LECTURE NOTES

On

Mechanical Metallurgy

ORISSA SCHOOL OF MINING ENGINEERING
Government of Odisha
ଓଡିଶା ଖଣି ଯାନ୍ତ୍ରିକ ବିଦ୍ୟାଳୟ, କେଓଁଝର

Course Co-ordinator: TUSHAR DAS PATTANAYAK, SR. LECT (MET)

Metallurgical Engineering Department

Orissa School of Mining Engineering Keonjhar

Course code:Th2, Semester: 6^{th} Sem

Vision and Mission of the Department

VISION: To offer quality technical education in the field of Metallurgical Engineering with orientation towards industry, entrepreneurship, higher education and to strive for developing professionally competent technicians meeting the needs of the global economy.

MISSION:

M1: To develop students in the field of Metallurgical Engineering as highly motivated, skillful and qualified manpower for employment and higher learning

M2: To promote a conducive environment for all round development of students.

M3: To promote linkages with external agencies to meet changing needs of industry and society.

M4: To Improve Laboratories

Program Education Objectives (PEOs)

PEO 1: Diploma professionals will be able to make a successful career in metallurgical industries or higher studies to meet the needs of future requirements.

PEO 2: Diploma metallurgists will have technical and behavioral competencies through adequate exposure to industry.

PEO 3: To impart technological knowledge and skills for solving real-time engineering problems.

PEO 4: To develop human resources with capabilities of effective communication, moral values and social responsibilities

MECHANICAL METALLURGY (Th-02)

Name of the Course: Diploma in Metallurgical Engineering			
Course code:		Semester	6^{th}
Total Period:	60	Examination :	3 hrs
Theory periods:	4P / week	Internal Assessment:	20
Maximum marks:	100	End Semester Examination	80

A.RATIONALE:

Major bulk of metals and alloys are converted to useable shapes by a group of manufacturing processes utilizing plastic deformation. These processes are important for a metallurgical engineer and are the subject matter of this topic.

B.OBJECTIVES:

Upon the completion of the course the students will have knowledge about:

1. Types of defects in crystal and their relation with plastic deformation.
2. Elastic and plastic behavior of metals with criteria for yielding.
3. Plastic deformation of single crystal and polycrystalline aggregate.
4. Strengthening mechanism
5. Working of metals - hot working and cold working.
6. Processes like rolling, forging, extrusion, drawing, sheet metal forming etc.

C. TOPIC WISE DISTRIBUTION OF PERIODS		
SL.NO.	**TOPIC**	**PERIODS**
1	Introduction	08
2	Deformation of metals	08
3	Strengthening mechanism	10
4	Fundamentals of metal working	06
5	Recovery Recrystallization & grain growth	04
6	Rolling	06
7	Forging	05
8	Extrusion	05
9	Wire drawing	04
10	Elementary concept of deep drawing Sheet working metal	04
	TOTAL	75

D.COURSE CONTENTS :

1.0 Introduction

1.1 Dislocation, types, its basic behavior & role in deformation.

1.2 Dislocation in various crystals

1.3 Source of dislocation

1.4 Twinning & deformation.
1.5 Slip & Deformation.

2.0 **Deformation of metals**:

- 2.1 Explain the elastic & plastic behavior of metals.
- 2.2 Explain yielding criteria.
- 2.3 Derive critically resolved shear stress.
- 2.4 Explain deformation of polycrystalline aggregates.

3.0 **Strengthening mechanism**:

- 3.1 Explain strengthening mechanism
- 3.2 Describe the role of grain boundary in strengthening
- 3.3 Define Hall Petch equation
- 3.4 Describe yield point phenomenon.
- 3.5 Explain strain-aging
- 3.6 Explain solid solution strengthening from fine particles
- 3.7 Describe fiber strengthening
- 3.8 Describe martensitic strengthening
- 3.9 Explain strain hardening
- 3.10 Describe Bauschinger's effect.

4.0 **Fundamentals of Metal working**:

- 4.1 Classify different metal working process.
- 4.2 Explain hot working and cold working of metals and alloys
- 4.3 State the advantages and disadvantages of hot and cold working

5.0 **Recovery, recrystallization and grain growth**

- 5.1 Explain the following phenomena,
  - (a) Recovery
  - (b) Recrystallization
  - (c) Grain growth

6.0 **Rolling:**

- 6. 1 Explain principles of rolling
- 6.2 Compare between hot rolling and cold rolling.
- 6.3 Explain the types of roll pass-open pass and box pass.
- 6.4 State different types of rolling detects and their control

7.0 **Forging:**

- 7.1 Explain types of forging process
- 7.2 Describe the properties of forged products
- 7.3 Explain the defects of forged products and their control

8.0 **Extrusion:**

- 8.1 Explain the elementary principle of extrusion
- 8.2 Classify the defects in extruded product
- 8.3 Explain the manufacturing of seamless pipes

9.0 **Wire drawing:**

- 9.1 Explain the elementary principle of wire drawing
- 9.2 Classify the defects of wire drawing

10.0 **Forming methods**

10.1 Describe the elementary concept of deep drawing
10.2 Explain different sheet metal forming - bending shearing aid blanking

Syllabus to be covered up to I.A.

Topics :1,2,3 & 4

Learning Resources:

Sl.No	Title of the Book	Name of Authors	Name of Publisher
1.	Mechanical metallurgy	Dieter	Mc Graw Hill
2.	Introduction to physical metallurgy	Avner	Mc Graw Hill
3.	Physical metallurgy principles	Reed Hill	EWP
4.	Mechanical Treatment of metals	R.N. Parkins	Geoge Allen &Unuin
5.	Mechanical Testing of Materials	C.Mohapatra	JJTP,Bhubaneswar

1.0 Introduction

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

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***.

1.1 Dislocation, types, its basic behavior & role in deformation.

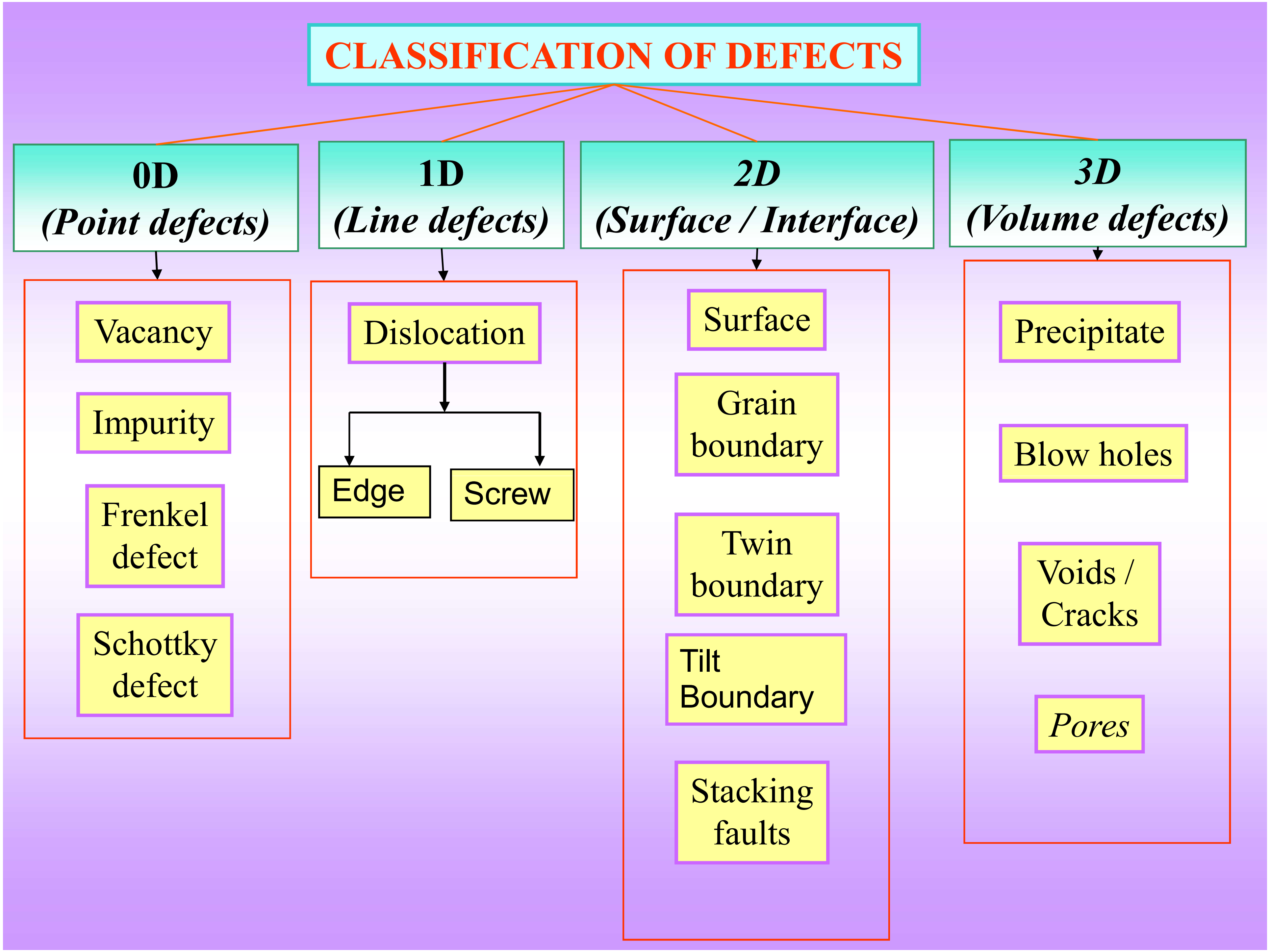
DEFECTS IN CRYSTALS

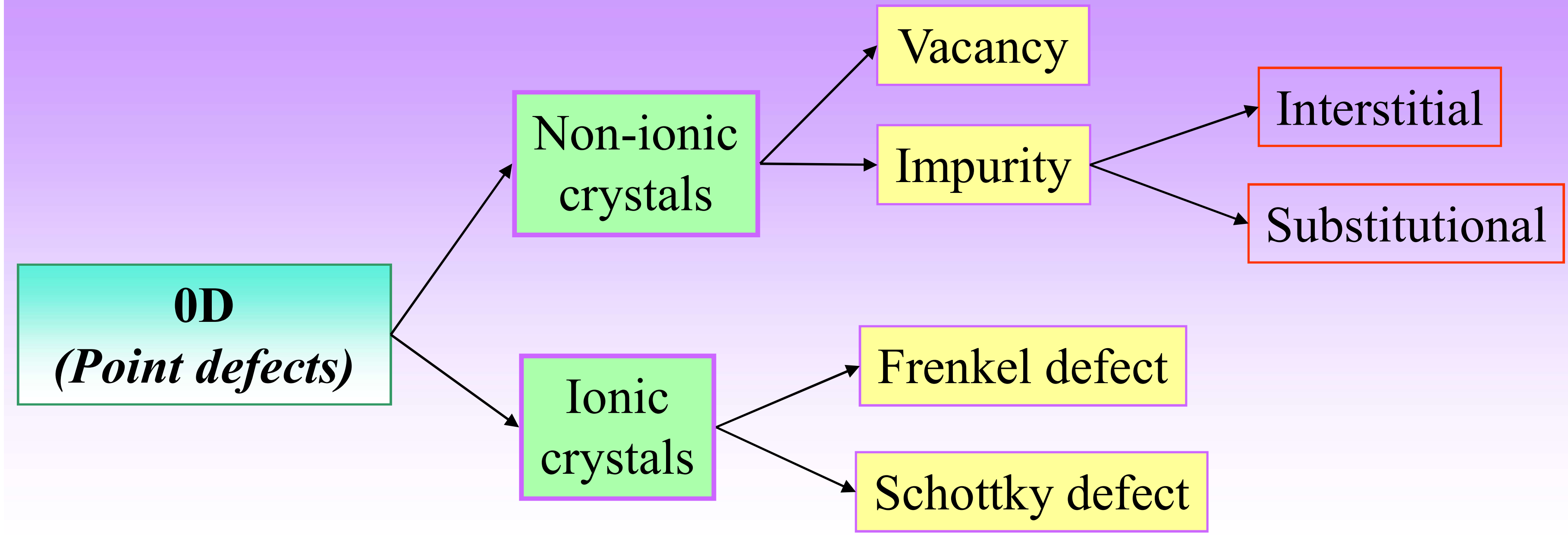
- Point defects
- Line defects
- Surface Defects
- Volume Defects

PROPERTIES

- Structure sensitive
  (Mechanical Properties)
  E.g. Yield stress, Hardness
- Structure Insensitive
  (Physical Properties)
  E.g. Density, elastic modulus

PROPERTY: A measurable quantity which gives chemical and physical characteristics of a substance.

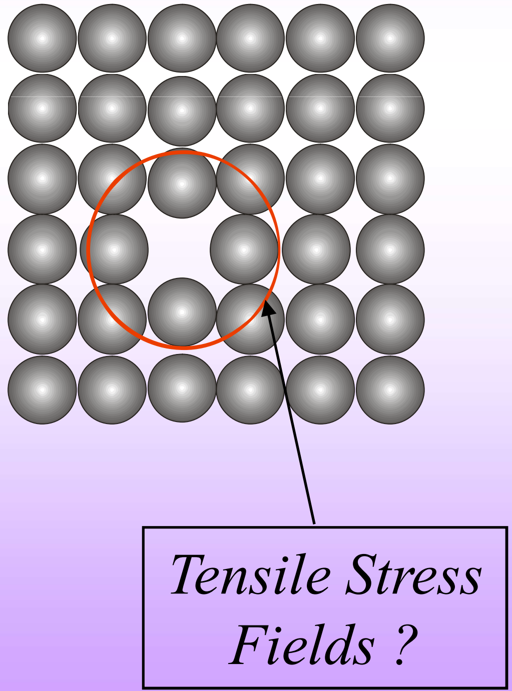

CLASSIFICATION OF DEFECTS
0D
(Point defects)
1D
(Line defects)
2D
(Surface / Interface)
3D
(Volume defects)
Vacancy
Impurity
Frenkel defect
Schottky defect
Dislocation
Edge
Screw
Surface
Grain boundary
Twin boundary
Tilt Boundary
Stacking faults
Precipitate
Blow holes
Voids / Cracks
Pores

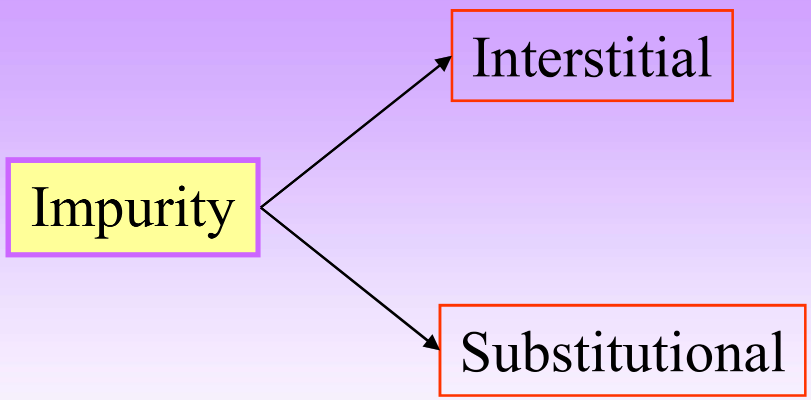


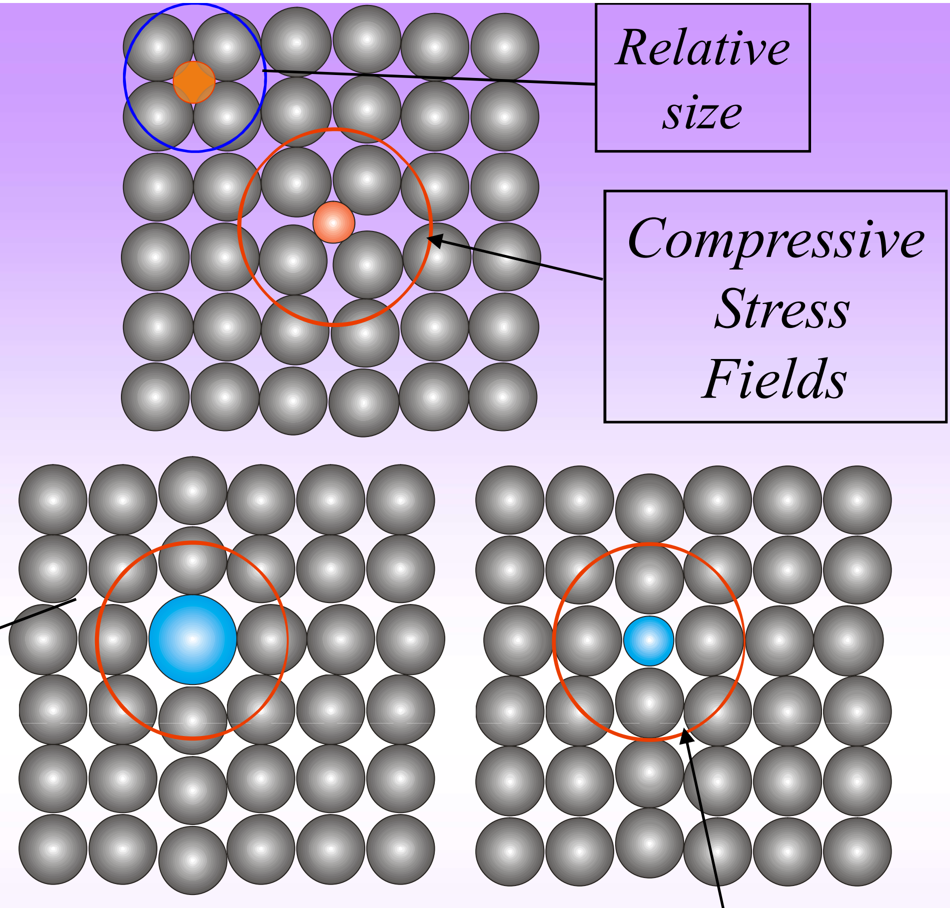
- Imperfect point-like regions in the crystal about the size of 1-2 atomic diameters

Vacancy

- Missing atom from an atomic site
- Atoms around the vacancy displaced
- Tensile stress field produced in the vicinity







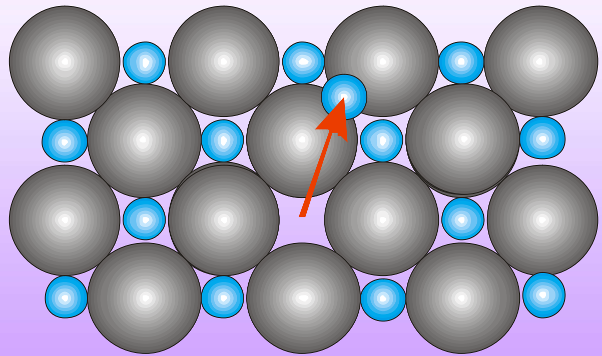
- **SUBSTITUTIONAL IMPURITY**
  - Foreign atom replacing the parent atom in the crystal
  - E.g. **Cu** sitting in the lattice site of FCC-**Ni**
- **INTERSTITIAL IMPURITY**
  - Foreign atom sitting in the void of a crystal
  - E.g. C sitting in the octahedral void in HT FCC-**Fe**

Ionic Crystals

- Overall electrical neutrality has to be maintained

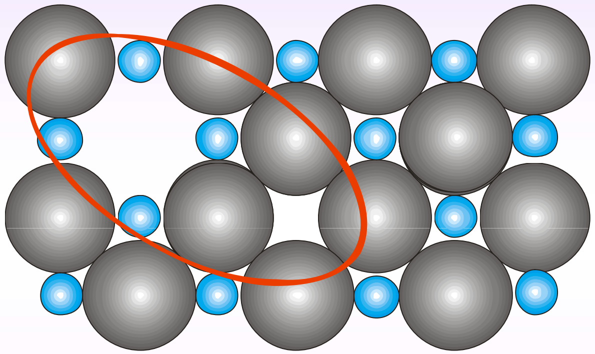
Frenkel defect

- Cation (being smaller get displaced to interstitial voids
- E.g. AgI, CaF_2



Schottky defect

- Pair of anion and cation missing from the lattice site
- E.g. Alkali halides

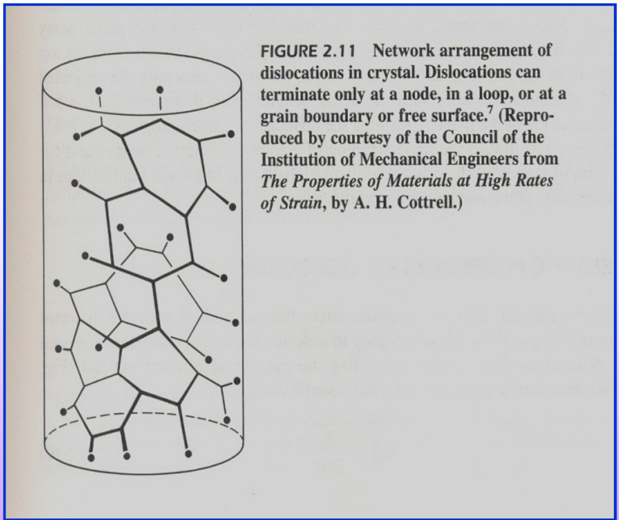


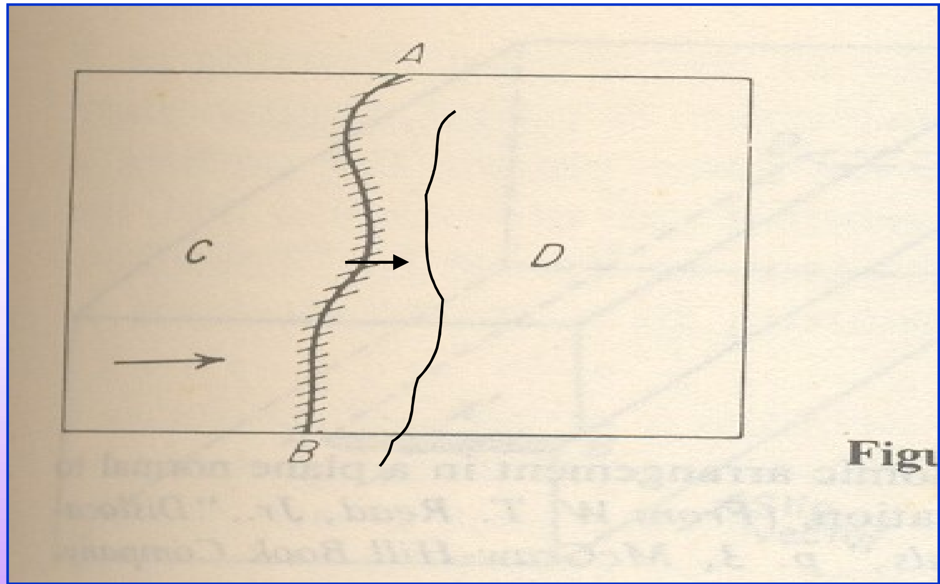
Line defect- Dislocation

Dislocations- Most important 1-D or line defects. They extend in a crystal as a line or 1-D net of lines.

Responsible for slip- Most important mechanism of plastic deformation.

Dislocation is a line separating slipped and unslipped region of a crystal.





Deformation by Slip

1.5 Slip & Deformation.

The usual method of plastic deformation is slip.

This is sliding of one block of crystal over other block.

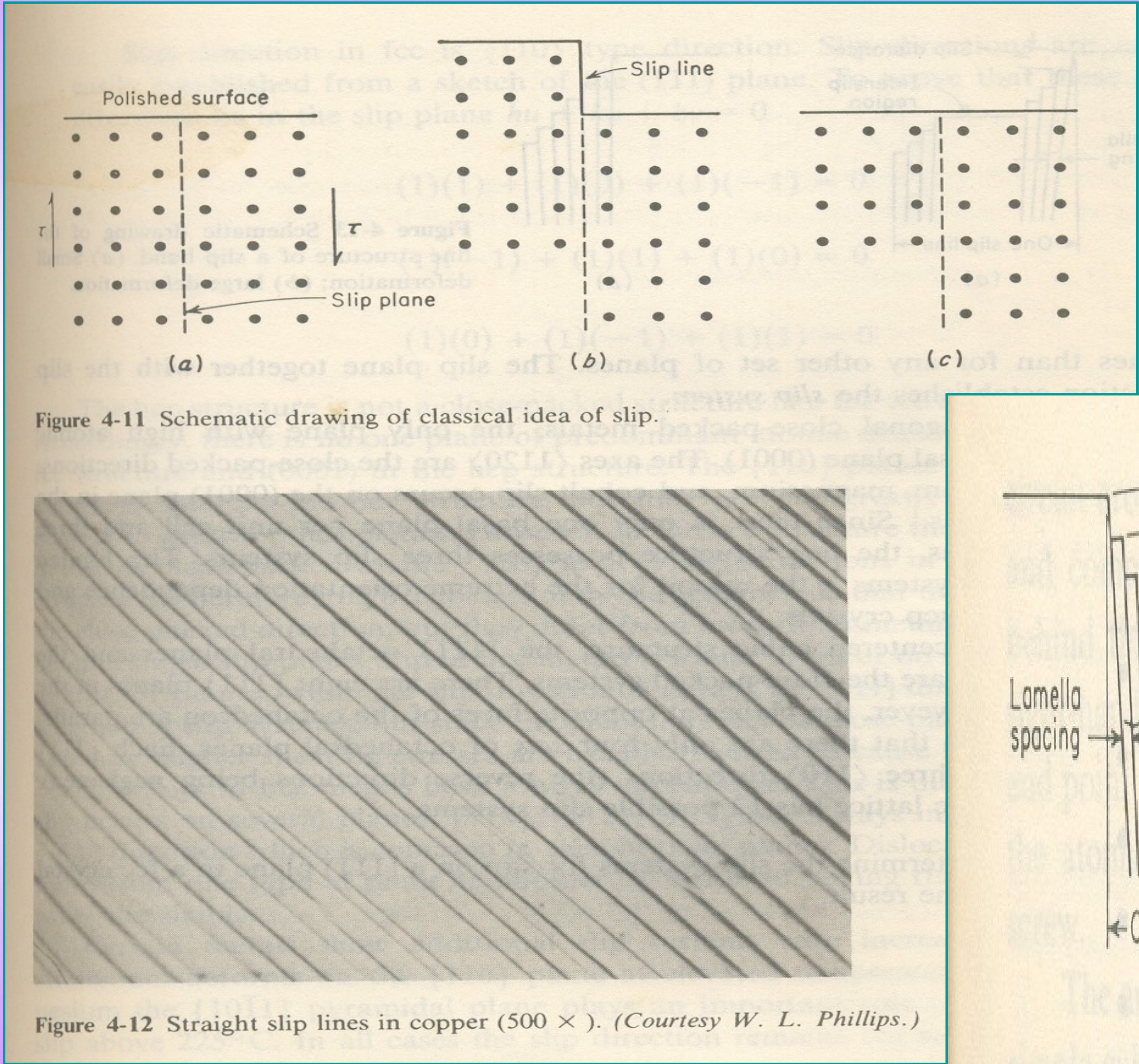
This takes place along a definite crystallographic plane (slip plane) and definite crystallographic direction (slip direction).

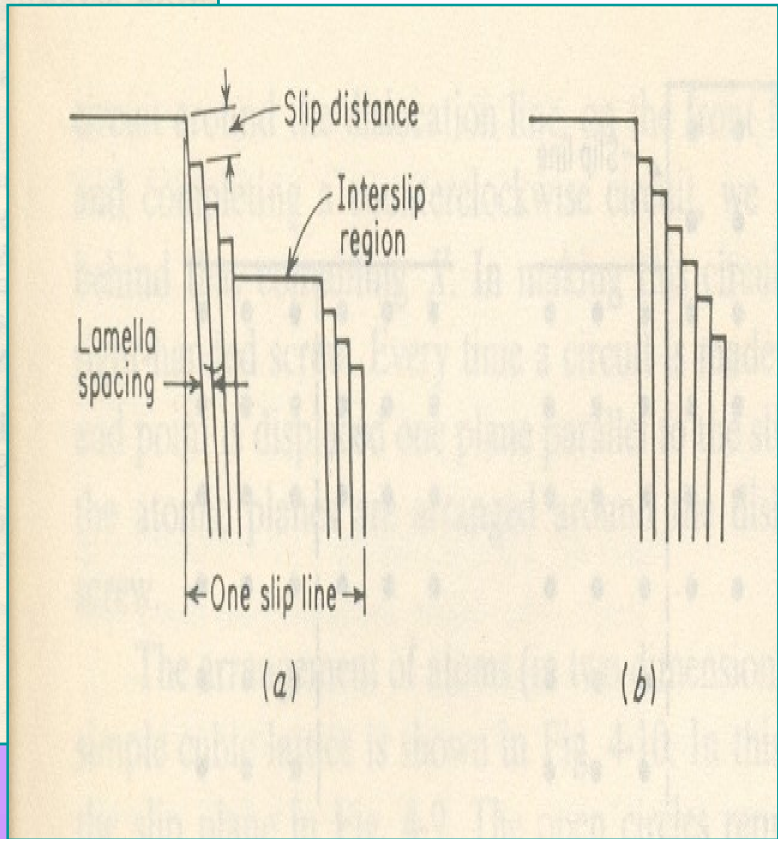
Crude approximation, it is like distortion produced in a deck of cards when pushed from one end.

Slip in a crystal can be understood with the help of the Fig.1

Fig. 1.a Classical Idea of Slip & Slip Lines

Fig. 1.b Fine Structure of Slip Band



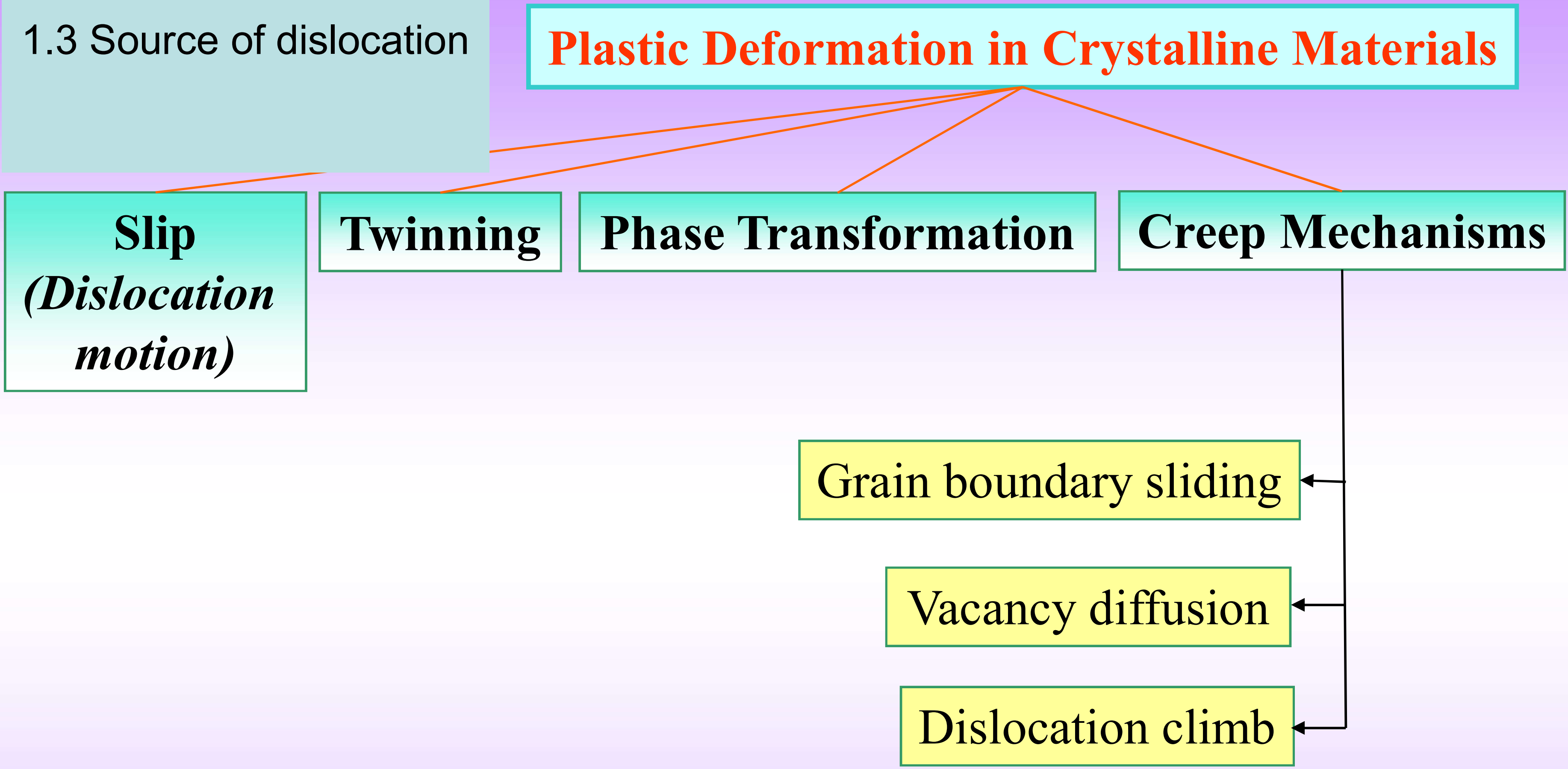


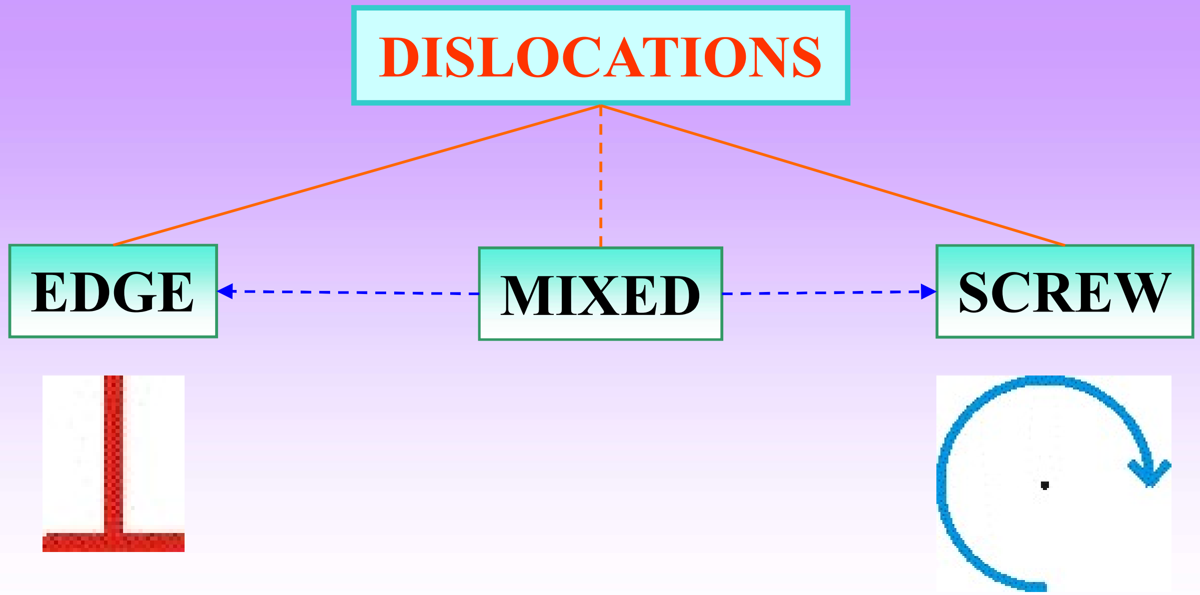
1.2 Dislocation in various crystals

DISLOCATIONS

- Edge dislocation
- Screw dislocation

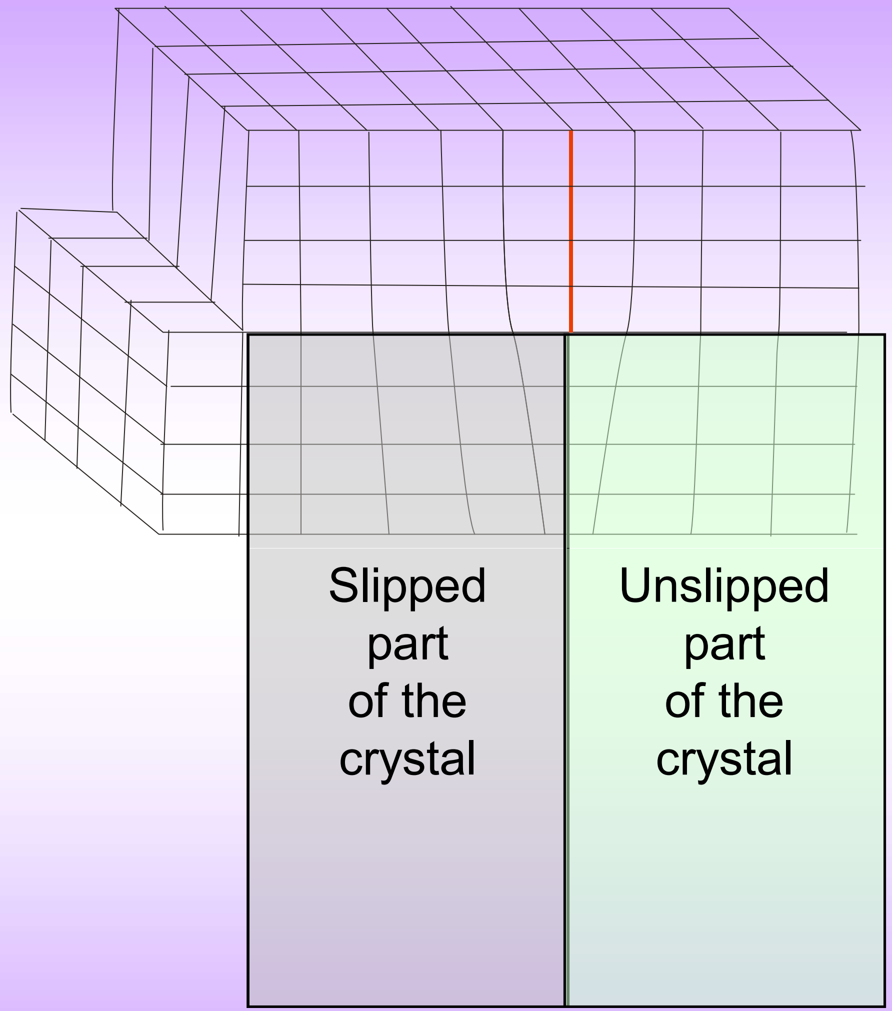
1.3 Source of dislocation





❑ Usually dislocations have a mixed character and *Edge* and *Screw* dislocations are the ideal extremes

▪ Geometrically necessary dislocations



Dislocation is a boundary between the slipped and the unslipped parts of the crystal lying over a slip plane

Edge Dislocation

Fig – A represents a simple cubic lattice under an external shear stress. The amount of slip or displacement is assumed to be one atomic spacing. The result of this shear is shown in the Fig. – B.

- This leaves an extra half plane cd below the slip plane in the right hand side, outside the crystal.
- It will also produce an extra half plane located above the slip plane and in the centre of the crystal.
- All other planes are realigned and continuity is maintained.
- The boundary of additional plane is called an edge dislocation.

Fig. Continued… Edge Dislocation

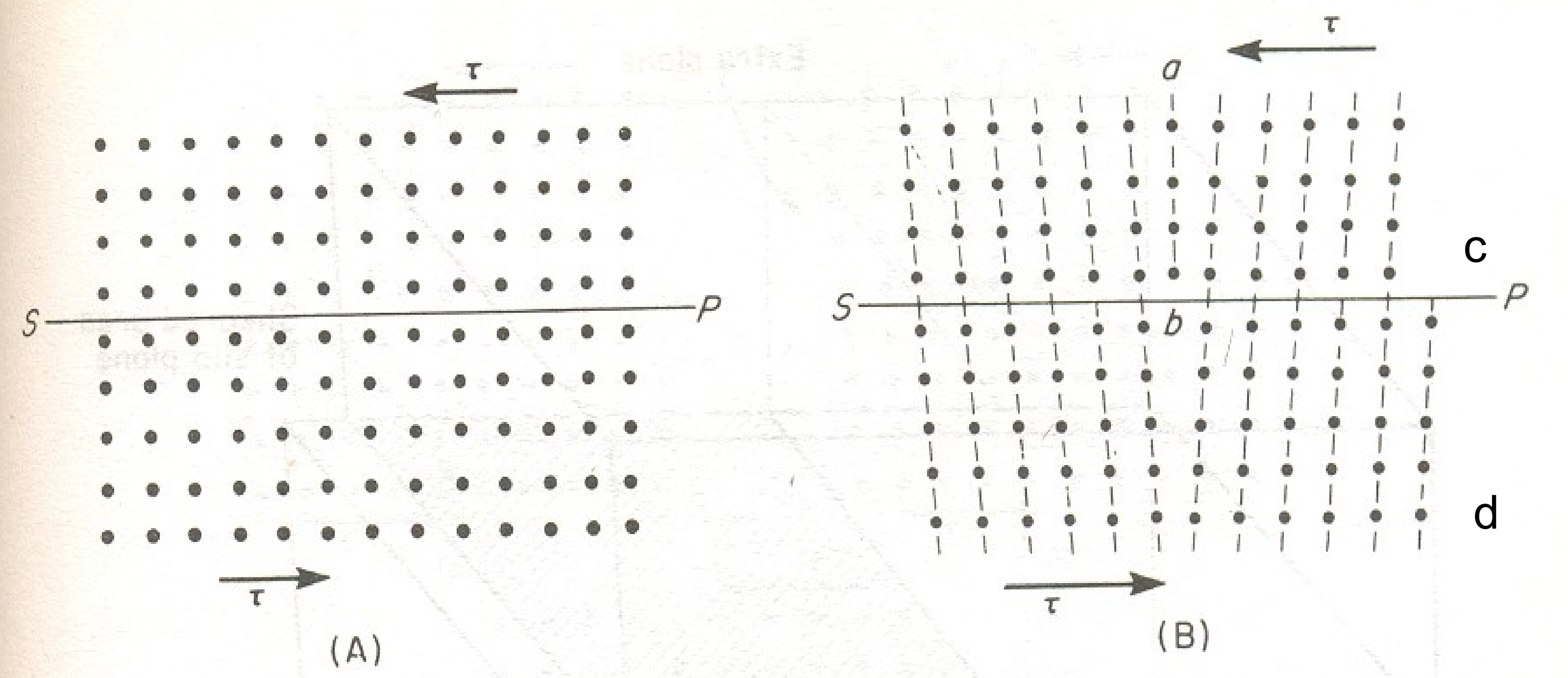


Fig. 4.10 An edge dislocation. (A) A perfect crystal. (B) When the crystal is sheared one atomic distance over part of the distance *S–P*, an edge dislocation is formed.

Edge Dislocation

- Fig. 4.5 represents a 3 – D sketch of the edge dislocation.
- The figure clearly shows that dislocation has the dimension of a line.
- Dislocation line marks the (separates) boundary between sheared and un-sheared part of the slip plane.

  This is the basic characteristics of a dislocation line.

  Dislocation may be defined as a line that forms a boundary on a slip plane between slipped and un-slipped region.

Fig. Continued Edge Disl.

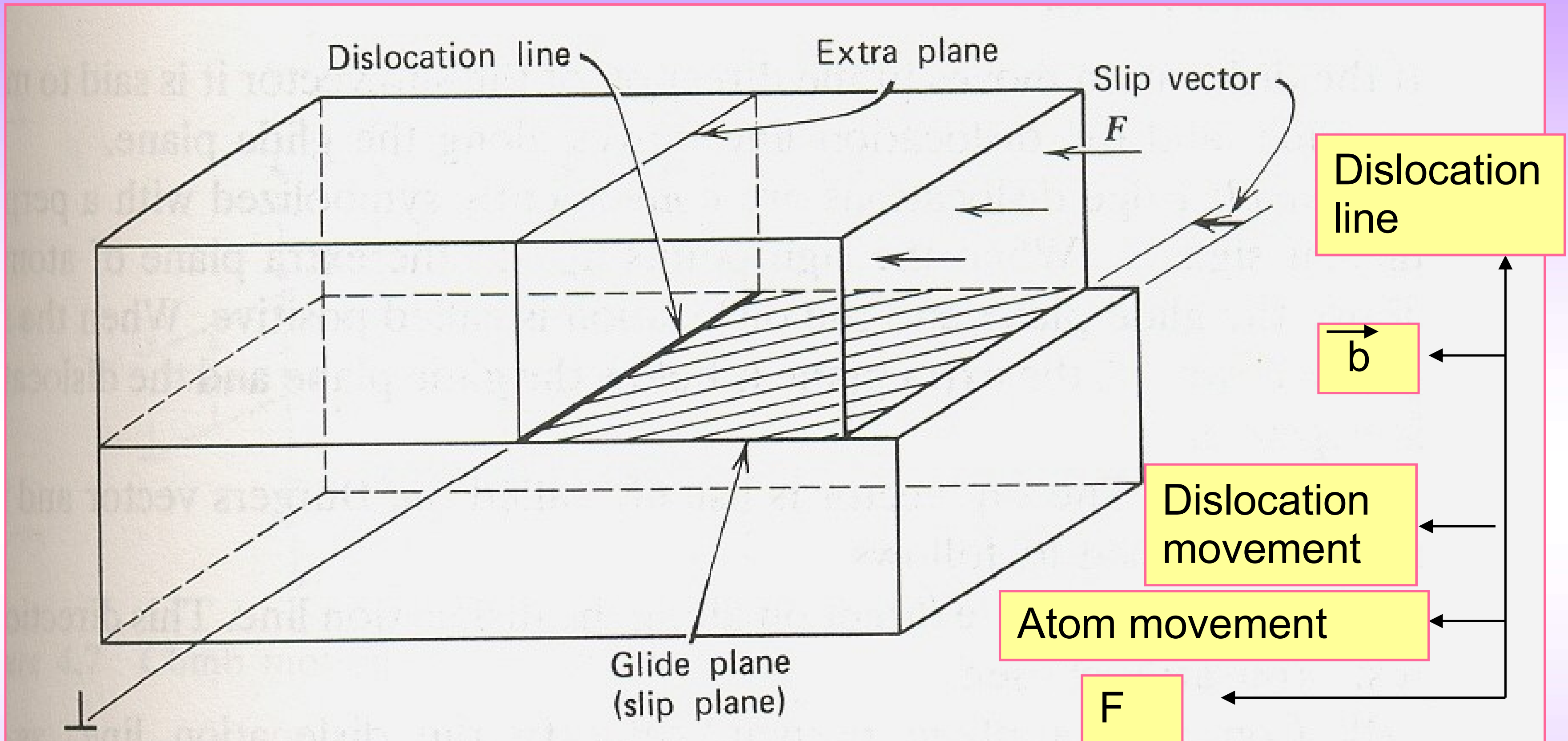


Figure **4.5** The edge dislocation.

Displacement vector or slip vector: Burgers vector, $\vec{b}$

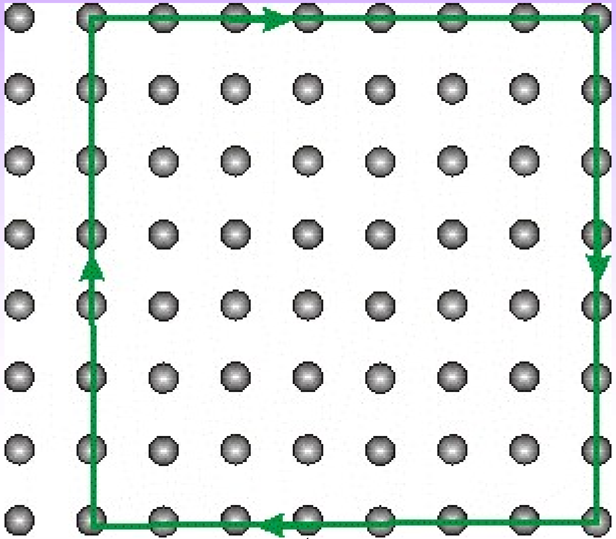
A dislocation is associated with one vector:

$\vec{b} \rightarrow$ The Burgers vector

The magnitude and direction of a dislocation can be determined by a vector called burgers vector.

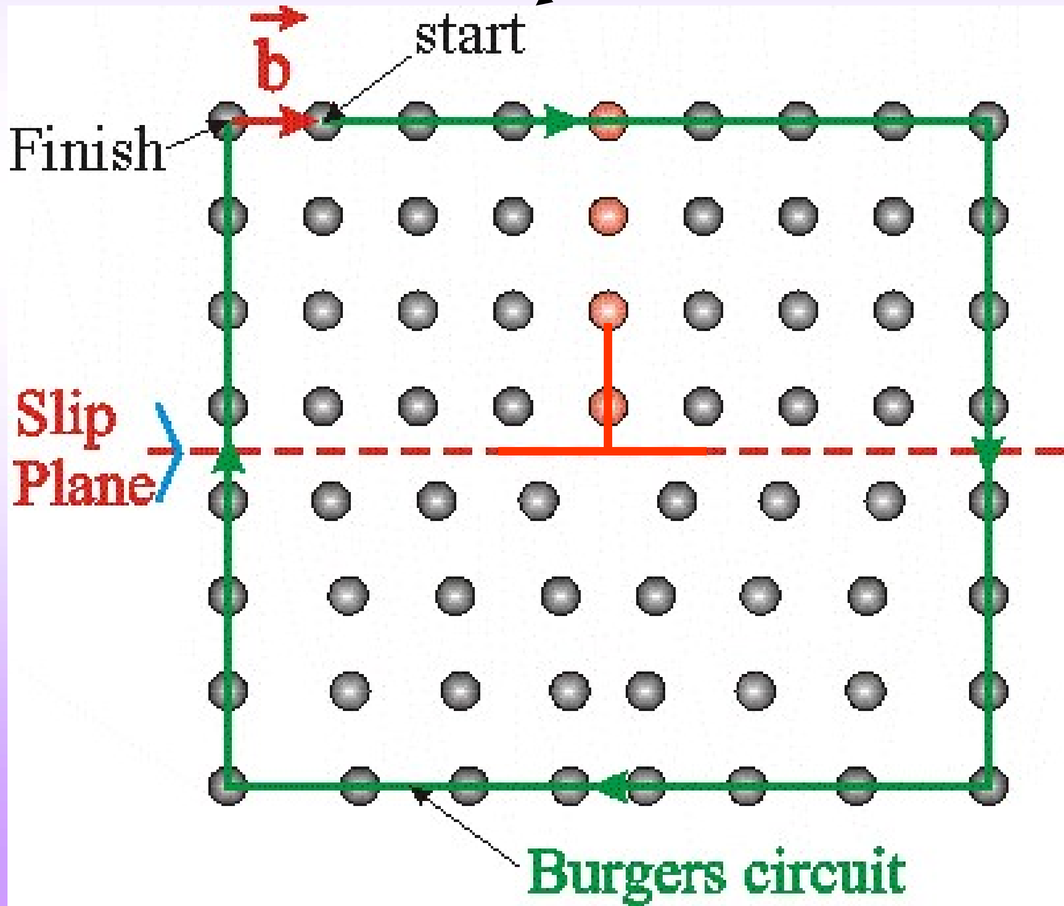
Burgers Vector

Edge dislocation



Perfect crystal

Crystal with edge dislocation



RHFS:
Right Hand Finish to Start convention

Fig. Continued Edge Disl.

