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Introduction

The need to know

Much of the world's wealth is the product of manufacturing industry. Even in instances where a valuable commodity is not specifically shaped into a manufactured product, as, for example, oil, minerals, diamonds or gold, nevertheless elements of engineering thought go into their processing and final presentation to a customer. However, the vast majority of manufactured goods represent the fruits of teamwork in industry, involving activity by planners as well as by machine operators. The artifacts with which we are all surrounded have been manufactured industrially on the basis of ideas from a variety of people. Being made of materials of one kind or another, it follows that the materials must have been selected by somebody. One purpose of this book is to help that somebody, be he a designer, a practising engineer, a student or whoever, to become more aware of the world of materials technology with which he has to be concerned.

In the twentieth century, no man can be an expert on all those aspects of a saleable article. Even though a craftsman whittling a wooden object may have a deep knowledge of the characteristics of wood as it responds to a sharpened carving tool, he will probably know little of the complex chemistry and biology of the material on which he is working. Even more remote is the likelihood that a designer, choosing a metal for a particular application, will be equally expert in its chemical corrosion properties, its morphology, its strength characteristics and the routes by which the metal is processed, to mention only a few of the aspects affecting selection. Let us assume, therefore, that anyone selecting materials will more often than not need the benefit of expert advice. One of the first questions to be raised, of course, is: 'Where can this advice be obtained?' This book seeks to answer that question and also many of the others which will crowd into the originator's brain at the beginning of a new project. How much needs to be known about service conditions to which the product will be

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exposed? What are the manufacturing routes by which it can be made most cheaply? What constraints on supply of the material might operate if quantities are required over a short or long period?

As well as aesthetic and technological problems posed by a new product concept, the designer has to fight other, more mundane, battles. He needs the support of his employer, who in turn might need convincing that the designer's contributions as an originator, and as a coordinator, are vital to the business. The designer himself has to be aware of the various factors in engineering, materials technology and production processing (to name only a few) of which he inevitably must be a focus. He has to ensure that the design brief given him is relevant, complete and timely. These aspects of the design activity are covered in the early part of the book, to set the scene for its main thrust, that of available materials properties and routines for their selection.

The product in its environment

At the outset of a design study, the constraints on the project and the requirements for the new product have to be assessed. Compared to preceding similar products new factors must be identified, such as possibilities for improved or wider ranging performance, the effects of artificial and natural environments, reliability expectations, aesthetic features and achievable economies in materials and energy during production, service and later recycling. Increasing demands are always being made on materials, requiring them to present new capabilities in extreme environments. These, coupled with the need for low lifecycle costs, force the designer to think in terms of improved reliability and of lower failure rates when compared with past performance.

Apart from having to withstand natural atmospheric weathering conditions, materials for aerospace, marine, chemical and industrial engineering applications will be subjected to various specific artificial environments. Temperatures experienced by a material may range from those attained momentarily on the surface of a space re-entry vehicle, to the continuous sub-zero temperatures imposed by space exposure or in modern cryogenic systems. Exposure of materials to ultra-violet or other high-energy radiation will depend not only on the immediate world climatic zone but also on distance from the earth's surface. Contact with water may range from the very low humidities at certain parts of the earth's crust to deep submergence situations in oceans. Additionally, while in service, materials may be subjected to long-term sustained stresses (potentially leading to creep) or to cyclic stresses of constant or varying amplitude, perhaps imposed by acceleration, vibration or impact, and likely to produce fatigue effects.

Consequently, during the design and development of a product, knowledge

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of the environmental performance of candidate materials is essential to ensure reliability in service during an adequate and predetermined lifetime.

The materials cycle

Materials may be described as one of the connective tissues of national and world economics; recently a system-concept has been derived; the 'materials cycle', of which the designer must be aware.

