



Strengthening Mechanism of Metals

Physical Metallurgy

Anything that impedes the free motion and / or generation of dislocations will strengthen the material. There are various methods through which the metals can be strengthened and put to use in our daily practice with lower failure probability.



Introduction

Anything that impedes the free motion and / or generation of dislocations will strengthen the material. A pure metal, either cast or hot-formed is extremely weak, with $\tau_y/G = 10^{-4}$, with τ_y = yield strength in shear and G is the shear modulus. These yield strengths are the order of 1000 psi or 6.89 MPa. There are enough dislocations to give lots of easy slip, but not enough to get in one another's way. ^[1]

Methods have been devised to modify the yield strength, ductility, and toughness of both crystalline and amorphous materials. These strengthening mechanisms give engineers the ability to tailor the mechanical properties of materials to suit a variety of different applications. For example, the favorable properties of steel result from interstitial incorporation of carbon into the iron lattice. Brass, a binary alloy of copper and zinc, has superior mechanical properties compared to its constituent metals due to solution strengthening. Work hardening (such as beating a red-hot piece of metal on anvil) has also been used for centuries by blacksmiths to introduce dislocations into materials, increasing their yield strengths. ^[2]

What is strengthening?

Plastic deformation occurs when large numbers of dislocations move and multiply so as to result in macroscopic deformation. In other words, it is the movement of dislocations in the material which allows for deformation. If we want to enhance a material's mechanical properties (i.e. increase the yield and tensile strength), we simply need to introduce a mechanism which prohibits the mobility of these dislocations. Whatever the mechanism may be, (work hardening, grain size reduction, etc) they all hinder dislocation motion and render the material stronger than previously.

The stress required to cause dislocation motion is orders of magnitude lower than the theoretical stress required shifting an entire plane of atoms, so this mode of stress relief is energetically favorable. Hence, the hardness and strength (both yield and tensile) critically depend on the ease with which dislocations move. Pinning points, or locations in the crystal that oppose the motion of dislocations, can be introduced into the lattice to reduce dislocation mobility, thereby increasing mechanical strength. Dislocations may be pinned due to stress field interactions with other dislocations and solute particles, or physical barriers from grain boundaries and second phase precipitates. There are four main strengthening mechanisms for metals, however the key concept to remember about strengthening of metallic materials is that it is all about preventing dislocation motion and propagation; you are making it energetically unfavorable for the dislocation to move or propagate. For a material that has been strengthened, by some processing method, the amount of force required to start irreversible (plastic) deformation is greater than it was for the original material.

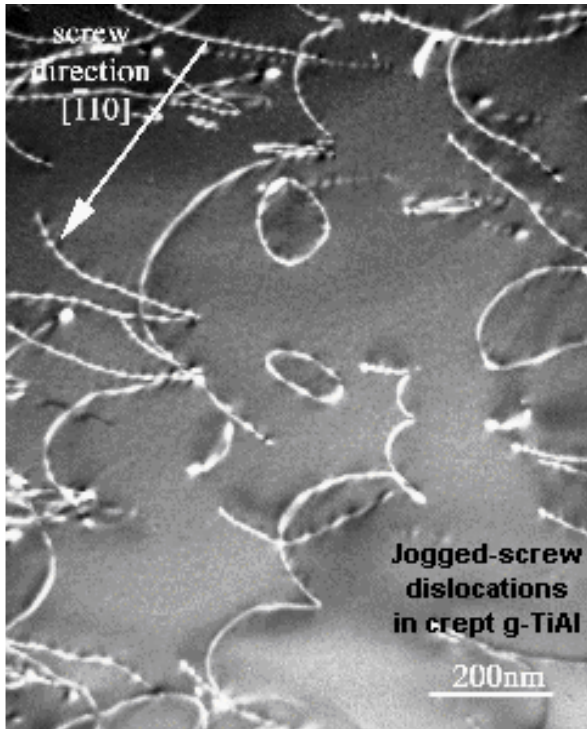
In amorphous materials such as polymers, amorphous ceramics (glass), and amorphous metals, the lack of long range order leads to yielding via mechanisms such as brittle fracture, crazing, and shear band formation. In these systems, strengthening mechanisms do not involve dislocations, but rather consist of modifications to the chemical structure and processing of the constituent material.

