Fundamentals of Mechanical Engineering and Automation

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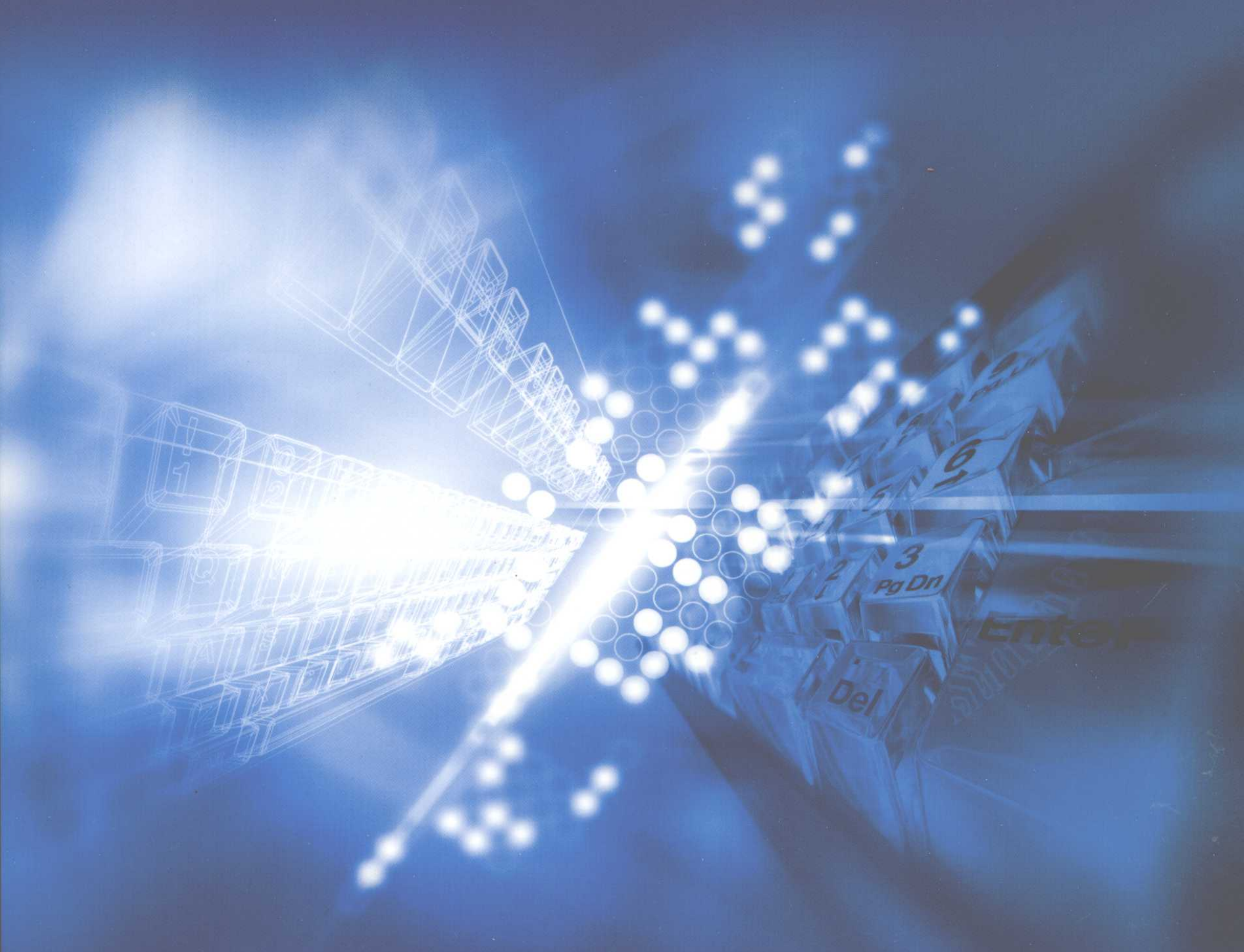
机械工程及自动化基础（英文版）

