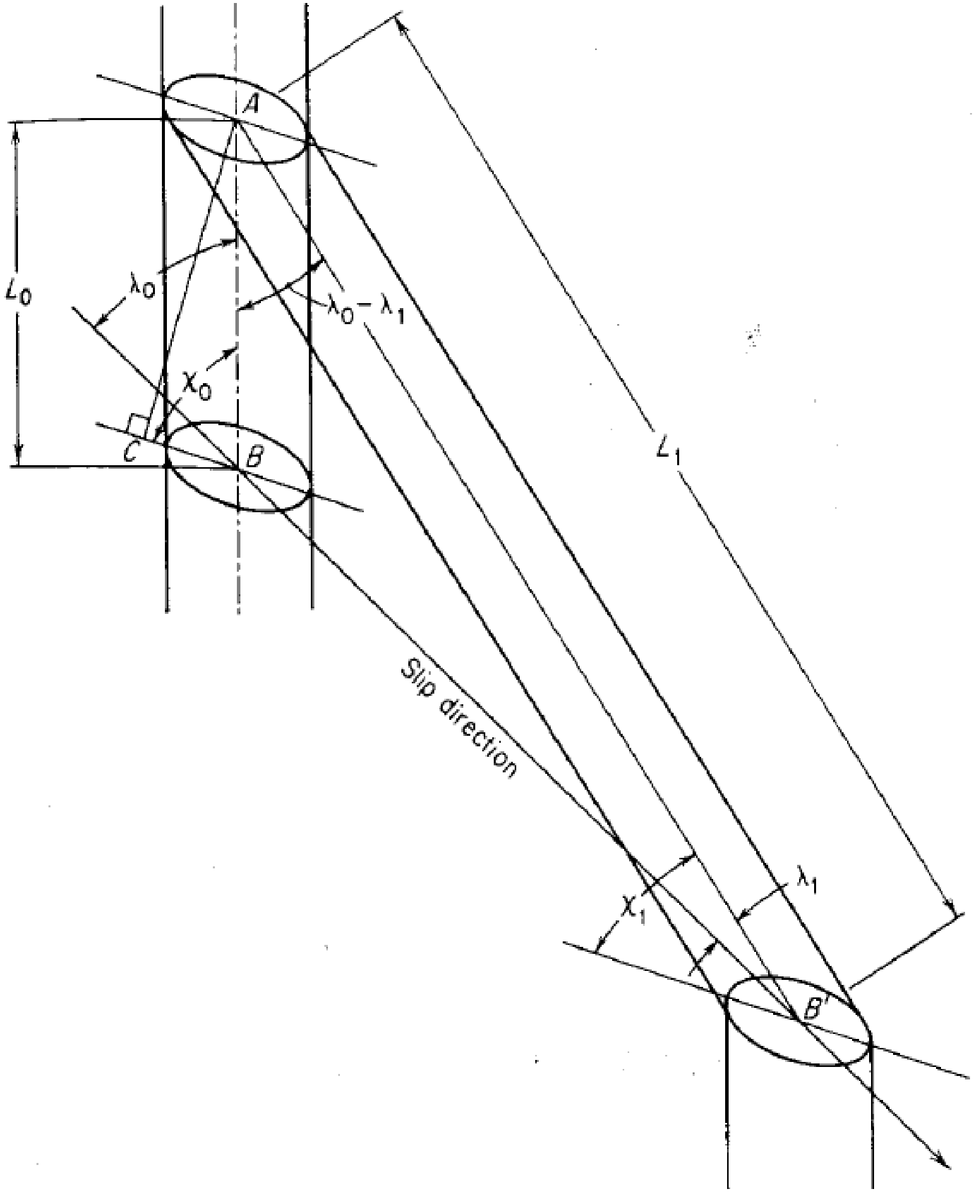


Figure Extension of a single crystal

Continued…

- Substitution in the expression for glide strain, and after considerable trigonometric manipulation, results in

$$\gamma = \frac{1}{\sin \chi_0}\left\{\left[\left(\frac{L_1}{L_0}\right)^2 - \sin^2 \lambda_0\right]^{1/2} - \cos \lambda_0\right\}$$

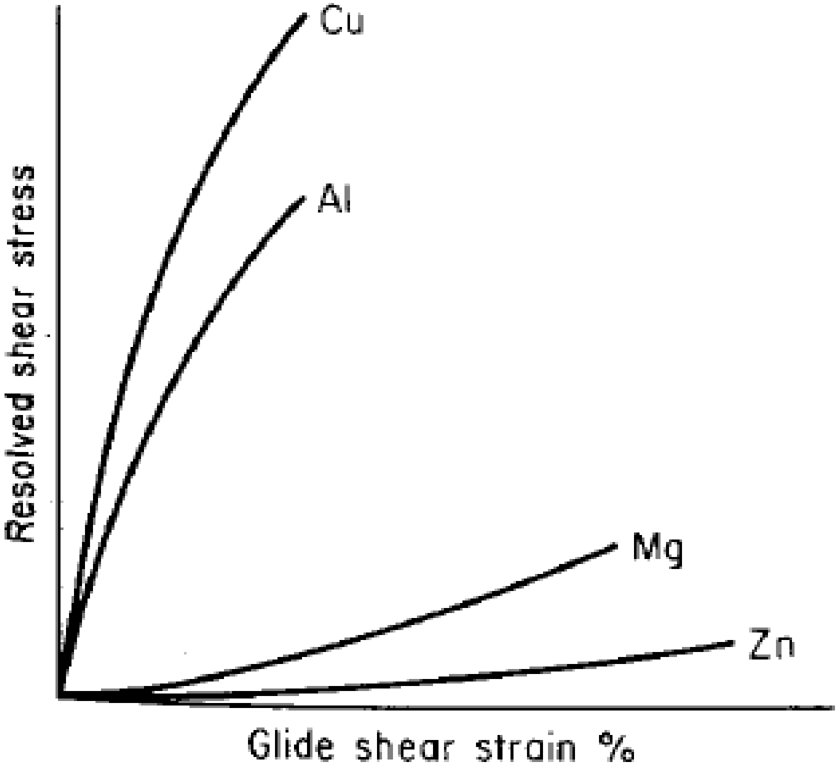
- Thus, the glide shear strain may be determined from the initial orientation of the slip plane and slip direction (xo and X0) and the extension of the specimen L_1/L_0. This analysis assumes that slip occurs on only a single slip system.

- If the orientation of the glide elements can be determined during or after deformation, the glide strain may be determined from

$$\gamma = \frac{\cos \lambda_1}{\sin \chi_1} - \frac{\cos \lambda_0}{\sin \chi_0}$$

Continued…

- ❑ The fundamental way to present single-crystal data is by plotting resolved shear stress vs. glide shear strain. Figure shows that there are important differences between metals. Typically, fcc metals exhibit greater strain hardening than hcp metals..



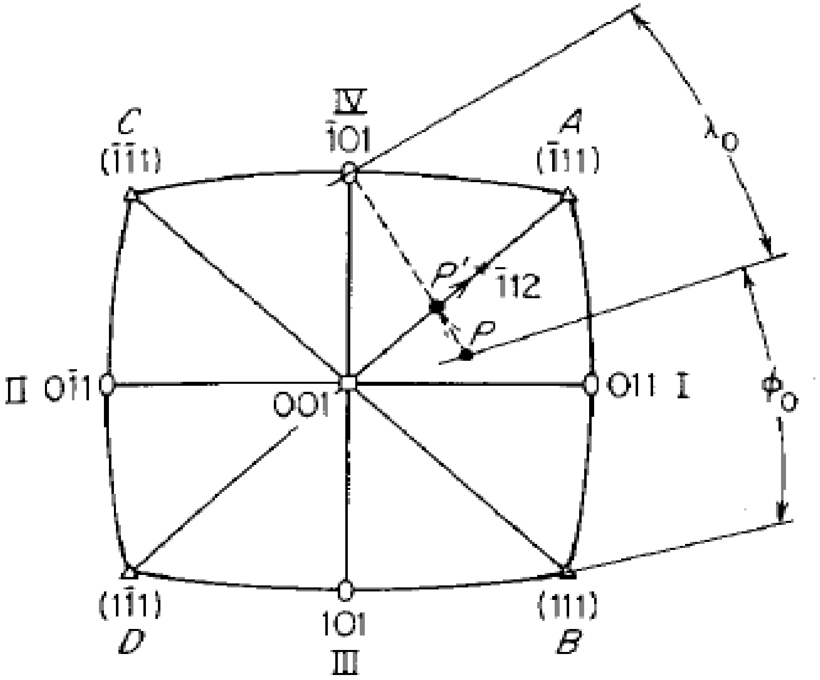
Typical single-crystal stress-strain curves

LECTURE-16

Deformation of face-centered cubic crystals

- Because FCC crystals have high symmetry and 12 potential slip systems, there is a wide choice of slip systems. The slip plane will not have to undergo much rotation before the resolved shear stress becomes high on another {111} <110> slip system.

- The initial operative slip system, the primary slip system, will be the one with the highest Schmid factor, m = sin χ cos λ. The primary system will depend on the orientation of the crystal relative to the tensile stress axis.



Standard (001) stereographic projection or a cubic crystal.

Continued…

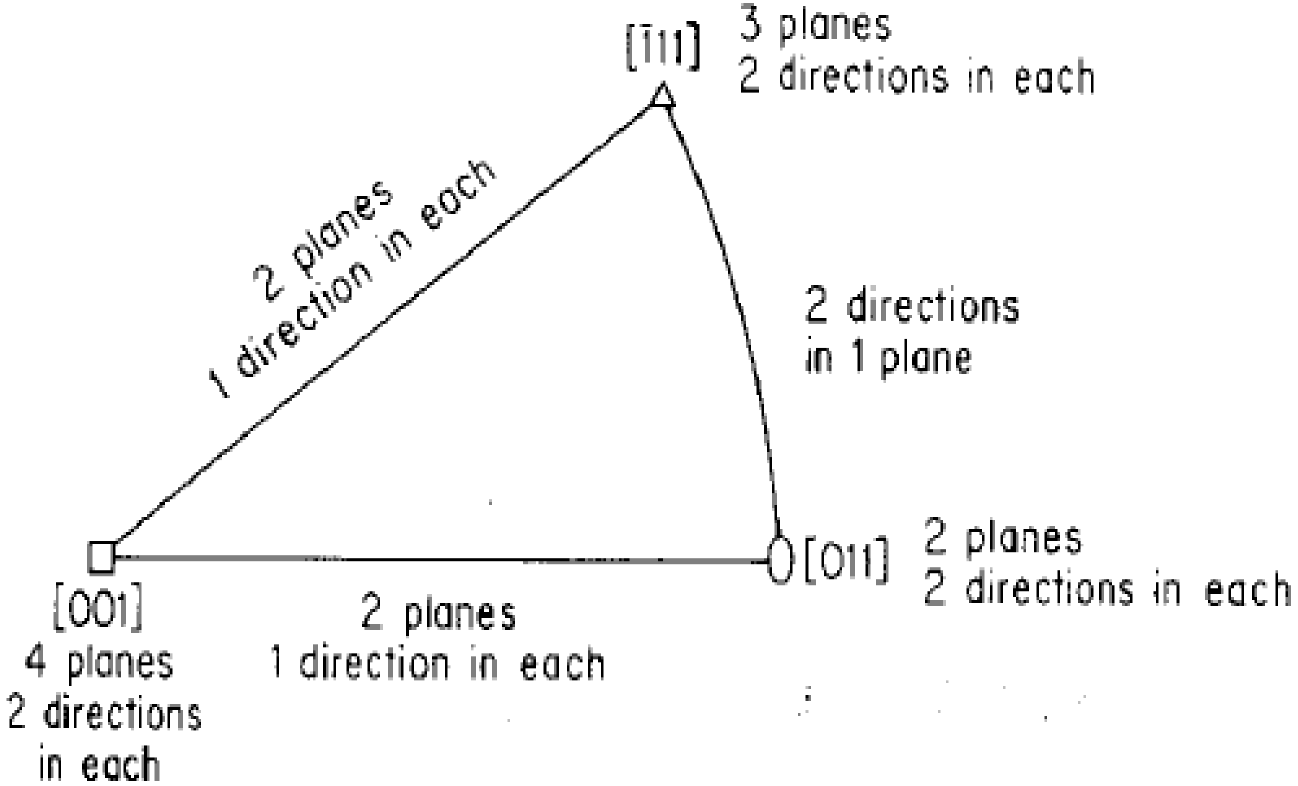
- The relationship between the stress axis and the 12 possible slip systems is best shown on a stereographic projection (Fig.), where each of the unit triangles defines a region in which a particular slip system operates.
- There are four (111) poles ABCD representing the normals to the octahedral {111} slip planes. Slip directions are indicated I through IV.
- For a specimen axis at P, the slip system BIV will be operative. Φ_0 and λ_0 are given by the great circles through B-P-IV.
- We can use the stereographic plot to follow the rotation of the slip system toward the tensile axis. As the specimen elongates, λ decreases and Φ increases. However it is more convenient to consider that the slip system remains fixed and the specimen axis rotates.

Continued…

- As the specimen elongates, the specimen axis eventually reaches the [001]-$[\bar{1}11]$ boundary at P'. Now the resolved shear stress is equal on the primary slip system and the conjugate slip system $(\bar{1}\bar{1}1)$[011]. At this point deformation proceeds on the two slip systems simultaneously to produce duplex slip or multiple slip.
- Under the microscope conjugate slip appears as another set of intersecting slip lines. The fact that slip can occur equally on both slip systems indicates that latent strain hardening must have occurred on the conjugate system when only the primary system was acting.
- The specimen axis rotates along the [001]-$[\bar{1}11]$ boundary to the $[\bar{1}12]$ pole, which is midway between the two operative slip directions $[\bar{1}01]$ and [011]. When the specimen axis reaches $[\bar{1}12]$ it stays at that orientation until the specimen necks down and fractures.

Continued…

- Crystals whose axes lie at orientations along the boundaries of the stereographic triangle represent a special situation because the critical resolved shear stress will be the same on more than one slip system.



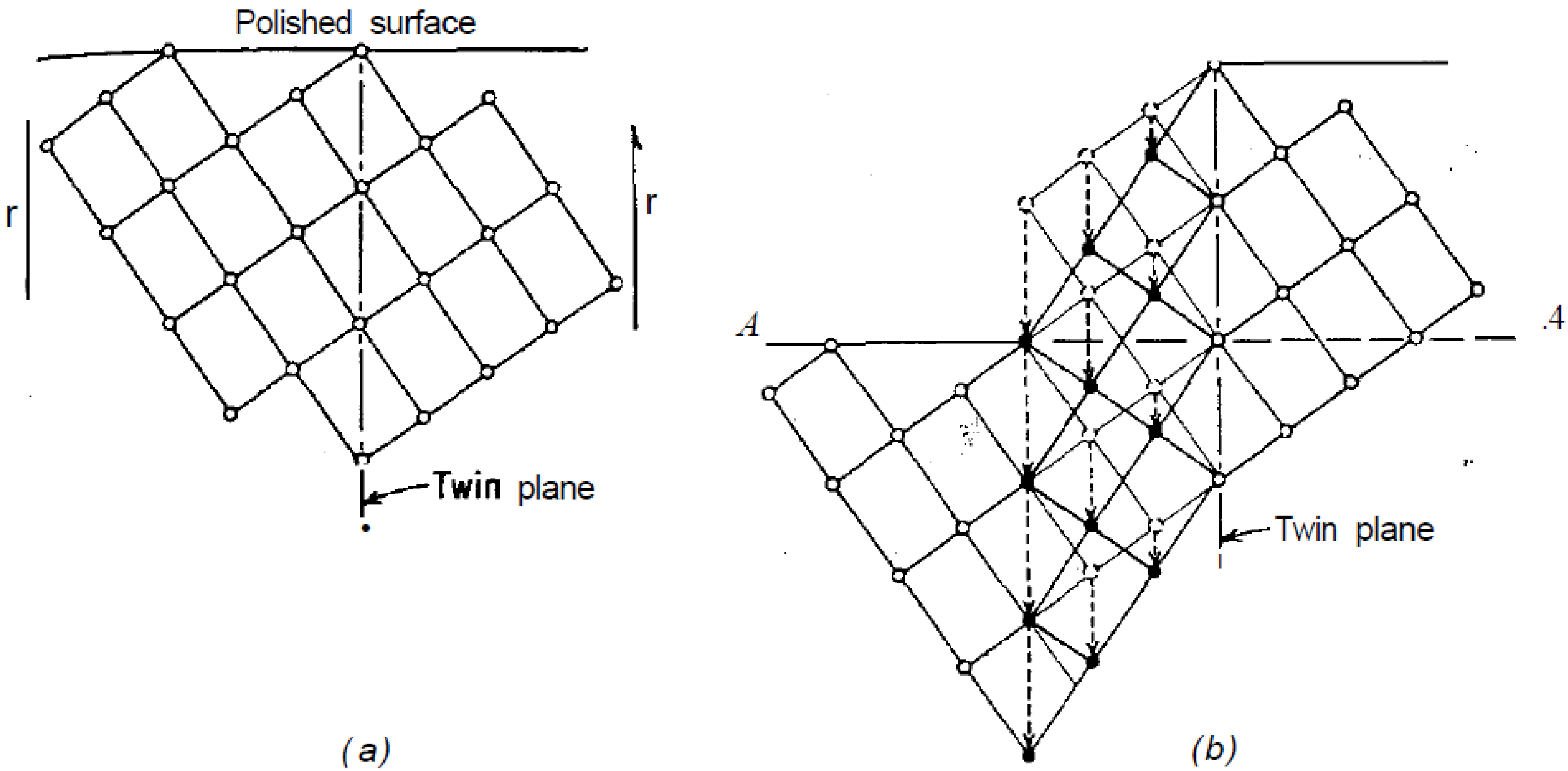
Operative slip systems along the boundaries of stereographic triangle

Continued…

- Therefore, plastic deformation will begin on more than one slip plane and they will initially deform by duplex slip. Figure shows the number of operative slip systems in a cubic crystal at these orientations.
- **Deformation by duplex slip results in a high degree of strain hardening because of interaction between dislocations on two intersecting slip systems.** This is shown in Fig. of **typical single-crystal stress-strain curves,** where Mg and Zn deform on a single Figure of Operative slip systems along boundaries of stereographic triangle. slip system (because of the hcp geometry) while the stress-strain curves for Al and Cu are for crystals oriented for duplex slip.

Continued…

Deformation by Twinning:



Classical picture of twinning

Continued…

- The **second important mechanism by which metals deform is the process known as twinning**.
- Twinning results when a portion of the crystal takes up an orientation that is related to the orientation of the rest of the untwinned lattice in a definite, symmetrical way.
- The **twinned portion of the crystal is a mirror image of the parent crystal.**
- **The plane of symmetry between the two portions is called *the twinning plane***.
- Figure illustrates the classical atomic picture of twinning. Figure (a) represents a section perpendicular to the surface in a cubic lattice with a low-index plane parallel to the paper and oriented at an angle to the plane of polish.
- The twinning plane is perpendicular to the paper.

Continued…

- If a shear stress is applied, the crystal will twin about the twinning plane (Fig. b). The region to the right of the twinning plane is undeformed. To the left of this plane, the planes of atoms have sheared in such a way as to make the lattice a mirror image across the twin plane.
- In Fig. (b), open circles represent atoms which have not moved, dashed circles indicate the original positions in the lattice of atoms which change position, and solid circles are the initial positions of these atoms in the twinned region.
- Note that the twin is visible on the polished surface because of the change in elevation produced by the deformation and because of the difference in crystallographic orientation between the deformed and undeformed regions.

Continued…

Difference between Slip & Twinning

Sl. No.	Slip	Twinning
1	The orientation of the crystal above and below the slip plane is the same after deformation as before.	While twinning results in an orientation difference across the twin plane.
2	Slip is usually considered to occur in discrete multiples of the atomic spacing	While in twinning the atom movements are much less than an atomic distance.
3	Slip occurs on relatively widely spread planes	The twinned region of a crystal every atomic plane is involved in the deformation.
4	Slip appears as thin lines	While twinning appears as a board lines or bands
5	There is very little change in lattice orientation and the steps are visible only on the surface of the crystal. If the steps are removed by polishing there will be no evidence that slip has taken place	In twinning, there is a different lattice orientation in the twinned region, removal of the steps by surface polishing will not destroy the evidence of twinning. Proper etching solutions, sensitive to the difference in orientation will reveal the twinned region
6	A delay time of several milliseconds before a slip band is formed	Form in a time as short as a few microseconds

Continued…

- If the surface were polished down to section AA, the difference in elevation would be eliminated but the twin would still be visible after etching because it possesses a different orientation from the untwinned region.
- Twins may be **produced by mechanical deformation or as the result of annealing following plastic deformation**. The **first type are known as mechanical twins; the latter are called annealing twins**.
- Mechanical twins are produced in BCC or HCP metals under conditions of rapid rate of loading (shock loading) and decreased temperature.
- FCC metals are not ordinarily considered to deform by mechanical twinning, although gold-silver alloys twin fairly readily when deformed at low temperature, and mechanical twins have been produced in copper by tensile deformation at 4 K and by shock loading.

Continued…

- Twins can form in a time as short as a few microseconds, while for slip there is a delay time of several milliseconds before a slip band is formed. Under certain conditions, **twins can be heard to form with a click or loud report [tin cry**].
- If twinning occurs during a tensile test, it produces serrations in the stress-strain curve. However, **twinning is not a dominant deformation mechanism in metals which possess many possible slip systems**.
- Twinning generally occurs **when the slip systems are restricted or when something increases the critical resolved shear stress (low temperature and high strain rate) so that the twinning stress is lower than the stress for slip**. This explains the occurrence of twinning at low temperatures or high strain rates in BCC and FCC metals or in HCP meals at orientations which are unfavorable for basal slip.