Unfortunately, strength of materials cannot infinitely increase. Each of the mechanisms elaborated below involves some trade off by which other material properties are compromised in the process of

strengthening.

Strengthening Mechanisms in Metals

Work Hardening



The primary species responsible for work hardening are dislocations. Dislocations interact with each other by generating stress fields in the material. The interaction between the stress fields of dislocations can impede dislocation motion by repulsive or attractive interactions. Additionally, if two dislocations cross, dislocation line entanglement occurs, causing the formation of a jog which opposes dislocation motion. These entanglements and jogs act as pinning points, which oppose dislocation motion. As both of these processes are more likely to occur when more dislocations are present, there is a correlation between dislocation density and yield strength,

$$\Delta\sigma_y = Gb\sqrt{\rho_{\perp}}$$

Where G is the shear modulus, b is the Burgers vector, and ρ_{\perp} is the dislocation density.

Increasing the dislocation density increases the yield strength which results in a higher shear stress required to move the dislocations. This process is easily observed while working a material. Theoretically, the strength of a material with no dislocations will be extremely high ($\tau=G/2$) because plastic deformation would require the breaking of many bonds simultaneously. However, at moderate dislocation density values of around 10^7 - 10^9 dislocations/ m^2 , the material will exhibit a significantly lower mechanical strength. Analogously, it is easier to move a rubber rug across a surface by propagating a small ripple through it than by dragging the whole rug. At dislocation densities of 10^{14} dislocations/ m^2 or higher, the strength of the material becomes high once again. It should be noted that the dislocation density can't be infinitely high because then the material would lose its crystalline structure.

Sites of the lattice creates a stress field that impedes dislocation movement.

Figure Source: http://met.iisc.ernet.in/~karthik/Pastprojects.html_txt_Jogs_cmp.gif

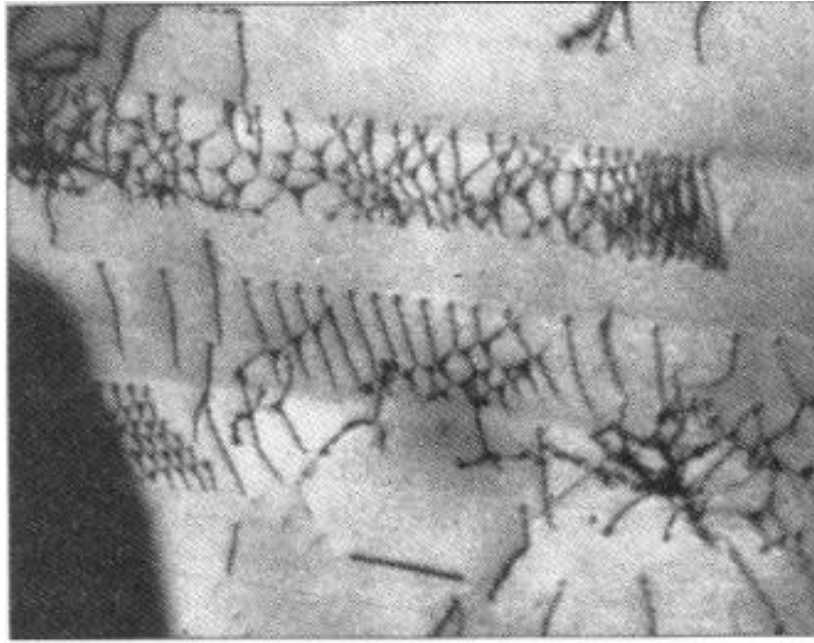


Figure: Dislocation pileup in steel

Figure Source: http://web.mse.uiuc.edu/courses/mse280/images/Disl_pileup_steel.gif

Solid Solution Strengthening/Alloying

For this strengthening mechanism, solute atoms of one element are added to another, resulting in either substitutional or interstitial point defects in the crystal (see Figure 1). The solute atoms cause lattice distortions that impede dislocation motion, increasing the yield stress of the material. Solute atoms have stress fields around them which can interact with those of dislocations. The presence of solute atoms imparts compressive or tensile stresses to the lattice, depending on solute size, which interfere with nearby dislocations, causing the solute atoms to act as potential barriers to dislocation propagation and/or multiplication.

