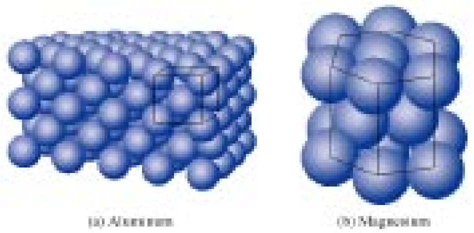
Iron and Steel

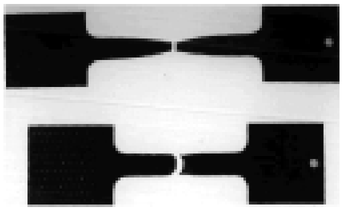
(Illustrations from JF Shackelford, *Introduction to Materials Science for Engineers, 4th ed.* , Prentice-Hall, 1996)

- **Structure of metals**

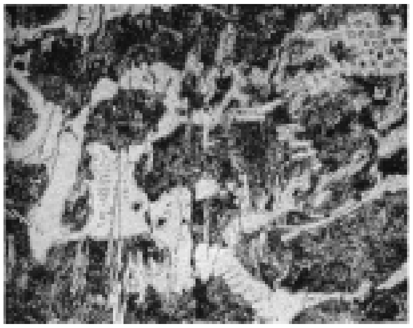


(a) Aluminum (b) Magnesium

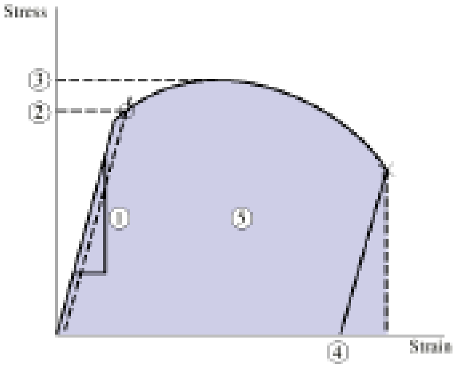
- **Plasticity and brittleness**



- **Cast iron**



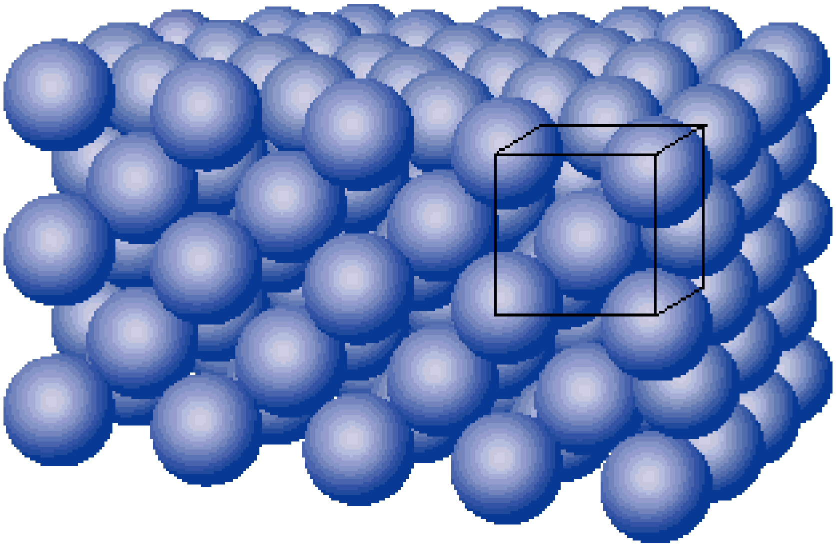
- **Steel**



Structure of Metals

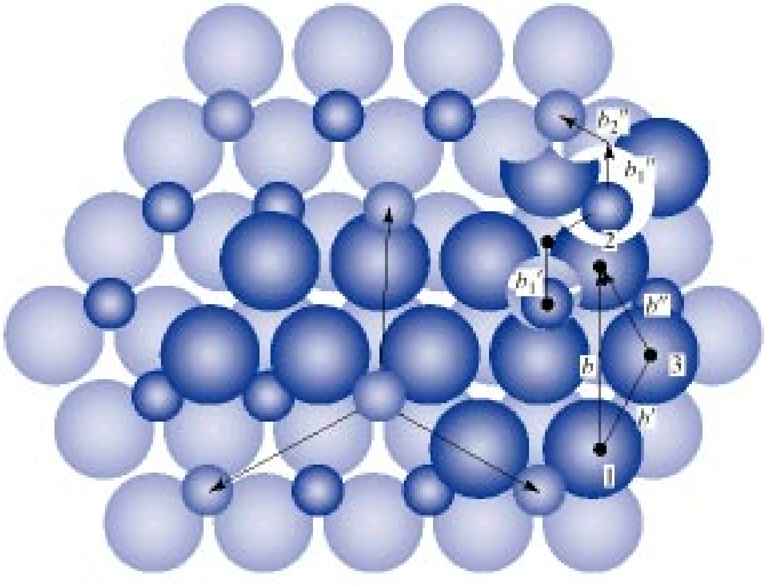
Pure metals have simple crystal structures, where the atoms pack together like ball bearings in a box.