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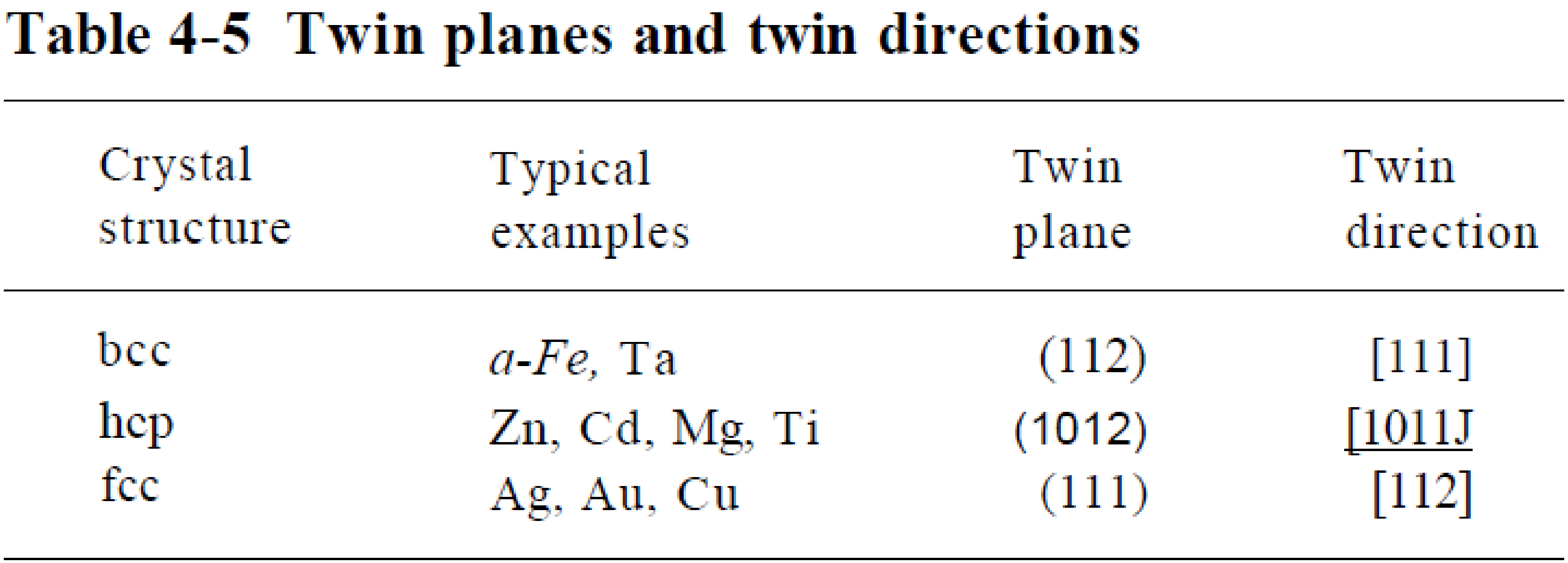

Table 4-5 Twin planes and twin directions

Crystal structure	Typical examples	Twin plane	Twin direction
bcc	*a-Fe*, Ta	(112)	[111]
hcp	Zn, Cd, Mg, Ti	(1012)	[1011J
fcc	Ag, Au, Cu	(111)	[112]

- Twinning is important in the overall deformation of metals with a **low number of slip systems, such as the HCP meals**. However, it should be understood that **only a relatively small fraction of the total volume of a crystal is reoriented by twinning**, and **therefore HCP metals** will, in general, **possess less ductility** than metals with a greater number of slip systems

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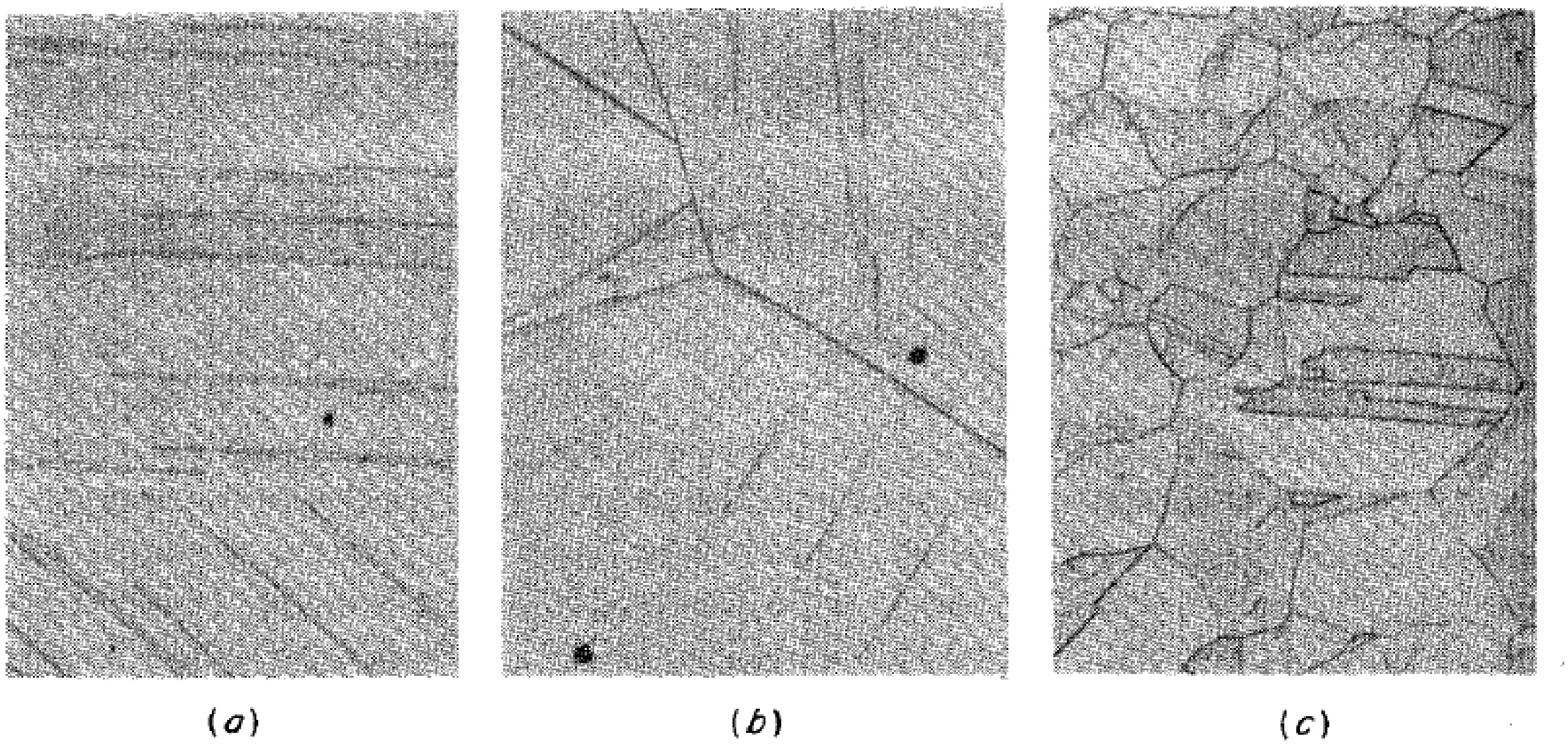


Microstructures of twins, (a) Neumann bands in iron; (b) mechanical twins produced in zinc by polishing; (c) annealing twins in gold-silver alloy.

Neumann bands in iron: Rectangular patterns of fine striations that appear in iron meteorites after they are cut, polished, and etched with dilute nitric acid

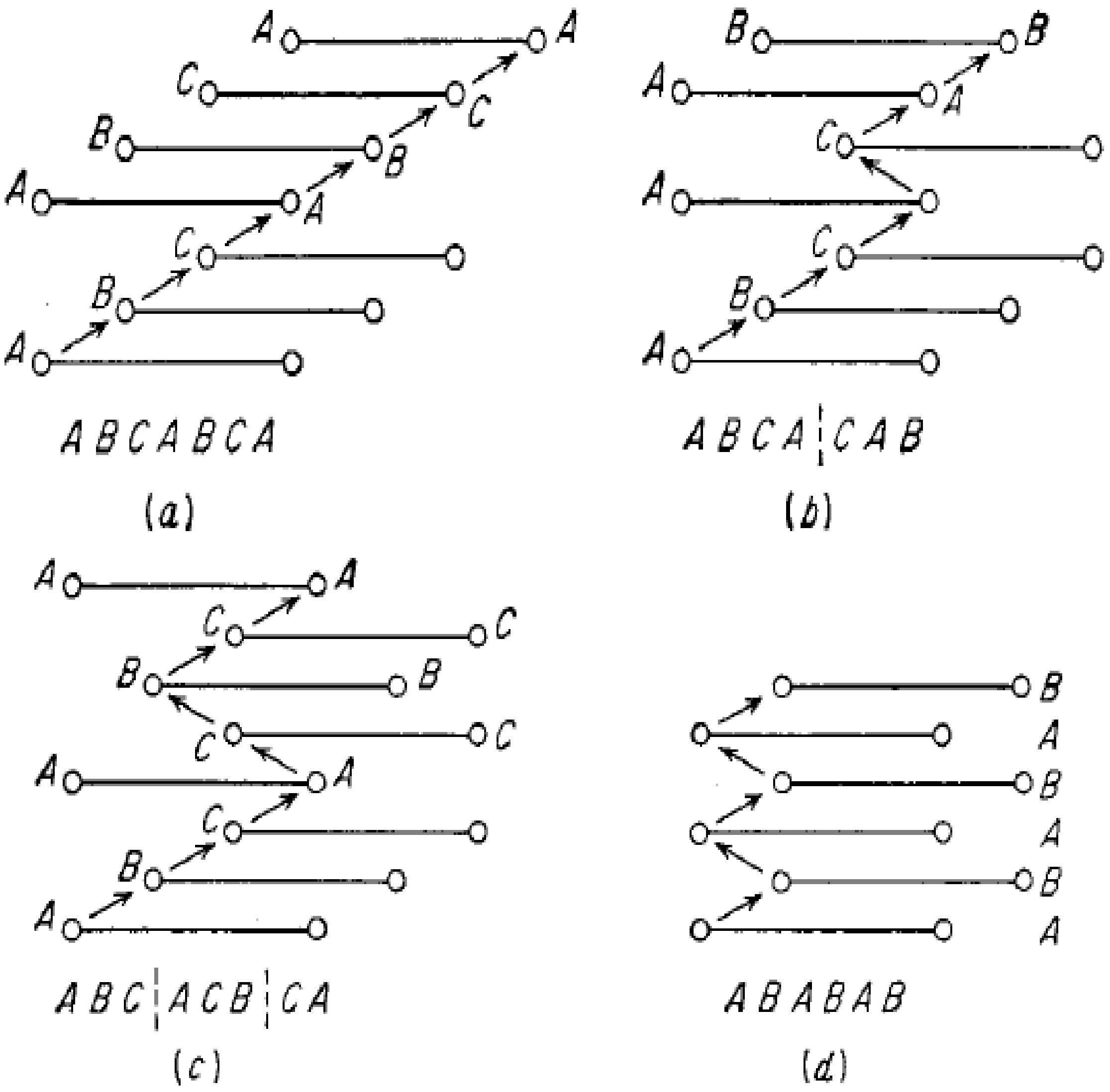
Continued…

A process closely related to twinning is the formation of a martensite region. by a diffusionless shear transformation. Although both processes produce a local region of new lattice orientation, the basic difference is that

- **A martensite plate the crystal structure is different from the parent crystal**.
- The diving force for martensitic transformation is the free energy difference between the parent crystal and the martensitic phase; whereas in twinning the driving force may be assisted by the applied shear stress.

LECTURE-17

Stacking Faults



Faulted structures, (a) FCC packing; (b) deformation fault in FCC; (c) twin fault in FCC; (d) HCP packing.

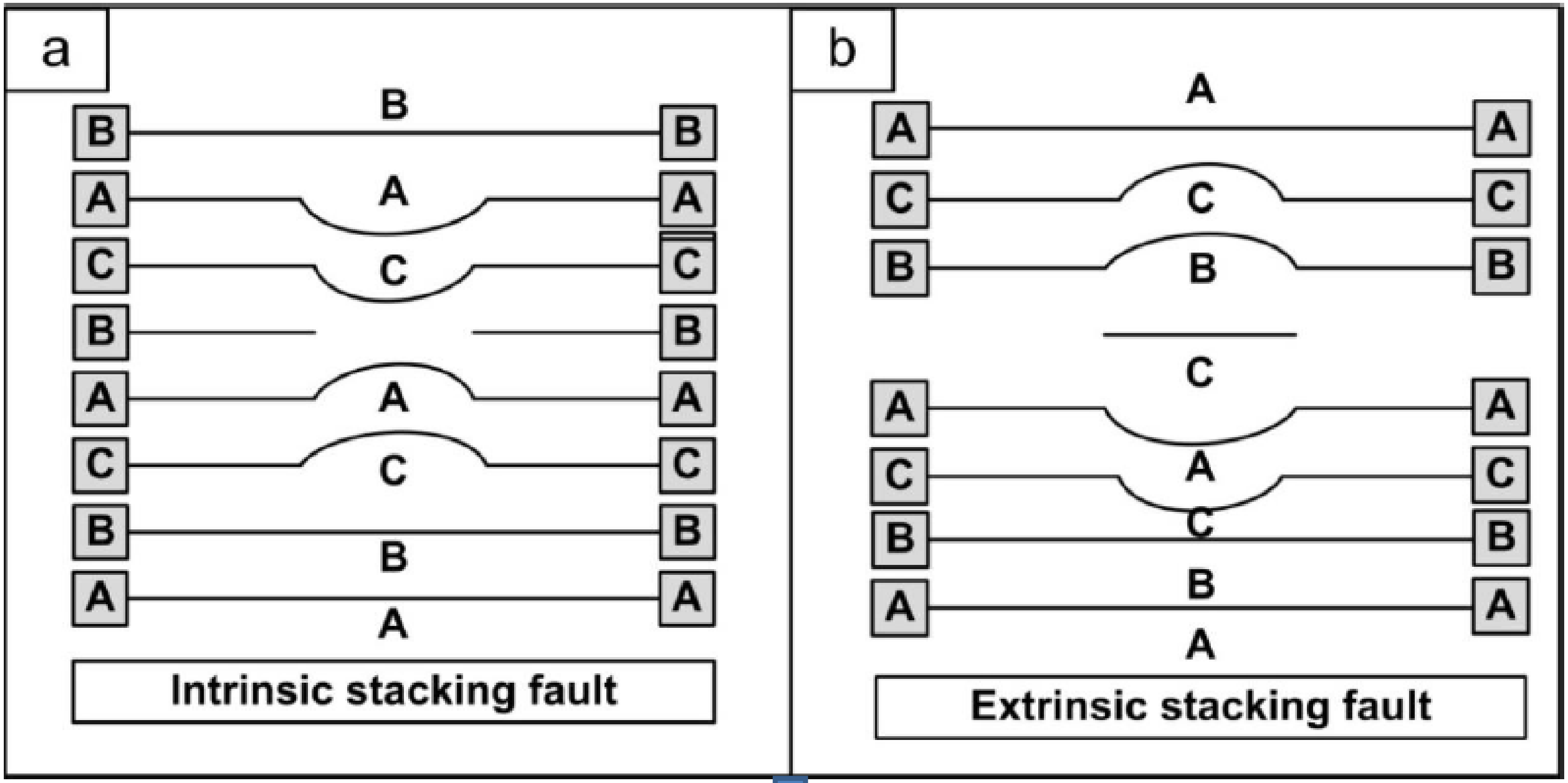
Continued…

- The atomic arrangement on the (111) plane of an fee structure and the {0001} plane of a HCP structure could be obtained by the stacking of close-packed planes of spheres. For the FCC structure, the stacking sequence of the planes of atoms is given by ABCABCABC. For the HCP structure, the stacking sequence is given by ABABAB.
- Errors, or faults, in the stacking sequence can be produced in most metals by plastic deformation. Slip on the {111} plane in an FCC lattice produces a deformation stacking fault by the process shown in Fig. b. Slip has occurred between an A and a B layer. The stacking sequence then becomes ABC AC AB.
- Comparison of this faulted stacking sequence (Fig. b) with the stacking sequence for an HCP structure without faults CACA (Fig. d) shows that the deformation stacking fault contains four layers of an HCP sequence.

Continued…

- Therefore, the formation of a stacking fault in an fcc metal is equivalent to the formation of a thin HCP region.
- Another way in which a stacking fault could occur in FCC metal is by the sequence shown in Fig. c. The stacking sequence **ABCACBCA is called an extrinsic, or twin, stacking fault**. The three layers ACB constitute the twin. Thus, stacking faults in FCC metals can also be considered as submicroscopic twins of nearly atomic thickness. The reason why mechanical twins of microscopically resolvable width are not formed readily when FCC metals are deformed is that the formation of stacking faults is so energetically favorable.
- The differences in the deformation behavior of FCC metals are due to the differences in stacking-fault behavior. The creation of a region with HCP stacking CACA introduces a region with higher free energy than the FCC structure.

Continued…



❑ Development of ISF can observe due to the removal of layer B atom from the regular stacking sequence.

❑ Formation of ESF is due to the insertion of a new atomic layer C into the regular stacking sequence.

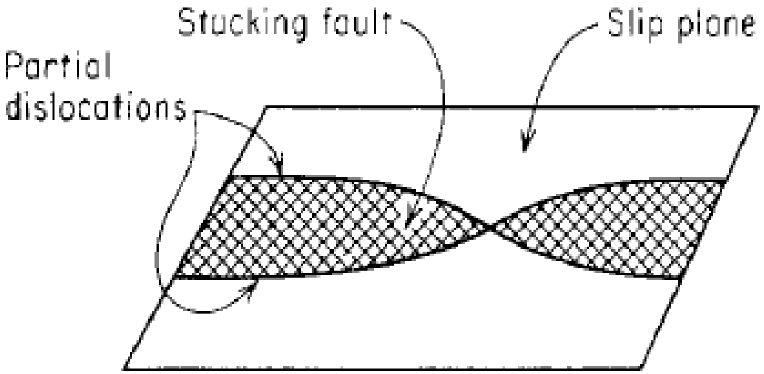
❑ In both cases, the regular stacking sequences of the atomic layers above and below the faulted layer remain in the same way.

Continued…

- A stacking fault in a fee metal, when viewed from dislocation theory, is an extended dislocation consisting of a thin HCP region bounded by partial dislocations (Figure). The nearly parallel partial dislocations tend to repel each other, but this is counterbalanced by the surface tension of the stacking fault pulling them together.

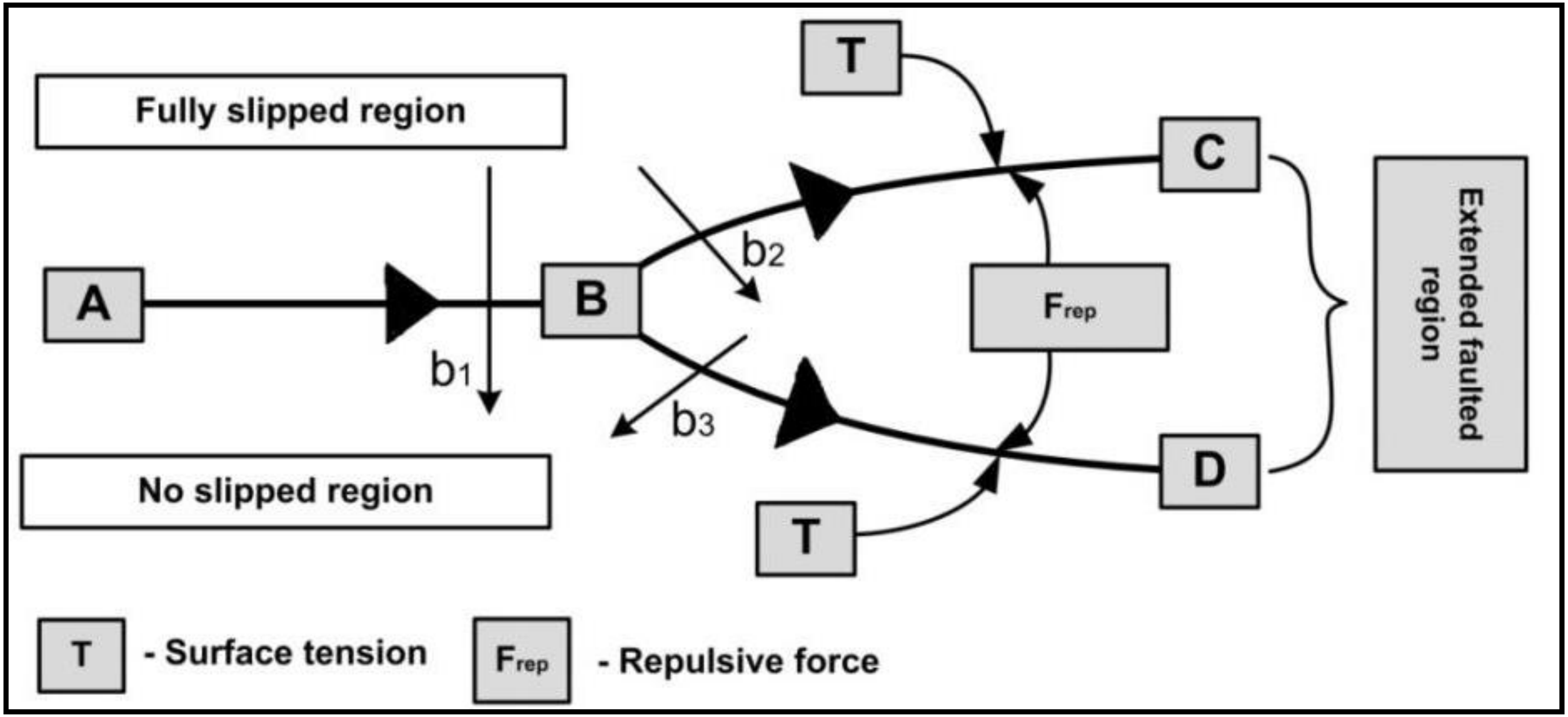
Table 4-6 Typical values of stacking-fault energy

Metal	Stacking-fault energy, $\mathrm{mJ\ m^{-2}}$ (= erg $\mathrm{cm^{-2}}$)
Brass	< 10
303 stainless steel	8
304 stainless steel	20
310 stainless steel	45
Silver	~ 25
Gold	~ 50
Copper	~ 80
Nickel	~ 150
Aluminum	~ 200



Schematic model of a stacking fault.

Continued…



- A full unit dislocation AB with burger vector $b1$ has dissociated into two partial dislocations BC and BD with burger vector $b2$ and $b3$, respectively.
- The dislocation dissociation reaction $b1 \rightarrow b2 + b3$ is energetically feasible when magnitudically

$$b_1^2 > b_2^2 + b_3^2$$

Continued…

- The **lower the stacking-fault energy the greater the separation between the partial dislocations and the wider the stacking fault**. Typical values for stacking fault energy (SFE) are given in Table 4-6. The data for the stainless steels illustrate that SFE is very sensitive to chemical composition.
- Stacking faults influence the plastic deformation in a number of ways. **Metals with wide stacking faults (low SFE) strain-harden more rapidly**, twin easily on annealing, and show a different temperature dependence of low stress than metals with narrow stacking faults.
- **Metals with high SFE have a deformation substructure of dislocation tangles and cells, while low-SFE metals show a deformation substructure of banded, linear arrays of dislocations.**

Continued…

DEFORMATION BANDS:

Inhomogeneous deformation of a crystal

↓ Leads to

Regions of different orientation called deformation bands

- **<u>Difference w.r.t. Slip Lines:</u>** Slip occurs without restraint in a perfectly homogeneous fashion and subsequent polishing the slip lines can be removed. Deformation bands occurs in region of different crystallographic orientation in a inhomogeneous fashion and can be observed even after repeated polishing and etching.

Continued…

Why the tendency for the formation of deformation bands is greater in polycrystalline specimens?

Ans: Because the restraints imposed by the grain boundaries make easy for orientation differences to arise in a grain during deformation. Usually, the deformation bands appear as irregular in shape and elongated in the direction of principal strain.

Why deformation bands have been observed in both FCC and BCC metals, but not in HCP metals?

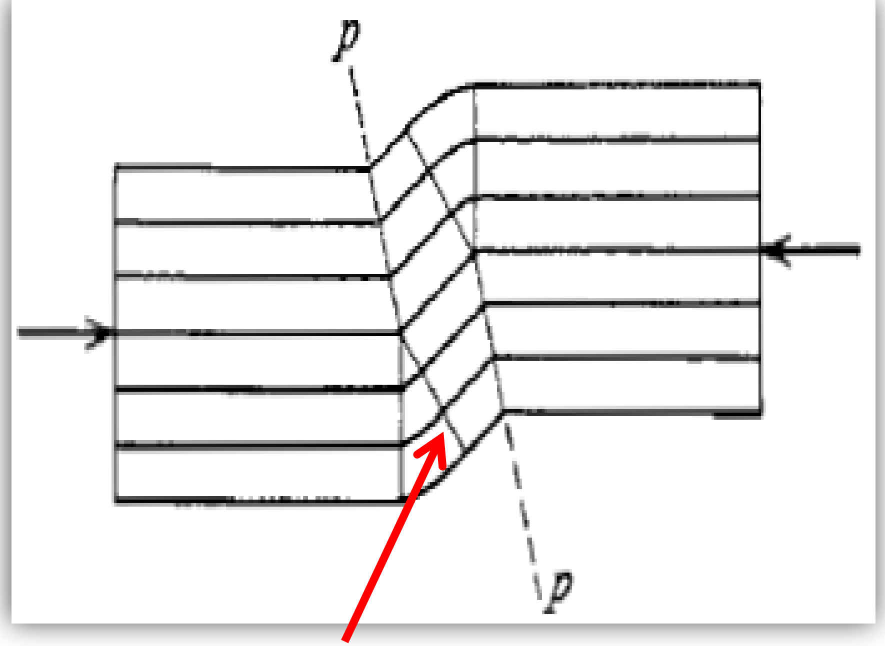
Ans: Because the shear stress required higher to deform a hexagonal crystal when the basal plane is nearly parallel to the crystal axis as per the equation for critical resolved shear stress. Hence, difficult to cause orientation difference across the individual grain to produce the deformation bands.

Continued…

KINK BANDS:

The bucking or kinking, behavior is illustrated in the below Fig. The horizontal lines represent basal planes, and the planes designated ***P*** are the **kink planes at which the orientation suddenly changes**. Distortion of the crystal is essentially confined to the kink band.

Example: The observation by Orowan that the cadmium (Cd) crystal show localized deformation cause suddenly snapping into a tilted position with a sudden shortening of the crystal under compression loading.



Kink planes

Continued…

- The study of kink bands by Hess and Barrett showed that **kink band can be considered to be a simple type of deformation band.**
- Kink bands have also been observed in zinc crystals tested in tension due to a non uniform distribution of slip that produce a bending moment to cause kink formation.

LECTURE-18

STRAIN HARDENING OF SINGLE CRYSTALS

- **Definition:** The shear stress required to produce slip continuously increases with increasing shear strain. The increase in the stress required to cause slip because of previous plastic deformation is known as strain hardening, or work hardening.

- Strain hardening is **caused by dislocations interacting with each other and with barriers which impede their motion through the crystal lattice**.

