Dislocations and Plastic Deformation

Edge and screw are the two fundamental dislocation types. In an edge dislocation, localized lattice distortion exists along the end of an extra half-plane of atoms, which also defines the dislocation line. A screw dislocation may be thought of as resulting from shear distortion; its dislocation line passes through the center of a spiral, atomic plane ramp. Many dislocations in crystalline materials have both edge and screw components; these are mixed dislocations.

Plastic deformation corresponds to the motion of large numbers of dislocations. An edge dislocation moves in response to a shear stress applied in a direction perpendicular to its line; the mechanics of dislocation motion are represented in Figure 1. Let the initial extra half-plane of atoms be plane A. When the shear stress is applied as indicated (Figure 1a), plane A is forced to the right; this in turn pushes the top halves of planes B, C, D, and so on, in the same direction. If the applied shear stress is of sufficient magnitude, the interatomic bonds of plane B are severed along the shear plane, and the upper half of plane B becomes the extra half-plane as plane A links up with the bottom half of plane B (Figure 1b). This process is subsequently repeated for the other planes, such that the extra half-plane, by discrete steps, moves from left to right by successive and repeated breaking of bonds and shifting by interatomic distances of upper half-planes. Before and after the movement of a dislocation through some particular region of the crystal, the atomic arrangement is ordered and perfect; it is only during the passage of the extra halfplane that the lattice structure is disrupted. Ultimately this extra half-plane may emerge from the right surface of the crystal, forming an edge that is one atomic distance wide; this is shown in Figure 1c.

The process by which plastic deformation is produced by dislocation motion is termed slip; the crystallographic plane along which the dislocation line traverses is the slip plane, as indicated in Figure 1. Macroscopic plastic deformation simply corresponds to permanent deformation that results from the movement of dislocations, or slip, in response to an applied shear stress.

Figure 1. Mechanism of slip
All metals and alloys contain some dislocations that were introduced during solidification, during plastic deformation, and as a consequence of thermal stresses that result from rapid cooling. The number of dislocations, or dislocation density in a material, is expressed as the total dislocation length per unit volume or, equivalently, the number of dislocations that intersect a unit area of a random section. The units of dislocation density are millimeters of dislocation per cubic millimeter or just per square millimetre.

**CHARACTERISTICS OF DISLOCATIONS**

Several characteristics of dislocations are important with regard to the mechanical properties of metals. These include strain fields that exist around dislocations, which are influential in determining the mobility of the dislocations, as well as their ability to multiply. When metals are plastically deformed, some fraction of the deformation energy (approximately 5%) is retained internally; the remainder is dissipated as heat. The major portion of this stored energy is as strain energy associated with dislocations.

The strain fields surrounding dislocations in close proximity to one another may interact such that forces are imposed on each dislocation by the combined interactions of all its neighboring dislocations. For example, consider two edge dislocations that have the same sign and the identical slip plane, as represented in Figure 2a. The compressive and tensile strain fields for both lie on the same side of the slip plane; the strain field interaction is such that there exists between these two isolated dislocations a mutual repulsive force that tends to move them apart.

![Figure 2a](image1)

**Figure 2** (a) Two edge dislocations of the same sign and lying on the same slip plane exert a repulsive force on each other; $C$ and $T$ denote compression and tensile regions, respectively. (b) Edge dislocations of opposite sign and lying on the same slip plane exert an attractive force on each other. Upon meeting, they annihilate each other and leave a region of perfect crystal.
On the other hand, two dislocations of opposite sign and having the same slip plane will be attracted to one another, as indicated in Figure 2b, and dislocation annihilation will occur when they meet. That is, the two extra half-planes of atoms will align and become a complete plane. Dislocation interactions are possible between edge, screw, and/or mixed dislocations, and for a variety of orientations. These strain fields and associated forces are important in the strengthening mechanisms for metals.

**PLASTIC DEFORMATION OF POLYCRYSTALLINE MATERIALS**

Deformation and slip in polycrystalline materials is somewhat more complex. Because of the random crystallographic orientations of the numerous grains, the direction of slip varies from one grain to another. For each, dislocation motion occurs along the slip system that has the most favorable orientation. Polycrystalline metals are stronger than their single-crystal equivalents, which means that greater stresses are required to initiate slip and the attendant yielding. This is, to a large degree, also a result of geometrical constraints that are imposed on the grains during deformation.