陈　飞　张永忠　编



中国矿业大学出版社
China University of Mining and Technoiogy Press

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内 容 提 要

本书介绍了机械工程及自动化的基础知识，另外，增加了关于矿山机械的内容。全书共分6章，分别为工程材料、机械设计、制造技术、自动控制、机电一体化和矿山机械等内容。

本书可作为机械工程及自动化专业的专业英语教材，也可供相关专业的技术人员参考使用。

图书在版编目(CIP)数据

机械工程及自动化基础＝Fundamentals of Mechanical Engineering and Automation：英文/陈飞，张永忠编.徐州：中国矿业大学出版社，2007.4

（应用型本科教材系列）

ISBN 978-7-81107-616-5

Ⅰ.机… Ⅱ.①陈…②张… Ⅲ.①机械工程—高等学校—教材—英文②自动化技术—高等学校—教材—英文 Ⅳ.TH TP2

中国版本图书馆CIP数据核字(2007)第052815号

书　　名　机械工程及自动化基础（英文版）
编　　者　陈　飞　张永忠
责任编辑　万士才　张怡菲
责任校对　晓　新
出版发行　中国矿业大学出版社
（江苏省徐州市中国矿业大学内　邮编 221008）
网　　址　http://www.cumtp.com　**E-mail**　cumtpvip@cumtp.com
排　　版　中国矿业大学出版社排版中心
印　　刷　徐州中矿大印发科技有限公司
经　　销　新华书店
开　　本　787×1092 1/16　**印张** 11.25　**字数** 280千字
版次印次　2007年4月第1版　2007年4月第1次印刷
定　　价　21.00元
（图书出现印装质量问题，本社负责调换）

应用型本科教材编写委员会

CONTENTS

PART ONE Materials of Engineering.

1.1 Introduction

Today' s engineers have a vast range, comprising of several thousand materials available to them. Some of these, timbers, stone and clay products, some cast irons and copper alloys have been in use as constructional materials for centuries. At the other hand of the scale, many polymers, high temperature superalloys, industrial ceramics and fibre reinforced composite materials have come into use in recent decades, while other materials of great potential interest, including new alloy compositions, new polymers, metallic glasses and metal-matrix composites are currently in the development stage. Running parallel to the invention of new and improved materials there have been equally important developments in materials processing including vacuum melting and casting, new moulding techniques for polymers, ceramics and composites, and new joining technologies.

In addition to the need for an increased knowledge of materials and processing technology, other challenges are having to be met by our design engineers. In earlier times, with a much smaller number of materials available, engineers often produced their designs and products by a process of trial and error, in many cases using far more material than was really necessary. Today there is a requirement to use materials more effectively and efficiently in order to manufacture quality products which can compete in world markets and to minimize cost. Also, the advent of product liability legislation places an increased burden on design and materials engineers and they now need to foresee and cater for possible misuse of the product in addition to normal usage by customers. For example, the materials and corrosion protection treatments specified and used in the production of a small car may be adequate for the normal user but a few vehicles may be purchased by inshore fishermen who will leave them for long periods on quaysides exposed to salt water spray.

There is a complex inter-dependence between design, material and manufacture, and the design engineer, material engineer and manufacture engineer need to function as a close-knit team. Many factors have to be considered when selecting possible material to fit a design and manufacturing requirement.

Does the material possess the necessary mechanical, electrical and thermal properties?

Can the material be formed to the desired shape?

Will the properties of the material alter with time during service?

Will the material be adversely affected by the environmental conditions and resist corrosion and other forms of attack?

Will the material be acceptable on aesthetic grounds?

Will the material give sufficient degree of reliability and quality?

Can the product be made at an acceptable cost?

1.2 The range of material

The complete range of material can be classified into the categories: metals, polymers, ceramics, inorganic glasses, composites.

The classification, composites, contains materials with constituents from any two of the first three categories, for example, fibre reinforced polymers. A broad comparison of the properties of metals, ceramics and polymers is given in Table 1. 1.