- Hardening due to dislocation interaction is a complicated problem because it **involves large groups of dislocations and it is difficult to specify group behavior in a simple mathematical way**.

Continued…

Dislocation Density (δ): It is a measure of the number of dislocations in a unit volume of a crystalline material. It can also be defined as the average dislocation length per unit volume.

- Unit is cm^{-2} or mm^{-2} .
- **δ =** 10^5 to 10^6 cm^{-2} (= 10^3 to 10^4 mm^{-2}) for a good annealed crystal.

  δ = 10^{10} to 10^{12} cm^{-2} (= 10^8 to 10^{10} mm^{-2}) in cold-worked metal.
- One of the earliest dislocation concepts to explain strain hardening was the idea that **dislocations pile up on slip planes at barriers in the crystal**.

Continued…

- **Dislocation Density (δ):** It is a measure of the number of dislocations in a unit volume of a crystalline material. It can also be defined as the average dislocation length per unit volume.
- Unit is cm^{-2} or mm^{-2} .
- The dislocation density of a good annealed crystal is 10^5 to 10^6 cm^{-2} (= 10^3 to 10^4 mm^{-2}), while the observed dislocation density in cold-worked metal is 10^{10} to 10^{12} cm^{-2} (= 10^8 to 10^{10} mm^{-2}).
- One of the earliest dislocation concepts to explain strain hardening was the idea that dislocations pile up on slip planes at barriers in the crystal.

Continued…

Back Stress (Bauschinger Effect):

- Back stress is a phenomenon that occurs in materials that exhibit the Bauschinger effect, which is **a decrease in the yield stress of a material when the direction of the stress is reversed**.
- The existence of a back stress was demonstrated experimentally by shear tests on zinc single crystals. Zn crystals are ideal for crystal-plasticity experiments because they slip only on the basal plane, and hence complications due to duplex slip are easily avoided.
- **Offset stress:** The larger the offset stress, the larger the Bauschinger effect.
- **Reverse plastic strain:** The larger the reverse plastic strain, the larger the Bauschinger effect.

Continued…

- **Bauschinger effect:** When a material is deformed, unloaded, and then reloaded in the opposite direction, the yield stress decreases. This is because the compressive flow stress after tensile prestraining is much smaller than the tensile flow stress.

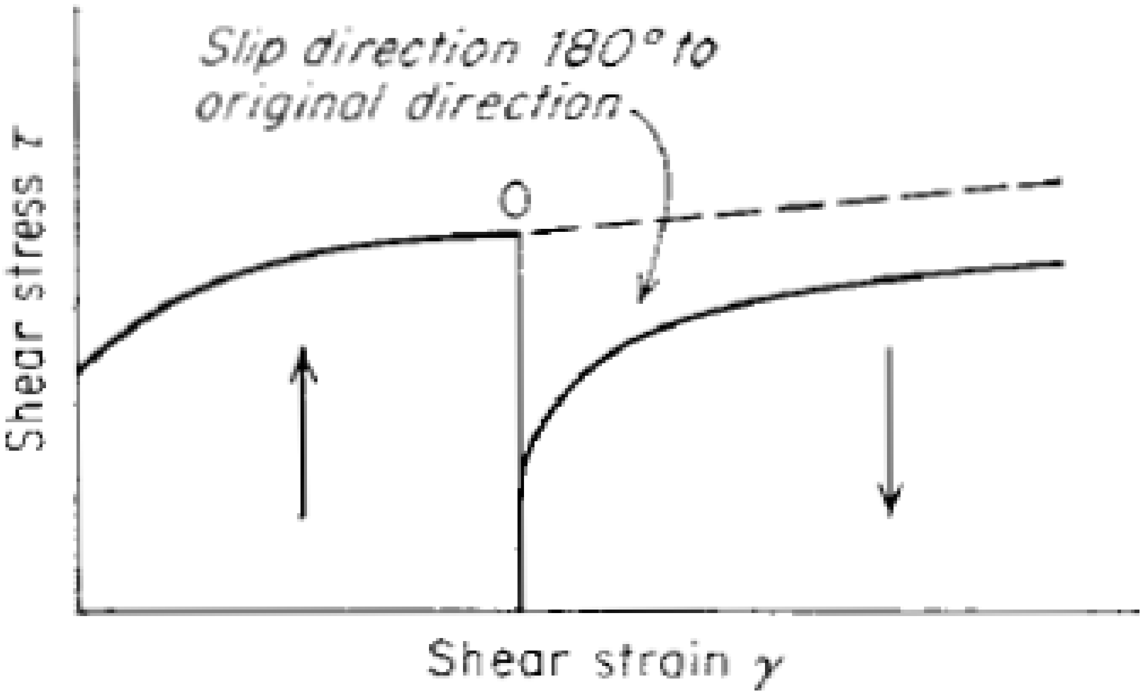


Fig: Effect of complete reversal of slip direction on stress-strain curve.

Continued…

- In Fig., the crystal is strained to point **O** unloaded, and then reloaded in the direction opposite to the original slip direction. Note that on reloading the crystal yields at a lower shear stress than when it was first loaded, because the **back stress** developed by **dislocations piling up** at barriers during the first loading cycle is **aiding dislocation movement** when the direction **of slip is reversed**.
- Furthermore, when the slip direction is reversed, dislocations of opposite sign could be created at the same sources that produced the dislocations responsible for strain in the first slip direction.
- Since dislocations of opposite sign attract and annihilate each other, the net effect would be a further softening of the lattice.

Continued…

SESSILE DISLOCATION

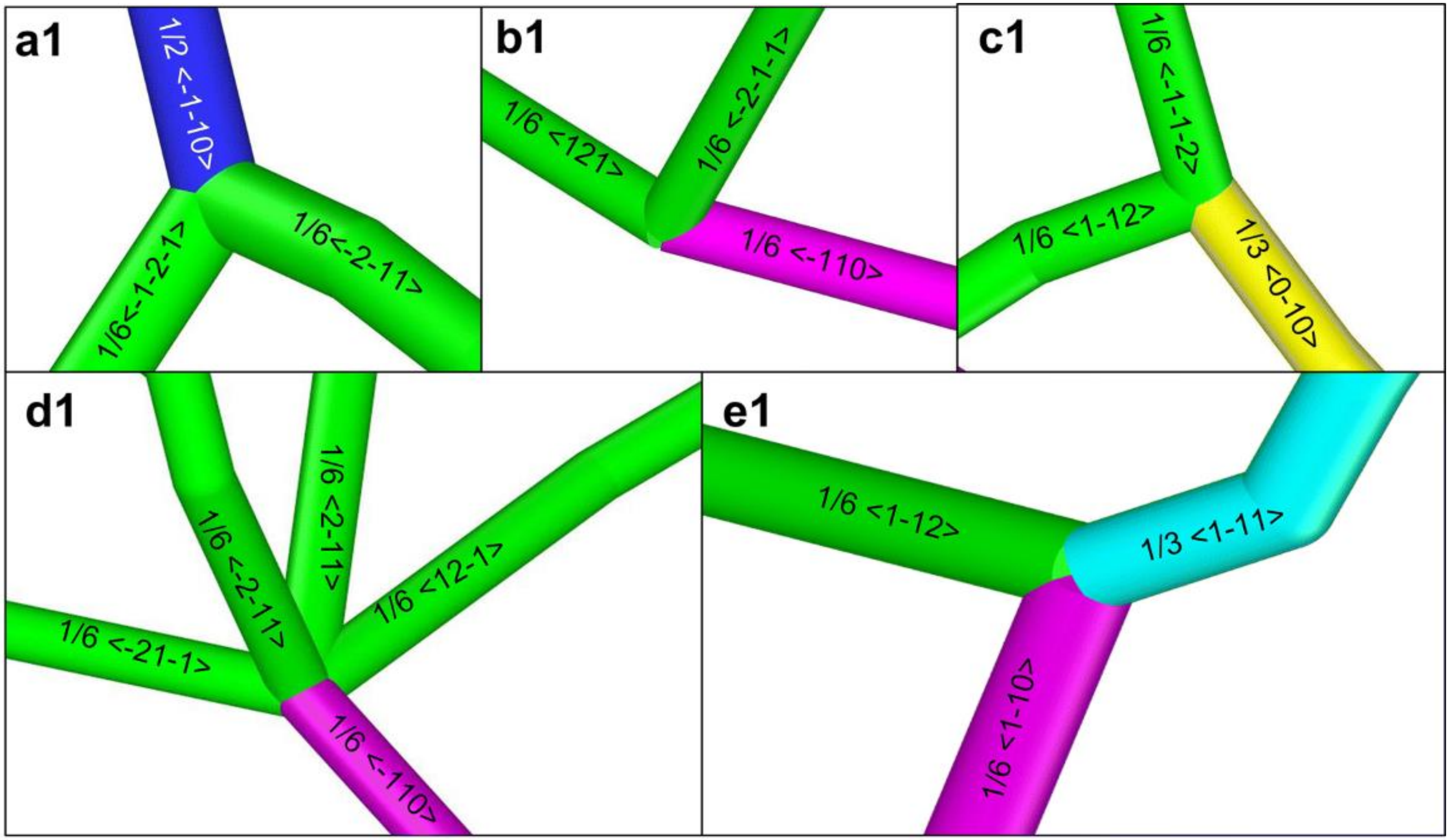
- The Shockley partial dislocation has its burger vector lying in the plane of the fault and hence is glissile. Some dislocations, however, have their Burgers vector not lying in the plane of the fault with which they are associated and are incapable of gliding, i.e. they are sessile.
- Since **sessile dislocations** do not lie on the slip plane of low shear stress, they have low mobility and act as a barrier to dislocation motion until the stress is increased to a high enough level to break down the barrier.
- **Examples:** Stair-rod dislocation, Frank partials, Lomer–Cottrell junction, etc.

LOMER-COTTRELL BARRIERS: The most important dislocation reaction, which leads to the formation of sessile dislocations, is the formation **of Lomer-Cottrell barriers** in FCC metals by slip of dislocations on intersecting {111} planes during duplex slip.

Continued…

Burger Vectors of following Sessile Dislocations:

Stair-rod Partials (1/6<110>), Frank Partial (1/3<111>, Hirth Partial (1/3<100>)

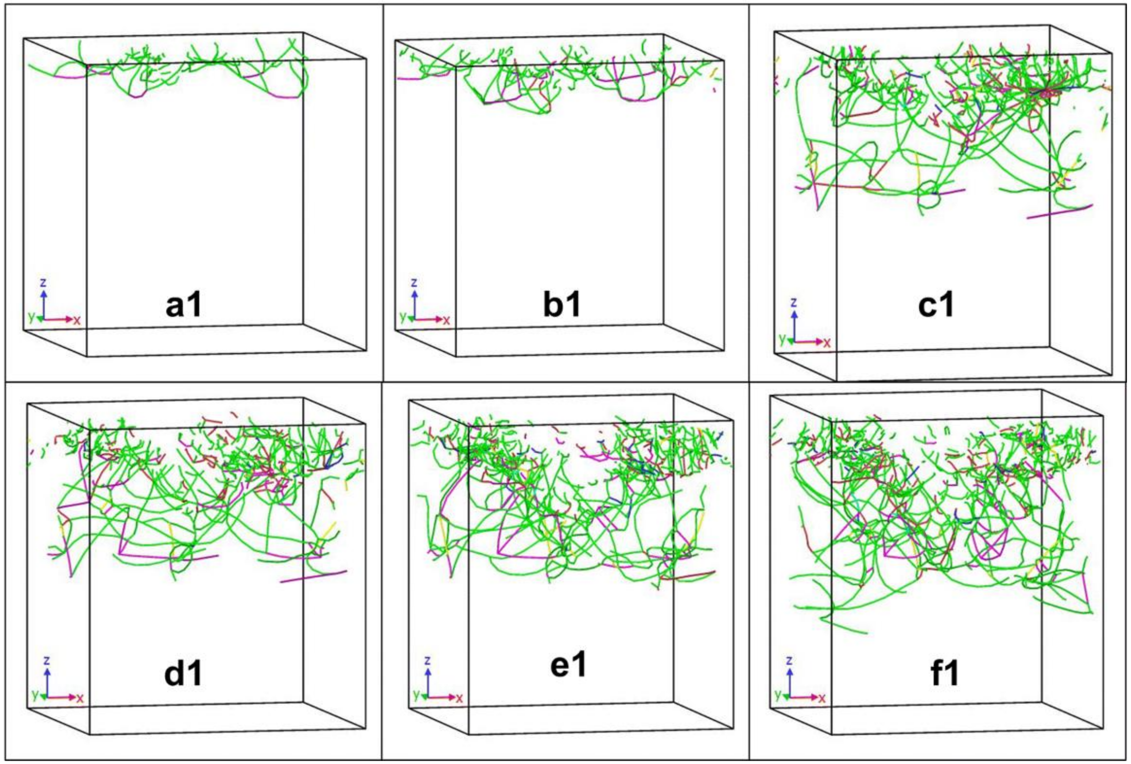


Reference: Mishra, D.K. *et al.* Dislocation Interaction and V-Shaped Growth of the Distorted Structure During Nanoindentation of $Cu_{20}Ni_{20}Al_{20}Co_{20}Fe_{20}$ (high-entropy alloy)-Coated Copper: A Molecular Dynamics Simulation-Based Study. *Trans Indian Inst Met* **72**, 167–180 (2019).

Continued…

DISLOCATION FOREST:

when dislocations moving in the slip plane cut through other dislocations intersecting the active slip plane. The dislocations threading through the active slip plane are often called a ***dislocation forest***, and this strain-hardening process is referred to as ***the intersection of a forest of dislocations***.

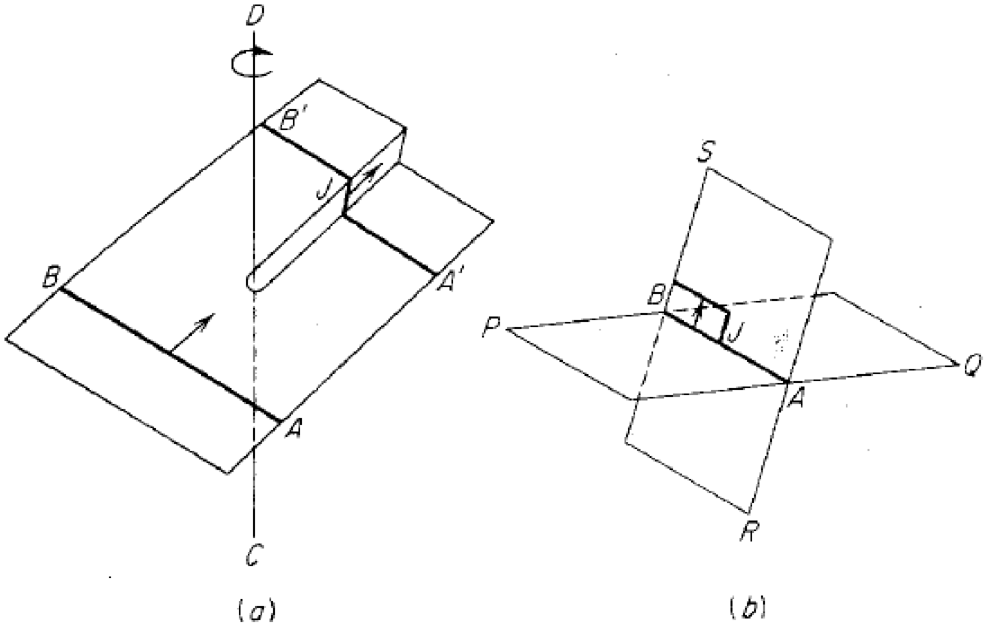


Reference: Mishra, D.K. *et al.* Dislocation Interaction and V-Shaped Growth of the Distorted Structure During Nanoindentation of $Cu_{20}Ni_{20}Al_{20}Co_{20}Fe_{20}$ (high-entropy alloy)-Coated Copper: A Molecular Dynamics Simulation-Based Study. *Trans Indian Inst Met* **72**, 167–180 (2019).

Continued…

JOGS

- Figure(a) shows that dislocation intersection results in a small step or jog in the dislocation line. Jogs on a dislocation restrict its motion so that they contribute to strain hardening. Jogs are also formed by a screw dislocation cross slipping from the primary slip plane to another plane which contains the common slip direction (Fig. b).

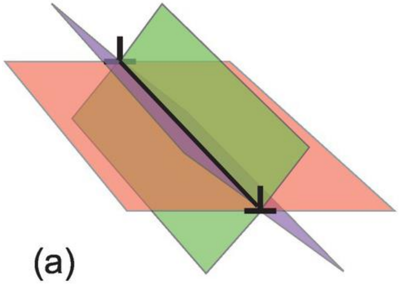


Formation of a jog J {a) by a dislocation cutting through a screw dislocation as it glides from AB to A'B' (b) by part of a screw dislocation line AB cross slipping from the primary slip plane PQ into the plane

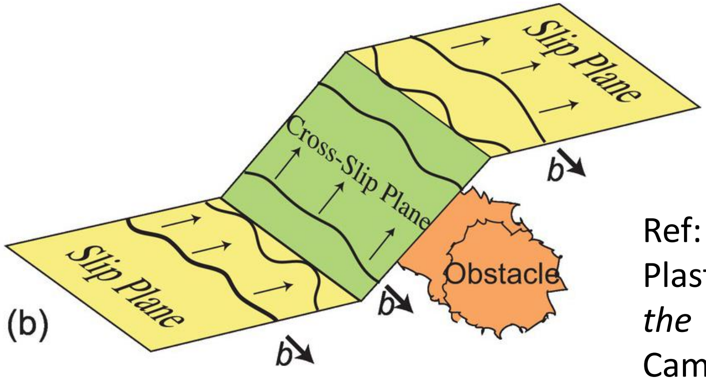
Continued…

CROSS SLIP

- Cross-slip is a thermally activated process by which **a screw dislocation changes its original glide plane to another glide plane which shares the same Burgers vector**. The phenomenon of cross slip is restricted to screw dislocations. Since the line of a screw dislocation and its Burgers vector are parallel, this does not define a specific plane as with an edge dislocation (where b is perpendicular to the dislocation line). To a screw dislocation, all directions around its axis look the same, and it can glide on any plane as long as it moves parallel to its original orientation.



(a)



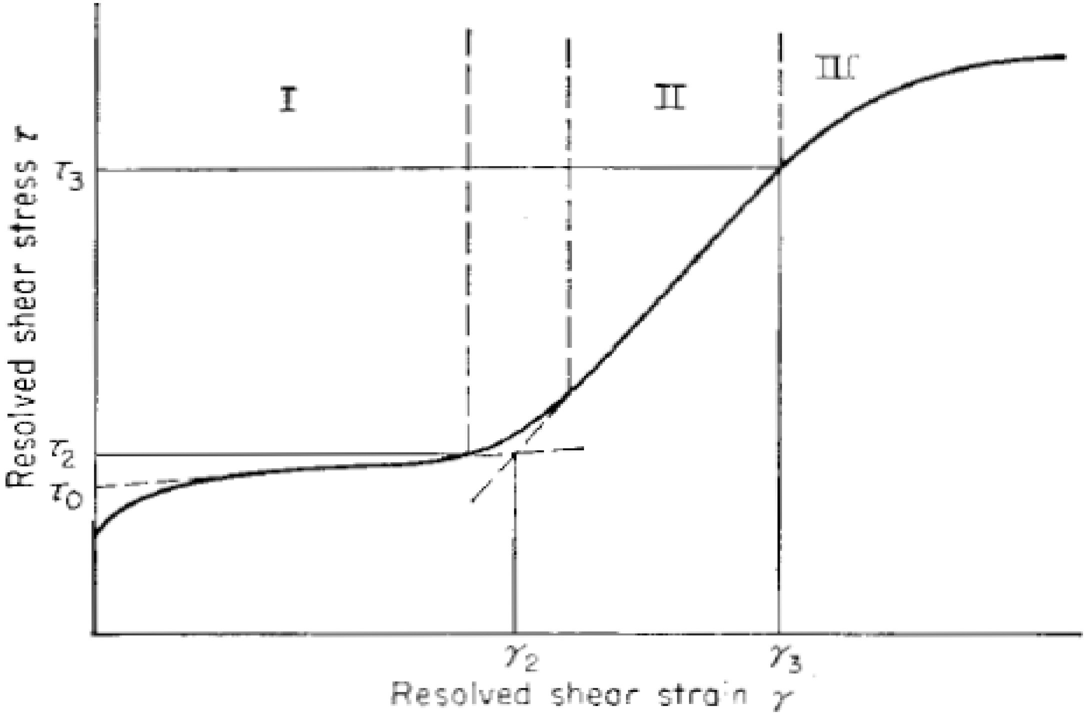
(b)

Ref: Clyne TW, Campbell JE. Mechanisms of Plastic Deformation in Metals. In: *Testing of the Plastic Deformation of Metals*. Cambridge University Press; 2021:43-80

Continued…

STRESS - STRAIN CURVES FOR SINGLE CRYSTALS

When the stress-strain curves for single crystals are plotted as resolved shear stress vs. shear strain, certain generalizations can be made for all fcc metals. Following the notation proposed by **Seeger**, the flow curve for pure-metal single crystals can be divided into three stages.



Generalized flow curve for fcc single crystals.

Continued…

STAGE – I

- The region of **easy glide** is a stage in which the crystal undergoes little strain hardening. During easy glide, the dislocations are able to move over **relatively large distances** without encountering barriers. The **low strain hardening** produced during this stage implies that most of the dislocations escape from the crystal at the surface. During easy glide, slip always occurs on only one slip system. For this reason, stage I slip is sometimes called laminar flow.

STAGE – II

- Stage II is a **nearly linear part of the flow curve** where strain hardening increases rapidly. In this stage, slip occurs on **more than one set of planes**.
- **The length of the active slip lines decreases with increasing strain**, which is consistent with the formation of a greater number of Lomer-Cottrell barriers with increasing strain.

Continued…

- During stage II, the ratio of the **strain-hardening coefficient** (the slope of the curve) to the shear **modulus is nearly independent of stress and temperature**, and approximately **independent of crystal orientation and purity.**
- The fact that the slope of the flow curve in stage II is nearly independent of temperature agrees with the theory that assumes the chief strain-hardening mechanism to be piled-up groups of dislocations.
- The average dislocation density in stage II correlates with resolved shear stress according to

$$\tau = \tau_0 + \alpha G \rho^{1/2}$$

Where τ_0 is the shear stress needed to move a dislocation in the absence of other dislocations and a is a numerical constant which varies from 0.3 to 0.6 for different fcc and bcc metals.

Continued…

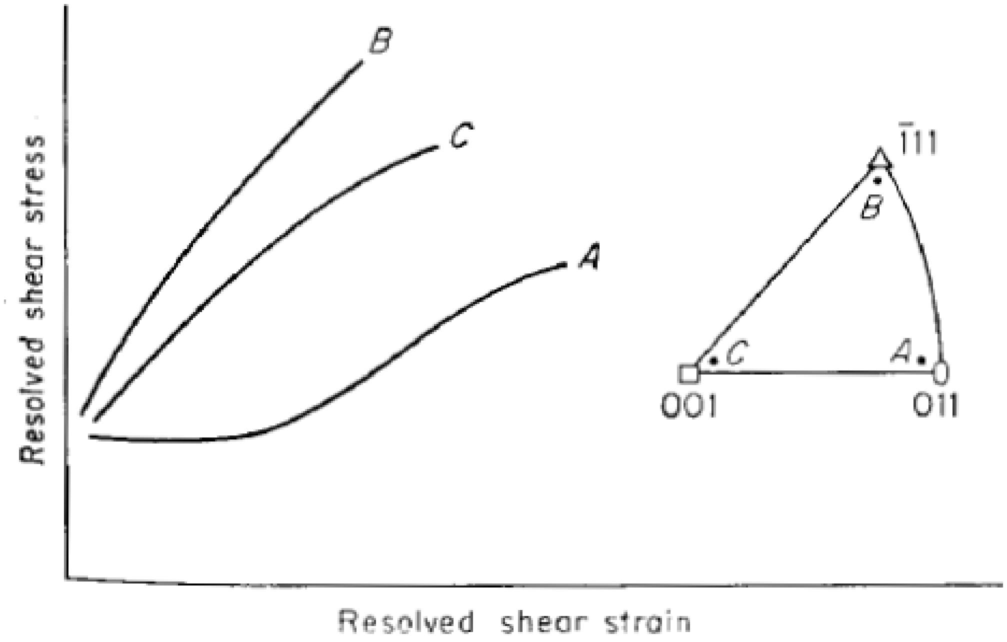
STAGE – III

- Stage III is a region of **decreasing rate of strain hardening**.
- The processes occurring during this stage are often called **dynamical recovery**.
- In this region of the flow curve, the stresses are high enough so that dislocations can take part in processes that are suppressed at lower stresses.
- **Cross slip** is believed to be the main process by which dislocations, piled up at obstacles during stage II, can escape and reduce the internal-strain field.
- The stress at which stage III begins, τ_3, **is strongly temperature-dependent**.
- Also, the flow stress of a crystal strained into stage III is more temperature-dependent than if it had been strained only into stage II.
- This temperature dependence suggests that the intersection of forests of dislocations is the chief strain-hardening mechanism in stage III.