The materials cycle reflects the situation that only a few materials are extracted from the earth by mining, drilling and harvesting. They are processed into bulk supplies, for example of metals, cement, clay, timber, natural rubber and petrochemicals. Alloys, glass, ceramics, bricks, plastics, elastomers and composites are produced from these bulk materials and subsequently worked up and assembled into structures, machines and consumer products. After use, discarded products are returned to the materials cycle for reclamation or for disposal by burning or burial. Many sectors of the materials cycle show strong interactions between energy utilisation, materials supply and the environment. For example, careless disposal of rejected waste from metal extractive processes can produce undesirable social and biological effects on general and local environment, and can also lock up other metals in a form not economically recoverable.

The close interplay between utilisation of materials and energy is particularly evident in the US economy. About one third of the energy consumed by American industry relates to the value added to extracted primary materials by their purification, production and subsequent fabrication. Selection of materials suitable for releasing or converting forms of energy is itself crucial. Many of the advanced energy conversion technologies such as gas turbines, nuclear reactors, magneto-hydrodynamics, solar energy and fossil fuel conversion, are at present materials-limited in terms of efficiency, reliability, safety and cost effectiveness. Even renewable energy resources such as wind, waves and biomass pose secondary materials problems in construction of effective operational machinery.

The materials cycle provides an analytical framework for examining perturbations in materials availability with respect to the whole world, a country, an industry, a company or a workplace. Flow rate of materials anywhere in the cycle can be affected by economic, political or social decisions made in other parts of the circuit. When analysed in this context, materials shortages are often found not to be caused by actual scarcity of natural resources, but rather by dislocations in the cycle which interfere with the anticipated arrival of materials, at appropriate manufacturing stages, in the required amounts and at reasonable prices. An example of this occurs when processing or transportation capacity in the car industry become inadequate somewhere in the cycle; this is

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seen at times of industrial unrest when components suppliers are unable to deliver the goods and centralised car assembly is thus impeded.

The role of processing

Reliability of an engineering structure or a component depends on the materials used, their properties, the influence of uncorrected defects, the processing or fabrication technique selected (and especially on any sensitivity of the materials to processing), and response to service environments. Failure of a material or product under stress is determined by the growth of defects which may originally have been present, and the subsequent propagation of cracks. Reliability demands the application of manufacturing techniques which reduce the incidence of crack initiators.

Optimisation of processing conditions is not easy, and fabrication and service requirements may conflict. For example, incorrect fabrication of fibre-reinforced synthetic resin composites can give rise to thermal stresses which may induce crack formation during subsequent use. To minimise this effect, low temperature curing systems should be selected. This, however, imposes a constraint on subsequent high-temperature use in service, because resins suitable for such performance usually require an elevated temperature cycle to cure them properly. A compromise between optimum service performance, processability and cost benefits may be necessary. Because of this, materials engineering in the true sense of the words has to be employed to select a ‘best material’ for the intended end use.

Materials structures

Materials science, technology and engineering are interdisciplinary activities concerned with the generation and application of knowledge relating to the composition, structure and processing of materials, the properties of which control end uses. Some parts of this spectrum of activities, when observed narrowly, may be regarded as science-dominated, whereas other parts may be engineering-dominated. No person educated only in a single discipline can hope to excel unaided in this broad field.

Literature offers excellent descriptions of the history of materials technology and materials, and of their use in jewellery, other art forms, ceramics, textiles, tools and weapons. Invariably, attention is drawn to the transition from the craftsman, with his molecular composition materials approach, to the present day structural – atomistic approach adopted by the professional technologist.

The structural – atomistic approach to materials has largely derived from increasingly penetrating experimental techniques to investigate their internal structure. Optical microscopy can be used to examine coarse microstructure, electron microscopy interprets sub-structure, crystal and molecular structures

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are investigated by X-ray diffraction, and atomic structure by various excitation spectroscopy methods. Nuclear structure is elucidated by high energy bombardment of materials with sub-atomic particles.