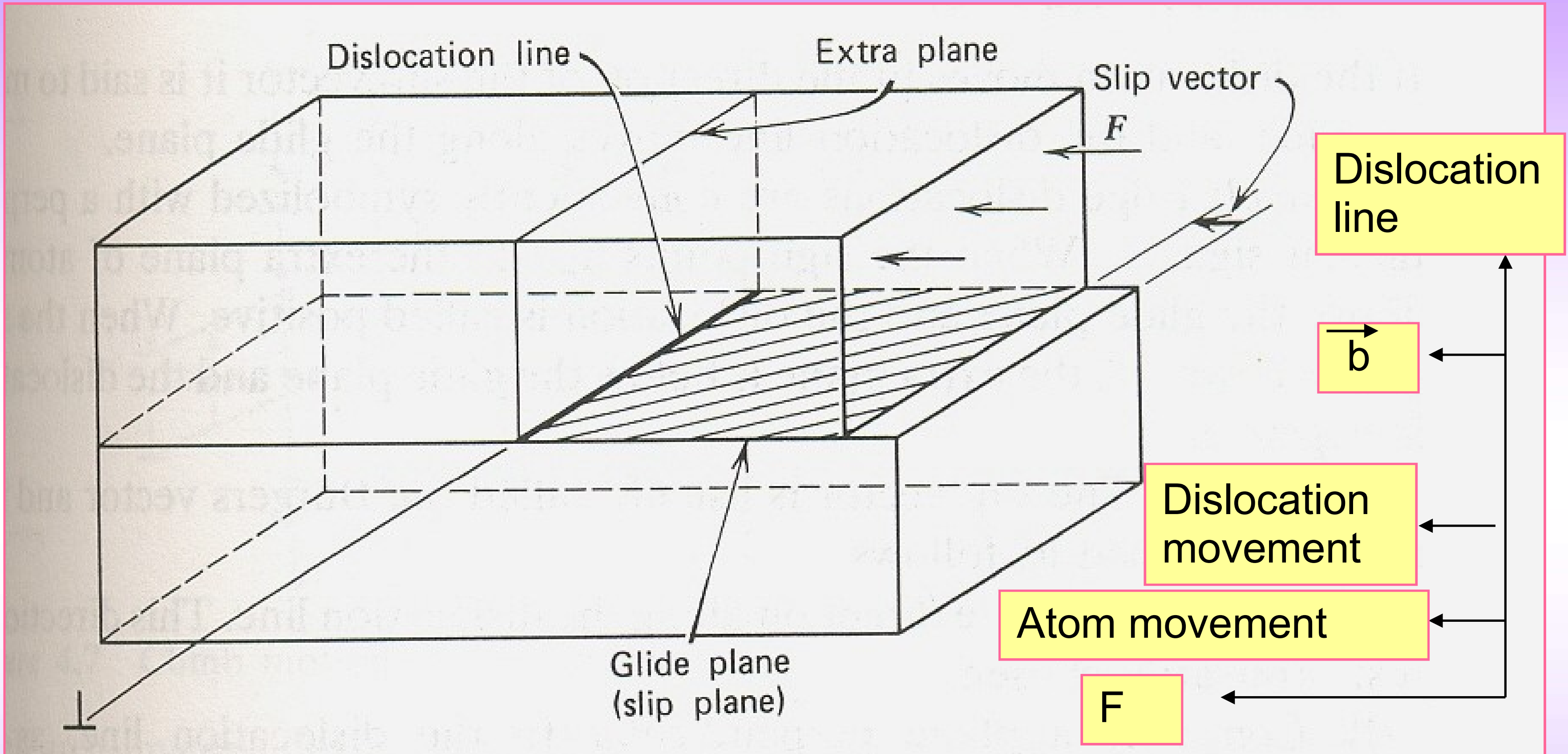
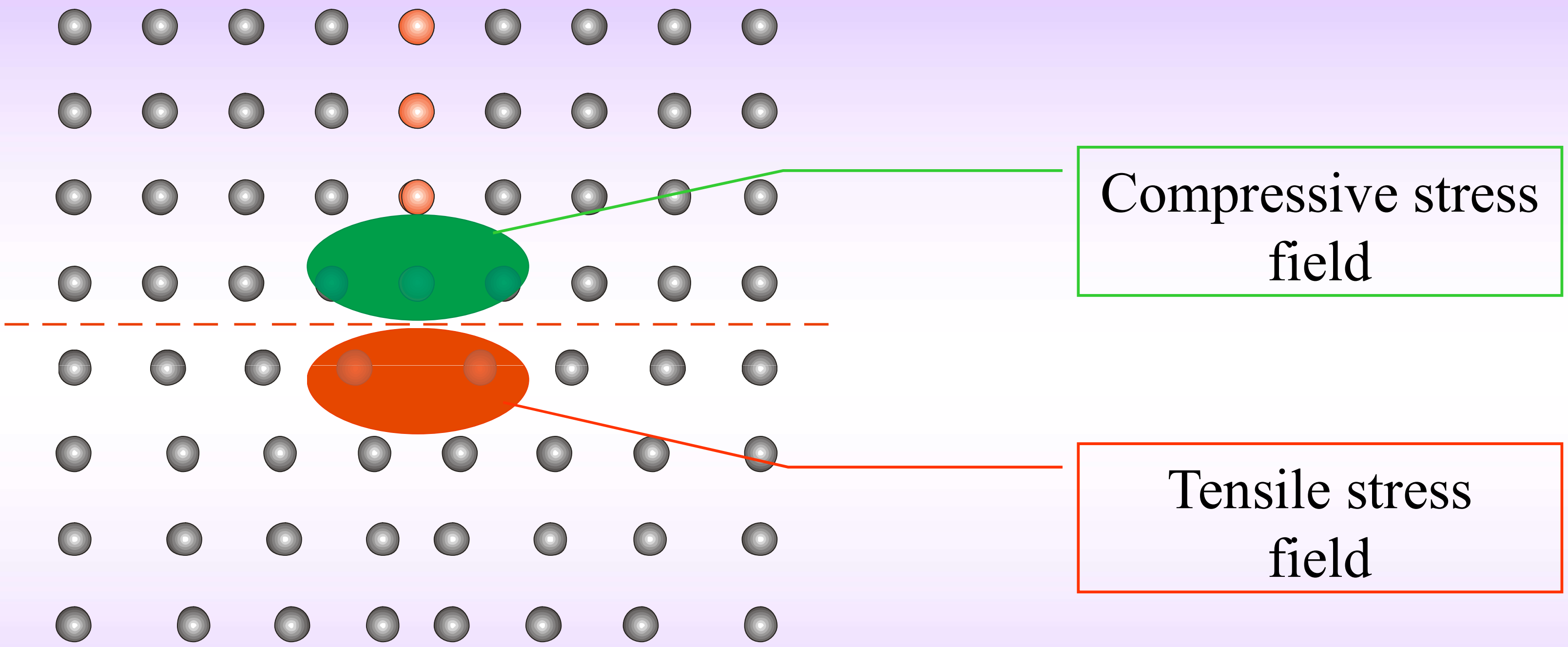


Figure **4.5** The edge dislocation.

Displacement vector or slip vector: Burgers vector, $\vec{b}$

- Dislocation is a boundary between the slipped and the unslipped parts of the crystal lying over a slip plane
- The intersection of the extra half-plane of atoms with the slip plane defines the dislocation line *(for an edge dislocation)*
- Direction and magnitude of slip is characterized by the Burgers vector of the dislocation
  (A dislocation is born with a Burgers vector and expresses it even in its death!)
- The Burgers vector is determined by the Burgers Circuit
- Right hand screw (finish to start) convention is used for determining the direction of the Burgers vector

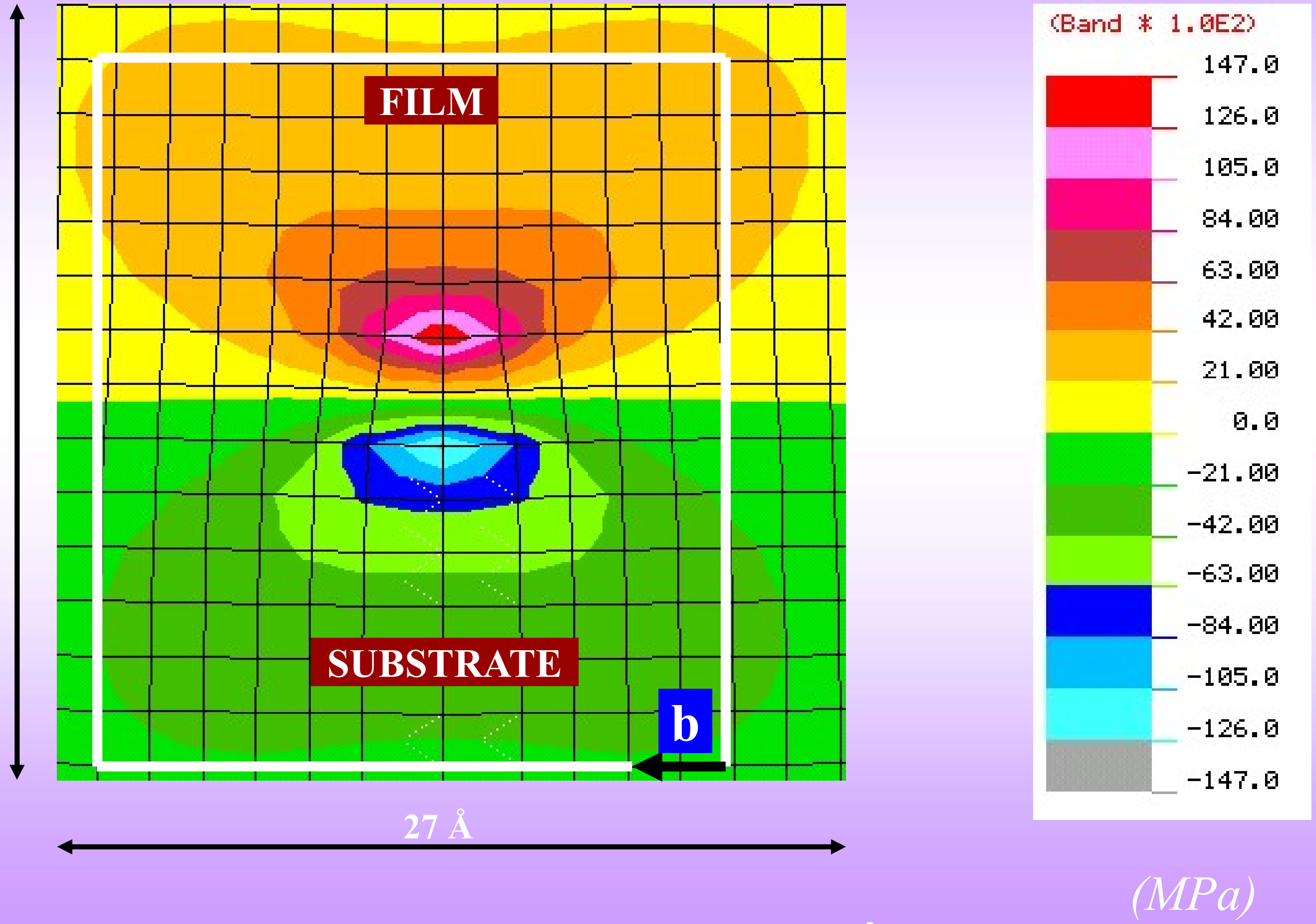
- The edge dislocation has compressive stress field above and tensile stress field below the slip plane
- Dislocations are non-equilibrium defects and would leave the crystal if given an opportunity



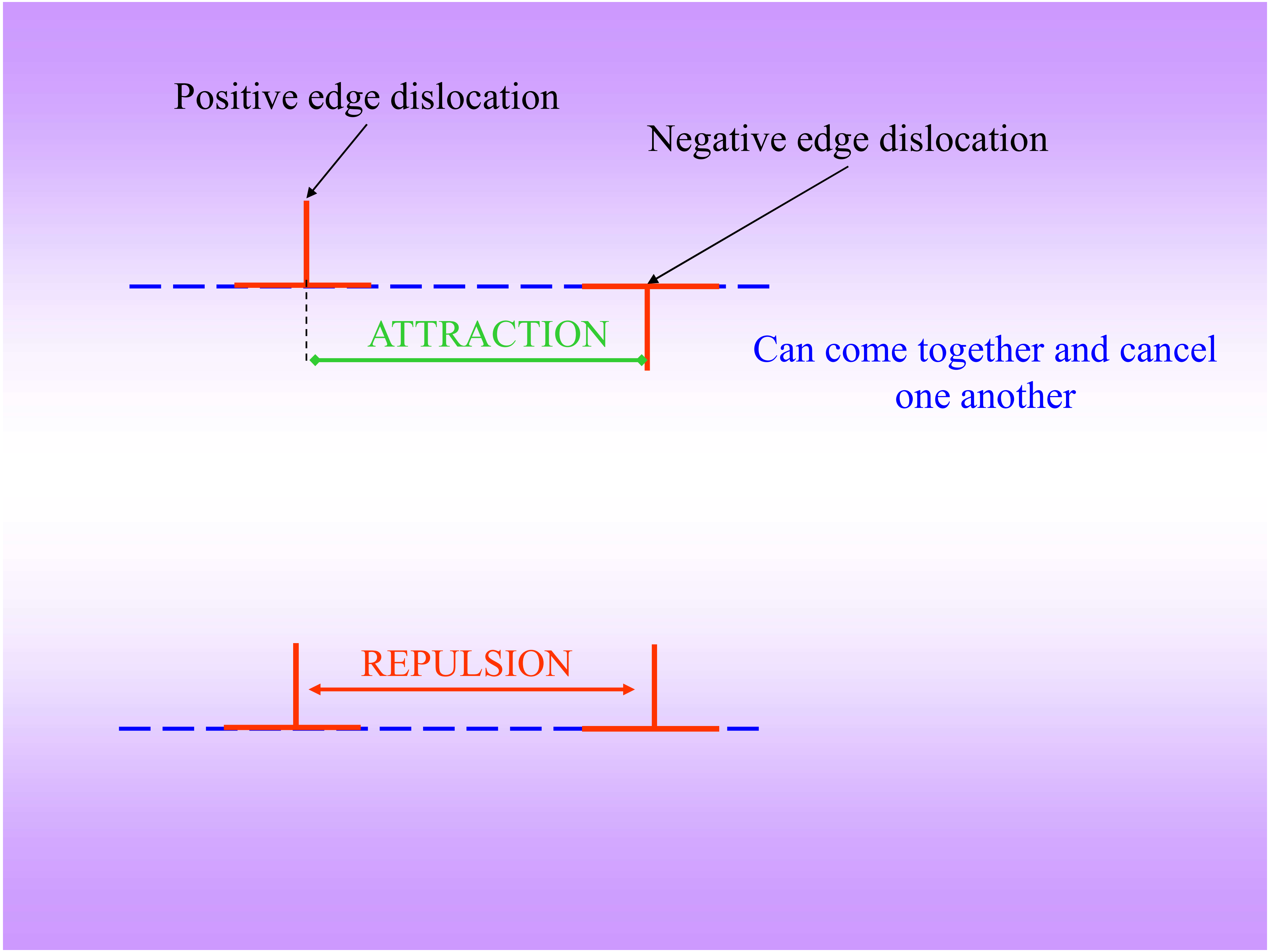
Compressive stress field
Tensile stress field

STRESS FIELD OF A EDGE DISLOCATION

σ_X – FEM SIMULATED CONTOURS



(x & y original grid size = b/2 = 1.92 Å)

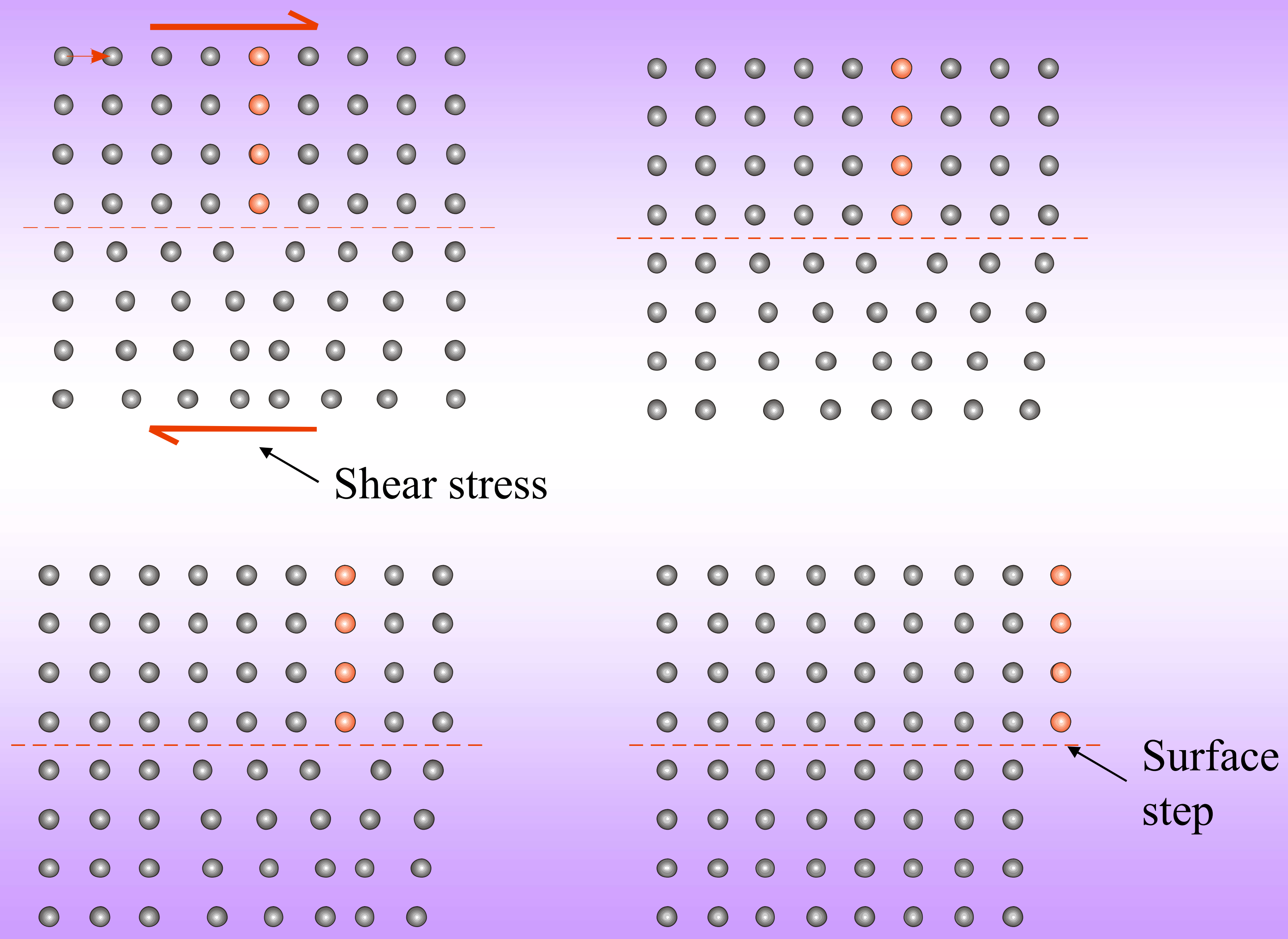

Positive edge dislocation
Negative edge dislocation
ATTRACTION
Can come together and cancel one another
REPULSION

Motion of Edge dislocation

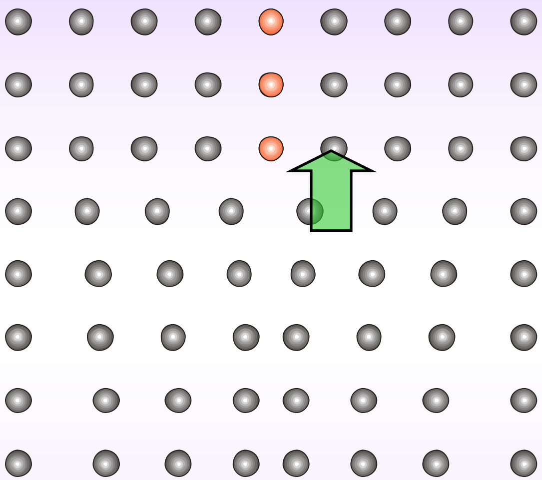
- **Conservative** *(Glide)* — Motion of dislocations On the slip plane
- **Non-conservative** *(Climb)* — Motion of dislocation ⊥ to the slip plane

- For edge dislocation: as **burgers vector** ⊥ **dislocation line**→ they define a plane → *the slip plane*
- Climb involves addition or subtraction of a row of atoms below the half plane
  - ► +ve climb = climb up → removal of a plane of atoms
  - ► –ve climb = climb down → addition of a plane of atoms

Edge Dislocation Glide

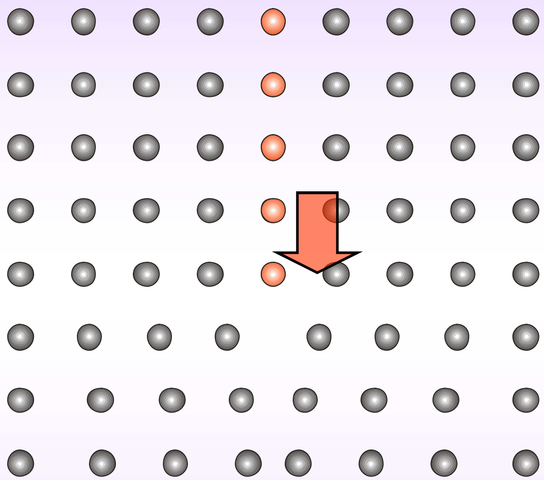


Edge Climb



Positive climb

Removal of a row of atoms



Negative climb

Addition of a row of atoms

Screw Dislocation

Schematically illustrated in Fig. 4.13 A.

- Here each small cube is considered to represent an atom. Fig. B represents the same crystal with the position of the dislocation line marked by DC.
- ABCD represents slip plane under the effect of stress. Upper front part has been sheared by one atomic distance to the left relative to the lower front portion.
- It is termed as screw dislocation because the lattice planes spiral the dislocation line DC. This can be proved by starting at point x in Fig. A then proceeding toward and around the crystal in the indicated direction. One circuit will end the crystal at point y. If it is continued it will finally end at y. This deformation is known as screw dislocation.

Dislocation line // Displacement vector and

moves perpendicular to Displacement vector

Fig. Contd…Screw Dislocation

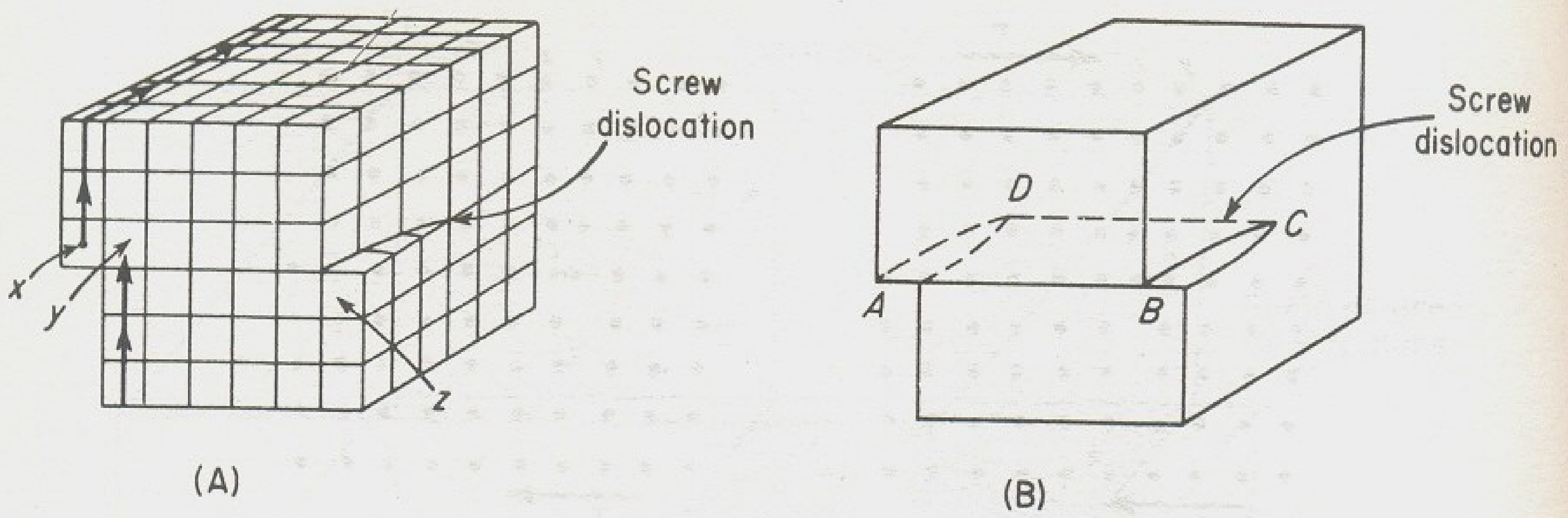
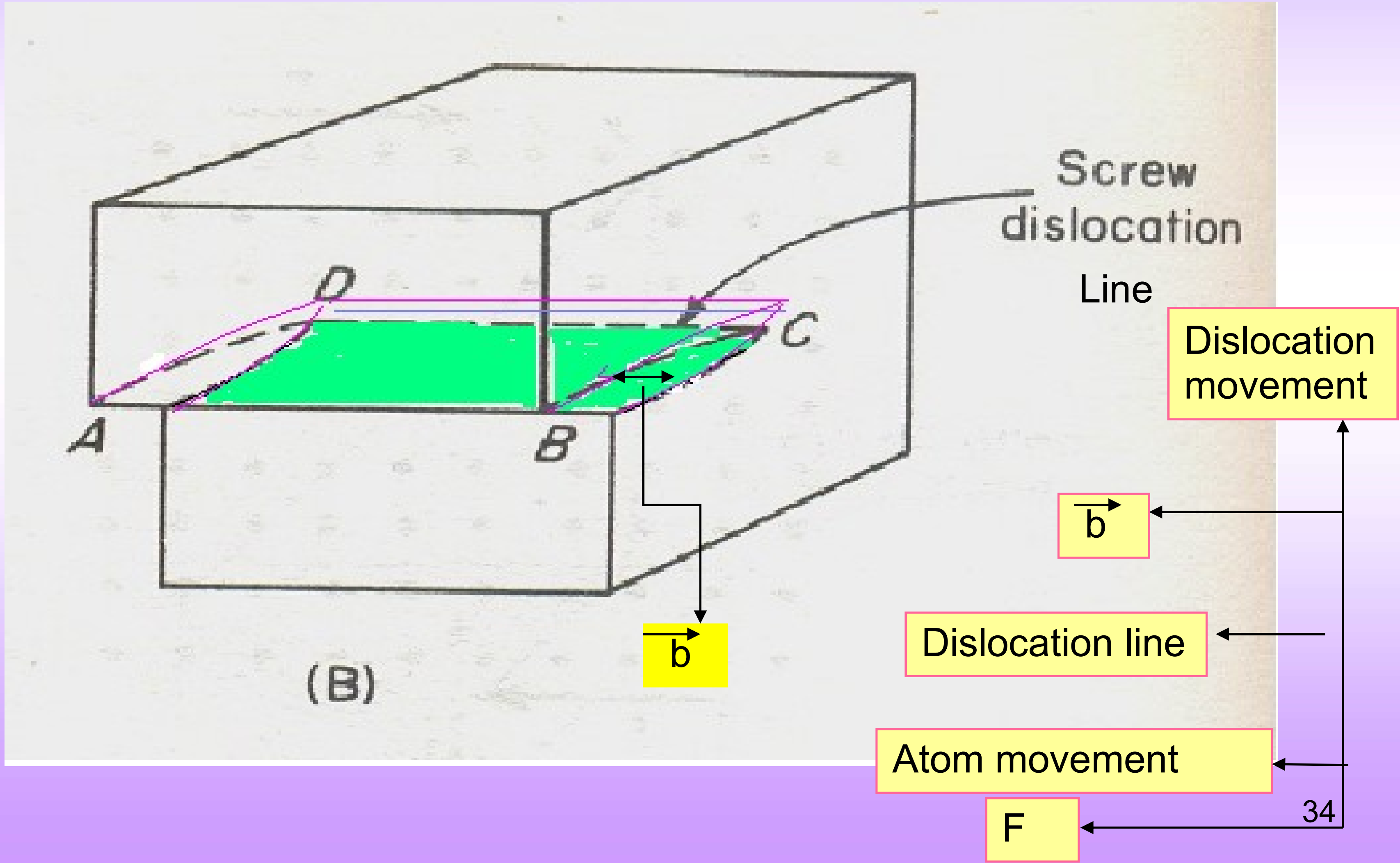
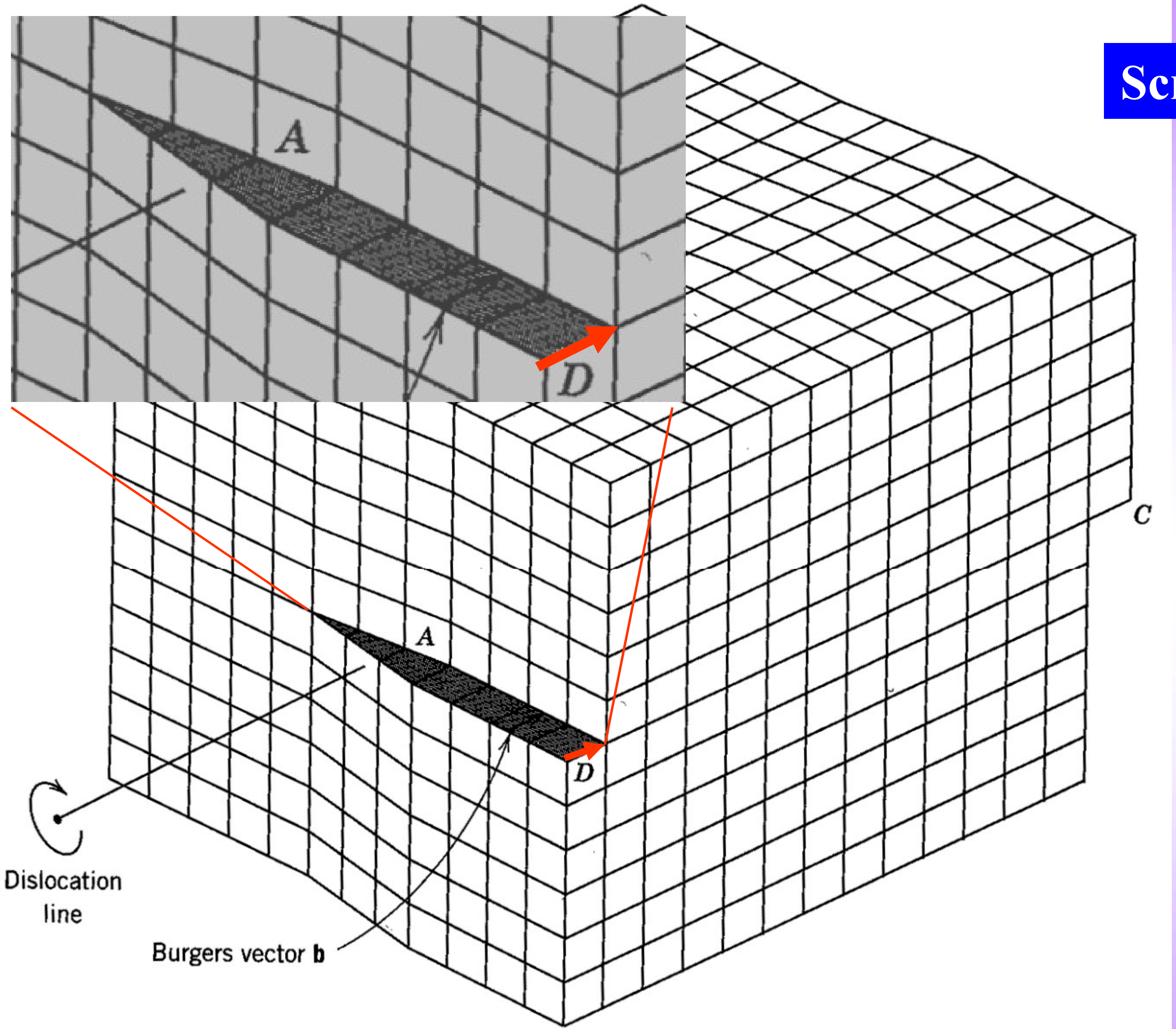


Fig. 4.13 Two representations of a screw dislocation. Notice that the planes in this dislocation spiral around the dislocation like a left-hand screw.


Screw
dislocation
Line
D
C
A
B
b
(B)
Dislocation movement
b
Dislocation line
Atom movement
F

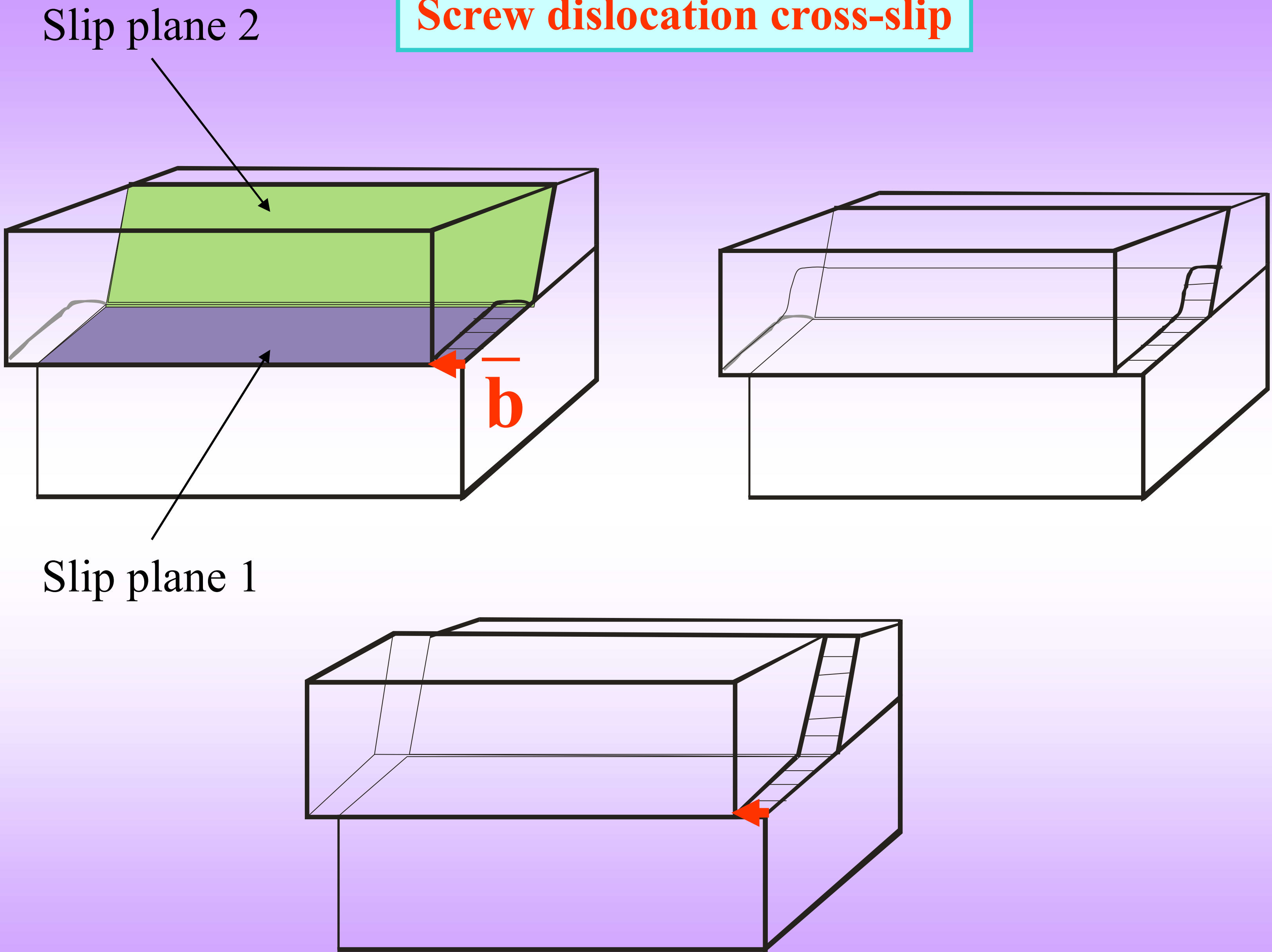
Screw dislocation



[1]

[1] Bryan Baker
chemed.chem.purdue.edu/genchem/ topicreview/bp/materials/defects3.html -

Screw dislocation cross-slip

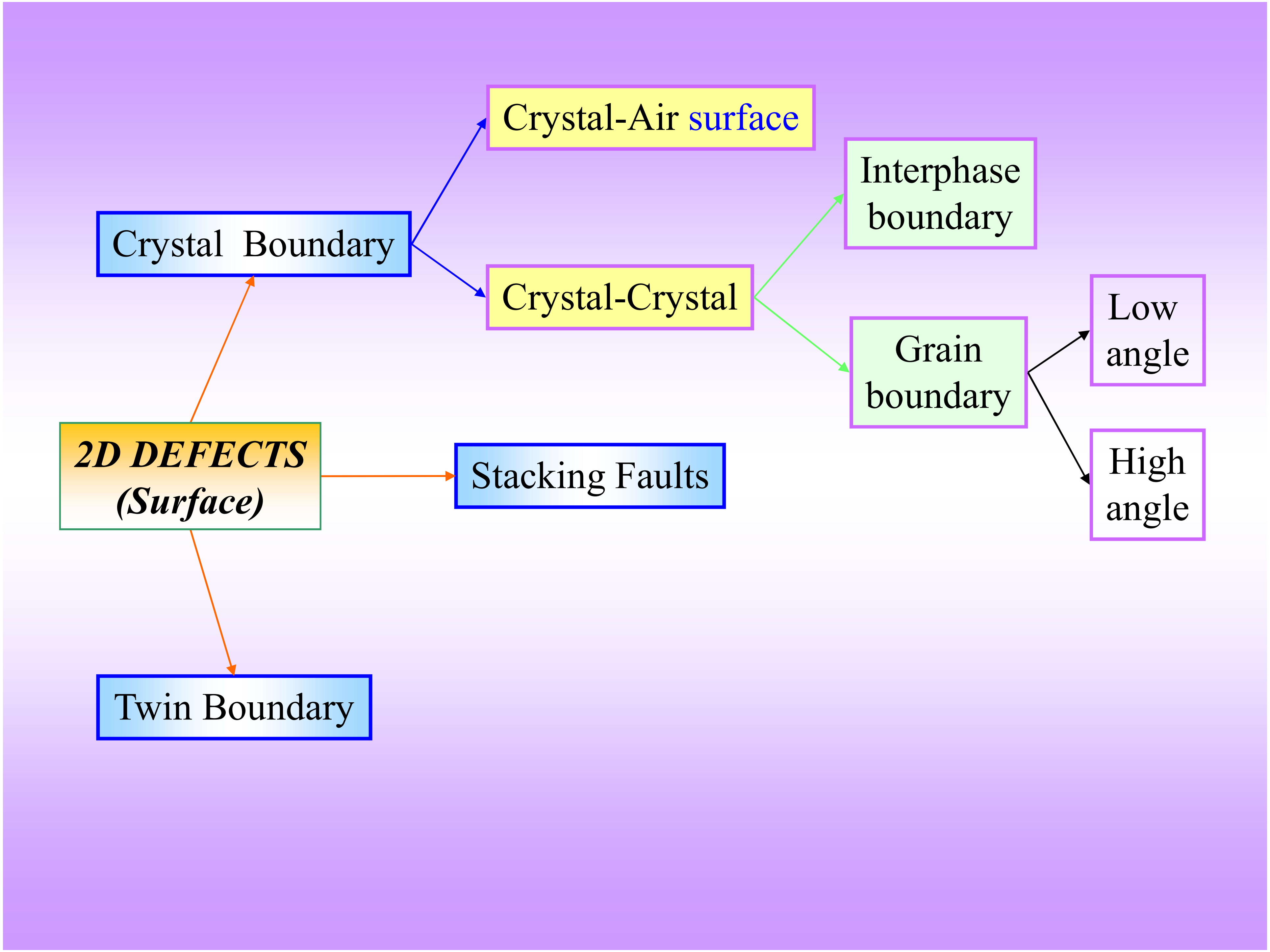


The dislocation is shown cross-slipping from the blue plane to the green plane

- The dislocation line ends on:
  - The free surface of the crystal
  - Internal surface or interface
  - Closes on itself to form a loop

Geometric properties of dislocations

Dislocation Property	Type of dislocation	
	Edge	**Screw**
Relation between dislocation line and **b**	⊥	||
Slip direction	|| to **b**	|| to **b**
Direction of dislocation line relative to **b**	||	⊥
Process by which dislocation may leave slip plane	climb	Cross-slip



2D DEFECTS
(Surface)
Crystal Boundary
Crystal-Air surface
Crystal-Crystal
Interphase boundary
Grain boundary
Low angle
High angle
Stacking Faults
Twin Boundary

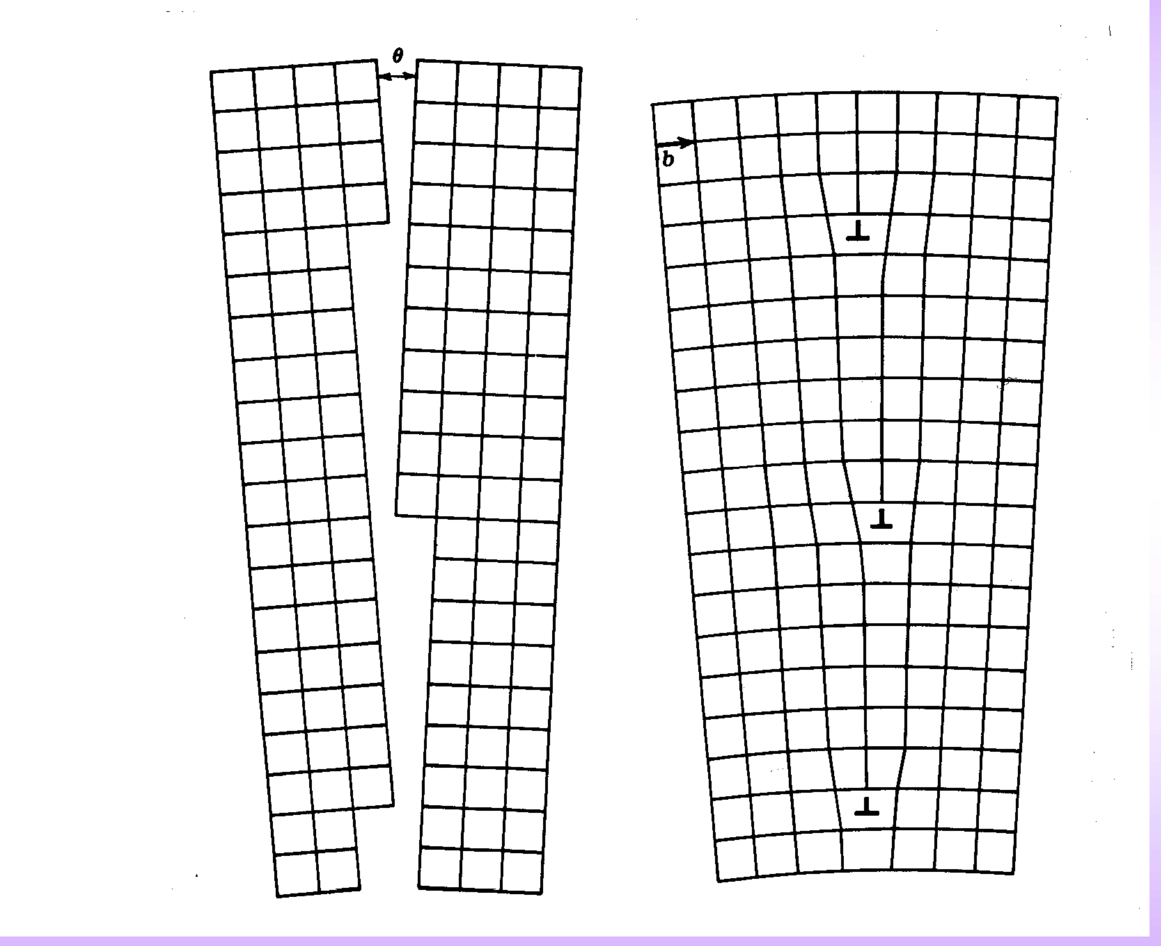
Surface Imperfections

- 2D in a mathematical sense
- The region of distortion is ~ few atomic diameters in thickness

Grain Boundary

- The thickness may be of the order of few atomic diameters
- The crystal orientation changes abruptly at the grain boundary
- In an low angle boundary the orientation difference is $< 10^o$
- In an High angle boundary the orientation difference is $> 10^o$
- Grain boundary energy is responsible for grain growth on heating $\sim (>0.5T_m)$

Low angle grain boundary



1.4 Twinning & deformation.

Twin Boundary

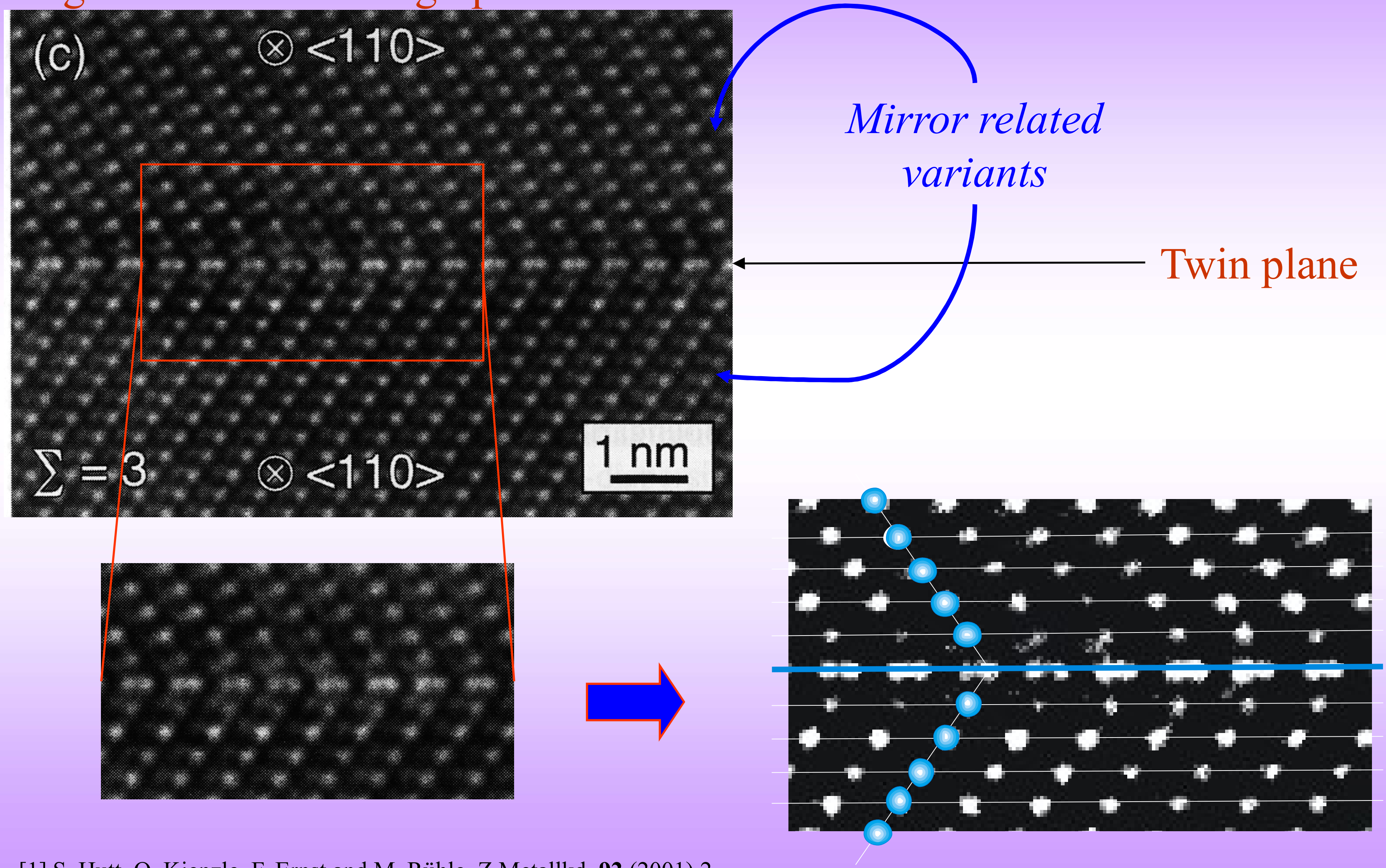
- The atomic arrangement on one side of the twin boundary is related to the other side by a symmetry operation (usually a mirror)
- Twin boundaries usually occur in pairs
- The region between the regions is called the twinned region

Twin → Annealing twins *(formed during recrystallization)*

Twin → Deformation or Mechanical twins *(formed during plastic deformation)*

Twin boundary in Fe doped $SrTiO_3$ bicrystals *(artificially prepared)*

High-resolution micrograph



[1] S. Hutt, O. Kienzle, F. Ernst and M. Rühle, Z Metallkd, **92** (2001) 2

Stacking Fault

- Error in the sequence of stacking atomic planes → Stacking fault

FCC stacking → …ABC ABC ABC ABC…

FCC stacking with a stacking fault → …ABC AB AB ABC…

Thin region of HCP type of stacking

- In above the number of nearest neighbours remains the same but next-nearest neighbours are different than that in FCC
- Stacking fault energy : Energy associated with stacking fault
- Stacking fault in FCC can lead to thin region of HCP kind of stacking