Continued…

Effect of Crystal Orientation on the flow curve of fcc single crystals

- Figure shows that crystal orientation can have a very strong effect on the low curve of fcc single crystals.
- When the tensile axis is parallel to a <011> direction, one slip system is carrying appreciably more shear stress than any other and the low curve shows a relatively large region of easy glide.
- When the tensile axis is close to a <100> or <111> direction, the stress on several slip systems is not very different and the low curves show rapid rates of strain hardening.



Effect of specimen orientation on the shape of the flow curve for fcc single crystals.

LECTURE-19

DISLOCATION THEORY

Introduction

- A dislocation is the linear lattice defect that is responsible for nearly all aspects of the plastic deformation of metals.
- This chapter is intended to present a more complete treatment of dislocation theory. Techniques for observing dislocations in metals are discussed. The effect on dislocation behavior of considering real fcc, bcc, or hcp crystal structures are considered.
- The origin of dislocations and the mechanisms for their multiplication are discussed. Interaction of dislocations with other dislocations, vacancies, and foreign atoms is discussed in some detail.

Continued…

- The object of this chapter is the presentation of the ***basic geometric*** and ***mathematical relationships*** which describe dislocation behavior.
- These relationships will be used to explain ***mechanical behavior and strengthening mechanisms*** in subsequent chapters of this book.

Observation of dislocations

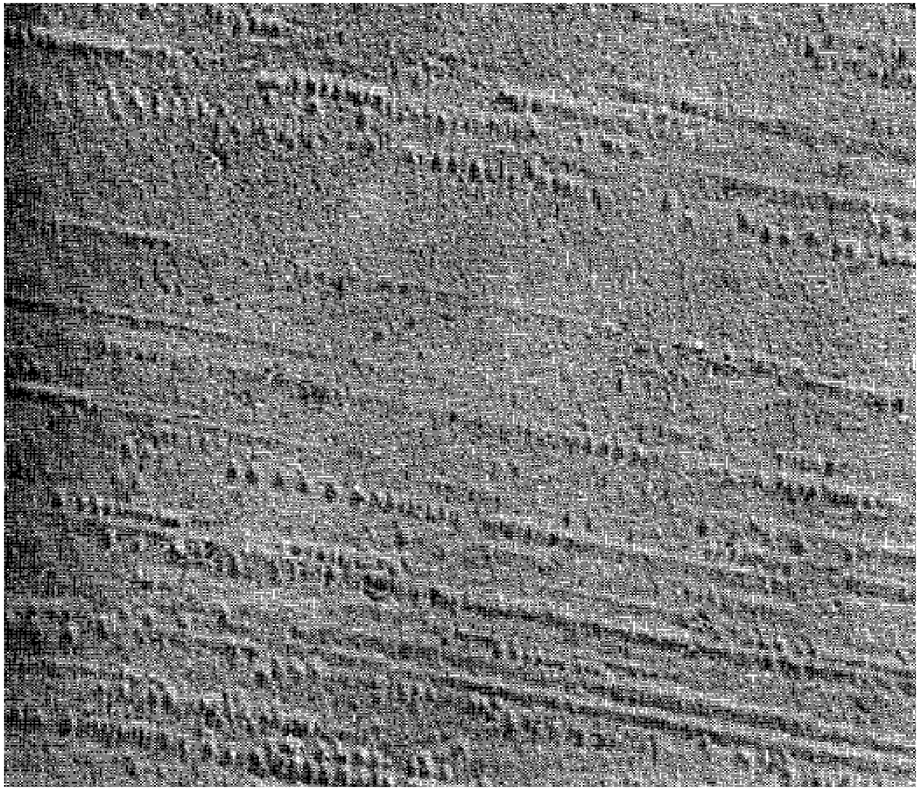
- The concept of the dislocation was proposed independently by Taylor, Orowan, and Polanyi1 in 1934, but the idea lay relatively undeveloped until the end of World War II. There followed a period of approximately 10 years in which the theory of dislocation behavior was developed extensively and applied to practically every aspect of the plastic deformation of metals.
- Practically all the experimental techniques for detecting dislocations utilize the strain field around a dislocation to increase its effective size.

Continued…

- These experimental techniques can be roughly classified into ***two categories,*** those ***involving chemical reactions*** with the dislocation, and those utilizing the ***physical changes at the site of a dislocation***.
- ***Chemical methods*** include ***etch-pit techniques*** and ***precipitation techniques***. Methods based on the ***physical structure*** at a dislocation ***site include transmission electron microscopy of thin films and x-ray diffraction techniques.***
- The simplest chemical technique is the use of an etchant which forms a pit at the point where a dislocation intersects the surface. Etch pits are formed at dislocation sites because the strain field surrounding the dislocation causes preferential chemical attack.

Continued…

- Figure shows the excellent resolution obtainable from etch-pit studies on alpha brass. Pits only 500 ^{0}A (= 50 nm) apart have been resolved. In the region of heavy slip shown in this electron micrograph the ***dislocation density is 10^{10} cm^{-2} (= 10^8 mm^{-2}).***
- A similar method of detecting dislocations is to form a visible precipitate along the dislocation lines. Usually a small amount of impurity is added to form the precipitate after suitable heat treatment. The procedure is called ***"decoration"*** of dislocations.

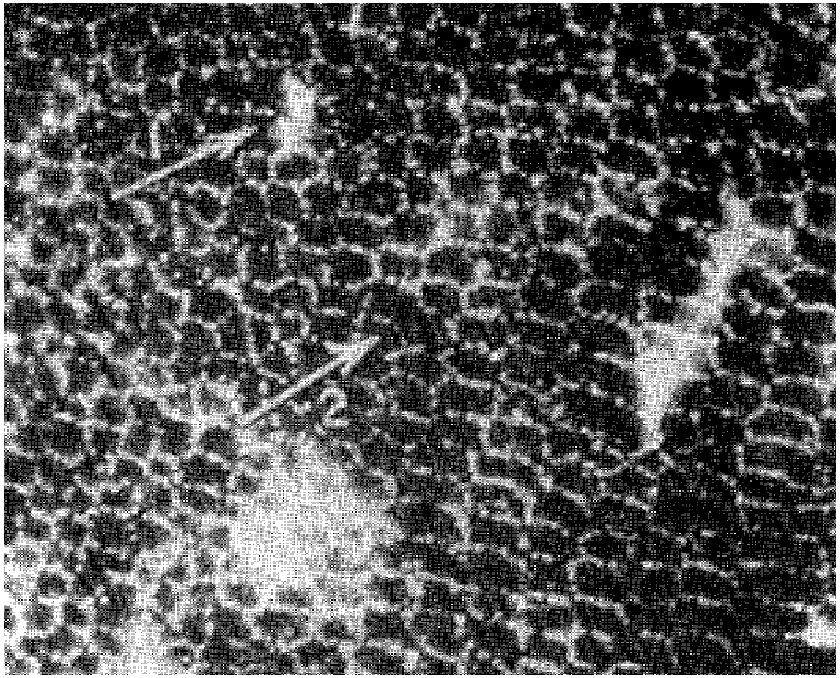


Etch pits on slip bands in alpha brass crystals (5,000 X).

Continued…

- This technique was first used by Hedges and Mitchell to decorate dislocations in AgBr with photolytic silver. It has since been used with many other ionic crystals such as AgCl, NaCl, KCl, and CaF_2. With these optically transparent crystals this technique has the advantage that it shows the internal structure of the dislocation lines.

- Figure shows a hexagonal network of dislocations in a NaCl crystal which was made visible by decoration.



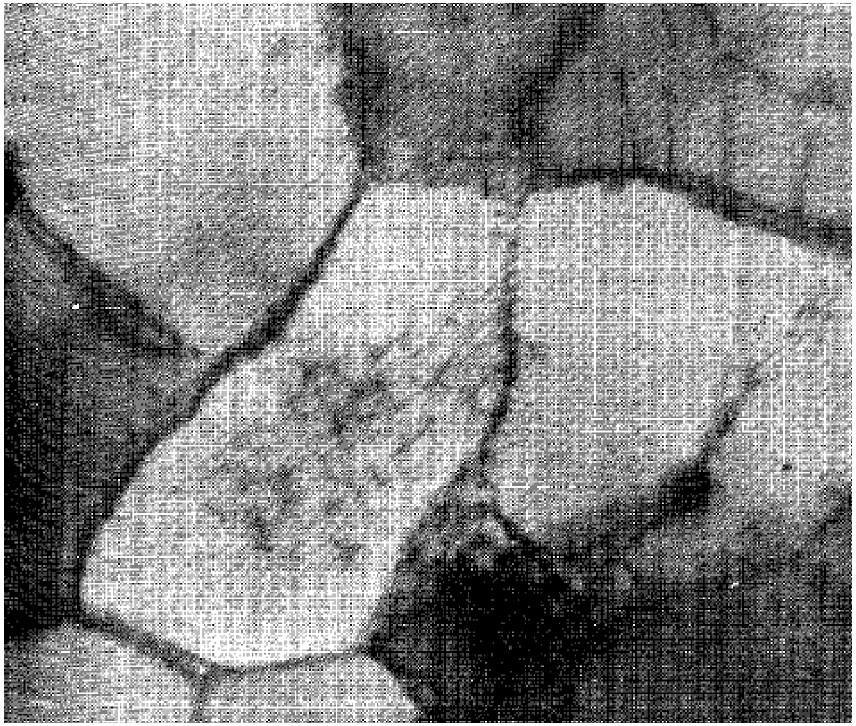
Hexagonal network of dislocations in NaCl detected by a decoration technique

Continued…

- The most powerful method available today for the detection of dislocations in metals is ***transmission electron microscopy of thin foils***. Thin sheet, less than 1 mm thick, is thinned after deformation by electro polishing to a thickness of about 1,000 A (= 100 nm). At this thickness the specimen is transparent to electrons in the electron microscope.
- In ***conventional transmission electron microscopy, individual dislocation lines can be observed because the intensity of the diffracted electron beam*** is altered by the strain field of the dislocation.
- The width of the diffraction image of a dislocation in a thin foil is about 100 A (= 10 nm), so that this technique can be used at dislocation densities up to about 10^{11} cm^{-2} (= 10^9 mm $^{-2}$).

Continued…

- By means of this technique it has been possible to observe dislocation networks (Fig.), stacking faults, dislocation pile-up at grain boundaries, Lomer-Cottrell barriers, and many other structural features of dislocation theory.
- However, this technique is not without disadvantages. Since only a miniscule volume of material is examined with thin films, great care must be exerted to obtain a representative sample. It is possible to alter the defect structure during sectioning and polishing to a thin film, and dislocation structures may relax in a very thin foil.



Dislocation network in cold-worked aluminum (32,500 X).

Continued…

- The greatest defect of transmission electron microscopy is that it is not very effective in detecting long-range stresses, nor does it give very much information about slip line lengths or surface step heights.
- The dislocation structure of a crystal can be detected by x-ray microscopy. The most common techniques are the Berg-Barrett reflection method.

Burgers vector and the dislocation loop

- The Burgers vector b is the vector which defines the magnitude and direction of slip. Therefore, it is the most characteristic feature of a dislocation.
- It has already been shown that for a pure edge dislocation the Burgers vector is perpendicular to the dislocation line, while for a pure screw dislocation the Burgers vector is parallel to the dislocation line.

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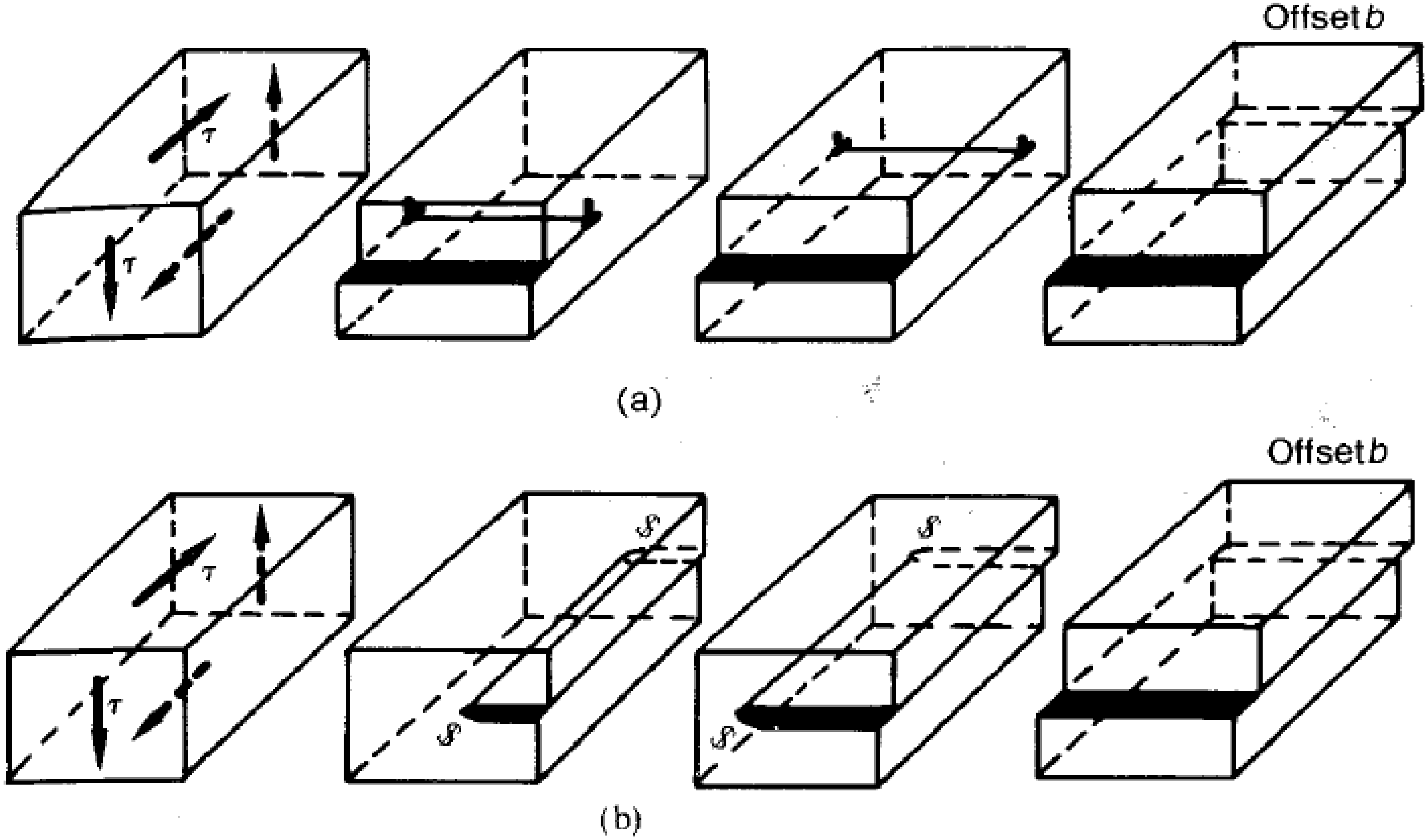
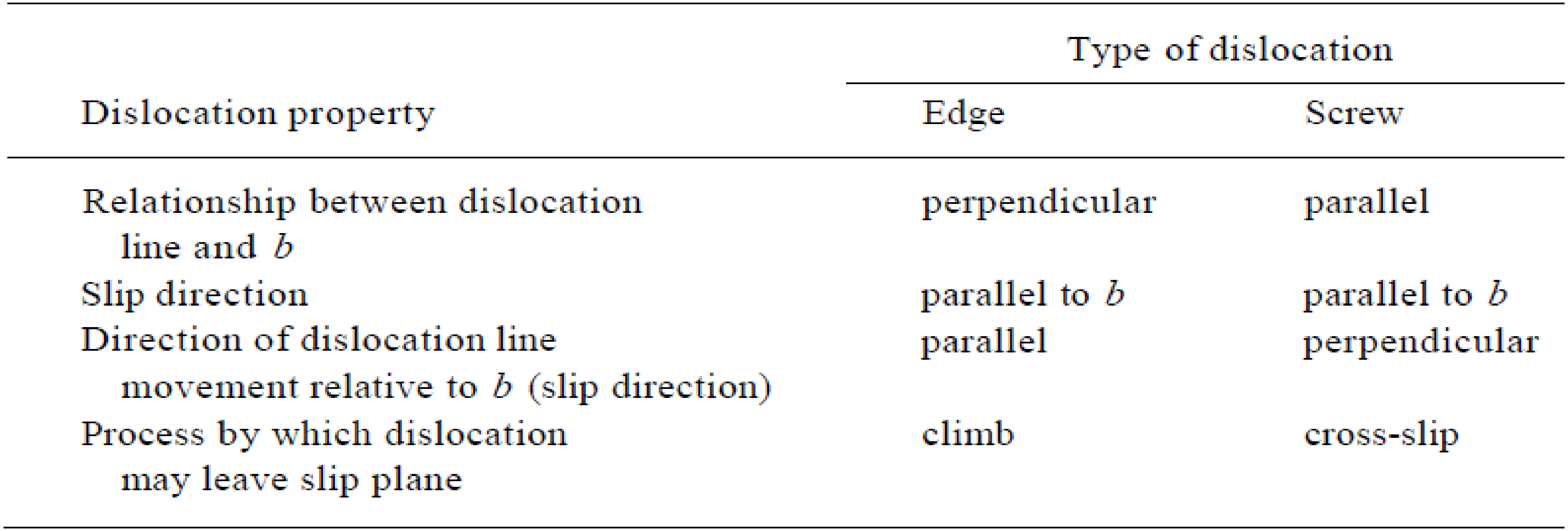


(a) Macroscopic deformation of a cube produced by glide of an edge dislocation. (b) Macroscopic deformation of a cube produced by glide of a screw dislocation. Note that the end result is identical for both situations

Continued…

- The macroscopic slip produced by the motion of an edge dislocation is shown in Fig. a and by a screw dislocation in Fig. b.
- For an edge dislocation the dislocation line moves parallel to the slip direction while the screw dislocation moves at right angles to it.

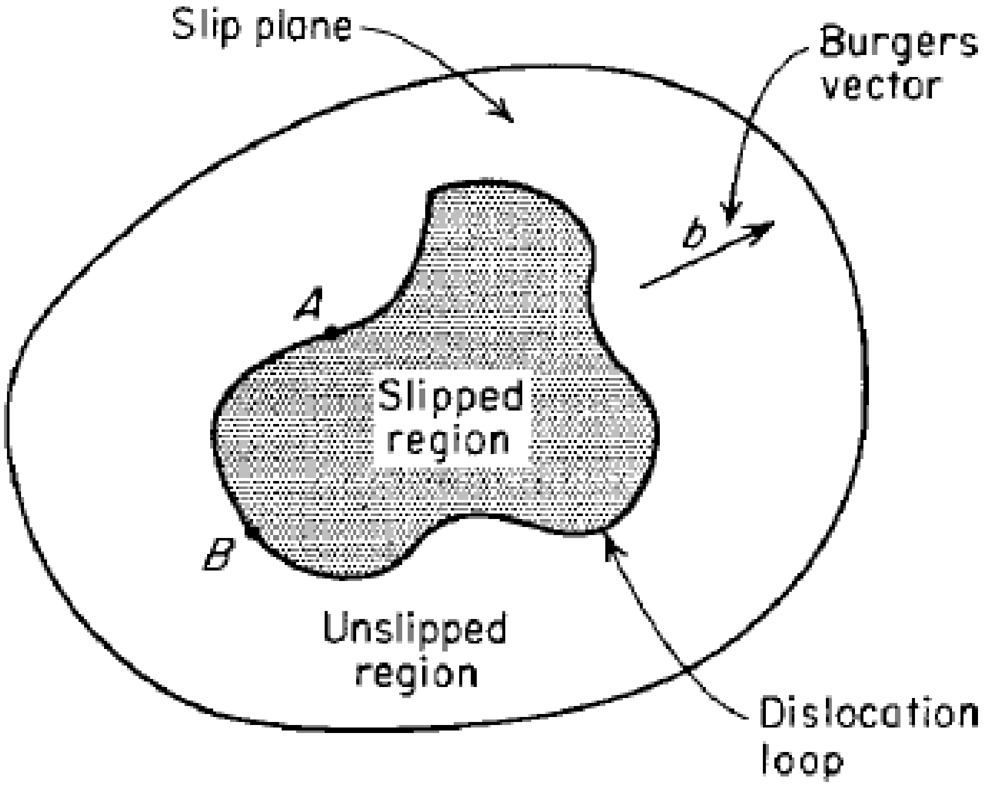


	Type of dislocation	
Dislocation property	Edge	Screw
Relationship between dislocation line and *b*	perpendicular	parallel
Slip direction	parallel to *b*	parallel to *b*
Direction of dislocation line movement relative to *b* (slip direction)	parallel	perpendicular
Process by which dislocation may leave slip plane	climb	cross-slip

LECTURE-20

- Actually, dislocations in real crystals are rarely straight lines and rarely lie in a single plane. In general, a dislocation will be partly edge and partly screw in character.

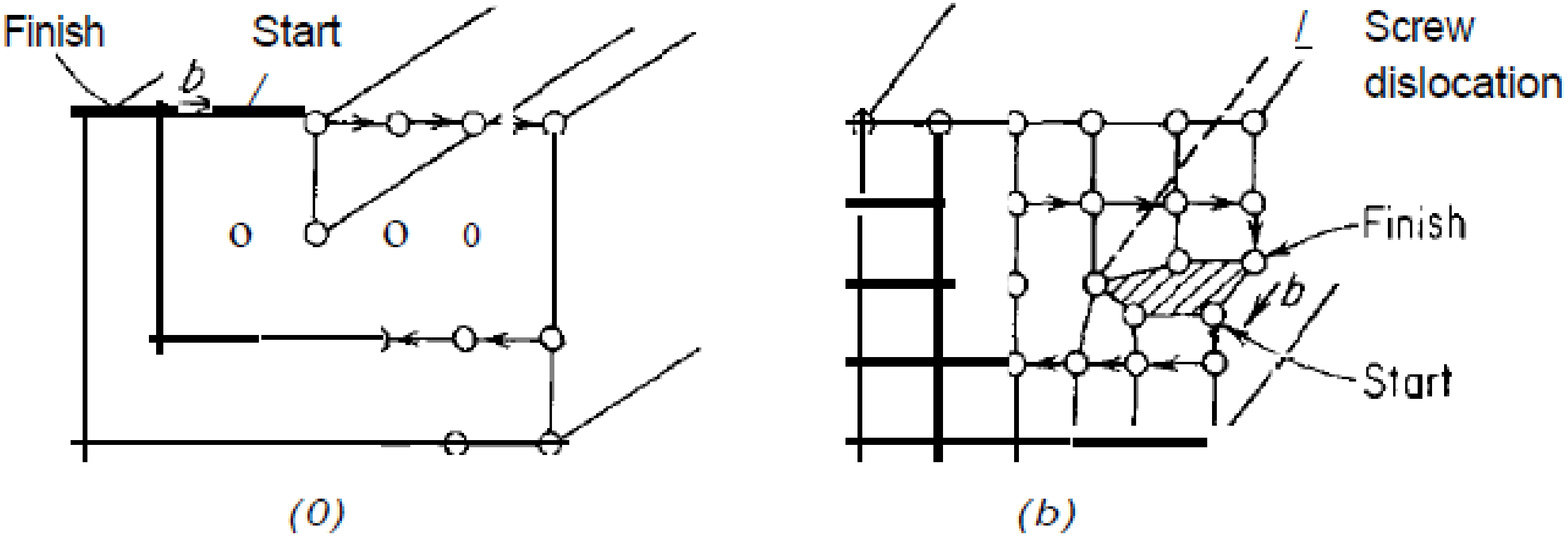
- For example, in ***Figure***, the dislocation loop is pure screw at point A and pure edge at point B, while along most of its length it has mixed edge and screw components. Note, however, that the Burgers vector is the same along the entire dislocation loop.



Dislocation loop lying in a slip plane

Continued…

- A convenient way of defining the ***Burgers vector*** of a ***dislocation is with a Burgers circuit***. Consider the positive edge dislocation shown in Fig. a. If we ***start at a lattice point and imagine a clockwise path traced*** from atom to atom an equal distance in each direction, we find that ***at the finish of the path the circuit does not close***.