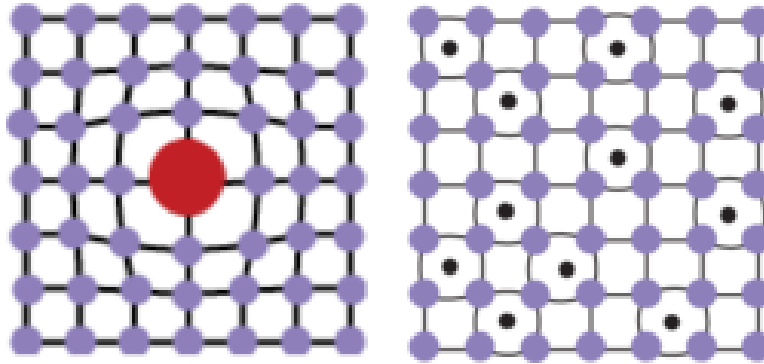


Figure 1: This is a schematic illustrating how the lattice is strained by the addition of substitutional and interstitial solute. Notice the strain in the lattice that the solute atoms cause. The interstitial solute could be carbon in iron for example. The carbon atoms in the interstitial.

The shear stress required to move dislocations in a material is:

$$\Delta\tau = Gb\sqrt{c\epsilon}^{3/2}$$

where c is the solute concentration and ϵ is the strain on the material caused by the solute.

Increasing the concentration of the solute atoms will increase the yield strength of a material; however, there is a limit to the amount of solute that can be added, and one should look at the phase diagram for the material and the alloy to make sure that a second phase is not created.

In general, the solid solution strengthening depends on the concentration of the solute atoms, shear modulus of the solute atoms, size of solute atoms, valency of solute atoms (for ionic materials), and the symmetry of the solute stress field. Note that the magnitude of strengthening is higher for non-symmetric stress fields because these solutes can interact with both edge and screw dislocations whereas symmetric stress fields, which cause only volume change and not shape change, can only interact with edge dislocations.

Figure Source: http://en.wikipedia.org/wiki/File:Substitutional_interstitial_solute.png

Precipitation Hardening

In most binary systems, alloying above a concentration given by the phase diagram will cause the formation of a second phase. A second phase can also be created by mechanical or thermal treatments. The particles that compose the second phase precipitates act as pinning points in a similar manner to solutes, though the particles are not necessarily single atoms.

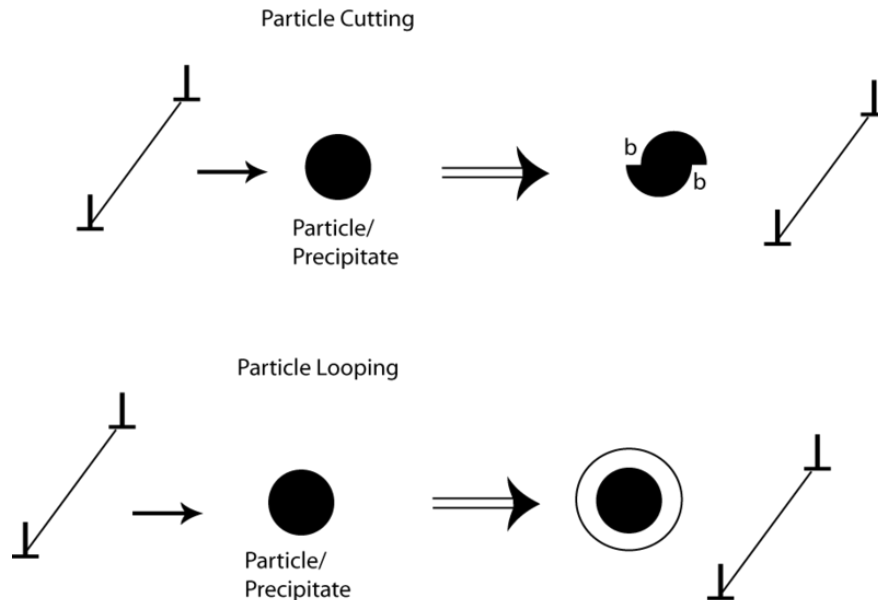


Figure 2: This is a schematic illustrating how the dislocations can interact with a particle. It can either cut through the particle or bow around the particle and create a dislocation loop as it moves over the particle.