Comparison of Energy of Various 2D Defects

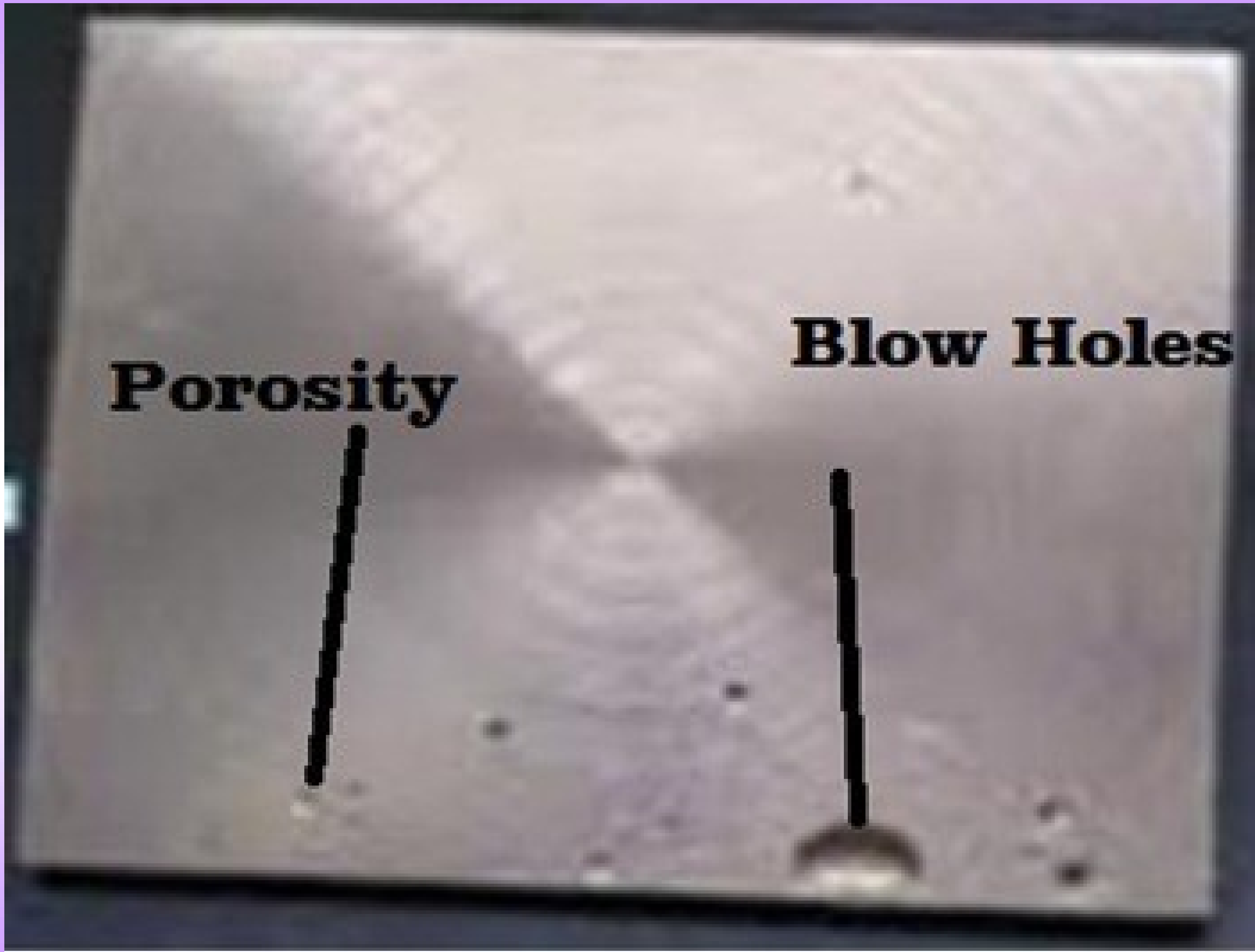
Type of boundary	Energy (J/m^2)
Surface	~ 0.89
Grain boundary	~0.85
Twin Boundary	~ 0.63 0.498 (Cu)
Stacking Fault	0.08 (Cu) 0.2 (Al)

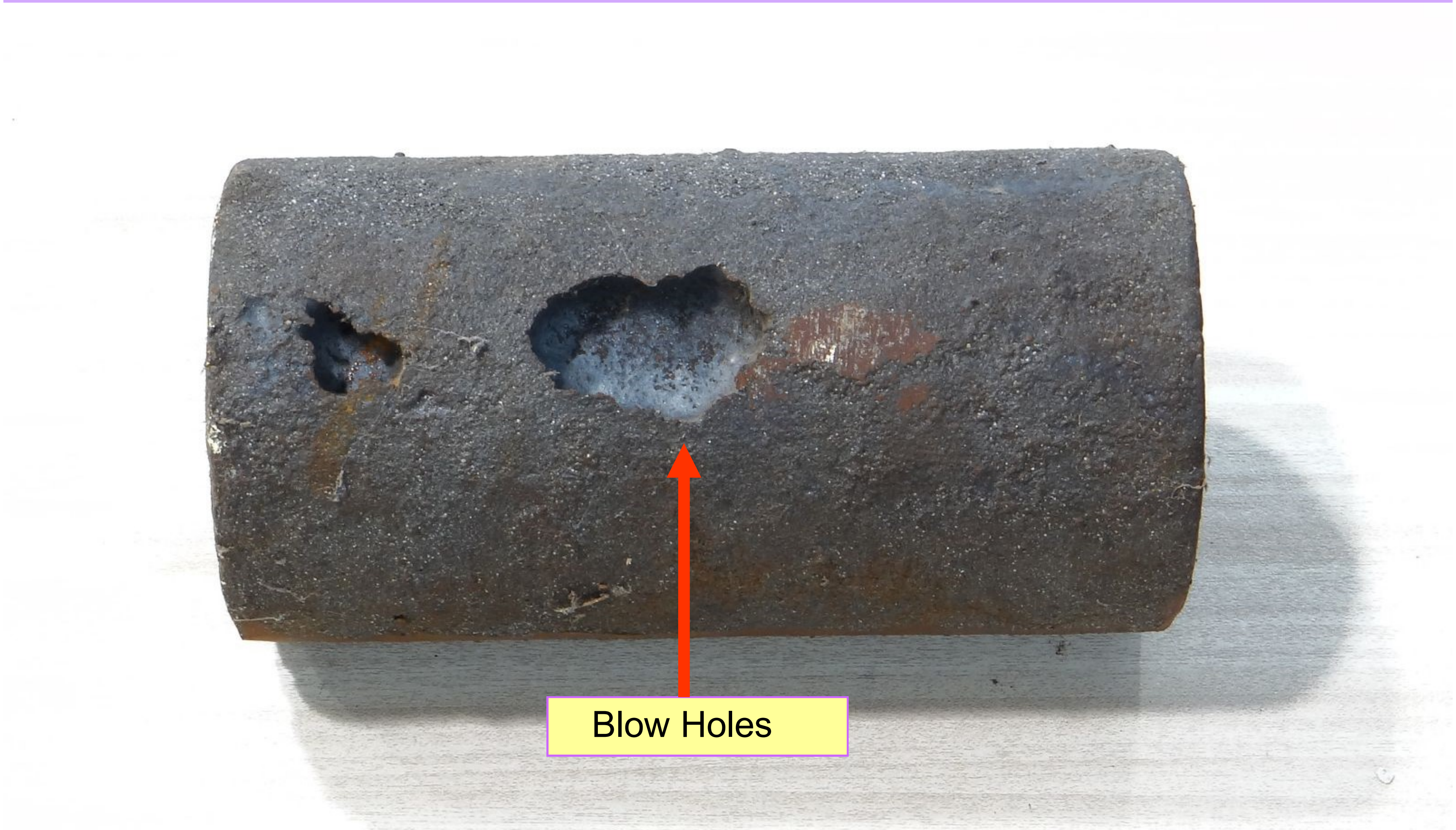
VOLUME DEFECTS

1 Blow holes

2 Voids / Cracks

3 *Pores*


Porosity
Blow Holes


Blow Holes

Voids are caused by high energy particles. e.g material used in nuclear reactors

- A group of atoms missing

Assignment Questions of Chapter-1 (Right side indicates Marks of that particular question)

1. Write down difference between Twinning and Slip. (5)
2. Explain Types of dislocations. (5)
3. Differentiate Edge vs Screw Dislocation (5)
4. Explain Edge and Screw Dislocation with neat sketch (10)
5. Differentiate glide vs cross slip. (5)
6. Both edge & Screw dislocation can glide but only screw dislocation can cross slip. Why? (2)
7. Explain different types of defects. (10)
8. Write short notes on Mixed Dislocation. (5)
9. Write down line diagram showing directional relationship between force, dislocation line, movement of dislocation and burger vector both in screw as well as edge dislocation. (5)
10. What is stacking fault? (2)

DEFECTS IN CRYSTALS

DEPARTMENT OF METALLURGY

ORISSA SCHOOL OF MINING ENGINEERING KEONJHAR

Presented by:

Tushar Das Pattanayak

1.1 Dislocation, types, its basic behavior & role in deformation.

DEFECTS IN CRYSTALS

- Point defects
- Line defects
- Surface Defects
- Volume Defects

PROPERTIES

- Structure sensitive (Mechanical Properties)
  - E.g. Yield stress, Hardness
- Structure Insensitive (Physical Properties)
  - E.g. Density, elastic modulus

PROPERTY: A measurable quantity which gives chemical and physical characteristics of a substance.

CLASSIFICATION OF DEFECTS

0D *(Point defects)*

- Vacancy
- Impurity
- Frenkel defect
- Schottky defect

1D *(Line defects)*

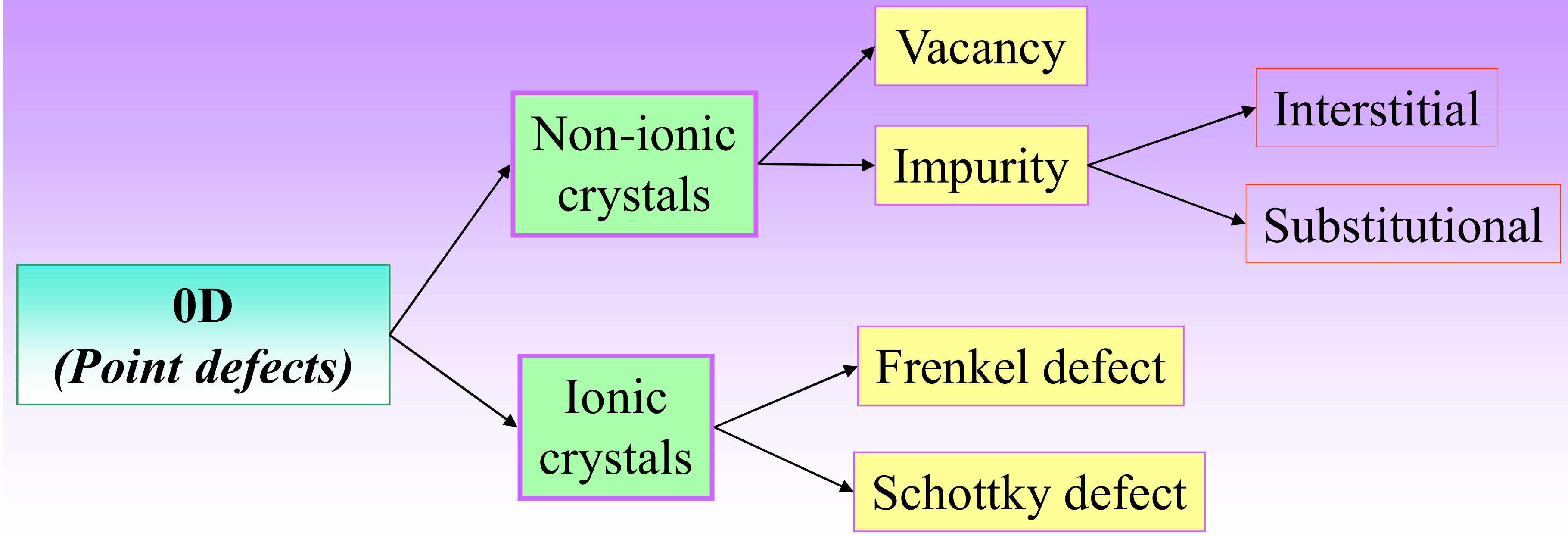
- Dislocation
  - Edge
  - Screw

2D *(Surface / Interface)*

- Surface
- Grain boundary
- Twin boundary
- Tilt Boundary
- Stacking faults

3D *(Volume defects)*

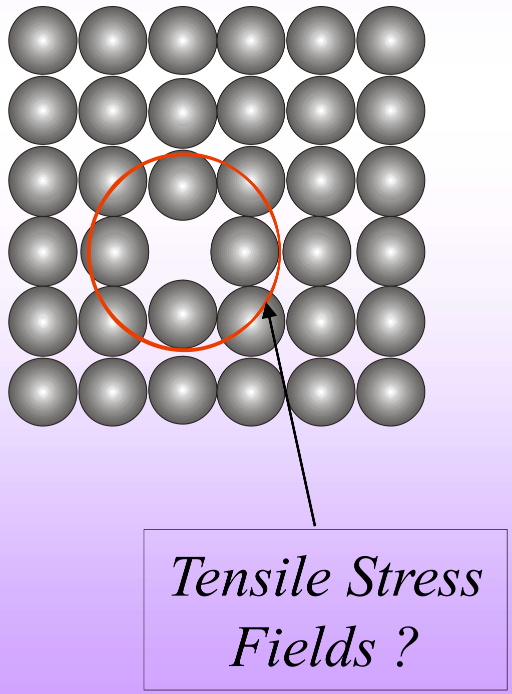
- Precipitate
- Blow holes
- Voids / Cracks
- *Pores*

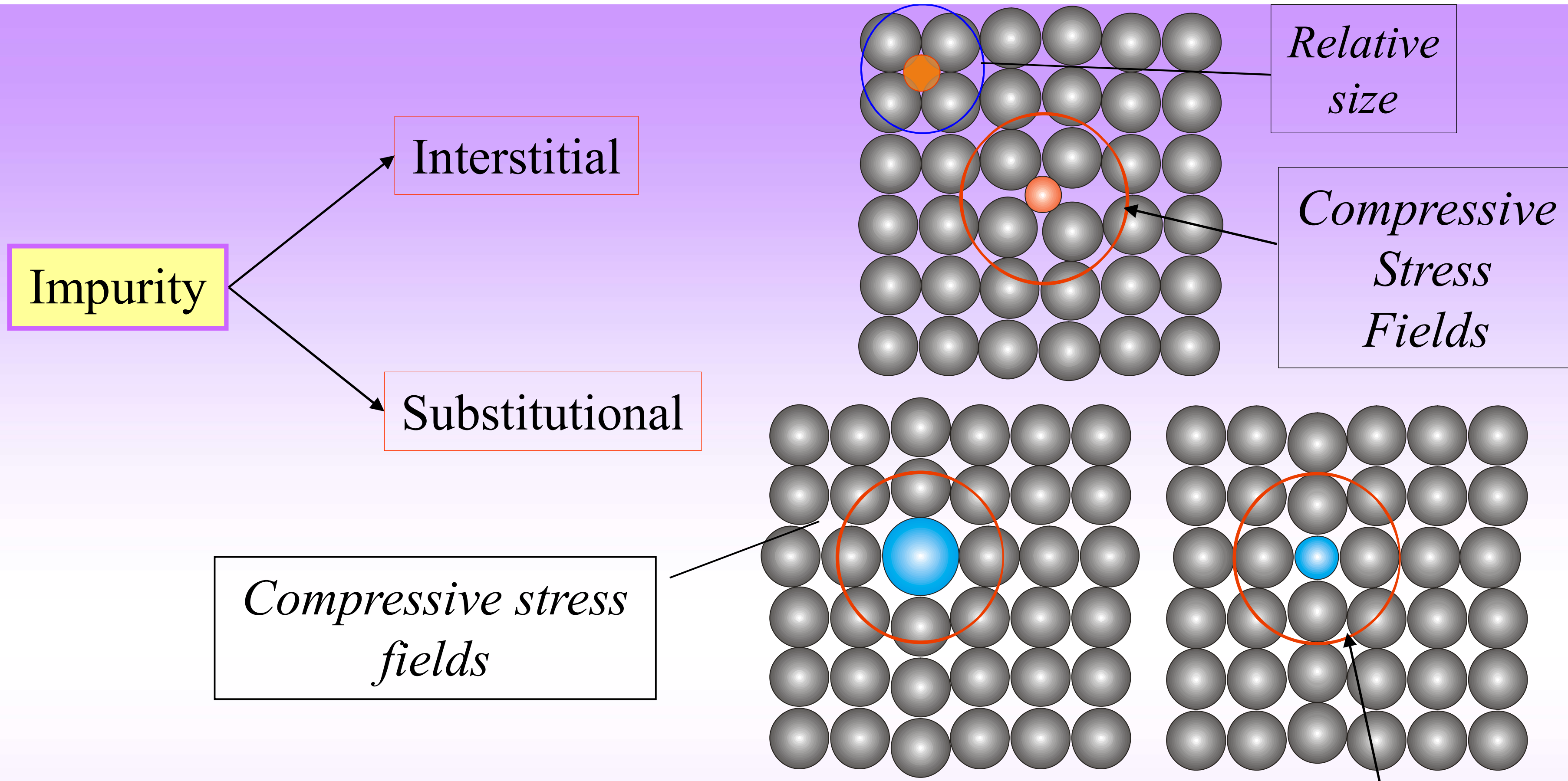


- Imperfect point-like regions in the crystal about the size of 1-2 atomic diameters

Vacancy

- Missing atom from an atomic site
- Atoms around the vacancy displaced
- Tensile stress field produced in the vicinity





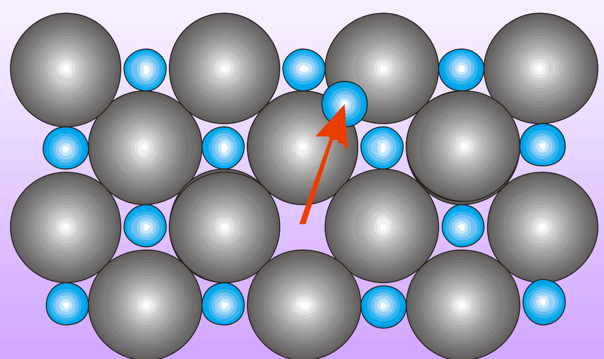
- **SUBSTITUTIONAL IMPURITY**
  - Foreign atom replacing the parent atom in the crystal
  - E.g. **Cu** sitting in the lattice site of FCC-**Ni**
- **INTERSTITIAL IMPURITY**
  - Foreign atom sitting in the void of a crystal
  - E.g. **C** sitting in the octahedral void in HT FCC-**Fe**

Ionic Crystals

- Overall electrical neutrality has to be maintained

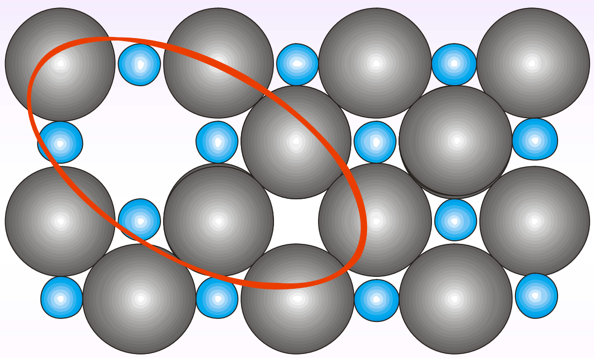
Frenkel defect

- Cation (being smaller get displaced to interstitial voids
- E.g. AgI, CaF_2



Schottky defect

- Pair of anion and cation missing from the lattice site
- E.g. Alkali halides



Line defect- Dislocation

Dislocations- Most important 1-D or line defects. They extend in a crystal as a line or 1-D net of lines.

Responsible for slip- Most important mechanism of plastic deformation.

Dislocation is a line separating slipped and unslipped region of a crystal.

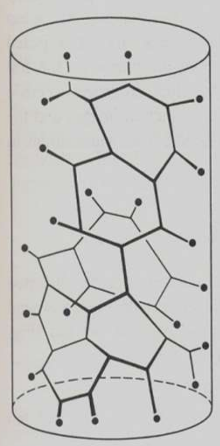
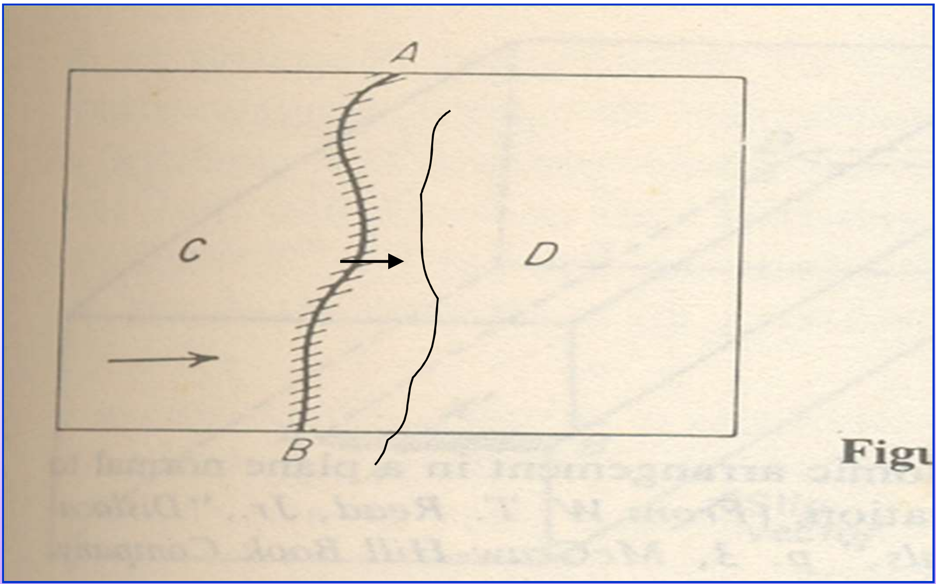


FIGURE 2.11 Network arrangement of dislocations in crystal. Dislocations can terminate only at a node, in a loop, or at a grain boundary or free surface.[7] (Reproduced by courtesy of the Council of the Institution of Mechanical Engineers from *The Properties of Materials at High Rates of Strain*, by A. H. Cottrell.)



Deformation by Slip

1.5 Slip & Deformation.

The usual method of plastic deformation is slip.

This is sliding of one block of crystal over other block.

This takes place along a definite crystallographic plane (slip plane) and definite crystallographic direction (slip direction).

Crude approximation, it is like distortion produced in a deck of cards when pushed from one end.

Slip in a crystal can be understood with the help of the Fig.1

Fig. 1.a Classical Idea of Slip & Slip Lines

Fig. 1.b Fine Structure of Slip Band

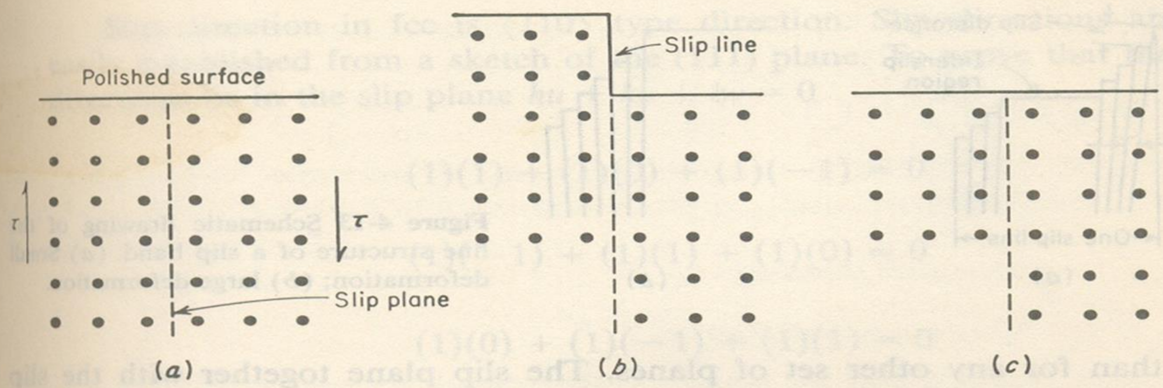
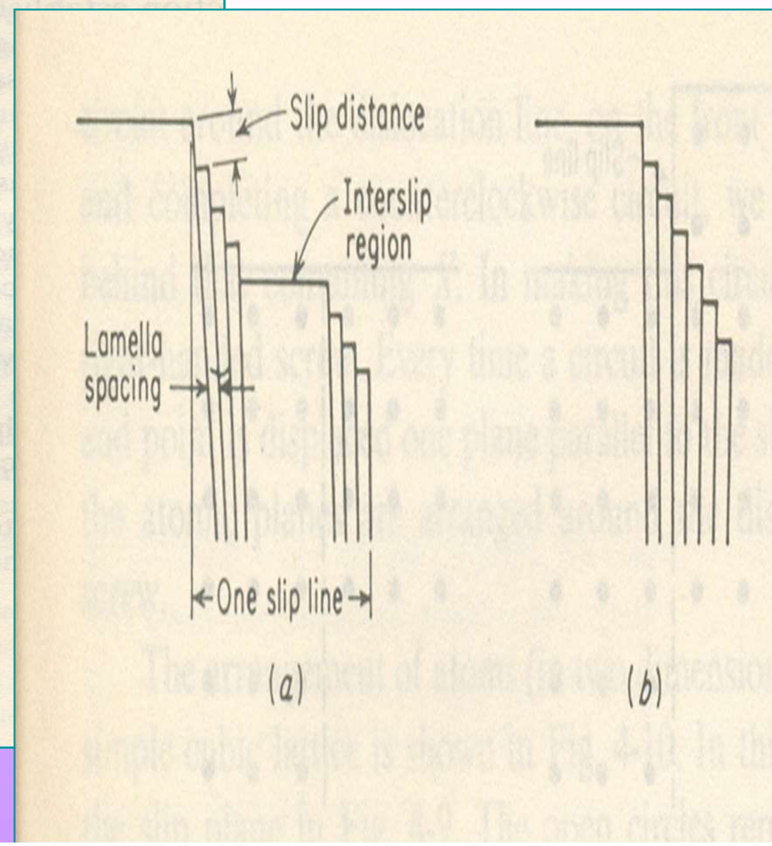


Figure 4-11 Schematic drawing of classical idea of slip.

Figure 4-12 Straight slip lines in copper (500 ×). *(Courtesy W. L. Phillips.)*



1.2 Dislocation in various crystals

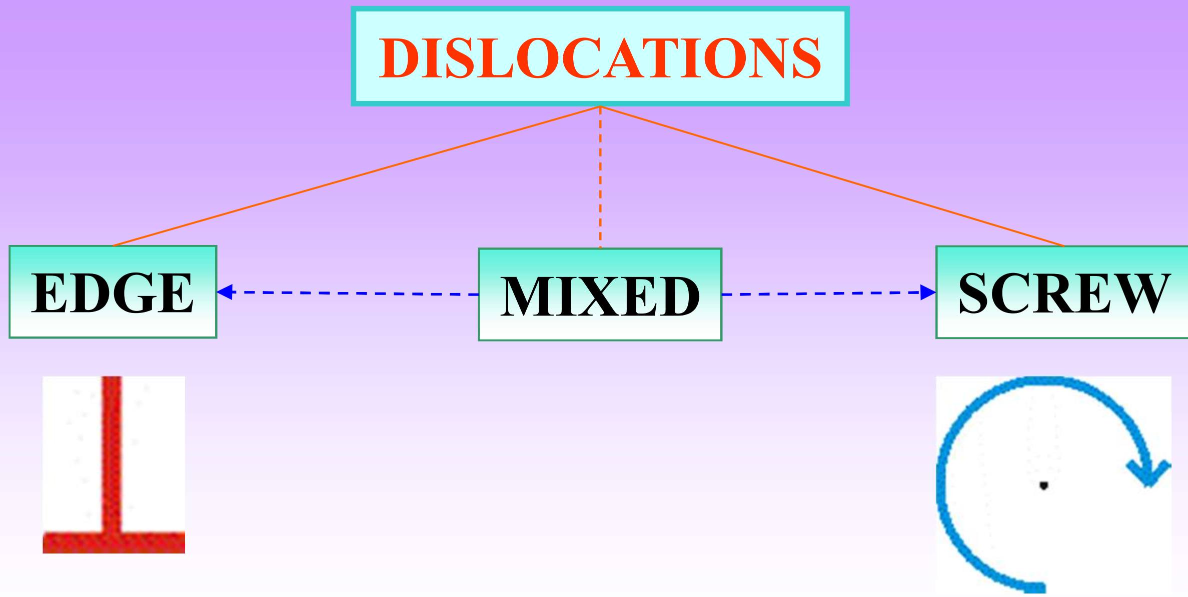
DISLOCATIONS

- Edge dislocation
- Screw dislocation

1.3 Source of dislocation

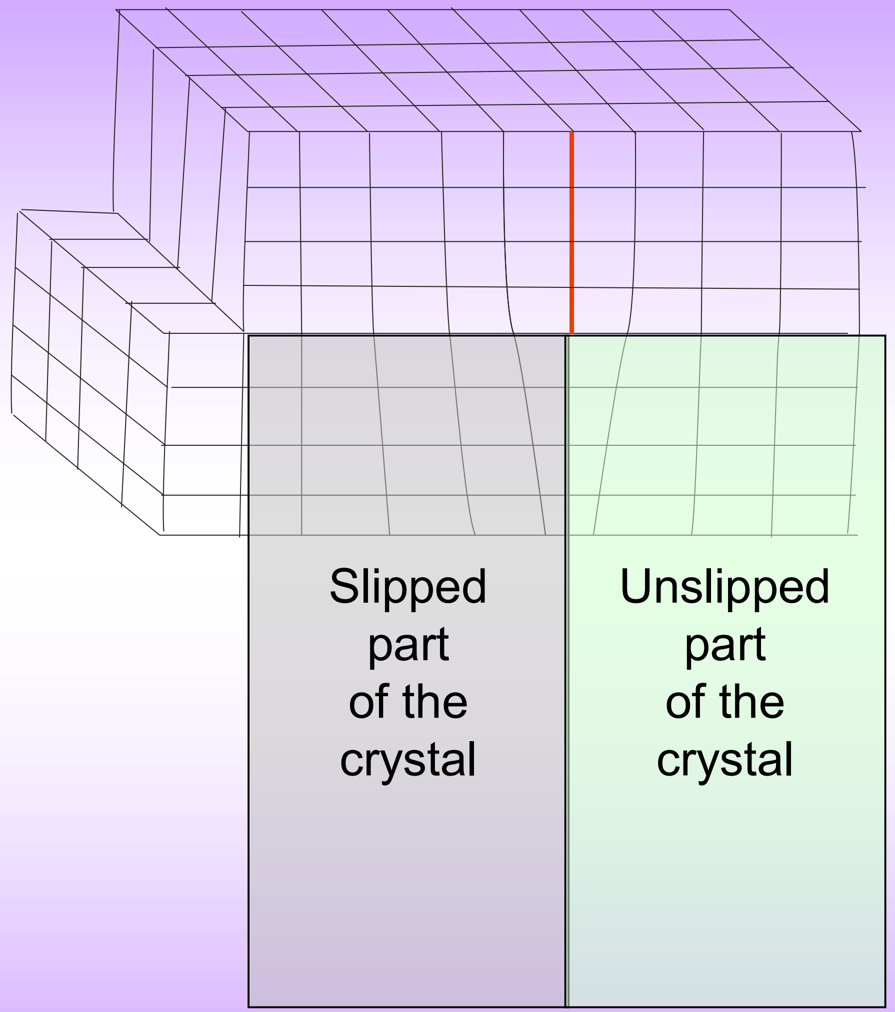
Plastic Deformation in Crystalline Materials

- **Slip** ***(Dislocation motion)***
- **Twinning**
- **Phase Transformation**
- **Creep Mechanisms**
  - Grain boundary sliding
  - Vacancy diffusion
  - Dislocation climb



- Usually dislocations have a mixed character and *Edge* and *Screw* dislocations are the ideal extremes

- Geometrically necessary dislocations



Dislocation is a boundary between the slipped and the unslipped parts of the crystal lying over a slip plane

Edge Dislocation

Fig – A represents a simple cubic lattice under an external shear stress. The amount of slip or displacement is assumed to be one atomic spacing. The result of this shear is shown in the Fig. – B.

- This leaves an extra half plane cd below the slip plane in the right hand side, outside the crystal.
- It will also produce an extra half plane located above the slip plane and in the centre of the crystal.
- All other planes are realigned and continuity is maintained.
- The boundary of additional plane is called an edge dislocation.

Fig. Continued… Edge Dislocation

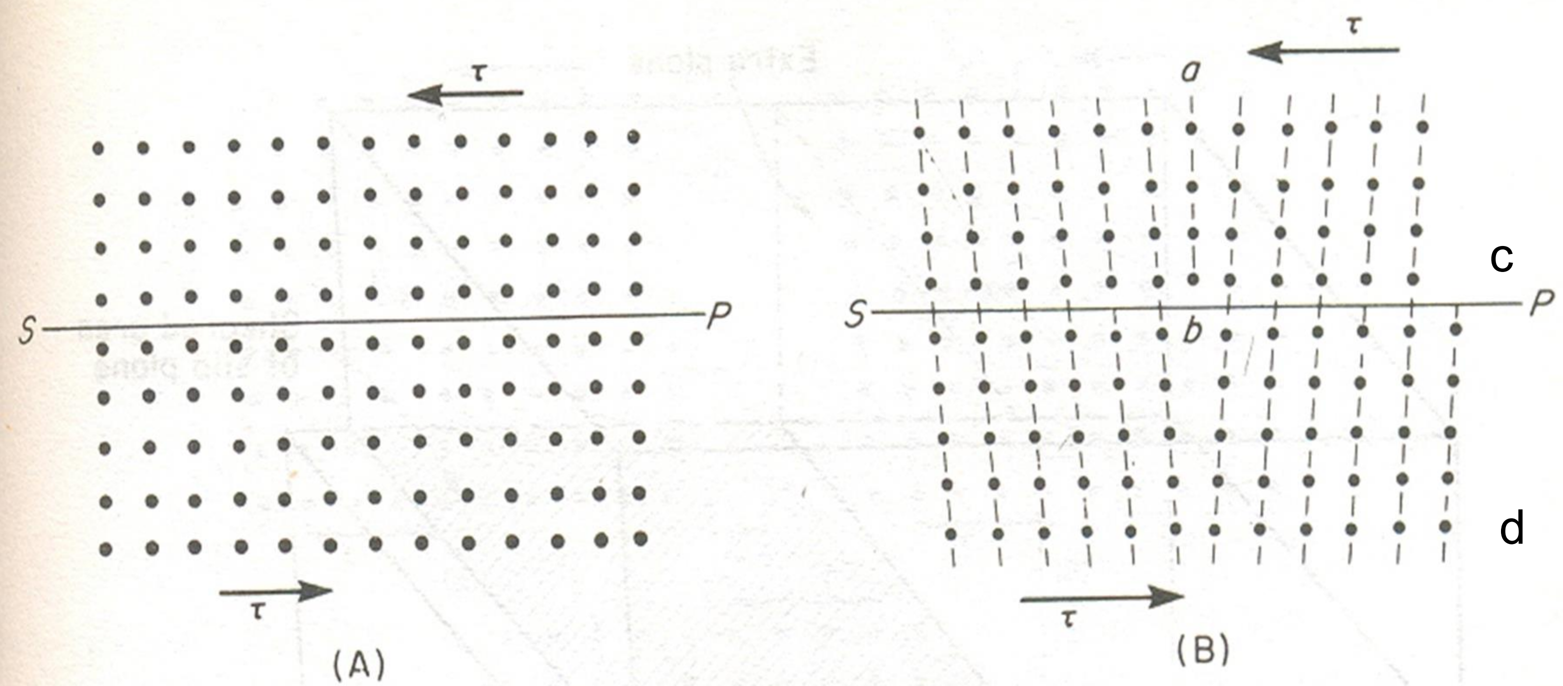


Fig. 4.10 An edge dislocation. (A) A perfect crystal. (B) When the crystal is sheared one atomic distance over part of the distance *S–P*, an edge dislocation is formed.

Edge Dislocation

- Fig. 4.5 represents a 3 – D sketch of the edge dislocation.
- The figure clearly shows that dislocation has the dimension of a line.
- Dislocation line marks the (separates) boundary between sheared and un-sheared part of the slip plane.

This is the basic characteristics of a dislocation line.

Dislocation may be defined as a line that forms a boundary on a slip plane between slipped and un-slipped region.

Fig. Continued Edge Disl.

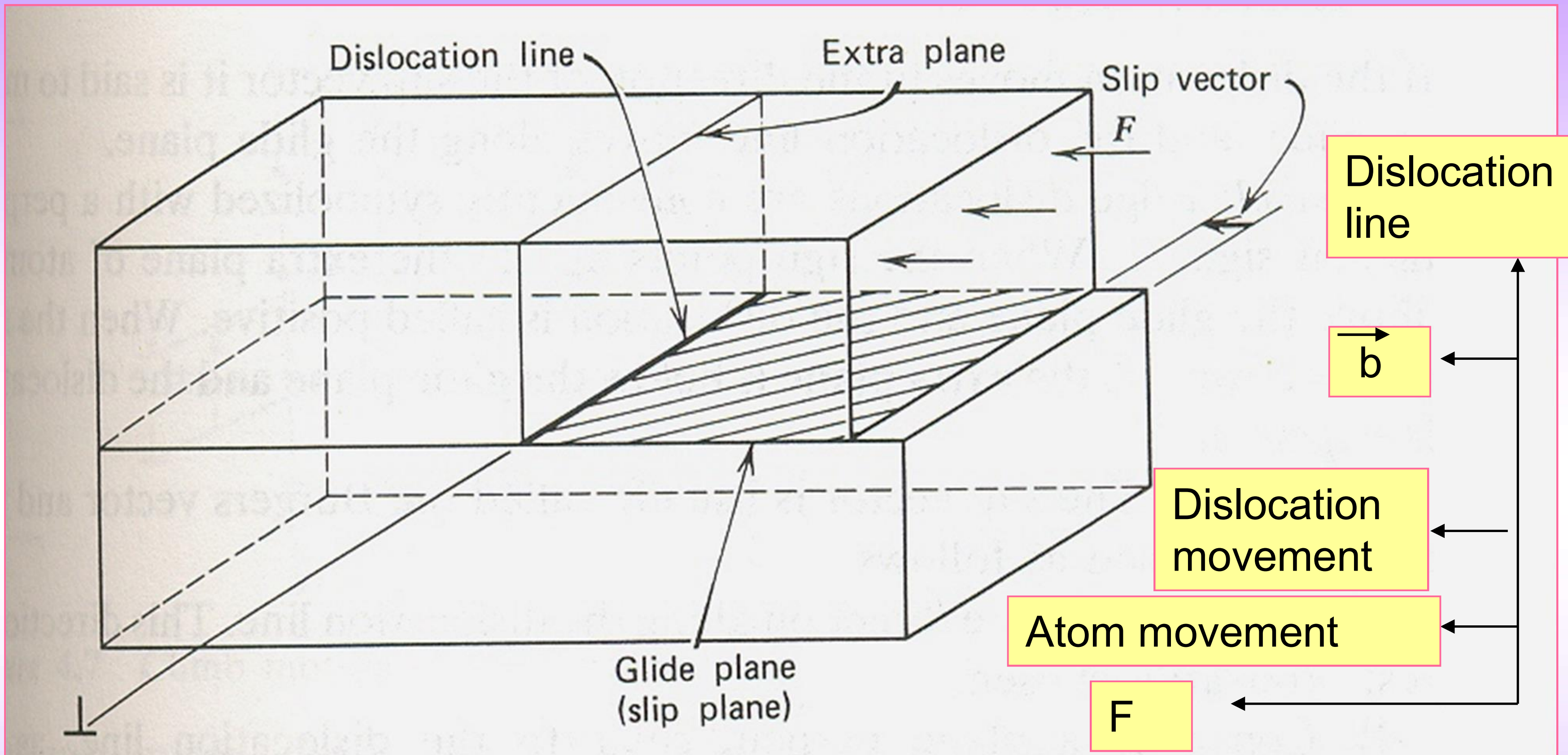


Figure 4.5 The edge dislocation.

Displacement vector or slip vector: Burgers vector, $\vec{b}$

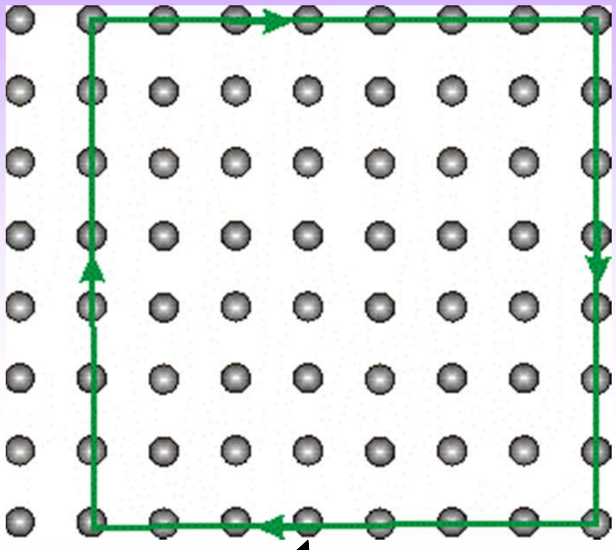
A dislocation is associated with one vector:

$\vec{b} \rightarrow$ The Burgers vector

The magnitude and direction of a dislocation can be determined by a vector called burgers vector.

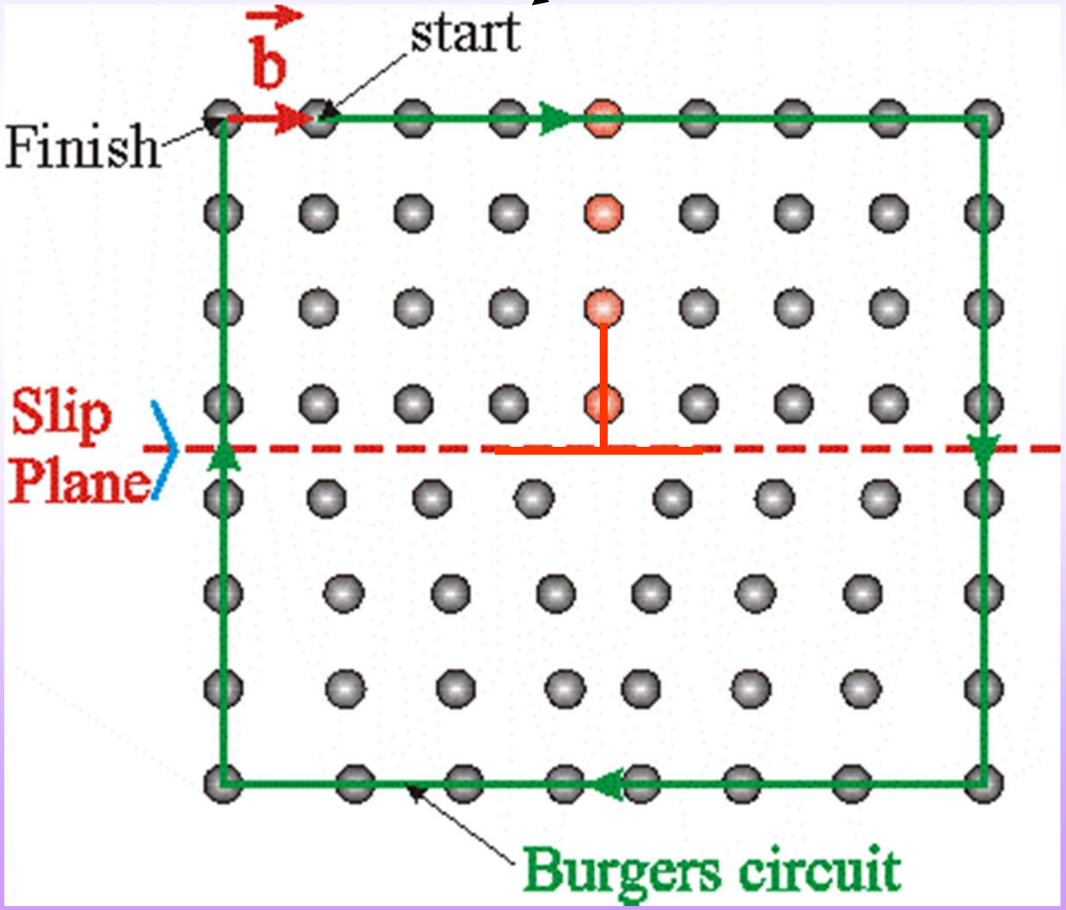
Burgers Vector

Edge dislocation



Perfect crystal

Crystal with edge dislocation



RHFS:
Right Hand Finish to Start convention

Fig. Continued Edge Disl.

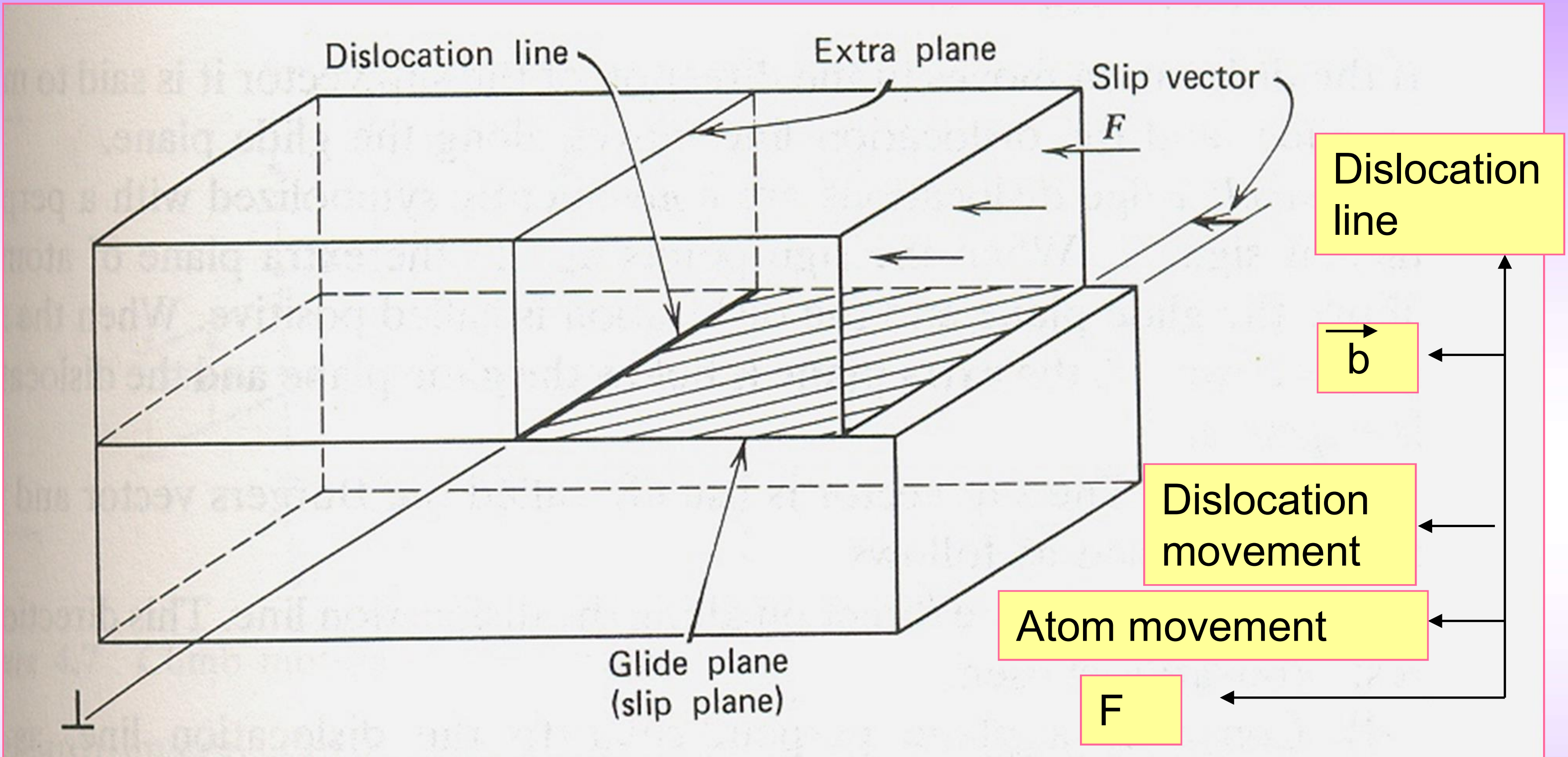
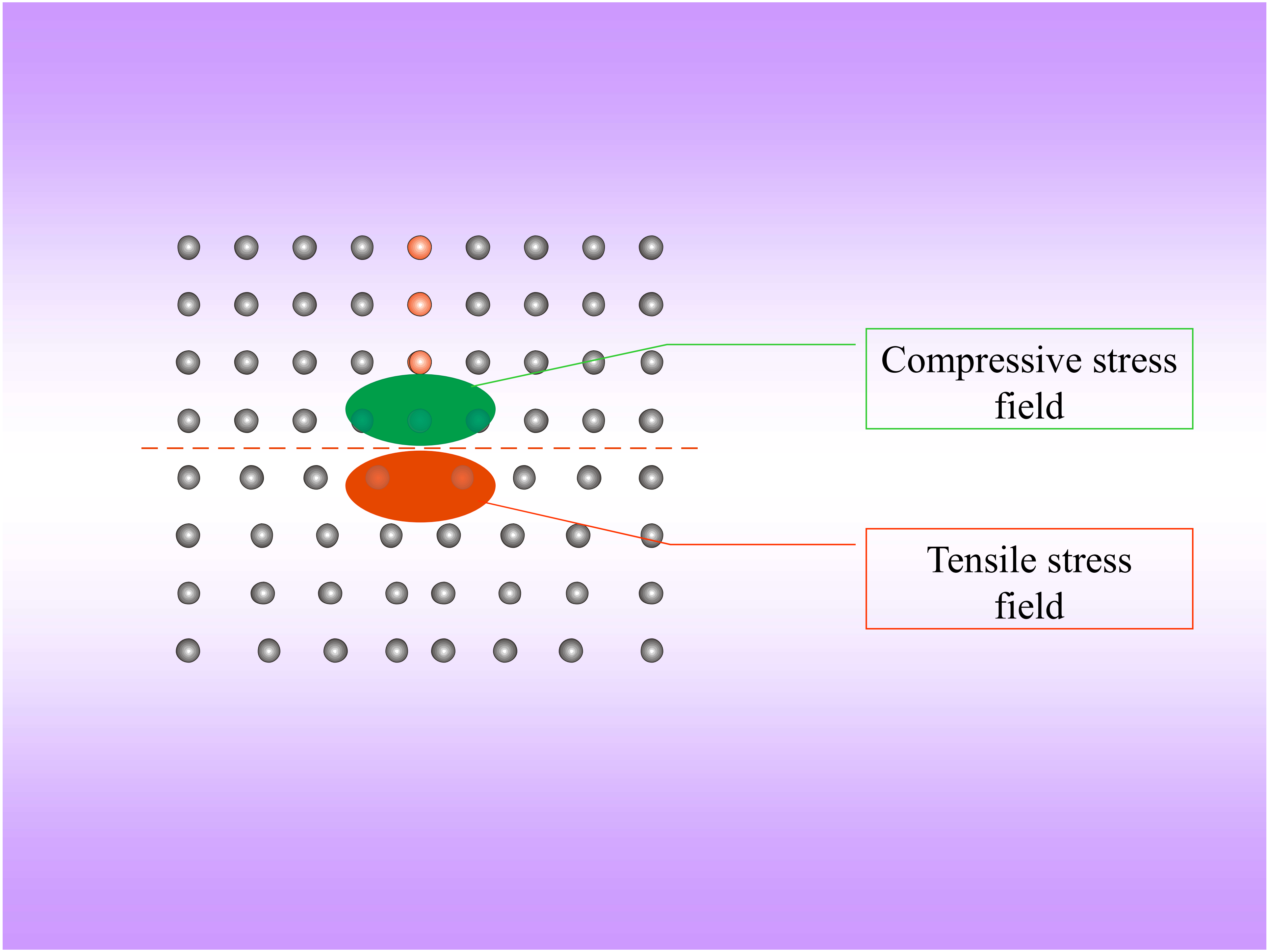


Figure 4.5 The edge dislocation.

