Ian Polmear

Light Alloys

From Traditional Alloys to Nanocrystals

Fourth Edition

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To
Andrea, Sally and David

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Fourth edition

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PREFACE TO THE FIRST EDITION

The fact that the light metals aluminium, magnesium and titanium have traditionally been associated with the aerospace industries has tended to obscure their growing importance as general engineering materials. For example, aluminium is now the second most widely used metal and production during the next two decades is predicted to expand at a rate greater than that for all other structural metals. Titanium, which has a unique combination of properties that have made its alloys vital for gas turbine engines, is now finding many applications in aircraft structures and in the chemical industry.

Light alloys have never been the subject of a single book. Moreover, although the general metallurgy of each class of light alloys has been covered in individual texts, the most recent published in English appeared some time ago—aluminium alloys in 1970, magnesium alloys in 1966 and titanium alloys in 1956. Many new developments have occurred in the intervening periods and important new applications are planned, particularly in transportation. Thus it is hoped that the appearance of this first text is timely.

In preparing the book I have sought to cover the essential features of the metallurgy of the light alloys. Extraction of each metal is considered briefly in Chapter one, after which the casting characteristics, alloying behaviour, heat treatment, properties, fabrication and major applications are discussed in more detail. I have briefly reviewed the physical metallurgy of aluminium alloys in Chapter two although the general principles also apply to the other metals. Particular attention has been devoted to microstructure/property relationships and the role of individual alloying elements, which provides the central theme. Special features of light alloys and their place in general engineering are highlighted although it will be appreciated that it has not been possible to pursue more than a few topics in depth.

The book has been written primarily for students of metallurgy and engineering although I believe it will also serve as a useful guide to both producers and users of light alloys. For this reason, books and articles for further reading are listed at the end of each chapter and are augmented by the references included with many of the figures and tables.

The book was commenced when I was on sabbatical leave at the Joint Department of Metallurgy at the University of Manchester Institute of Science and Technology and University of Manchester, so that thanks are due to Professor K. M. Entwistle and Professor E. Smith for the generous facilities placed at my disposal. I am also indebted for assistance given by the Aluminium Development Council of Australia and to many associates who have provided me with advice and information. In this regard, I wish particularly to mention the late Dr E. Emley, formerly of The British Aluminium Company Ltd; Dr C. Hammond, The University of Leeds; Dr M. Jacobs; TI Research Laboratories; Dr D. Driver, Rolls-Royce Ltd; Dr J. King and Mr W. Unsworth, Magnesium Elektron Ltd; Mr R. Duncan, IMI Titanium; Dr D. Stratford, University of Birmingham; Dr C. Bennett, Comalco Australia Ltd; and my colleague Dr B. Parker, Monash University. Acknowledgement is also made to publishers, societies and individuals who have provided figures and diagrams which they have permitted to be reproduced in their original or modified form.

Finally I must express my special gratitude to my secretary Miss P. O'Leary and to Mrs J. Colclough of the University of Manchester who typed the manuscript and many drafts, as well as to Julie Fraser and Robert Alexander of Monash University who carefully produced most of the photographs and diagrams.

IJP
Melbourne
1980

PREFACE TO THE SECOND EDITION

In this second edition, the overall format has been retained although some new sections have been included. For the most part, the revision takes the form of additional material that has arisen through the development of new compositions, processing methods and applications of light alloys during the last eight years.

Most changes have occurred with aluminium alloys which, because of their widespread use and ease of handling, are often used to model new processes. Faced with increasing competition from fibre-reinforced plastics, the aluminium industry has developed a new range of light-weight alloys containing lithium. These alloys are discussed in detail because they are expected to be important materials of construction for the next generation of passenger aircraft. More attention is given to the powder metallurgy route for fabricating components made from aluminium and titanium alloys. Treatment of this topic includes an account of techniques of rapid solidification processing which are enabling new ranges of alloys to be produced having properties that are not attainable by conventional ingot metallurgy. Metal-matrix composites based on aluminium are also finding commercial applications because of the unique properties they offer and similar magnesium alloys are being developed. New methods of processing range from methods such as squeeze casting through to advances in superplastic forming.

In preparing this new edition, I have again paid particular attention to microstructure/property relationships and to the special features of light alloys that lead to their widespread industrial use. In addition to an expanded text, the number of figures has been increased by some 40% and the lists of books and articles for further reading have been extended. Once more, the book is directed primarily at undergraduate and postgraduate students although I believe it will serve as a useful guide to producers and users of light alloys.

