

MANUFACTURING SCIENCE

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Preface

The conventional treatment of manufacturing processes mainly emphasizes the operational procedures. This study, on the other hand, seeks to highlight the basic scientific principles, the stress being on how things are made. Such an approach would, hopefully, make the reader appreciate the reasons why things are made the way they are and the possibilities of improving upon given methods.

Material properties play a key role in manufacturing processes. This volume therefore starts with a discussion on these properties. This is followed by a detailed analysis of the various processes, namely, casting, forming, machining, and joining. Also, the unconventional processes, so essential in a modern text, have been included. For a better understanding of the theory, a large number of worked-out problems, supplemented by about the same number of exercises, are given. Because of space constraints, some topics, e.g., processing of polymers and particulate processes, have not been covered.

The text uses SI units and is addressed primarily to the undergraduate in mechanical engineering. It should also be of value to the graduate as well as to the practising engineer.

We wish to gratefully acknowledge the generous financial support we obtained from the Quality Improvement Programme established by the Ministry of Education and Culture at the Indian Institute of Technology, Kanpur, for the preparation of the manuscript. Also, we are indebted to Dr. B.N. Bannerjee for making valuable suggestions. Finally, our sincere thanks are due to V. Raghuram, J.D. Verma, J.P. Gupta, P.P. Singh, and M.M. Singh for their cooperation and help at various stages of this work.

Despite careful scrutiny, some errors are likely to have remained in the text. We shall therefore be happy to receive corrections as also suggestions for improvement and constructive criticism.

Amitabha Ghosh
Asok Kumar Mallik

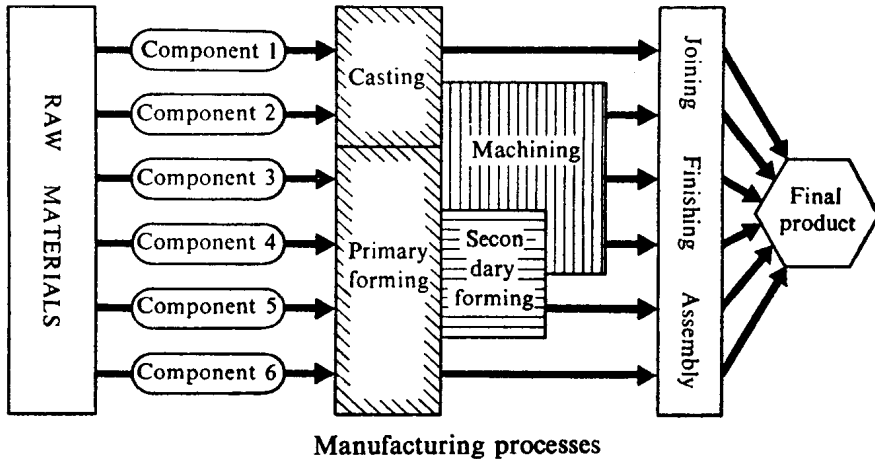
Introduction

Since the beginning of civilization, man has been continuously engaged in converting the natural resources into useful products. The entire discipline of engineering is mainly concerned with this. Of all the subdisciplines of engineering, manufacturing is perhaps most important because it involves the conversion of raw material into final product.

Industrial revolution was a major corner-stone in human history in that it set in motion the battle for abundance. The world today is totally dependent on science and technology and the nations are classified now according to their degree of industrialization. Since manufacturing plays a key role in extracting wealth from the mother Earth, it is quite easy to realize the importance of the subject which deals with this activity. In spite of this, manufacturing engineering has received very little attention from scientists and engineers. This is probably due to the thumb-rule nature of the manufacturing activity and its heavy dependence on empirical relations, experience, and trial-and-error methods. But no branch of science and technology can progress fast enough with trial-and-error methods and thumb rules. Throughout the world market today, there is a continuous struggle for cheaper production with better quality. This can be achieved only through optimal utilization of both material and human resources. Apart from this, with the advancement in technology, the manufacturing engineers are facing challenging problems requiring development of newer and better methods of production. The required rate of growth in manufacturing cannot be achieved through trial and error and a scientific approach is necessary. This has attracted the scientists and engineers and *manufacturing*, which was an art, has become a science.

The conversion of resources into raw materials is normally taken care of by two subdisciplines of engineering—mining and metallurgy. The real shaping starts from the stage a material is available in raw form. Changing a raw material into a final product generally involves various processes

(see figure). The major processes a component undergoes before being converted into a final product are (i) casting, (ii) primary and secondary forming, (iii) machining, and (iv) joining, assembly, and finishing. A material is often subjected to primary forming for producing standard shapes such as those of rods, bars, and sheets. However, it may also undergo secondary forming, and this is performed when the objective is to obtain a shape other than the standard shapes.