Table 1. 1 Comparison of properties of metals, ceramics and polymers

Property	metals	ceramics	polymers
Density ($\times 10^{-3}$kg/m^3)	2～16(average 8)	2～17(average 5)	1～2
Melting point	Low to high Sn 232 ℃, W 3,400 ℃	High, up to 4,000 ℃	Low
Hardness	Medium	High	Low
Machineability	Good	Poor	Good
Tensile strength (MPa)	Up to 2,500	Up to 400	Up to 120
Compressive Strength (MPa)	Up to 2,500	Up to 5,000	Up to 350
Young's Modulus (GPa)	40～400	150～450	0.001～3.5
High temperature creep resistance	Poor	Excellent	—
Thermal expansion	Medium to high	Low to medium	Very high
Thermal conductivity	Medium	Medium but often decreases rapidly with temperature	Very low
Thermal shock resistance	Good	Generally poor	—
Electrical properties	Conductors	Insulators	Insulators
Chemical resistance	Low to medium	Excellent	Generally good
Oxidation resistance at high temperature	Poor, except for rare metals	Oxides excellent SiC, Si_3N_4 good	—

Composite materials have been developed to overcome some of the deficiencies of members of a particular class of materials and there are examples of ceramic/metal, polymer/ceramic and metal/polymer composites in current use. Ceramics, though strong in compression, generally are weak in tension, but metals tend to have equal strength in both tension and compression. Reinforced and prestressed concretes are composites designed to improve the tensile characteristics of concrete structural members. Polymers have low densities but also have low strength and stiffness. The use of glass, carbon or other fibre reinforcement gives greatly increased strength and stiffness without adding an excessive weight penalty. The load bearing characteristics of metals and the low friction characteristics of polymer such as PTFE are combined to good effect in metal particle/PTFE composites developed as bearing materials.

1.3 Properties of engineering materials

Very many properties, or qualities, of materials have to be considered when choosing a material to meet a design requirement (see table 1.2). These include a wide range of physical, chemical and mechanical properties together with forming, or manufacturing characteristics, cost and availability data and, in addition, more subjective aesthetic qualities such as appearance and texture.

Table 1.2 **Material properties and qualities**

Physical properties	Density, melting point, hardness, elastic module, damping capacity
Mechanical properties	Yield, tensile, compressive and torsional strengths. Ductility, fatigue strength, Creep strength, fracture toughness
Manufacturing properties	Ability to be shaped by: moulding and casting, plastic deformation, power processing, machining. Ability to be joined by adhesives, welding, etc.
Chemical properties	Resistance to oxidation, corrosion, solvents and environmental factors
Other non-mechanical properties	Electrical, magnetic, optical and thermal properties
Economic properties	Raw material and processing costs. Availability
Aesthetic properties	Appearance, texture and ability to accept special finishes

1.4 Cost and availability

One of the most important aspects affecting the selection and use of materials is cost and availability. In many cases purchase cost of materials accounts for about one-half of the total works cost of the finished product. It follows from this that the use of a cheaper raw material should have a significant effect on the final product cost. This is not always true as, in some cases, the choice of an expensive material may permit the use of relatively simple and low cost processing methods whereas a cheaper material may require lengthy, complex and expensive production methods.

It is usual to see the cost of materials quoted per unit mass, for example £100 per tonne. This may give a misleading picture as often it is the volume of material which is important rather than the mass. The relative position of material in league table of cost may change when the criterion is altered from £($)per tonne to £($) per unit volume. Much of the data for metals in the cost table are for refined metal in ingot form and it should be realized that the costs of processed products, such as sheet, plate, sections and forgings will be much higher. Every process and heat treatment will give added value and increase the final material cost. Also, the process of alloying will mean that, generally, the costs of alloys will be higher than those for unalloyed metals. For example, the cost of mild steel cold rolled strip material is approximately twice that of mild steel ingot while stainless steel sheet is almost six times the cost of mild steel sheet. Similarly, in the aluminium industry, an alloy of aluminium with 5 per cent magnesium is about 50 per cent more expensive than commercial purity aluminium.

Availability also influences the choice of a material. In the 19th century, during the growth period of railway, most railway bridges in Britain were constructed of masonry or wrought iron. In the same period when tracks were being pushed westwards in the United States and Canada, bridges and viaducts were usually of trestle construction owing to the ready availability of suitable timber close to the point of use. The same principle holds today and often a material or source of material supply will be chosen on the basis of proximity or availability.