I am again indebted for assistance given by colleagues and associates who have provided me with information. Acknowledgement is also made to publishers, societies and individuals who have provided photographs and diagrams which they have permitted to be produced in their original or modified form.

Finally I wish to express my gratitude to Mesdames J. Carrucan, C. Marich and V. Palmer, who typed the manuscript, as well as to Julie Fraser, Alan Colenso and Robert Alexander of Monash University who carefully produced most of the photographs and diagrams.

I. J. Polmear
Melbourne 1988

PREFACE TO THE THIRD EDITION

The central theme of the first two editions was microstructure/property relationships in which special attention was given to the roles of the various alloying elements present in light alloys. This general theme has been maintained in the third edition although some significant changes have been made to the format and content.

As before, much of this revision involves the inclusion of new material which, in this case, has arisen from developments during the seven years since the second edition was published. The most notable change in format has been to group together, into a new chapter, information on what have been called new materials and processing methods. Examples are metal matrix and other composites, structural intermetallic compounds, nanophase and amorphous alloys. Interest in these and other novel light alloys has increased considerably during the last decade because of the unceasing demands for improvements in the properties of engineering materials. Since light alloys have been at the forefront of many of these developments, the opportunity has been taken to review this area which has been the focus of so much recent research in materials science.

Another feature of the third edition is the greater attention given to applications of light alloys and their place in engineering. More case studies have been included, such as the use of light alloys in aircraft and motor cars. Economic factors associated with materials selection are also discussed in more detail. Moreover, since the light metals are often placed at a competitive disadvantage because of the high costs associated with their extraction from minerals, more attention has been given to these processes. This has led to a considerable increase in the size of the first chapter. Joining processes are described in more detail and, once again, service performance of light alloys is discussed with particular regard to mechanical behaviour and corrosion resistance.

As a result of these various changes, the text has been expanded and the number of figures has been increased by a further 20%. Lists of books and articles for further reading have been updated. While the book continues to be directed primarily at senior undergraduate and postgraduate students, I believe it will again serve as a useful guide to the producers and users of light alloys.

I am again indebted for assistance given by colleagues and associates who have provided me with information and helpful discussions. General acknowledgement is made to publishers, societies and individuals who have responded to requests for photographs and diagrams that have been reproduced in their original or modified form. Finally I wish to express my gratitude to my wife Margaret for her constant encouragement, to Carol Marich and Pam Hermansen who typed the manuscript and to Julie Fraser and Robert Alexander who once again carefully produced so many of the photographs and diagrams.

I. J. Polmear
Melbourne 1995

PREFACE TO FOURTH EDITION

Since the third edition of Light Alloys appeared in 1995, developments with new alloys and processes have continued at an escalating rate. Competition between different materials, metallic and non-metallic, has increased as producers seek both to defend their traditional markets and to penetrate the markets of others. New compositions of aluminium, magnesium and titanium alloy have been formulated and increasing attention has been given to the development of novel and more economical processing methods. Because of their ease of handling, aluminium alloys in particular have been used as experimental models for many of the changes. Recently, potential automotive applications have led to a resurgence of interest in cast and wrought magnesium alloys.

The central theme of earlier editions was microstructure/property relationships and particular attention was given to the roles of the various alloying elements present in light alloys. This general theme has been maintained in the fourth edition although further significant changes have been made to format and content. Special consideration has again been given to the physical metallurgy of aluminium alloys and many of the general principles also apply to magnesium and titanium alloys. The description of changes occurring during the processing of the major class of non-heat treatable aluminium alloys has been extended. Although a century has now elapsed since the discovery of age hardening by Alfred Wilm, new observations are still being made as the latest experimental techniques reveal more details of the actual atomic processes involved. As examples, more information is now available about the role of solute and vacancy clusters during the early stages of ageing, as well as other phenomena such as secondary hardening. Some success has been achieved with the modelling of precipitation processes. Precipitation hardening was hailed as the first nanotechnology and now it is possible to develop fine-scale microstructures in a much wider range of alloys through the use of novel processing methods.

Some new topics in this fourth edition are strip and slab casting, creep forming, joining technologies such as friction stir and laser welding, metallic foams, quasicrystals, and the production of nanophase materials. Economic factors associated with the production and selection of light metals and alloys are considered in more detail and information on recycling has been included. Sections dealing with the commercial applications of light alloys and their general place in engineering have also been expanded. This applies particularly to transportation as aluminium alloys face increasing competition from fibre-reinforced polymers for aircraft structures, and where higher fuel costs make both aluminium and magnesium alloys more attractive for reducing the weight of motor vehicles.

