**Unit 1**

Index Notation, Transformation of axes, Stress-engineering and true, Principal stress, Plane stress, Deviatoric Stress, Hydrostatic Stress, Strain-engineering and true, Principal Strain, Plane strain, Deviatoric Strain, Hydrostatic Strain.

Reference Books

1. Mechanical Metallurgy, Dieter G. E., Mc Graw Hill, 1988.
2. Mechanical Behaviour of Materials, William F. Hosford, Cambridge University Press, 2010.
3. Introduction to Continuum Mechanics. Michael Lai, Erhard Krempl, Davis Rubin, Elsevier Inc, 2010.

**Unit 2**

Stress-Strain Curves, Yielding Criterions, Defects-point, line, surface, volumetric, slip, twinning, movement of dislocations, Burger vector, Burger circuit, stress required for slip, Stress Field around a Dislocation, strain energy, Peach-Koehler Equation, Force between two dislocations, Strain Hardening, Strengthening Mechanisms, Yielding phenomenon, Bauschinger effect, Texture, Recovery, Recrystallisation, Grain Growth

Reference Books

1. Mechanical Metallurgy, Dieter G. E., Mc Graw Hill, 1988.
2. Mechanical Behaviour of Materials, William F. Hosford, Cambridge University Press, 2010.
3. Introduction to Dislocations, D. Hull & D.J. Bacon, Butterworth Heinemann, 2001.
4. Physical Metallurgy Principles, Robert E. Reed-Hill, Affiliated E-W Press Pvt. Ltd., 2008.
5. Materials Science & Engineering: An Introduction, William D. Callister, Jr., John Wiley & Sons, Inc., 2007**.**

**Unit 3**

Testing of materials-Destructive, Non-Destructive, Hardness-Rockwell, Brinell, Vickers, Knoop, Meyers, Tensile Test, Compressive Test, Impact Test-Izod, Charpy

Reference Books

1. Mechanical Metallurgy, Dieter G. E., Mc Graw Hill, 1988.
2. Mechanical Behaviour of Materials, William F. Hosford, Cambridge University Press, 2010.
3. Materials Science & Engineering: An Introduction, William D. Callister, Jr., John Wiley & Sons, Inc., 2007**.**

**Unit 4**

Fracture Theory- Types and modes, Fracture Mechanics - Griffith’s theory and its modification, Ductile to Brittle Transition

Reference Books

1. Mechanical Metallurgy, Dieter G. E., Mc Graw Hill, 1988.
2. Mechanical Behaviour of Materials, William F. Hosford, Cambridge University Press, 2010.
3. Materials Science & Engineering: An Introduction, William D. Callister, Jr., John Wiley & Sons, Inc., 2007**.**

**Unit 5**

Introduction of creep , Creep Curve, Structural Changes during Creep, Creep mechanisms, Temperature dependence of creep, Deformation maps, Extrapolation of creep data, Alloys for high temp. use, Fatigue introduction, Nomenclature, Effect of Mean Stress, Miner’s Rule, S-N curve, Factors affecting fatigue, LCF, HCF, Structural changes in fatigue, Crack Propagation

Reference Books

1. Mechanical Metallurgy, Dieter G. E., Mc Graw Hill, 1988.
2. Mechanical Behaviour of Materials, William F. Hosford, Cambridge University Press, 2010.
3. Materials Science & Engineering: An Introduction, William D. Callister, Jr., John Wiley & Sons, Inc., 2007**.**

**Important Concepts**

**Index Notation**

It is the notation for vector, tensor equations. For example:

In cartesian co-ordinates , ,

Corollary to rule 1: The free index in each term of the equation has to be the same.

Rule 2: Einstein summation Convention

If an index repeats (dummy index), it means summation over that index

Corollary to rule 2: In a single term, an index should not be repeated more than two times.

For example

Kronecker Delta Function,

The Alternating Tensor,

**Transformation of axes**

If is the orthogonal coordinate system in which stress, is represented and is the new axis in which is to be represented, then the general form of the transformation is:

And

Where is the cosine of the angle between x’ and x and hence the rest.

**Stress**

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

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

A normal stress (compressive or tensile) is the one in which force acts on the area that is normal to it whereas in shear force, force is parallel to the area.

 indicates that the force is in x-direction and it acts on a plane normal to x

In tensor notation, the state of stress is expressed as

**Principal Stresses**

In a set of axis where no shear stresses exist and only normal stresses are present, these normal stresses, are called principal stresses and 1,2 and 3 axes are called the principal stress axes. The magnitude of the principal stresses, , are the roots of the equation

Where

 are called stress invariants

**Plane Stress**

A stress condition in which the stresses in one of the primary directions is zero

**Deviatoric Stress or stress deviator,**

Component of the total stress that causes plastic deformation

**Hydrostatic stress,**

The other component of stress (apart from stress deviator) is called spherical or hydrostatic stress

The stress deviator is given by

The Principal Stress Deviators are the roots of the cubic equation

**Strain**

Linear strain is defined as the ratio of change in length to the original length of the same dimension