1.5 Possibility for the future

The world's mineral resources are non-renewable and finite. According to present day estimates, the present known reserves of some metals of economic importance, including copper, lead, silver, tin and zinc, could be exhausted in the early of the 21th century, and will within the lifetimes of today's young engineers. These estimates on the size of reserves are based on knowledge of the availability of the sources being worked at present. This does not necessarily mean that these metals would not be available at all. These metallic elements are present in small quantities, lower than in current workable ores, in other rock formation. If it becomes necessary to extract the metals from such low level deposits then the cost of extraction and, more importantly, the energy consumption for extraction would rise considerably. A high production of the metal products made today is derived from primary metal, which is produced direct from ores. Greater emphasis will need to be placed on use of secondary metal sources, which is metal obtained by recovery from recycled scrap. Some problem may be overcome by substitution of one material for another. An example of this is the replacement of tin-plated steel by aluminium for can manufacture. Much of the substitution which has taken place, however, is substitution of polymers for metals. The future supply position for polymers may also be uncertain as they are largely derived from petroleum. The supply situation for ceramic materials is much different as the raw materials for ceramic manufacture are present in great abundance. The earth's crust is composed mainly of silicates and alumino-silicates.

Changes in the relative quantities, cost and availabilities of materials will provide a series of major challenges to engineers and designers.

1.6 Non-ferrous metals and alloys

Although there are very many metallic elements, it is customary to divide metals and alloys into major categories, ferrous and non-ferrous. The former category covers the element iron and its alloys. While all the other metallic elements and their alloys are classified as non-ferrous. The division is not quite as unbalances as might at first appear, because iron occupies very special position among metallic materials, owing to its availability, comparatively low cost, and the very useful range of alloys that are formed when iron is alloyed with carbon and other elements. Some 94 per cent of the total world consumption of metallic materials is in the form of steels and cast irons. On the other hand, out of all the non-ferrous metals, only a few, aluminium, copper, lead, magnesium, nickel, tin, titanium and zinc, are produced in moderately large quantities. Many of the other metallic elements play an important part in engineering, both as alloying elements and as metals in their own right. The role of some of these, including beryllium, cobalt, molybdenum and tungsten, as alloying elements in some steels and non-ferrous alloys is mentioned in this and the following chapters but a detailed coverage of the metallurgy of these metals is outside the scope of the volume.

1.6.1 Aluminium and its alloys

Aluminium is one of the most abundant elements in the earth's crust, owing to its high affinity for oxygen, it cannot be reduced to the metallic state by reduction with carbon or carbon monoxide, as in the case with many metallic oxides. Aluminium was first produced in the early part of nineteenth century by reduction with potassium. This was a very expensive process, and until 1850 the price of aluminium was about £250($437.5) per kilogram and, because of its great cost at that time, some European royal houses used aluminium cutlery at state banquets. In 1886, Charles Hall devised a new method for the relatively cheep production of aluminium. The Hall method involved the electrolysis of a molten solution of alumina in the mineral cryolite (Na_3AlF_6) at a temperature of 950 ℃.

Aluminium possesses a number of properties that make it an extremely useful engineering material. Its good corrosion resistance and low density make it particularly suitable for applications in the field of transportation. The pure metal has a very low strength but, by alloying with other elements, the strength may be increased considerably to give alloys with very good strength to weight ratios. Like all metals with a face centred cubic crystal structure, aluminium is highly ductile and can be shaped easily by a wide variety of methods. The good electrical conductivity of the metal makes it suitable for many applications in the electrical industry. Aluminium has an extremely high affinity for oxygen and any fresh metal surface will oxidize rapidly. The surface oxide layer that forms is only a few atoms in thickness, but it is impermeable to oxygen and protects the surface from further attack. The corrosion resistance of aluminium is due to the presence of this oxide coating. The corrosion resistance of aluminium may be improved further by anodizing. In an anodizing operation the aluminium is made the anode of an electrolytic cell. Oxygen is liberated at the anode and the thickness of the protective aluminium oxide film increased. The anodic coating is cellular in structure and immersion of the anodized material in boiling water will seal this cellular structure and give a hard, smooth surface.