Because of these and other developments, the text has been updated and expanded by about 20%. A further 50 figures and several new tables have been added. References to original sources of information are shown with most figures and tables but are not included in the general text. Relevant articles and books for further reading have been revised and are listed at the end of each chapter. As originally intended, the book is directed primarily at senior undergraduate and postgraduate students, but it is also believed it will to serve as a useful general guide to producers and users of light alloys.

I am again indebted for the assistance given by colleagues and associates who have provided me with information and advice. In this regard, special mention should be made of J. Griffiths, E. Grosjean J. Jorstad, R. Lumley, J-F Nie, R. R. Sanders, H. Shercliff, J. Taylor and the Australian Aluminium Council. General acknowledgment is again made to publishers, societies and individuals who have responded to requests for photographs and diagrams. Facilities provided by the Department of Materials Engineering at Monash University have been much appreciated and, as with all other editions, many of the figures have been skilfully reproduced in their original or modified form by Julie Fraser. Finally I wish to express my gratitude to my wife Margaret for her constant support.

I. J. Polmear
Melbourne, 2005

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THE LIGHT METALS

1.1 GENERAL INTRODUCTION

The term ‘light metals’ has traditionally been given to both aluminium and magnesium because they are frequently used to reduce the weight of components and structures. On this basis, titanium also qualifies and beryllium should be included although it is little used and will not be considered in detail in this book. These four metals have relative densities ranging from 1.7 (magnesium) to 4.5 (titanium) which compare with 7.9 and 8.9 for the older structural metals, iron and copper, and 22.6 for osmium, the heaviest of all metals. Ten other elements that are classified as metals are lighter than titanium but, with the exception of boron in the form of strong fibres contained in a suitable matrix, none is used as a base material for structural purposes. The alkali metals lithium, potassium, sodium, rubidium and caesium, and the alkaline earth metals calcium and strontium are too reactive, whereas yttrium and scandium are comparatively rare.

1.1.1 Characteristics of light metals and alloys

The property of lightness translates directly to material property enhancement for many products since by far the greatest weight reduction is achieved by a decrease in density (Fig. 1.1). This is an obvious reason why light metals have been associated with transportation, notably aerospace, which has provided great stimulus to the development of light alloys during the last 50 years. Strength: weight ratios have also been a dominant consideration and the central positions of the light alloys based on aluminium, magnesium and titanium with respect both to other engineering alloys, and to all materials are represented in an Ashby diagram in Fig. 1.2. The advantages of decreased density become even more important in engineering design when parameters such as stiffness and resistance to buckling are involved. For example, the stiffness of a simple rectangular beam is directly proportional to the product of the elastic modulus and the cube of the thickness. The significance of this relationship is illustrated by the nomograph

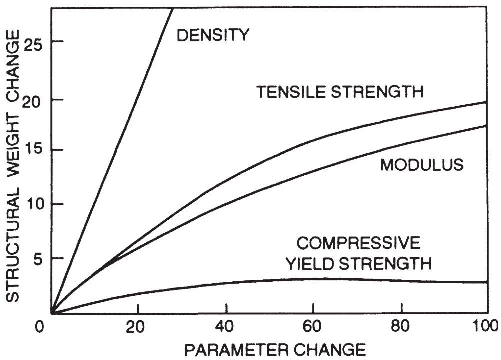

Fig. 1.1 Effect of property improvement on structural weight (courtesy of Lockheed Corporation).

shown in Fig. 1.3 which allows the weights of similar beams of different metals and alloys to be estimated for equal values of stiffness. An iron (or steel) beam weighing 10 kg will have the same stiffness as beams of equal width and length weighing 7 kg in titanium, 4.9 kg in aluminium, 3.8 kg in magnesium, and only 2.2 kg in beryllium. The Mg–Li alloy is included because it is the lightest (relative density 1.35) structural alloy that is available commercially. Comparative stiffness for equal weights of a similar beam increase in the ratios 1:2.9:8.2:18.9 for steel, titanium, aluminium, and magnesium respectively.

Concern with aspects of weight saving should not obscure the fact that light metals possess other properties of considerable technological importance, e.g. the high corrosion resistance and high electrical and thermal conductivities of aluminium, the machinability of magnesium, and extreme corrosion resistance of titanium. Comparisons of some physical properties are made in Table 1.1.

