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

Dr.Haydar Al-Ethari

References:

1- Derek Hull, David Bacon, (2001), Introduction to Dislocations, fourth edition, Butterworth-Heinemann.

2- Hosford W.F, (2005), Mechanical Behavior of Materials, Cambridge

3- Meyers M.A. and Chawla K.K., (2009). Mechanical Behavior of Materials, Prentice- Hall.

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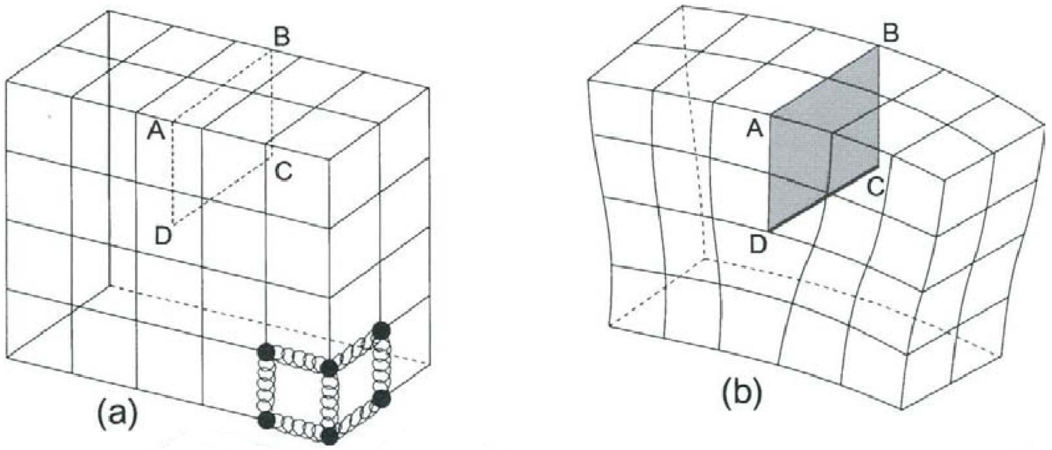
Line defects (1D) / Dislocations

The approximate calculations show that τ_{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 un slipped regions of a crystal.

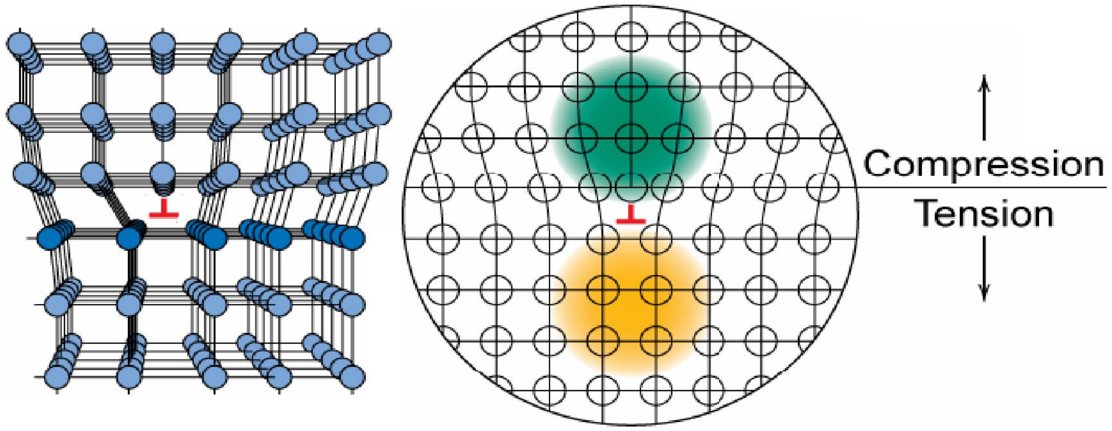
Dislocations are also connected with nearly all other mechanical phenomena such as strain hardening, yield point, creep, fatigue, and brittle fracture.

1st - Edge Dislocation:



(a) Model of a simple cubic lattice; the atoms are represented by filled circles, and the bonds between atoms by springs.

