Chapter 1

The Structure of Metals

QUALITATIVE PROBLEMS

1.15 What is the significance of the fact that some metals undergo allotropism?

Allotropism (also called polymorphism) means that a metal can change from one crystal structure to another. Since properties vary with crystal structures, allotropism is useful and essential in heat treating of metals to achieve desired properties (Chapter 4). A major application is hardening of steel, which involves the change in iron from the fcc structure to the bcc structure (see Fig. 1.4 on p. 49). By heating the steel to the fcc structure and quenching, it develops into martensite, which is a very hard, hence strong, structure.

1.16 Is it possible for two pieces of the same metal to have different recrystallization temperatures? Is it possible for recrystallization to take place in some regions of a part before it does other regions of the same part? Explain.

Two pieces of the same metal can have different recrystallization temperatures if the pieces have been cold worked to different amounts. The piece that was cold worked to a greater extent (higher strains), will have more internal energy (stored energy) to drive the recrystallization process, hence its recrystallization temperature will be lower. Recrystallization may also occur in some regions of the part before others if it has been unevenly strained (since varying amounts of cold work have different recrystallization temperatures), or if the part has different thicknesses in various sections. The thinner sections will heat up to the recrystallization temperature faster.

1.17 A cold-worked piece of metal has been recrystallized. When tested, it is found to be anisotropic. Explain the probable reason.

The anisotropy of the workpiece is likely due to preferred orientation remaining from the recrystallization process (see pp. 59-60). Copper is an example of a metal that has a very strong preferred orientation after annealing. Also, it has been shown that below a critical amount of plastic deformation, typically 5%, no recrystallization occurs.

1.18 Explain the advantages and limitations of cold, warm, and hot working, respectively.

As described in Section 1.7 on p. 60, cold working a metal results in higher strength, usually a smoother surface finish, and closer dimensional accuracy than hot working, but the ductility of the piece is lower. Hot working is accompanied by recrystallization of the deformed metal, which preserves the ductility of the workpiece; also, the stress required to deform the metal is lower. The workpiece, however, will have a rougher surface finish due to oxidation at higher temperatures, and the thermal expansion and contraction prevents achieving close dimensional control. Also, because of inherent limitations in bulk deformation processes, the desired shape may not be attainable in hot working. For example, hot-rolled foils are not routinely available. Warm working has advantages intermediate to both hot and cold working; the forces required are lower than cold working, and the dimensional accuracy and surface finish are better than for hot working.

1.19 Do you think that it might be important to know whether a raw material for a manufacturing process has anisotropic properties? What about anisotropy in the finished product? Explain.

Anisotropy is important in cold-working processes, especially sheet-metal forming where the material's properties should preferably be uniform in the plane of the sheet and stronger in the thickness direction. As shown in Section 16.7, these characteristics allow for deep drawing of parts (like beverage cans) without earing, tearing, or cracking in the forming operations involved. In a finished part, anisotropy is important so that the strongest direction of the part can be designed to support the largest load in service. Also, the efficiency of transformers can be improved by using a sheet steel with anisotropy that can reduce *magnetic hysteresis* losses. Hysteresis is well known in ferromagnetic materials. When an external magnetic field is applied to a ferromagnet, the ferromagnet absorbs some of the external field. When sheet steel is highly anisotropic, it contains small grains and a crystallographic orientation that is far more uniform than for isotropic materials, and this orientation will reduce magnetic hysteresis losses.

1.20 Explain why the strength of a polycrystalline metal at room temperature decreases as its grain size increases.

Strength increases as more entanglements of dislocations occur with grain boundaries (Section 1.3.2 on p. 54). Metals with larger grains have less grain-boundary area per unit volume, and hence will not be as able to generate as many entanglements at grain boundaries, thus the strength will be lower.

1.21 What is the significance of the fact that such metals as lead and tin have recrystallization temperatures at about room temperature?

Recrystallization around room temperature prevents these metals from work hardening when cold worked. This characteristic prevents their strengthening and hardening, thus requiring a recrystallization cycle to restore their ductility. This behavior is also useful in experimental verification of analytical results concerning force and energy requirements in metalworking processes (see Part III of the text).