The principal properties of pure aluminium (99.9 per cent) are given below:

Melting point	660 ℃
Crystal structure	face centred cubic
Density	2.70×10^{3} kg/m^{3}
Young's modulus (E)	70.5 GPa
Tensile strength	45 MPa
Electrical resistivity	2.66×10^{-8} Ωm at 20 ℃
Corrosion resistance	very good

Aluminium may be alloyed with a number of elements to produce a series of useful engineering materials. The alloys of aluminium may be sub-divided into those that are not heat-treatable, and those that are heat-treatable. Alloys in the first group may be strengthened by cold working operations, and the only type of heat treatment that may be given is an annealing treatment to soften a work hardened sample. The heat treatable alloys, on the other hand, may be strengthened by giving them a special type of heat treatment. The principal heat-treatable alloys are those of the following systems: Au-Cu, Au-Cu-Ni, Au-Mg-Si, Al-Zn-Cu and Au-Li. The non-heat-treatable alloys are those of the Al-Mn, Al-Mg and Al-Si systems. Manganese enters solid solution in aluminium to a limited extent, and the only commercial alloy in this system is that containing 1.25 per cent of manganese. This alloy is some 15 per cent stronger, and has a slightly better corrosion resistance, than commercial purity aluminium. Its principal uses are for production of domestic utensils, including pressure cookers and, in the form of corrugated sheet, for the cladding of buildings. Magnesium enters solid solution in aluminium to a limited extent and gives a considerable solid solution strengthening effect. Magnesium also improves the resistance to corrosion, particularly to corrosion in a marine environment. Silicon forms a eutectic with aluminium, and it also increases the fluidity of the molten aluminium. Alloys containing silicon are very suitable for the manufacture of both sand and die castings.

1.6.2 Copper and its alloys

Copper is one of the oldest metals known to man, and, together with tin in the alloy bronze, has been worked for over 5,000 years. Copper and bronze were used for both utilitarian and decorative purposes in the early civilizations. Today, there are very many extremely useful copper alloys but, owing to present high price of the metal, copper and its alloys are being replaced by cheaper materials, such as aluminium and plastics, in many application.

The principal ores of copper are generally complex mixtures of copper and iron sulphides, and copper production from the ore may either be carried out by a smelting process, or by electrolytic extraction. Smelting operations are carried out in a blast furnace, or reverberatory furnace, and roasted sulphide ore, cock and flux make up the charge. A matte, which is a high-density double sulphide of iron and copper, collects at the base of the furnace and the gangue, or waste material, forms a lower-density slag, which separates easily from the matte. The matte is reduced to copper in converter, similar to a Bessemer converter. The copper produced in this way is highly oxidized, and is termed blister copper. It is of the order of 99 per cent pure and it may be refined to higher purities by electrolytic, or fire refining, techniques. For electrolytic extraction, the finely divided ore is digested with dilute sulphuric acid. Copper compounds are dissolved, but most other minerals in the ore are not attacked. The solution obtained is then purified and electrolysed. The copper produced in this way is termed cathode copper, and may be of purity ranging from 99. 2 to 99. 7 per cent copper. Cathode copper may be refined either electrolytically, or in a reverberatory furnace.

The principal properties of pure copper are given below:

Melting point	1,083 ℃
Crystal structure	face centred cubic
Density	8.93×10^3 kg/m^3
Young's modulus E	122. 5 GPa
Tensile strength	220 MPa
Electrical resistivity	1.67×10^{-8} Ωm at 20 ℃
Corrosion resistance	very good

Some applications of the various grades of pure copper are: wire, for electrical windings and wiring; sheet, for architectural cladding, and for shaping into articles, such as domestic water tanks and vessels used in the food and chemical industries; for heat exchangers and domestic installations.

Copper may be alloyed with a number of elements to provide a range of useful alloys. The importance alloy systems are: copper-zinc (brasses), copper-tin (bronzes and gun-metals), copper-aluminium (aluminium bronzes) and copper-nickel (cupronickels).