The dislocations in a material can interact with the precipitate atoms in one of two ways (see Figure 2). If the precipitate atoms are small, the dislocations would cut through them. As a result, new surfaces (b in Figure 2) of the particle would get exposed to the matrix and the particle/matrix interfacial energy would increase. For larger precipitate particles, looping or bowing of the dislocations would occur which results in dislocations getting longer. Hence, at a critical radius of about 5nm, dislocations will preferably cut across the obstacle while for a radius of 30nm, the dislocations will readily bow or loop to overcome the obstacle.

The mathematical descriptions are as follows:

For Particle Bowing-
$$\Delta\tau = \frac{Gb}{L - 2r}$$

For Particle Cutting-
$$\Delta\tau = \frac{\gamma\pi r}{bL}$$

Grain Boundary Strengthening

In a polycrystalline metal, grain size has a tremendous influence on the mechanical properties. Because grains usually have varying crystallographic orientations, grain boundaries arise. While an undergoing deformation, slip motion will take place. Grain boundaries act as an impediment to dislocation motion for the following two reasons:

1. Dislocation must change its direction of motion due to the differing orientation of grains^[3]
2. Discontinuity of slip planes from grain 1 to grain 2.^[4]

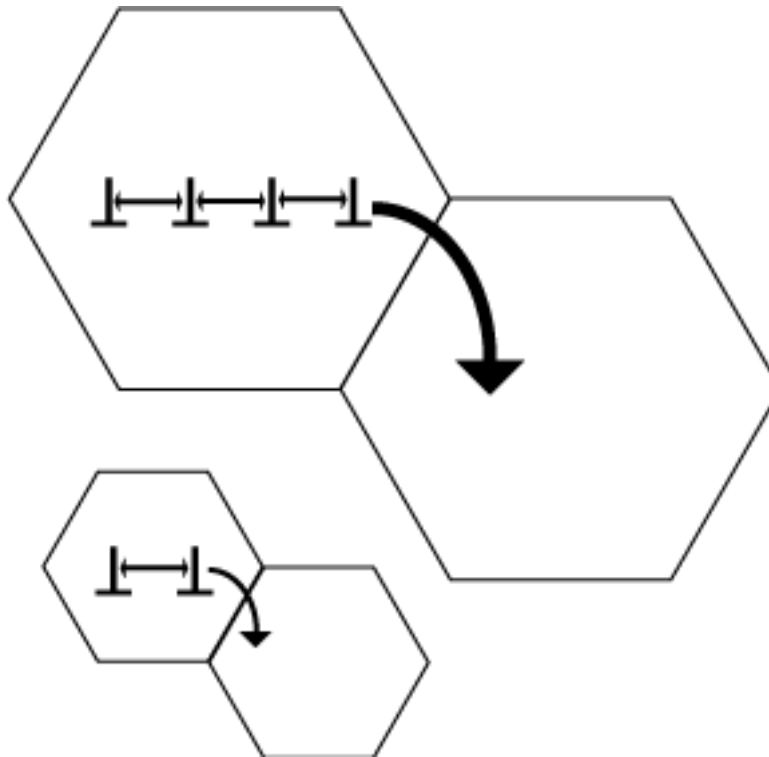


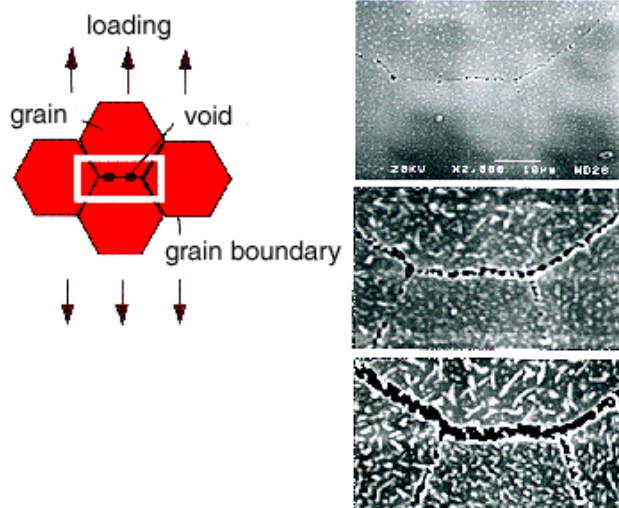
Figure 3: This is a schematic roughly illustrating the concept of dislocation pile up and how it effects the strength of the material. A material with larger grain size is able to have more dislocation to pile up leading to a bigger driving force for dislocations to move from one grain to another. Thus you will have to apply less force to move a dislocation from a larger than from a smaller grain, leading materials with smaller grains to exhibit higher yield stress.