Displacement vector or slip vector: Burgers vector, $\vec{b}$

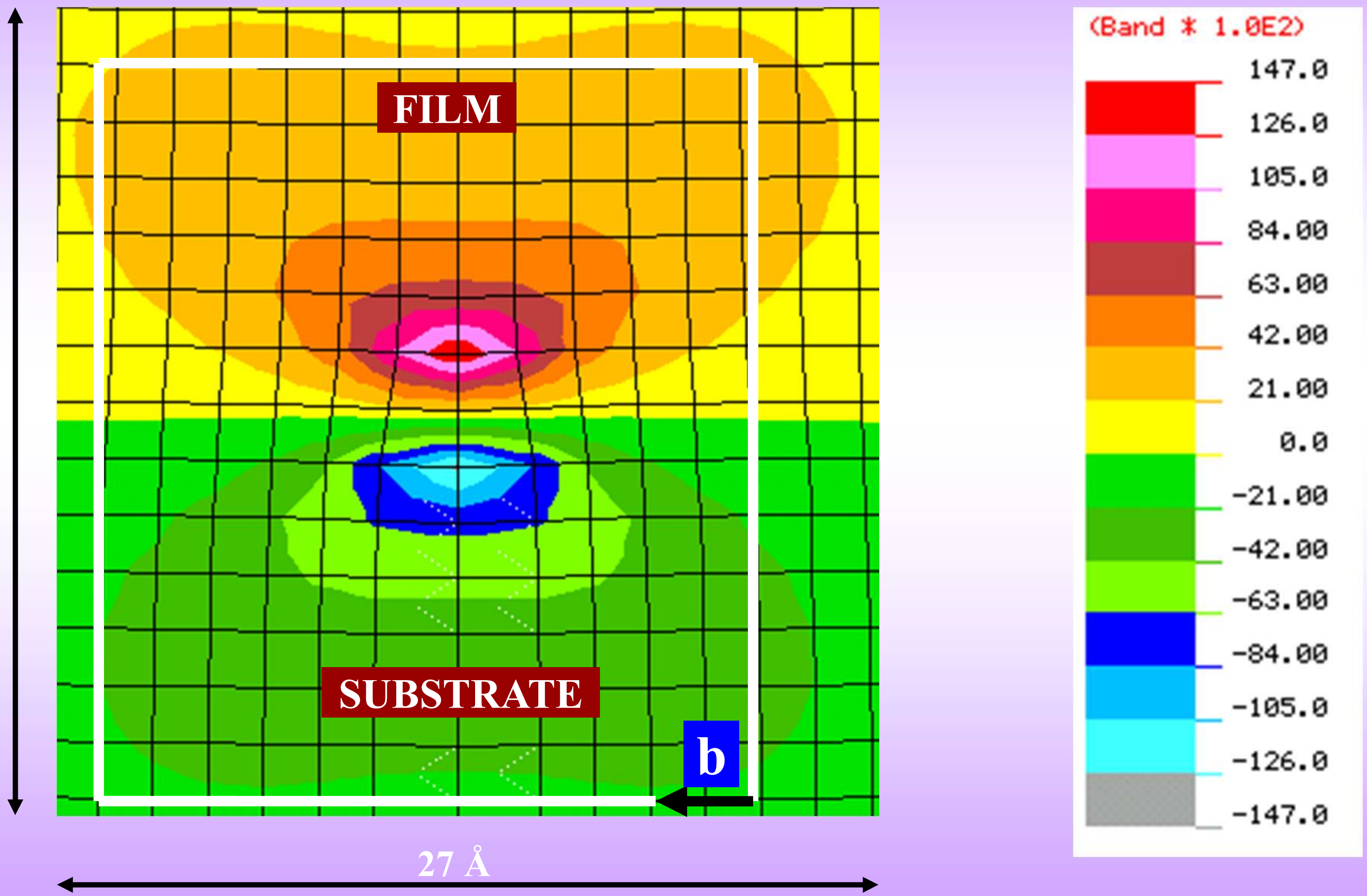
- Dislocation is a boundary between the slipped and the unslipped parts of the crystal lying over a slip plane
- The intersection of the extra half-plane of atoms with the slip plane defines the dislocation line *(for an edge dislocation)*
- Direction and magnitude of slip is characterized by the Burgers vector of the dislocation
  (A dislocation is born with a Burgers vector and expresses it even in its death!)
- The Burgers vector is determined by the Burgers Circuit
- Right hand screw (finish to start) convention is used for determining the direction of the Burgers vector

- The edge dislocation has compressive stress field above and tensile stress field below the slip plane
- Dislocations are non-equilibrium defects and would leave the crystal if given an opportunity


Compressive stress field
Tensile stress field

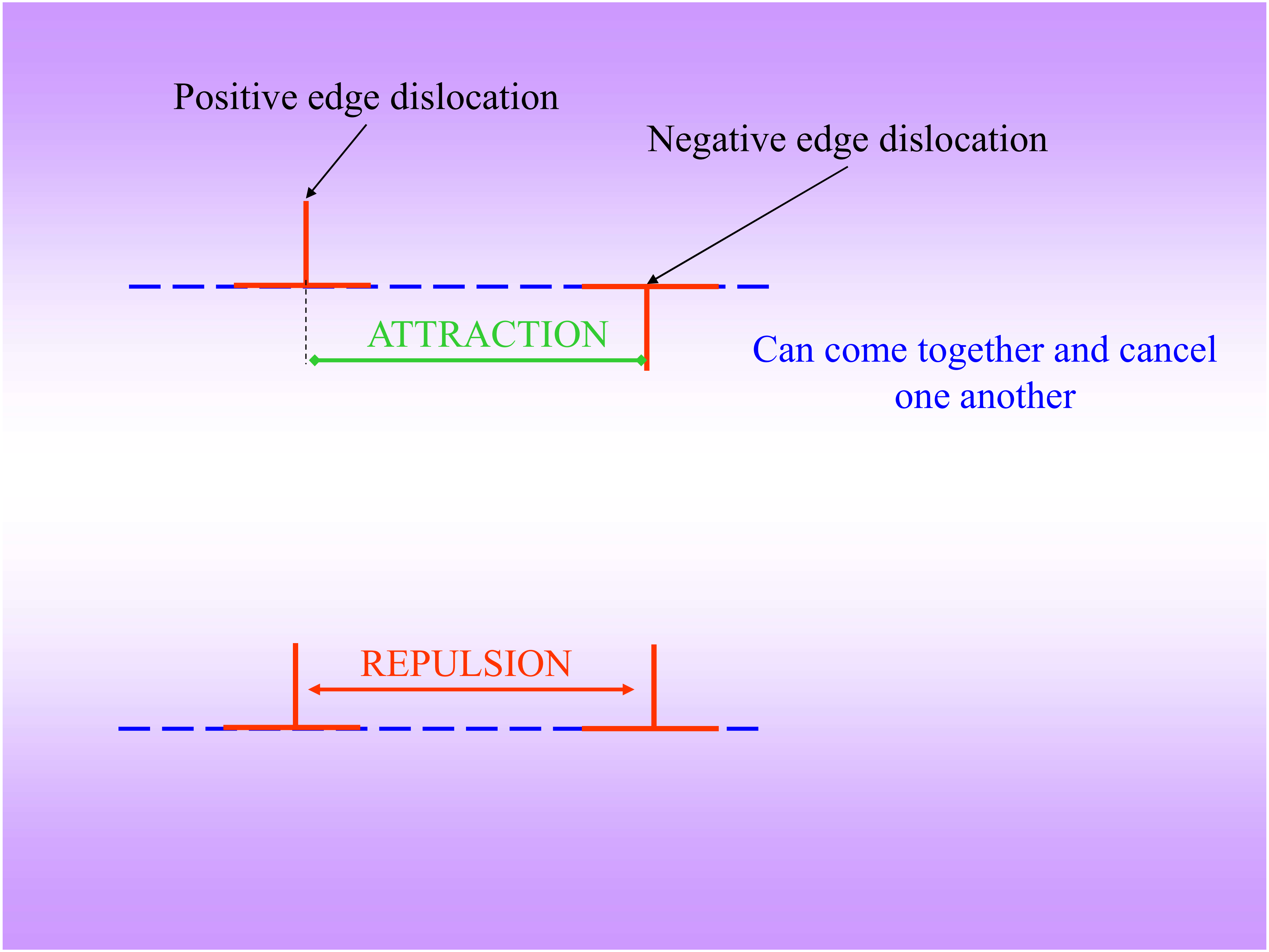
STRESS FIELD OF A EDGE DISLOCATION

σ_X – FEM SIMULATED CONTOURS

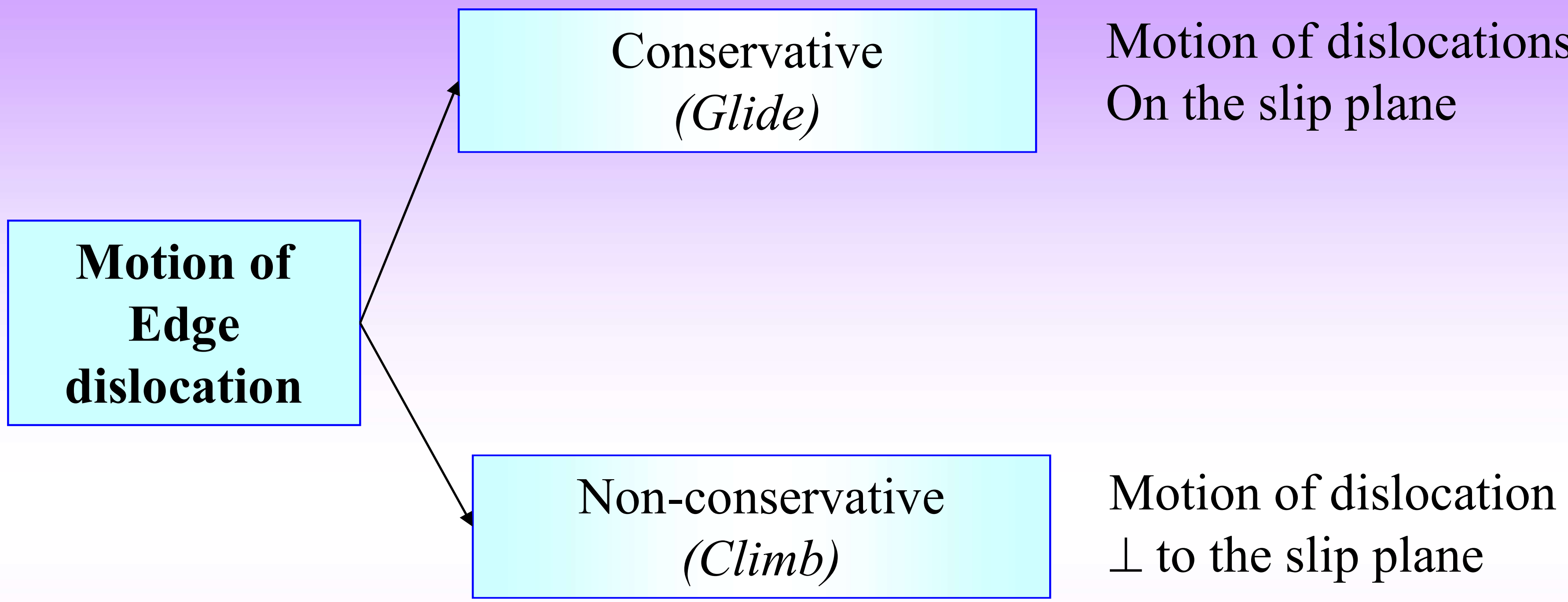


(MPa)

(x & y original grid size = b/2 = 1.92 Å)

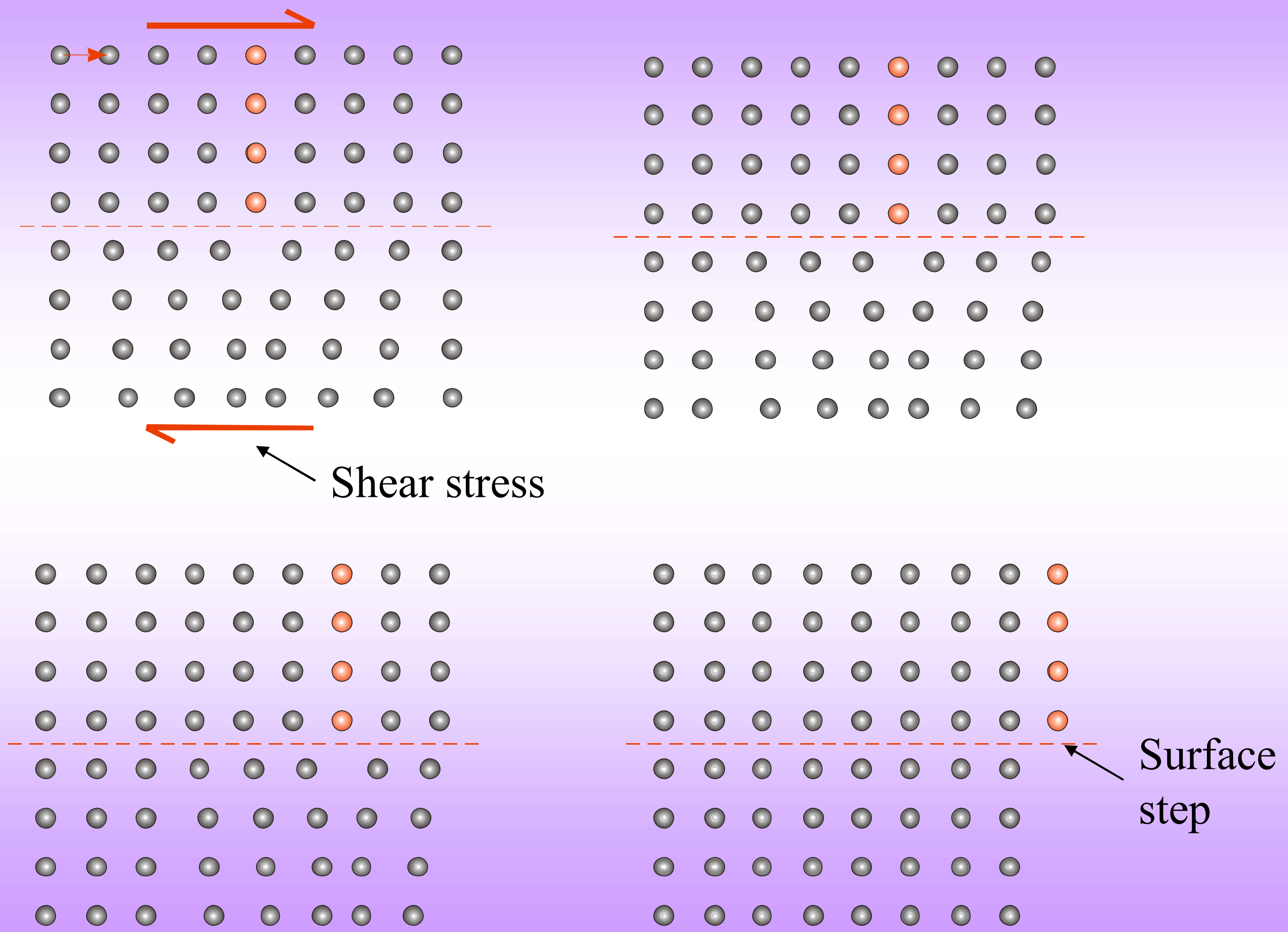


Positive edge dislocation
Negative edge dislocation
ATTRACTION
Can come together and cancel one another
REPULSION

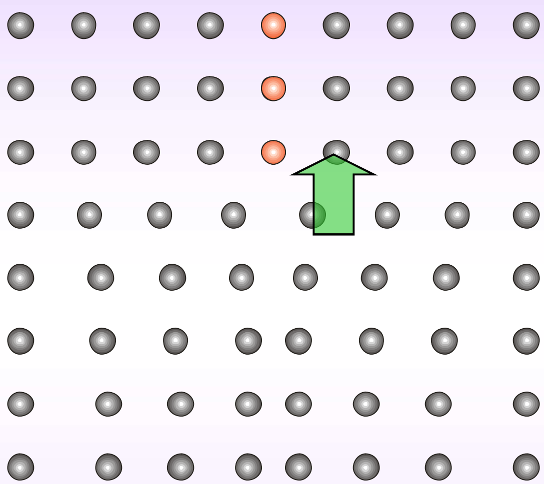


- For edge dislocation: as **burgers vector ⊥ dislocation line**→ they define a plane → *the slip plane*
- Climb involves addition or subtraction of a row of atoms below the half plane
  - ► +ve climb = climb up → removal of a plane of atoms
  - ► –ve climb = climb down → addition of a plane of atoms

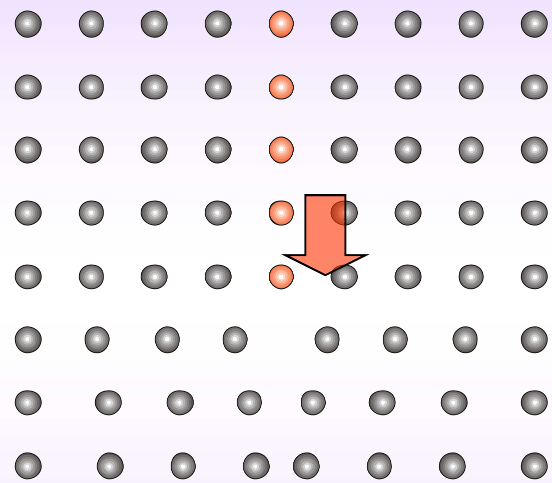
Edge Dislocation Glide



Edge Climb



Positive climb
Removal of a row of atoms



Negative climb
Addition of a row of atoms

Screw Dislocation

Schematically illustrated in Fig. 4.13 A.

- Here each small cube is considered to represent an atom. Fig. B represents the same crystal with the position of the dislocation line marked by DC.
- ABCD represents slip plane under the effect of stress. Upper front part has been sheared by one atomic distance to the left relative to the lower front portion.
- It is termed as screw dislocation because the lattice planes spiral the dislocation line DC. This can be proved by starting at point x in Fig. A then proceeding toward and around the crystal in the indicated direction. One circuit will end the crystal at point y. If it is continued it will finally end at y. This deformation is known as screw dislocation.

Dislocation line // Displacement vector and

moves perpendicular to Displacement vector

Fig. Contd…Screw Dislocation

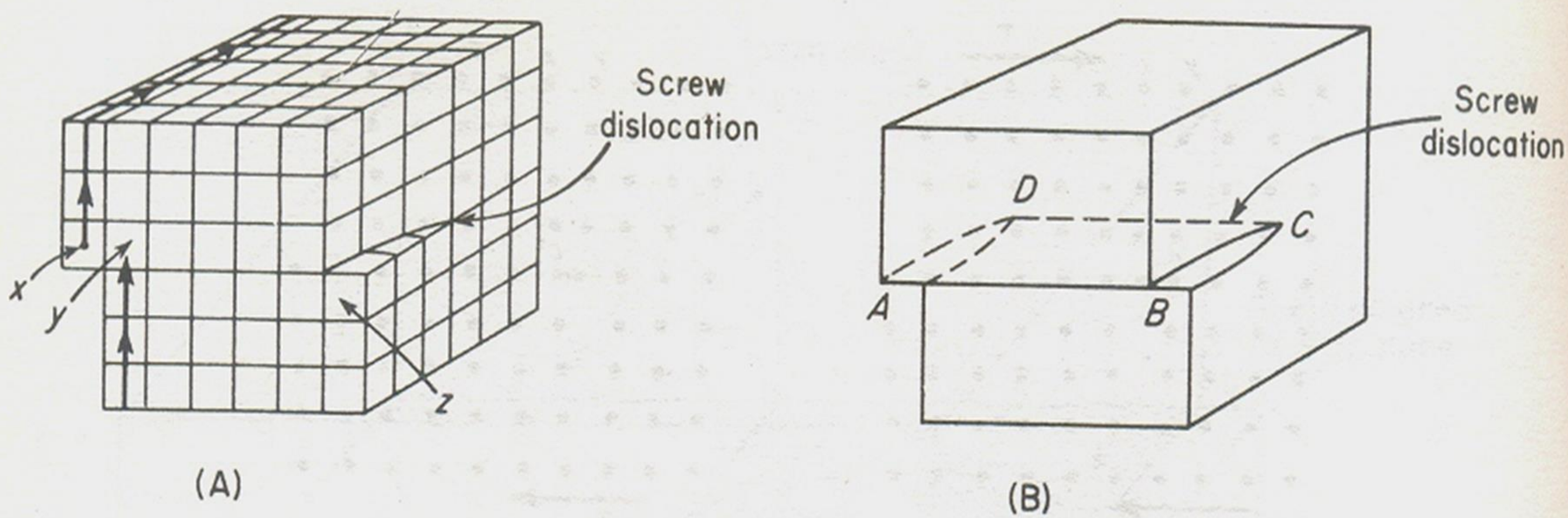
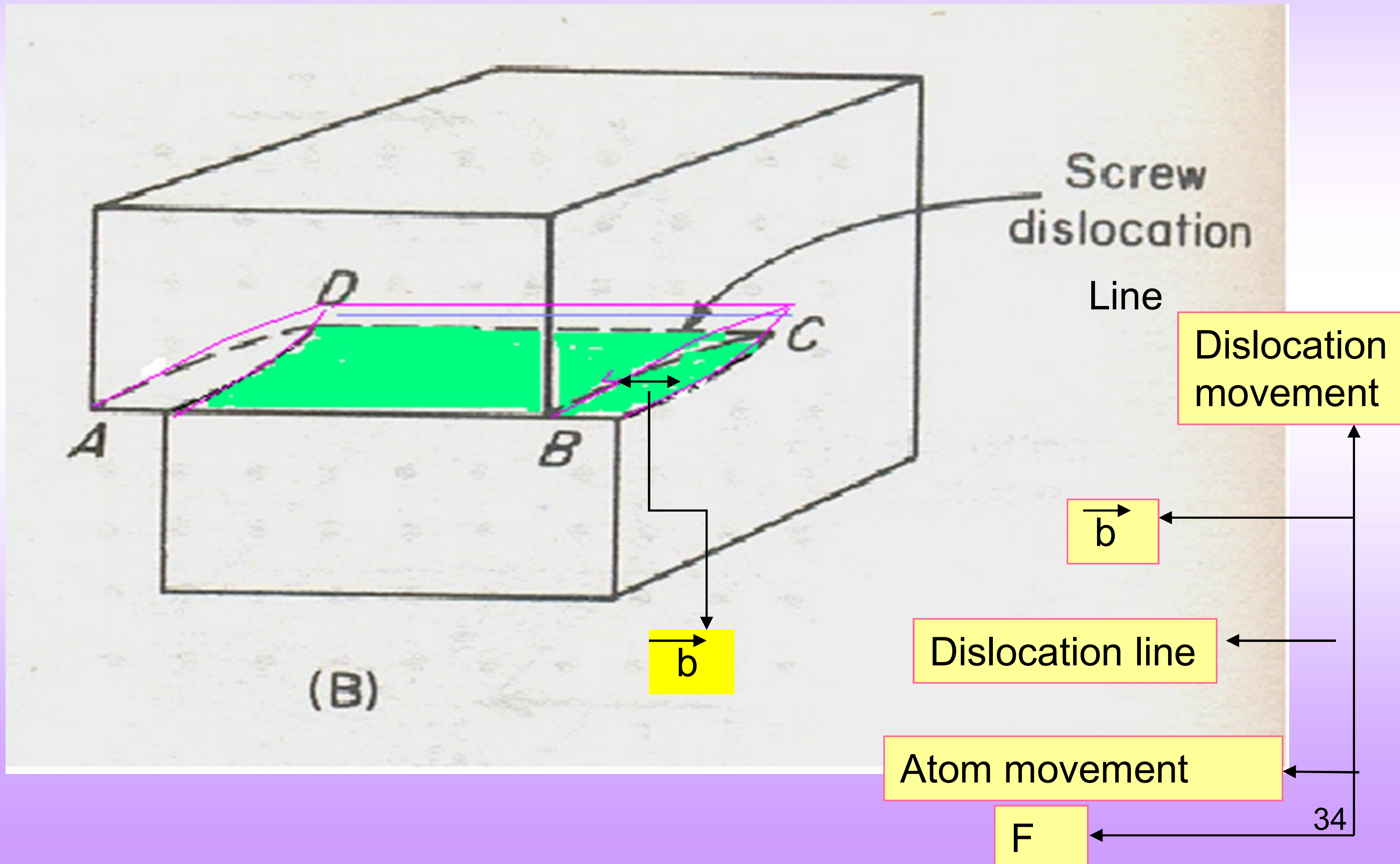
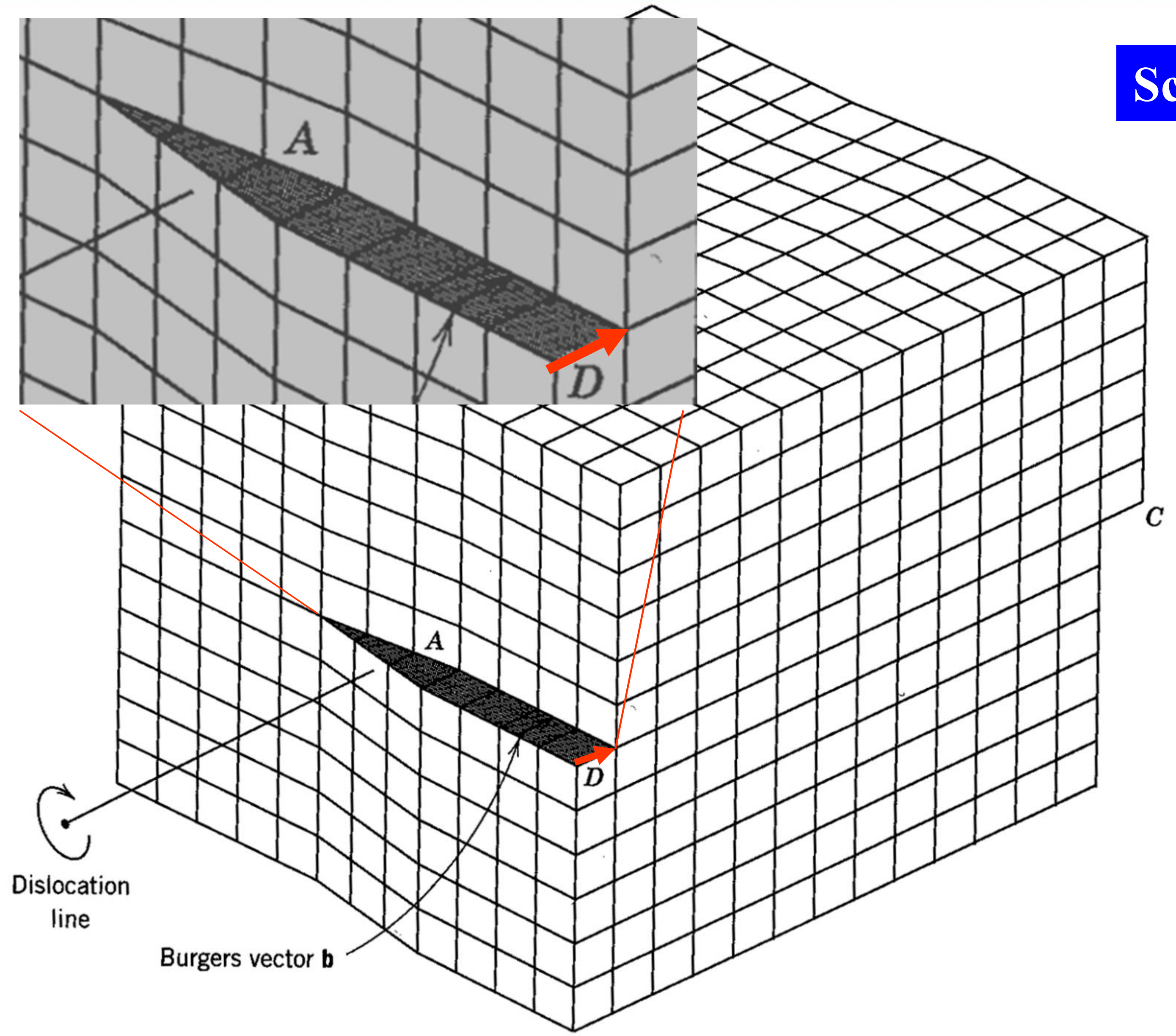


Fig. 4.13 Two representations of a screw dislocation. Notice that the planes in this dislocation spiral around the dislocation like a left-hand screw.


Screw dislocation
Line
D
C
A
B
b
(B)
Dislocation movement
b
Dislocation line
Atom movement
F

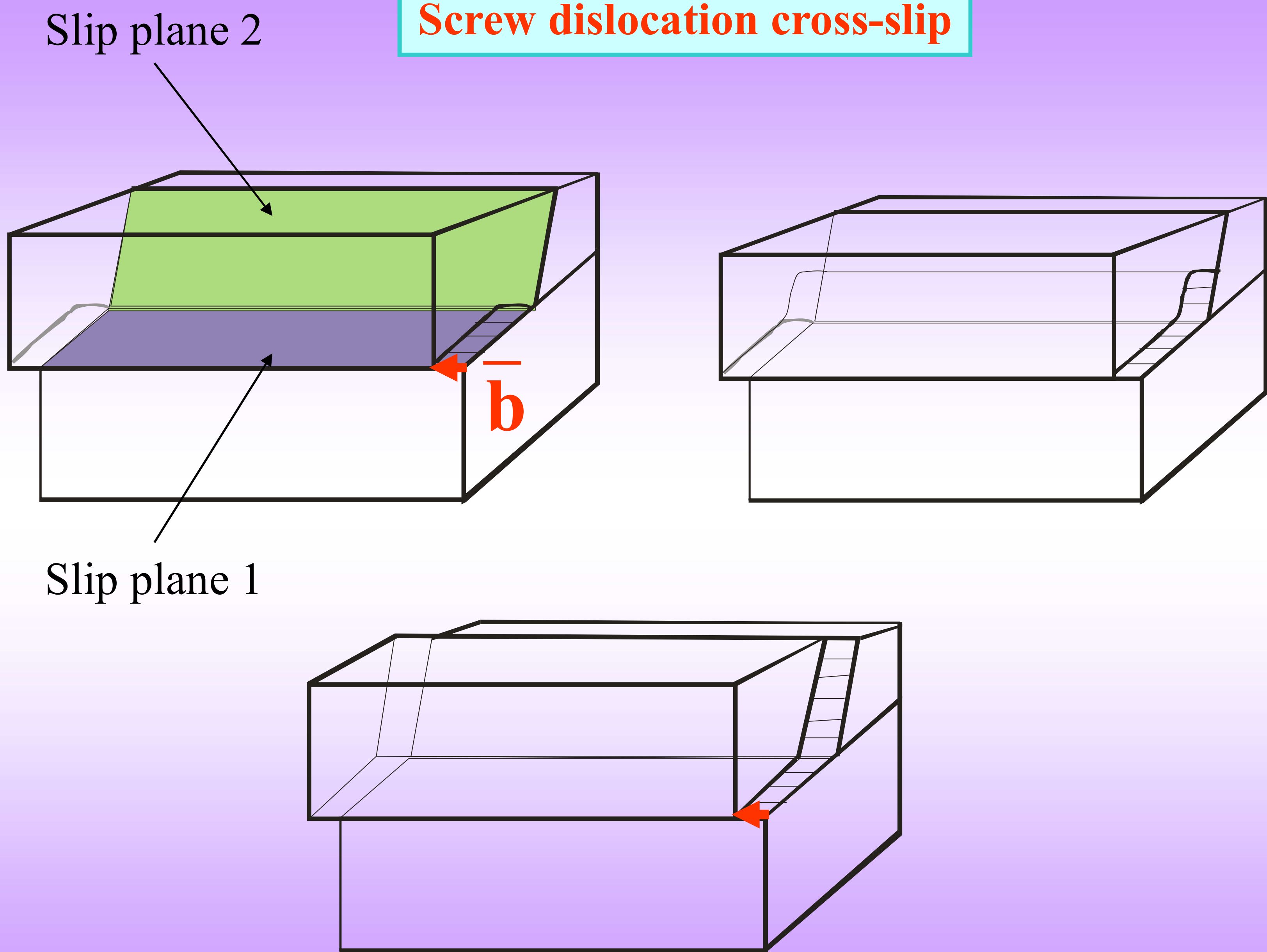
Screw dislocation



[1]

[1] Bryan Baker
chemed.chem.purdue.edu/genchem/ topicreview/bp/materials/defects3.html -

Screw dislocation cross-slip

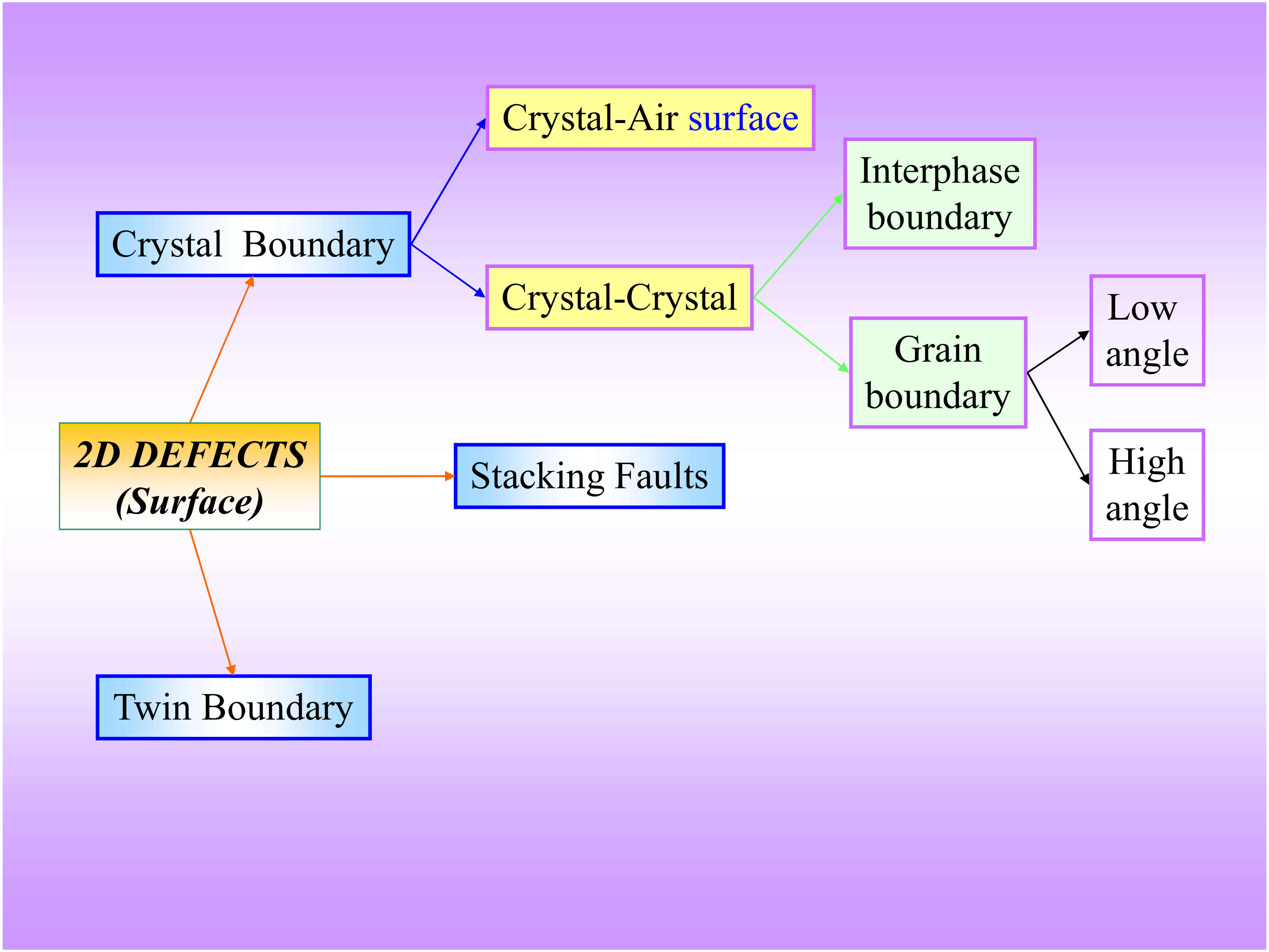


The dislocation is shown cross-slipping from the blue plane to the green plane

- The dislocation line ends on:
  - The free surface of the crystal
  - Internal surface or interface
  - Closes on itself to form a loop

Geometric properties of dislocations

Dislocation Property	Type of dislocation	
	Edge	**Screw**
Relation between dislocation line and **b**	⊥	||
Slip direction	|| to **b**	|| to **b**
Direction of dislocation line relative to **b**	||	⊥
Process by which dislocation may leave slip plane	climb	Cross-slip



Crystal-Air surface
Interphase boundary
Crystal Boundary
Crystal-Crystal
Low angle
Grain boundary
2D DEFECTS (Surface)
Stacking Faults
High angle
Twin Boundary

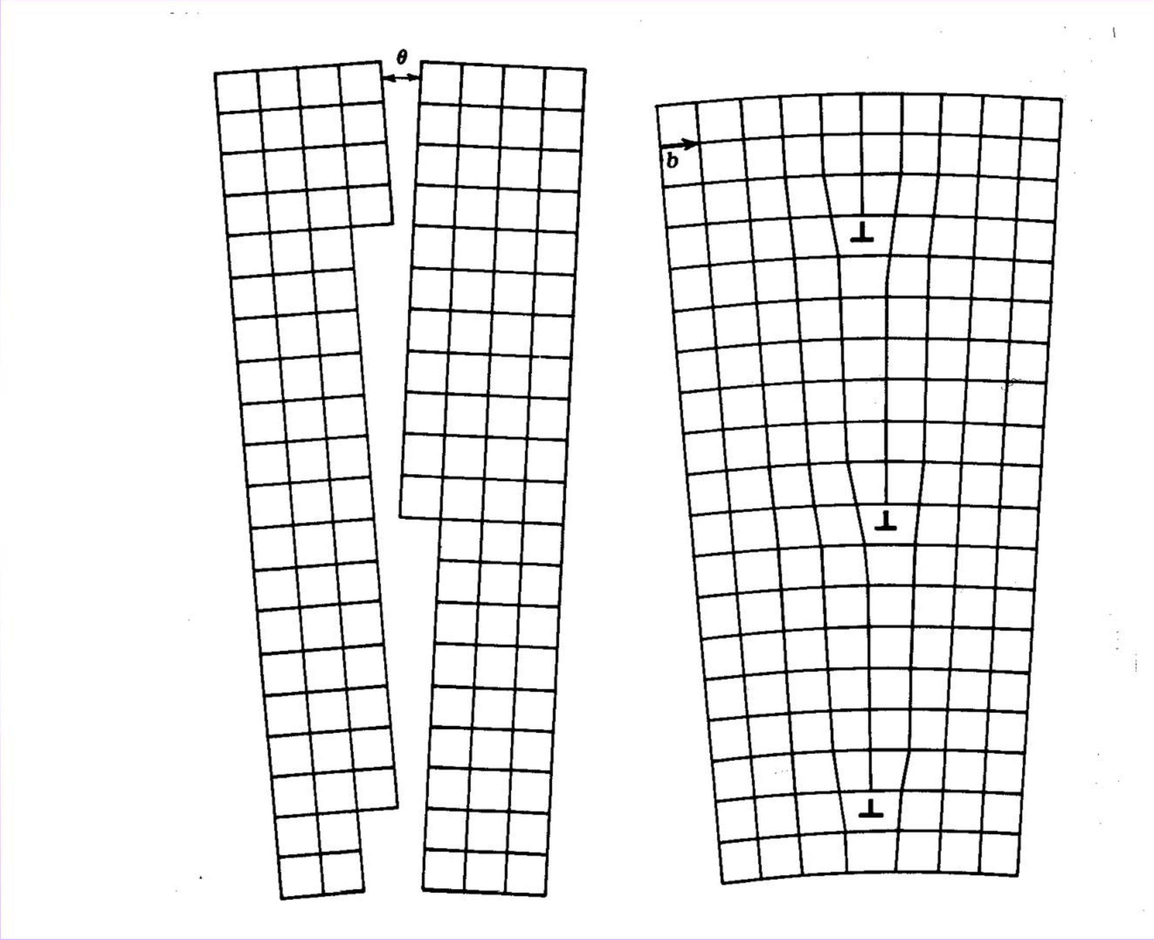
Surface Imperfections

- 2D in a mathematical sense
- The region of distortion is ~ few atomic diameters in thickness

Grain Boundary

- The thickness may be of the order of few atomic diameters
- The crystal orientation changes abruptly at the grain boundary
- In an low angle boundary the orientation difference is $< 10^{o}$
- In an High angle boundary the orientation difference is $> 10^{o}$
- Grain boundary energy is responsible for grain growth on heating $\sim (>0.5T_m)$

Low angle grain boundary



1.4 Twinning & deformation.

Twin Boundary

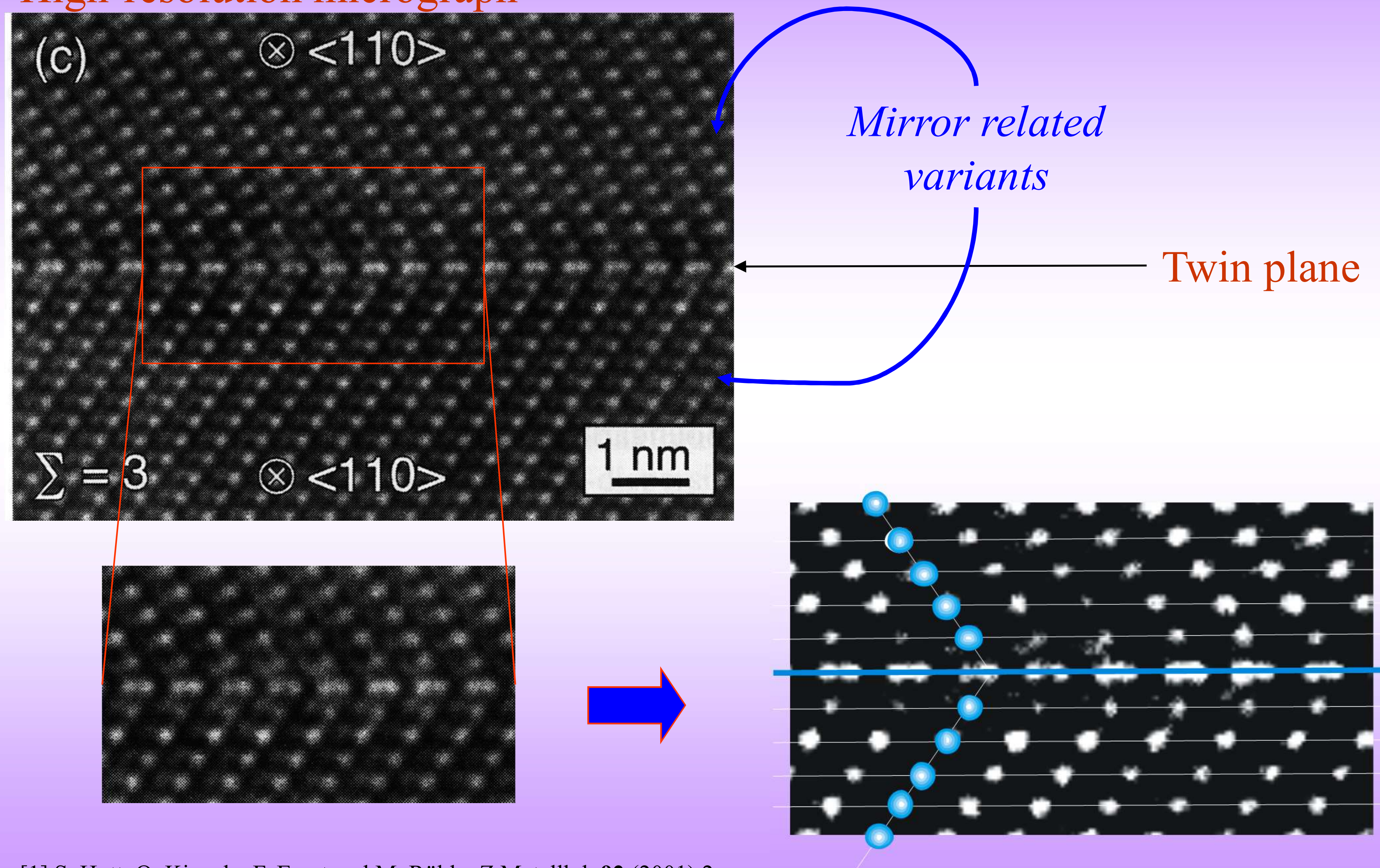
- The atomic arrangement on one side of the twin boundary is related to the other side by a symmetry operation (usually a mirror)
- Twin boundaries usually occur in pairs
- The region between the regions is called the twinned region

Twin → Annealing twins *(formed during recrystallization)*

Twin → Deformation or Mechanical twins *(formed during plastic deformation)*

Twin boundary in Fe doped $SrTiO_3$ bicrystals *(artificially prepared)*

High-resolution micrograph



[1] S. Hutt, O. Kienzle, F. Ernst and M. Rühle, Z Metallkd, **92** (2001) 2

Stacking Fault

- Error in the sequence of stacking atomic planes → Stacking fault

FCC stacking → …ABC ABC ABC ABC…

FCC stacking with a stacking fault → …ABC AB AB ABC…

Thin region of HCP type of stacking

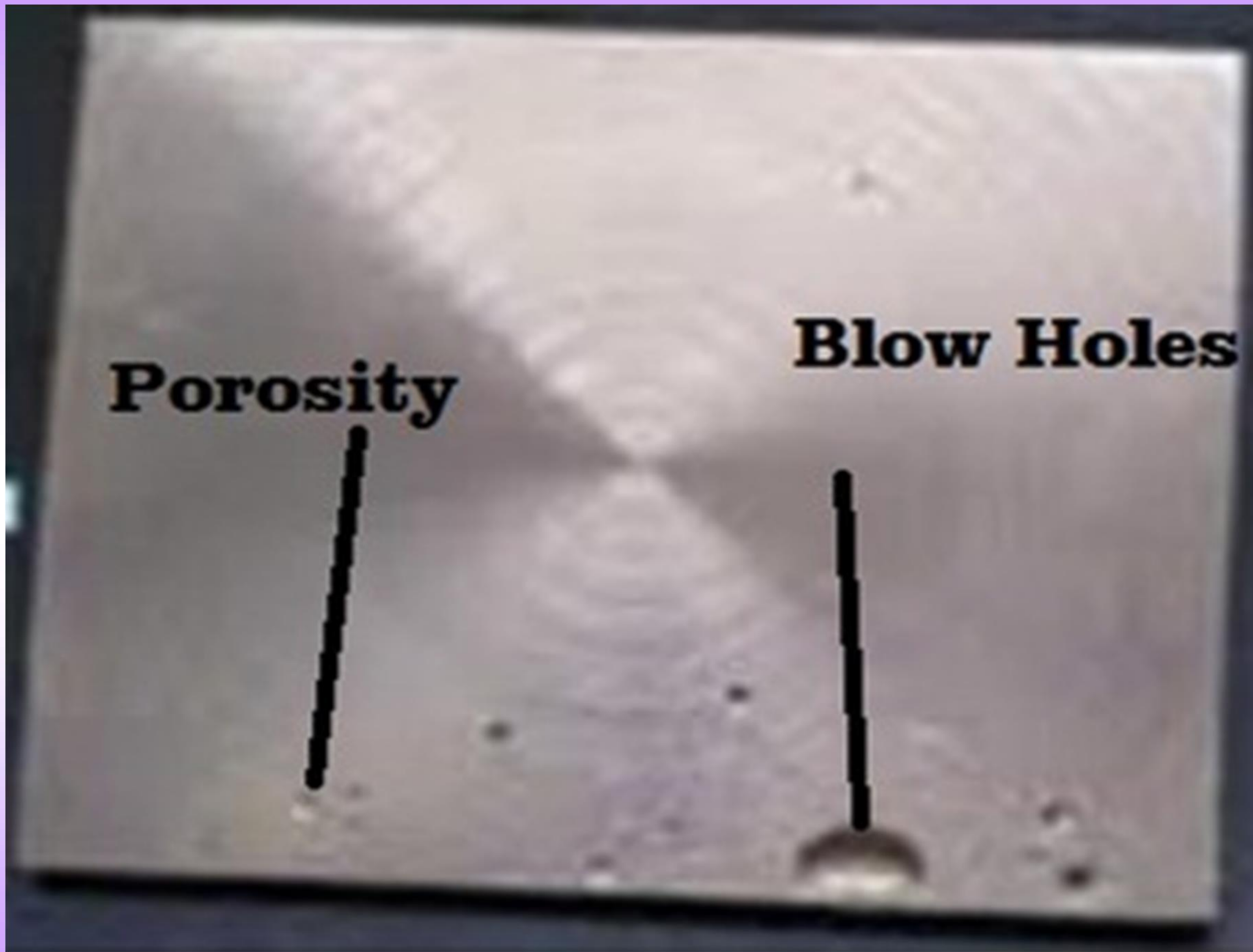
- In above the number of nearest neighbours remains the same but next-nearest neighbours are different than that in FCC
- Stacking fault energy : Energy associated with stacking fault
- Stacking fault in FCC can lead to thin region of HCP kind of stacking

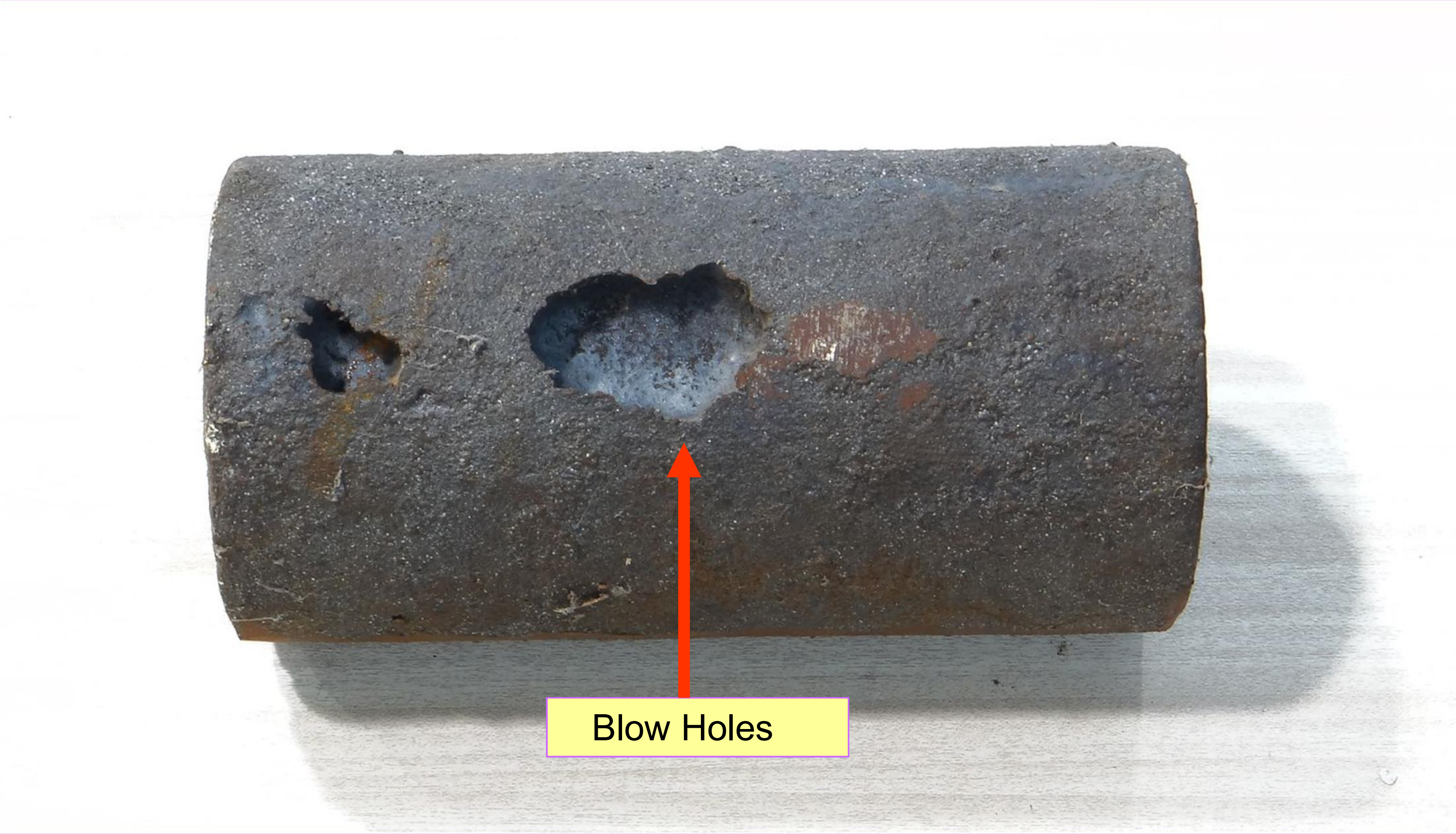
Comparison of Energy of Various 2D Defects

Type of boundary	Energy (J/m^2)
Surface	~ 0.89
Grain boundary	~0.85
Twin Boundary	~ 0.63 0.498 (Cu)
Stacking Fault	0.08 (Cu) 0.2 (Al)

VOLUME DEFECTS

1. Blow holes
2. Voids / Cracks
3. *Pores*


Porosity
Blow Holes


Blow Holes

Voids are caused by high energy particles. e.g material used in nuclear reactors

- A group of atoms missing

2.0 Deformation of Metals

2.1 Elastic & Plastic Behaviour of Metals

Fundamentally – atoms arranged in periodic order

A crystal is an orderly array of atoms in space.