Beryllium was discovered by Vauquelin in France in 1798 as the oxide in the mineral beryl (beryllium aluminium silicate), and in emerald. It was first isolated independently by Wöhler and Bussy in 1828 who reduced the chloride with potassium. Beryl has traditionally been a by-product of emerald mining and was until recently the major source of beryllium metal. Currently more beryllium is extracted from the closely associated mineral bertrandite (beryllium silicate hydroxide).

Beryllium has some remarkable properties (Table 1.1). Its stiffness, as measured by specific elastic modulus, is nearly an order of magnitude greater than that for the other light metals, or for the commonly used metals iron, copper and nickel. This has led to its use in gyroscopes and in inertial guidance systems. It has a relatively high melting point, and its capture cross-section (i.e. permeability) for neutrons is lower than for any other metal. These properties have stimulated much interest by the aerospace and nuclear industries. For example, a design study specifying beryllium as the major structural material for a supersonic transport aircraft has indicated possible weight savings of up to 50% for

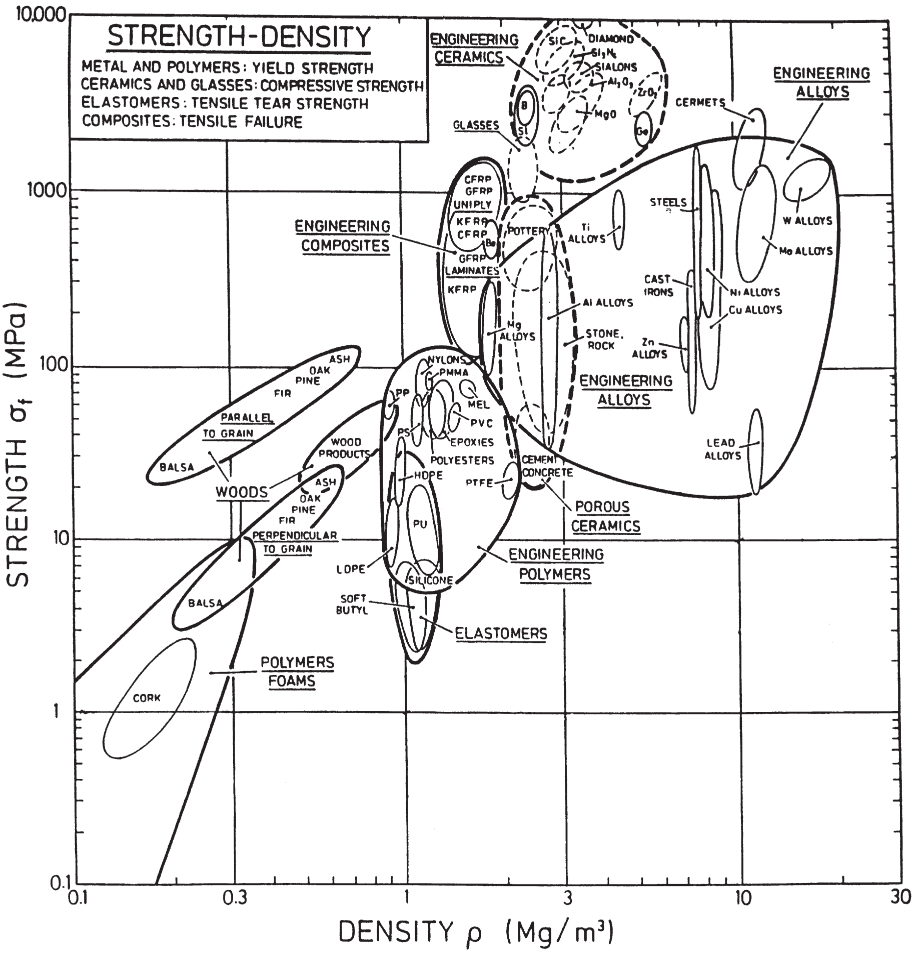

Fig. 1.2 Strength: density relationships for light alloys and other engineering materials. Note that yield strength in used as the measure of strength for metals and polymers, compressive strength for ceramics, tear strength for elastomers and tensile strength for composites (courtesy M. F. Ashby).