Aluminum atoms pack into a cubic arrangement:



Since the atoms are closely packed, identical in size, and have no electrical charge, it is easy for one layer of atoms to slide over another. If a metal is stretched slightly, the atoms move apart but remain in their orderly arrangement. This is what happens when you slip a paper clip over a few sheets of paper: the coils of the clip move apart, but when the clip is removed from the paper, the coils snap back to their original position (and the atoms in the metal move back to their original positions). If the body returns to its original shape, then the previous deformation was *elastic*. However, when a large stress is applied to a pure metal, the atoms "slip". This is what happens if you bend a paper clip so much that it doesn't spring back. Such permanent deformation is called *plastic*, and it results from slip of atomic planes.

In contrast to metals, oxides are brittle. When aluminum reacts with oxygen, electrons are transferred from the aluminum atoms to the oxygen atoms, so aluminum oxide consists of positively charged aluminum ions and negatively charged oxygen ions. It is difficult for slip to occur in such a material, because the ions have different sizes and different charges. Since ions with the same charge repel one another, it takes a high stress to make one slide past the other. Slip in aluminum oxide follows a complicated path, as illustrated below:

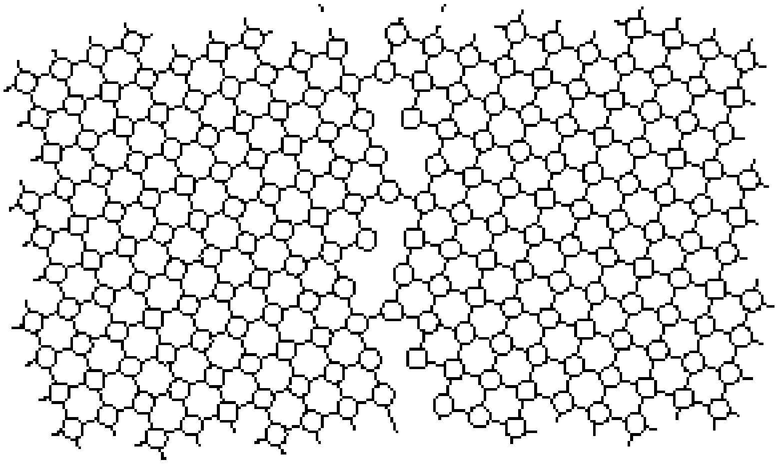


(The small spheres are aluminum and the large ones are oxygen.)

The material is more likely to crack than to perform such a complex dance, so oxides are *brittle*.

Anything that impedes slip of the atoms, such as imperfections in the crystal structure or a particle of some other material, increases brittleness.

A gem consists of a single crystal; that is, the whole object has ideal packing of the sort illustrated above (e.g., rubies are crystals of aluminum oxide with impurities that give color). Most common materials consist of many tiny crystals (called *grains*). For example, brass doorknobs develop a patchwork appearance after years of use, because the acid on people’s hands etches the boundaries between the crystals. The grains of brass are large enough to be seen by eye, but in many materials the grains are invisibly small. At the boundary between two grains, the crystal planes are not aligned:



This grain boundary is an obstacle to slip, so the smaller the grains, the harder it is for a material to deform plastically.

Probably the most important impediment to slip is a particle of another material (an *inclusion*) embedded within the metal. Sliding past such a thing is like ice-skating over pebbles.

In fact, pure metals are too soft (that is, they yield plastically at too low a stress), so for practical purposes it is desirable to have some grain boundaries and some inclusions to make the metal more rigid. The science of metallurgy provides a fundamental understanding of the factors controlling plasticity and strength of metals, allowing rational design of processing and alloying to achieve the desired properties.