Most metals crystallize: *bcc, fcc* & *hcp*

Unit cells: Smallest group of atoms possessing the symmetry of crystal

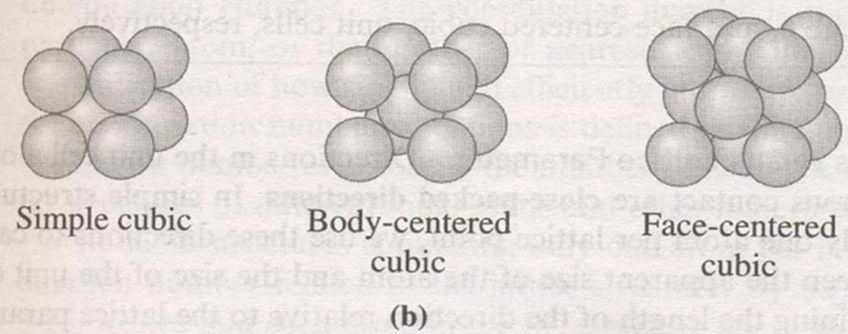


Figure 3-13 (a) Illustration showing sharing of face and corner atoms. (b) The models for simple cubic (SC), body-centered cubic (BCC), and face-centered cubic (FCC) unit cells, assuming only one atom per lattice point.

Lattice Defects

Real crystals deviate from perfect periodicity and known as lattice defects.

Defects affect Physical & Mechanical Properties.

Structure sensitive and insensitive properties

- Structure sensitive - Mechanical Properties
- Structure insensitive - Physical Properties

Lattice defects

1. Point Defects: Vacancies, Interstitials & Impurities
2. Line Defects : Dislocations
3. Surface Defects: Stacking fault, Grain boundary, Low angle grain boundary, Twinned region etc.

Line defect- Dislocation

Dislocations- Most important 2-D or line defects. They extend in a crystal as a line or 2-D net of lines.

Responsible for slip- Most important mechanism of plastic deformation.

Dislocation is a line separating slipped and unslipped region of a crystal.

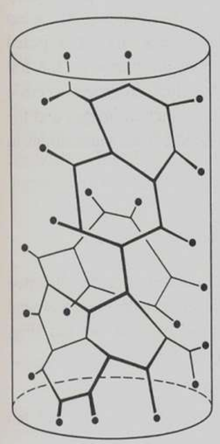
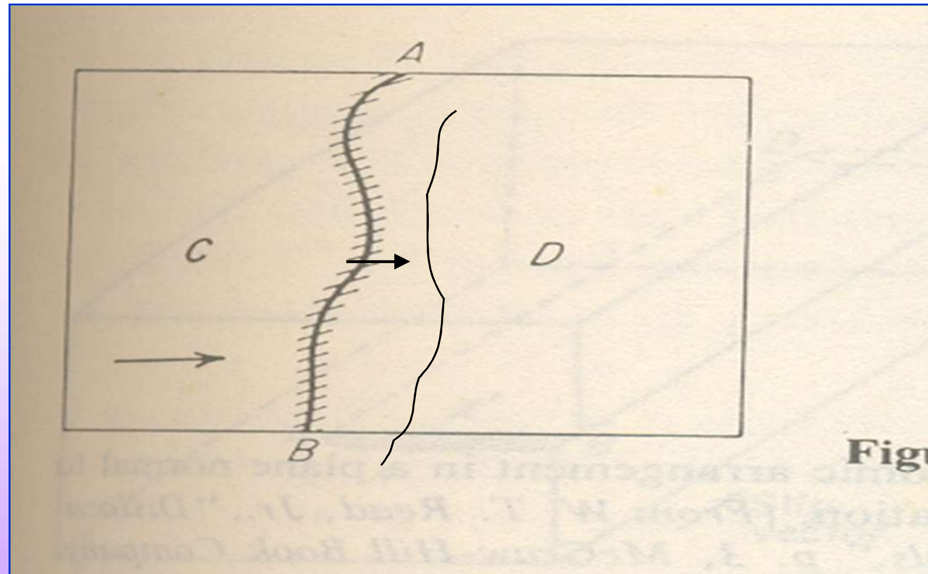


FIGURE 2.11 Network arrangement of dislocations in crystal. Dislocations can terminate only at a node, in a loop, or at a grain boundary or free surface.[7] (Reproduced by courtesy of the Council of the Institution of Mechanical Engineers from *The Properties of Materials at High Rates of Strain*, by A. H. Cottrell.)



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This takes place along a definite crystallographic plane (slip plane).

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Slip in a crystal can be understood with the help of the Fig.1

Fig. 1.a Classical Idea of Slip & Slip Lines

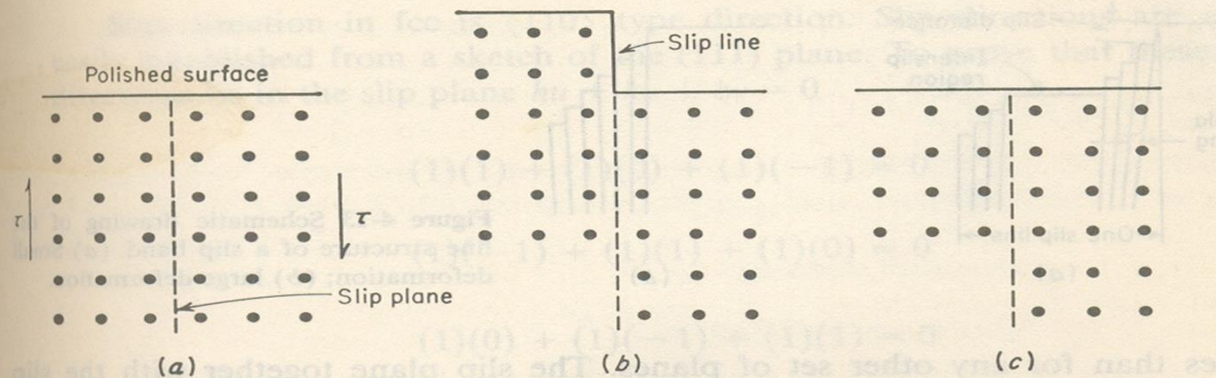
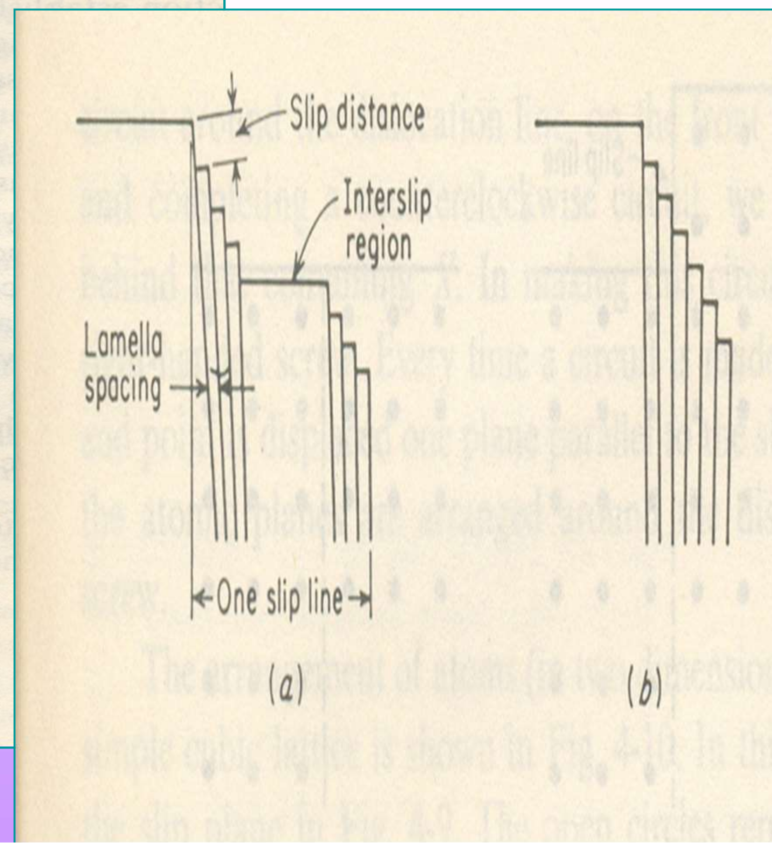


Figure 4-11 Schematic drawing of classical idea of slip.

Figure 4-12 Straight slip lines in copper (500 ×). *(Courtesy W. L. Phillips.)*

Fig. 1.b Fine Structure of Slip Band



Effect of Shear Stress

- Slip takes place along certain crystallographic planes and directions (there are only limited no. of planes and directions).

- Stress must exceed a critical level.
- Slip displacement is an integral multiple of atomic distance (each atom moves an integral multiple of atomic spacing).

Due to symmetry of a crystal lattice, the crystal structure is perfectly restored, if deformation is uniform. Each atom in the slipped part move by the same integral multiple of lattice spacing.

Slip lines appears as changes in elevation. Under Electron Microscope the change in elevation of slip appears as a band. The band in actually composed of number of individual slip steps.

Slip Plane & Direction

Slip occurs most readily in specific direction on a certain specific crystallographic planes.

Generally, **slip planes** are plane of greatest atomic density. **Slip directions** are closest–packed directions within the slip planes.

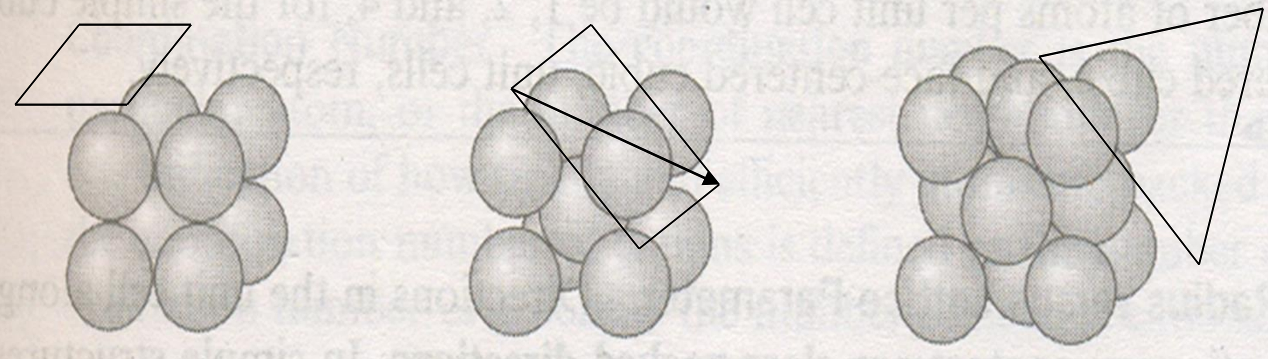
• Since the planes of highest atomic density are most widely spaced planes in the crystal systems, the resistance to slip is least along the set of planes.

• Slip directions are closed packed direction, therefore the movement of atoms in the direction is least.

• **The slip plane together with the slip direction is considered as slip systems.**

The most common crystation lattice in metallic materials are ***bcc, hcp* and *fcc***. The figures show the hard ball model and stacking sequences in the above crystal systems

Fig. 2



Simple cubic | Body-centered cubic | Face-centered cubic

(b)

Figure 3-13 (a) Illustration showing sharing of face and corner atoms. (b) The models for simple cubic (SC), body-centered cubic (BCC), and face-centered cubic (FCC) unit cells, assuming only one atom per lattice point.

hcp Crystals

In *hcp* crystals basal plane, (0001) has maximum atomic density: **slip plane** (closed packed plane).

The axes [11 -2] are the closed packed directions and hence the slip directions

No. of Basal Plane - 1

No. of Slip direction - 3

In each basal plane

No. of my slip system = 1 x 3 = 3

This is the reason ***hcp* crystals are highly orientation dependent.**

Mg, Zn, Co, Ti.

In case of hexagonal closed packed system, *Miller Bravais* indical notation is used to describe the direction and planes. Four coordinates are used, Fourth Indical notation by (a1 a2 a3 c) [a1 a2 a3 c].

Unit vector direction is a/3 [2 $\bar{1}$ $\bar{1}$ 0]

Fig. 3

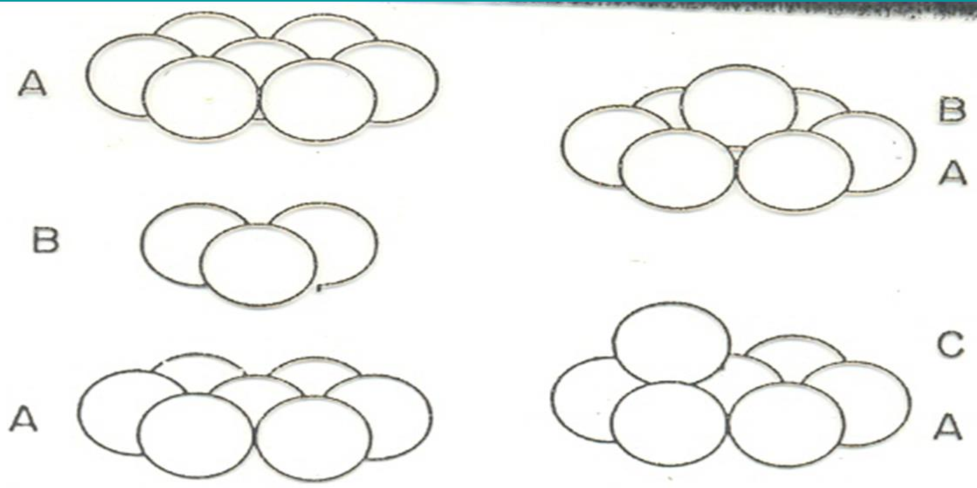


FIGURE 4–8. Stacking of close-packed atomic layers.

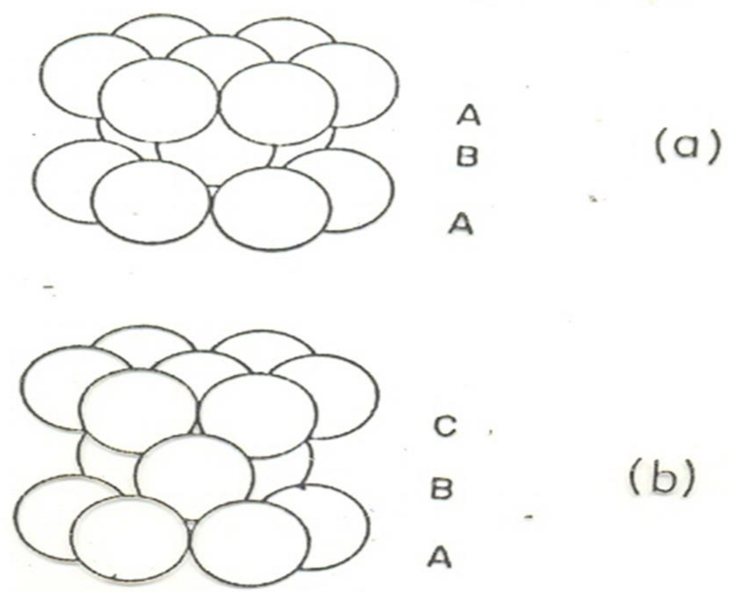
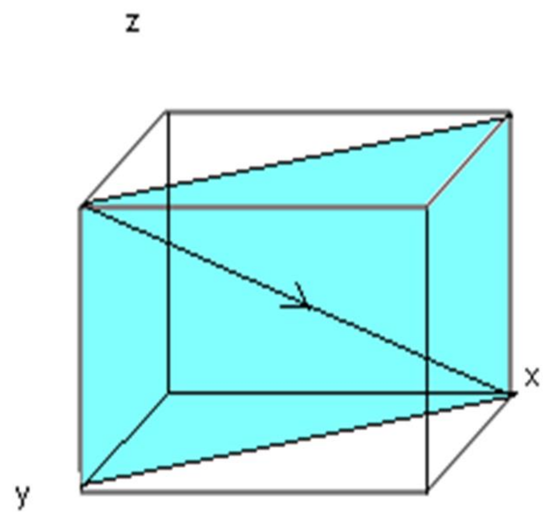
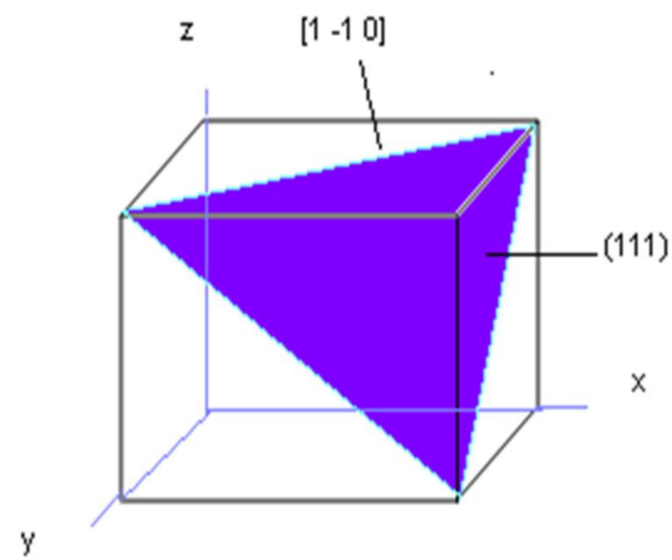


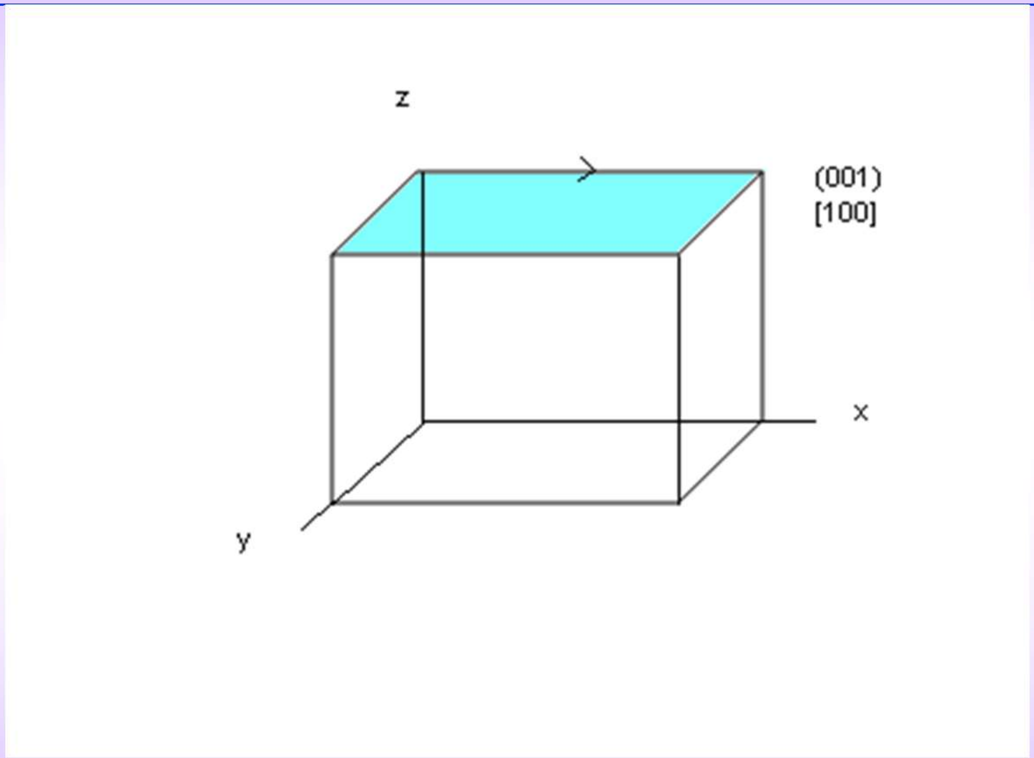
FIGURE 4–9. (a) Hexagonal close-packed; (b) face-centered cubic.

(110) Plane & [1 -1 -1] Direction in bcc & (111) and [1 -1 0] in fcc Systems





(001) Plane & [100] Direction in Simple Cubic Systems



fcc Crystals

- (111) planes are closed packed planes / planes of highest atomic density.
- <110> are closed packed direction.

There are eight {111} planes but opposite plane are parallel. Therefore, there are only four set of octahedral planes. Each plane contains three closed packed directions.

No. of slip systems = 3 x 4 = 12

Ag, Cu, Ni, Pt, γ-Fe

Slip planes/ directions in fcc

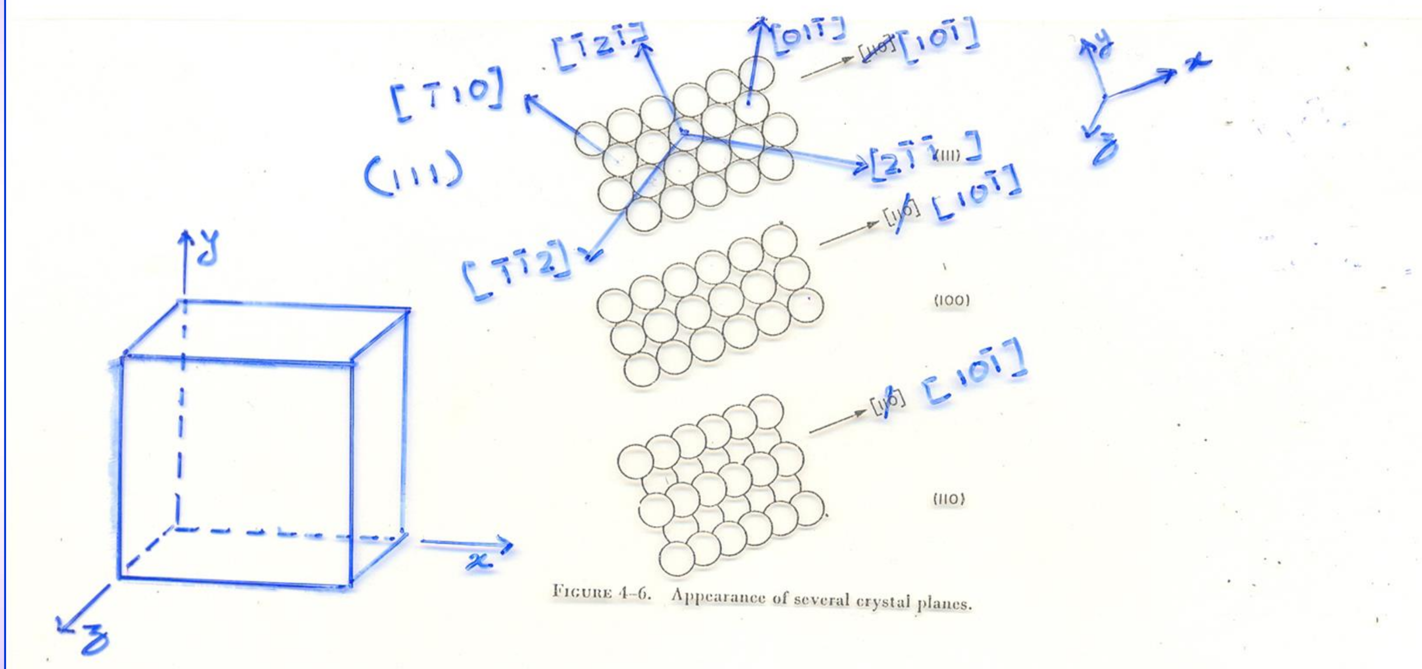


FIGURE 4-6. Appearance of several crystal planes.

Slip planes/ directions in bcc

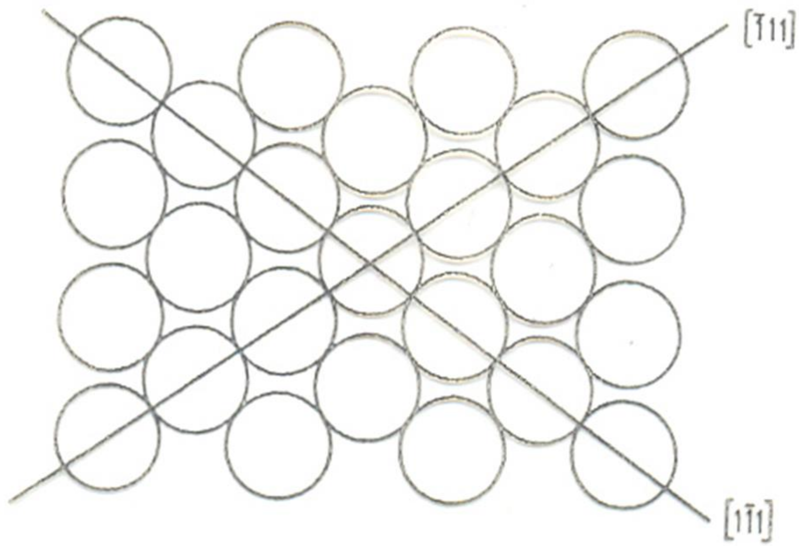


Fig. 4.45 The (110) plane of the body-centered cubic lattice.

bcc Crystals

bcc is not a closed packed structure.

Not even a single closed packed plane.

{110} planes have higher atomic density.

<111> direction are as closed as <110> in *fcc* and {11-20} in *hcp*.

The slip planes are not definite

- Common slip planes {110}, {112} & {123}
- Directions always {111}.

There are 48 slip systems. But planes are not really closed packed, therefore, the shear stress required is higher.

Slip moves (cross slip) from one plane to other resulting into *irregular wavy slip bands*.

The examples of *bcc* metals α – Fe, Mo, Cr, Nb.

Displacement vectors in cubic system

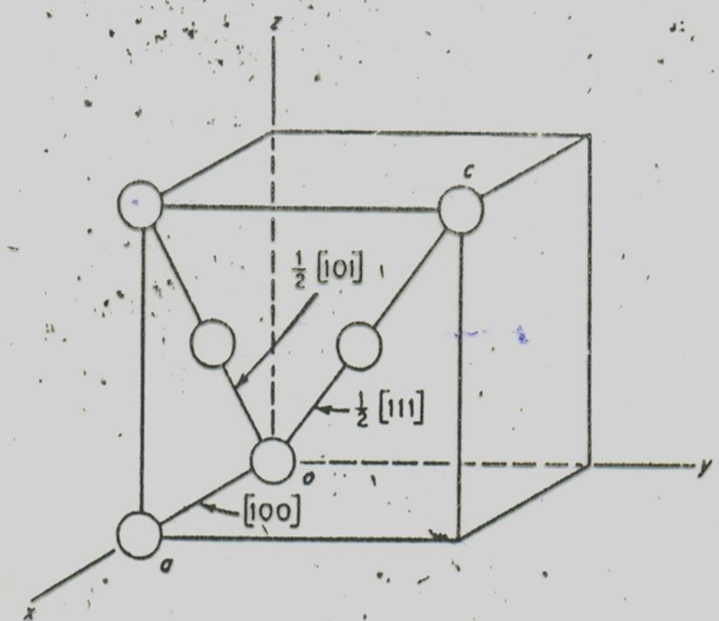


Fig. 5.11 The spacing between atoms in the close-packed directions of the different cubic systems: face-centered cubic, body-centered cubic, and simple cubic.

Slip in a Perfect Lattice

Calculation of Theoretical Shear Strength

Slip is translation of one atomic plane over other. This movement of atomic plane requires a critical level of shear stress.

Fig.

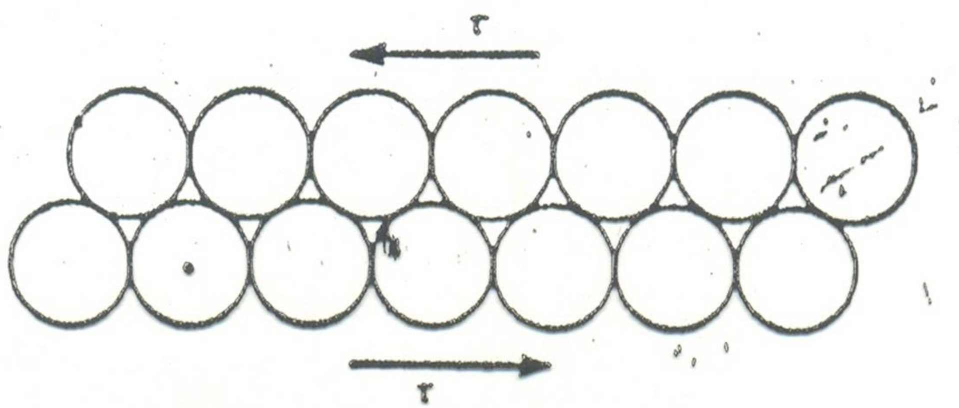


Fig. 4.4 Initial position of the atoms on a slip plane.

- Continued .. Slip in perfect crystal

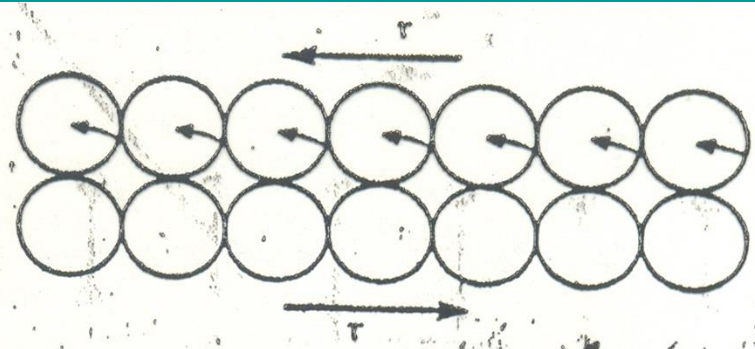


Fig. 4.5 The saddle point for the shear of one plane of atoms over another.

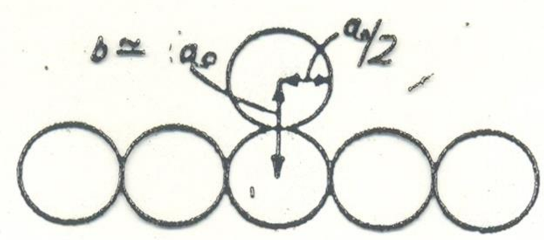
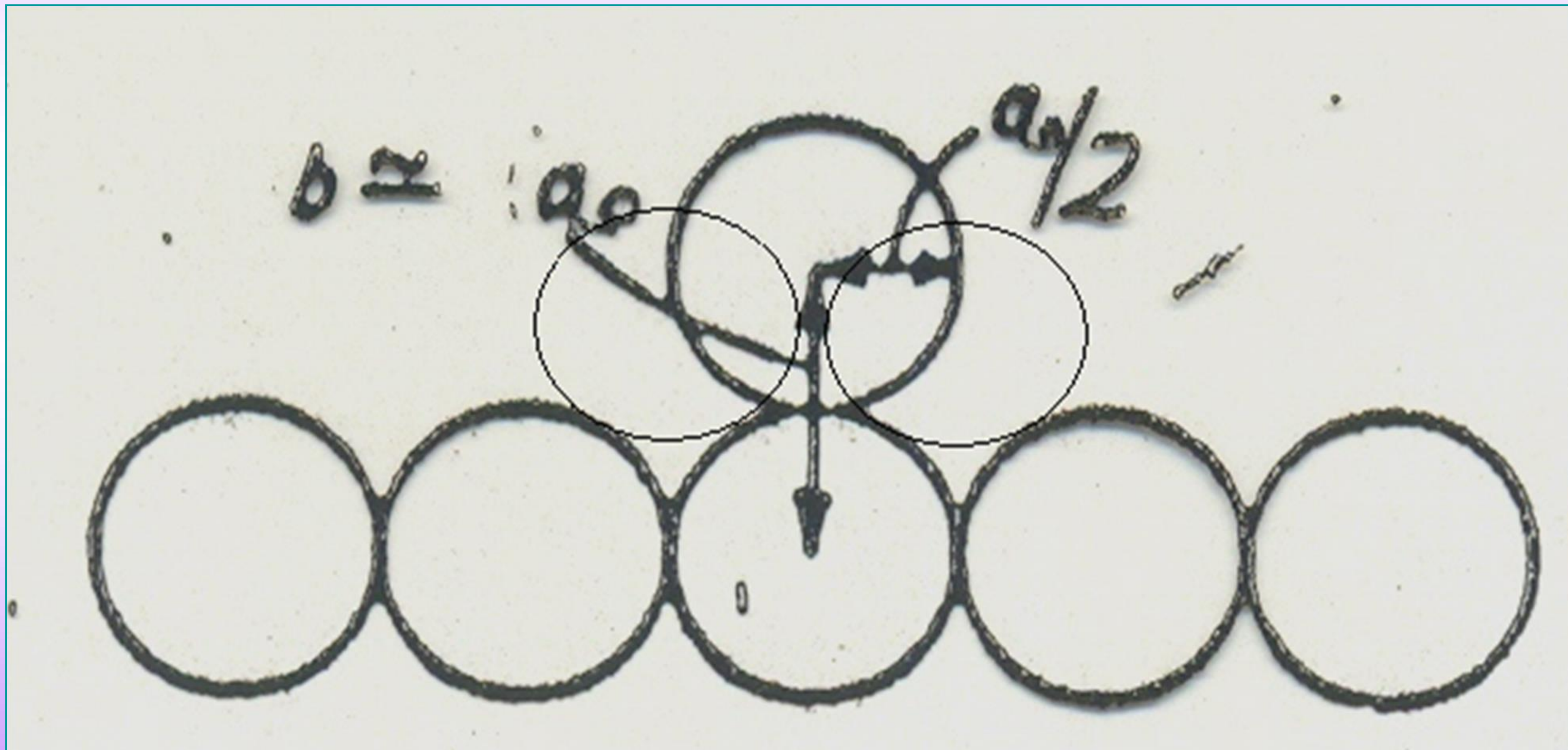


Fig. 4.6 The shear at the saddle point is approximately a/b or 1/2.



Continued… Slip in perfect lattice Fig.

$$\tau = \tau_m \sin \frac{2\pi x}{b} \qquad (2\text{-}1)$$

where τ = applied shear stress
τ_m = maximum theoretical strength of crystal
x = distance atoms are moved
b = distance between equilibrium positions

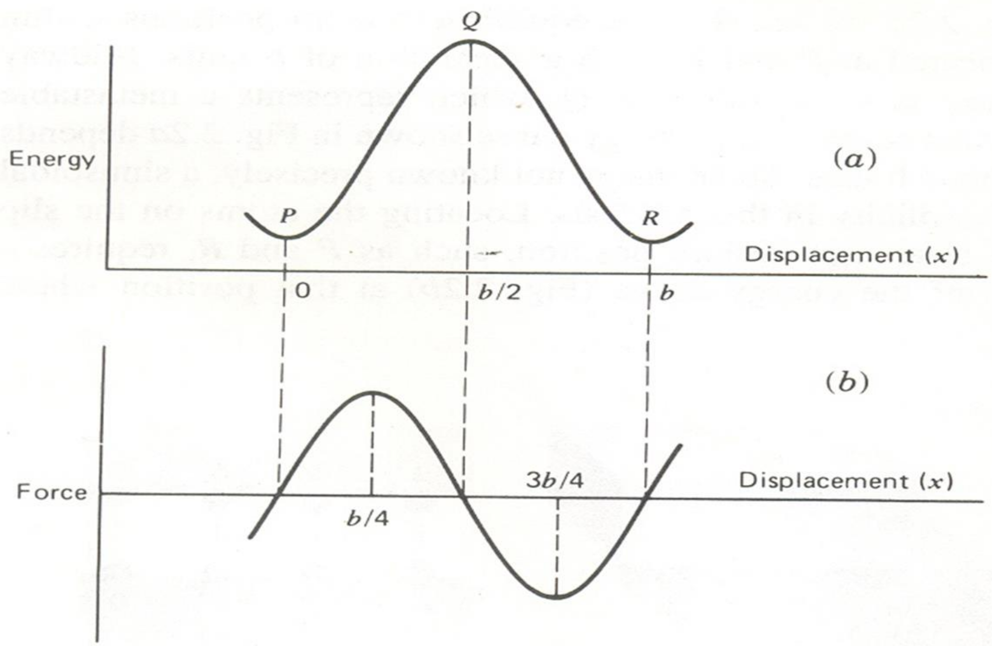


FIGURE 2.2 **The periodic nature of a lattice. (*a*) Variation of energy with atom position in lattice. Preferred atom sites are at *P* and *R*, associated with minimum energy; (*b*) variation in force acting on atoms throughout lattice. Force is zero at equilibrium site positions and maximum at *b*/4, 3*b*/4, 5*b*/4, ..., (2*n* − 1)*b*/4.**

The shear stress is a periodic function of the displacement. A sinusoidal relationship can be assumed

$$\tau = \tau_m \sin \frac{2 \Pi x}{b}$$

here τ_m is amplitude of sine wave. a is interatomic spacing, b is period & x is small displacement

Now $\tau = Gr = G \frac{x}{a}$

For small displacement, $\tau_m = \frac{G}{2\Pi} \frac{b}{a}$

$$G \frac{x}{a} = \tau_m \frac{2\Pi x}{b}$$

As a rough approximate a ≈ b

$$\tau_{max} = \frac{G}{2\Pi}$$

Shear Modulus = 20 – 150 GP in metals.

Theoretical shear stress = 3 to 30 GPa.

However, shear stress to cause shear in metal single crystals are 0.5 to 10 MPa

Even more refined calculation shows:

$$\tau_m = \frac{G}{16} \quad \text{for fcc metals}$$

$$= \frac{G}{8} \quad \text{for NaCl crystals}$$

$$= \frac{G}{4} \quad \text{for Covalent bonded diamond structure}$$

Since the theoretical shear stress of metal is 100 times greater than the actual. It indicates the mechanism either than bodily satisfying of atoms is responsible for slip.

Theoretical shear strength, explanation

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

The concept of dislocation was first introduced to explain discrepancy between the observed and theoretical shear strength of metals. If this concept is true it is necessary to show: 1) they are visible, 2) the motion of a dislocation requires a shear stress much smaller than the theoretical shear strength. 3) the movement of dislocation produces a steps at the free surface. All three concepts are found to be true in real crystals. **This indicates the validity of the concept of dislocation.**

- It is possible to see these dislocations with aid of Transmission Electron Microscope.

  For this purpose very thin slice of metal is taken (few thousand Ǻ thick) from a deformed crystal.

- Etch Pit Technique revels the location of intersection of dislocation line with the surface.

Figs. Disl. Network & Etch pits

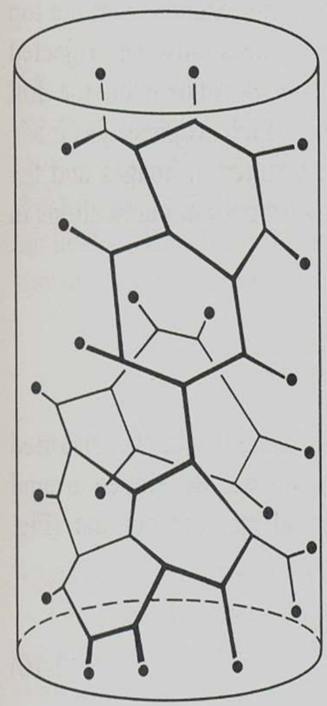


FIGURE 2.11 Network arrangement of dislocations in crystal. Dislocations can terminate only at a node, in a loop, or at a grain boundary or free surface.[7] (Reproduced by courtesy of the Council of the Institution of Mechanical Engineers from *The Properties of Materials at High Rates of Strain*, by A. H. Cottrell.)

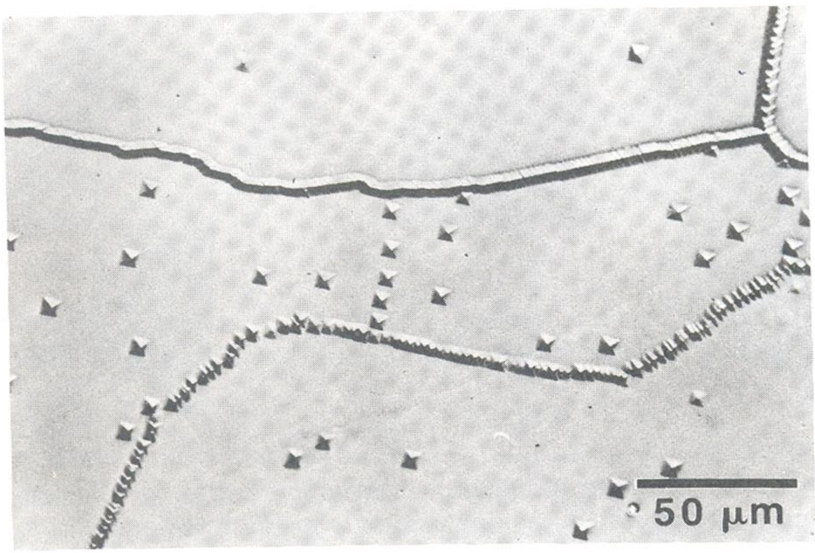
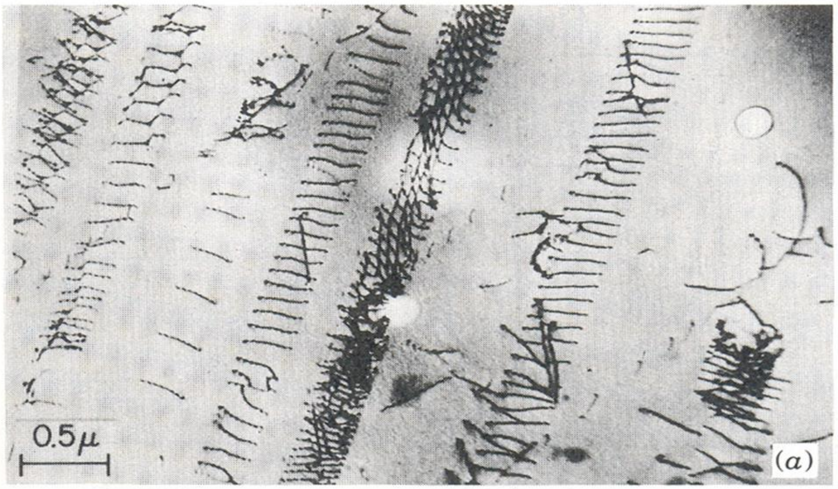
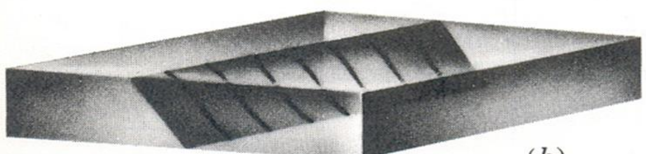


FIGURE 2.12 Etch pits on polished surface of lithium fluoride, each associated with an individual dislocation. The etch pit lineage indicates alignment of many dislocations in the form of low-angle boundaries (see Section 2.6). (From Gilman and Johnston;[18] reprinted by permission of General Electric Co.)

Fig. Observation of Disl. in thin foil





(b)

FIGURE 2.13 Observation of individual dislocations in thin foil. (*a*) Planar arrays of dislocations in 18Cr–8Ni stainless steels (from Michalak,[10] *Metals Handbook,* Vol. 8, copyright American Society for Metals, Metals Park, OH, 1973; used with permission); (*b*) diagram showing position of dislocations on the guide plane in the foil (after Hull[11]).

Edge Dislocation

Fig – A represents a simple cubic lattice under an external shear stress. The amount of slip or displacement is assumed to be one atomic spacing. The result of this shear is shown in the Fig. – B.

- This leaves an extra half plane CD below the slip plane in the right hand side, outside the crystal.
- It will also produce an extra half plane located above the slip plane and in the centre of the crystal.
- All other planes are realigned and continuity is maintained.
- Distortion decrease as moved away from the edge of the extra plane.
- The boundary of additional plane is called an edge dislocation.

Fig. Continued… Edge Dislocation

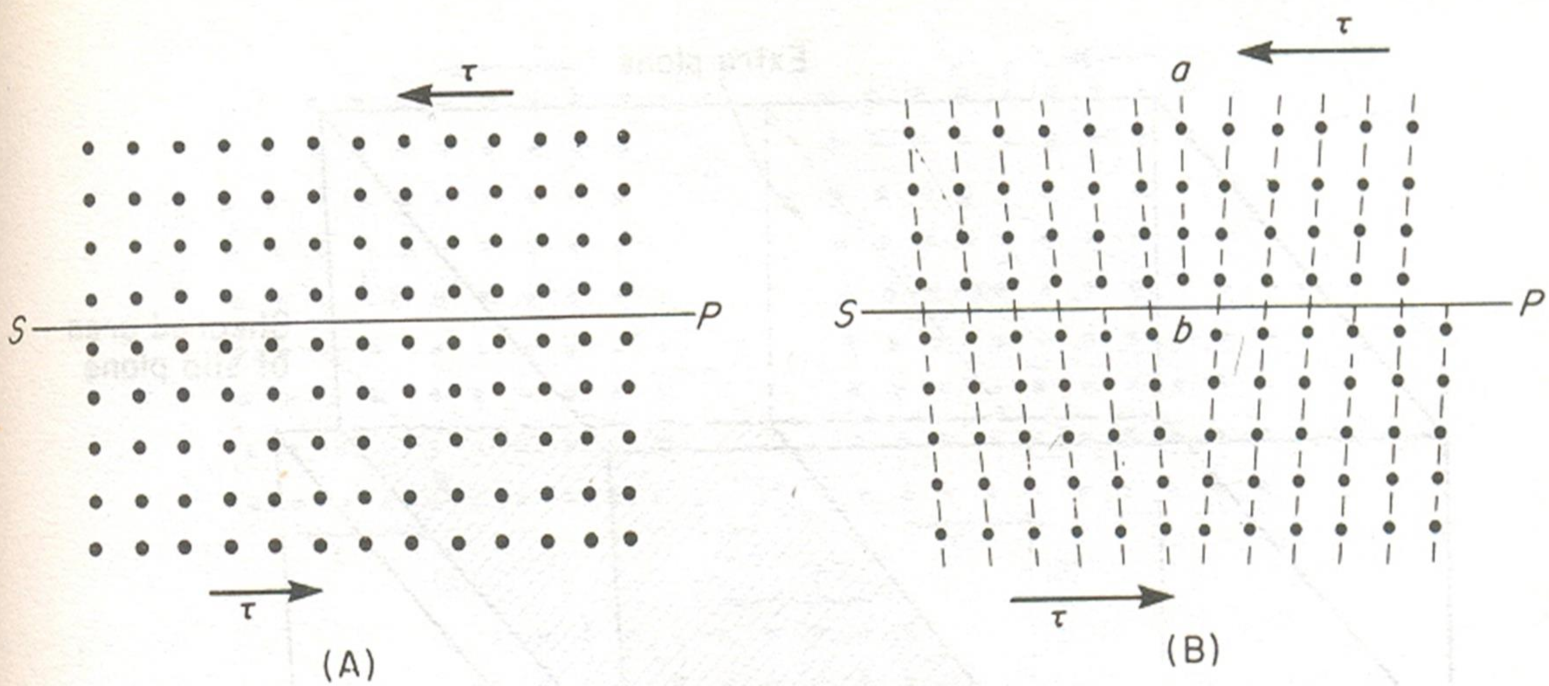


Fig. 4.10 An edge dislocation. (A) A perfect crystal. (B) When the crystal is sheared one atomic distance over part of the distance S–P, an edge dislocation is formed.