Engineering or normal Strain,

True strain, , where L is the final length

True Stress,

The transformation of axes for strain are same as that for stress (refer to transformation of stress)

Plane Strain

Strain condition where all the deformation is confined to xy or yz or xz plane

Volumetric Strain,

In an analogous manner, the strain at any point can be divided into deviator and hydrostatic strain

**Stress-strain relations**

 Hooke’s Law

Generalised Hooks law

**Stress-Strain Curves**

A typical Engineering stress-strain curve for a ductile material is shown below:



At lower strains – elastic deformation, reversible

For higher stresses – plastic deformation

Following information can be obtained from the curve:

Youngs Modulus, E – slope of the elastic region of the curve

Elastic limit – Stress that causes first plastic deformation

Proportionality limit – stress that causes first departure from linearity

Yield Point – Onset of plasticity is usually described by yield point. If the transition between elastic and plastic regions is not clear, offset yield point is used. It is found by constructing a straight lone parallel to the initial linear portion of the stress-strain curve but offset from it by a strain of 0.2%

Ultimate Tensile Stress- The maximum stress that is sustained by a material without fracture. Necking starts from this point

Fracture Point – stress at which the materials fails in two parts

Resilience – Capacity of a material to absorb the energy when loaded elastically and to have this energy recovered when unloaded. In a linear elastic region, modulus of elasticity,

Toughness – ability of a material to absorb energy till fracture

Ductility – degree of plastic deformation (unidirectional) sustained till fracture

**Effect of strain rate**

The effect of strain rate on the flow stress at a fixed strain and temperature can be described as

 is the strain rate sensitivity

**Effect of temperature**

As temperature increases, the whole level of the stress-strain curve generally drops

Decreasing temperature has the same effect as increasing strain rate

Q is activation energy

T is absolute Temperature

R is gas constant

**Yielding Criterions**

Von-Mises – It can be expressed as

In a tension test, and at yielding,

Tresca or Maximum shear stress criterion – yielding will occur when the largest shear stress reaches a critical value. Largest shear stress is

**Defects**

Point-vacancy, interstitials

Vacancy is a vacant lattice site, generally occupied by an atom. Vacancy moves as a result of an atom jumping into a hole.

 is the equilibrium number of vacancies for a given quantity of material

N is the total number of atomic sites,

is the energy required for the formation of a vacancy

 T is the absolute temperature1 in kelvins

k is the gas or Boltzmann’s constant**.**

Interstitials

 Usually small atoms like C, N, O

Is usually crowded in an interstitial site

Introduces large distortions in the neighbouring surroundings

Line defects

A *dislocation* is a linear or one-dimensional defect around which some of the atoms are misaligned. In order to understand the high theoretically obtained critically resolved shear stress than the experimentally observed critically resolved shear stress, the concept of dislocations was introduced. Generally three types of linear defects are present

Edge dislocation

Screw Dislocation

Mixed Dislocation

Slip: The plastic deformation of crystalline materials generally occurs by slip, which is the sliding of planes of atoms over one another. The planes on which slip occurs are called slip planes and the directions of deformation are called slip directions. Dislocation is thus also defined as the boundary between the slipped and unslipped portions of the plane.

Burger Vector, and tangent/unit vector, are the characteristics of slip.

Burger Vector, represents the direction of slip. It is the shortest possible path between two atoms.

tangent/unit vector, represents the dislocation line

 is perpendicular to – edge dislocation

 is parallel to – screw dislocation

 is neither perpendicular to nor parallel to – mixed dislocation

Edge dislocation is the edge of the extra half plane of atoms in a crystal.

Can be positive or negative depending where the extra half plane is located. If it is located on the top side then positive, otherwise negative. The distinction is, however, relative.

Screw dislocation The dislocation that transforms a set of parallel planes initially perpendicular to it, into a single surface by the distortion of the planes is a screw dislocation. Differentiated into right handed and left handed, where the former is the one where b and t are antiparallel

Burger circuit (RHFS rule – Right hand finish to start)

A close circuit in a perfect crystal that fails to close in an imperfect crystal thereby indicating the presence of dislocation. Hence, burger vector is a vector that closes this circuit.

Strain energy of edge dislocation

Strain energy of screw dislocation

Strain energy of mixed dislocation

Surface defects

External surface – Surface atoms are not bonded to maximum atoms and re therefore in high energy state. The bonds of these atoms give rise to surface energy.

Grain Boundaries – Grain boundary separates two grains. Based on degree of difference in orientation, the GB can be sub boundaries, high angle and low angle grain boundaries. On the basis of type of difference in orientation, they can be tilt, twist and coincident grain boundary. On the basis of continuity of atoms on both sides of the boundary, it can be coherent, semi-coherent or incoherent grain boundary.