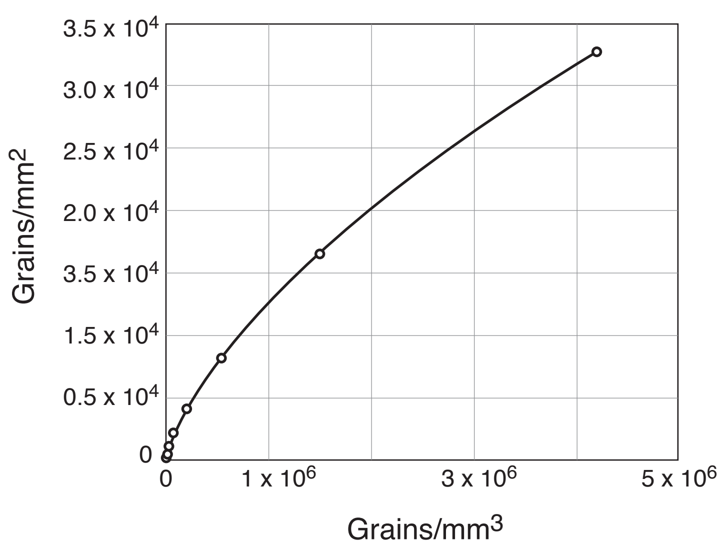
1.22 It has been noted that the more a metal has been cold worked, the less it strain hardens. Explain why.

This phenomenon can be observed in stress-strain curves, such as those shown in Figs. 2.2, 2.3, 2.5, and 2.7. Recall that the main effects of cold working are that grains become elongated and that the average grain size becomes smaller (as grains break down) with strain. Strain hardening occurs when dislocations interfere with each other and with grain boundaries. When a metal is annealed, the grains are large, and a small strain results in grains moving relatively easily at first, but they increasingly interfere with each other as strain increases. This explains that there is strain hardening for annealed materials at low strain. To understand why there is less strain hardening at higher levels of cold work, consider the extreme case of a very highly cold-worked material, with very small grains and very many dislocations that already interfere with each other. For this highly cold-worked material, the stress cannot be increased much more with strain, because the dislocations have nowhere else to go - they already interfere with each other and are pinned at grain boundaries.

QUANTITATIVE PROBLEMS

1.23 Plot the data given in Table 1.1 in terms of grains/mm^2 vs. grains/mm^3, and state your observations.

The plot is shown below. It can be seen that the grains per cubic millimeter increases faster than the grains per square millimeter. This relationship is to be expected since the volume of an equiaxed grain depends on the diameter cubed, whereas its area depends on the diameter squared.



1.24 By cold working, a strip of metal is reduced from 40 mm in thickness to 20 mm. A similar strip is reduced in a similar way from 40 mm to 30 mm. Which one of these cold-worked strips will recrystallize at a lower temperature? Why?

The first strip undergoes a reduction of (40-20)/40=0.5, or 50% in thickness, while the second strip undergoes a reduction of (40-30)/40=0.25, or 25% reduction. Since the first strip has undergone a higher amount of cold work, it will recrystallize at a lower temperature. The extra cold work adds stored energy in the form of dislocations to the strip, hence the energy needed for recrystallization (in the form of thermal energy) is reduced.

1.25 A paper clip is made of wire that is 5 in. long and 1/32-in. in diameter. If the ASTM grain size is 9, how many grains are there in the paper clip?

From Table 1.1 on p. 55, we find that a metal with an ASTM grain size of 9 has about 185,000 grains/mm^3. The volume of the paper clip is

$$V = \frac{\pi}{4}\left(\frac{1}{32}\text{ in.}\right)^2 (5\text{ in.}) = 0.00383\text{ in}^3$$

Converting this to cubic millimeters gives a volume of 62.8 mm^3. Multiplying the volume by the grains per millimeter cube gives the number of grains in the paper clip as about 11.6 million.

1.26 How many atoms are on the surface of the head of a pin? Assume the head of a pin is spherical with a 1 mm diameter and has an ASTM grain size of 2.