components for which it could be used. However, its structural uses have been confined largely to components for spacecraft, and for applications such as satellite antenna booms. In nuclear engineering it has had potential for use as a fuel element can in power reactors. Another unique property of beryllium is its high specific heat which is approximately twice that of aluminium and magnesium, and four times that of titanium. This inherent capacity to absorb heat, when combined with its low density, led to the selection of beryllium as the basis for the re-entry heat shield of the Mercury capsule used for the first manned spacecraft developed in the United States. In a more general application, it has served as

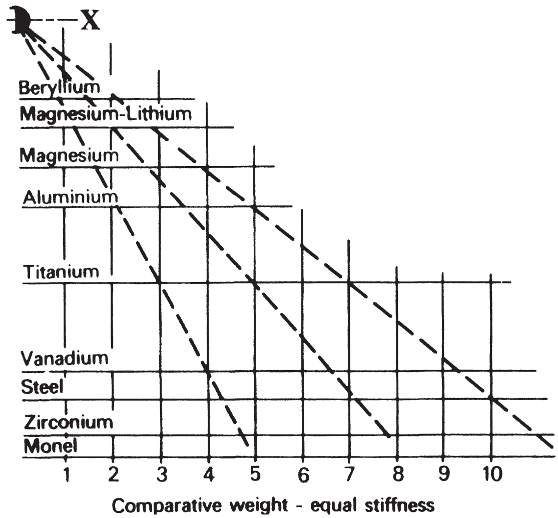

Fig. 1.3 Nomograph allowing the comparative weights of different metals or alloys to be compared for equal levels of stiffness. These values can be obtained from the intercepts which lines drawn from point X make with lines representing the different metals or alloys (courtesy Brooks and Perkins Inc.).

a heat sink when inserted in the centre of composite disc brakes used in the landing gear of a large military transport aircraft. Beryllium also shows outstanding optical reflectivity, particularly in the infrared, which have led to its combat use in target acquisition systems, as well as in space telescopes.

Despite much research in several countries, wider use has not been made of beryllium because it is costly to mine and extract, it has an inherently low ductility at ambient temperatures, and the fact that the powdered oxide is extremely toxic to some people. The problem of low ductility arises because of the dimensions of the close-packed hexagonal crystal structure of beryllium. The c/a ratio of the unit cell is 1.567 which is the lowest and most removed of all metals from the ideal value of 1.633. One result of this is a high degree of anisotropy between mechanical properties in the a and c crystallographic directions. At room temperature, slip is limited and only possible on the basal plane, which also happens to be the plane along which cleavage occurs. Furthermore, there has also been little opportunity to improve properties by alloying because the small size of the beryllium atom severely restricts its solubility for other elements. One exception is the eutectic composition Be-38Al in which some useful ductility has been achieved. This alloy was developed by the Lockheed Aircraft Company and became known as Lockalloy. Because beryllium and aluminium have little mutual solid solubility in each other, the alloy is essentially a composite material with a microstructure comprising stiff beryllium particles in a softer aluminium matrix. Light weight (specific gravity 2.09) extrusions and sheet have found limited aerospace applications.

Table 1.1 Some physical properties of pure metals (from Lide, D.R. (Ed), *Handbook of Chemistry & Physics*, 72nd edn, CRC Press, Boca Raton, USA, 1991–92; *Metals Handbook*, Volume 2, 10th edn, ASM International, Metals Park, Ohio, USA, 1990)

Property	Unit	Al	Mg	Ti	Be	Fe	Cu
Atomic number	–	13	12	22	4	26	29
Relative atomic mass (C = 12.000)	–	26.982	24.305	47.90	9.012	55.847	63.546
Crystal structure	–	fcc	cph	cph	cph	bcc	fcc
a	nm	0.4041	0.3203	0.2950	0.2286	0.2866	0.3615
c	nm	–	0.5199	0.4653	0.3583	–	–
Melting point	°C	660	650	1678	1289	1535	1083
Boiling point	°C	2520	1090	3289	2472	2862	2563
Relative density (d)	–	2.70	1.74	4.51	1.85	7.87	8.96
Elastic modulus (E)	GPa	70	45	120	295	211	130
Specific modulus (E/d)	–	26	26	26	160	27	14
Mean specific heat 0–100 °C	$J\ kg^{-1}\ K^{-1}$	917	1038	528	2052	456	386
Thermal conductivity 20–100 °C	$W\ m^{-1}\ K^{-1}$	238	156	26	194	78	397
Coefficient of thermal expansion 0–100 °C	$10^{-6}\ K^{-1}$	23.5	26.0	8.9	12.0	12.1	17.0
Electrical resistivity at 20 °C	μ ohm cm^{-1}	2.67	4.2	54	3.3	10.1	1.69

Note: Conversion factors for S1 and Imperial units are given in the Appendix.