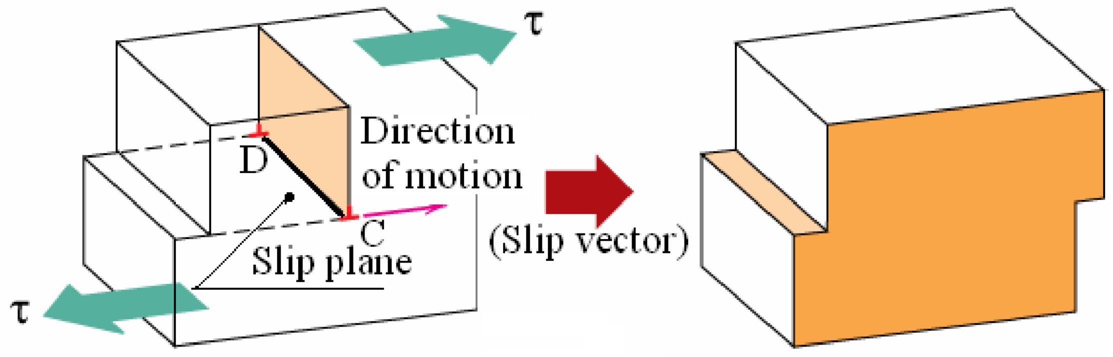
(b) positive edge dislocation *DC* formed by inserting an extra half-plane of atoms in ABCD.



(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.

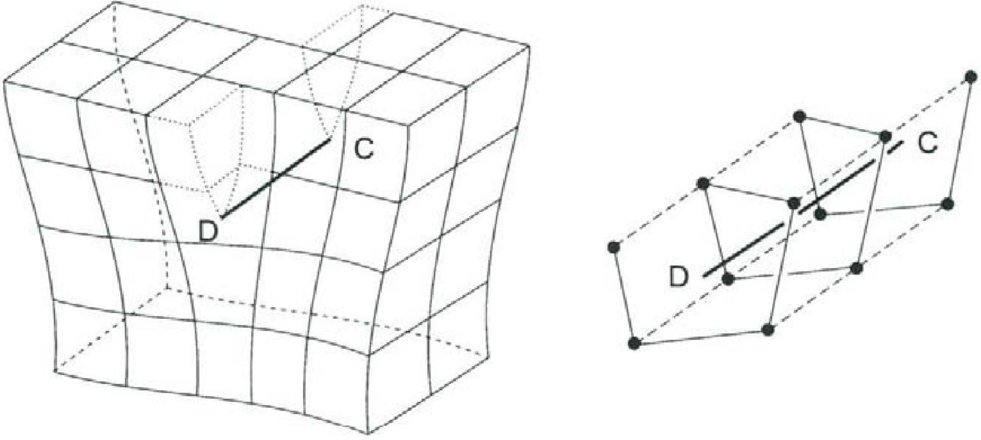
- An edge dislocation with the extra plane of atoms above the slip plane, is called a positive edge dislocation and indicated by ⊥ and if the extra plane of atoms lies below the slip plane, the dislocation is a negative edge dislocation, ⊤ .



(d) Dislocation moves along slip plane in slip direction perpendicular to dislocation line CD. A pure edge dislocation can glide or slip in a direction perpendicular to its length. It may move vertically by a process known as climb, if diffusion of atoms or vacancies can take place.

To move upward (positive direction of climb), it is necessary to remove the extra atom directly over ⊥ or to add a vacancy to this spot. If the dislocation moves down, atoms would have to be added. Movement by climb is diffusion-controlled, motion is much slower than in glide and less likely except at high temperatures.

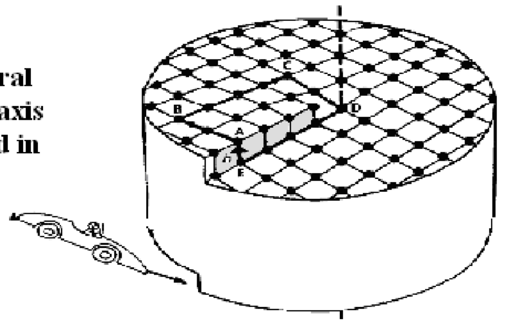
2nd – Screw or Burgers dislocation:



(a) 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, slip vector or (Burgers vector)

(b) spiral of atoms adjacent to the line *DC in* (a).

