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General introduction

Composites make up a very broad and important class of engineering materials. World annual production is over 10 million tonnes and the market has in recent years been growing at 5–10% per annum. Composites are used in a wide variety of applications. Furthermore, there is considerable scope for tailoring their structure to suit the service conditions. This concept is well illustrated by biological materials such as wood, bone, teeth and hide; these are all composites with complex internal structures designed to give mechanical properties well suited to the performance requirements. Adaptation of manufactured composite structures for different engineering purposes requires input from several branches of science. In this introductory chapter, an overview is given of the types of composite that have been developed.

1.1 Types of composite material

Many materials are effectively composites. This is particularly true of natural biological materials, which are often made up of at least two constituents. In many cases, a strong and stiff component is present, often in elongated form, embedded in a softer constituent forming the **matrix**. For example, wood is made up of fibrous chains of cellulose molecules in a matrix of lignin, while bone and teeth are both essentially composed of hard inorganic crystals (hydroxyapatite or osteones) in a matrix of a tough organic constituent called collagen (Currey 1983). Commonly, such composite materials show marked **anisotropy** – that is to say, their properties vary significantly when measured in different directions. This usually arises because the harder constituent is in fibrous form, with the fibre axes preferentially aligned in particular directions. In addition, one or more of the constituents may exhibit inherent anisotropy

as a result of their crystal structure. In natural materials, such anisotropy of mechanical properties is often exploited within the structure. For example, wood is much stronger in the direction of the fibre tracheids, which are usually aligned parallel to the axis of the trunk or branch, than it is in the transverse directions. High strength is required in the axial direction, since a branch becomes loaded like a cantilevered beam by its own weight and the trunk is stressed in a similar way by the action of the wind. Such beam bending causes high stresses along its length, but not through the thickness.

In making artificial composite materials, this potential for controlled anisotropy offers considerable scope for integration between the processes of material specification and component design. This is an important point about use of composites, since it represents a departure from conventional engineering practice. An engineer designing a component commonly takes material properties to be isotropic. This is often inaccurate even for conventional materials; for example, metal sheet usually has different properties in the plane of the sheet from those in the through-thickness direction, as a result of crystallographic texture (preferred orientation) produced during rolling – although such variations are in many cases relatively small. In a composite material, on the other hand, large anisotropies in stiffness and strength are possible and must be taken into account during design. Not only must variations in strength with direction be considered, but the effect of any anisotropy in stiffness on the stresses set up in the component under a given external load should also be taken into account. The material should be produced bearing in mind the way it will be loaded when it is made into a component. Thus, the processes of material production and component manufacture must be integrated into a single operation. This, of course, is exactly what happens when biological materials are produced.

There are several different types of composite. Examples of typical microstructures for the three main classes, grouped according to the nature of the matrix, are shown in Fig. 1.1. Most composites in industrial use are based on polymeric matrices; thermosets and thermoplastics. These are usually reinforced with aligned ceramic fibres, such as glass or carbon. They commonly exhibit marked anisotropy, since the matrix is much weaker and less stiff than the fibres. More recently, there has been considerable interest in metal matrix composites (MMCs), such as aluminium reinforced with ceramic particles or short fibres, and titanium containing long, large-diameter fibres. The property enhancements being sought by the introduction of reinforcement are often less pronounced

1.1 Types of composite material

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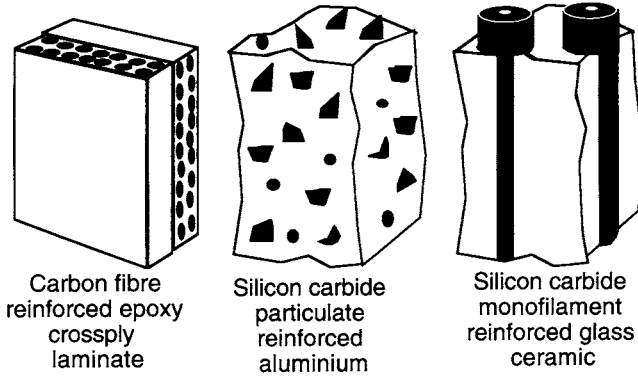


Fig. 1.1 Schematic depiction of representative polymer, metal and ceramic matrix composites.

than for polymers, with improvements in high-temperature performance or tribological properties often of interest. While various industrial applications have been developed or are being explored for MMCs, their commercial usage is still quite limited when compared to that of polymer composites (PMCs). Finally, composites based on ceramic materials (CMCs) are also being studied. The objective here is usually to impart toughness to the matrix by the introduction of other constituents, since the stiffness and strength are unlikely to be much affected. Such materials are still, for the most part, in the early stages of development, partly because they are rather difficult to manufacture.