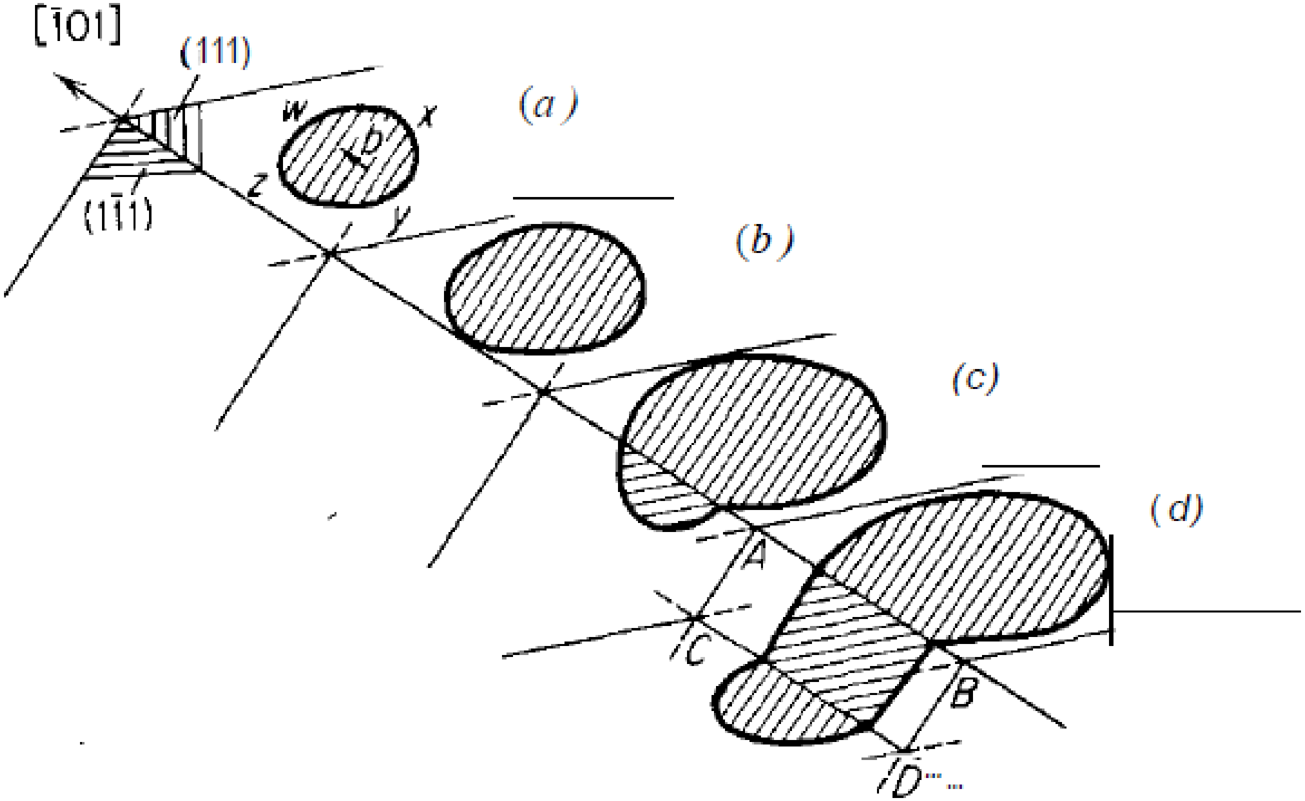
Burgers circuits, (a) Around positive edge dislocation; (b) around a right-handed dislocation

Continued…

- ***The closure failure from finish to start is the Burgers vector b of the dislocation***. (If we had made the Burgers circuit around the dislocation in the anticlockwise direction, the direction of the Burgers vector would have been in the opposite sense.)
- Moreover, if we traverse a ***Burgers circuit about the screw dislocation*** shown in Fig. b, we would find the closure error pointing out of the front face of the crystal. This is a right-handed screw dislocation since in traversing the circuit around the dislocation line; we advance the helix one atomic plane into the crystal.

Continued…

- The process of ***cross slip*** illustrated in below figure, will serve as an example of dislocation loops. In Fig. (a), a small loop of dislocation line with b = $a_0/2[101]$ is moving on a (111) plane in an fcc crystal.



Cross slip in a face-centered cubic crystal

Continued…

- The dislocation loop is pure positive edge at w and pure negative edge at y. At x the dislocation is a right-handed screw while at z the dislocation loop is a pure left-handed screw dislocation. At some stage (Fig. b), the shear stress causing expansion of the loop tends to move the dislocation on the intersecting (111) plane.
- Since the dislocation is pure screw at z, it is free to move on this plane. In Fig. (c) the loop has expanded on the second plane, while in Fig. (d) ***double cross slip*** has taken place as the loop glides back onto the original (111) plane.

Continued…

- Note that during the glide of the dislocation on the cross-slip plane only the screw component of the loop has moved. Because a dislocation ***represents the boundary between the slipped and unslipped region of a crystal***, topographic considerations require that it either must be a closed loop or else must end at the free surface of a crystal or at a grain boundary.
- In general, a ***dislocation line cannot end inside of a crystal***. The ***exception is at a node***, where ***three or four dislocation lines meet.*** At a node two dislocations with Burgers vectors b_1 and b_2 combine to produce a resultant dislocation b_3. ***The vector b_3 is given by the vector sum of b_l and b_2***.
- A dislocation with a Burgers vector equal to one lattice spacing is said to be a dislocation of unit strength. Because of energy considerations dislocations with strengths larger than unity are generally unstable and dissociate into two or more dislocations of lower strength.

Continued…

- The criterion for deciding whether or not dissociation will occur is base on the fact that the strain energy of a dislocation is proportional to the square of its Burgers vector.
- Therefore, the dissociation reaction $\boldsymbol{b_1} \rightarrow \boldsymbol{b_2} + \boldsymbol{b_3}$ will occur when $\boldsymbol{b_1} > \boldsymbol{b}_2^2 + \boldsymbol{b}_3^2$, but not if $\boldsymbol{b_1} < \boldsymbol{b}_2^2 + \boldsymbol{b}_3^2$
- In adding Burgers vectors, each of the corresponding components is added separately. Thus $b_1 + b_2$ = **a_0[110] + a_0[211] = a_0[321].** In adding or subtracting components common unit vectors must be used. Thus a_0/3[112] + a_0/6[11-1] must be expressed as a_0/6[224] + a0/6[11-1]] = a_0/6[333] = a_0/2[111].
- **Example :** Determine whether the dislocation dissociation reaction is feasible.

$$b_1 = b_2 + b_3$$

$$\frac{a}{2}[0\bar{1}1] = \frac{a}{6}[1\bar{2}1] + \frac{a}{6}[\bar{1}\bar{1}2]$$

Continued…

- Since this is a vector equation the x, y, and z components of the right-hand side of the equation must equal the x, y, and z components of the left side (original dislocation).

x components: $0 = \frac{1}{6} - \frac{1}{6}$

y components: $-\frac{1}{2} = -\frac{2}{6} - \frac{1}{6} = -\frac{1}{2}$

z components: $\frac{1}{2} = \frac{1}{6} + \frac{2}{6} = \frac{1}{2}$

For the dissociation to be energetically favorable $b_1^2 > b_2^2 + b_3^2$

$$b_1 = \frac{a}{2}[0 + (\_1)2 + (1)2r/2 = \frac{\sqrt{2}\,a}{2} \qquad b_1^2 = \frac{a^2}{2}$$

$$b_2 = \frac{a}{6}[(1)2 + (\_2)2 + (1)^2]^{1/2} = \frac{\sqrt{6}\,a}{6} \qquad b_2^2 = \frac{a^2}{6}$$

$$b_3 = \frac{a}{6}[(\_1)2 + (\_1)2 + (2)2r/2 = \frac{\sqrt{6}\,a}{6} \qquad b_3^2 = \frac{a^2}{6}$$

$\therefore$ $b_1^2 > b_2^2 + b_3^2$ and the dislocation reaction is feasible.

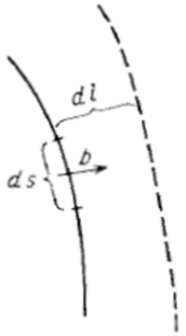
Continued…

- A dislocation of unit strength, or unit dislocation, has a minimum energy when its Burgers vector is parallel to a direction of closest atomic packing in the lattice. This agrees with the experimental observation that crystals always slip in the close-packed directions.
- A unit dislocation of this type is also said to be a ***perfect dislocation*** because translation equal to one Burgers vector produces an identity translation.
- A unit dislocation parallel to the slip direction cannot dissociate further unless it becomes an ***imperfect dislocation***, where a translation of one Burgers vector does not result in an identity translation

LECTURE-21

FORCES ON DISLOCATIONS

- When an external force of sufficient magnitude is applied to a crystal, the dislocations move and produce slip. Thus, there is force acting on a dislocation line which tends to drive it forward.
- Figure shows a dislocation line moving in the direction of its Burgers vector under the influence of a uniform shear stress τ. An element of the dislocation line ds is displaced in the direction of slip normal to ds by an amount dl. The area swept out by the line element is then ds dl.



Force acting on a dislocation line

Continued…

- This corresponds to an **average displacement of the crystal above the slip plane to the crystal below the slip plane of an amount (dsdl/A) b**, where A is the area of the slip plane. The **applied force creating the shear stress is τA**. The work done when the increment of slip occurs is

$$dW = \tau A\left(\frac{dsdl}{A}\right)b = \tau b(dl\ ds)$$

- The force on a dislocation is always defined as a force F per unit length of dislocation line. Since F = dW/dl and remembering that this is a force per unit length (ds), we have

$$F = \frac{dW}{dl\ ds} = \tau b$$

Continued…

FORCES BETWEEN DISLOCATIONS

- Dislocations of opposite sign on the same slip plane will attract each other, run together, and annihilate each other.
- This can be seen readily for the case of an edge dislocation (Fig. 4-8) where the superposition of a positive and negative dislocation on the same slip plane would eliminate the extra plane of atoms and therefore the dislocation would disappear.
- Conversely, dislocations of like sign on the same slip plane will repel each other.
- We can understand this by considering the energy changes. For two dislocations separated at a large distance, the elastic strain energy for the combined situations will be

$$2 \cdot \frac{Gb^2}{4\pi(1-\nu)} \ln \frac{r_1}{r_0}$$

Continued…

- When the two dislocations are very close together the configuration can be approximated by a single dislocation of strength 2b. For this case, the elastic strain energy will be

$$\frac{G(2b)^2}{4\pi(1-\nu)}\ln\left(\frac{r_1}{r_0}\right)$$

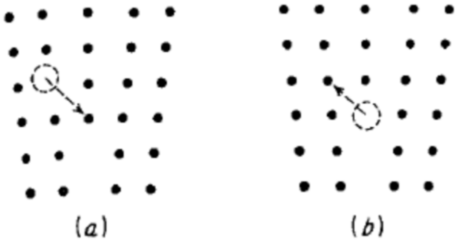
DISLOCATION CLIMB

- An edge dislocation can glide only in the slip plane containing the dislocation line and its Burgers vector. However, under certain conditions an edge dislocation can move out of the slip plane onto a parallel plane directly above or below the slip plane. This is the process of dislocation climb.
- This type of movement is termed nonconservative, as compared with conservative movement when a dislocation glides in its slip plane.

Continued…

- Dislocation climb occurs by the diffusion of vacancies or interstitials to or away from the site of the dislocation. Since climb is diffusion-controlled, it is thermally activated and occurs more readily at elevated temperature. In ***positive climb*** atoms are removed from the extra half plane of atoms at a positive edge dislocation so that this extra half plane moves up one atom spacing.

- In negative climb a row of atoms is added below the extra half plane so that the dislocation line moves down one atom spacing.



(a) Diffusion of vacancy to edge dislocation;
(b) dislocation climbs up one lattice spacing.

Continued…

Dislocation Interactions

- Dislocation-dislocation interactions usually develops dislocation barriers that later on obstruct the easy slide to cause strain hardening.

INTERSECTION OF DISLOCATIONS

The intersection of two dislocations produces a sharp break, a few atom spacings in length, in the dislocation line. These breaks can be of two types.

a. A ***jog*** is a sharp break in the dislocation moving it out of the slip plane.

b. A ***kink*** is a sharp break in the dislocation line which remains in the slip plane.

Continued…

Dislocation Interactions

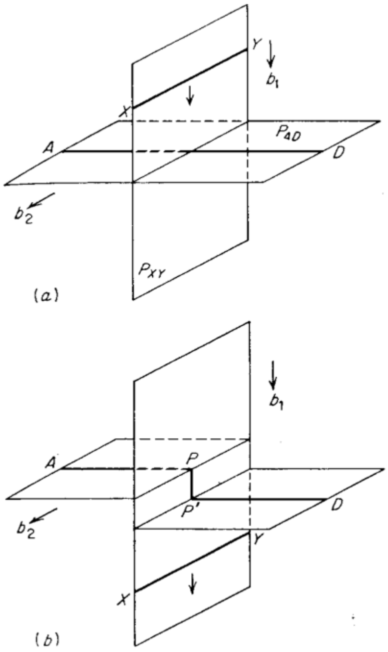


Figure 5-19 Intersection of two edge dislocations. *(From W. T. Read, Jr., "Dislocations in Crystals," McGraw-Hill Book Company, New York, 1953.)*

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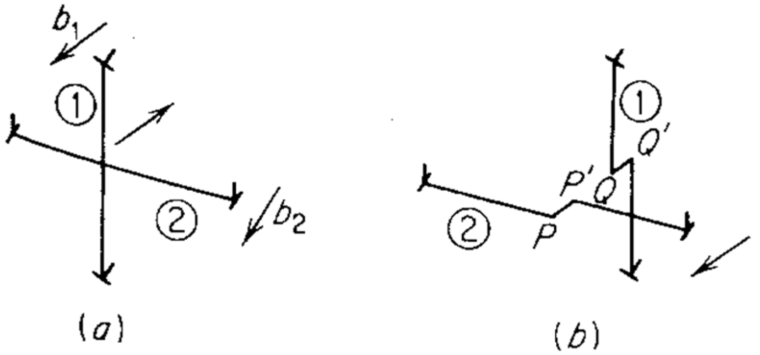

Figure 5-20 Intersection of edge dislocations with parallel Burgers vectors. (*a*) Before intersection; (*b*) after intersection.

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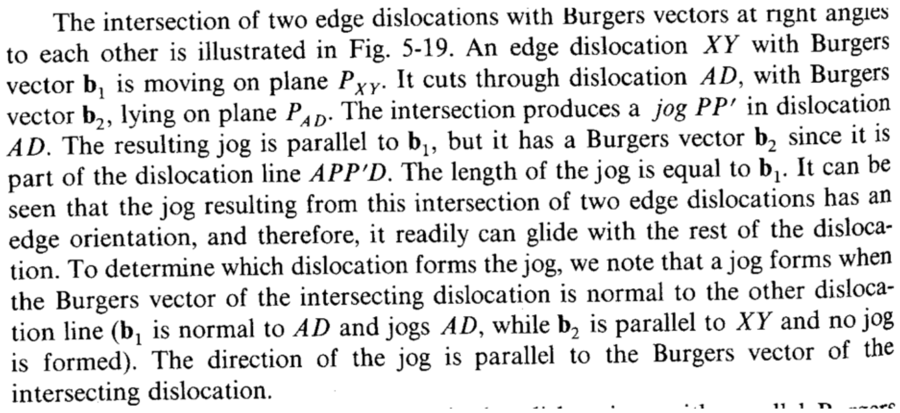

The intersection of two edge dislocations with Burgers vectors at right angles to each other is illustrated in Fig. 5-19. An edge dislocation XY with Burgers vector $\mathbf{b}_1$ is moving on plane P_{XY}. It cuts through dislocation AD, with Burgers vector $\mathbf{b}_2$, lying on plane P_{AD}. The intersection produces a *jog* PP' in dislocation AD. The resulting jog is parallel to $\mathbf{b}_1$, but it has a Burgers vector $\mathbf{b}_2$ since it is part of the dislocation line $APP'D$. The length of the jog is equal to $\mathbf{b}_1$. It can be seen that the jog resulting from this intersection of two edge dislocations has an edge orientation, and therefore, it readily can glide with the rest of the dislocation. To determine which dislocation forms the jog, we note that a jog forms when the Burgers vector of the intersecting dislocation is normal to the other dislocation line ($\mathbf{b}_1$ is normal to AD and jogs AD, while $\mathbf{b}_2$ is parallel to XY and no jog is formed). The direction of the jog is parallel to the Burgers vector of the intersecting dislocation.

[Re-Deiter G.E., Mechanical Metallurgy]

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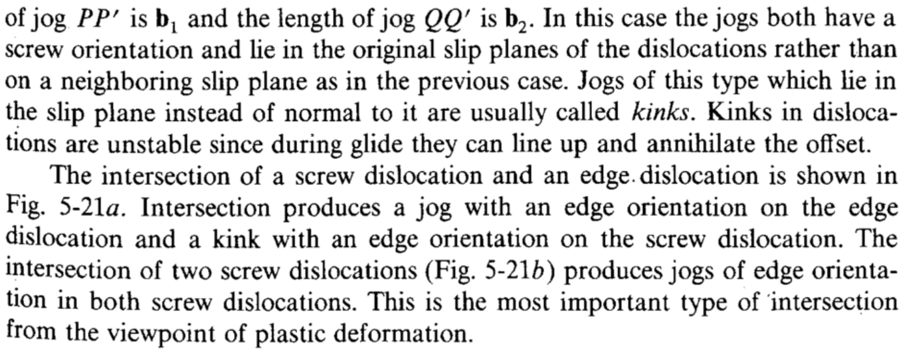

of jog PP' is $\mathbf{b}_1$ and the length of jog QQ' is $\mathbf{b}_2$. In this case the jogs both have a screw orientation and lie in the original slip planes of the dislocations rather than on a neighboring slip plane as in the previous case. Jogs of this type which lie in the slip plane instead of normal to it are usually called *kinks*. Kinks in dislocations are unstable since during glide they can line up and annihilate the offset.

The intersection of a screw dislocation and an edge dislocation is shown in Fig. 5-21*a*. Intersection produces a jog with an edge orientation on the edge dislocation and a kink with an edge orientation on the screw dislocation. The intersection of two screw dislocations (Fig. 5-21*b*) produces jogs of edge orientation in both screw dislocations. This is the most important type of intersection from the viewpoint of plastic deformation.

[Re-Deiter G.E., Mechanical Metallurgy]

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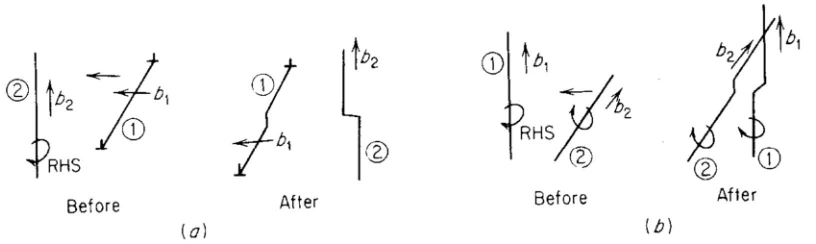


Figure 5-21 (*a*) Intersection of edge and screw dislocation; (*b*) intersection of two screw dislocations.

LECTURE-22

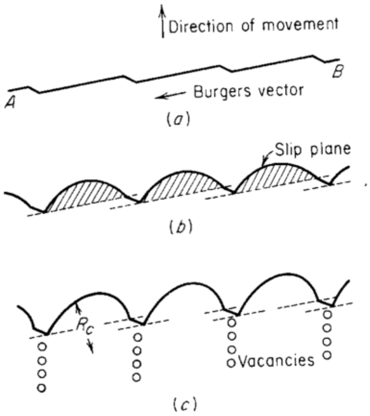


Figure 5-24 Movement of jogged screw dislocation. (*a*) Straight dislocation under zero stress; (*b*) dislocation bowed out in slip plane between the jogs due to applied shear stress; (*c*) movement of dislocation leaving trails of vacancies behind the jogs. *(From D. Hull, "Introduction to Dislocations," p. 136, Pergamon Press, New York, 1965. By permission of the publishers.)*

- ❑ Under the action of shear stress along the slip direction, jog will act as the pinning points.
- ❑ Dislocation will bow out in the form of semi-circle between the jogs.
- ❑ After critical radius, the applied stress cause the non-conservative climb by means of leaving a trail of vacancies behind each jog.

Continued…

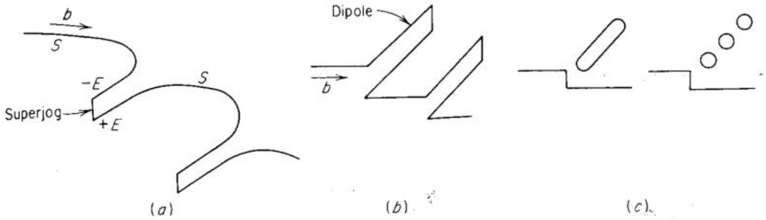
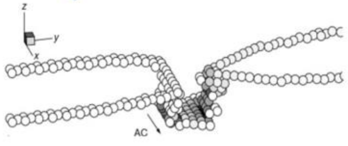


Figure 5-25 (*a*) Bowing out of dislocation between superjogs to produce (*b*) dislocation dipoles; (*c*) formation of dislocation loops from dipole.

- ❑ **Superjog**: A superjog (stable structure) is created when the stress fields of two dislocations moving towards each other combine to form a larger stress field. This increases the energy of the configuration, causing the dislocations to repel each other.
- ❑ The super jogs are created by local fluctuations in the stresses in the dislocation core.



Ref: Basic Aspects of Radiation Effects in Solids/Basic Aspects of Multi-Scale Modeling Y.N. Osetsky, D.J. Bacon, in Comprehensive Nuclear Materials, 2012

Continued…

MULTIPLICATION OF DISLOCATIONS

- One of the original stumbling blocks (circumstances that cause difficulty) in the development of dislocation theory was the **formulation of a reasonable mechanism by which sources originally present in the metal could produce new dislocations by the process of slip**.
- Such a mechanism is **required when it is realized that the surface displacement at a slip band** is due to the movement at about 1000 dislocations over the slip plane.
- Thus the number of dislocation sources initially present in a metal could not account for the observed slip-band spacing and displacement unless there were some way in which **each dislocation source could produce large amounts of slip before it became immobilized**.

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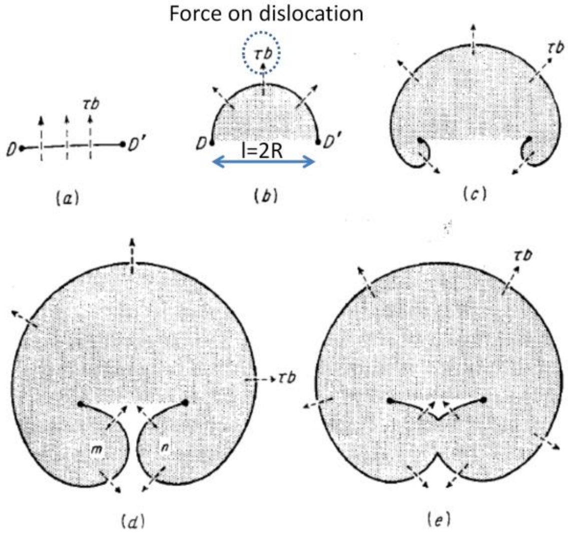


Schematic representation of the operation of a Frank-Read source.

Continued…

- **Method of generating dislocations or of multiplying the number initially present to produce the high dislocation density** found in cold-worked metal.

- The scheme by which **dislocations could be generated from existing dislocations was proposed by Frank and Rea**d and is commonly called a ***Frank-Read source.***

- Consider a dislocation line DD' lying in a slip plane (Fig. (a)). The dislocation line leaves the slip plane at points D and D', so it is immobilized at these points. This could occur if D and D' were nodes where the dislocation in the plane of the paper intersects dislocations in other slip planes, or the anchoring could be caused by impurity atoms

Continued…

- The maximum value of shear stress is required **when the dislocation bulge (unusual increase in size) becomes a semicircle** so that **R has the minimum value l/2** (Fig. (b)). The stress required to produce this configuration is

$$\tau = \frac{Gb}{2R} = \frac{Gb}{l} \qquad (since\ 2R = l \Rightarrow R = l/2)$$

- **Beyond this point R will increase and the dislocation loop will continue to expand under a decreasing stress** (Fig. (c)). When the loop reaches Fig. (d), the segments at m and n will meet and annihilate each other to form a large loop and a new dislocation (Fig. (e)).