The three engineering activities that require an understanding of the manufacturing processes are designing, production, and development of new techniques. At the design stage, manufacturing considerations have to be taken into account not only for producing the part in the most economic manner but also for imparting to the part some required properties such as strength and hardness. Further, in a production shop, a successful engineer must have a thorough understanding of the subject if he has to select and implement the right processes. The selection of the important process parameters is extremely important to achieve success in manufacturing. The third type of activity is development of new manufacturing processes and modification of the existing technology. It has already been mentioned that the production engineers are encountering more and more challenging problems, and often such problems cannot be solved with the help of existing conventional methods. Thus, a host of new processes has been evolved during the past two decades; this group of manufacturing processes is generally known as *unconventional processes* or *new technology*.

Unlike the fundamental subjects in science and engineering, the subject dealing with the manufacturing processes is interdisciplinary in nature. Obviously, therefore, understanding the science underlying the processes is not simple since, generally, the situations are not idealistic. However, many important generalized conclusions can be drawn with the help of simple models. The same information would otherwise require a large number of experiments or long experience.

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1 Manufacturing Properties of Materials

1.1 STRUCTURE OF MATTER

The properties of a material are intimately connected to its basic molecular structure. Some knowledge of this structure is therefore essential for understanding the various macroscopic properties exhibited by the material. A general characteristic of all solids is their capability to retain definite shapes, and so we start from the mechanics of bonding between the molecules forming a solid.

1.1.1 BONDING OF SOLIDS

When two atoms are sufficiently close to each other, the outer electrons are shared by both the nuclei. This results in an attractive force between the two atoms. This force increases with the decrease in distance between the two atoms, as shown in Fig. 1.1. However, the two atoms do not collapse as a repulsive force is generated when the two nuclei come very close. This

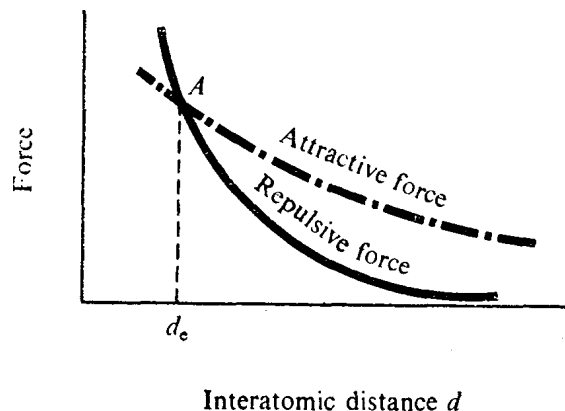


Fig. 1.1 Force between two atoms.

repulsive force increases rapidly with decreasing interatomic distance. The equilibrium interatomic distance d_e is that distance when the attractive and the repulsive forces are equal in magnitude (Fig. 1.1). The slope of the repulsive force curve is always more than that of the attractive force curve at the point of intersection A of the curves. Therefore, the equilibrium is of stable nature.

The mechanism we have discussed is one of the various possible interactions resulting in bonding between atoms, and is known as *covalent bonding*. In a given solid, one or more bonding mechanisms can be simultaneously operative. The nature of a bonding mechanism depends on the electronic structure of the atoms involved. The bonding mechanisms predominant in solids include *metallic bonding* (in metals) and the *van der Waals bonding* (in molecular crystals). In a metal, a large number of free electrons are present, resulting in the formation of a common electron cloud; the rest of the system consists of positively-charged ions which are held together by the cloud (Fig. 1.2a). The mechanism of bonding in alloys is similar. Since the inert atoms do not possess free electrons, the metallic bonding mechanism cannot be operative. In such instances, however, a very weak short range attraction is generated due to the van der Waals force. The origin of this force is attributed to a rapidly-fluctuating dipole moment.