(1) Brasses. The range of alloys known as the brasses are, primarily, alloy of copper and zinc. The addition of zinc to copper brings about an increase in strength because the zinc enters into solid solution in copper. A unusual feature is that the ductility of the alloys also increases with dissolved zinc content, reaching a maximum value at a zinc content of 30 per cent. The ductility of the material then decreases with further zinc content until at a composition of 37 per cent of zinc, the limit of the α phase, the ductility of the alloy is of similar value to that of pure copper. The α brasses are widely used for deep drawing,

spinning and tube manufacture, because of their high ductilities. The alloy containing 30 per cent zinc, 70/30 brass, is known as cartridge brass and used for the manufacture of cartridge and shell cases because of its high ductility.

(2) Bronzes. The bronzes are high-strength alloy with a good resistance to corrosion. Although, according to the phase diagram, copper can hold up to 14 per cent of tin in solid solution, cast alloys containing more than 5 per cent of tin will show some δ phase in the microstructure. This is because pronounced dendritic coring occurs owing to the wide freezing-temperature range of these alloys. Coring may be removed by a lengthy annealing treatment. The α phase cold working alloys do not normally contain more than 7 per cent of tin. These α alloys are ductile and suitable for cold working, although work harden rapidly. The uses of these alloys include the manufacture of non-ferrous springs, coinage, and sheet metal for ornamental work. Alloys containing the brittle δ phase are unsuitable for working, and are used in the "as cast" condition. Bronzes need to be deoxidized before casting and phosphorus is used for this purpose. Sufficient phosphorus is normally added to give a certain residual phosphorus content in the deoxidized alloy. The materials are then termed phosphor bronzes. The effect of the residual phosphorus is to strengthen the alloy. A major application for $(\alpha+\delta)$ bronze is as a bearing material. The duplex structure of the material is most suitable for this purpose as the α phase matrix will be highly resistant to shock, and the very hard δ phase particles will sustain some of the load and reduce wear. Zinc and lead may be added to bronzes. Zinc can be used to cheapen the alloy, and it also improves the casting performance of the material. Alloys containing zinc are termed gun-metals, as they were used in former days for the casting of heavy ordnance. Small lead additions improve the machining characteristics of bronzes and gun-metals, while large additions, up to 25 per cent of lead, are added to some bearing metals.

(3) Aluminium bronzes. The aluminium bronzes possess similar strengths to bronzes. Again, the α alloys are cold working materials, while $(\alpha+\delta)$ alloys are used for the manufacture of casting and hot worked products. The main characteristic of aluminium bronzes is its excellent corrosion resistance, particularly in marine environments.

(4) Cupronickels. Nickel is soluble in solid copper in all proportions, and the cupronickel alloys are strong, ductile alloys with a face centred cube crystal structure. Cupronickels possess an excellent resistance to corrosion. British "silver" coinage is a cupronickel containing 25 per cent of nickel. Other applications include use for condenser tubing and heat exchangers.

1.7 Types of steel and their uses

The hardness and strength of steels vary very considerably with both carbon content and type of heat treatment. Certain names, which relate to the carbon content, are used connection with steels. Mild or low carbon steels are those containing up to 0.3 per cent of carbon. Steels containing between 0. 3 and 0. 6 per cent carbon are termed medium carbon steels, and these may be hardened and tempered. Steel containing more than 0. 6 per cent of carbon are always used in hardened and tempered condition, and these are known as high carbon steels, or tool steels.

Table 1. 3 gives some typical uses of steels of various carbon contents.

Table 1. 3 **Compositions and typical applications of steels**

C (per cent)	Name	Applications
0. 05	Dead mild steel	Sheet and strip for presswork, car bodies, tin-plat, wire, rod, tubing
0. 08～0. 15	Mild steel	Sheet and strip for presswork, wire and rod for nails, screws, concrete reinforcement bar
0. 15	Mild steel	Case, carburising quality
0. 10～0. 30	Mild steel	Steel plate and sections, for structural work
0. 25～0. 40	Medium carbon steel	Bright drawn bar
0. 30～0. 45	Medium carbon steel	Shafts and high-tensile tubing
0. 40～0. 50	Medium carbon steel	Shafts, gears, railway tyres
0. 55～0. 65	High carbon steel	Forging dies, railway rails, springs
0. 65～0. 75	High carbon steel	Hammers, saws, cylinder linings
0. 75～0. 85	High carbon steel	Cold chisels, forging die blocks
0. 85～0. 95	High carbon steel	Punches, shear blades, high-tensile wire
0. 95～1. 10	High carbon steel	Knives, axes, picks, screwing dies and taps, milling cutter
1. 10～1. 40	High carbon steel	Ball bearings, drills, wood-cutting and metal-cutting tools, razors

1. 8 Alloy steels

Alloy steel are generally classified into two major categories, low-alloy steels and high-alloy steels.