Edge Dislocation

- Fig. 4.11 represents a 3 – D sketch of the edge dislocation.
- The figure clearly shows that dislocation has the dimension of a line.
- Dislocation line marks the (separates) boundary between sheared and un-sheared part of the slip plane.

This is the basic characteristics of a dislocation line.

Dislocation may be defined as a line that forms a boundary on a slip plane between slipped and un-slipped region.

Displacement vector: *Burgers Vector, $\bar{b}$* .

Fig. Continued Edge Disl.

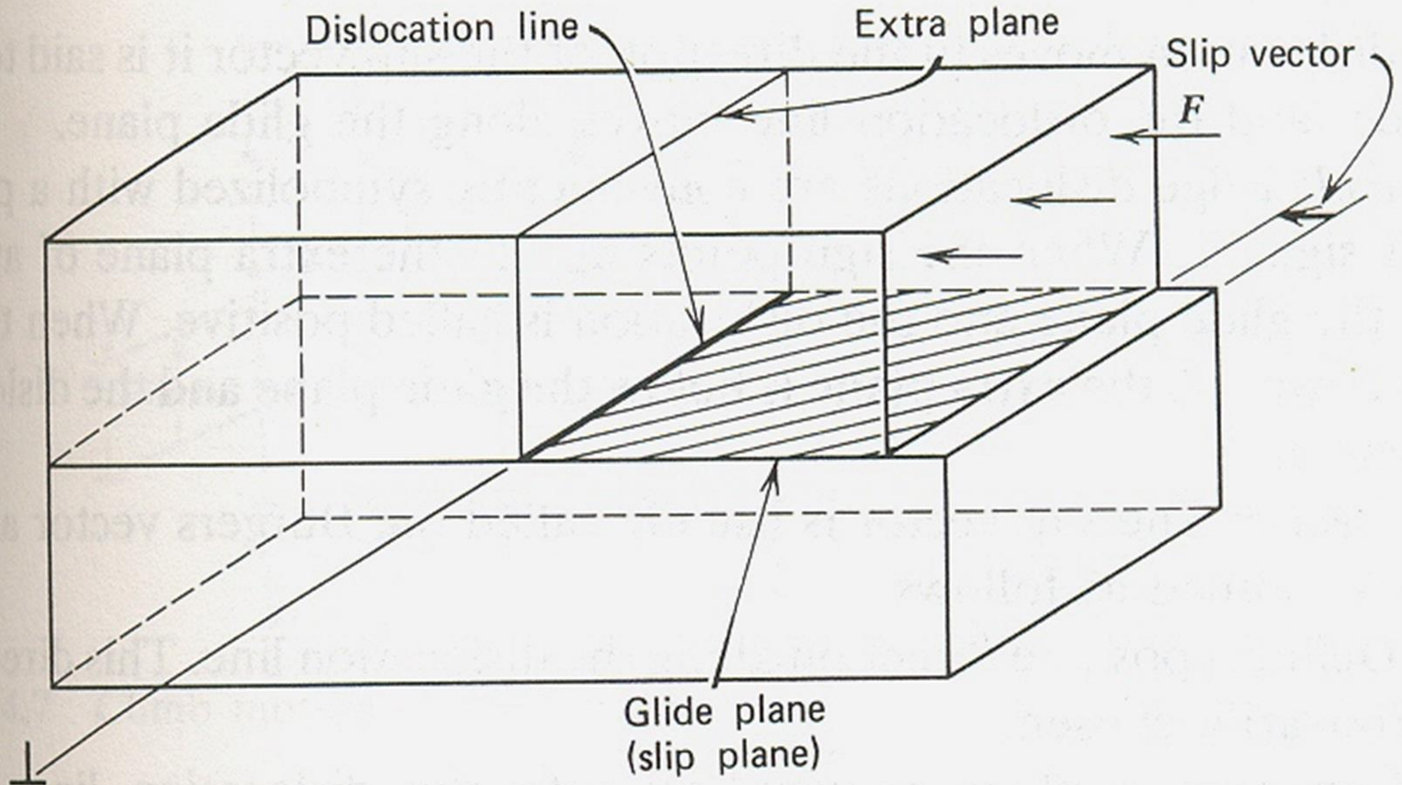
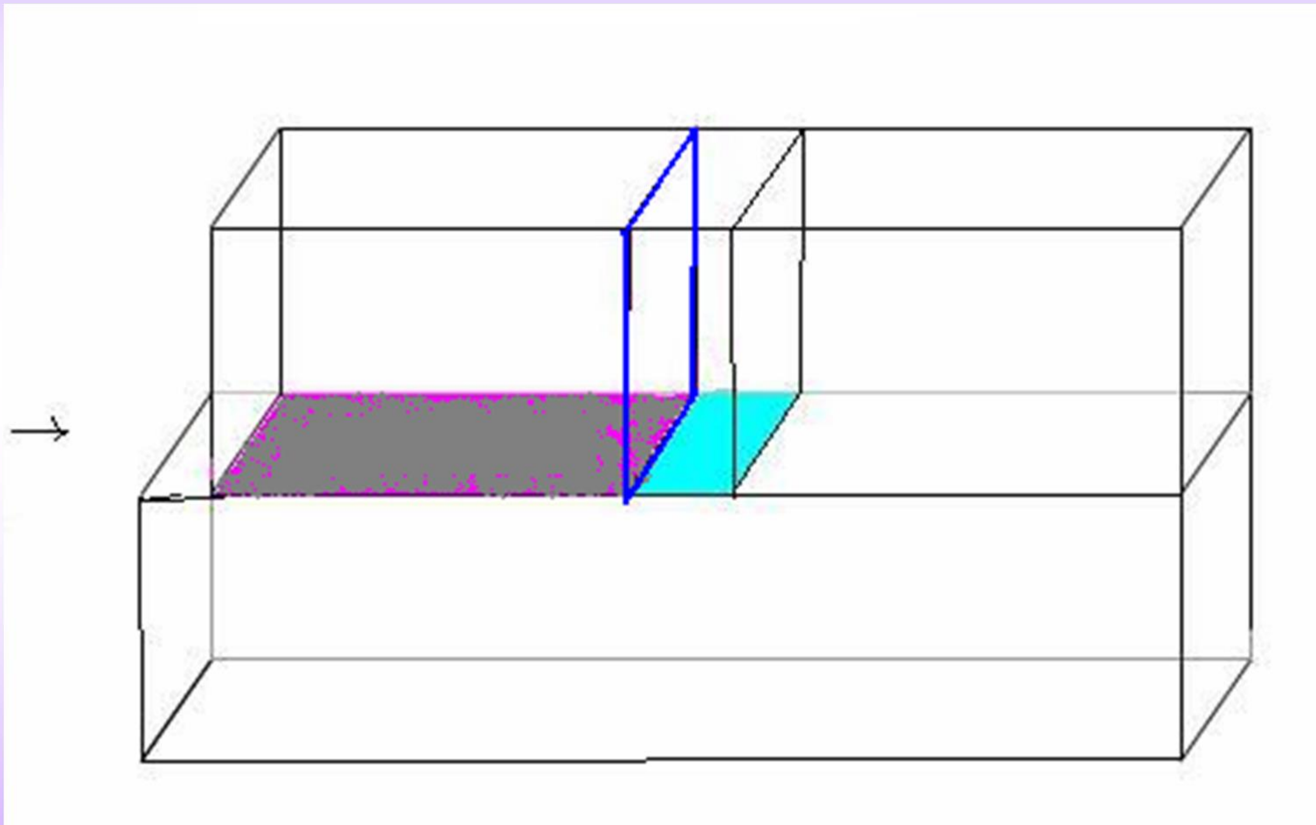


Figure 4.5 The edge dislocation.



Screw Dislocation

Schematically illustrated in Fig. 4.13 A.

- Here each small cube is considered to represent an atom. Fig. B represents the same crystal with the position of the dislocation line marked by DC.
- ABCD represents slip plane under the effect of stress. Upper front part has been sheared by one atomic distance to the left relative to the lower front portion.
- It is termed as screw dislocation because the lattice planes spiral the dislocation line DC. This can be proved by starting at point x in Fig. A then proceeding toward and around the crystal in the indicated direction. One circuit will end the crystal at point y. If it is continued it will finally end at y. This deformation is known as screw dislocation.

Dislocation line // Displacement vector and moves perpendicular to Displacement vector

Fig. Contd…Screw Dislocation

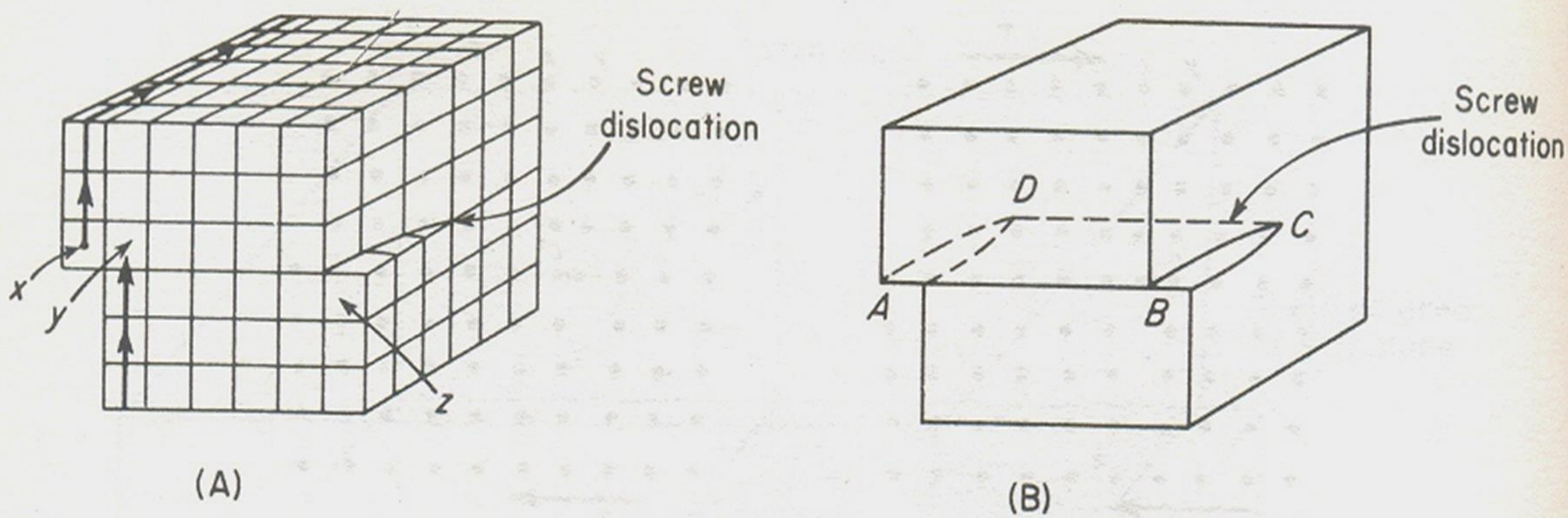


Fig. 4.13 Two representations of a screw dislocation. Notice that the planes in this dislocation spiral around the dislocation like a left-hand screw.

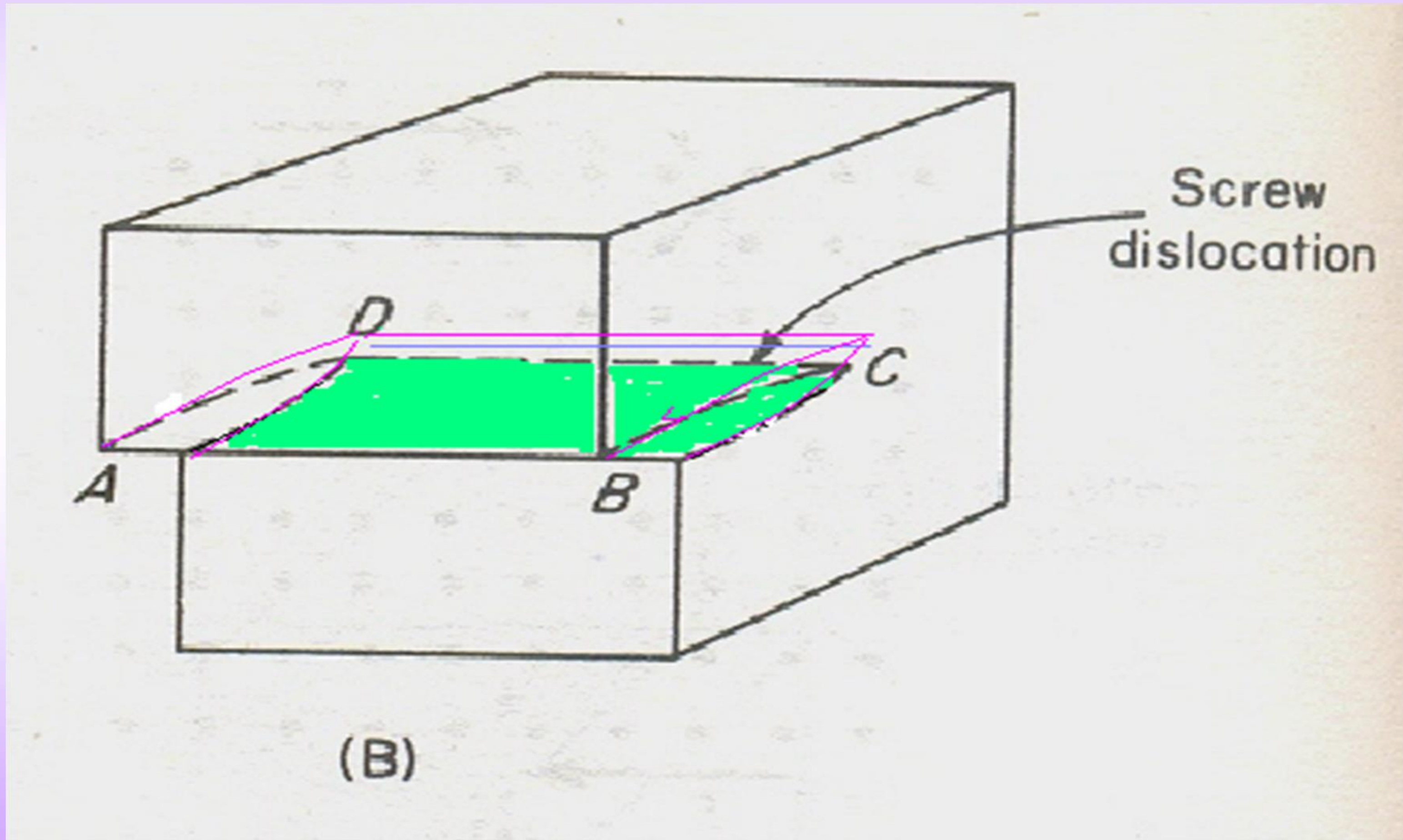

Screw
dislocation
D
C
A
B
(B)

Fig. Cont.d…Screw Dislocation

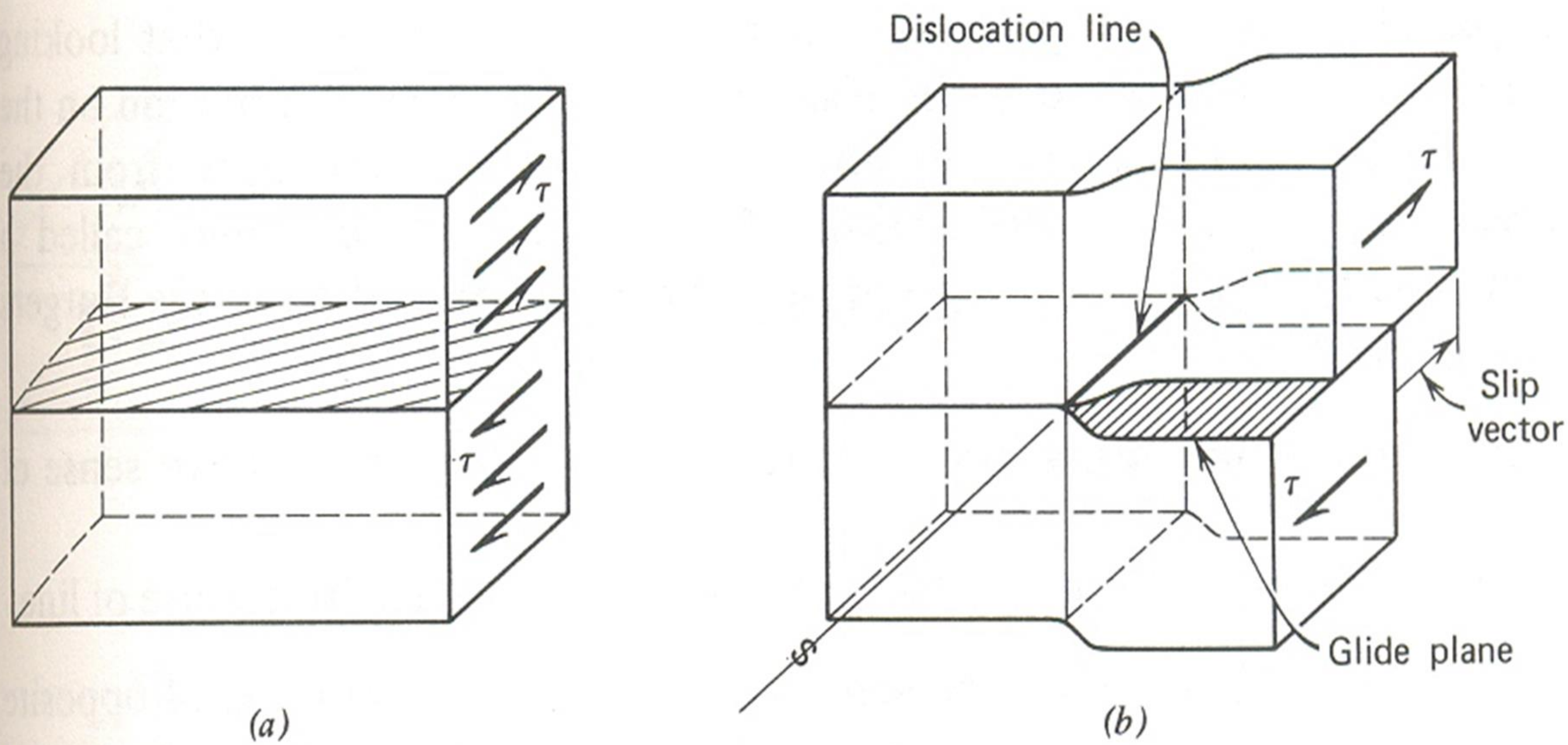


Figure 4.9 The screw dislocation.

Edge vs Screw Dislocations

- The Fig. A, shown earlier has an incomplete plane which lies above the slip plane. These dislocations are represented by and ┴. Here the "—" represents slip plane and "I" vertical line extra-half plane.
- It is also possible to introduce an incomplete plane below the slip plane these dislocations are differentiated by calling the first one as positive(┴) and second a negative (┬)edge dislocation.
- It may be noted that the difference between these dislocations is arbitrary. A single rotation of a positive edge dislocation by 180° turns it into negative edge dislocation.

The illustrated Screw dislocation is Left Hand Dislocation. Because the lattice planes spiral the dislocation line like a left hand screw.

In other case, lattice planes spiral the dislocation like a right hand screw (*anti-clock wise movement of lattice planes results the advancement towards its operator/ right*). All there dislocations are shown in the Figs. 4.14.

Fig. Continued… Edge, Screw Disl.

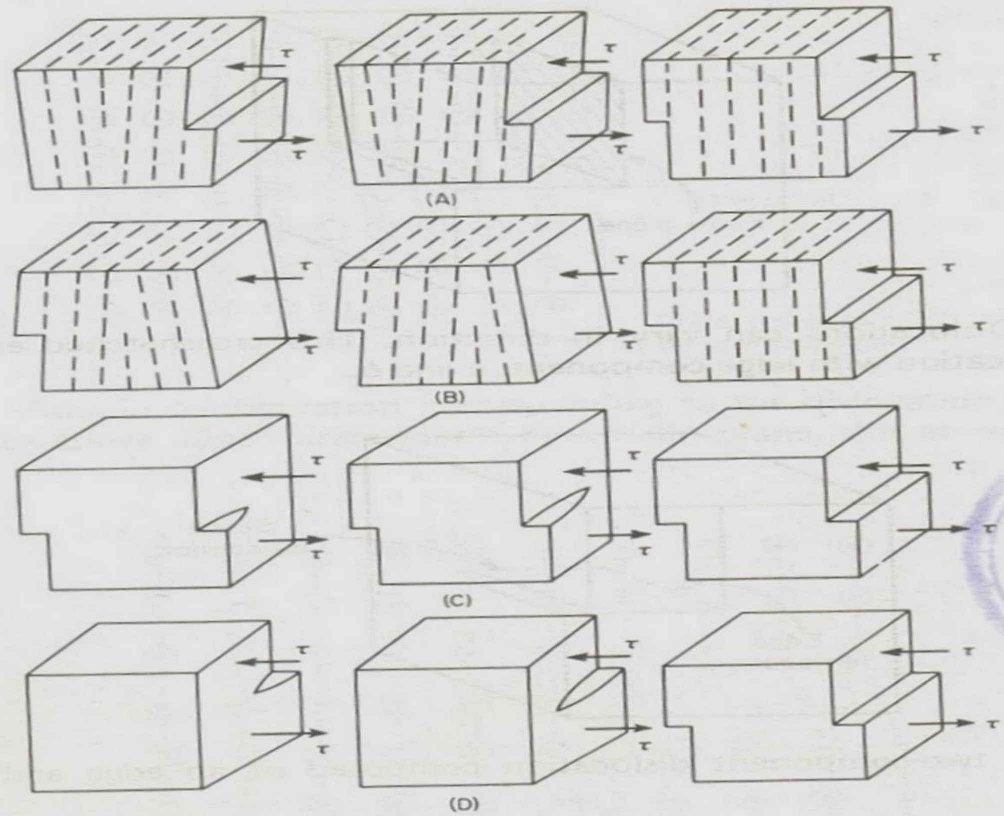


Fig. 4.14 The ways that the four basic orientations of a dislocation move under the same applied stress: (A) Positive edge, (B) Negative edge, (C) Left-hand screw, and (D) Right-hand screw.

Cont… Edge vs Screw dislocations

- In (+) edge dislocation, line move to the left, when stress is applied on the upper half.
- In (-) edge dislocation, line moves in the right direction when stress is applied on lower half.
- Similarly anti-clock wise movement makes the advancement towards left in left handed screw.
- Anti-clock wise movement makes the advancement in the right direction in case of right hand screw dislocation.

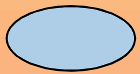
What is common?

Continue shearing of the crystal in all cases result into formation of steps on both the surfaces.

Cont… Edge vs Screw dislocations

In the above cases dislocations are terminated on the surface of the crystals. However, they can also form a continues loop within it.

- In a loop  two basic types of dislocations. Screw and edge dislocations.

- An  irregular area can also get sheared inside the crystal.

In all the cases displacement is equal to a vector (length equal to an atomic spacing or its multiple). This is a discontinuity at which lattice shifts from un-sheared to shear state.

Dislocation loop

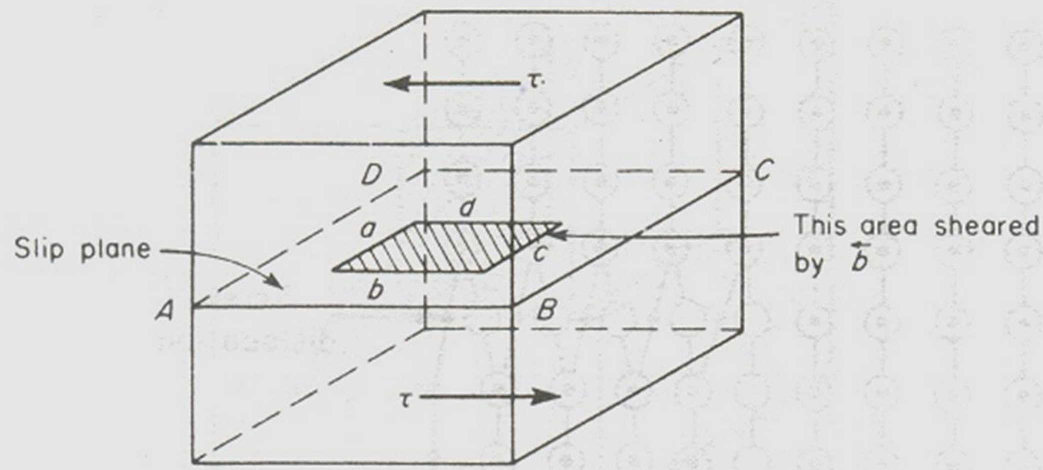


Fig. 4.19 A closed dislocation loop consisting of (*A*) Positive edge, (*B*) Right-hand screw, (*C*) Negative edge, and (*D*) Left-hand screw.

Fig. 4.20 A curved dislocation loop lying in a slip plane.

Mixed Dislocation

If b.v. is ⊥ar to line, an Edge Dislocation.

If bv is ∥ to line, a Screw Dislocation.

At any other angels, dislocation is mixed in nature, a **Mixed Dislocation**.

The Fig. 4.13 (a) shows an effect, atoms in area A – C – B have shifted to one atomic distance relative to the atoms below. The boundary of shift is not linear rather curved. The top view of crystal is shown in Fig. 4.13 (b).

Mixed Dislocation

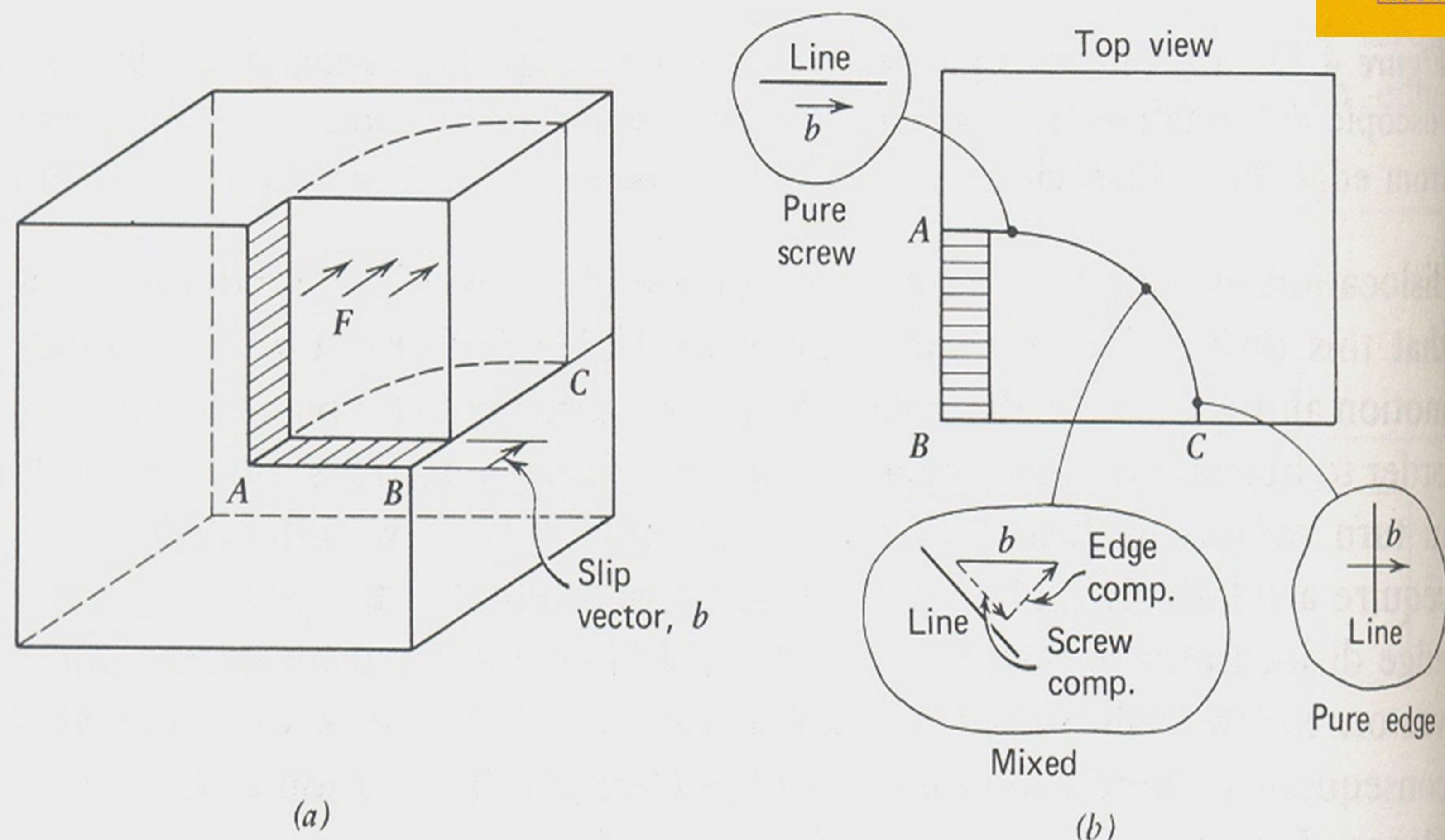
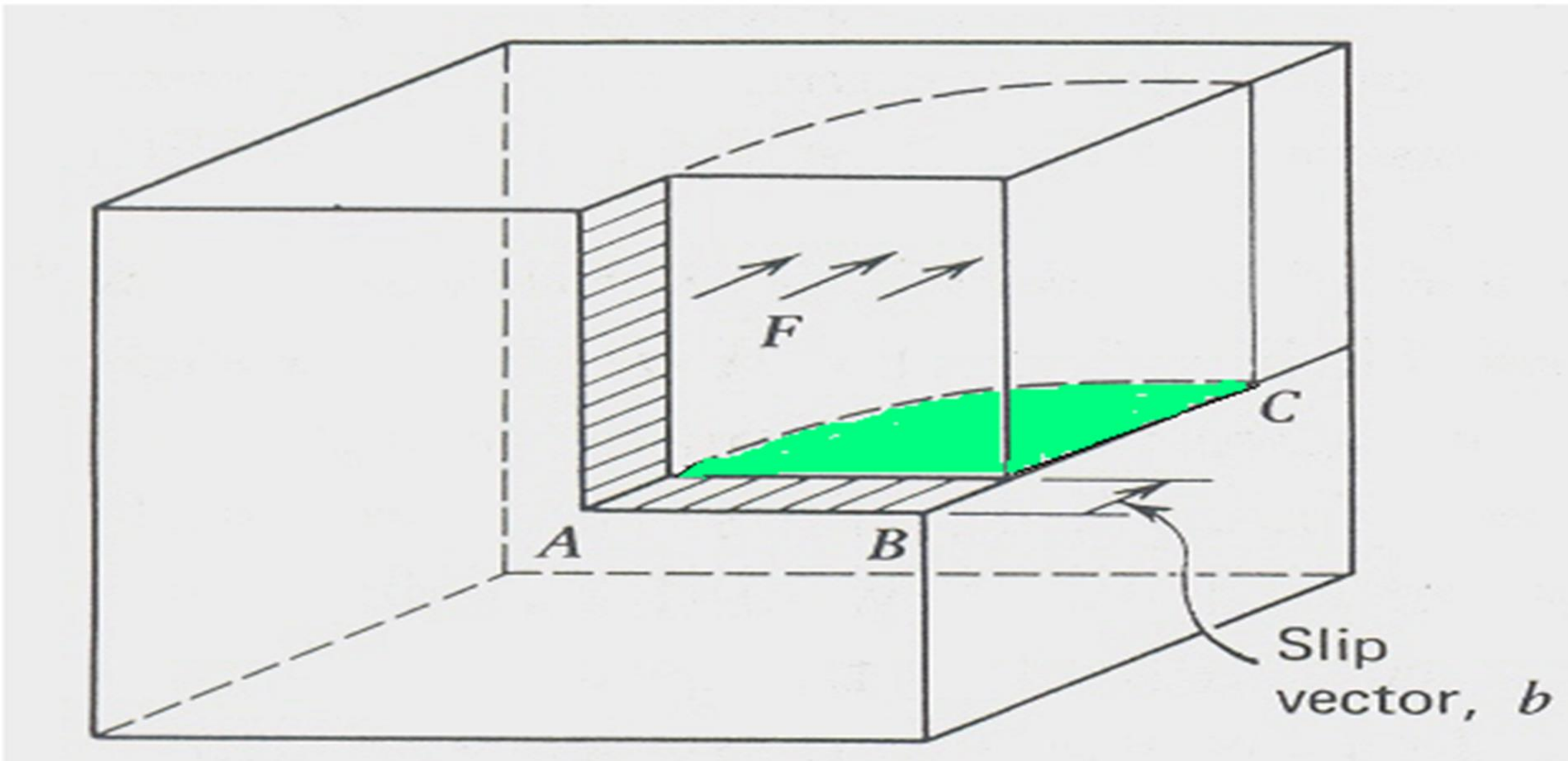


Figure 4.13 A mixed dislocation.

- Shift vector is same at all the points.

- A mixed distance can be resolved into an edge and a screw dislocation. These resolved dislocation is called edge and screw components of the line.

- The generation of mixed dislocation is very difficult to visualize. Fig. 4.14 shows the top view of the curved distance presented in Fig. 4.13. The open circle (○) represents the atoms just above the slip (glide) plane and close circles (●) just below. Atoms are in their equilibrium positions in region x and y. Atomic disturbance is noticed along dislocation line.


F
A
B
C
Slip
vector, b

Contd…Mixed Dislocation

C –Pure E Disl, A- Pure S Disl. Between A & C Mixed Disl

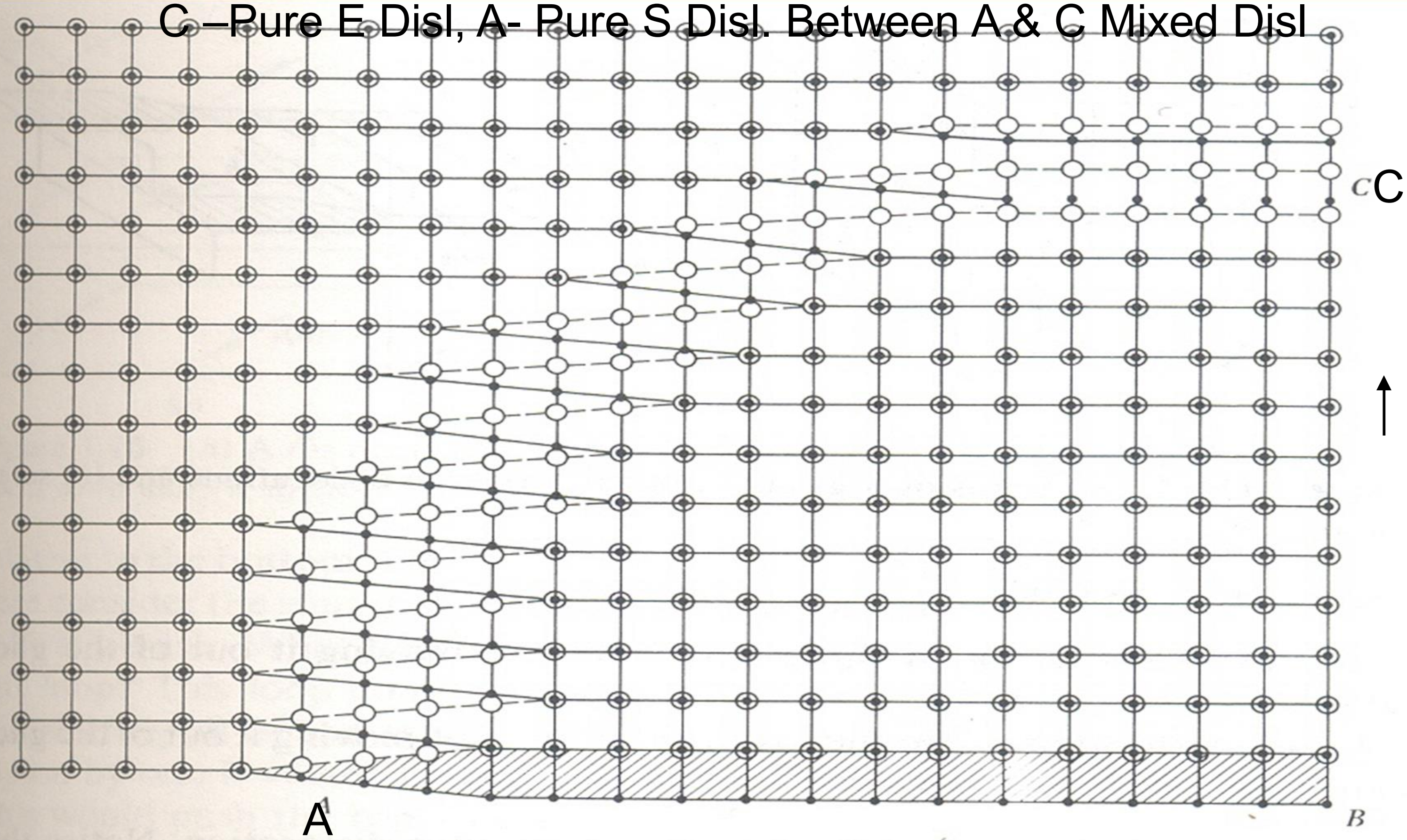


Figure 4.14 A top view of the mixed dislocation showing atom positions. Atoms above glide plane are open circles and atoms below are solid circles. (From Ref. 10, Copyright 1953, McGraw-Hill Book Co. Used with permission of McGraw-Hill Book Co.)

Imperfect /Partial Dislocation

- When atoms move from one equilibrium position to next lattice site- **perfect dislocation**. (Fig.b)

  When a perfect dislocation moves along its slip plane, leaves behind the atoms in position equivalent to those they occupied originally.

- In Fig.(c) shows an **imperfect dislocation** resulting a relative displacement '*a*/2'. It can be seen that as the imperfect dislocation moves to the left the atoms are shifted into sites that are not equivalent to their original position.

Cont…. Partial Disl.

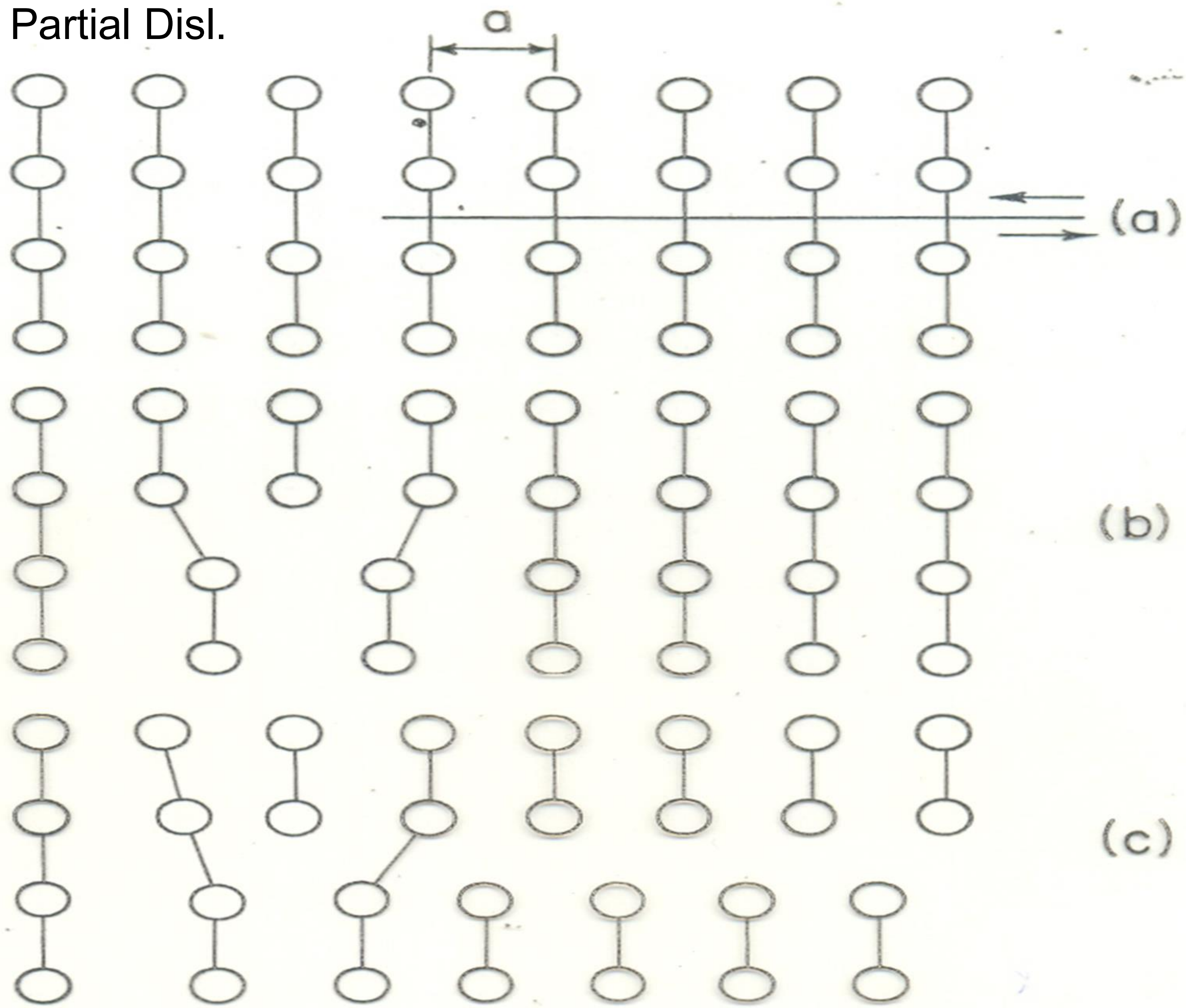


FIGURE 4–5. (a) A dislocation is made by shifting atoms on cut surface; (b) perfect dislocation; (c) imperfect dislocation.

2.2 Yielding Criteria for Ductile Material

1. **Von Mises' or Distortion-Energy Criterion**
2. **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.

$$J_2 = k^2$$

Where,

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

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), the maximum shear stress is given by

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

2.3 Critical Resolved Shear Stress

The extent of slip in crystal depends on the magnitude of the shearing stress produced by external loads, geometry of the crystal, structure and the orientation slip plane /direction with respect to the shearing stress.

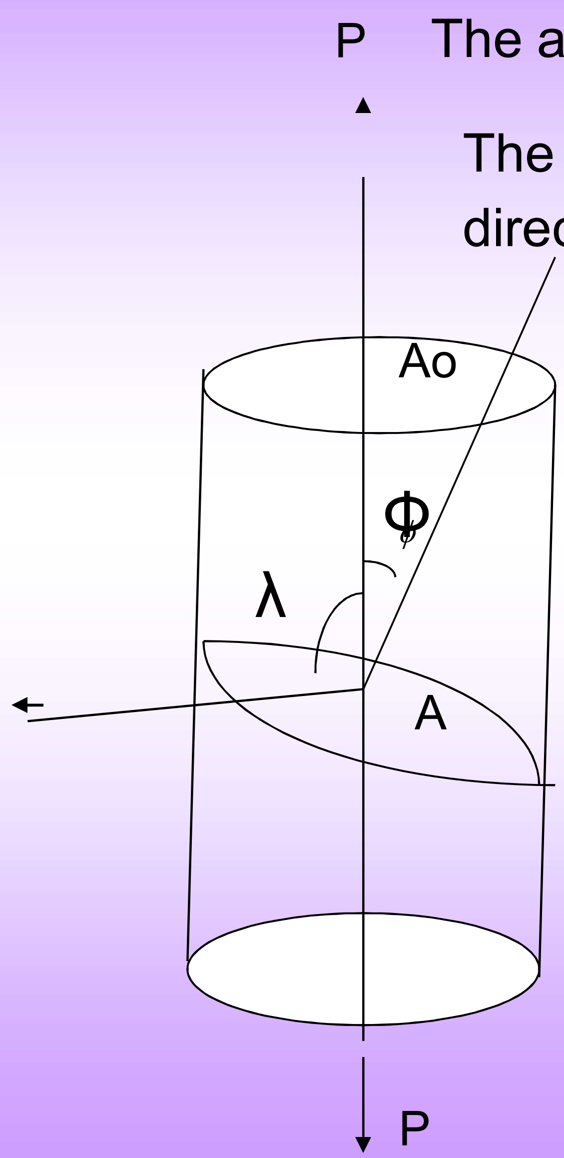
Slip begins when the shearing stress (resolved) on the slip plane in the slip direction reached a critical threshold value, called **critical resolved shear stress**.

This depends on composition and temperature

(introduced by *Schmid*).

The area of the slip = $A_0/\cos\phi$

The component shear stress in the slip direction = $P\cos\lambda$



Resolved shear stress on the slip plane in the slip direction τ

= $S \cos\lambda \cos\phi$

= τ_c (Slip occurs when RSS, critical for the material and that condition is achived

- Shear resolved stress has maximum value when $\phi = \lambda = 45°$
- Resolved shear stress has zero value if the tensile axis is normal to the slip plane (λ =90°)or
- if it is parallel to slip plane ϕ =90°).

  Slip will not occur in these conditions.
- **Crystal close to these orientation fracture rather than slip.**

Contd...CRSS

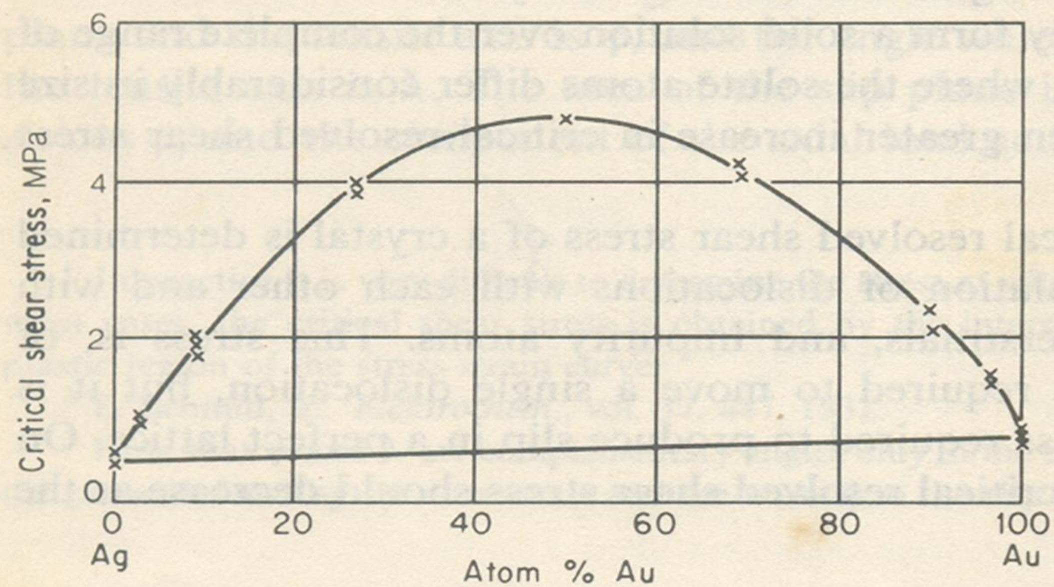


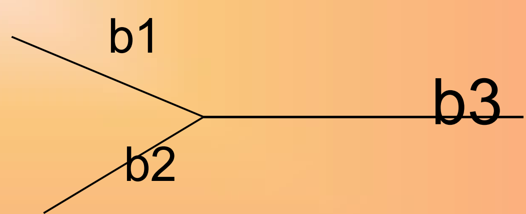
Figure 4-19 Variation of critical resolved shear stress with composition in silver-gold-alloy single crystals. *(After G. Sachs and J. Weerts, Z. Phys., vol. 62, p. 473, 1930.)*

CRSS is a material constant.

- It is a function of chemistry (Importance of alloy)
- It varies with the temperature (Working at elevated temp)
- *bcc* materials are very sensitive to temperature
  (D/B transition temp.)
- *hcp* crystals are very sensitive to orientation changes

Dislocation Reaction

Dislocation represents a boundary between slipped and un-slipped region of a crystal. Topographically conside-ration requires that a dislocation can not terminate within the crystal.



However at node 3 or 4 dislocations meet. At a node two dislocation b1 and b2 may combine to form b3.

a_0 [110] + a_0 [211] → ao [321]

(During addition / subtraction common unit vector must be used)

- a_0 /3 [112] + a_0 /6[11-1] = ao/6 [224] + a_0/6 [11-1]
  → ao/6 [333] = a_0/2 [111]

SLIP VS TWINING

Difference between Slip & Twinning

Slip	Twinning
1. The orientation of the crystal above and below the slip plane is the same after deformation as before.	1. 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	2. While in twinning the atom movements are much less than anatomic distance.
3. Slip occurs on relatively widely spread planes	3. The twinned region of a crystal every atomic plane is involved in the deformation.
4. Slip appears as thin lines	4. 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	5. 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

2.4 Deformation of Polycrystalline Aggregates

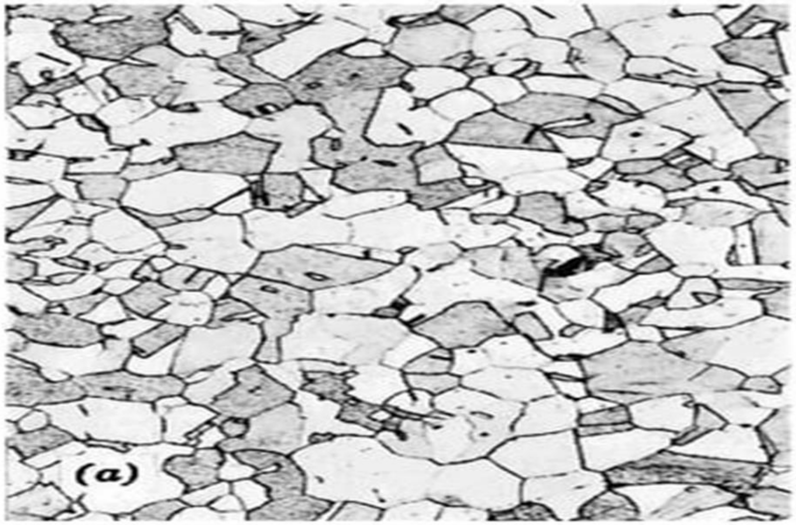
Plastic Deformation of polycrystalline materials

Grain orientations with respect to applied stress are random.