Beryllium is now prepared mainly by powder metallurgy methods. Metal extracted from the minerals beryl or bertrandite is vacuum melted and then either cast into small ingots, machined into chips and impact ground, or directly inert gas atomised to produce powders. The powders are usually consolidated by hot isostatic pressing (HIP) and the resulting billets have properties that are more isotropic than are obtained with cast ingots. Tensile properties depend on the levels of retained BeO (usually 1 to 2%) and impurities (iron, aluminium and silicon) and ductilities usually range from 3 to 5%. The billets can then be hot worked by forging, rolling to sheet, or extruding to produce bar or tube. Lockalloy (now also known as AlBeMet™ 162) is now also manufactured by inert gas atomisation of molten pre-alloyed mixtures and the resulting powders are consolidated and hot worked as described above.

1.1.2 Relative abundance

The estimated crustal abundance of the major chemical elements is given in Table 1.2 which shows that the light metals aluminium, magnesium, and titanium are first, third and fourth in order of occurrence of the structural metals. It can also be seen that the traditional metals copper, lead, and zinc are each present in amounts less than 0.10%. Estimates are also available for the occurrence of metals in the ocean which is the major commercial source of magnesium. Sea water contains 0.13% of this metal so that 1.3 million tonnes are present in each km^3, which is approximately equivalent to three times the annual world consumption of magnesium in 2004. Overall, the reserves of the light metals are adequate to cope with anticipated demands for some centuries to come. The extent to which they will be used would seem to be controlled mainly by their future costs relative

Table 1.2 Crustal abundance of major chemical elements (from Stanner, R. J. L., *American Scientist*, **64**, 258, 1976)

Element	% by weight
Oxygen	45.2
Silicon	27.2
Aluminium	8.0
Iron	5.8
Calcium	5.06
Magnesium	2.77
Sodium	2.32
Potassium	1.68
Titanium	0.86
Hydrogen	0.14
Manganese	0.10
Phosphorus	0.10
Total	99.23

to competing materials such as steel and plastics, as well as the availability of electrical energy that is needed for their extraction from minerals.

1.1.3 Trends in production and applications

Trends in the production of various metals and plastics are shown in Fig. 1.4 and it is clear that the light metals are very much materials of the twentieth century. Between 1900 and 1950, the annual world production of aluminium increased 250 times from around 6000 tonnes to 1.5 million tonnes. A further eightfold increase took place during the next quarter century when aluminium surpassed copper as the second most used metal.

During this period the annual rate of increase in aluminium production averaged 9.2%. Since the late 1970s the demand for most basic materials has fluctuated and overall annual increases have been much less (Fig. 1.4). These trends reflect world economic cycles, the emergence of China and the Russian Federation as major trading nations, and the greater attention being given to recycling. World

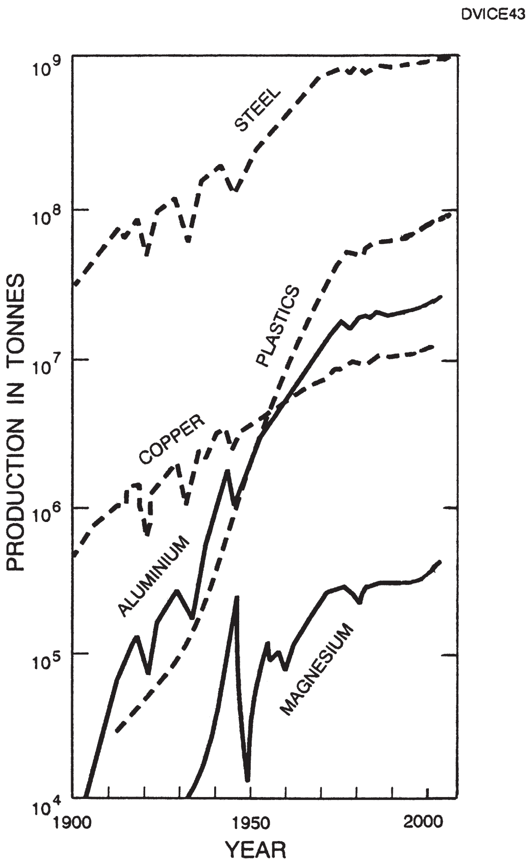

Fig. 1.4 World production figures for various metals and plastics.