Cast Iron

Iron is one of the most abundant elements, but it is not found in the earth as pure metal. The oxygen in the atmosphere guarantees that any metal that can oxidize (that is, almost anything but gold or platinum) will do so over geological time. Therefore, iron is found as an oxide, either ferric oxide (FeO), ferrous oxide (Fe_2O_3), or the magnetic oxide (Fe_3O_4), and is mixed with varying amounts of oxides of other metals. To convert it to metal, the oxygen must be removed by reaction with carbon at high temperatures:

$$Fe_2O_3 + 3C \rightarrow 2Fe + 3CO\uparrow$$

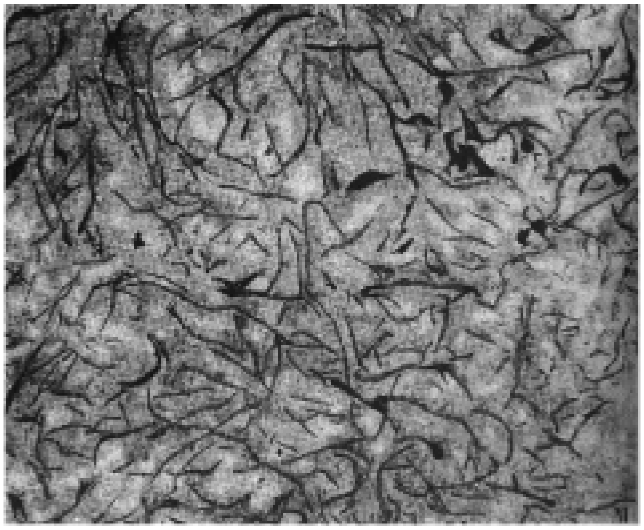
The vertical arrow indicates that carbon monoxide (CO) escapes as a gas. Four thousand years ago it was discovered that iron ore could be reduced to pure iron metal by heating it (without melting) over a charcoal fire. This material (*wrought iron*) could then be worked into shapes by hammering. The material is relatively soft and the production rate is slow. The blast furnace, invented in the 15th century, melted the ore in a charcoal fire; the metal would accumulate in the bottom of the furnace, where it was tapped and allowed to run into channels in a sandbed. (The sandbed was laid out in a comb pattern - a main channel with many perpendicular tributaries. The vague resemblance of this shape to a sow feeding her litter gave rise to the term *pig iron*.) The product of the blast furnace contains carbon dissolved in the iron, so it is much less pure than wrought iron, and is too brittle to be shaped by hammering. Its advantage is the economy of production and the ease of casting the material directly into the desired shape (hence the name *cast iron*).

In the ancient process the iron was not melted, so the carbon from the charcoal could not readily enter the iron, and the product

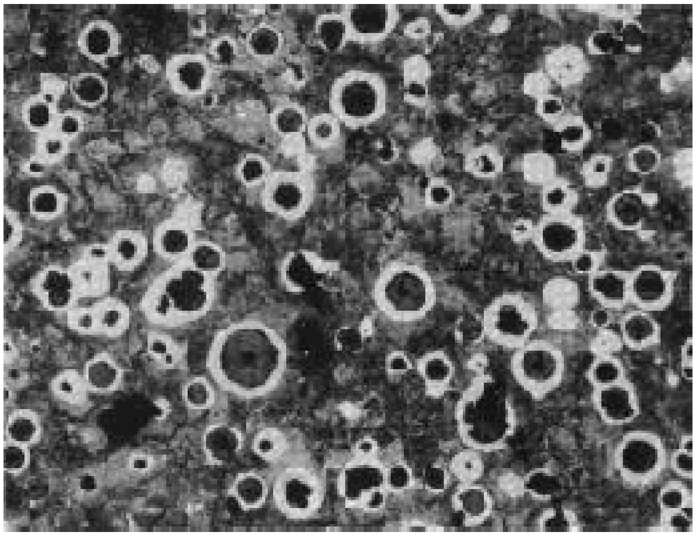
was a rather pure metal that was malleable (able to be shaped by hammering). The blast furnace reduces large quantities of iron ore at a high rate, but the carbon is able to dissolve in the liquid metal, and that leads to brittleness. One problem is the formation of a hard, brittle compound called *cementite*, whose composition is Fe_3C. This is the predominant material in *white cast iron*:

The bright regions in the photo are cementite in white cast iron. The width of this image is ~300 microns (~0.01inch).