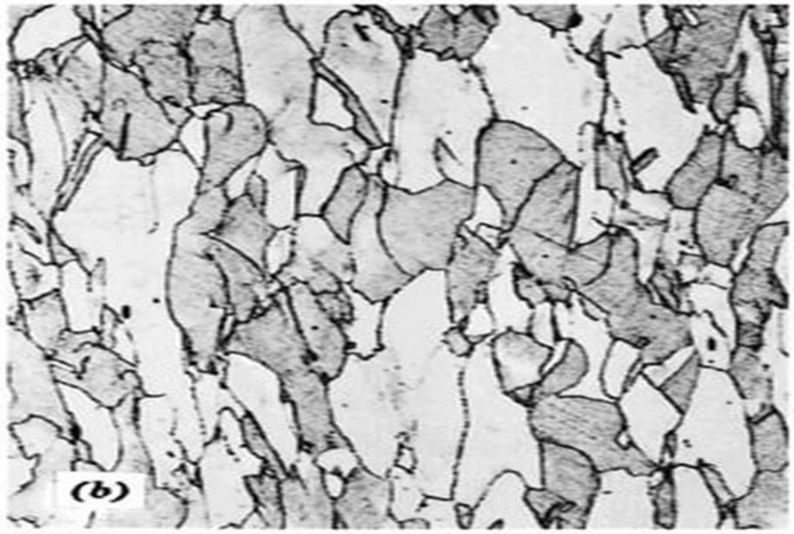
The dislocation motion occurs along the slip systems with favorable orientation (i.e. that with highest resolved shear stress).

Plastic deformation of polycrystalline materials

Larger plastic deformation corresponds to elongation of grains along direction of applied stress.



Before



After

Plastic deformation of polycrystalline materials

- Slip directions vary from crystal to crystal $\Rightarrow$ Some grains are unfavorably oriented with respect to the applied stress (i.e. $\cos\phi \cos\lambda$ low)
- Even those grains for which $\cos\phi \cos\lambda$ is high may be limited in deformation by adjacent grains which cannot deform so easily
- Dislocations cannot easily cross grain boundaries because of changes in direction of slip plane and atomic disorder at grain boundaries
- **As a result, polycrystalline metals are stronger than single crystals** (the exception is the perfect single crystal without any defects, as in whiskers)

Chapter 3

- Strengthening Mechanism

Chapter Outline

Dislocations and Strengthening Mechanisms

What is happening in material during plastic deformation?

- **Dislocations and Plastic Deformation**
  - ✓ Motion of dislocations in response to stress
  - ✓ Slip Systems
  - ✓ Plastic deformation in
    - single crystals
    - polycrystalline materials
- **Strengthening mechanisms**
  - ✓ Grain Size Reduction
  - ✓ Solid Solution Strengthening
  - ✓ Strain Hardening
- **Recovery, Recrystallization, and Grain Growth**

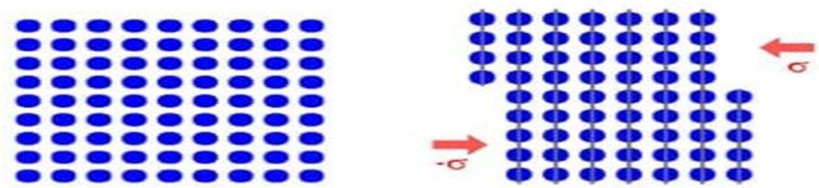
Not tested: 7.7 Deformation by twinning,
Direction and plane nomenclature in §7.4.

Introduction

Why metals could be plastically deformed?

Why the plastic deformation properties could be changed to a very large degree by forging without changing the chemical composition?

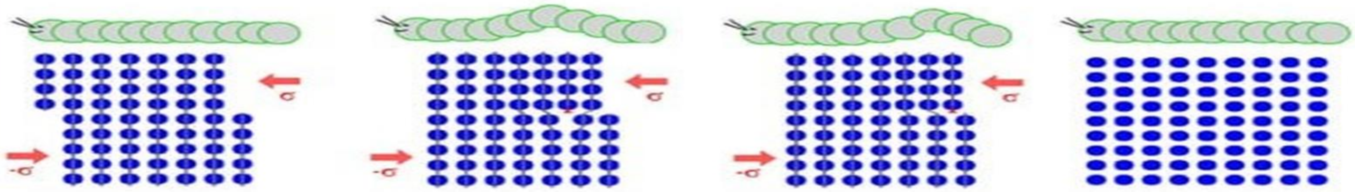
Why plastic deformation occurs at stresses that are much smaller than the theoretical strength of perfect crystals?



Plastic deformation – the force to break all bonds in the slip plane is much higher than the force needed to cause the deformation. Why?

These questions can be answered based on the idea proposed in 1934 by Taylor, Orowan and Polyani: **Plastic deformation is due to the motion of a large number of dislocations.**

Dislocations allow deformation at much lower stress than in a perfect crystal

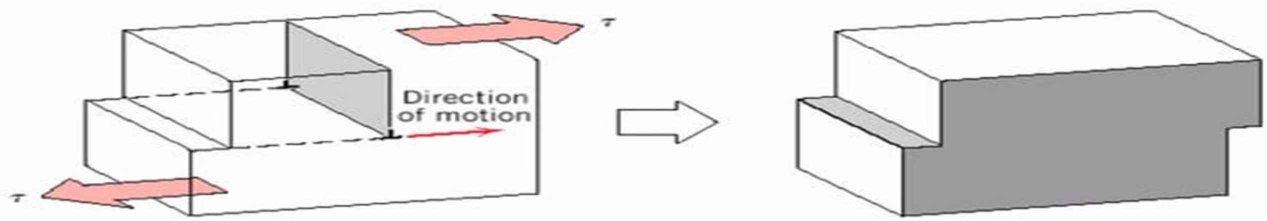


If the top half of the crystal is slipping one plane at a time then only a small fraction of the bonds are broken at any given time and this would require a much smaller force.

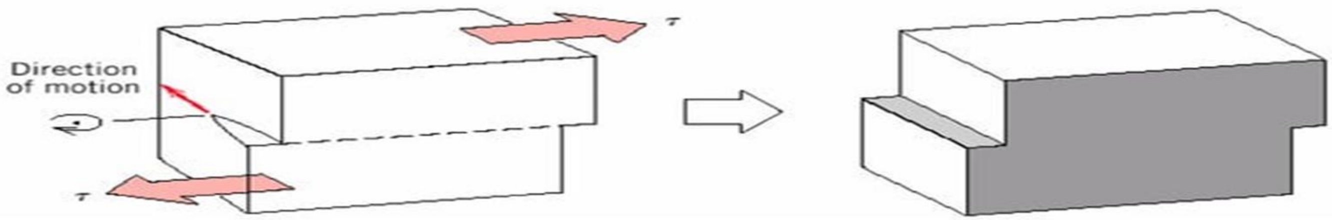
The propagation of one dislocation across the plane causes the top half of the crystal to move (**to slip**) with respect to the bottom half but we do not have to break all the bonds across the middle plane simultaneously (which would require a very large force).

The slip plane – the crystallographic plane of dislocation motion.

Direction of the dislocation motion



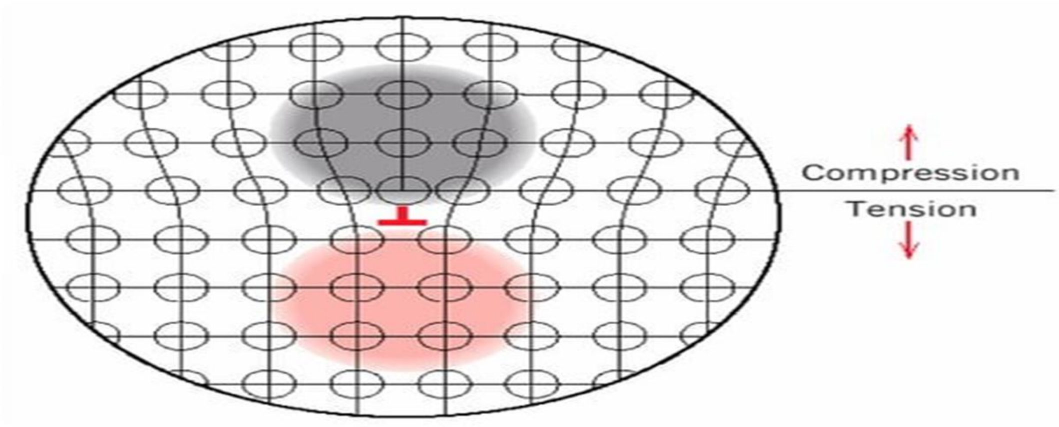
Edge dislocation line moves parallel to applied stress



Screw dislocation line moves perpendicular to applied stress

For mixed dislocations, direction of motion is in between parallel and perpendicular to the applied shear stress

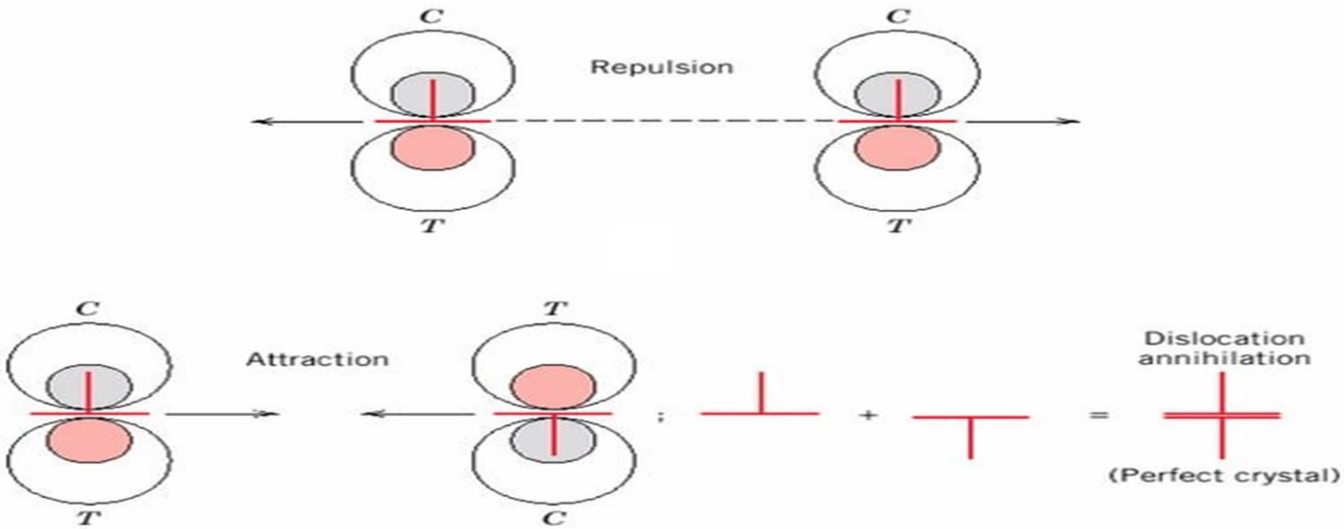
Strain field around dislocations



Dislocations have strain fields arising from distortions at their cores - strain drops radially with distance from the dislocation core

Edge dislocations introduce compressive, tensile, and shear lattice strains, screw dislocations introduce shear strain only.

Interactions between dislocations

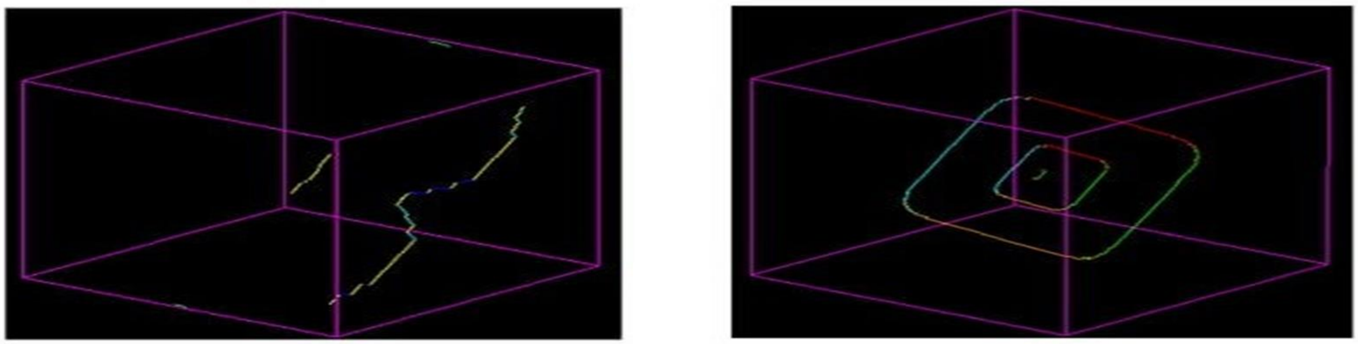


The strain fields around dislocations cause them to **interact** (exert force on each other). When they are in the same plane, they repel if they have the same sign (direction of the Burgers vector) and attract/annihilate if they have opposite signs.

Where do dislocations come from ?

The number of dislocations in a material is expressed as the **dislocation density** - the total dislocation length per unit volume or the number of dislocations intersecting a unit area. Dislocation densities can vary from 10^5 cm^{-2} in carefully grown metal crystals to 10^{12} cm^{-2} in heavily deformed metals.

Most crystalline materials, especially metals, have dislocations in their as-formed state, mainly as a result of stresses (mechanical, thermal...) associated with the forming process.

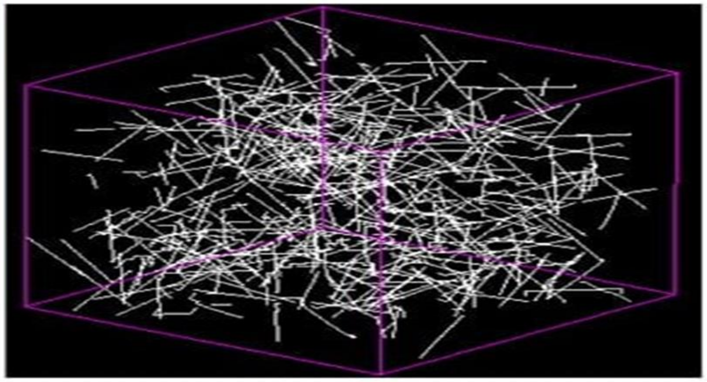


Computer simulation of Frank-Read source: Emission of dislocation loops from a dislocation segment pinned at its ends

http://zig.onera.fr/lem/DisGallery/3D.html

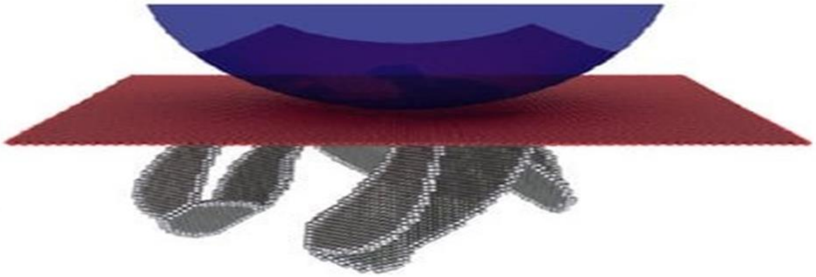
Where do dislocations come from ?

The number of dislocations increases dramatically during plastic deformation. Dislocations spawn from existing dislocations, grain boundaries and surfaces.



Simulation of plastic deformation in a fcc single crystal (Cu) of linear dimension 15 micrometers.

http://zig.onera.fr/lem/DisGallery/3D.html



Emission of dislocation loops in nanoindentation of copper

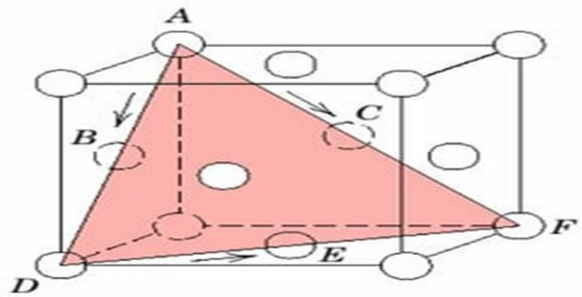
http://merapi.physik.uni-kl.de/~gerolf/Nanoindentation/

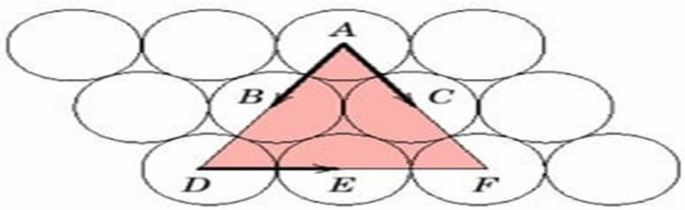
Slip Systems

In single crystals there are preferred planes where dislocations move (**slip planes**). Within the slip planes there are preferred crystallographic directions for dislocation movement (**slip directions**). The set of slip planes and directions constitute **slip systems**.

The slip planes and directions are those of highest packing density. Since the distance between atoms is shorter than the average, the distance perpendicular to the plane has to be longer than average. Being relatively far apart, the planes can slip more easily relatively to each other.

BCC and FCC crystals have more slip systems as compared to HCP, there are more ways for dislocation to propagate ⇒ FCC and BCC crystals are more ductile than HCP crystals. Remember our discussion of close packed planes in FCC and HCP, Chapter 3.



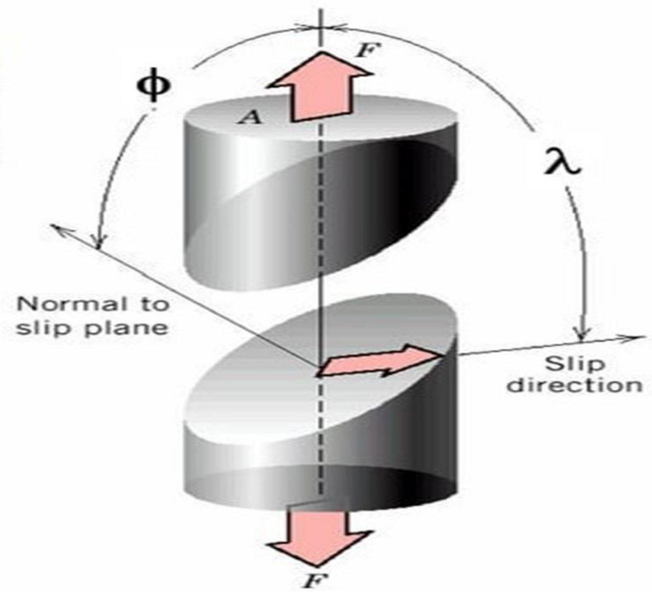


Slip in single crystals - resolving the applied stress onto the slip system

Dislocations move in particular directions on particular planes (the slip system) in response to shear stresses applied along these planes and directions ⇒ we need to determine how the applied stress is **resolved** onto the slip systems.

Let us define the **resolved shear stress,** τ_R, (which produces plastic deformation) that result from application of a simple tensile stress, σ.

$$\tau_R = \sigma \cos\phi \cos\lambda$$



Slip in single crystals - critical resolved shear stress

When the resolved shear stress becomes sufficiently large, the crystal will start to yield (dislocations start to move along the most favorably oriented slip system). The onset of yielding corresponds to the yield stress, σ_y (Chapter 6). The minimum shear stress required to initiate slip is termed **the critical resolved shear stress**:

$$\tau_{CRSS} = \sigma_y (\cos\phi \cos\lambda)_{MAX}$$

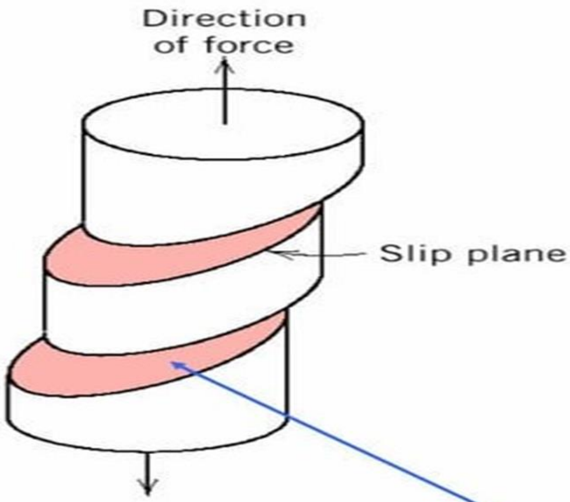
$$\sigma_y = \frac{\tau_{CRSS}}{(\cos\phi \cos\lambda)_{MAX}}$$

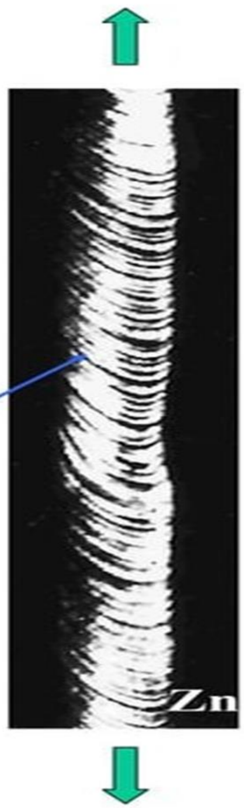
Maximum value of $(\cos\phi \cos\lambda)$ corresponds to

$\phi = \lambda = 45^o \Rightarrow \cos\phi \cos\lambda = 0.5 \Rightarrow \sigma_y = 2\tau_{CRSS}$

Slip will occur first in slip systems oriented close to these angles ($\phi = \lambda = 45^o$) with respect to the applied stress

Slip in a single crystal





Each step (shear band) result from the generation of a large number of dislocations and their propagation in the slip system with maximum resolved shear stress.

Strengthening

The ability of a metal to deform depends on the ability of dislocations to move

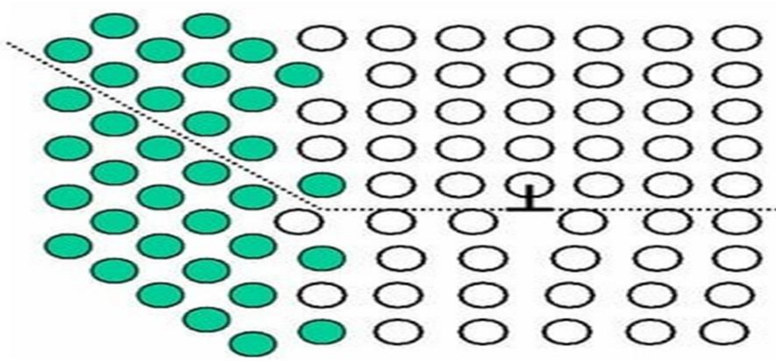
Restricting dislocation motion makes the material stronger

Mechanisms of strengthening in single-phase metals:

- grain-size reduction
- solid-solution alloying
- strain hardening

Ordinarily, strengthening reduces ductility

Strengthening by grain-size reduction (I)



Grain boundary barrier to dislocation motion: slip plane discontinues or change orientation.

Small angle grain boundaries are not very effective in blocking dislocations.

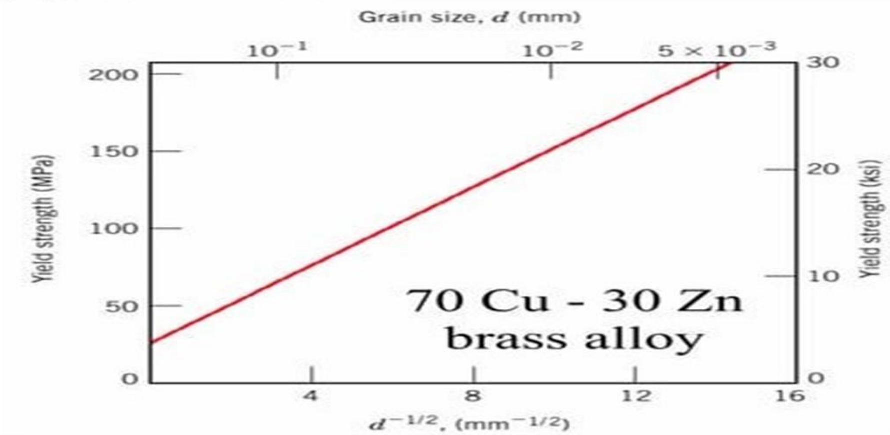
High-angle grain boundaries block slip and increase strength of the material. A stress concentration at end of a slip plane may trigger new dislocations in an adjacent grain.

Strengthening by grain-size reduction (II)

The finer the grains, the larger the area of grain boundaries that impedes dislocation motion. Grain-size reduction usually improves toughness as well. Usually, the yield strength varies with grain size d according to Hall-Petch equation:

$$\sigma_y = \sigma_0 + k_y / \sqrt{d}$$

where σ_0 and k_y are constants for a particular material, **d** is the average grain diameter.



Grain size **d** can be controlled by the rate of solidification, by plastic deformation and by appropriate heat treatment.

Solid-Solution Strengthening (I)

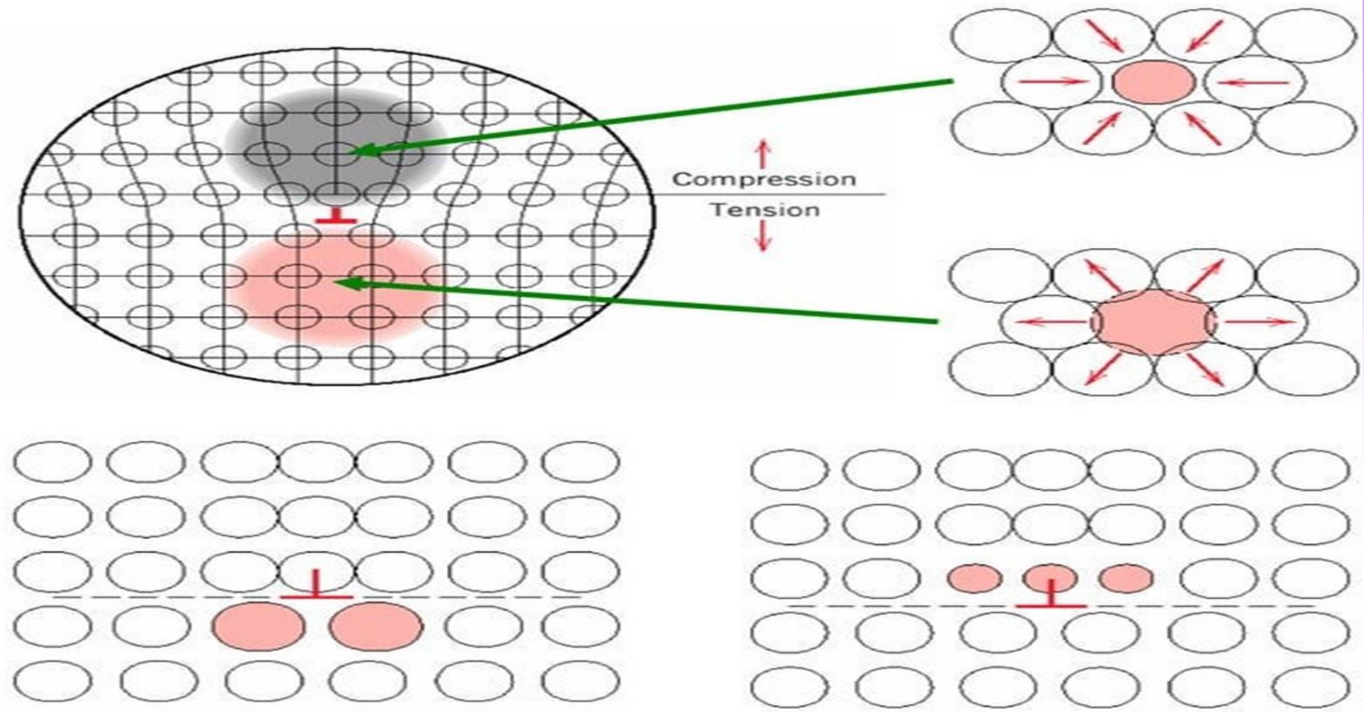
Alloys are usually stronger than pure metals

Interstitial or substitutional impurities cause lattice strain. As a result, these impurities interact with dislocation strain fields and **hinder dislocation motion**.

Impurities tend to diffuse and **segregate around dislocation cores** to find atomic sites that suit their radii. This reduces the overall strain energy and "anchors" the dislocations.

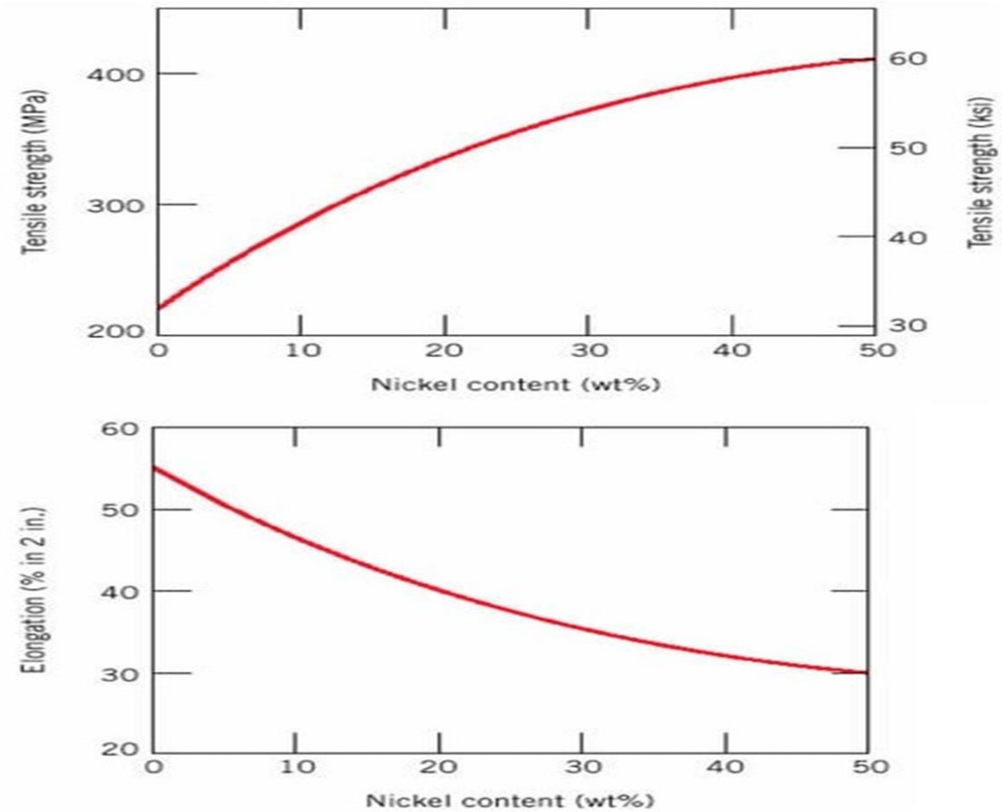
Motion of a dislocation core away from the impurities moves it to a region of lattice where the atomic strains are greater (i.e. the dislocation strains are no longer compensated by the impurity atoms).

Solid-Solution Strengthening (II)



Smaller and larger substitutional impurities tend to diffuse into strained regions around dislocations, leading to partial cancellation of impurity-dislocation lattice strains.

Solid-Solution Strengthening (III)



Strengthening by increase of dislocation density
(Strain Hardening = Work Hardening = Cold Working)

Ductile metals become stronger when they are deformed plastically at temperatures well below the melting point.

The reason for strain hardening is the increase of dislocation density with plastic deformation. The average distance between dislocations decreases and dislocations start blocking the motion of each other.

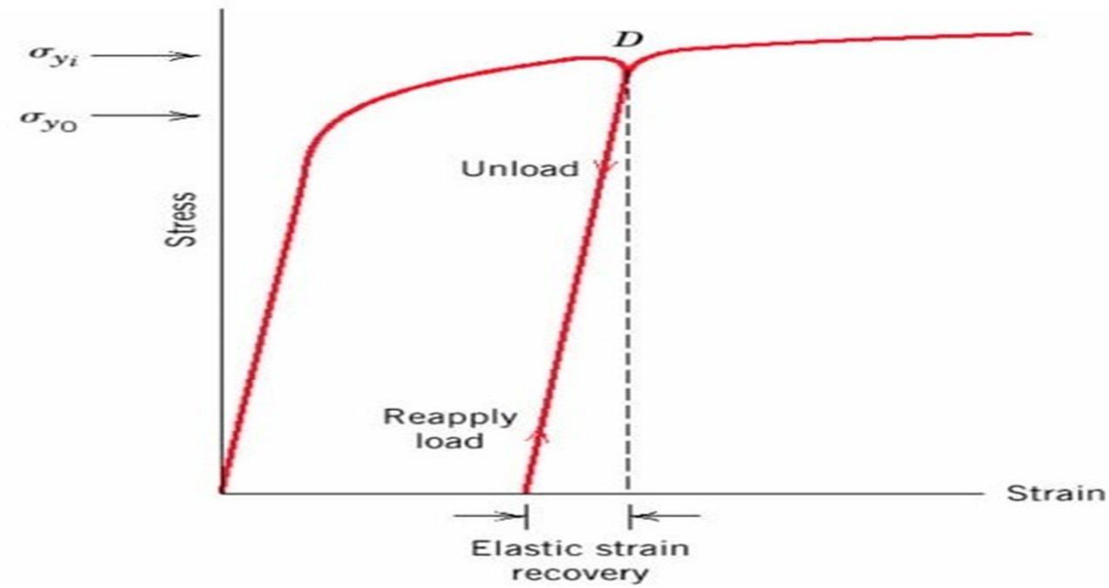
The percent cold work (%CW) is often used to express the degree of plastic deformation:

$$\%CW = \left(\frac{A_0 - A_d}{A_0}\right) \times 100$$

where A_0 is the original cross-section area, A_d is the area after deformation.

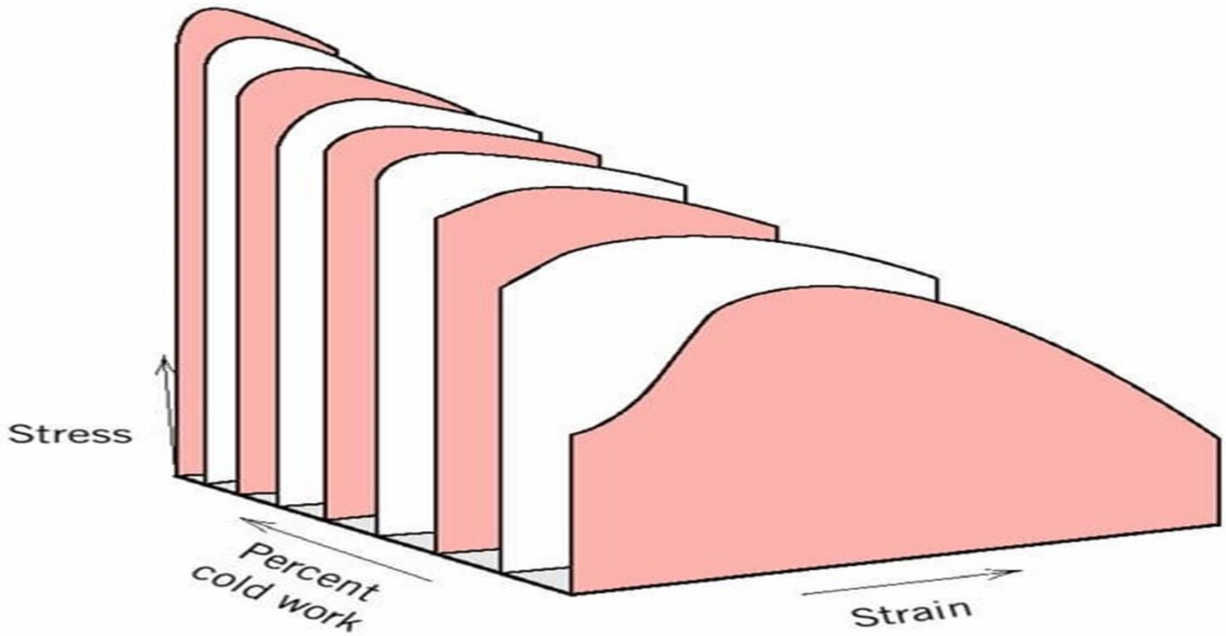
%CW is just another measure of the degree of plastic deformation, in addition to strain.

Strain hardening (II)



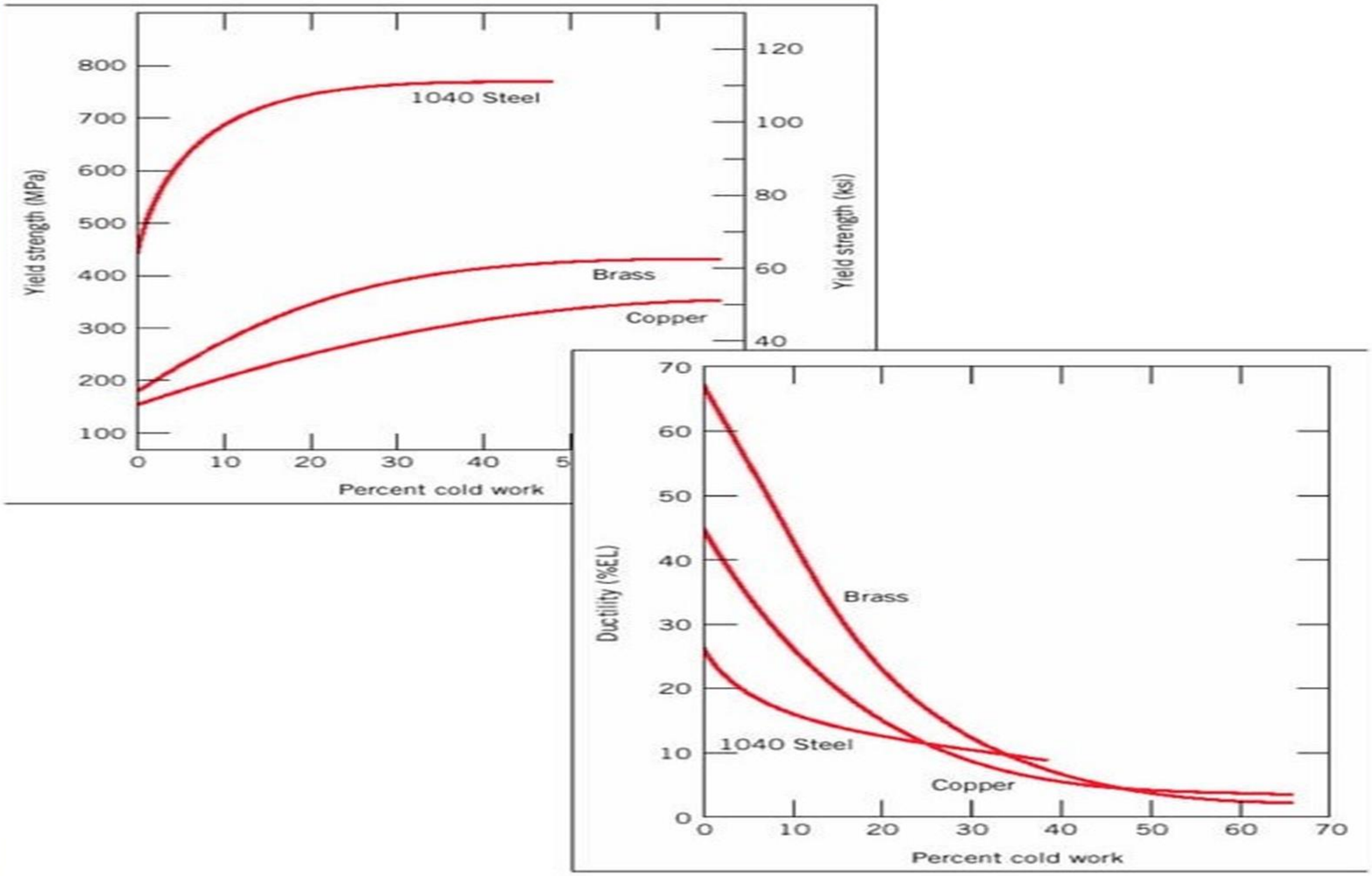
New yield strength σ_{y_i} is higher than the initial yield strength, σ_{y_0}. The reason for this effect - strain hardening.

Strain hardening (III)



Yield strength and hardness are increasing as a result of strain hardening but **ductility is decreasing** (material becomes more brittle).

Strain hardening (IV)



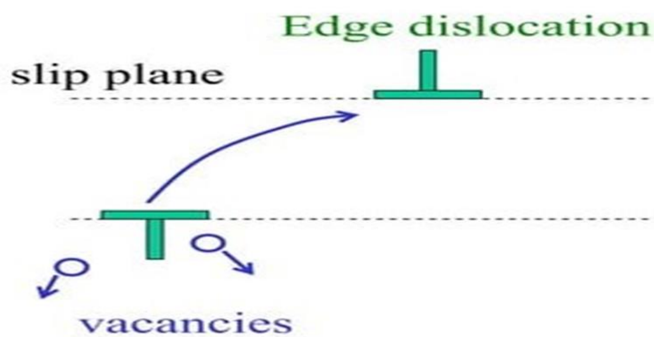
Recovery, recrystallization, and grain growth

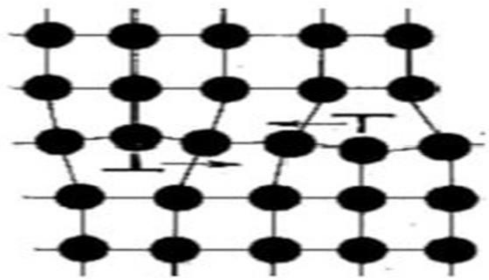
- **Plastic deformation increases dislocation density (single and polycrystalline materials) and changes grain size distributions (polycrystalline materials).**
- This corresponds to stored strain energy in the system (dislocation strain fields and grain distortions).
- When applied external stress is removed - most of the dislocations, grain distortions and associated strain energy are retained.
- Restoration to the state before cold-work can be done by heat-treatment and involves two processes: **recovery** and **recrystallization**. These may be followed by **grain growth**.

Recovery

Heating → increased diffusion → enhanced dislocation motion → decrease in dislocation density by annihilation, formation of low-energy dislocation configurations → relieve of the internal strain energy

Some of the mechanisms of dislocation annihilation:





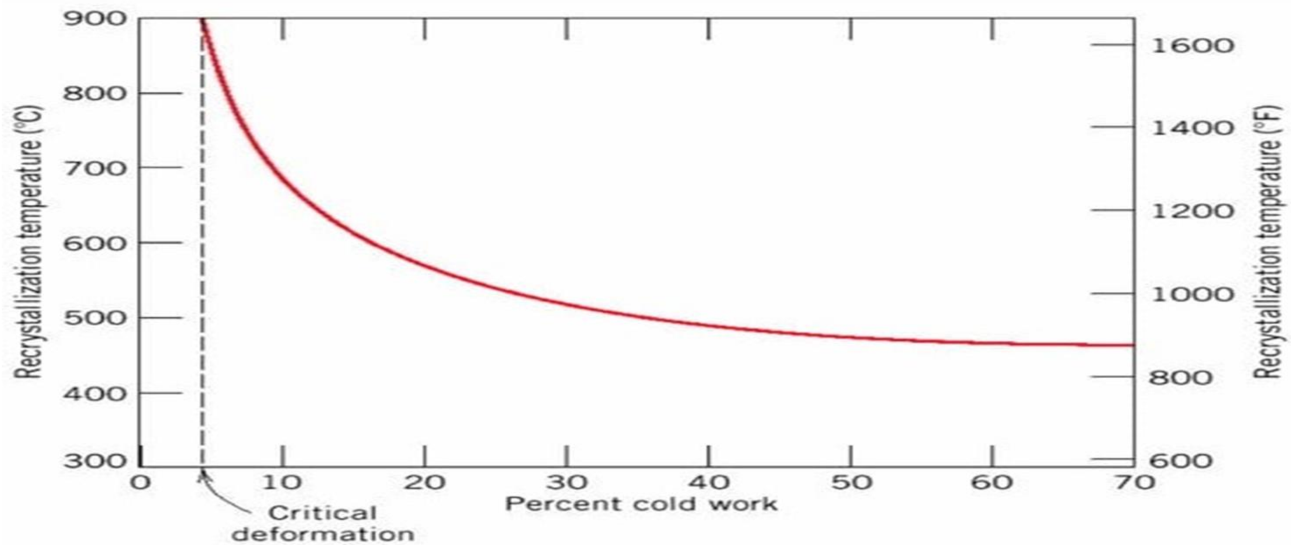
Recrystallization (I)

- Even after recovery the grains can be strained. These strained grains of cold-worked metal can be replaced, upon heating, by strain-free grains with low density of dislocations.
- This occurs through **recrystallization – nucleation and growth of new grains**.
- The *driving force* for recrystallization is the difference in internal energy between strained and unstrained material.
- Grain growth involves short-range diffusion → the extend of recrystallization depends on both temperature and time.
- Recristallization is slower in alloys as compared to pure metals

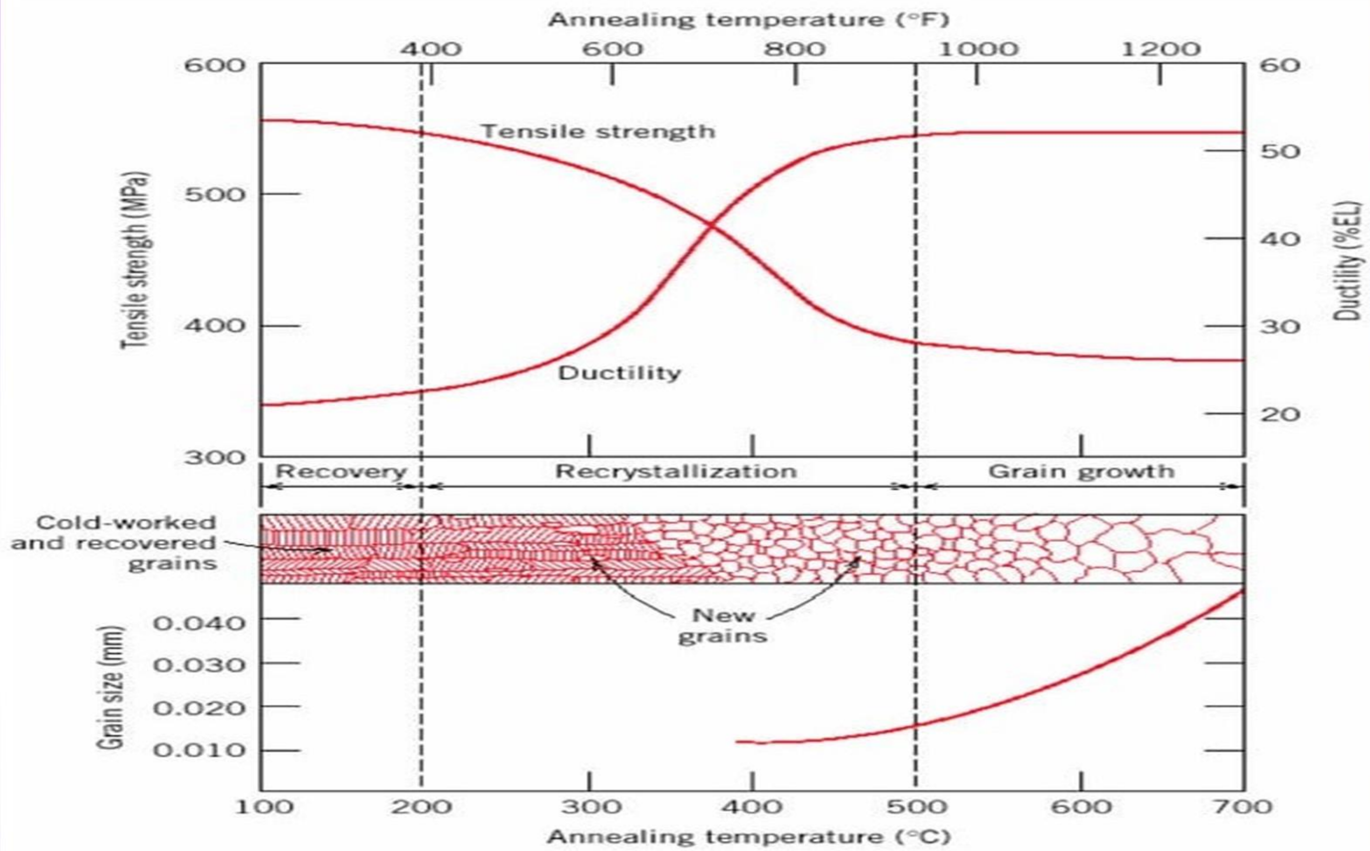
Recrystallization (II)

Recrystallization temperature: The temperature at which the process is complete in one hour. It is typically 1/3 to 1/2 of the melting temperature (can be as high as 0.7 T_m in some alloys).

Recrystallization temperature increases as the %CW is decreased. Below a "critical deformation", recrystallization does not occur.

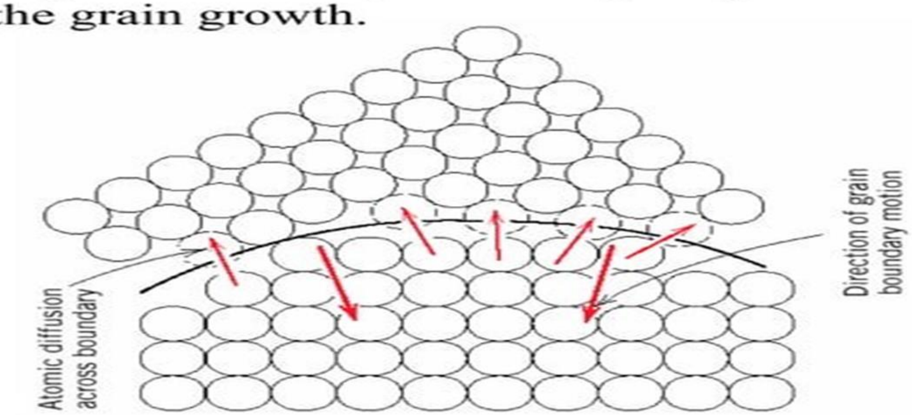


Recrystallization (III)



Grain growth

- If deformed polycrystalline material is maintained at annealing temperature following complete recrystallization, then further **grain growth** occurs.
- *Driving force* is reduction of the total grain boundary area and, hence, the energy of the system. Big grains grow at the expense of the small ones.
- Grain growth during annealing occurs in all polycrystalline materials (i.e. they do not have to be deformed or undergo recrystallization first).
- Boundary motion occurs by short range diffusion of atoms across the grain boundary → strong temperature dependence of the grain growth.