Scientific knowledge accruing from these investigations has accelerated development of new man-made engineering materials such as synthetic fibres, plastics, elastomers, high strength and high temperature metal alloys, ceramics, glasses and composite materials. It behoves the designer to know something of these, and they are discussed in later chapters.

Engineering materials can be categorised either as crystalline solids, in which atoms and molecules are stacked in a more-or-less regular array, as with metals, or as amorphous materials having unique rheological properties and no long-range atomic structure. Plastics and elastomers fall into this class. There are, of course, many intermediate forms of structure: few amorphous materials have no crystalline areas at all; metals are always crystalline unless very specially treated.

The study of materials science, technology and engineering has been defined in terms of three different levels of materials structure, which control properties and from which an understanding of materials behaviour can be obtained.

At the engineering level, a material can be considered as continuous and homogeneous, average properties being assumed to apply throughout the whole volume. This approach rationalises evaluation of mechanical properties with large test specimens, under conditions closely resembling those prevailing in an engineering structure. One example is the use of steel to fabricate a beam.

A material at the microstructural level may be considered as a composite of different phases. These phases may be similar, as in metals, and may be in thermodynamic equilibrium, or may comprise a mixture of dissimilar and unrelated solids, for example fibre-reinforced composites. At the microstructural level generalised treatments for the understanding of multiphase materials behaviour can be developed. This approach can explain the mechanical behaviour of cast iron.

At the molecular level, a material is considered as made up of discrete particles of molecular size. This concept is used to explain the melting behaviour of solids. Although there is some limited relationship to the engineering and materials structural levels, the discrete atomic particles and discontinuities at molecular levels represent a different order of behaviour, and offer difficulties in visualising conceptual links with the other two levels. Thus one cannot readily look at a molecular structure and deduce from it a valid range of materials properties in samples of a size appropriate to engineering uses.

Stemming from an understanding of materials microstructural and molecular status, modification and development have led to advances in polymer molecular engineering to produce, for example, isotactic and syndiotactic

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polymers. Similarly, in metallurgy, developments include production of unidirectionally solidified alloys; glasses have been highly refined in the quest for communication by fibre optics.

The foregoing exposition seeks to convince the reader that more than a superficial review of published materials properties is needed to achieve proper comprehension of the subject.

Selecting materials

Selection of material for a specified application is one of the earliest and most important design decisions in product development. Expert judgement is required to ensure that the material will be suitable with respect to cost, for manufacturability of the structure or component, and to meet in-service performance specifications. Such considerations are not mutually exclusive, but all decisions about them must be recognised as compromises balancing trade-offs between different levels of reliability, performance and maintainability in order to achieve minimum lifetime cost.

For good design decisions experience is irreplaceable, as it is seldom possible to analyse in depth, from first principles, all aspects of an engineering problem. As many decisions may perforce be made using inadequate data, it is obvious that seeking additional expert help should be considered in all but trivial cases, in order to broaden the experience base available (and to share the responsibility!)

Designers are ultimately limited by the properties of materials which can be obtained commercially. To make effective use of available data on materials properties, they should be aware that reported property values are influenced by variations in composition, by processing technology and by the test methods used to obtain the data. A 'gut-feeling' view of materials science will lead to appreciation of how property limitations might depend on the structure of material as considered at the three levels described earlier.

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The impact of design on manufacturing industry

The first assertion in the Introduction was that the designer has a key part to play in creation of wealth by manufacturing industry. A little more exploration of this theme seems justified to deal with the role of the design function and of the designer personally in industries which create goods from lower orders of materials supply. Various parts of this chapter will review how industry in turn sees the way in which design can serve its needs, and will focus on those specific contributions which the design office and the designer himself can make, provided that sufficient support facilities are offered to him. The chapter is rounded off in moving towards the central theme of this book by reviewing those aspects of design which are specifically important when selecting materials.

