

**MATERIALS OF
ENGINEERING**

CARL A. KEYSER

MATERIALS OF ENGINEERING

Properties, Fabrication, Uses, and Testing

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MATERIALS
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To Dot, Aunt M, and the boys.

Preface

This book has been written to serve all persons interested in the properties, fabrication, uses, and testing of basic engineering materials.

It is divided into three parts. Part I consists of Chapters 1 through 12 and deals with metallic materials. Part II consists of Chapters 13 through 15 and covers inorganic nonmetallic materials. Part III consists of Chapters 16 through 19 and is concerned with organic substances which are, of course, nonmetallic materials.

The author wishes to express his appreciation to the staff of the School of Engineering, University of Massachusetts, for their suggestions, interest, and encouragement; to the many companies who supplied illustrations and other information; and to his students who by their questions aided in the crystallization of the thoughts expressed herein.

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Amherst, Massachusetts

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PART I

Metallic Materials

CHAPTER 1

Fundamentals of Metal Structure

1.1 Submicroscopic Structure of Metals. The submicroscopic structure of metals has been determined largely by x-ray diffraction, electron diffraction, and electron microscopy. (1.1), (1.2), (1.3), (1.4), and (1.5)¹ These studies have shown that solid metals consist of basic blocks known as **unit cells**. The unit cell is the smallest subdivision of metal in which there is an orderly arrangement or spacing between similar adjoining atoms. This orderly arrangement characterizing unit cells is repeated over and over in space in all directions and is typical of all crystalline substances. Metals, then, are crystalline substances, and crystals are characterized by an orderly rather than random array of atoms. The opposite of crystalline is **amorphous**. Amorphous materials are characterized by a relatively disordered and random spacing of atoms.

Only three kinds of unit cells are necessary to describe the submicroscopic structure of most, but not all, solid metals. These unit cells are shown in Fig. 1.1. They are known as body-centered cubic, face-centered cubic, and hexagonal close-packed, abbreviated respectively **BCC**, **FCC**, and **HCP**. Crystals of metals consist of many millions of unit cells arranged like neatly stacked building blocks. Similar or corresponding faces of any two unit cells in a single, perfect (rare) crystal are parallel to one another, as shown in Fig. 1.2(a).

Some metals exist in more than one crystal form. For instance, pure iron has a body-centered cubic structure up to 1670°F (910°C). Between 1670°F and 2552°F (1400°C) iron has a face-centered cubic structure. Such a change from one crystalline form to another is known as an allotropic change.

Metals encountered in everyday living are called **polycrystalline** since they contain many crystals or grains (as the crystals are called in this case). Within each grain of polycrystalline metal the identical faces of

¹ *Italicized* numbers in parentheses refer to the bibliography at the end of each chapter.

all unit cells are parallel, but the identical faces of unit cells in adjoining grains are not parallel. This cannot readily be shown in a three-dimensional drawing but has been represented in a two-dimensional sketch, Fig. 1.2(b). Note how the atomic spacing of the unit cells is altered where adjoining crystals meet. This region of relative disorder, known as the **grain boundary**, possesses properties different from those