In considering the formulation of a composite material for a particular type of application, it is important to consider the properties exhibited by the potential constituents. The properties of particular interest are the stiffness (Young's modulus), strength and toughness. Density is of great significance in many situations, since the mass of the component may be of critical importance. Thermal properties, such as expansivity and conductivity, must also be taken into account. In particular, because composite materials are subject to temperature changes (during manufacture and/or in service), a mismatch between the thermal expansivities of the constituents leads to internal residual stresses. These can have a strong effect on the mechanical behaviour. Some representative property data are shown in Table 1.1 for various types of matrix and reinforcement, as well as for some typical engineering materials and a few representative composites. Inspection of these data shows that some attractive property combinations (for example, high stiffness/strength and low density) can

Table 1.1. Overview of properties exhibited by different classes of material

| Type of material (example) | Density ρ (Mg m^{-3}) | Young's modulus E (GPa) | Tensile strength σ (MPa) | Fracture toughness K_{Ic} ($\text{MPa}\sqrt{\text{m}}$) | Thermal conductivity K ($\text{W m}^{-1}\text{K}^{-1}$) | Thermal expansivity α (10^{-6}K^{-1}) |
|--|---|------------------------------------|--|--|--|--|
| Thermosetting resin (epoxy) | 1.25 | 3.5 | 50 | 0.5 | 0.3 | 60 |
| Engineering thermoplastic (nylon) | 1.1 | 2.5 | 80 | 4 | 0.2 | 80 |
| Rubber (polyurethane) | 1.2 | 0.01 | 20 | 0.1 | 0.2 | 200 |
| Metal (mild steel) | 7.8 | 208 | 400 | 140 | 60 | 17 |
| Construction ceramic (concrete) | 2.4 | 40 | 20 | 0.2 | 2 | 12 |
| Engineering ceramic (alumina) | 3.9 | 380 | 500 | 4 | 25 | 8 |
| Wood (load // grain) | 0.6 | 16 | 80 | 6 | 0.5 | 3 |
| (spruce) (load \perp grain) | 0.6 | 1 | 2 | 0.5 | 0.3 | 10 |
| General PMC (in-plane) (chopped strand mat) | 1.8 | 20 | 300 | 40 | 8 | 20 |
| Adv. PMC (load // fibres) | 1.6 | 200 | 1500 | 40 | 200 | 0 |
| (APC-2) (load \perp fibres) | 1.6 | 3 | 50 | 5 | 40 | 30 |
| MMC (Al-20%SiC _p) | 2.8 | 90 | 500 | 15 | 140 | 18 |

1.2 Design of composite materials

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be obtained with composites. An outline of how such properties can be predicted from those of the individual constituents forms an important part of the contents of this book.

1.2 Design of composite materials

Choosing the composition and structure of a composite material for a particular application is not a simple matter. The introduction of reinforcement into a matrix alters all the properties. It is also necessary to take account of possible changes in the microstructure of the matrix resulting from the presence of the reinforcement. The generation of residual stresses from differential thermal contraction during manufacture may also be significant. Before considering such secondary effects, it is useful to take a broad view of the property combinations obtainable from different composite systems. This can be visualised using *property maps*. An example is presented in Fig. 1.2. This shows a plot of Young's modulus, E , against density, ρ . A particular material (or type of material) is associated with a point or a region. This is a convenient method of comparing the property combinations offered by potential matrices and reinforcements with those of alternative conventional materials.

Attractive matrix/reinforcement combinations can be identified by deriving a '*merit index*' for the performance required, in the form of a specified combination of properties. Appropriate models can then be used to place upper and lower bounds on the composite properties involved in the merit index, for a given volume fraction of reinforcement. The framework for such predictions has been set out by Ashby (Ashby 1993). An example is shown in Fig. 1.3 for three different fibres and a polymer matrix. The shaded areas joining the points corresponding to a fibre to that of the matrix represent the possible combinations of E and ρ obtainable from a composite of the two constituents concerned. (The density of a composite is given simply by the weighted mean of the constituents; the stiffness, however, can only be identified as lying between upper and lower bounds – see Chapter 4 – unless more information is given about fibre orientation.)