Summary

Make sure you understand language and concepts:

- Cold working
- Critical resolved shear stress
- Dislocation density
- Grain growth
- Lattice strain
- Recovery
- Recrystallization
- Recrystallization temperature
- Resolved shear stress
- Slip
- Slip system
- Strain hardening
- Solid-solution strengthening

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. Rather than having a flow curve with a gradual transition from elastic to plastic behavior, such as was shown in Fig. 3-1, metals with a yield point have a low curve or, what is equivalent, a load-elongation diagram similar Fig. 6-8.
- 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.
- 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.
- Usually the yield point can be associated with small amounts of interstitial or substitutional impuities. For example, it has been shown1 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 subambient temperatures.

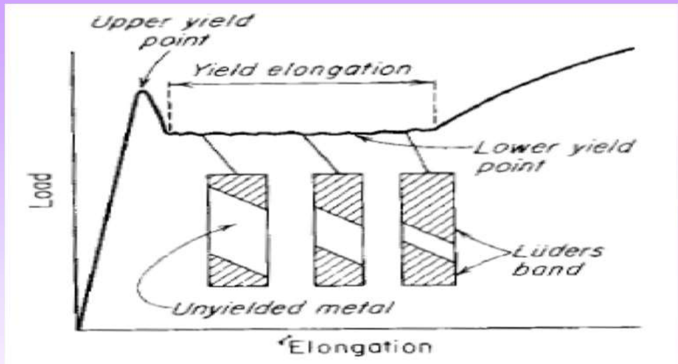


Figure 6-8 Typical yield-point behavior.

- 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 (Sec. 5-15).
- 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.
- 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

- 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. 6-9, which schematically describes the effect of strain aging on the low curve of a low-carbon steel.
- Region A of Fig. 6-9 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.

- 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.

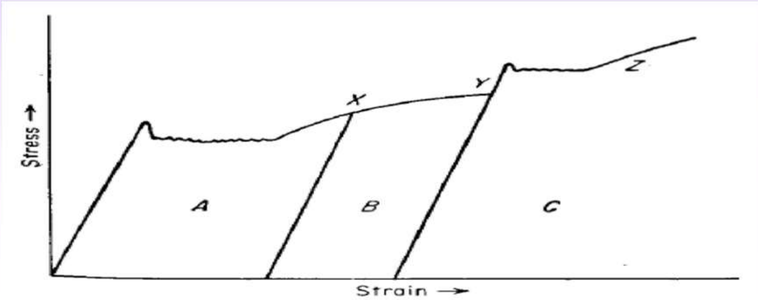


Figure 6-9 Stress-strain curves for low-carbon steel showing strain aging. **Region A**, original material strained through yield point. **Region B**, immediately retested after reaching point X. **Region C**, reappearance and increase in yield point after aging at 400 K ($\approx 130\ ^0$ C)

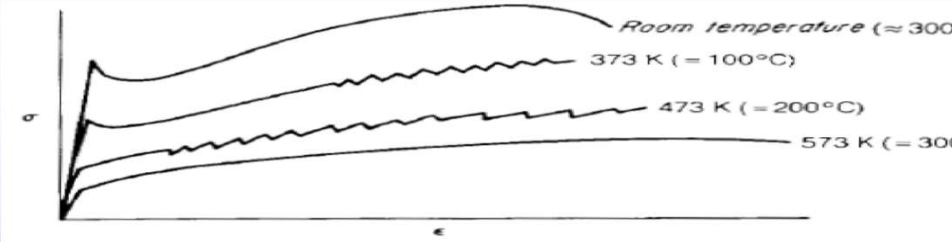


Figure 6-10 Portevin-LeChatelier effect in iron (schematic).

- 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 reap pearance 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.
- 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 (Fig. 6-10) 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.
- 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.

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. If the solute and solvent atoms are roughly similar in size, the solute atoms will occupy lattice points in the crystal lattice of the solvent atoms. This is called substitutional solid solution.
- 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 Hume-Rothery.
- 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.

- 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 tend to form intermetallic compounds.
- The relative valence of the solute and solvent also is important. 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.
- This relative-valence effect can be rationalized to a certain extent in terms of the electron-atom ratio.1 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.

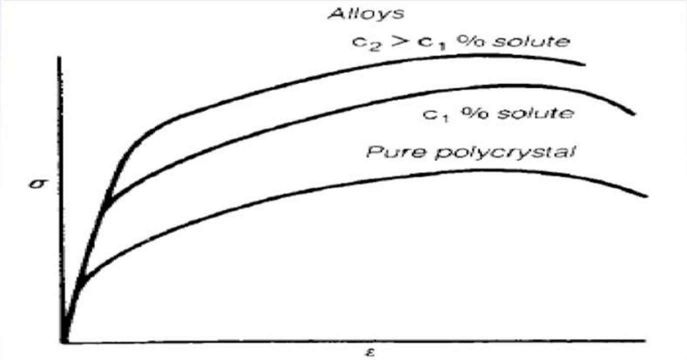


Figure 6-12 Effect of solute alloy additions on stress strain curve.

Solute atoms can interact with dislocations by the following mechanisms:

1. Elastic interaction
2. Modulus interaction
3. Stacking-fault interaction
4. Electrical interaction
5. Short-range order interaction
6. Long-range order interaction

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, 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.
- The age-hardening aluminum alloys and copper-beryllium alloys are common examples. 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.

FIBER STRENGTHENING

- Materials of high strength, and especially high strength-to-weight ratio, can be produced by incorporating fine fibers in a ductile matrix.
- The fibers must have high strength and high elastic modulus while the matrix must be ductile and nonreactive with the fibers. Because of their very high strength, whiskers of materials such as Al203 have been used with good results, but most fiber- strengthened materials use fibers of boron or graphite or metal wires such as tungsten.
- 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.

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.
- Figure 6-26 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.
- 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 ine twin structure or the high dislocation density.

- The second important contribution to the strength of martensite comes from the carbon atoms. Figure 6-26 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.

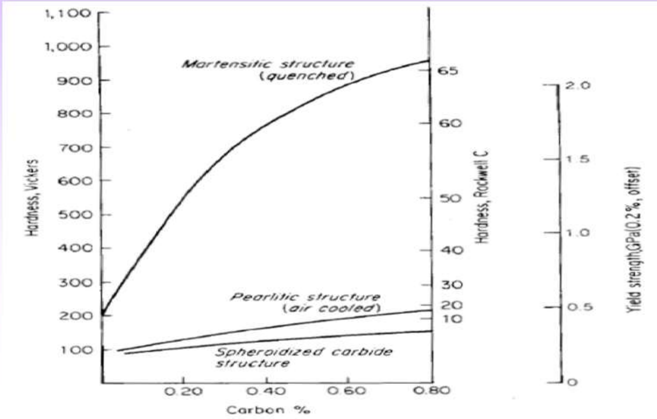


Figure 6-26 Hardness of various transformation products in steel.

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.

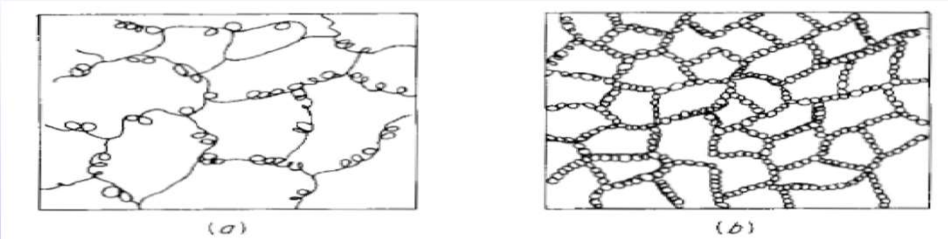


Figure 6-28 (a) Deformed to 10 percent strain. Beginning of cell formation with dislocation tangles; (b) deformed to 50 percent strain. Equilibrium cell size with heavy dislocation density in cell walls (schematic)

- 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.
- 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.
- 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.

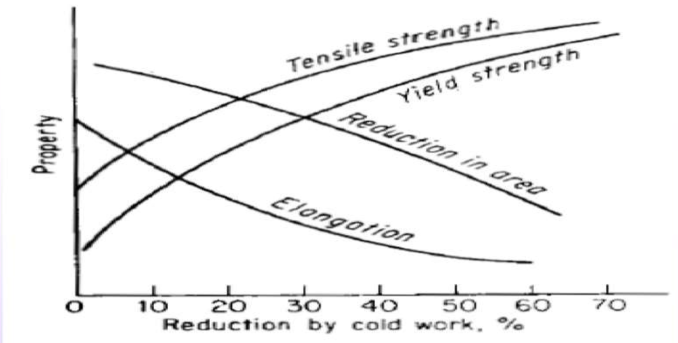


Figure 6-29 Variation of tensile properties with amount of cold-work.

- Figure 6-29 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 (Sec. 6-17). In addition to the changes in tensile properties shown in Fig. 6-29, cold-working produces changes in other physical properties.

- 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.
- 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.
- 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.
- Figure 6-30 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.

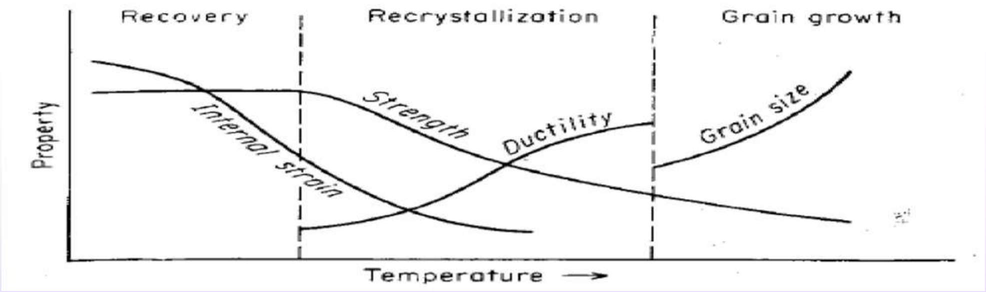


Figure 6-30 Schematic drawing indicating recovery, recrystallization, and grain growth and chief property changes in each, region.

- 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)

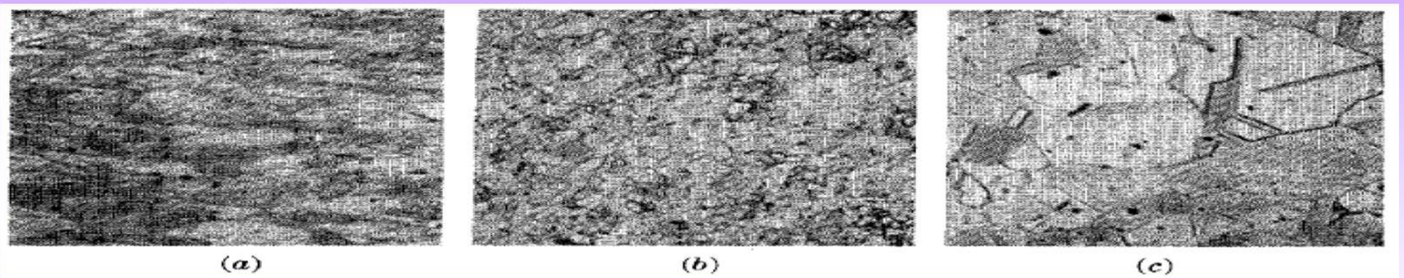


Figure 6-31 Changes in microstructure of cold-worked 70-30 brass with annealing, (a) Cold-worked 40 percent; (b) 440oC, 15 min; (c) 5750C, 15 min (150X)

- 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.
- 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.
- 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.
- Figure 6-31 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.
- 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.

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.
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.

bauschinger effect

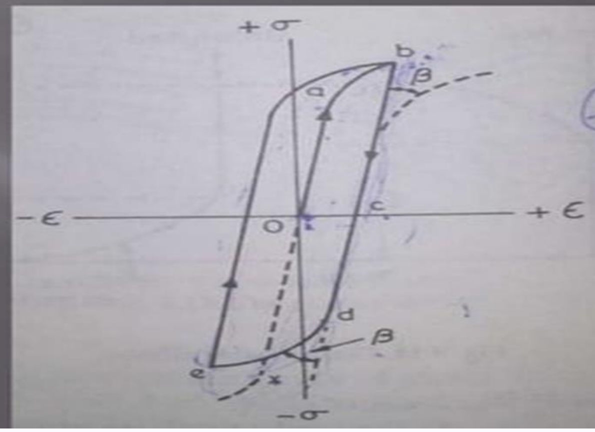
- The Bauschinger effect was discovered by Ohann Bauschinger in 1886.
- Bauschinger effect is a phenomenon in plastic flow.
- In most materials plastic deformation in one direction will affect subsequent response in another direction.
- .

- *The phenomenon by which plastic deformation of a metal increases the yield strength in the direction of plastic flow and decreases the yield strength in the opposite direction*

STRESS STRAIN GRAPH

- Let the material has the yield stress in tension as 'a' and the same in compression as 'x'.

  If a new specimen of the same material is loaded in tension past the tensile yield stress to 'b' along the path 'oab' and then it is unloaded, it will follow the path 'bc'. If now, the specimen is subjected to reverse stress i.e. the compressive stress, the plastic flow will begin at the stress corresponding to point 'd' which is apparently lower than the original compressive yield stress

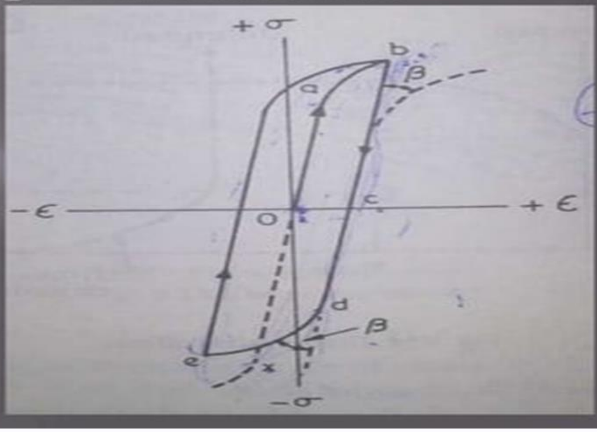


of the material, corresponding to point 'x'.

- Thus while the yield stress in tension was increased by strain hardening from 'a to b' the yield stress in compression is decreased from 'x' to'd'. This is BAUSCHINGER EFFECT.
- Bauschinger effect is reversible,i.e the specimen originally been stressed plastically in compression, the yeild stress in tension would have been decreased.
- The Bauschinger strain B, helps describing the Bauschinger effect.
- B is the difference between strain and compression curve at a given stress

STRES STRAIN CURVE

- Let the material has a yield stress in tension as 'a' and the same in compression as 'x'. If a new specimen of same material is loaded, it will follow the path 'bc'. If now specimen is subjected to reverse stress i.e, the compressive stress, the plastic flow at the stress corresponding to the point 'd' which is apparently lower then the original compressive yield stress of the material, corresponding



CONCLUSION FROM BAUSCHINGER EFFECT

- Metal forming operations result in situations exposing the metal workpiece to stresses of reversed sign. The Bauschinger effect contributes to work softening of the workpiece, for example in straightening of drawn bars or rolled sheets, where rollers subject the workpiece to alternate bending stresses, thereby reducing the yield strength and enabling greater cold drawability of the workpiece

Thank You

4.0 Fundamentals of Metal working:

METAL WORKING

Mechanical working of metal is defined as an intentional deformation of metals plastically under the action of externally applied force.

4.1 Classify different metal working process.

Mechanical working of metals is classified as:

1. Hot working
2. Cold working

Recrystallization Temperature

- Recrystallization is a process in which at a certain temperature range, a new equiaxed & stressfree grains are formed.
- Recrystallization temperature is generally defined as temperature at which complete recrystallization occurs within approximately one hour.

4.2 Explain hot working and cold working of metals and alloys

4.3 State the advantages and disadvantages of hot and cold working

(1) Hot Working:

The working of metal above the recrystallization temperature is called hot working.Hot working of metal has following advantage:

1. The porosity of metal largely eliminated.
2. The grain structure of metal is refined.
3. The mechanical properties such as toughness, ductility improved.
4. The deformation of metal is easy.

Disadvantages.

- It requires expensive tools
- It produces poor surface finish
- Close tolerances cannot be maintained.

(2) Cold working:

The working of metal below their recrystallization temperature is known as cold working. Advantages of cold working:

1. Residual stresses set up in the metal

2. Strength and hardness of metal are increased.
3. Surface finish improved.
4. Close dimensional tolerances maintained.

Disadvantages ...

- Cold working distorted the material
- Requires much higher pressures than hot working.

Metal forming processes:

- Rolling
- Forging
- Extrusion
- Tube and Wire Drawing
- Deep Drawing
- Punching and Blanking (due to similarity to Deep Drawing)

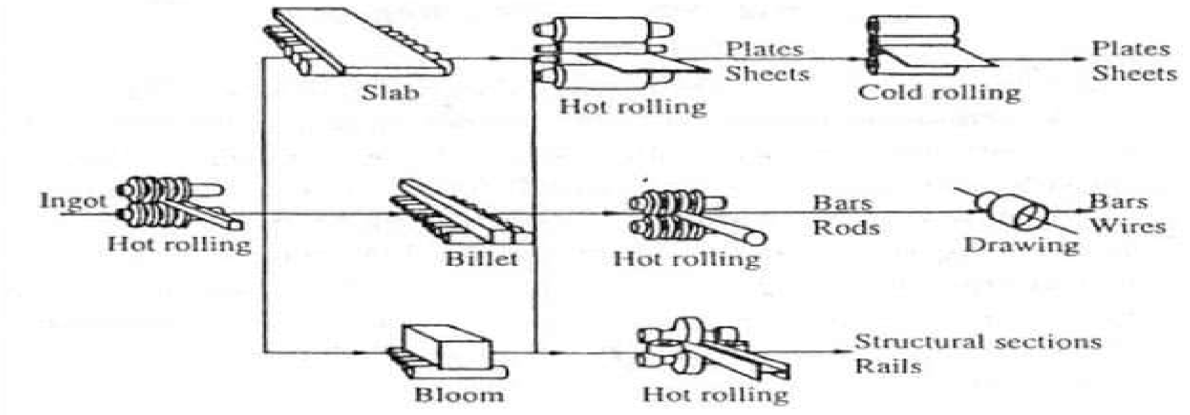
6.0 Rolling:

Rolling:

Rolling is the deformation process of a metal that is widely used in the metal forming process. It is done by passing the strip of the metal between the rollers. This paper discussion will be made about the rolling process, the working principle of the rolling process along with that the working principle of the rolling mills. Then the types of rolling mills will be discussed. Apart from that, in this assessment rolling and its defects are included briefly.

Definition of Rolling process: Rolling is defined as a process to form metals where the metal strip is pressed by two or multiple rollers, thus the uniform thickness is formed. To do this, the temperature is essential. There are two types of processes. One is Hot rolled and another is Cold Rolled. If the strip is rolled after heating the strip above the re-crystallization temperature then it is termed as Hot rolled and if that done in room temperature then it is termed as the Cold rolled. Rolling is a process that is widely used and has very high production.

Sequence of operations for obtaining different shapes



6. 1 Explain principles of rolling

Working Principle of Rolling Process: The rolling process is a metal forming process, in which stock of the material is passed between one or more pairs of rollers in order to reduce and to maintain the uniform thickness.

This process is mainly focused on the cross-section of the ingot or the metal which is forming.

Mainly by this process, we reduce the thickness of the metal workpiece. Now, the rolling processes are mainly focused on the increasing length and the decreasing thickness without changing the width of the workpiece.

There are certain types of the rolling process, whereas, in the hot rolling process, the metal is heated at its desirable temperature, when the metal is properly heated then the metal should be passed between the one or more rolling mills to gain the proper desirable shape.

This process is vastly used in respect of any other rolling process. In this process, the metal is heated above the recrystallization temperature. In the hot working process, the metal is changing its grain structure because of the heat, now there were a new set of strain-free grains in the metal and this process needs less amount of force which correspondingly reduces the quality of the surface finish, of that metal. Now there is another rolling process, which is a cold rolling process.

This rolling process is done below the recrystallization temperature of the metal it varies upon the metal, room temperature can also be a below recrystallization temperature. In this process, the force is much more required than the hot working process to pass the metal from the rollers and this process offers good surface finish.

Types of Rolling Mills: There are five rolling mills which are commonly used for rolling metals:

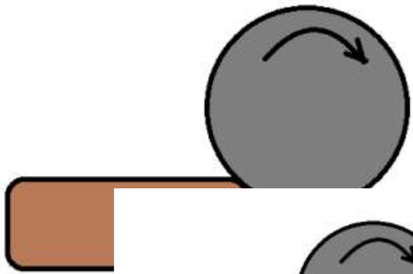
1. Two-High Rolling Mills
2. Three-High Rolling Mills
3. Four High Rolling Mills
4. Tandem Rolling Mills
5. Cluster Rolling Mills

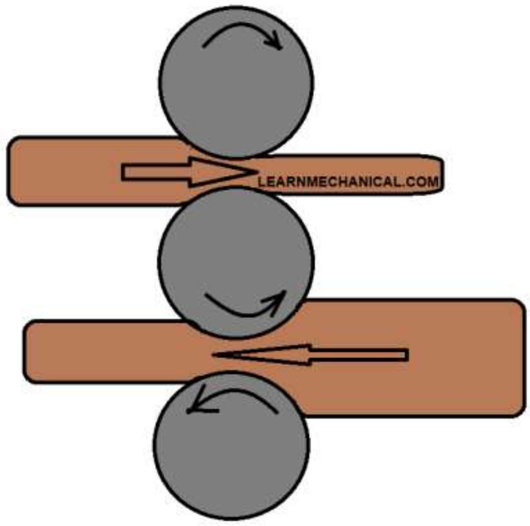
1. **Two-High Rolling Mills:** This type of mill has two types. Those are:
    - Reversing Mills
    - In reversing Mills

In this rolling mill, there are two rolls used.

Two High Reversing Mill: In this type of mill, the rollers are both adjustable. In these mills, rotation of that two rolls is made in two different directions. In this operation, the metal is passed between two rollers that rotate at the same speed but it is in the opposite direction. It is used in slabbing, plumbing, rail, plate roughing work and many other areas. As there is the need for a reversible drive, this mill is cheaper compared to the others.

Two High Non-Reversing Mills: In these mills, two rolls continuously revolve in the same direction and we can't reverse the direction of the rollers. In this operation, the motive power is less costly.





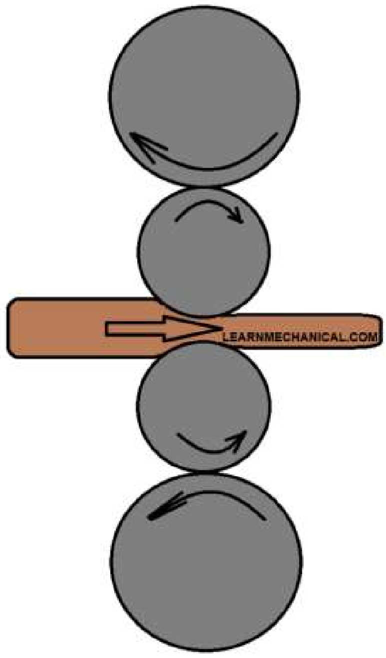
THREE HIGH ROLLING MILLS

2. **Three-High Rolling Mills:**
In this mill, the three rolls stand in parallel one by others. The rolls are rotating in opposite directions. In this mill, between the first and the second rolls, the material passes. If the

second roll rotates in a direction then the bottom roll rotates in another direction. The material is rolled both in forward and return in three high rolling mills. At first, it passes forward through the last and second roller and then comes back through the first and second roller. In that mill, the thickness of the material is reduced and being uniform by each pass. Here transition system and a motor are needed which is less powerful.

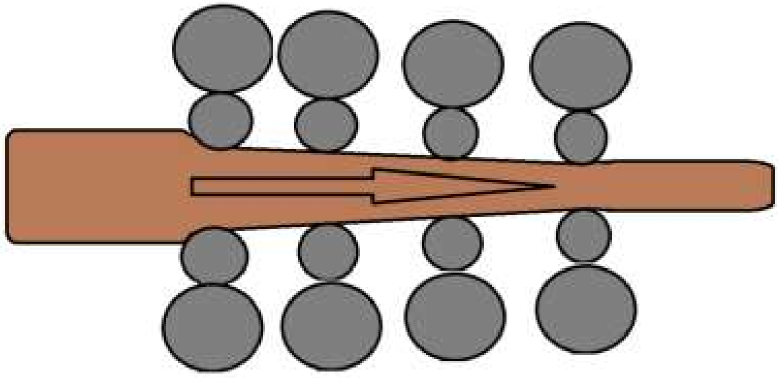
3. **Four High Rolling Mills:** In this type of mill, there are four parallel rolls one by another. In this operation, the rotation of the first and the fourth rolls take place in the opposite direction of the second and the third rolls. The second and third rolls are smaller to provide rigidity in necessity. So those are known as back up rolls.

   It is used in the hot rolling process of the armor and in the cold rolling process of sheets, strips, and plates.



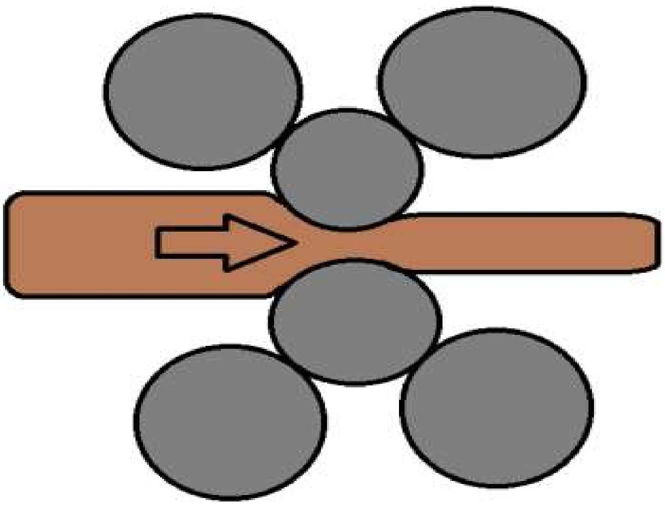
FOUR HIGH ROLLING MILL

4. **Tandem Rolling Mills**: In this type of rolling mill, there are two or more sets of rolls in the parallel alignment which make the continuous passes and successively decrease the thickness and make that uniform.



TANDEM ROLLING MILL

5. **Cluster Rolling Mills**: In this type of rolling mill, there are two basic roles that are backed up by two or more rolls which are bigger than those two basic rolls. These backed up rolls give more pressure to the basic rolls to heavily press the strip.



CLUSTER ROLLING MILL

Application of Rolling:

The rolling operation used in various industries such as:

- Rods, seamless hollow tubes are made by rolling.
- Rolling is used to producing cross-section of large sections. Rolling is used to cutting the gears on the gear blank.
- The threaded parts, bolts, screws, etc. which have mass production is made by the rolling process. In automotive industries, various parts are manufactured by the rolling process.
- The rolling process is used to made plates, steel sheets, etc.

- Bearing, Turbines rings are rolling products

6.2 Compare between hot rolling and cold rolling.

Apart from that, in the rolling applications, there are two types of rolling products. Those are as follows:

- Hot Rolled Products
- Cold rolled products

Hot rolled products are made by a hot rolling process. In that process, the process is done at a very high temperature like over 1,700 Degree Fahrenheit. For most of the metals, this temperature is re-crystallization temperature.

Such Hot Rolled products are as follows:

- Rods
- Rails Plates
- Sheets and strip
- Structural Bars etc.

Hot Rolled products also used to make body panel, piping and tubes, and construction materials.

Cold Rolled Product:

Cold rolled product is made from the hot-rolled product. When the hot-rolled product is cooled, then that is re-rolled in the room temperature. It is known as Cold Rolled Product. It is used to do to get more exact or perfect dimensions and to make the surface quality better.

There are such Cold rolled products.

Those are as follows:

- wire sheet etc.
- Cold-rolled products, such that the wire is used to make screws and bolts, cold-rolled sheets are used to make strip and sheets for external applications of the automotive industries like doors, electrical motors, etc.

6.4 State different types of rolling detects and their control

Rolling Defects:

Defects of Rolling:

As the deflection of rolls occurred by the high forces of rolling. There are two types of rolling defects.

Those are as follows:

- Surface rolling defects
- Internal structural rolling defects

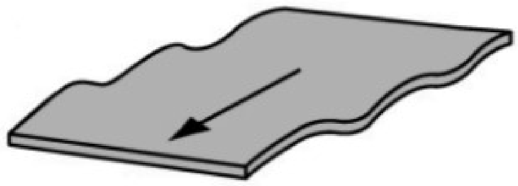
Surface Defects:

Surface defects in rolling can be categorized into following types, and those are:

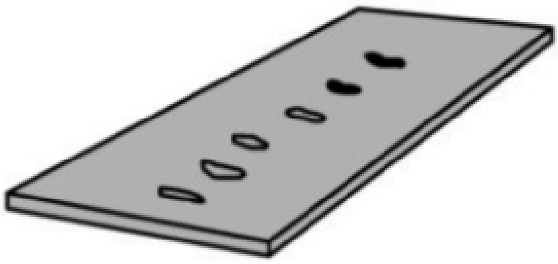
Internal Structural Defects: There are some types of internal structure defects. Those are as follows:

Wavy Edges Crack: The result is thicker as the middle portion of the rolling part is bent or deflected by the compressive load. There are some different cases. Those are as follows:

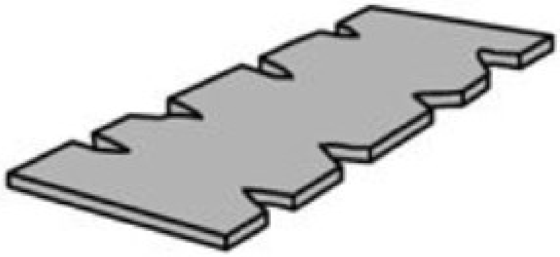
- For the imperfection of the roll gaps, variation occurs on the rolling sheets.
- If the thickness varies and along with that volume and width are constant then the center is shortened than the edges. But the body is continuous.
- Then the edges portions are in the compression and the center portion is the tension.
- The result of the edge is wavy.



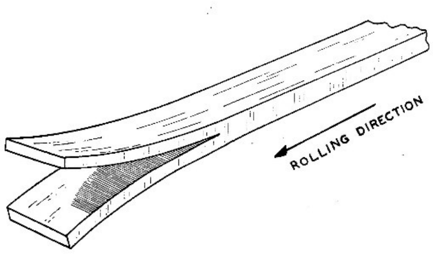
Zipper Cracks in Centre of Strip: Zipper Crack is a type of Wavy Crack. If there is an uneven stress distribution on the strip, then the crack occurs in the centreline of the strip. It is called Zipper Cracks in the Centre of Strip. This crack looks like a zip so that it called Zipper Cracks.



Edge Crack: Edge cracks occur when the hot rolls are cooled. It happens as excessive quenching effects on the strip. If excess water is used to cool the edges. The use of excess water might give the result of unflattens in the strips. The edges of the metal got rounded off as the friction force prevents the corners and increases the length of the centre portion.



Alligator Crack: Alligator Crack is one type of cracking where the metal has any inclusions or weakness of metallurgy. That causes factor in the strip. As this crack separates the layers and increases the slabs openings, it looks like the mouth of an alligator. So that name of this crack is Alligator Crack.



7.0 Forging:

FORGING:

- Forging is the process in which the work piece is shaped by compressive forces applied through the various dies and tools.
- It is one of the oldest metal working metal working metals.
- Simple forging can be performed with a heavy hand hammer and anvil.
- Typically forged product are bolts and rivets, connecting rods, shafts for turbine etc.

Forging may be done at room temperature (cold forging) or at elevated temperature(warm or hot forging).

7.1 Explain types of forging process

Hot forging

It consists of heating the metal and then the pressure is applied to form it into desired shapes and sizes.

The following processes are commonly used for hot forging:

1. Hammer or smith forging: it is also known as open die forging.

because it involves the compression of the billet between flat dies with no constraint on the spread of the metal.

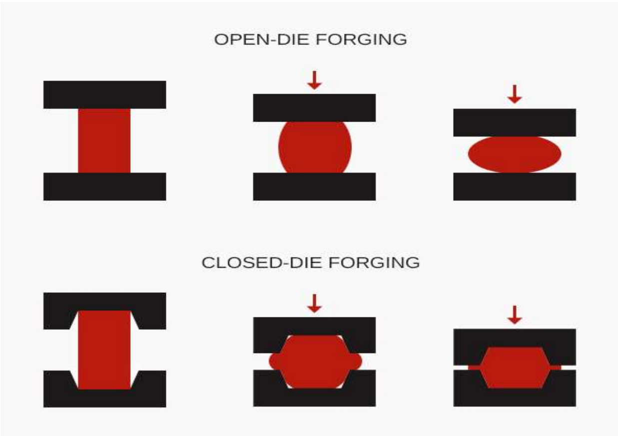
Press forging: Hammer forging dissipates large amount of energy near surface of metal. So when a large section of high quality is required, then press forging used.

The press operates by hydraulic or by mechanical means such as crank or screw.

Upset forging:
This process involves increasing the diameter of the end of a bar of metal by compressing its length.
This process was developed to form heads on bolts, rivets etc.

Drop or die forging: Smith forging is not suitable for the production of large number of identical forging.
• For this drop forging used (closed die forming)
This consist of hammering heated bars or billets of steels into closed impression dies. Upper die fastened to the ram the lower die is fastened to the anvil.

Advantages:
1. Relatively good utilization of material.
2. Good dimensional accuracy.



Cold forging:

- The cold forging is also called swaging.
- In this process, the metal is allowed to flow in predetermined shape according to design of dies, by a compressive force or impact
- Some cold forging process:

1**. Sizing**

2. Cold heading: the process is extensively used for making bolts,rivets and other similar headed parts, this is done on cold header machine

Equipment must be able to withstand the high pressure.

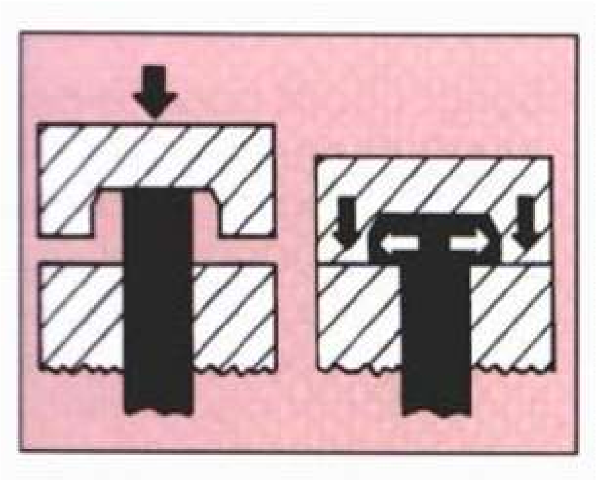
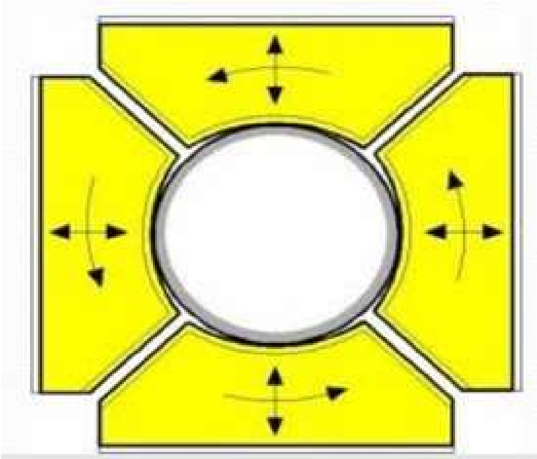


Fig: cold heading

Rotary swaging: this method is used for reducing the diameters of round bars and tubes by rotating dies, which open and close rapidly on the work. End of rods reduced in size by a combination of pressure and impact.



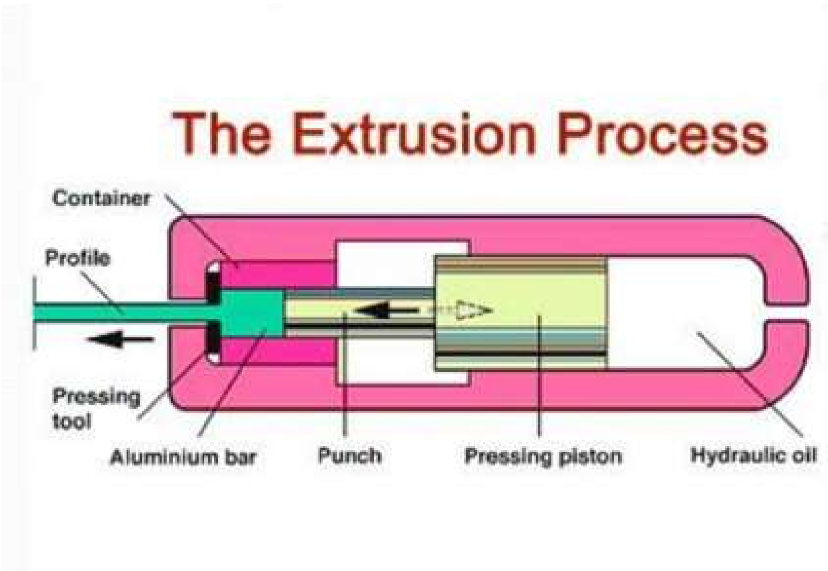
8.0 Extrusion:

EXTRUSION:

8.1 Explain the elementary principle of extrusion

• In Extrusion Process, a billet is forced through a Die, in a manner similar to squeezing toothpaste from tube.

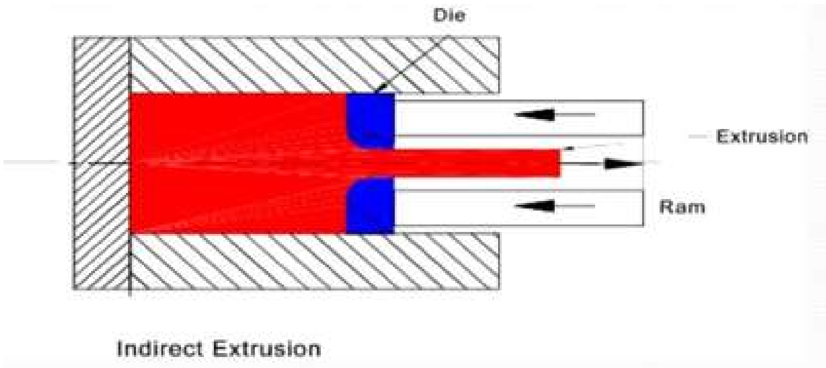
Typical products made by extrusion are tubing's having various cross-sections, structural and architectural shapes.



Extrusion (Indirect):

In indirect Extrusion metal flows to the direction opposite to the ram motion

This require less force as compare to the direct process because there is no friction between the billet and inside wall of container.



Direct extrusion:

In this extrusion process, the direction of ram and the direction of extruded metal is in the same direction. This mode of extrusion is also called forward extrusion. The main advantage of this process is, by this type we can extrude longer workpieces.

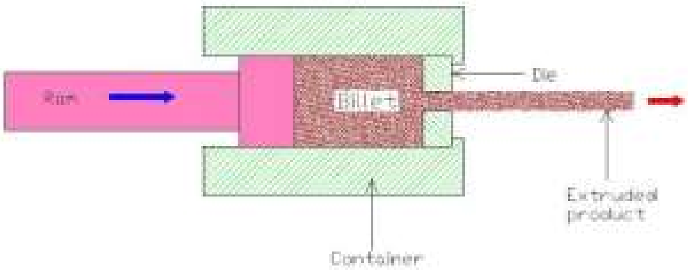


Fig: Direct extrusion

Advantages of Extrusion Process: Extrusion includes several advantages which are as follows;

- The extrusion process is widely used to create a complex profile of materials within the least time as compared to other metal forming process.
- The extrusion process is very useful to work with brittle and ductile materials.
- Mechanical properties which can be developed by the extrusion process is very precise that enhance the life cycle of products.

Disadvantages of Extrusion Process: Some disadvantages of extrusion is listed below:

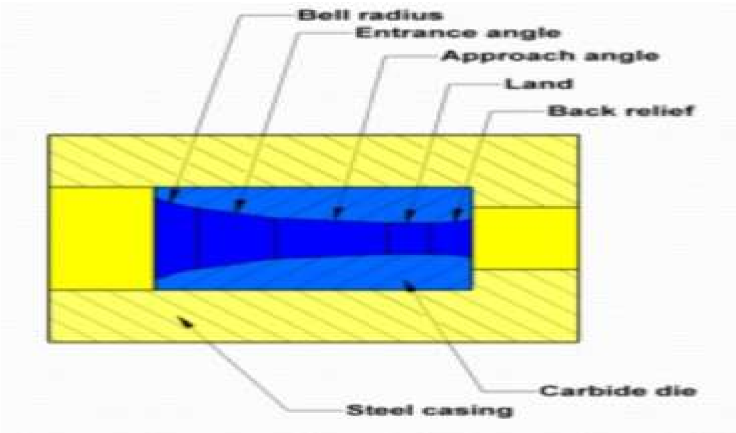
- The time consumption of this process is very high.
- Set-up cost at the initial stage is also very high.

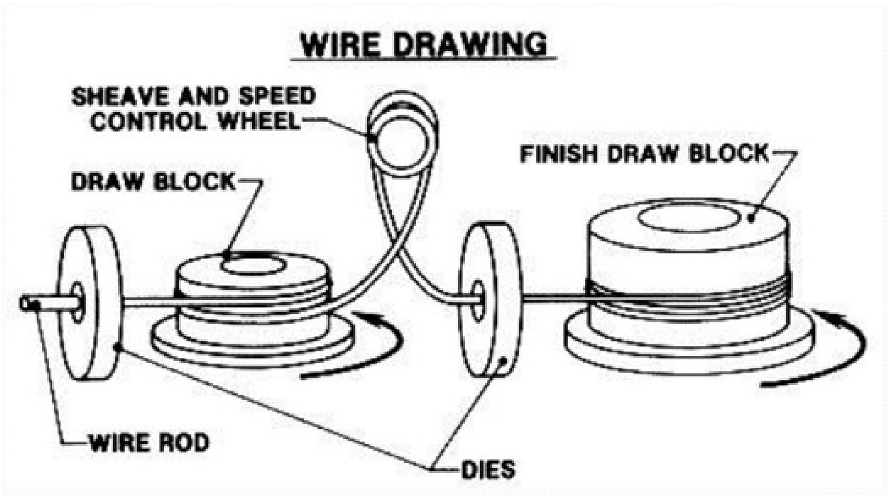
- The amount of compressive force that required for the extrusion process is also very high, and due to which the operator needs to ensurethat the plunger is fixed in the press appropriately.

9.0 Wire Drawing:

9.1 Explain the elementary principle of wire drawing

• In Drawing, the cross-section of a round rod, or wire is typically reduced by pulling it through a die.





Examples of wire drawing are:
1. High carbon steel wires for springs
2. wires for musical instruments.

10.0 Forming methods

Forming Method:

Forming Process also known as Metal Forming is a large set of manufacturing process by which a raw material converted into a product. In this process, we apply stresses like tension, compression, shear, etc. to deformed the raw material. The example of forming processes are sheet metal manufacturing, forging, rolling, extrusion, wire drawing, thread rolling, rotary swinging, and so on.

Classification or Types of Forming Process in Detail:

Forming Process can broadly be categorized into there types, and those are:

1. Bulk Forming
    - Rolling Process
    - Extrusion Process
    - Forging Process
    - Wire Drawing
    - Squeezing
2. Sheet metal Forming
    - Bending
    - Deep Drawing
    - Shearing
3. Powder Metal Forming
    - Powder Forging
    - Powder Injection
    - Powder Extrusion Moulding

10.2 Explain different sheet metal forming - bending shearing aid blanking

Sheet Metal Forming:

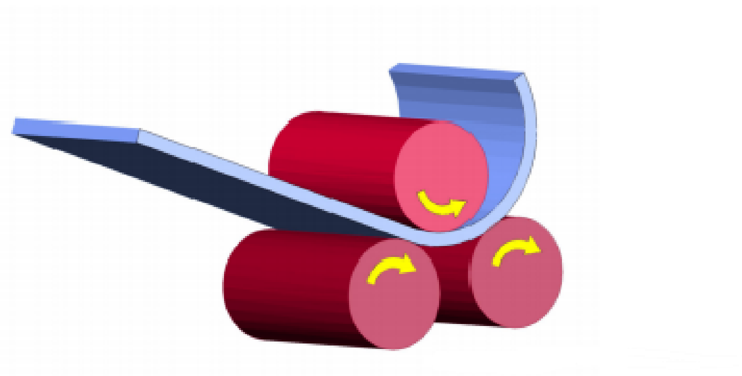
Another important forming process is the Sheet Forming process. This sheet forming process works due to either the tensile force or the shear force. Usually, this force can be used in Hydraulic presses in order to produce the product from the sheets however some

Bending Operation Diagram, Learn Mechanical Deep Drawing Operation Diagram, Learn Mechanical more steps like squeezing, bending and so on are also included in this process.

In this process, no material is added or removes. Example of this type of forging is bending, deep drawing, shearing, etc.

a. **Bending:**

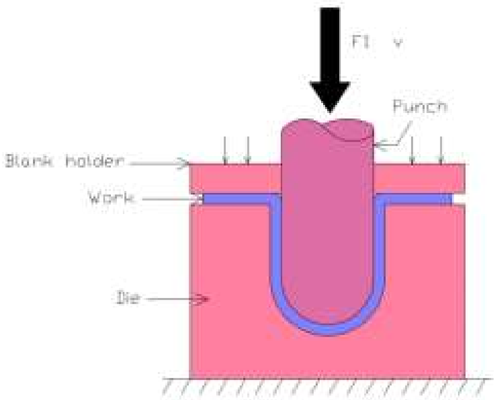
Bending is the process of forming where an angle is used in order to pressed by the compressive force of the metal plate that helps the material to bend in a particular angle so that, the plate can get its necessary shape. The shape of the angle usually looked like either the English letter "V" or "U".



10.1 Describe the elementary concept of deep drawing

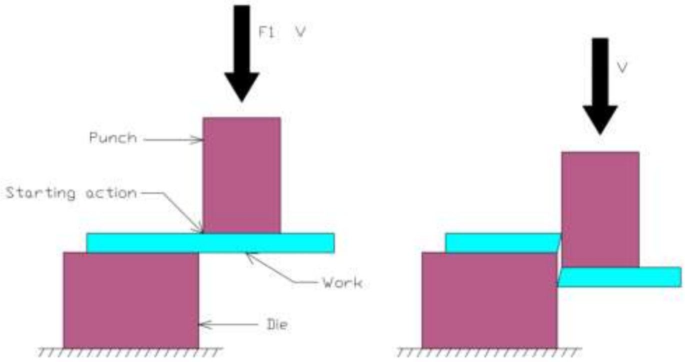
b. **Deep Drawing:**

In this operation, a hollow cup shape die is used. The die is clamped using the blank holder. In this process, the workpiece (sheet metal) placed over the die and a punch exerted the force on the workpiece, by this force sheet metal extend and filled the cavity and takes the shape of the die.



c. **Shearing:**

Shearing operation Diagram, Learn Mechanical In this operation, the metal sheet is in cantilever position, and a punch coming from the top exerted the force on the cantilever position of the sheet. Shearing is just a cutting operation of the metal sheet.



Applications of Metal Forming Process:

Some major applications of the forming process are as follows:

- Seamless tubes, rods can be made with the help of the aforementioned process.
- Turbine rings can be produced by this method.
- Cement kilns can also be made with the help of this process.
- Bearings, plates, steel sheets, and various components of an automotive car can be developed with the help of this forming process.
- The missile, aircraft components are also manufactured through this process.
- Along with that, hinge, bolt, nails can also be formed by this process.
- Moreover, agricultural tools, military products are also produced with the help of this process.
- Furniture, hook, pin, screws can also be made from this process.
- Windows, doors, and other components of a car can be developed with the help of the forming process. Furthermore, the forming process can also be used in order to develop plastic products.

Assignment Questions of Chapter-1 (Right side indicates Marks of that particular question)

1. Write down difference between Twinning and Slip. (5)
2. Explain Types of dislocations. (5)
3. Differentiate Edge vs Screw Dislocation (5)
4. Explain Edge and Screw Dislocation with neat sketch (10)
5. Differentiate glide vs cross slip. (5)
6. Both edge & Screw dislocation can glide but only screw dislocation can cross slip. Why? (2)
7. Explain different types of defects. (10)
8. Write short notes on Mixed Dislocation. (5)
9. Write down line diagram showing directional relationship between force, dislocation line, movement of dislocation and burger vector both in screw as well as edge dislocation. (5)
10. What is stacking fault? (2)

<u>Assignment Questions of Chapter-2 (Right side indicates Marks of that particular question)</u>

1. Write down yielding criteria. (2)
2. Derive critically resolved shear stress with neat sketch (10)
3. Explain deformation of polycrystalline aggregates. (5)
4. Derive theoretical shear stress required for slip with neat sketch (10)
5. Derive relationship between True stress vs engineering stress and true strain vs Engineering strain (10)

<u>Assignment Questions of Chapter-3 (Right side indicates Marks of that particular question)</u>

1. Define Hall Petch equation (2)
2. Describe yield point phenomenon. (10)
3. Explain strain-aging (5)
4. Explain solid solution strengthening from fine particles (5)
5. Describe fiber strengthening (5)
6. Describe martensitic strengthening (5)
7. Explain strain hardening (5)
8. Write short Notes on Bauschinger's effect. (5)

Assignment Questions of Chapter-4 (Right side indicates Marks of that particular question)

1. Classify different metal working process. (2)
2. Explain hot working and cold working of metals and alloys (5)
3. State the advantages and disadvantages of hot and cold working (5)

Assignment Questions of Chapter-5 (Right side indicates Marks of that particular question)

1. Explain the following phenomena,
(a) Recovery (10)
(b) Recrystallization
(c) Grain growth

Assignment Questions of Chapter-6 (Right side indicates Marks of that particular question)

1. Explain principles of rolling (2)
2. Compare between hot rolling and cold rolling. (5)
3. Explain the types of roll pass-open pass and box pass. (5)
4. State different types of rolling detects and their control (10)

Assignment Questions of Chapter-7 (Right side indicates Marks of that particular question)

1. Explain types of forging process (5)
2. Describe the properties of forged products (5)
3. Explain the defects of forged products and their control (5)

Assignment Questions of Chapter-8 (Right side indicates Marks of that particular question)

1. Explain the elementary principle of extrusion (2)
2. Classify the defects in extruded product (5)
3. Explain the manufacturing of seamless pipes (5)

Assignment Questions of Chapter-9 (Right side indicates Marks of that particular question)

1. Explain the elementary principle of wire drawing (2)
2. Classify the defects of wire drawing (5)

Assignment Questions of Chapter-10 (Right side indicates Marks of that particular question)

1. Describe the elementary concept of deep drawing (2)
2. Explain different sheet metal forming - bending shearing aid blanking (10)