Lecture # 11
- Line defects (1-D) / Dislocations
- Planer defects (2D)
- Volume Defects
- Burgers vector
- Slip
- Slip Systems in FCC crystals
- Slip systems in HCP
- Slip systems in BCC

References:
2- Hosford W.F, (2005), Mechanical Behavior of Materials, Cambridge
4- Dieter G.E., (1986), Mechanical Metallurgy, McGraw-Hill

Line defects (1D) / Dislocations
The approximate calculations show that $\tau_{th}$ is many orders of magnitude greater than the observed values of the shear stress. This striking difference between prediction and experiment was accounted for by the presence of dislocations independently by Orowan, Polanyi and Taylor in 1934.

The dislocation is the defect responsible for the phenomenon of slip, by which most metals deform plastically, it is the region of localized lattice disturbance separating the slipped and unslipped regions of a crystal.

In the absence of obstacles, a dislocation can move easily on the application of only a small force; this helps explain why real crystals deform much more readily than would be expected for a crystal with a perfect lattice. Dislocations are also connected with nearly all other mechanical phenomena such as strain hardening, the yield point, creep, fatigue, and brittle fracture.
(a) Model of a simple cubic lattice; the atoms are represented by filled circles, and the bonds between atoms by springs,

1\textsuperscript{st} - Edge Dislocation:
(b) positive edge dislocation $DC$ formed by inserting an extra half-plane of atoms in $ABCD$;
(c) Atomic arrangement in a plane normal to an edge dislocation.
- The atomic arrangement results in compressive stress above the slip plane and a tensile stress below the slip plane.
- An edge dislocation with the extra plane of atoms above the slip plane, is called a positive edge dislocation and indicated by $\perp$ and if the extra plane of atoms lies below the slip plane, the dislocation is a negative edge dislocation, $\Upsilon$.

(d) Dislocation lies along $\overline{AB}$, perpendicular to slip direction. Slip has occurred over area $\overline{ABCD}$ (slip plane).
- **Burger vector** $b$ (the amount by which the parts of the crystal have been displaced with respect to each other) **is always perpendicular to the dislocation line.**

A pure edge dislocation can glide or slip in a direction perpendicular to its length. However, it may move vertically by a process known as climb, if diffusion of atoms or vacancies can take place at an appreciable rate. For the edge dislocation to move upward (positive direction of climb), it is necessary to remove the extra atom directly over the symbol $\perp$ or to add a vacancy to this spot. Conversely, if the dislocation moved down, atoms would have to be added. Atoms could be removed from the extra plane of atoms by the extra atom interacting with a lattice vacancy. Atoms are added to the extra plane for negative climb by the diffusion of an atom from the surrounding crystal, creating a vacancy. Since movement by climb is diffusion-controlled, motion is much slower than in glide and less likely except at high temperatures.

**2\textsuperscript{nd} – Screw or Burgers dislocation:**

(e) left-handed screw dislocation $DC$ formed by displacing the faces $ABCD$ relative to each other in direction $AB$;

- The dislocation line is parallel to its Burgers vector, or slip vector

(f) spiral of atoms adjacent to the line $DC$ in (e).

- The screw dislocation can be visualized as a spiral ramp parking structure. One circuit around the axis leads one plane up or down. Planes are connected in a manner similar to the levels of a spiral parking ramp.
- A screw dislocation does not have a preferred slip plane, as an edge dislocation has, and therefore its motion is less restricted than the motion of an edge dislocation. Movement by climb is not possible with a screw dislocation.

**Planer defects (2D)**
All of them distort the periodicity of the crystal lattice and induce strain fields.

**Stacking Faults**
Perfect crystals can be described as a stack of atom layers arranged in a regular sequence.
A stacking fault is a planar defect. It is a local region in the crystal where the regular sequence has been interrupted.

For ABCABC... or ABABAB... stacking of the close-packed planes in close-packed structures there are two possible positions of one layer resting on another, a close-packed layer of atoms resting on an A layer can rest equally well in either a B or a C position and geometrically there is no reason for the selection of a particular position.

In a face-centered cubic lattice two types of stacking fault are possible,
a) part of a C layer removed this results in a break in the stacking sequence and an intrinsic fault, b) If an extra A layer has been introduced between a B and a C layer this referred to as an extrinsic fault. The presence of stacking faults can play an important role in the plasticity of crystals. It should be noted, for example, that the intrinsic fault in the face-centered cubic structure can be produced by a sliding process. They destroy the
perfection of the host crystal, and the associated energy per unit area of fault is known as the stacking-fault energy.

**Grain Boundaries**
Crystalline solids usually consist of a large number of randomly oriented *grains* separated by grain boundaries. Each grain is a single crystal and contains the defects already described. When the misorientation between the grains is large, the atomic arrangement at the boundary is complicated and varies significantly with the angle of misorientation.

A grain boundary is an array of dislocations that line up to form a plane that forms a boundary between two crystalline regions (grains) that are misoriented relative to one another.