Stacking faults – Fault in the arrangement of atoms

Volumetric defects

Precipitates

Voides

Pores

Blow Holes

**Movement of dislocations**

Glide – Motion of a dislocation on its own slip plane (containing b and t). Edge dislocations move through climb

Climb – Jump of edge dislocations. It is of two types, climb up and climb down. This motion is assisted by movement of vacancies away from and towards the dislocation.

Cross-slip Movement of screw dislocation. A screw dislocation can cross between planes where b is parallel to t and hence the name.

**Peach-Koehler Equation**

It is the force on a dislocation due to a stress that causes its motion.

Force per unit length of dislocation,

**Generation of dislocation**

Frank-Read Sources-Explains how the number of dislocations increases with deformation. Consider a finite length of dislocation in a slip plane having pinned end points. A shear stress acting on the plane will create a force that causes the dislocation to bow. As the shear stress is increased, the dislocation will continue to bow out until it spirals back on itself. The sections that touch annihilate each other leaving a dislocation loop that expands under the stress and a restored dislocation segment between the pinning points. The process can repeat, producing many loops.

The stress necessary to operate a Frank-Read source, , where d is the size of the source (length of the dislocation)

**Strengthening Mechanisms**

|  |  |  |  |
| --- | --- | --- | --- |
| S.No. | Strengthening Mechanism | Obstacle | Dimensionality of obstruction |
| 1 | Solid Solution strengthening | Solute atoms | Point (0D) |
| 2 | Strain Hardening | Dislocation | Line (1D) |
| 3 | Grain size reduction | Grain Boundary | Surface (2D) |
| 4 | Age/Precipitate Hardening | Precipitates | Volume (3D) |
| 5 | Dispersion Hardening | Dispersoids | Volume (3D) |

**Yielding phenomenon**

In some materials the transformation from elastic to plastic region is gradual and the yield point is determined from offset method.

In certain other materials (low carbon steels), yield point phenomenon is observed where a sharp distinction between the elastic and plastic region is determined by the upper and lower yield point.

These bands (may be more than one, either at both fillets or at different stress concentration points), are called Ludder Bands or Hartmann Lines.

After traversing the entire region, the flow curve starts to increase like the normal curve for ductile materials.

In steels, due to the presence of Carbon and Nitrogen, Cottrell effect comes into effect with these interstitials blocking the movement of dislocations thereby creating yield point phenomenon.

**Bauschinger effect**

Directionality of strain hardening. The yield stress in tension increases when tensile-compression cycle is subjected on a specimen due to strain hardening, however, in compression, it decreases.

Can be explained on the basis of back stresses. When loaded in tension, the dislocation pile up against an obstacle with the front dislocations closer than the rearer ones thereby creating back stress. If now the load is reversed, the back stress assists in the dislocation movement in opposite direction.

**Texture**

A non-random preferred orientation of frains in a polycrystalline material is called texture.

Texture can originate in a material when solidified or casted (growth direction) or when coated by hot dipping, vapor deposition or by various processing routes like rolling, wire drawing, extrusion, forging

**Recovery, Recrystallisation, Grain Growth**

The microstructural and property changes occur in materials when subjected to plastic deformation at temperatures lower than the melting point.

Recovery

Annihilation of dislocations

Physical properties like electrical and thermal conductivities are recovered to their pre-cold worked states.

Sub-grain formation

Recrystallisation

New set of strain fee and equiaxed grains are formed

Driving force is the difference in internal energy

Mechanical Properties return back to pre-cold worked condition

Grain-growth

With further increase in temperature, grain growth takes place

Strain-free grains grow.

Driving force is decrease in grain boundary energy

 is grain diameter after time t, is initial grain size

 are constants

**Fracture**

Fracture is the separation of a body into two or more pieces in response to a static load which is applied at a temperature lower than the melting point of the material.

Fracture involves crack initiation and crack propagation.

**Classification**

Types of fracture

Ductile and Britle

Ductile

Excessive Plastic deformation near the crack

Crack propagation is slow

More strain energy is required to induce ductile cracks

Dimples can be seen on the fractured surface

Brittle

Crack Propagation speed is high with negligible or no plastic deformation

Occurs suddenly without any warning

Fracture may occur by cleavage (fracture on certain crystallographic planes)

Grain boundary fracture also called intergranular fracture.

**Modes of fracture**

There are three modes of fracture, Mode I, Mode II and Mode III



The stress intensity factor, is given by

Fracture Mechanics

Theoretical Fracture Strength where E is the modulus which is vastly different from the experimentally observed ones

**Griffith’s theory and its modification**

According to Griffith, materials always have pre-existing cracks. He mainly considered glass for his work. He considered a large plate with a central crack under a remote stress and calculated the change in energy with crack size.

This is Griffiths criterion. It means that a pre-existing crack of size greater than 2a will grow spontaneously till the above equation is satisfied.

Orowan’s modification

For metals Orowan proposed that the energy used for producing new surface by fracture is not the surface energy , but the plastic deformation is also to be taken in account. The griffith’s equation is thus modified to

Where includes the plastic work in generating fracture surface.