Continued…

- The stage shown in Fig. (d) can best be understood if we assume that the original **pinned length DD' has a screw orientation**. Then **segments m and n are in edge orientation but of opposite sign**, so that annihilation will occur. Once the loop moves into the stage shown in Fig. (c), the loop can continue to expand under increased shear stress and the pinned segment DD' is in a position to repeat the process.
- This process can be repeated over and over again at a single source, each time producing a dislocation loop which produces slip of one Burgers vector along the slip plane.
- However, **once the source is initiated it does not continue indefinitely**. The **back stress produced by the dislocations piling up along the slip plane opposes the applied stress** and when this equals the critical stress **the source ceases to operate**.

LECTURE-23

STRENGTHENING MECHANISMS

Different types of strengthening mechanisms

I. Fine grain size is often desired for high strength

II. Large additions of solute atoms are added to increase strength

III. Bring about new phase relationships

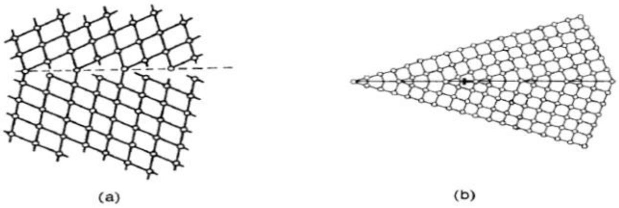
IV. Fine-particles may be added to increase strength

V. Phase transformations may be utilized to increase strength

Continued…

GRAIN BOUNDARIES AND DEFORMATION

- **Misorientation across GB:** The crystallographic **orientation changes abruptly in passing from one grain to the next** across the grain boundary (GB).
- The ordinary high-angle grain boundary represents a region of random misfit between the adjoining crystal lattices. As the **difference in orientation between the grains on each side of the boundary decreases, the state of order in the boundary increases**.



(a) Schematic atomic model of a GB; (b) dislocation model of a GB

Continued…

- Figure (a) schematically illustrates the structure at a **high-angle GB (misorientation angle more than 15 degrees)**. Note the unorganized structure, with a **few atoms belonging to both grains, while most belong to neither. Those atoms that belong to both grains are called coincidence sites.**

- This **GB structure contains GB dislocations** (Fig. b). These **are not mobile dislocations** producing extensive slip; rather, their chief role is that they group together within the boundary to **form a step or GB ledge**.

- **High-angle grain boundaries are boundaries with high surface energy**. For example, a grain boundary in copper has an interfacial surface energy of about, 600 mJ m^{-2}, while the energy of a twin boundary is only about 25mJ m^{-2}.

- **Concept of Operative Slip System with Ductility:** Von Mises showed that **“For a crystal to undergo a general change of shape by slip requires the operation of five independent slip systems**.”

- Crystals which do not possess five independent slip systems are never ductile in polycrystalline form, although small plastic elongation may be obtained if there is twinning or a favorable preferred orientation.

  - **At room temperature**, HCP and other low-symmetry metals do not satisfy this requirement of five independent slip systems and have low ductility at room temperature in polycrystalline form.

  - **At some elevated temperature,** polycrystalline Zn and Mg become ductile at which non basal slip can become operative and increase the number of slip systems to at least five.

- Cubic metals easily satisfy this requirement, which accounts for their general high ductility.

Continued…

- **GB Sliding and Equicohesive Temperature:** At temperatures above about one-half of the melting point, deformation can occur by sliding along grain boundaries well-known as **GB sliding**.

- **GB sliding becomes more prominent with increased temperature and decreasing strain rate**.

- **Equicohesive Temperature:** Temperature at which strength at GB is equal with strength of interior of crystal.

  - **Above this temp**, GB region is weaker than the grain interior and strength increases with increasing grain size.
  - **Below this temp**, GB region is stronger than the grain interior and strength increases with decreasing grain size (increasing grain-boundary area).

Continued…

- The strengthening mechanisms discussed in this chapter are operative at temperatures below 0.5T_m, which impede the conservative motion of dislocations.

STRENGTHENING FROM GRAIN BOUNDARIES

- **Evidence on GB Strengthening:** Experiments on bicrystals (type of crystal structure that consists of two adjoining crystals with different orientations and symmetries) is found with systematic variation in the orientation difference between a longitudinal GB. That cause linear increase in the yield stress with the increase in misorientation across the GB.

- This imply that the strengthening due to GBs results from mutual interference to slip within the grains.

Continued…

- The resolved shear stress in a single crystal was given by

$$\tau = \sigma\, sin\chi\, cos\boldsymbol{\lambda} = \frac{\sigma}{M}$$

Where M is an orientation factor (the reciprocal of the Schmid factor). For a polycrystal the orientation factor M varies from grain to grain. The best estimate for an FCC lattice is M = 3.1, obtained by G. I. Taylor.

- Two important relations used find out the strain-hardening rate

$$\sigma = \bar{M}\tau \;\&\; \varepsilon = \frac{\gamma}{\bar{M}}$$

$$=> \frac{d\sigma}{d\varepsilon} = \bar{M}^2 \frac{d\tau}{d\gamma}$$

LECTURE-24

HALL-PETCH (H-P) RELATION

- A general relationship between yield stress (and other mechanical properties) and grain size was proposed by Hall and greatly extended by Petch

$$\sigma_0 = \sigma_i + kD^{-1/2}$$

Where, σ_0 = the yield stress

σ_i= the "friction stress," representing the overall resistance of the crystal lattice to dislocation movement

K=the "locking parameter," which measures the relative hardening contribution of the grain boundaries

D = grain diameter

- The Hall-Petch equation was originally **based on yield-point measurements in low-carbon steel**.

Continued…

- **Overall Dependence Grain Size on Yield Strength :** It has been found to express the grain-size dependence of the low stress at **any plastic strain out to ductile fracture** and also to express the variation of **brittle fracture stress** with grain size and the dependence of fatigue strength on grain size.

- The **original dislocation model for the H-P equation** was based on the concept that **GBs act as barriers to dislocation motion**.

- However, H-P equation is **also applied on other kinds of boundaries such as ferrite-Cementite in pearlite, mechanical twins, and martensite plates.**

Continued…

- Consider a dislocation source at the center of a grain D which sends out dislocations to pile-up at the GB. The stress at the tip of this pile-up must exceed some critical shear stress τ_c to continue slip past the GB barrier. we have

$$\tau_c = n\tau_s = \frac{\pi\tau_s^2 D}{4Gb}$$

No. of dislocations in pile-up

Resolved shear stress required to overcome the barrier

- τ_s can be taken equal to the applied stress less the friction stress to overcome lattice resistance to dislocation motion τ_i,

$$\tau_s = \tau - \tau_i$$

Continued…

- Therefore,

$$\tau_c = \frac{\pi(\tau - \tau_i)^2 D}{4Gb}$$

$$(\tau - \tau_i)^2 = \frac{\tau_c 4Gb}{\pi D}$$

$$\Rightarrow \tau - \tau_i = \left(\frac{\tau_c 4Gb}{\pi D}\right)^{1/2}$$

$$\Rightarrow \tau = \tau_i + \left(\frac{\tau_c 4Gb}{\pi D}\right)^{1/2}$$

$$\tau = \tau_i + \left(\frac{\tau_c 4Gb}{\pi D}\right)^{1/2} = \tau_i + k'D^{-1/2}$$

- Expressing above equation in terms of normal stresses, gives

$$\sigma_0 = \sigma_i + kD^{-1/2}$$

[Comparing above equation with equation of straight line, for σ_0 is plotted against $D^{-1/2}$, **the factor k is the slope (m) of the straight line and σ_i is the intercept**.]

- It is interpreted as the friction stress (σ_i) needed to move unlocked dislocations along the slip plane and it depends strongly on temperature, strain, and alloy (impurity) content.

Continued…

- ☐ While the H-P equation is a very general relationship, it must be used with some caution.

⬇

[For example, if $\sigma_0 = \sigma_i + kD^{-1/2}$ were extrapolated to the smallest grain size approximately 4 nm, it would predict strength levels close to the theoretical shear strength. Such an extrapolation is in error because the H-P equation was derived for large pile-ups containing more than 50 dislocations. For small pile-ups other equations must be considered.]

- ☐ A more general model proposed by Li to avoid the description of the stresses at GBs and instead concentrates on the influence of grain size on the dislocation density, and hence, on the yield or low stress. The flow stress is given in terms of dislocation density (ρ) by

$$\sigma_0 = \sigma_i + \underset{\downarrow}{\alpha} G b \rho^{1/2}$$

α is a numerical constant generally between 0.3 and 0.6

Continued…

- ☐ The tie-in with grain size is based on the experimental observation that ρ is an inverse function of the grain size ($\rho = 1/D$), the previous relation becomes

$$\sigma_0 = \sigma_i + \alpha G b D^{-1/2} = \sigma_i + k' D^{-1/2}$$

Continued…

LOW-ANGLE GRAIN BOUNDARIES (Misorientation angle less than 15 degrees):

☐ Perhaps the most general method of

a. **Producing a substructure network is by introducing a small amount of deformation** (about 1-10 % pre-strain).

b. **Following this with an annealing treatment to rearrange the dislocations into sub grain boundaries**.

☐ The amount of deformation and temperature must be low enough to prevent the formation of new grains by recrystallization. This process has been called recrystallization in situ, or ***polygonization.***

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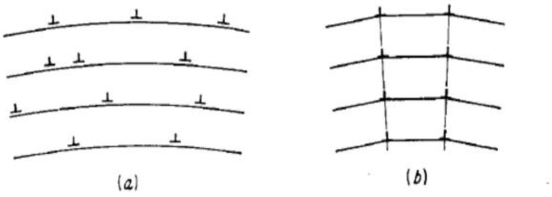

Fig: Movement of dislocations to produce polygonization

- Polygonization was used to describe the situation that occurs when a single crystal is bent to a relatively small radius of curvature and then annealed.

a) Bending results in the introduction of an excess number of dislocations of one sign. These dislocations are distributed along the bent-glide planes.

b) When the crystal is heated, the dislocations group themselves into the lower-energy configuration of a low-angle boundary by dislocation climb. The resulting structure is a polygon like network of low-angle GBs.

Continued…

Example: The effect of a substructure of low-angle GBs on the stress-strain curve of 1020 steel is shown in Figure.

Note:

- Cold-reduced and annealed of material produce a substructure, has a higher yield point and tensile strength than both the annealed material and the material which as only cold-reduced.
- Moreover, the ductility of the material containing a substructure is almost as good as the ductility of the annealed steel.

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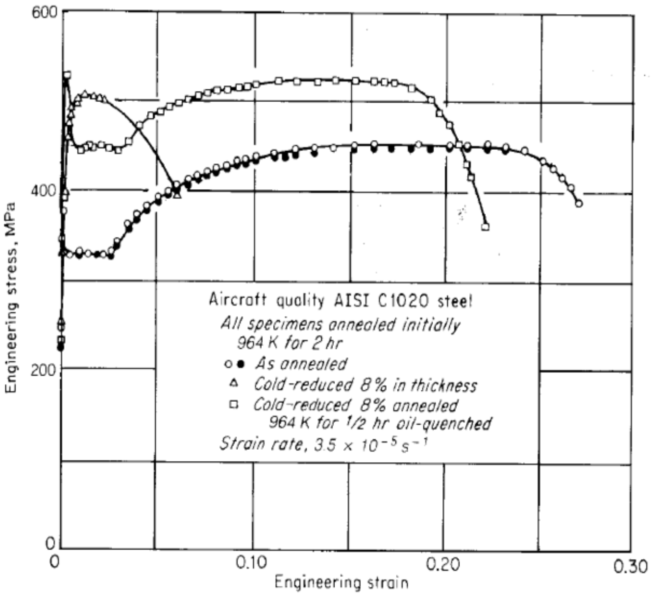
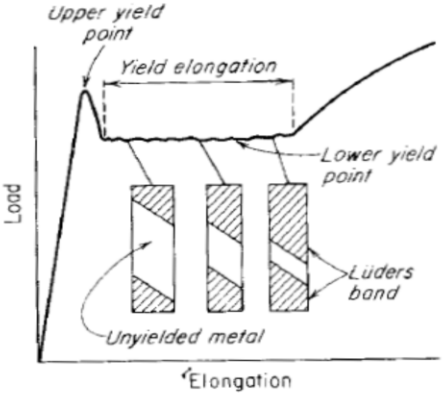

Engineering stress, MPa
600
400
200
0
0
0.10
0.20
0.30
Engineering strain
Aircraft quality AISI C1020 steel
All specimens annealed initially
964 K for 2 hr
○● As annealed
△ Cold-reduced 8% in thickness
□ Cold-reduced 8% annealed
964 K for 1/2 hr oil-quenched
Strain rate, 3.5 × 10⁻⁵ s⁻¹

LECTURE-25

YIELD-POINT PHENOMENON

- Many metals, particularly low-carbon steel, show a localized, heterogeneous type of transition from elastic to plastic deformation which produces a yield point in the stress-strain curve.



Typical yield point behavior

- Rather than having a flow curve with a gradual transition from elastic to plastic behavior. Metals with a yield point have a low curve or, what is equivalent, a load-elongation diagram similar to above Fig.

Continued…

- The load increases steadily with elastic strain, drops suddenly, fluctuates about some approximately constant value of load, and then rises with further strain. The load at which the sudden drop occurs is called the ***upper yield Point***. The constant load is called the ***lower yield point***, and the elongation which occurs at constant load is called the yield-point elongation.
- The deformation occurring throughout the yield-point elongation is heterogeneous. At the upper yield point a discrete band of deformed metal, often readily visible with the eye, appears at a stress concentration such as a fillet, and coincident with the formation of the band the load drops to the lower yield point. The band then propagates along the length of the specimen, causing the yield-point elongation.

Continued…

- In the usual case several bands will form at several points of stress concentration. These bands are generally at approximately 45° to the tensile axis. They are usually called ***Luders bands, Hartmann lines, or stretcher strains***, and this type of deformation is sometimes referred to as the ***Piobert efect***.
- The yield-point phenomenon was found originally in low-carbon steel. A pronounced upper and lower yield point and a yield-point elongation of over 10 percent can be obtained with this material under proper conditions.
- More recently the yield point has come to be accepted as a general phenomenon, since it has been observed in a number of other metals and alloys. In addition to iron and steel, yield points have been observed in polycrystalline molybdenum, titanium, and aluminum alloys and in single crystals of iron, cadmium, zinc, alpha and beta brass, and aluminum.

Continued…

- Usually the yield point can be associated with small amounts of interstitial or substitutional impurities. For example, it has been shown that almost complete removal of carbon and nitrogen from low carbon steel by wet-hydrogen treatment will remove the yield point. However, only about 0.001 percent of either of these elements is required for a reappearance of the yield point.
- A number of experimental factors affect the attainment of a sharp upper yield point. A sharp upper yield point is promoted by the use of an elastically rigid (hard) testing machine, very careful axial alignment of the specimen, the use of specimens free from stress concentrations, high rate of loading, and, frequently, testing at sub-ambient temperatures.

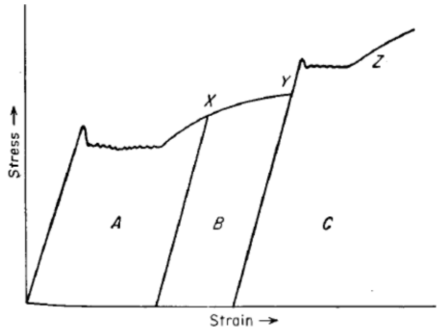
Continued…

- If the stress to operate the sources is high, then the initial yield stress is high. The explanation of the yield-point phenomenon in terms of dislocation behavior arose originally from the idea that the dislocation sources were locked or pinned by solute atom interactions.
- The explanation of this behavior was one of the early triumphs of dislocation theory. Carbon or nitrogen atoms in iron readily diffuse to the position of minimum energy just below the extra plane of atoms in a positive edge dislocation. The elastic interaction is so strong that the impurity atmosphere becomes completely saturated and condenses into a row of atoms along the core of the dislocation.

Continued…

- Pinning can arise from the solute-dislocation inter- action or by precipitation of fine carbides or nitrides along the dislocation. The yield point occurs as a result of unlocking the dislocations by a high stress, or for case of strong pinning, by creating new dislocations at the points of stress concentration.

STRAIN AGING



Stress-strain curves for low-carbon steel showing strain aging. Region A, original material strained through yield point. Region B, immediately retested after reaching point X. Region C, reappearance and increase in yield point after aging at 400 K (≈ 130 ^{0} C)

Continued…

- Strain aging is a type of behavior, usually associated with the yield-point phenomenon, in which the strength of a metal is increased and the ductility is decreased on heating at a relatively low temperature after cold-working. This behavior can best be illustrated by considering Fig., which schematically describes the effect of strain aging on the low curve of a low-carbon steel.
- Region A of Fig. shows the stress-strain curve for a low-carbon steel strained plastically through the yield-point elongation to a strain corresponding to point X.
- The specimen is then unloaded and retested without appreciable delay or any heat treatment (region B). Note that on reloading the yield point does not occur, since the dislocations have been torn away from the atmosphere of carbon and nitrogen atoms.

Continued…

- Consider now that the specimen is strained to point Y and unloaded. If it is reloaded after aging for several days at room temperature or several hours at an aging temperature like 400 K, the yield point will reappear.
- Moreover, the yield point will be increased by the aging treatment from Y to Z. The reappearance of the yield point is due to the diffusion of carbon and nitrogen atoms to the dislocations during the aging period to form new atmospheres of interstitials anchoring the dislocations.
- Support for this mechanism is found in the fact that the activation energy for the return of the yield point on aging is in good agreement with the activation energy for the diffusion of carbon in alpha iron.

Continued…

- Nitrogen plays a more important role in the strain aging of iron than carbon because it has a higher solubility and diffusion coefficient and produces less complete precipitation during slow cooling. From a practical standpoint it is important to eliminate strain aging in deep-drawing steel because the reappearance of the yield point can lead to difficulties with surface markings or "stretcher strains" due to the localized heterogeneous deformation.
- To control strain aging, it is usually desirable to lower the amount of carbon and nitrogen in solution by adding elements which will take part of the interstitials out of solution by forming stable carbides or nitrides. Aluminum, vanadium, titanium, columbium, and boron have been added for this purpose.

Continued…

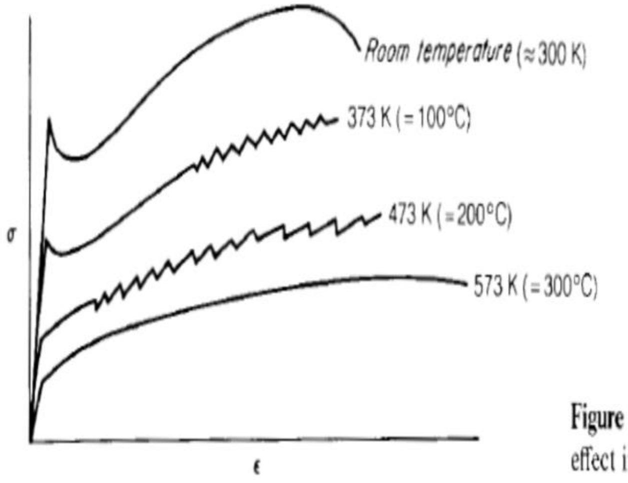


Figure 6-10 Portevin-LeChatelier effect in iron (schematic).

Continued…

- The occurrence of strain aging is a fairly general phenomenon in metals. In addition to the return of the yield point and an increase in the yield stress after aging, strain aging also produces a decrease in ductility and a low value of strain-rate sensitivity Strain aging also is associated with the occurrence of serrations in the stress-strain curve (discontinuous or repeated yielding). This dynamic strain-aging behavior (above Fig.) is called the ***Portevin-LeChatelier effect.***
- The solute atoms are able to diffuse in the specimen at a rate faster than the speed of the dislocations so as to catch and lock them. Therefore, the load must increase and when the dislocations are torn away from the solute atoms there is a load drop. This process occurs many times, causing the serrations in the stress-strain curve.
- .

Continued…

- For plain carbon steel discontinuous yielding occurs in the temperature region of 500 to 650 K. This temperature region is known as the blue brittle region because steel heated in this temperature region shows a decreased tensile ductility and decreased notched-impact resistance. This temperature range is also the region in which steels show a minimum in strain-rate sensitivity and a maximum in the rate of strain aging.
- The phenomenon of strain aging should be distinguished from a process known as quench aging, which occurs in low-carbon steels. Quench aging is a type of true precipitation hardening that occurs on quenching from the temperature of maximum solubility of carbon and nitrogen in ferrite. Subsequent aging at room temperature, or somewhat above, produces an increase in hardness and yield stress, as in the age hardening of aluminum alloys. Plastic deformation is not necessary to produce quench aging.

LECTURE-26

SOLID-SOLUTION STRENGTHENING

- The **introduction of solute atoms into solid solution** in the solvent-atom lattice invariably **produces an alloy which is stronger than the pure metal**.
- There are two types of solid solutions.

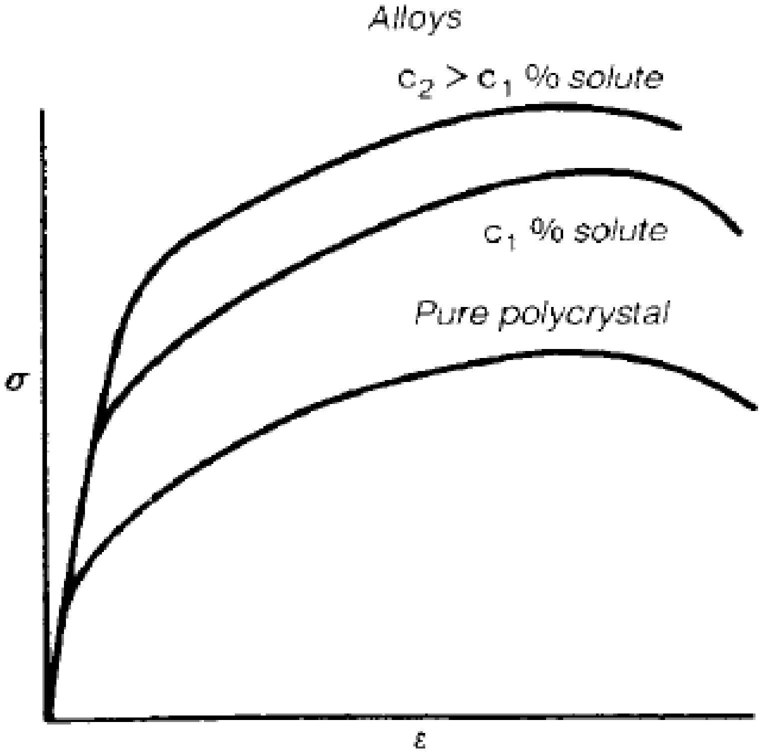
I. If the **solute and solvent atoms are roughly similar in size**, the solute atoms will occupy lattice points (regular positions) in the crystal lattice of the solvent atoms. This is called **substitutional solid solution**.

II. If the **solute atoms are much smaller than the solvent atoms**, they occupy interstitial positions in the solvent lattice. Carbon, nitrogen, oxygen, hydrogen, and boron are the elements which commonly form **interstitial solid solutions**.

- The factors which control the tendency for **the formation of substitutional solid solutions** have been uncovered chiefly through the work of <u>**Hume-Rothery**</u>.

Continued…

- If the sizes of the two atoms, as approximately indicated by the lattice parameter, **differ by less than 15 percent**, the size factor is **favorable for solid-solution formation**. When the size factor is greater than 15 percent, the extent of solid solubility is usually restricted to less than 1 percent.



Effect of solute alloy additions on stress strain curve

- **Crystal structures of solute and solvent must be similar**. Metals which **do not have a strong chemical affinity for each other** tend to form solid solutions. While metals which are far apart on the electromotive series (strong affinity for each other) tend to form intermetallic compounds.

Continued…

- ❑ **Complete solubility occurs when the solvent and solute have the same valency.**

a. The solubility of a metal with higher valence in a solvent of lower valence is more extensive than for the reverse situation. For example, zinc is much more soluble in copper than is copper in zinc.

b. This relative-valence effect can be rationalized to a certain extent in terms of the electron-atom ratio. For certain solvent metals, the limit of solubility occurs at approximately the same value of electron-atom ratio for solute atoms of different valence.

- Finally, for complete solid solubility over the entire range of composition the solute and solvent atoms **must have the same crystal structure**.

Continued…

Solute atoms can interact with dislocations by the following mechanisms:

- Stacking-fault interaction
- Electrical interaction
- Short-range order interaction

Short-range i.e. strong interactions and contribute strongly to flow stress at lower temperature.