**DEFORMATION BY TWINNING**

In addition to slip, plastic deformation in some metallic materials can occur by the formation of mechanical twins, or twinning. The concept of a twin is, a shear force can produce atomic displacements such that on one side of a plane (the twin boundary), atoms are located in mirror-image positions of atoms on the other side. The manner in which this is accomplished is demonstrated.

Schematic diagram showing how twinning results from an applied shear stress. In (b), open circles represent atoms that did not change position; dashed and solid circles represent original and final atom positions, respectively.

The manner in which this is accomplished is demonstrated in Figure. Here, open circles represent atoms that did not move, and dashed and solid circles represent original and final positions.
respectively, of atoms within the twinned region. As may be noted in this figure, the displacement magnitude within the twin region (indicated by arrows) is proportional to the distance from the twin plane. Furthermore, twinning occurs on a definite crystallographic plane and in a specific direction that depend on crystal structure. For example, for BCC metals, the twin plane and direction are (112) and [111], respectively.

**Slip v/s twinning**

- Amount of movement: In slip atoms move a whole number of interatomic spacing, while in twinning atoms move fractional amount.
- Microscopic appearance: slip appear as thin lines and twinning as broad lines or bands.
- Lattice orientation: In slip there a little change in lattice orientation and steps are visible only on the surface which can be removed by polishing. In twinning there is different lattice orientation and polishing will not remove the steps.

**Mechanisms of Strengthening in Metals**

- Important to the understanding of strengthening mechanisms is the relation between dislocation motion and mechanical behavior of metals. Because macroscopic plastic deformation corresponds to the motion of large numbers of dislocations, *the ability of a metal to plastically deform depends on the ability of dislocations to move*. all strengthening techniques rely on the simple principle: *restricting or hindering dislocation motion renders a material harder and stronger*.

**Types of Strengthening**

- Strengthening by grain size reduction
- Solid-solution strengthening
- Strain hardening

**Strengthening by grain size reduction**

- Adjacent grains normally have different crystallographic orientations and, of course, a common grain boundary, as indicated in Figure.
- During plastic deformation, slip or dislocation motion must take place across this common boundary.
- A fine-grained material is harder and stronger than one that is coarse grained, since the former has a greater total grain boundary area to impede dislocation motion. It should also be
mentioned that grain size reduction improves not only strength, but also the toughness of many alloys.

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**Solid-solution strengthening**

- Another technique to strengthen and harden metals is alloying with impurity atoms that go into either substitutional or interstitial solid solution. Accordingly, this is called **solid-solution strengthening**.
- Alloys are stronger than pure metals because impurity atoms that go into solid solution ordinarily impose lattice strains on the surrounding host atoms. Lattice strain field interactions between dislocations and these impurity atoms result, and, consequently, dislocation movement is restricted.
- Resistance to slip is greater when impurity atoms are present
- Smaller substitution solute atoms tend to diffuse to and segregate around dislocations in a way so as to reduce the overall strain energy—that is, to cancel some of the strain in the lattice surrounding a dislocation
- larger substitution atom imposes compressive strains in its vicinity

**Strain hardening**

- It is the phenomenon whereby a ductile metal becomes harder and stronger as it is plastically deformed below recrystallisation temperature. Sometimes it is also called **work hardening**. *Most metals strain hardens at room temperature.*
- **Additional energy stored in the crystal increases the stress required to cause slip**

**Mechanism of strain hardening**

- The dislocation density in a metal increases with deformation or cold work, due to dislocation multiplication or the formation of new dislocations.
- Consequently, the average distance of separation between dislocations decreases.
- The net result is that the motion of a dislocation is hindered by the presence of other dislocations.
- Thus, the imposed stress necessary to deform a metal increases with increasing cold work.
- consider two edge dislocations that have the same sign and the identical slip plane, as represented in *The compressive and tensile strain fields for both lie on the same side* of the slip
plane; the strain field interaction is such that there exists between these two isolated dislocations a mutual repulsive force that tends to move them apart.

- On the other hand, two dislocations of opposite sign and having the same slip plane will be attracted to one another, as indicated in Figure 2 and dislocation annihilation will occur when they meet. These strain fields and associated forces are important in the strengthening mechanisms for metals.