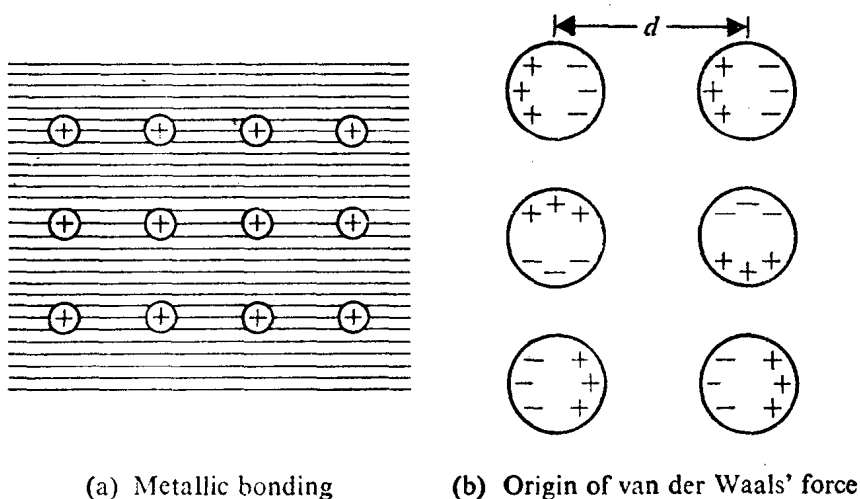


Fig. 1.2 Bonding mechanisms.

Figure 1.2b shows two molecules at a distance d , each of which has a symmetric charge distribution. All the three different overall configurations of the charge distributions, shown in the figure, lead to the development of an attractive force though individually the molecules are neutral. This force is inversely proportional to d^4 and is called *van der Waals' force*. This type of bonding is very weak and is active in weak and low melting point materials such as paraffin and plastics. It is obvious that the strength of the bond controls the properties, e.g., melting point, of a material.

1.1.2 CRYSTAL STRUCTURE

The properties of a material depend not only on the bond strength but also on the arrangement of the atoms. In all metals and in many nonmetallic solids, the atoms are arranged in a well-ordered pattern. Such solids are

commonly called *crystalline solids*. Of course, in a large number of situations, the whole solid is seldom composed of one single crystal. Instead, a very large number of small, randomly-oriented crystalline grains form the whole solid. Such materials are termed *polycrystalline*. Figures 1.3a and 1.3b show a single-crystal and a polycrystalline solid, respectively.

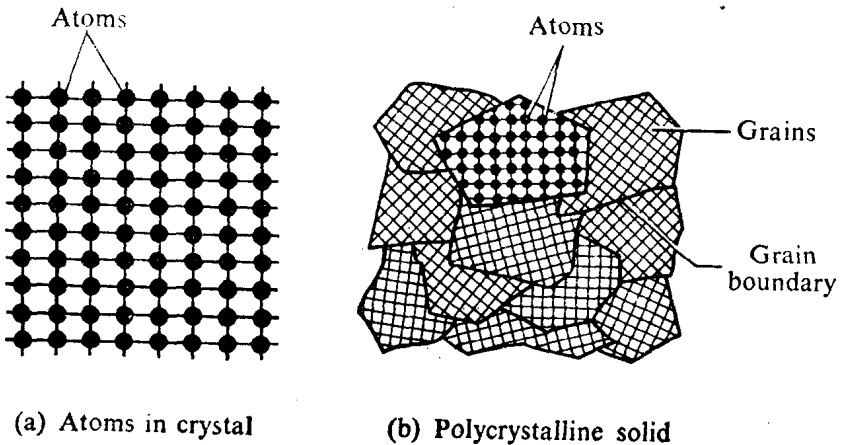


Fig. 1.3 Structure of crystals and polycrystalline solids.

In a crystal, we can identify the unit cell the repetition of which forms the whole crystal. The structure of a crystal is identified and described by this unit cell. The three commonly-observed crystal structures in metals are shown in Fig. 1.4. Of these three basic structures, the fcc and the cph crystals have the most dense packing. The interatomic distance in such

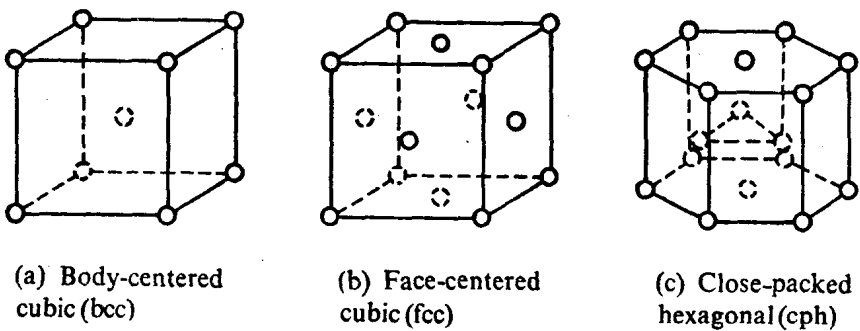


Fig. 1.4 Some common unit cells.

crystals is of the order of 10^{-7} mm. The crystal structures of some common metals are given in Table 1.1.