- Elastic interaction
- Modulus interaction
- Long-range order interaction

Long-range i.e. continue to act about 0.6 Tm then after relatively insensitive to temperature.

Continued…

Solute atoms can interact with dislocations by the following mechanisms:

- ☐ **Stacking-fault interaction:** Solute preferentially segregate at SFs in extended dislocations to increase separation between dislocations and lowering the SFE.
- ☐ **Electrical interaction:** Association of charge with solute atoms of dissimilar valency to act as charge centers that interact with dislocation dipoles. Comparatively these interactions are weaker than elastic and modulus interaction.
- ☐ **Short-range order (Clustering) interaction:** Solute atoms rearranged themselves to have more number of dissimilar neighbors than equilibrium number. Hence, dislocation interaction cause increase in energy of alloy.

Continued…

- **Elastic interaction:** Mutual interactions of elastic fields of both solute atoms and dislocations. This is directly proportional to misfit of the solute.

- **Modulus interaction:** Presence of solute atoms alter the modulus of crystal. This is led by the change in shear modulus of solute atoms wrt matrix. If it smaller than matrix, then cause strong attraction (interaction) between solute and matrix.

- **Long-range order interaction:** Arise in alloys which form superlattice that is a long range periodic arrangement of dissimilar atoms. The movement of atoms through a superlattice cause development of anti-phase boundaries (APB).

Continued…

STRENGTHENING FROM FINE PARTICLES

- ☐ Small second-phase particles distributed in a ductile matrix are a common source of alloy strengthening. In dispersion hardening the hard particles are mixed with matrix powder and consolidated and processed by powder metallurgy techniques. However, very many alloy systems can be strengthened by precipitation reactions in the solid state.
- ☐ **Precipitation hardening or age hardening:** It is produced by solution treating and quenching an alloy in which a second phase is in solid solution at the elevated temperature but precipitates upon quenching and aging at a lower temperature. Example: Age-hardening aluminum alloys and copper-beryllium alloys are common examples.

Continued…

- For precipitation hardening to occur, the second phase must be soluble at an elevated temperature but must exhibit decreasing solubility with decreasing temperature. By contrast, the second phase in dispersion-hardening systems has very little solubility in the matrix, even at elevated temperatures.
- Decrease in solubility with temperature limits the use of precipitation-hardening alloys. On the other hand, the dispersion strengthened alloy systems by mixing fine metallic powders and second phase particles (oxides, carbides, nitrides, etc.) and consolidated them via powder metallurgy route make it thermally stable at higher temperatures. Further, it has more resistant to recrystallization and grain growth.

FIBER STRENGTHENING

- Materials of high strength, and especially high strength-to-weight ratio, can be produced by incorporating fine fibers in a ductile matrix.

Continued…

- The fibers may be long and continuous, or they may be discontinuous. Metals and polymers have been used as matrix materials. Glass-fiber-reinforced polymers are the most common fiber-strengthened materials. Fiber-reinforced materials are an important group of materials generally known as composite materials.

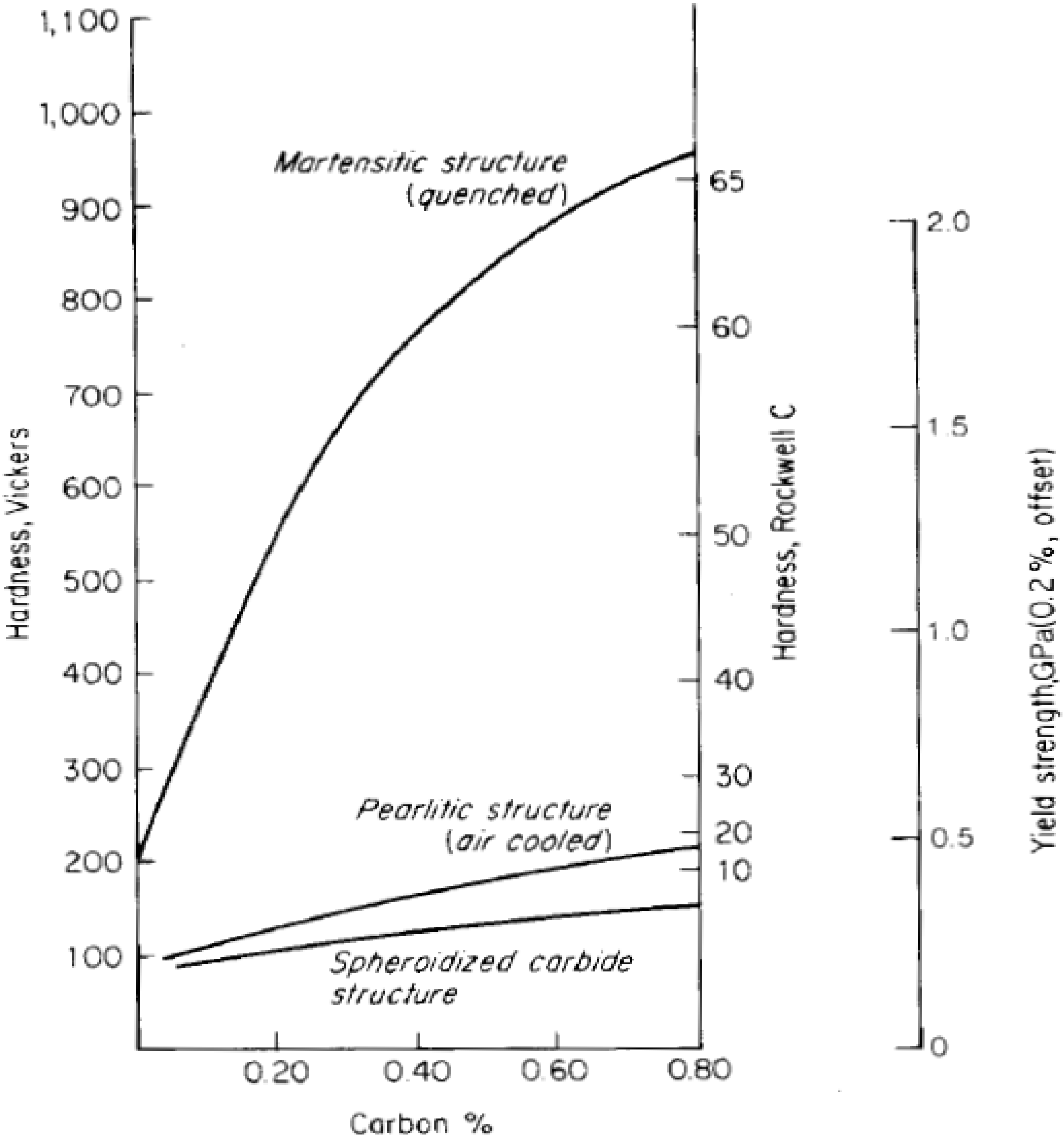
LECTURE-27

MARTENSITE STRENGTHENING

- The transformation of austenite to martensite by diffusion less shear-type transformation in quenching of steel is one of the most common strengthening processes used in engineering materials.
- Although martensitic transformations occur in a number of metallurgical systems, only the alloys based on iron and carbon show such a pronounced strengthening effect.

Continued…

- Figure shows how the hardness of martensite varies with carbon content and compares this degree of strengthening with that achieved in dispersed aggregates of iron and cementite.



Hardness of various transformation products in steel.

Continued…

- The high strength of martensite implies that there are many strong barriers to dislocation motion in this structure. The complexity of the system allows for considerable controversy and hardening mechanisms abound, but it appears that there are ***two main contributions*** to the high strength of martensite.
- The conventional martensite has a plate structure with a unique habit plane and an internal structure of parallel twins each about 0.1 µm thick within the plates.
- The other type of martensite structure is a block martensite containing a high dislocation density of 10^9 to 10^{10} mm^{-2}, comparable to that in a highly deformed metal. Thus, part of the high strength of martensite arises from the effective barriers to slip provided by the fine twin structure or the high dislocation density.

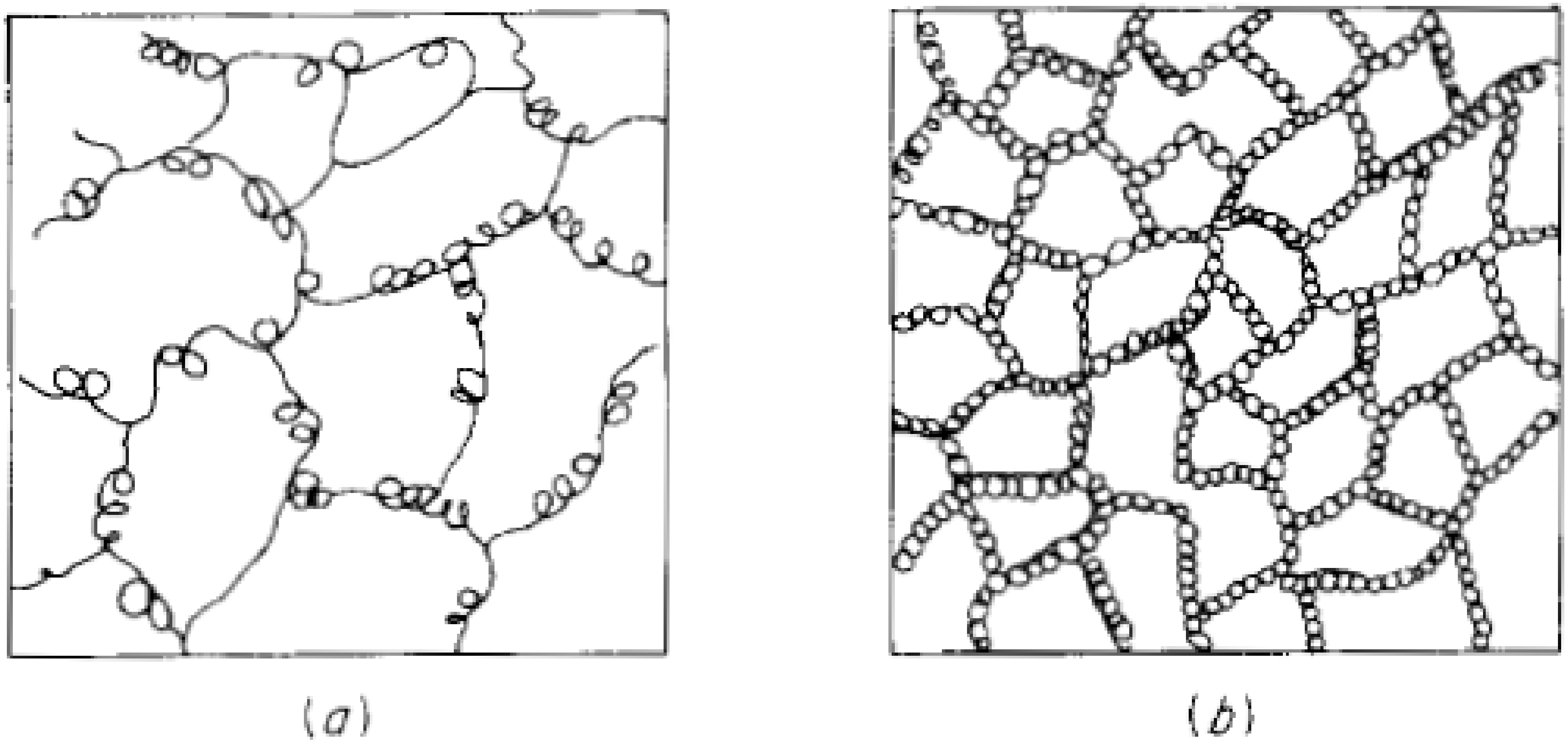
Continued…

- The second important contribution to the strength of martensite comes from the carbon atoms. Figure shows that the hardness of martensite is very sensitive to carbon content below 0.4 percent. On rapidly transforming from austenite to ferrite in the quench, the solubility of carbon in iron is greatly reduced. The carbon atoms strain the ferrite lattice and this strain can be relieved by redistribution of carbon atoms by diffusion at room temperature.

COLD-WORKED STRUCTURE

- Plastic deformation which is carried out in a temperature region and over a time interval such that the strain hardening is not relieved is called cold-work.

Continued…



(a) Deformed to 10 percent strain. Beginning of cell formation with dislocation tangles; (b) deformed to 50 percent strain. Equilibrium cell size with heavy dislocation density in cell walls

Continued…

- Plastic deformation produces an increase in the number of dislocations, which by virtue of their interaction results in a higher state of internal stress. An annealed metal contains about 10^4 to 10^6 dislocations per mm^2, while a severely plastically deformed metal contains about 10^{10} mm^{-2}.
- Strain hardening or cold work can be readily detected by x-ray diffraction, although detailed analysis of the x-ray patterns in terms of the structure of the cold-worked state is not usually possible.

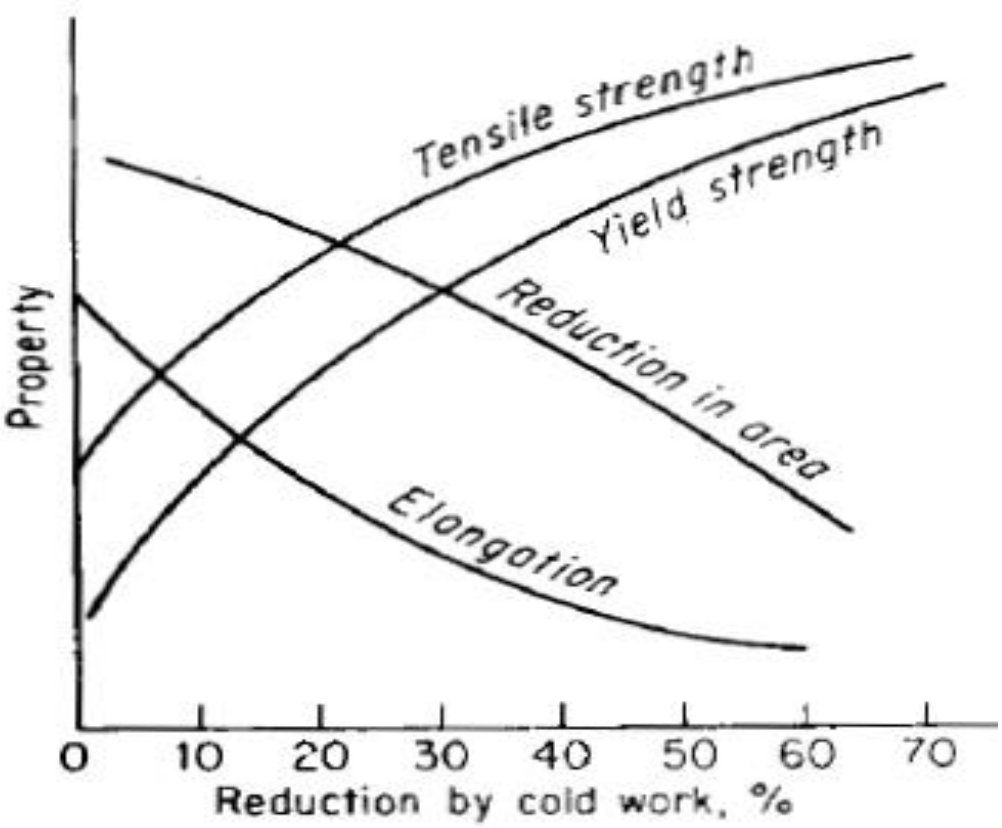
STRAIN HARDENING

- Strain hardening or cold-working is an important industrial process that is used to harden metals or alloys that do not respond to heat treatment.
- The rate of strain hardening can be gaged from the slope of the low curve.

Continued…

- Generally, the rate of strain hardening is lower for hcp metals than for cubic metals. Increasing temperature also lowers the rate of strain hardening.

- For alloys strengthened by solid-solution additions the rate of strain hardening may be either increased or decreased compared with the behavior for the pure metal.



Variation of tensile properties with amount of cold-work.

Continued…

- However, the final strength of a cold-worked solid-solution alloy is almost always greater than that of the pure metal cold-worked to the same extent.
- Figure shows the typical variation of strength and ductility parameters with increasing amount of cold-work.
- Since in most cold-working processes one or two dimensions of the metal are reduced at the expense of an increase in the other dimensions, cold-work produces elongation of the grains in the principal direction of working.
- Severe deformation produces a reorientation of the grains into a preferred orientation. In addition to the changes in tensile properties shown in Fig. , cold-working produces changes in other physical properties.

Continued…

- A high rate of strain hardening implies mutual obstruction of dislocations gliding on intersecting systems. This can come about

  (1) through interaction of the stress fields of the dislocations,

  (2) through interactions which produce sessile locks, and

  (3) through the interpenetration of one slip system by another (like cutting trees in a forest) which results in the formation of dislocation jogs.

ANNEALING OF COLD-WORKED METAL

- The cold-worked state is a condition of higher internal energy than the undeformed metal. Although the cold worked dislocation cell structure is mechanically stable, it is not thermodynamically stable.

Continued…

- A high rate of strain hardening implies mutual obstruction of dislocations gliding on intersecting systems. This can come about

  (1) through interaction of the stress fields of the dislocations,

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LECTURE-28

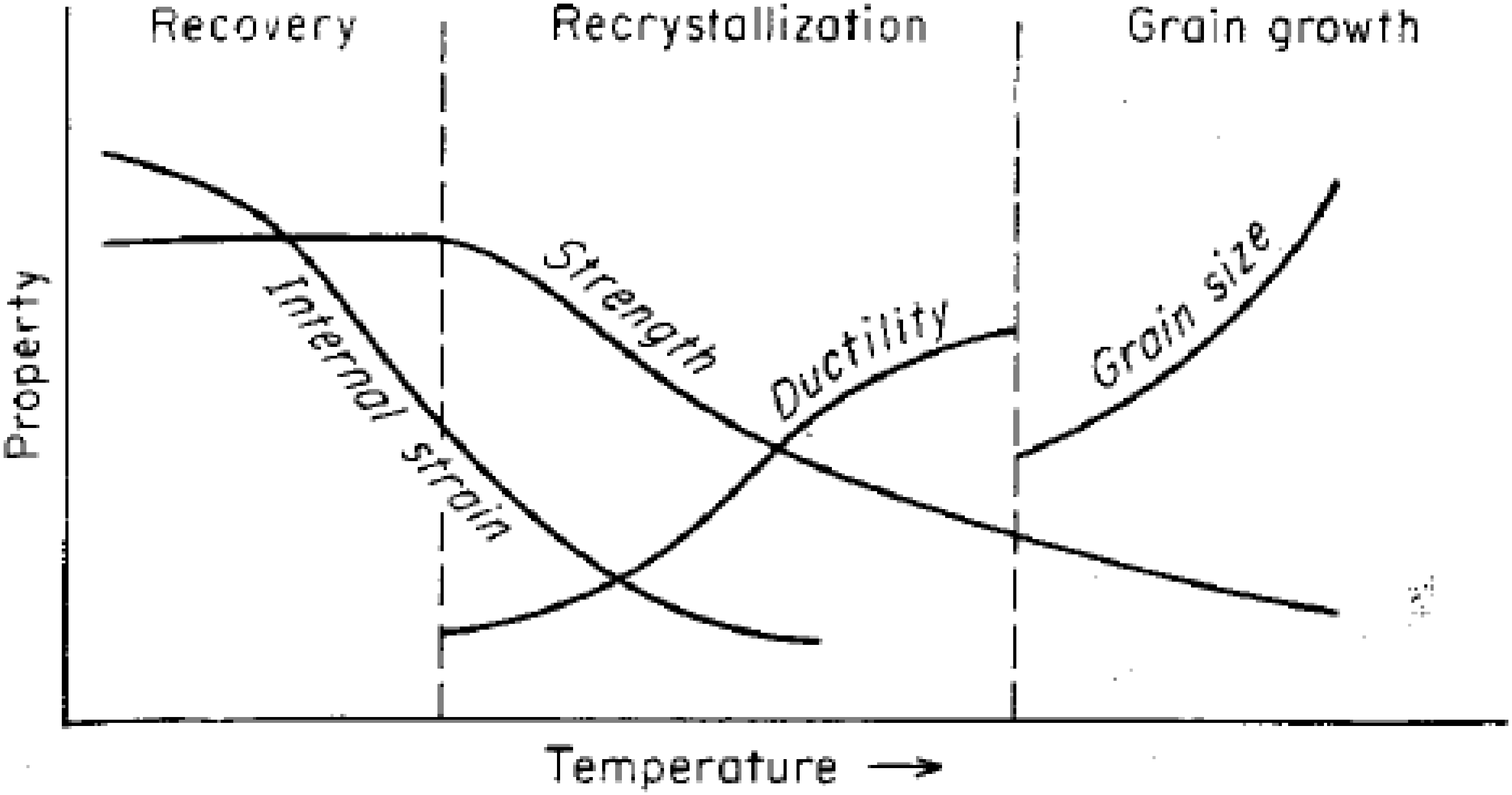
ANNEALING OF COLD-WORKED METAL

- The cold-worked state is a condition of higher internal energy than the undeformed metal. Although the cold worked dislocation cell structure is mechanically stable, it is not thermodynamically stable.
- With increasing temperature the cold-worked state becomes more and more unstable. Eventually the metal softens and reverts to a strain-free condition.
- The overall process by which this occurs is known as annealing. Annealing is very important commercially because it restores the ductility to a metal that has been severely strain-hardened.

Continued…

- Therefore, by interposing annealing operations after severe deformation it is possible to deform most metals to a very great extent.
- The process of annealing can be divided into three fairly distinct processes: recovery, recrystallization, and grain growth.
- The below figure will help to distinguish between these processes. Recovery is usually defined as the restoration of the physical properties of the cold-worked metal without any observable change in microstructure.

Continued…



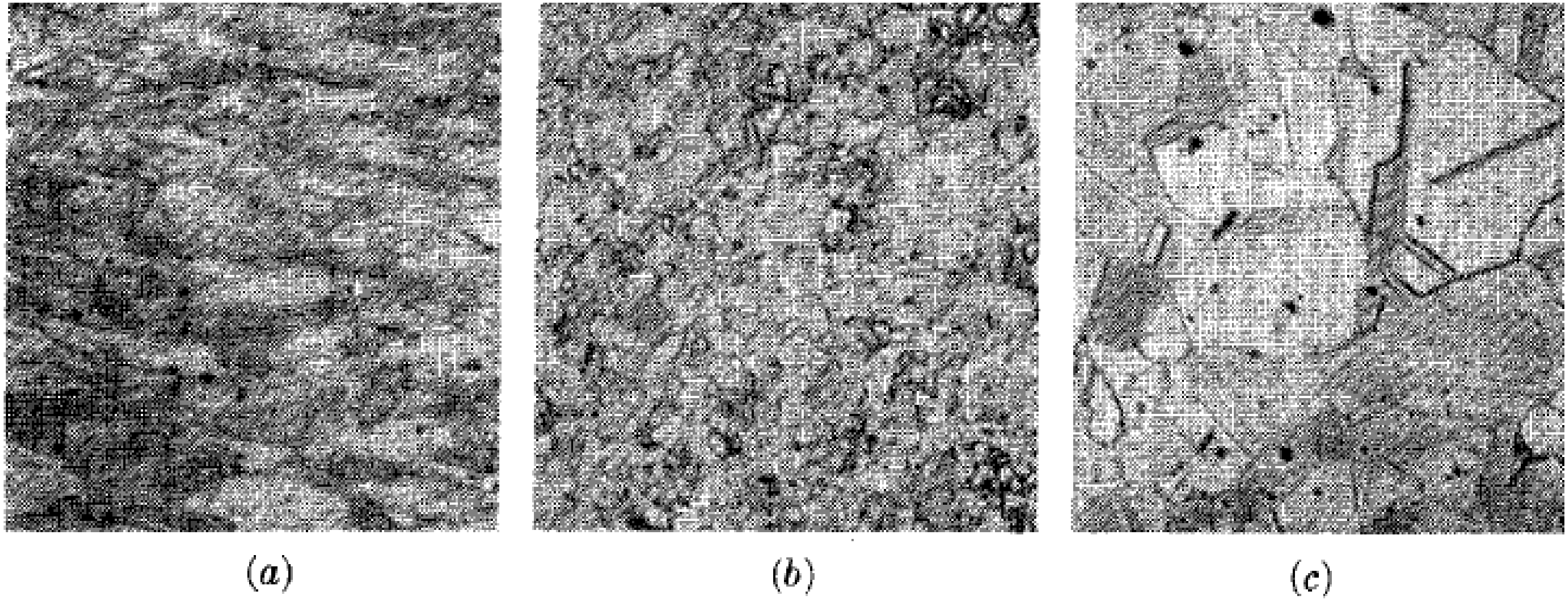
Schematic drawing indicating recovery, recrystallization, and grain growth and chief property changes in each, region.