Also shown on Fig. 1.3 are lines corresponding to constant values of the ratios E/ρ , E/ρ^2 and E/ρ^3 . These ratios represent the merit indices to be maximised to obtain minimum component weight consistent with a maximum permissible deflection for different component shapes and loading configurations. For example, the lightest square-section beam able to support a given load without exceeding a specified deflection is

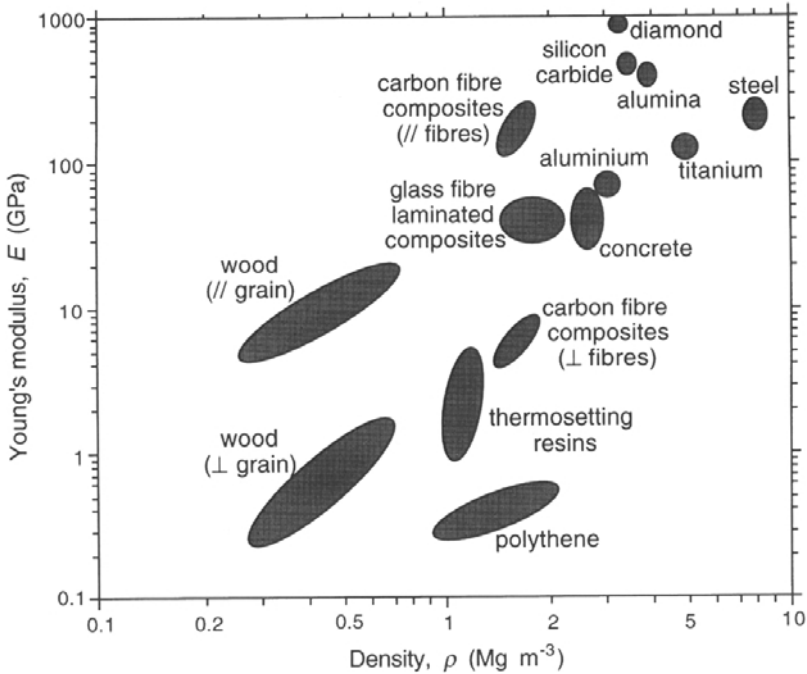


Fig. 1.2 Data for some engineering materials in the form of areas on a map of Young's modulus E against density ρ .

the one made of the material with the largest value of E/ρ^2 . It can be seen from the figure that, while the introduction of carbon and silicon carbide fibres would improve the E/ρ ratio in similar fashions, carbon fibres would be much the more effective of the two if the ratio E/ρ^3 were the appropriate merit index.

1.3 The concept of load transfer

Central to an understanding of the mechanical behaviour of a composite is the concept of load sharing between the matrix and the reinforcing phase. The stress may vary sharply from point to point (particularly with short fibres or particles as reinforcement), but the proportion of the external load borne by each of the individual constituents can be gauged by volume-averaging the load within them. Of course, at equilibrium, the external load must equal the sum of the volume-averaged loads borne by

1.3 The concept of load transfer

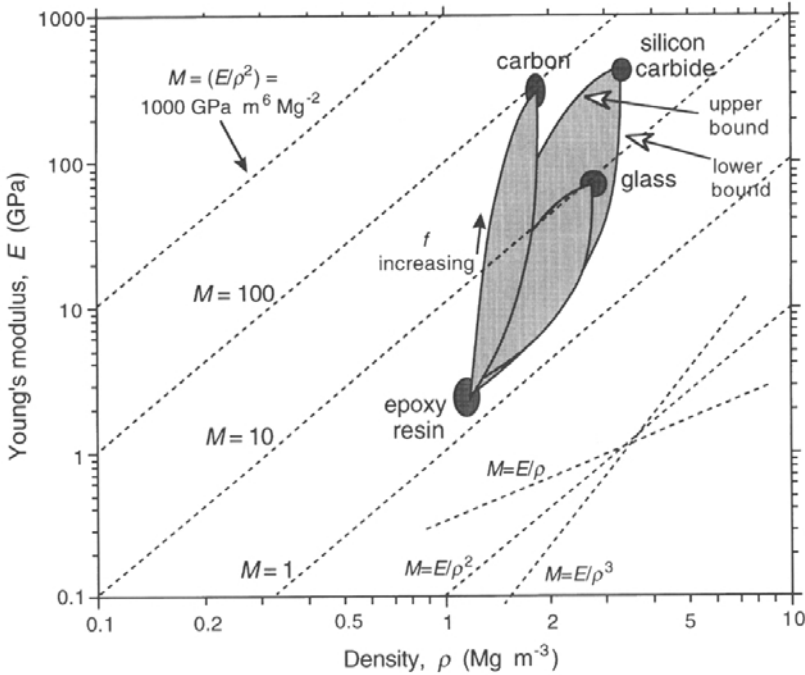


Fig. 1.3 Predicted map of Young’s modulus E against density ρ for composites of glass, carbon or silicon carbide fibres in a matrix of epoxy resin. The shaded areas are bounded by the axial and transverse values of E predicted for the composite systems. The diagonal dotted lines represent constant values of three merit indices (E/ρ , E/ρ^2 and E/ρ^3). For the E/ρ^2 case, several lines are shown corresponding to different values of the ratio.