When a liquid metal solidifies by cooling, the atoms arrange themselves in regular space lattices, forming a crystal. The crystallization starts simultaneously at various places within the liquid mass. Figure 1.5 shows the

Table 1.1 Crystal structure of some common metals

bcc	fcc	cph
Chromium	Aluminium	Titanium
Tungsten	Copper	Zinc
Vanadium	Lead	Zirconium
Molybdenum	Nickel	Magnesium
Iron (except in temperature range 910–1400°C)	Silver	Cobalt
	Iron (910–1400°C)	

growth of the crystal grains and the ultimate formation of the polycrystalline metal. Most metals have only one crystal structure. A few metals, however, can have more than one type of crystal structure. Such metals are called allotropic. Table 1.1 indicates that iron is an allotropic metal.

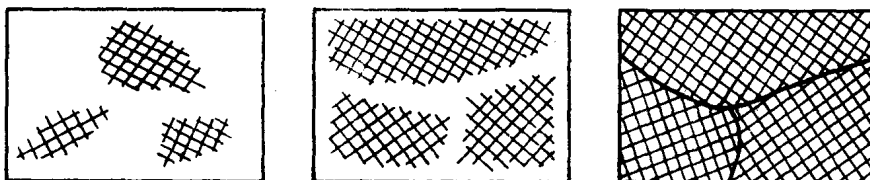


Fig. 1.5 Formation of grains and grain boundaries during solidification.

A number of material properties, in general, can be associated with the type of crystal structure. For example, the bcc structures are usually harder, whereas the fcc structures are more ductile. In cph structures, the ductility is low.

1.1.3 CRYSTAL IMPERFECTIONS

We noted in Section 1.1.2 that some properties of a crystalline solid depend on the basic crystal structure of the solid. However, in almost all instances, the crystals are not perfect, i.e., the lattices are not without imperfections. These imperfections govern most of the mechanical properties of crystalline solids (see Table 1.2). The study of the crystal imperfections and their effects on the properties of a material is a subject by itself. In our discussion therefore, we shall give only those concepts that will be required for an understanding of the various phenomena associated with different processes, e.g., plastic deformation and heat treatment.

Table 1.2 Properties dependent on crystal structure and defect

Property dependent on basic crystal structure	Property dependent on crystal imperfection
Density	Electrical conductivity
Specific heat	Yield stress
Coefficient of thermal expansion	Creep
Melting point	Fracture strength
Elastic constants	Semiconductivity
Hardness and ductility	Work hardening
	Fatigue strength

The imperfections in a crystal lattice structure can be classified as follows:

(i) If an imperfection is restricted to the neighbourhood of a lattice point, the imperfection is referred to as a *point defect*. This type of imperfection can be due to various reasons. Figure 1.6 illustrates the three different types of point defects. In Fig. 1.6a, one lattice atom is missing, creating a *vacancy*.

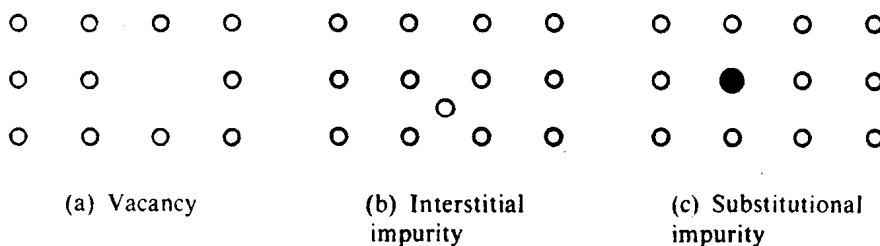


Fig. 1.6 Types of point defects.

Since an atom vibrates about its lattice position, the tendency of the atom to jump out of its regular position creating a vacancy increases rapidly with its energy, i.e., the temperature. For example, the usual order of vacancy at 500°C is one in 10^{10} which increases to one in 300 at 2000°C. It is possible to increase the vacancy density at a given temperature by rapid cooling or extensive plastic deformation. In Fig. 1.6b, an atom is occupying an abnormal position. Such an atom is called an *interstitial impurity atom*. An interstitial impurity can be caused when an atom possesses large enough thermal energy or when its energy is increased by nuclear bombardment. In Fig. 1.6c, a regular lattice position is occupied by an atom of a different material.

(ii) If an imperfection extending along a line has a length much larger than the lattice spacing, the imperfection is called a *line defect* or, commonly, a *dislocation*. Two common, simple types of dislocations are illustrated in Fig. 1.7. When an extra half-plane of atoms is accommodated by distorting the regular lattice arrangement (as done with the XX' half-plane in