Continued…

- Electrical conductivity increases rapidly toward the annealed value during recovery, and lattice strain, as measured with x-rays, is appreciably reduced. The properties that are most affected by recovery are those which are sensitive to point defects.
- The strength properties, which are controlled by dislocations, are not affected at recovery temperatures. An exception to this is single crystals of hcp metals which have deformed on only one set of planes (easy glide)
- Recrystallization is the replacement of the cold-worked structure by a new set of strain-free grains.
- Recrystallization is readily detected by metallographic methods and is evidenced by a decrease in hardness or strength and an increase in ductility. The density of dislocations decreases considerably on recrystallization, and all effects of strain hardening are eliminated.

Continued…

- The stored energy of cold-work is the driving force for both recovery and recrystallization. If the new strain-free grains are heated at a temperature greater than that required to cause recrystallization, there will be a progressive increase in grain size.



Changes in microstructure of cold-worked 70-30 brass with annealing, (a) Cold-worked 40 percent; (b) 440oC, 15 min; (c) 5750C, 15 min (150X)

Continued…

- The driving force for grain growth is the decrease in free energy resulting from a decreased grain-boundary area due to an increase in grain size.
- Above figure shows the progression from a cold-worked microstructure to a fine recrystallized grain structure, and finally to a larger grain size by grain growth.

Six main variables influence recrystallization behavior. They are

(1) Amount of prior deformation,

(2) Temperature,

(3) Time,

(4) Initial grain size,

(5) Composition,

(6) Amount of recovery or polygonization prior to the start of recrystallization.

Continued…

- Because the temperature at which recrystallization occurs depends on the above variables, it is not a fixed temperature in the sense of a melting temperature.
- For practical considerations a recrystallization temperature can be defined as the temperature at which a given alloy in a highly cold-worked state completely recrystallizes in 1 h.
- Because the driving force for grain growth is appreciably lower than the driving force for recrystallization, at a temperature at which recrystallization occurs readily grain growth will occur slowly. However, grain growth is strongly temperature-dependent, and a grain-coarsening region will soon be reached in which the grains increase in size very rapidly.

LECTURE-29

The relationship of the above variables to the recrystallization process can be summarized as follows:

1. A minimum amount of deformation is needed to cause recrystallization.

2. The smaller the degree of deformation, the higher the temperature required to cause recrystallization.

3. Increasing the annealing time decreases the recrystallization temperature. However, temperature is far more important than time. Doubling the annealing time is approximately equivalent to increasing the annealing temperature 10oC.

4. The initial grain size depends chiefly on the degree of deformation and to a lesser extent on the annealing temperature. The greater the degree of deformation, and the lower the annealing temperature, the smaller the recrystallized grain size.

Continued…

5. The larger the original grain size, the greater the amount of cold-work required to produce an equivalent recrystallization temperature.

6. The recrystallization temperature decreases with increasing purity of the metal. Solid-solution alloying additions always raise the recrystallization temperature.

7. The amount of deformation required to produce equivalent recrystallization behavior increases with increased temperature of working.

8. For a given reduction in cross section, different metalworking processes, such as rolling, drawing, etc., produce somewhat different effective deformations. Therefore, identical recrystallization behavior may not be obtained.

Continued…

Differences between Crystalline and Non-crystalline Materials

- In crystalline materials, permanent deformation is generally related to identified defects such as dislocation, atom diffusion involving voids, vacancies, etc.
- The macroscopic deformation is similar in both crystalline and non-crystalline (i.e. behave in a brittle manner under high strain rate and low temperature)
- In non-crystalline materials, permanent deformation is often related to localized slip and/or viscous flow (low stress or high temperature)
- The non-crystalline arrangement is thermodynamically stable above material's Tm. The crystalline just opposite (below the Tm is more stable) Crystalline arrangement is more ordered ⇒ less molar volume.

Ref-http://mech-india.yolasite.com/resources/Deformation%20of%20Noncrystalline%20Materials.pdf

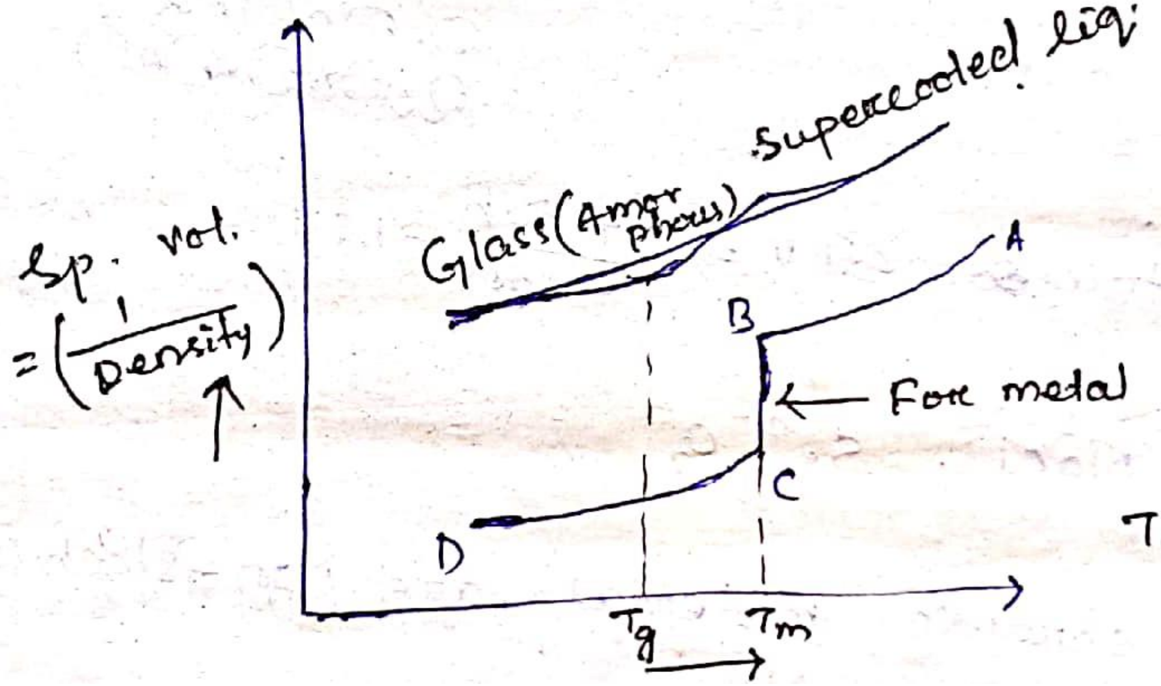
Continued…

DEFORMATION OF NON-CRYSTALLINE MATERIALS:

- In non-crystalline materials, permanent deformation is usually related to viscous flow or localized slip.
- Viscous flow is occurred due to permanent movement of atoms from different parts of the material.
- Glass transition temperature is a major factor in the determination of non-crystalline material deformation.
- The glass transition is the reversible transition in amorphous materials from a hard and relatively brittle state into a molten or rubber-like state.

Continued…

★★Glass is an inorganic which is cooled without Crystallisation. Therefore it is amorphous but solid.



Tg → Glass Transit^n^ Temp.

Continued…

Glass Transition Temperature and Molar Volume

- The ratio T_g/T_m can determine the ease of glass formation (ratio >0.67 is favorable)
- T_g relates to a reduction in atomic mobility
- Heating an amorphous material below itsT_m can enhance the crystallization process

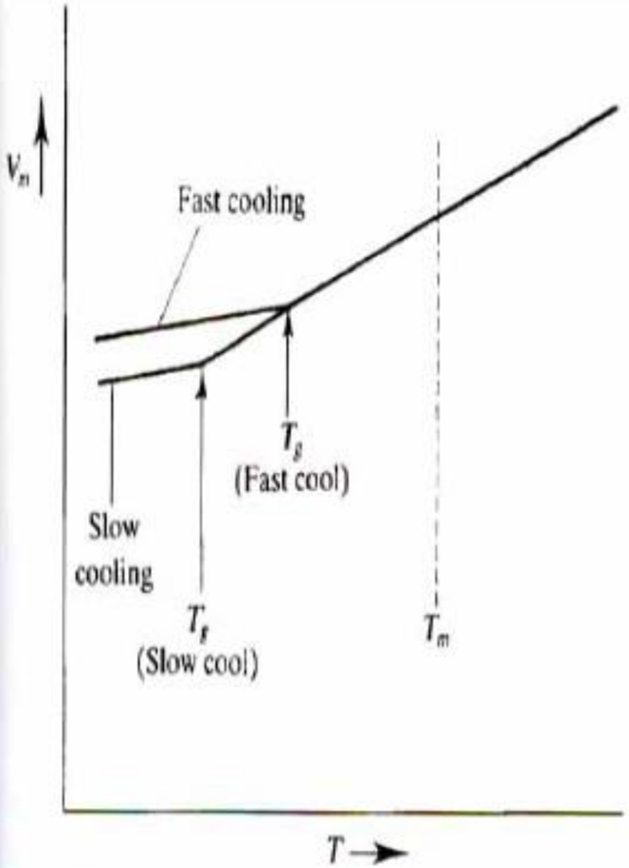
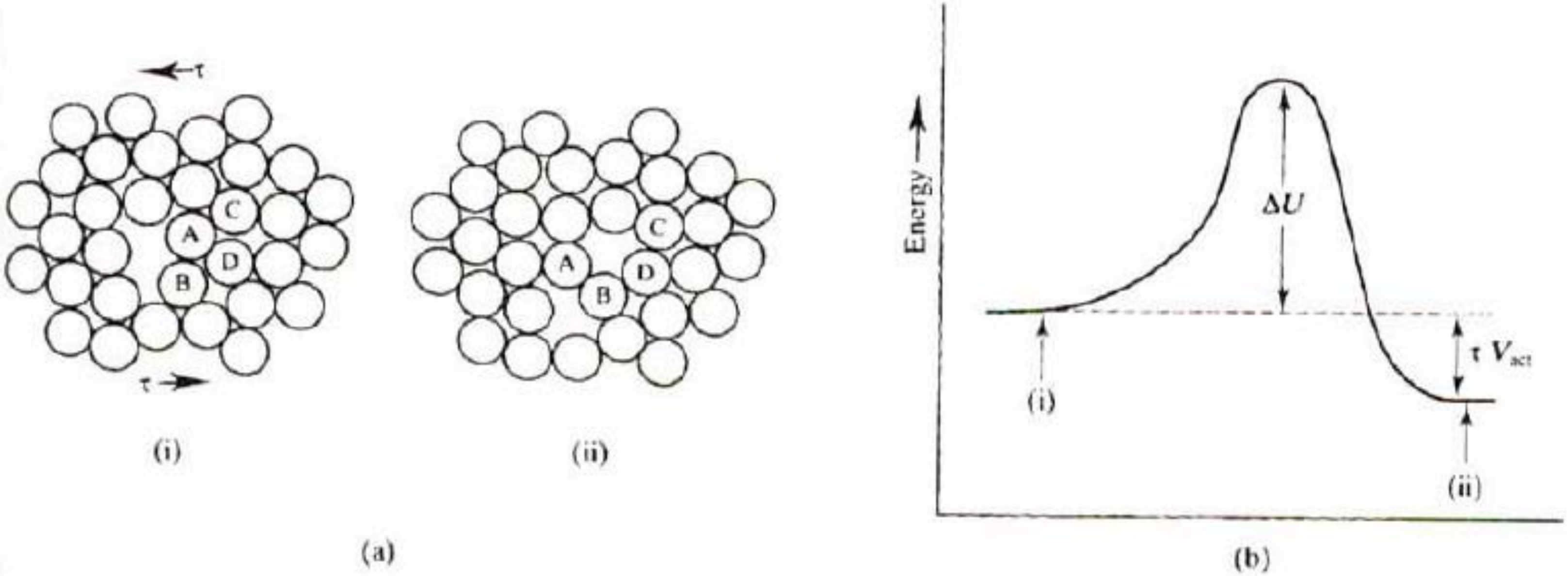


Figure 8.5
The glass transition temperature is a function of cooling rate; T_g increases with more rapid cooling. A material with a higher T_g also has a greater molar volume.

Ref-http://mech-india.yolasite.com/resources/Deformation%20of%20Noncrystalline%20Materials.pdf

Continued…

Viscous Flow in Amorphous Materials



(a)

(b)

Figure 8.6

Viscous flow in an amorphous material. An applied shear stress (a(i)) induces flow of the upper portion of the material with respect to the lower. The flow is accomplished (a(ii)) by atomic or molecular jumps (e.g., atom A). As shown here, most such displacements occur in regions where the local atomic volume is highest. (b) Energy-reaction coordinate diagram for the process of (a). The atomic displacements require an activation energy (ΔU), but the displacements are stress-aided with an energy τV_{act} (V_{act} = activation volume). Kinetic principles (see text) determine the stress–strain rate relationship.

Ref-http://mech-india.yolasite.com/resources/Deformation%20of%20Noncrystalline%20Materials.pdf

Continued…

- Viscous flow is due to permanent displacement of atoms in different locations within the material.
- Glass transition temperature is an important factor to the deformation in noncrystalline material.
- Stress, temperature and free volume are key factors to a deformation mechanism.
- Shear band is another deformation mechanism in non-crystalline material – crazing.

LECTURE-30

Deformation of Metallic Glasses

- This is a deformation mechanism map.
- Three distinct regions: elastic, viscoelastic and viscous regions.
- Heterogeneous deformation at high stress and low temperature.
- Homogeneous deformation at low stress and low temperature.
- At high stresses and low temperatures, permanent deformation is associated with shear bands.

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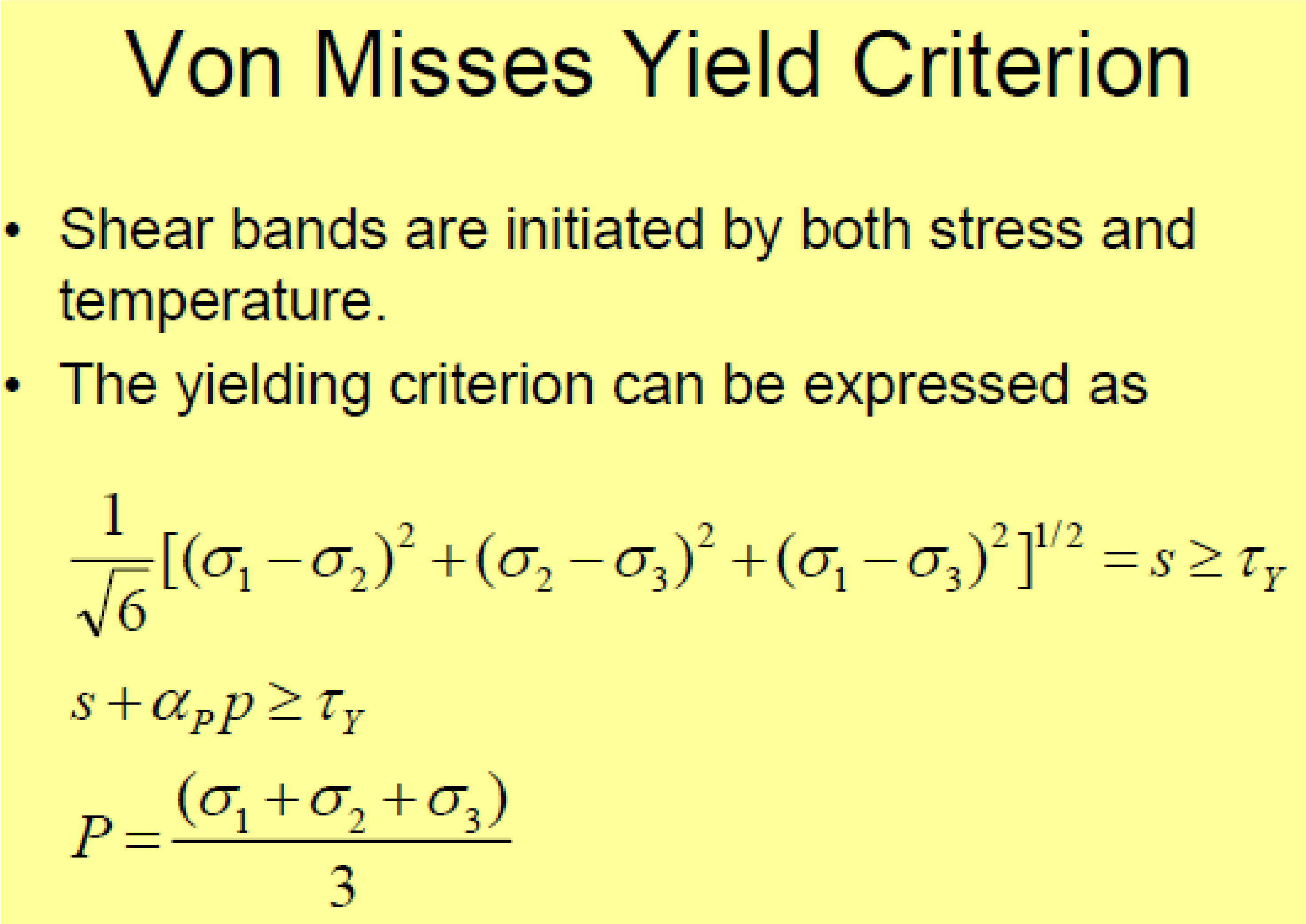

Von Misses Yield Criterion

- Shear bands are initiated by both stress and temperature.
- The yielding criterion can be expressed as

$$\frac{1}{\sqrt{6}}[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_1-\sigma_3)^2]^{1/2}=s\geq\tau_Y$$

$$s+\alpha_P p\geq\tau_Y$$

$$P=\frac{(\sigma_1+\sigma_2+\sigma_3)}{3}$$

Ref-http://mech-india.yolasite.com/resources/Deformation%20of%20Noncrystalline%20Materials.pdf

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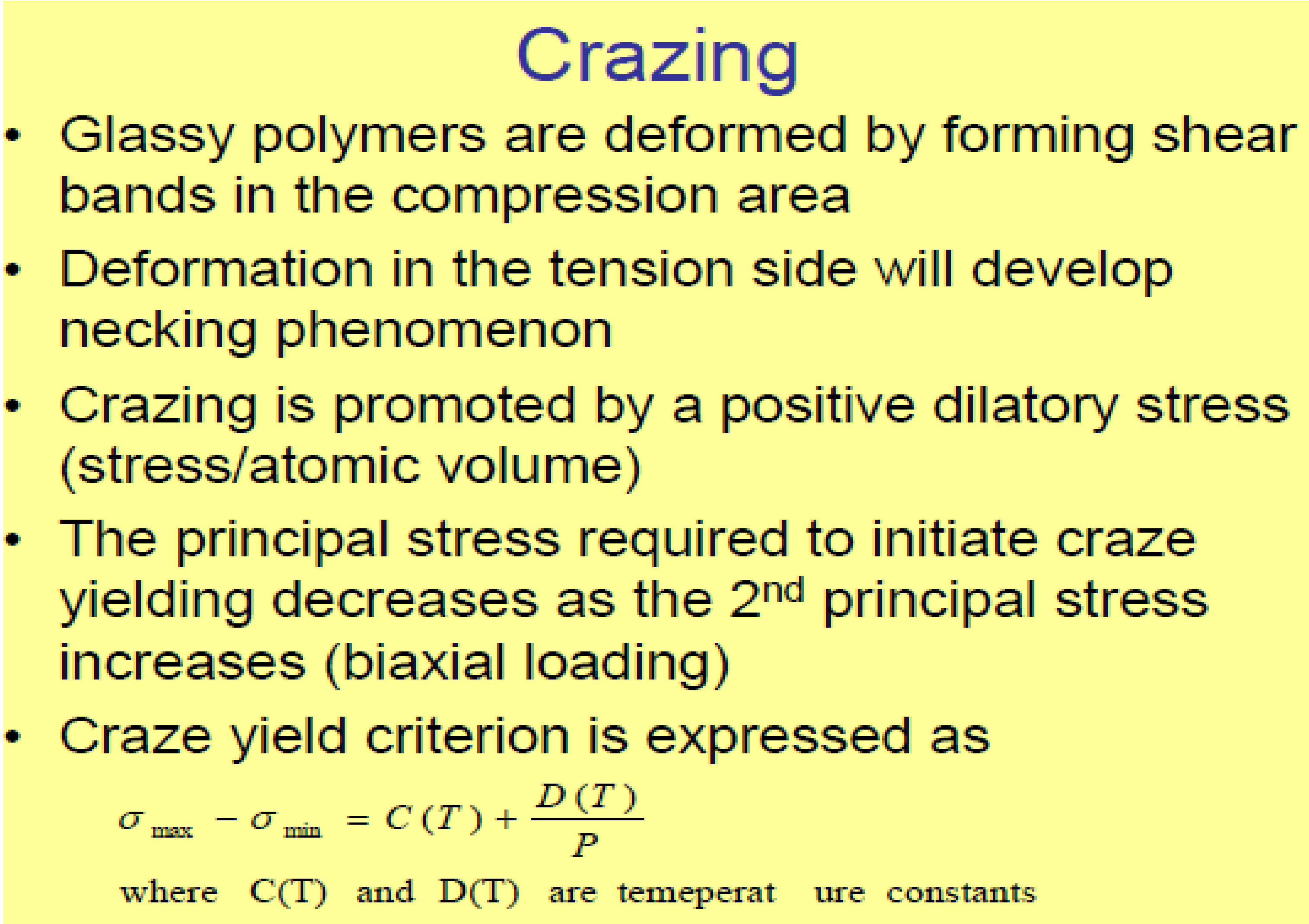

Crazing

- Glassy polymers are deformed by forming shear bands in the compression area
- Deformation in the tension side will develop necking phenomenon
- Crazing is promoted by a positive dilatory stress (stress/atomic volume)
- The principal stress required to initiate craze yielding decreases as the 2nd principal stress increases (biaxial loading)
- Craze yield criterion is expressed as

$$\sigma_{\max} - \sigma_{\min} = C(T) + \frac{D(T)}{P}$$

where C(T) and D(T) are temeperature constants

Ref-http://mech-india.yolasite.com/resources/Deformation%20of%20Noncrystalline%20Materials.pdf

Continued…

DEFORMATION OF POLYMERS:

- A polymer is a large molecule composed of repeating monomers. These sub-units are typically connected by covalent chemical bonds. **Example**: proteins, rubber, polythenes etc.

- Polymers have different elastic properties than metals. Their elastic moduli are very small when compared to those of metals.

- Polymers are undergone large deformation without rupture or can still return to their original shape.

- Further, polymers’ elastic modulus is increased with temperature.

Continued…

Deformation in Ceramic:

Ceramics Properties:

- High hardness, high elastic modulus, low ductility.
- High dimensional stability, Good wear resistance.
- High resistance to corrosion and chemical attack.
- High weather resistance, High melting point, High working temperature.
- Low thermal expansion, Low to medium thermal conductivity
- Good electrical insulation, Low to medium tensile strength
- High compressive strength, Medium machinability
- Brittleness, Poor impact strength, Low thermal shock resistance

Ref-https://ceramics.org/about/what-are-engineered-ceramics-and-glass/structure-and-properties-of-ceramics

Continued…

Crystal Structures

- Ceramic bonds are usually mixed of covalent and ionic with a proportion that depends on the type of ceramics.

- The ionic character is a function of difference in electronegativity between cations and anions.

- Covalent bonds are involved with valence electrons sharing.

- Ionic crystals are involved with cations such as alkalis or alkaline-earths and anions such as halogens or oxygen.

Continued…

Defects in Ceramic:

- It mainly concludes impurities and point defects whose development is mostly affected by charge neutrality.

- Non-stoichiometry in ceramic refers to compositional change of elements.

- Moreover the charge neutrality includes the Frenkel and Schottky defects, where Frenkel defect is a interstitial-vacancy pair of cations and Schottky-defect refers to a pair of neighborhood cation and anion vacancies.

Continued…

- Impurity atoms in the lattice is the condition of charge maintained. The electronegative impurities are usually substitute the electropositive substitutional impurities or lattice anions.

- More likely defects will appear in the place of imbalance in impurities charge.

Dislocations in Ceramics

- Limited slip systems, so facing difficulties during activation and further the Burgers vectors are very large. So, dislocation climb in terms of diffusion is frequently observed.

QUIZ TEST-6

Q.1 – How dispersion hardening takes place, explain.

Q.2 – How high rate of strain hardening can be achieved?

Q.3 – What is main driving force for recovery and recrystallization

Q.4 –State the Differences between Crystalline and Non-crystalline Materials.

Q.5 –What happens in metallic glasses at high stresses and low temperatures?

Assignment

Briefly explain the different strain hardening components in polycrystalline material.

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