The stress required to move a dislocation from one grain to another in order to plastically deform a material depends on the grain size. The average number of dislocations per grain decreases with average grain size (see Figure 3). A lower number of dislocations per grain results in a lower dislocation 'pressure' building up at grain boundaries. This makes it more difficult for dislocations to move into adjacent grains. This relationship is the Hall-Petch Relationship and can be mathematically described as follows:

$$\sigma_y = \sigma_{y,0} + \frac{k}{d^x}$$

Where k is a constant, d is the average grain diameter and $\sigma_{y,0}$ is the original yield stress.

The fact that the yield strength increases with decreasing grain size is accompanied by the caveat that the grain size cannot be decreased infinitely. As the grain size decreases, more free volume is generated resulting in lattice mismatch. However, below approximately 10 nm, the grain boundaries will tend to slide instead; a phenomenon known as grain-boundary sliding. If the grain size gets too small, it becomes more difficult to fit the dislocations in the grain and the stress required to move them is less. It was not possible to produce materials with grain sizes below 10 nm until recently, so the discovery that strength decreases below a critical grain size is still exciting.



Voids nucleated (top), grew (middle), and coalesced (bottom) along the grain boundary of Ni based alloy loaded at 800 degrees cent. Fine and coarse precipitates are visible in the grains.

Figure Sources: http://jolifukyu.tokai-sc.jaea.go.jp/fukyu/tayu/ACT96E/GIF/Z05_03.GIF

Hall-Petch Strengthening Limit

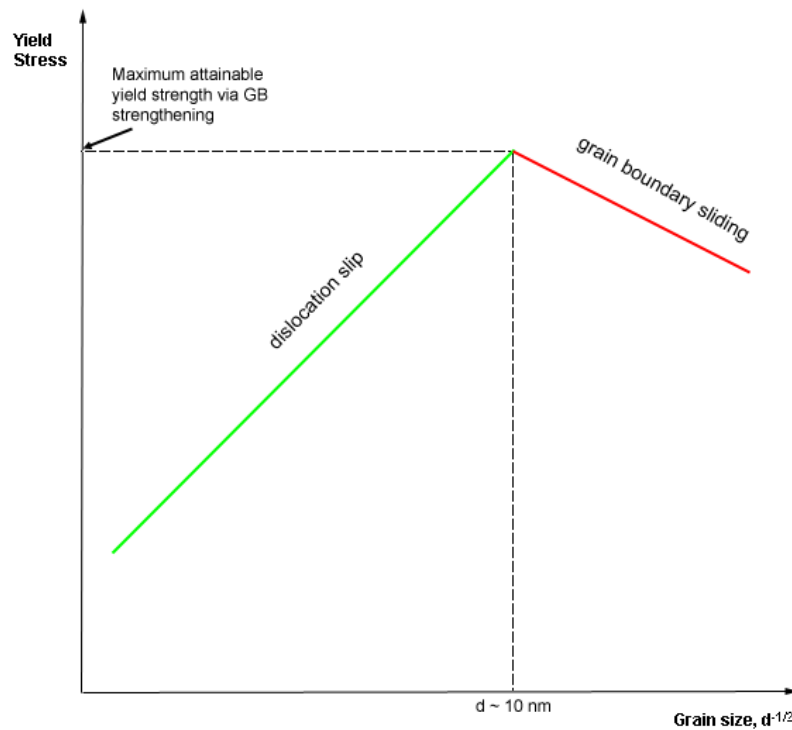


Figure Sources: http://www.ces.rwth-aachen.de/institutes-chairs/images/imm_1.jpg

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