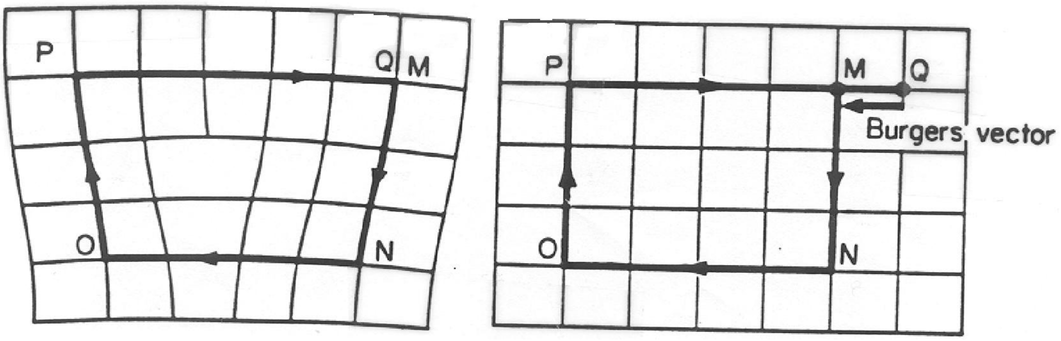
- The screw dislocation can be visualized as a spiral -ramp parking structure. One circuit around the axis leads one plane up or down. Planes are connected in a manner similar to the levels of a spiral-parking ramp.



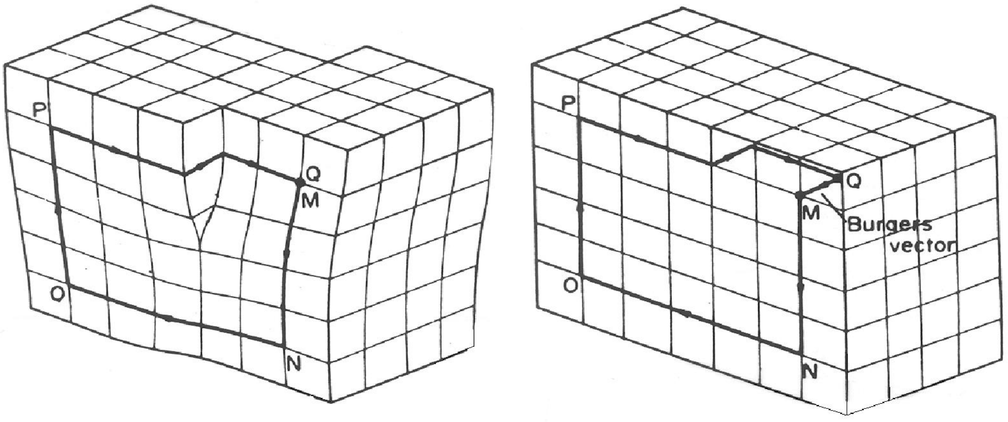
- A screw dislocation does not have a preferred slip plane, as an edge dislocation has, and therefore its motion is less restricted than the motion of an edge dislocation. Movement by climb is not possible with a screw dislocation.

Burgers vector

The Burgers vector (the amount by which the parts of the crystal have been displaced with respect to each other) is a characteristic entity of a dislocation.



(a) 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.



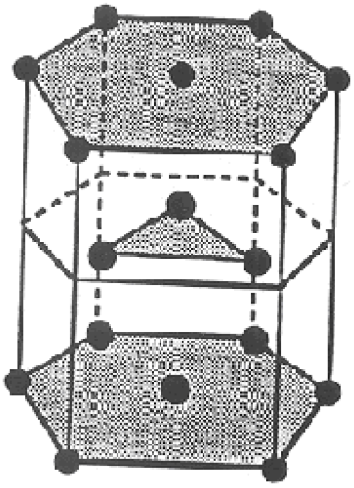
(b) The construction of the Burgers vector in a **screw dislocation** by taking a loop around the dislocation and the same loop in a dislocation free crystal. Notice that the Burgers vector **b** needed to close the loop in a dislocation-free crystal in such that: the dislocation line is **parallel** to its Burgers vector.

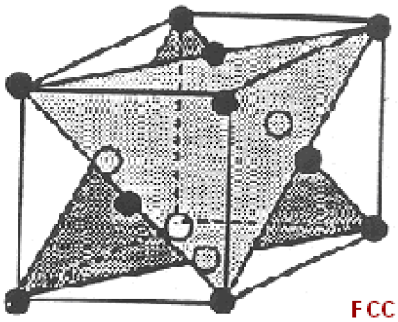
Planer defects (2D)

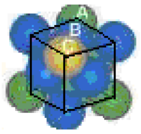
All of them distort the periodicity of the crystal lattice and induce strain fields.