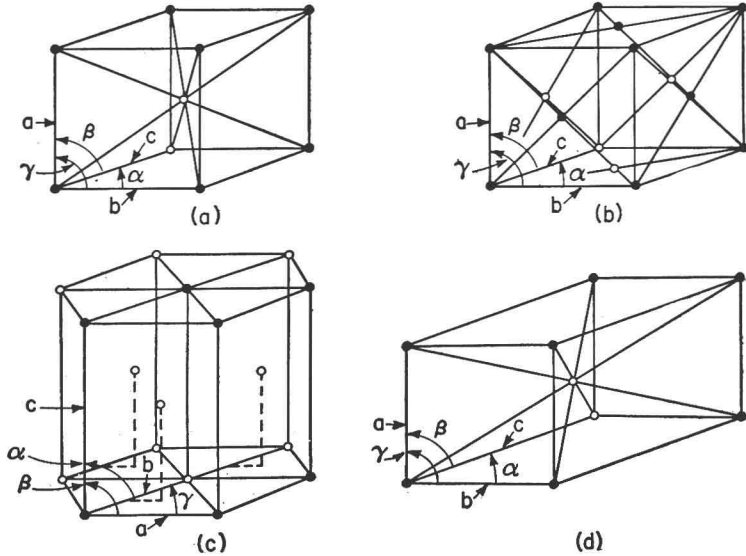


Fig. 1.1. Unit cells of the common metals. The sides of the unit cells are assigned the letters a , b , and c ; corresponding angles opposite the sides are called α , β , and γ . (a) Body-centered cubic: $a = b = c$, and $\alpha = \beta = \gamma = 90^\circ$. Ex: α — Fe, Mo, W. (b) Face-centered cubic: $a = b = c$, and $\alpha = \beta = \gamma = 90^\circ$. Ex: γ — Fe, Al, Cu, Ni. (c) Hexagonal close-packed: $a = b \neq c$, and $\alpha = \beta = 90^\circ$, $\gamma = 120^\circ$. Ex: Mg, Zn. (d) Body-centered tetragonal: $a = b \neq c$, and $\alpha = \beta = \gamma = 90^\circ$. Ex: γ — Mn, β — Sn.

of the grain center. The crystals or grains found in polycrystalline metals are often spoken of as **crystallites**. A fine-grained metal is one in which the crystallites are smaller and the proportion of grain boundary material is higher than in a coarse-grained metal.

1.2 Metallic Crystal Binding. Although unit cells have been described as regular and orderly arrangements of atoms, the statement is not, strictly speaking, accurate. Actually, in solid metals, atoms are not believed to exist as such, but, rather, are present as ions floating in a “sea” of valence electrons. The term **metallic crystal binding** refers to

the forces which are acting to position the ions in the unit cell. The positions which the ions assume depend upon the establishment of equilibrium between all the forces involved. Similar electric charges on each ion tend to establish repellant forces between any pair of ions. For the same reason the electrons maintain a fairly uniform distribution in the electron "sea." There are also forces of attraction between the

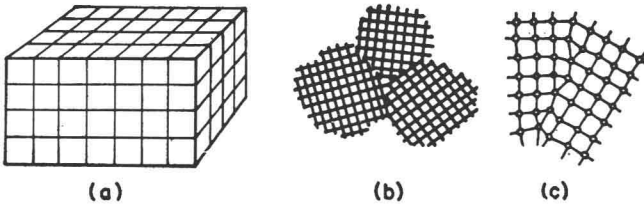


Fig. 1.2. Submicroscopic structure of metal. (a) A single crystal, showing how the unit cells are arranged like building blocks. (b) A two-dimensional sketch, showing three grains meeting at a point. (c) The point of intersection, magnified to show distribution of the unit cells at the grain boundary.

ions (carrying positive charges) and the electrons (carrying negative charges). There are also relatively weak forces of gravitational attraction between the ions. It will be recalled that gravitational attraction between two bodies varies directly as the product of the masses and inversely as the square of the distance between them. Although the mass of the ion is small, being approximately equal to the atomic mass divided by Avogadro's number (10^{23}), the distance between ions is also extremely small, being of the order of magnitude of about two Angstrom units (abbreviated 2\AA) which is equal to 2×10^{-8} cm. The gravitational forces are much less significant than the electrical forces. A description of other types of binding forces encountered in nonmetallic crystals is given in references (1.1) and (1.6).

1.3 Anisotropy. When measured in directions differing with respect to the crystal axes, the properties of metal single crystals vary. Measurements made in directions parallel to one another give the same results. The directionality of properties is known as **anisotropy**. Anisotropy is probably associated with similarity of ionic spacing in similar crystallographic directions and differences in spacing in unlike directions. Anisotropy applies to mechanical, physical, and chemical properties such as strength, electric resistance, thermal conductivity, and resistance