1.1 The role of design in product manufacturing

The prime purpose of design in industry is to maximise the value which purchasers of manufactured goods are likely to place on the finished product. Naturally, enhancement of this value is what manufacturing activity is primarily concerned with in a capitalist system. Industrial design recognises well-established customer preferences in the market place, often defined in terms of colour, texture, shape, safety features, and physical proportions, as well as less tangible manifestations of 'joy of ownership', such as reduction or elimination of dirt, heat, smell or noise, which might distinguish the product from competing or earlier offerings of the same kind. Furthermore customer preferences can sometimes, at least in the case of ephemeral products, be focused on novelty or on innovation for its own sake. Of perhaps greater importance to the controllers of industry is the thought that design can enhance the value of a product, in relation to competing products, by providing increased performance, durability, strength, improved functions, greater versatility or, of course, less cost.

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To achieve these ends the design function in a company or industry has to apply what are, by now, well-proven principles to ensure that all new features are properly evaluated and are then adopted, modified or discarded in accordance with the market being addressed. In this way, the manufacturing company can provide what the customer wishes to possess and is prepared to pay for.

Even in the present period of economic stringency and slow emergence from a long period of recession, still not enough people in industry or in the marketplace recognise the importance of good design to the success of a commercial enterprise. Although in the marketing of any goods, timeliness of delivery, quality and reliability must be maximised to compete successfully in world markets, particularly in the engineering industries, the other factor, that of design, can operate by making the product more appealing to the customer and hence provide a market-place advantage. Design also plays its part within the parent industry or company by improving the ease of production and the productivity of existing plant, thus enhancing the creation of wealth and retention of jobs.

That the design process must continually operate even in an established manufacturing operation, is obvious from a consideration of Figure 1.1, Judd (1984*a*). Here we see that each product offered in the market-place has a lifecycle. Research and development (R&D) enables its introduction to be effected, prior to the period of growth during which the product finds acceptance. After a while, it becomes mature, either through built-in obsolescence or as a result of new developments; by this time the far-seeing company will have replacement products already in the R&D stage. Inevitably (and this may occupy a period of months or of decades), the product will go into market decline, and decisions must be made as to whether any of the design features can be retained to produce a new revitalised product, or whether the operation has to be closed down to make way for an entirely new family of products.

Leslie (1982) discusses clearly the impact of industrial design awareness on a large multinational corporation. As new products become increasingly complex, and as more functions are required, improvements in industrial design and revision of human factors engineering become necessary. These together ensure that complex equipment can be accepted by a wide range of operators to reduce the likelihood both of long-term operating stress and a significant error rate in use. Another feature of the design process in industry is to enhance 'corporate image' which, of course, is of real value to the originating company only as long as its goods retain a well-deserved good name in the market-place. Leslie shows the necessity of a management programme at sufficiently high level to enable an industrial design department to be set up in the company. Not the least part of such a programme is recognition of the need for liaison between designers and experts in other fields such as materials, surface finishes,