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.



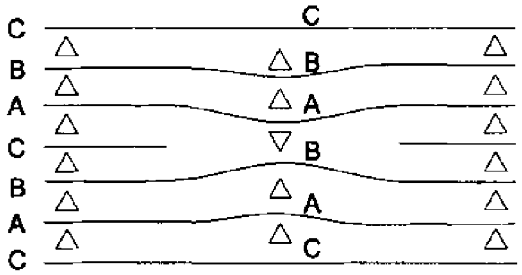


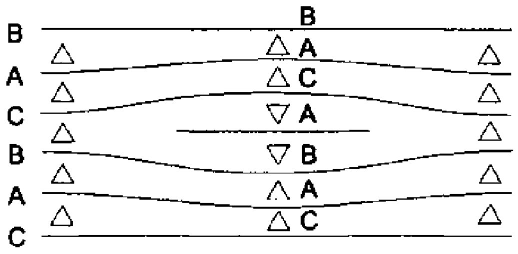


FCC Unit Cell
FCC STACKING SEQUENCE
ABC ABC... Stacking Sequence

HCP STACKING SEQUENCE
AB AB AB...... Stacking Sequence

In a face-centered cubic lattice two types of stacking fault are possible:





(a) intrinsic stacking fault, (b) extrinsic stacking fault.

Planes in normal relation to one another are separated by Δ, those with a stacking error by ∇.

a) part of a C layer removed this results in a break in the stacking sequence and an **intrinsic fault**.

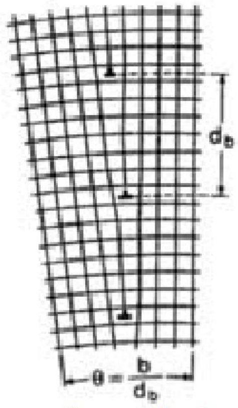
b) If an extra *A* layer has been introduced between a *B* and a C layer this referred to as an **extrinsic fault**.

The presence of stacking faults can play an important role in the plasticity of crystals. They destroy the perfection of the host crystal. The associated energy per unit area of fault is known as **the stacking-fault energy**.

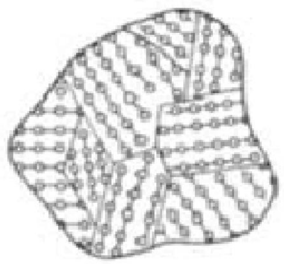
Grain Boundaries:

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

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.



Low angle grain boundaries



High 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:

The regular internal structure of a crystal may be interrupted in such a way that two pieces of the crystal are related to one another by rotation about an axis or reflection in a mirror plane.

Twins may be produced by mechanical deformation or as the result of annealing following plastic deformation. The first is called mechanical twins (or deformation twinning); the letter are called annealing twins.

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 under conditions of rapid rate of loading (shock loading) and decreased temperature. FCC metals are not ordinarily deform by mechanical twinning, although gold-silver alloys twin fairly when deformed at low temperature.

Annealing twins often form in FCC metals such as Cu,Al, Ni that have been cold worked and annealed. As the crystal regrows a stacking fault leads to the formation of twins.

The important role of twinning in plastic deformation comes not from the strain produced by the twinning process but from the fact that orientation changes resulting from twinning may place new slip systems in a favorable orientation with respect to the stress axis so that additional slip can take place. Thus, twinning is important in the overall deformation of metals with a low number of slip systems, such as the hcp meals. However, it should be understood that only a relatively small fraction of the total volume of a crystal is reoriented by twinning, and therefore hcp metals will, in general, possess less ductility than metals with a greater number of slip systems.