If 2-3 % silicon is added to the melt, the result is *gray cast iron*, which contains flakes of graphite instead of cementite:

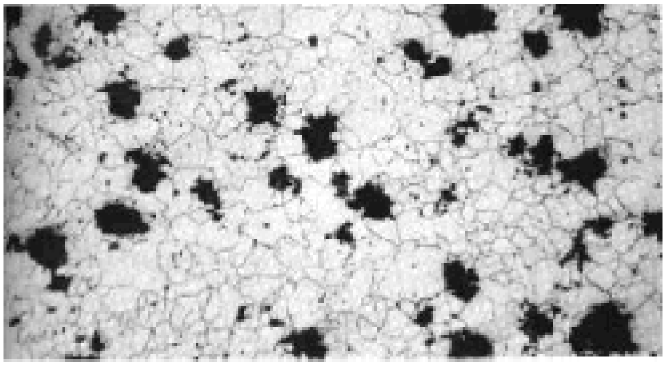


The graphite flakes are essentially cracks, so this material breaks under small stresses. If a small amount (~0.05%) of magnesium is added to white iron, it is converted to *ductile iron*, because the graphite is converted from flakes to balls:



The dark circles are spheres of graphite, and the bright rings around them contain pure iron. The remainder (gray background) consists of fine grains of iron and cementite. This material is ~20 times more ductile than gray iron.

Finally, if white iron is given a suitable heat treatment, the cementite grains convert to spheroidal graphite particles:

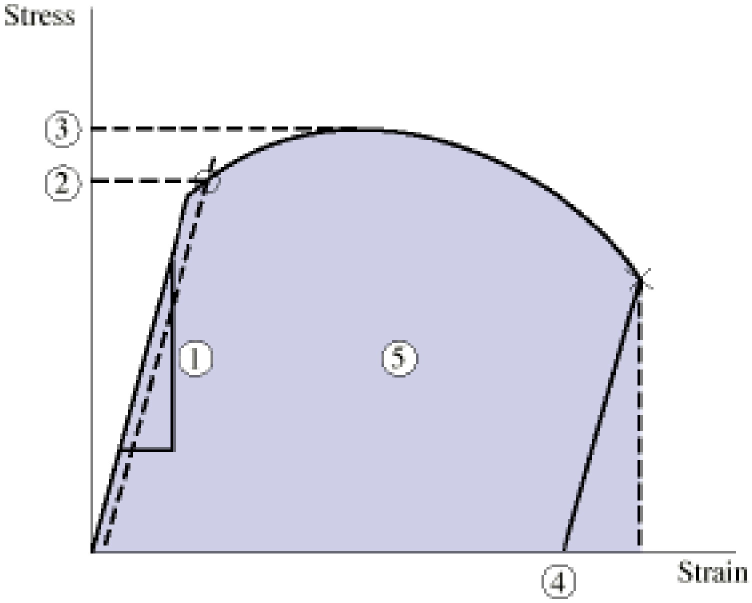


This material is called *malleable iron*, because it is much less brittle.

Steel

The distinction between cast iron and steel is that steel contains less than 2 % carbon by weight, while cast iron contains more. This dividing line is chosen because hot iron can fully dissolve up to 2% carbon to form a homogeneous solid solution called *austenite*. If cast iron is heated it does not form a solid solution; below the melting point it is always a mixture of solids, or a slurry of solid particles in a liquid. Consequently, the structure of cast iron is always coarse. In contrast, when austenite is cooled, the cementite can precipitate as extremely fine particles. If austenite is rapidly quenched from high temperature, the carbon can be prevented entirely from precipitating, which results in a very hard material called *martensite*. What is important about this is that one can work with a single material (say, iron containing 0.4% carbon) and control the heat treatment in such a way as to make the material very ductile and tough, or very hard or brittle.

The typical stress-strain behavior of steel is shown below:



In region 1, the strain (i.e., elongation) is proportional to the stress

(stretching force); that is, the steel behaves like a spring, stretching twice as much when the applied force is doubled. If the force is released in this region, the metal springs back to its original length. At point 2, called the *yield stress*, the atomic planes begin to slip and the metal exhibits plastic deformation. If the force is removed, the elastic part of the strain is recovered, but the slip is permanent, so the metal would contract along the dotted line if the stress were released at point 2. Cast iron would crack, rather than deforming plastically. This is very serious for a material used in construction, because there is no warning of an impending problem, just a sudden failure. In contrast, steel yields and stretches, which provides a warning that the stresses are excessive. At point 3 in the diagram, the metal has become unstable: stretching becomes concentrated in one region (called a *neck*):

Even at this stage, the material does not suddenly fail: it continues to stretch to the point marked X before breaking. If the load is removed before breaking, the elastic strain is recovered and the metal contracts along the dotted line to point 4. It is the toughness of steel - its resistance to sudden catastrophic failure - that makes it so useful.