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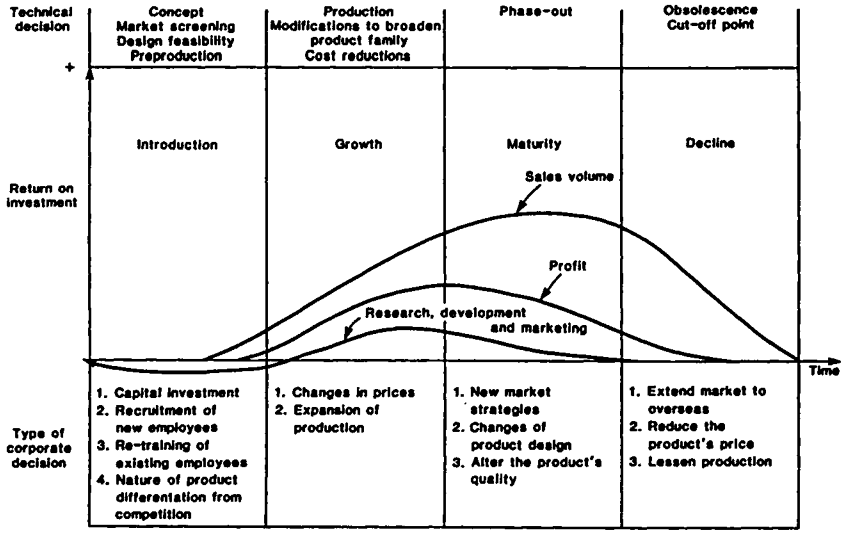
manufacturing technology, associated component part technology and international standards, some of which themes will be explored in later chapters. An industrial design team has to operate in close conjunction with other departments in a manufacturing enterprise; it is, as a consequence, very important that these other departments see their interaction with individual designers as an essential feature of success in the business, and not just as an irritating and unproductive side-line. This puts the onus back on designers, as they have to be aware of the basic knowledge available to the other people with whom they have to deal, so that they can discuss problems intelligently and, even more importantly, can understand the answers they receive from these other experts.

There is still a belief in industry that an industrial designer is no more than a stylist who attractively packages a product and, if lucky, provides some sort of a corporate identity to a range of related products. However, the true industrial designer has much more to offer than this. He must be able to appreciate all aspects of the service operation of equipment, to consider form and function independently and, by his creative skills, visualise a concept at an early stage and show it in a workable form which will appeal in the market-place. Technically sophisticated products may often only have been operated as laboratory models, and the designer has to transfer this functional concept into an attractive and useful product, often by considerable redesign of the original idea. The impact of a designer is, of course, maximised if he is brought in at the very earliest stage of a product concept, and this implies management awareness to

Fig. 1.1. Life cycle of a product. (After Judd 1984.)



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ensure that he is involved in meetings with others whose expertise will also be brought to bear on the problem.

Another area in which industrial design, and indeed the designer himself, can assist in maximising company profits, is to be aware of alternatives to traditional constructional materials, methods, surface finishes and so on, and perhaps also to be aware of newer production processes which might, if adopted, revolutionise the engineering and cost concept of a new development.

In short, although the design process varies between products, there are usually several well-defined stages in any development which should be followed in an accepted order. The first important step is to carefully define the brief given to the industrial designer, in order to establish the objectives and the various stages which are necessary to achieve them. Figures reflecting anticipated production quantities, and certainly the target selling price, should be produced at an early stage, since these can significantly affect the chosen design, which, of course, is always influenced by the existing manufacturing techniques and availability of plant at the time.

The second stage of the process is to look at the product concept as though one were a user, in order to determine how the product would be handled, by whom, and when. At this stage there could be involvement with codes of practice, accepted trade practices, patents, safety aspects, standardisation, and so on. Only then should the designer produce a number of sketches or models to illustrate his ideas, having collaborated with other technical experts so that their united skills can be brought to bear on the problem of achieving maximum innovation and marketability. Having done all this, the designer then finishes off the project by supervising the production of specifications, working drawings and models as necessary.

What has gone before really reflects the optimum situation based on a stable economy in a stable world. It presumes that designers are very important but are still only people in a team who can bring to bear only their own skills to the common good. However, there are views that the designer has a more important role in the community at large, and has responsibilities for the future of modern society. Rams (1983*a*) asserts that designers, particularly of modern products, are often confronted with adverse criticism deriving from the technology shock which sometimes occurs even in our own scientifically aware generation. A designer cannot drop out of society and take refuge in artistic activities only, in an effort to escape from technology. Designers really do have to be critics of civilisation, of technology and of society, and in this spirit should try continually to find something new and better which can stand up to informed criticism in the future. The designer must look at the socio-economic structure of the world and worry about socio-political conflicts between east and west or north and south, restrictions in trade, the impact of see-sawing energy prices,

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