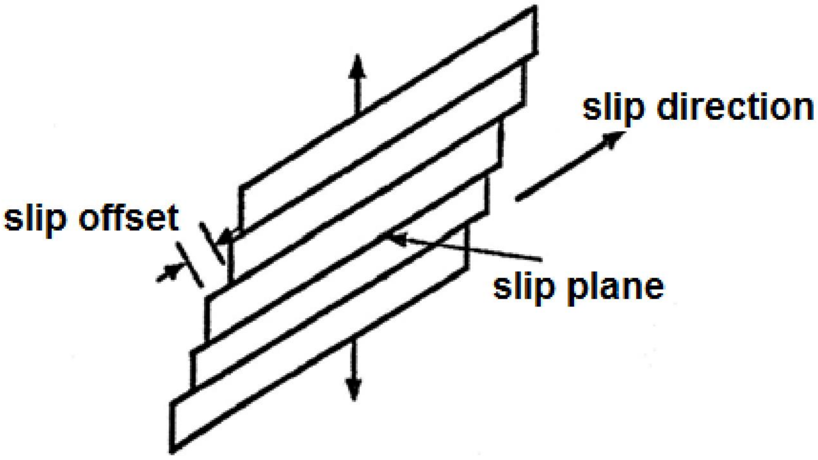
Volume Defects:

- Inclusions (as MnS in steel), Dispersed particles (as Al_2O_3 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.

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.

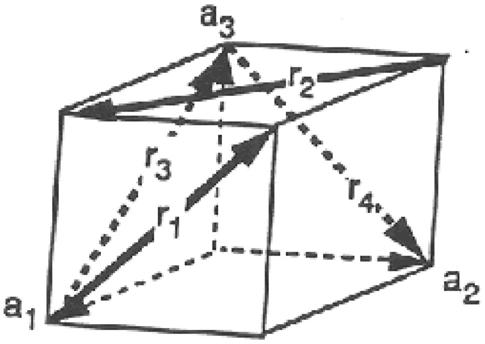


Almost without exception the slip directions are the crystallographic directions with the shortest distance between like atoms or ions and the slip planes are usually densely packed planes. Since the planes of greatest atomic density are the most widely spaced planes in the crystal structure, the resistance 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

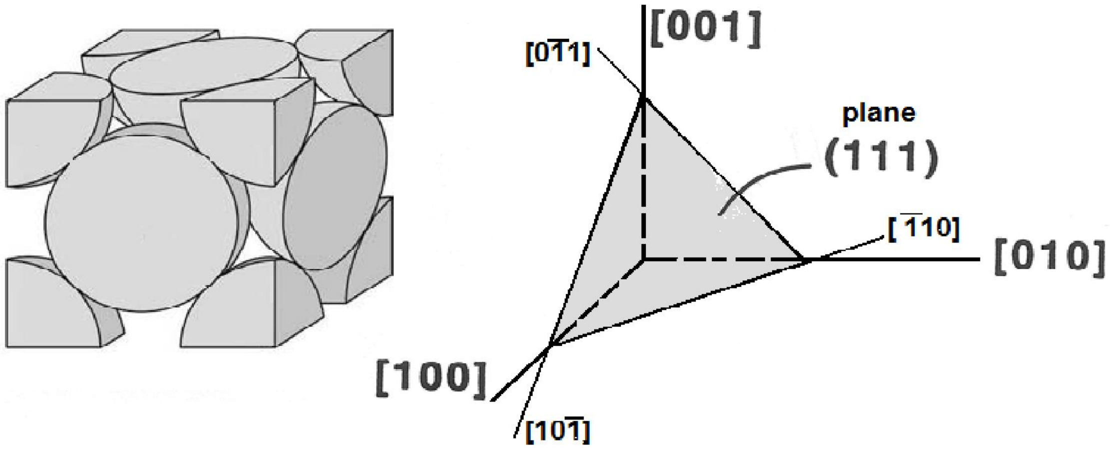


The directions for the vectors shown are $\mathbf{r}_1 = [011]$, $\mathbf{r}_2 = [1\bar{1}0]$, $\mathbf{r}_3 = [\bar{1}01]$ and $\mathbf{r}_4 = [01\bar{1}]$.

There are 4 close-packed planes with 3 close-packed directions in each plane $<\bar{1}10>$ – a total of 12 slip systems.

The close-packed directions are the slip directions. They are: $<\bar{1}10>$.