If a pin has a spherical head with a diameter of 1 mm, then its surface area is

$$A = \pi d^2 = \pi\text{ mm}^2 = \pi \times 10^{-6}\text{ m}^2$$

Note from Table 1.1 on p. 55 that for ASTM grain size of 2, there are 32 grains per square millimeter. Therefore, we expect that there will be $\pi(32)$=100 grains on the head of a pin. The number of atoms depends on the particular material used, but let's assume we have a steel pin. The diameter of an iron atom is 2.5 angstroms, so this is the value that will be used. The number of atoms actually on the surface will depend on how well the atoms are packed, but an estimate can be made by assuming that one-half the area of an atom is on the surface, so that the area per atom is

$$A_{\text{atom}} = \frac{1}{2}\pi d^2 = \frac{1}{2}\pi\left(2.5 \times 10^{-10}\text{ m}\right)^2 = 6.283 \times 10^{-20}\text{ m}^2$$

Therefore the number of atoms is

$$n = \frac{3.1415 \times 10^{-6}}{6.283 \times 10^{-20}} = 5 \times 10^{13}\text{ atoms}$$

1.27 A technician determines that the grain size of a certain etched specimen is 8. Upon further checking, it is found that the magnification used was 180x instead of the 100x that is required by the ASTM standards. Determine the correct grain size.

If the grain size is 8, then there are 2048 grains per square millimeter (see Table 1.1 on p. 55). However, the magnification was too large, meaning that too small of an area was examined. For a magnification of 100×, the area is reduced by a factor of 1/1.82=0.309. Therefore, there really are 632 grains per mm^2, which corresponds to a grain size between 6 and 7.

1.28 If the diameter of the aluminum atom is 0.5 nm, how many atoms are there in a grain with ASTM grain size 5?

If the grain size is 5, there are 2900 grains per cubic millimeter of aluminum. Each grain has a volume of $1/2900 = 3.45 \times 10^{-4}$ mm^3. Note that for an fcc material there are four atoms per unit cell, with a total volume of $16\pi R^3/3$, and that the diagonal, a, of the unit cell is given by

$$a = \left(2\sqrt{2}\right) R$$

Hence,

$$\text{APF}_{\text{fcc}} = \frac{(16\pi R^3/3)}{\left(2R\sqrt{2}\right)^3} = 0.74$$

Note that as long as all the atoms in the unit cell have the same size, the atomic packing factors do not depend on the atomic radius. Therefore, the volume of the grain which is taken up by atoms is $(3.45 \times 10^{-4})(0.74) = 2.55 \times 10^{-4}$ mm^3. (Recall that 1 mm=10^6 nm.) If the diameter of an aluminum atom is 0.5 nm, then its radius is 0.25 nm or 0.25×10^{-6} mm. The volume of an aluminum atom is then $V = 4\pi R^3/3 = 4\pi(0.25 \times 10^{-6})^3/3 = 6.54x10-20$ mm^3. Dividing the volume of aluminum in the grain by the volume of an aluminum atom yields the total number of atoms in the grain as $(2.55 \times 10^{-4})/(6.54 \times 10^{-20}) = 3.90 \times 10^{15}$.

SYNTHESIS, DESIGN, AND PROJECTS

1.29 By stretching a thin strip of polished metal (as in a tension-testing machine) demonstrate and comment on what happens to its reflectivity as it is stretched.

The polished surface is initially smooth, which allows light to be reflected uniformly across the surface. As the metal is stretched, the reflective surface of the polished sheet metal will begin to become dull. The slip and twin bands developed at the surface cause roughening (see Fig. 1.7), which tends to scatter the reflected light.

1.30 Draw some analogies to mechanical fibering (for example, layers of thin dough sprinkled with flour or butter between each layer).

By the student. A wide variety of acceptable answers are possible based on the student's experience and creativity. Some examples of mechanical fibering include: (a) food products such as lasagna, where layers of noodles bound sauce, or pastries with many thin layers, such as baklava; (b) log cabins, where tree trunks are oriented to construct walls and then sealed with a matrix; and (c) straw-reinforced mud.