(1) Low-alloy steels. A low-alloy steel generally contains up to 3 or 4 per cent of one or more alloying elements and is characterized by possessing similar microstructures to, and requiring similar heat treatments to, plain carbon steels. Frequently they are referred to as pearlitic alloy steels as the normalised structure contains the eutectoid pearlite. The presence of alloying elements provides enhanced properties such as increased strength without loss of toughness and increased hardenability. The applications of low-alloy steels are similar to those quoted in table 1. 3 for plain carbon steels of equivalent carbon content, for example, 0. 4 per cent carbon is quoted as typical for the manufacture of shafts, an alloy steel containing 1 per cent nickel and 0. 4 per cent carbon is an ideal shaft material with improved strength and toughness over a plain carbon steel and also an increase in the resistance to fatigue conferred by the presence of nickel. A major category of low-alloy steels is the high strength low-alloy steel (HSLA). This is a group of low-alloy steels produced with a very fine grain size. This is achieved by the addition of small

controlled amounts of niobium, titanium, or vanadium and these elements form carbonitride precipitates which inhibit austenite grain growth during got working operations. This effect, coupled with close control of hot working temperatures and a controlled cooling rate, gives an extremely fine grain structure which, together with effect of dispersed precipitate, results in a range of low-alloy steels for structural applications with tensile yield strengths between 350 and 560 MPa.

(2) High-alloy steels. High-alloy steels are those that possess structures and require heat treatments, which differ considerably from those of plain carbon steels. Their room temperature structures after normalizing may be austenitic, martensitic or contain precipitated carbides. Generally, they contain more than 5 per cent of alloying element. A few examples of some high-alloy steels are given below.

a. High-speed tool steels. Tungsten and chromium form very hard and stable carbides. Both elements also raise the critical temperature and, also, cause an increase in softening temperature. High carbon steels rich in these elements provide hard wearing metal-cutting tools, which retain their high hardness at temperatures up to 600 ℃. A widely used high-speed tool steel composition is 18/4/1 steel, containing 18 per cent of tungsten, 4 per cent of chromium, 1 per cent of vanadium and 0. 8 per cent of carbon. In a steel of such a composition very hard and stable chromium carbides, vanadium carbide and complex iron-tungsten carbides are formed instead of the normal cementite.

b. Stainless steel. When chromium is present in amounts, in excess of 12 per cent, the steel becomes highly resistant to corrosion, owing to the protective film of chromium oxide that forms on the metal surface. Chromium also raises the α to γ transportation temperature of iron, and tends to stabilize ferrite in the structure. There are several types of stainless steel, such as ferritic stainless steels, martensitic stainless steels and austenitic stainless steels.

c. Maraging steels. These are very high-strength materials that can be hardened to give tensile strengths of up to 1,900 MPa. They contain 18 per cent nickel, 7 per cent cobalt and small amounts of other elements such as titanium. The carbon content is low, generally less than 0. 05 per cent: A major advantage of maraging steels is that after the solution treatment they are soft enough to be worked and machined with comparative ease. Although the basic material cost of the maraging steel is very high, the final cost of a complex component made from a maraging steel may be less than if made from a more conventional and cheaper high strength steel because of the much lower machining costs. One major use of maraging steels is for the manufacture of aircraft undercarriage components.

d. Hadfields manganese steel. This is a high-alloy steel that contains 12～14 per cent manganese, and 1 per cent of carbon. The high manganese content renders this steel component austenitic at all temperature. It is also, therefore, non-magnetic. This type of steel is unique in that any attempt to deform, or abrade, the material greatly increases the