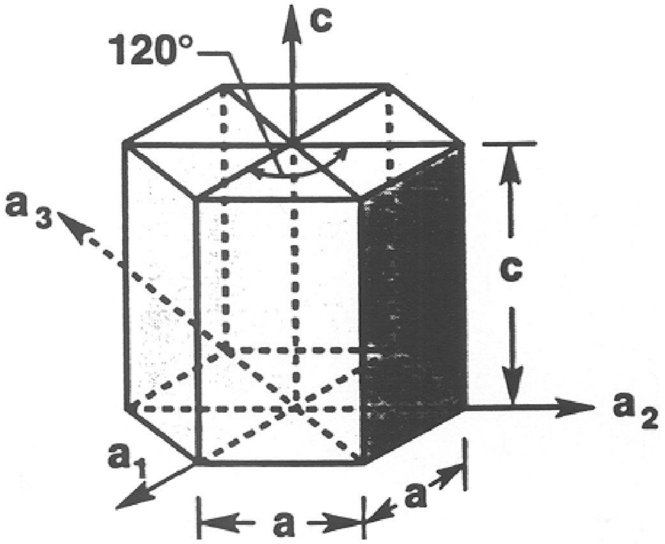
There are three such directions for each slip plane, e.g. for the plane (111) the slip directions are: $[\bar{1}10]$, $[0\bar{1}1]$ and $[10\bar{1}]$.
Thus there are 4 slip planes with each having 3 slip directions: A total of 12 slip systems for FCC crystals.

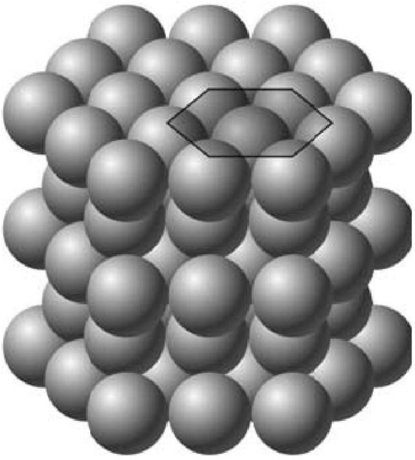


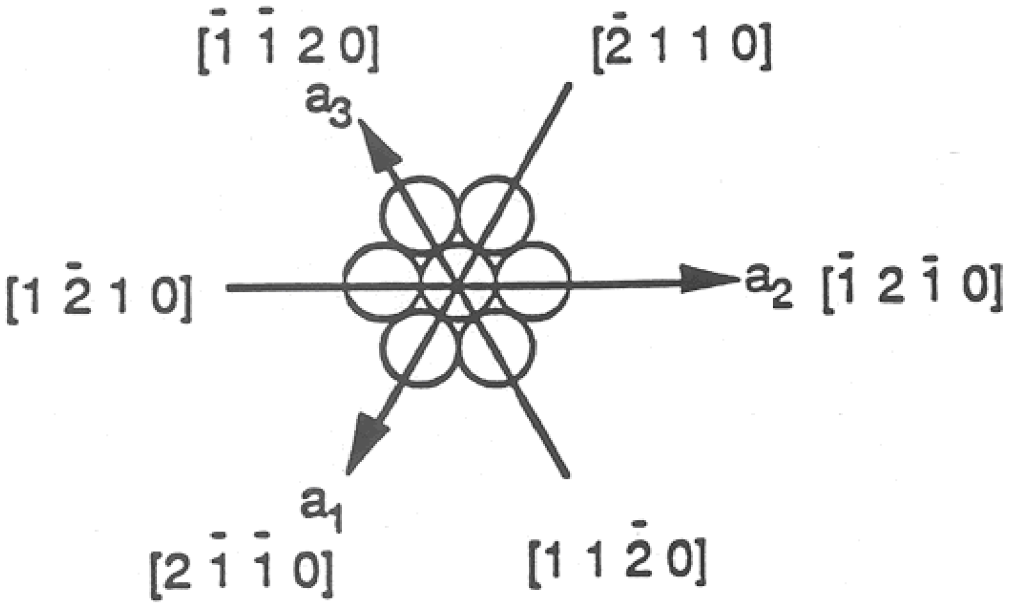
For the plane (111) the slip directions are: $[\bar{1}10]$, $[0\bar{1}1]$ and $[10\bar{1}]$.

Slip systems in HCP

The close-packed plane in HCP is the basal plane (0001) and there are 3 close-packed directions $\langle 11\bar{2}0 \rangle$.