the constituents[†] (e.g. the matrix and the fibre). This gives rise to the condition

$$f\bar{\sigma}_m + (1 - f)\bar{\sigma}_f = \sigma_A \tag{1.1}$$

governing the volume-averaged matrix and fibre stresses ($\bar{\sigma}_m$, $\bar{\sigma}_f$) in a composite under an external applied stress σ_A , containing a volume fraction f of reinforcement. Thus, for a simple two-constituent composite under a given applied load, a certain proportion of that load will be carried by the fibre and the remainder by the matrix. Provided the response of the composite remains elastic, this proportion will be inde-

[†]In the absence of an externally applied load, the individual constituents may still be stressed (due to the presence of residual stresses), but these must balance one another according to Eqn (1.1).

pendent of the applied load and it represents an important characteristic of the material. It depends on the volume fraction, shape and orientation of the reinforcement and on the elastic properties of both constituents. The reinforcement may be regarded as acting efficiently if it carries a relatively high proportion of the externally applied load. This can result in higher strength, as well as greater stiffness, because the reinforcement is usually stronger, as well as stiffer, than the matrix. Analysis of the load sharing which occurs in a composite is central to an understanding of the mechanical behaviour of composite materials.

References and further reading

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Fibres and matrices

In this chapter, the underlying science of fibres and matrices is described. Some specific examples are given to illustrate the key factors involved. A wide range of reinforcements, mostly in the form of fibres, is now available commercially. Their properties can be related directly to the atomic arrangement and the defect content of the reinforcement, which must be controlled in the manufacturing processes. Matrices may be based on polymers, metals or ceramics. The choice of matrix is related to the required properties, the intended applications of the composite and the method of manufacture. The properties of the matrix depend on microstructure which, in turn, depends on manufacturing route and subsequent thermal and mechanical treatments. Certain properties of the composite may be sensitive to the nature of the reinforcement/matrix interface; this topic is covered in detail in Chapter 7.

2.1 Reinforcements

Many reinforcements are now available, some designed for a particular matrix system. A selection is listed in Table 2.1. Typical properties of fibres are given in Table 2.2. All have high stiffness and relatively low density. Carbon, glass and aramid fibres are now used extensively in polymer matrix composites. Carbon fibres are also important for carbon/carbon composites. Ceramic fibres, whiskers and particles can be used to reinforce metal and ceramic matrices.

2.1.1 Carbon fibres

In a graphite single crystal, the carbon atoms are arranged in hexagonal arrays, stacked in a regular ABABAB... sequence. The atoms in these

Table 2.1 *Some common types of reinforcement*

| Form | Size (μm) | | Fabrication route | Examples |
|--|------------------------|----------|--|---|
| | d | L | | |
| <i>Monofilaments</i> (large-diameter single fibres) | 100–150 | ∞ | CVD onto core fibres (e.g. of C or W) | SiC (SCS-6 TM) Boron |
| <i>Multifilaments</i> (tows or woven rovings with up to 14 000 fibres per strand) | 7–30 | ∞ | Precursor stretching; pyrolysing; melt spinning | Carbon (HS & HM) Glass Nicalon TM Kevlar TM 49 FP TM alumina |
| <i>Short fibres</i> (staple fibres aggregated into blankets, tapes, wool, etc.) | 1–10 | 50–5000 | Spinning of slurries or solutions, heat treatment | Saffil TM Kaowool Fiberfrax TM |
| <i>Whiskers</i> (fine single crystals in loose aggregates) | 0.1–1 | 5–100 | Vapour phase growth/reaction | SiC Al ₂ O ₃ |
| <i>Particulate</i> (loose powder) | 5–20 | 5–20 | Steelmaking byproduct; refined ore; sol-gel processing, etc. | SiC Al ₂ O ₃ B ₄ C TiB ₂ |

basal planes are held together by strong covalent bonds, with only weak van der Waals forces between them. The basic crystal units are therefore highly anisotropic; the in-plane Young's modulus (normal to the c -axis) is about 1000 GPa, while that perpendicular to the basal planes (parallel to the c -axis) is only 35 GPa.

Carbon fibres, which are typically about 8 μm in diameter, consist of small crystallites of 'turbostratic' graphite, one of the allotropic forms of carbon. Turbostratic graphite closely resembles graphite single crystals, except that the layer planes are not regularly packed in the c -axis direction. The structure is represented schematically in Fig. 2.1. To obtain high axial modulus and strength, good alignment of the basal planes parallel to the fibre axis is required. The arrangement of the layer planes in the cross-section of the fibre is also important, since it affects the transverse and shear properties. Compilations are available (Weeton *et al.* 1987) of the properties exhibited by commercially used carbon fibres.