![Grain boundary image]

Low angle grain boundaries

Grain-boundary *dislocations* are not mobile dislocations producing extensive slip; rather, their chief role is that they group together within the boundary to form a step or *grain-boundary ledge*. As the misorientation angle of the grain boundary increases the density of the ledges increases.

**Twin Boundaries**
Deformation twinning is a process in which a region of a crystal undergoes a homogeneous shear that produces the original crystal structure in a new orientation. In the simplest cases, this results in the atoms of the original crystal (‘parent’) and those of the product crystal (‘twin’) being mirror images of each other by reflection in a *composition plane*. Deformation twinning can be induced by plastic deformation and is particularly important in body centered cubic and close-packed hexagonal metals.

**Volume Defects**
- Inclusions (as MnS in steel), Dispersed particles (as Al₂O₃ in Al)
- Precipitates (coherent, incoherent, partially coherent)
- Crystal defects such as precipitates, voids and bubbles can occur under certain circumstances and have important effects on the properties of
crystalline solids. As an example, the interaction of dislocations with precipitates has played a vital role in the development of high-strength alloys.

**Burgers vector**
The Burgers vector is a characteristic entity of a dislocation.

The fig. shows the construction of the Burgers vector in an edge dislocation by taking a loop around the dislocation and the same loop in a dislocation free crystal. The vector \( b \) needed to close the loop is the **Burgers vector**. Burger vector \( b \) is always perpendicular to the dislocation line.

The fig. shows the construction of the Burgers vector in a screw dislocation by taking a loop around the dislocation and the same loop in a dislocation free crystal. Notice that the Burgers vector \( b \) needed to close the loop in a dislocation-free crystal in such that: The dislocation line is parallel to its Burgers vector.
**Slip**
Plastic deformation of crystalline materials usually occurs by *slip*, which is the sliding of planes of atoms over one another. The planes on which slip occurs are called *slip planes* and the directions of the shear are the *slip directions*. These are crystallographic planes and directions that are characteristic of the crystal structure.

![Slip Diagram](image)

Almost without exception the slip directions are the crystallographic directions with the shortest distance between like atoms or ions and the slip planes are usually densely packed planes. Since the planes of greatest atomic density are the most widely spaced planes in the crystal structure, the resistance to slip is generally less for these planes than any other set of planes. **The slip plane together with the slip direction establishes the slip system.**

**Slip Systems in FCC crystals**
The family of close-packed planes in FCC is \{111\}. There are four such planes in a crystal, they are: \( (111) \ (\bar{1}11) \ (1\bar{1}1) \ (11\bar{1}) \)

![Close packed directions in FCC](image)

The directions for the vectors shown are \( r_1 = [011] \), \( r_2 = [1\bar{1}0] \), \( r_3 = [\bar{1}01] \) and \( r_4 = [01\bar{1}] \).
There are 4 close-packed planes with 3 close-packed directions in each plane \(<\overline{1}10>\) – a total of 12 slip systems. The close-packed directions are the slip directions. They are: \(<\overline{1}10>\).

There are three such directions for each slip plane, e.g. for the plane (111) the slip directions are: \([\overline{1}10]\), \([0\overline{1}1]\) and \([10\overline{1}]\).

Thus there are 4 slip planes with each having 3 slip directions: A total of 12 slip systems for FCC crystals.

Slip systems in HCP
The close-packed plane in HCP is the basal plane (0001) and there are 3 close-packed directions \(<11\overline{2}0>\).
Hence in HCP there are 3 slip systems. This low number of slip systems means that it is difficult to plastically deform an HCP metal. It can be shown that 5 slip systems must operate in each grain of a polycrystal if it is to deform in a manner compatible with the deformations of its neighbors. To meet these constraints the HCP polycrystal must deform by mechanical twinning to avoid cracking at the grain boundaries.

Since the basal plane is not ideally close-packed, we find that for HCP crystals slip often takes place on other planes in some materials.

**Slip systems in BCC**

There are no close-packed planes in BCC. However, there are three types of planes which are nearly tied for the highest packing density. They are:

- near close-packed planes in BCC: \{110\} \{321\} \{211\}

All these planes have been observed to be slip planes. Thus we have the following slip systems in BCC crystals:

- 6 \{110\} planes each with 2 \langle 111 \rangle directions
- 24 \{321\} planes each with 1 \langle 111 \rangle direction
- 12 \{211\} planes each with 1 \langle 111 \rangle direction
i.e. a total of 48 slip systems for BCC crystals. Since BCC crystals have many possible slip planes intersecting along the $<111>$ direction, they can cross slip.

There are 48 possible slip systems, but since the planes are not so closed-packed as in the FCC structure, higher shearing stresses are usually required to cause slip.

Certain metals show additional slip systems with increased temperature. Aluminum deforms on the $\{110\}$ plane at elevated temperature, while in magnesium the $\{10\bar{1}\}$ pyramidal plane plays an important role in deformation by slip above $225^\circ$C. In all cases the slip direction remains the same when the slip plane changes with temperature.