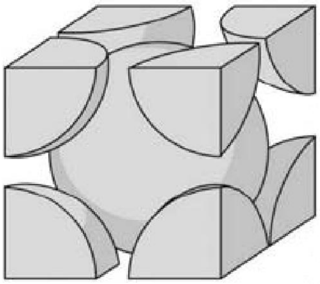


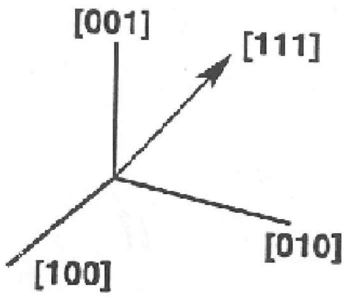
Hence in HCP there are 3 slip systems. This low number of slip systems means that it is difficult to plastically deform an HCP metal. It can be shown that 5 slip systems must operate in each grain of a polycrystal if it is to deform in a manner compatible with the deformations of its neighbors. To meet 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.

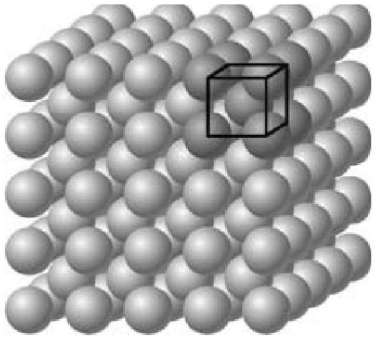
Slip systems in BCC

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:

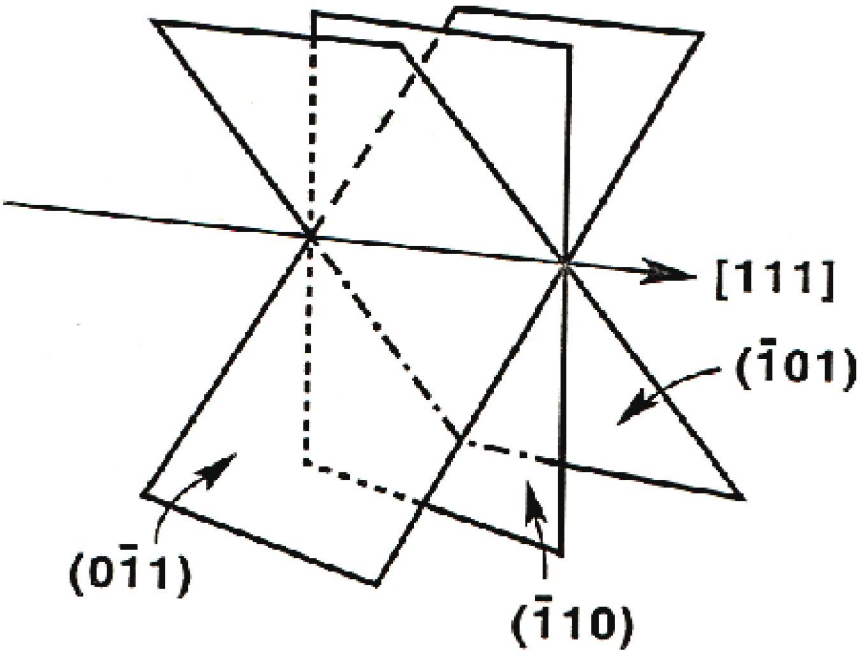
- 6 {110} planes each with 2 < 111 > directions
- 24 {321} planes each with 1 < 111 > direction
- 12 {211} planes each with 1 < 111 > direction



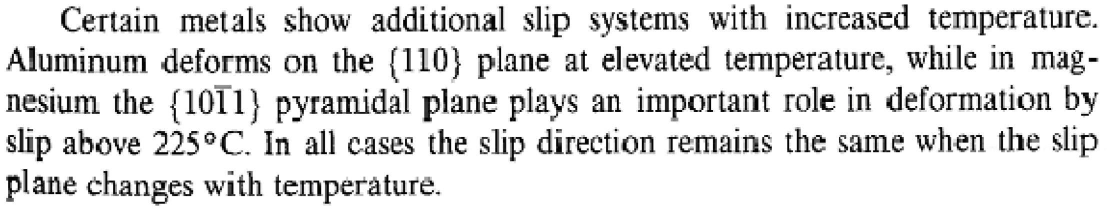




i.e. a total of **48 slip systems** for BCC crystals.
Since BCC crystals have many possible slip planes intersecting along the < 111 > direction, they can **cross slip**.



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 $\{10\bar{1}1\}$ pyramidal plane plays an important role in deformation by slip above 225°C. In all cases the slip direction remains the same when the slip plane changes with temperature.