1 General Introduction

The usage of composite materials continues to expand rapidly. The current world-wide market value is not easy to estimate, but is certainly more than US$100 billion. Composites now constitute one of the broadest and most important classes of engineering materials – second only to steels in industrial significance and range of applications. There are several reasons for this. One is that they often offer highly attractive combinations of stiffness, strength, toughness, lightness and corrosion resistance. Another is that there is considerable scope for tailoring their structure to suit service conditions. This concept is well illustrated by biological materials such as wood, bone, teeth and hide, which are all composites with complex internal structures that have been designed (via evolutionary processes) to give mechanical properties well suited to the performance requirements. This versatility is, of course, attractive for many industrial purposes, although it also leads to complexity that needs to be well understood if they are to be used effectively. In fact, 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 composites 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 and more compliant 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 (hydroxy-apatite or osteones) in a matrix of a tough organic constituent called collagen. Many of the complexities of the structure and properties of bone are well illustrated in the extensive work of Currey [1,2] and a brief survey of biological composites is presented later in this book (Chapter 13).

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 (and stiffer) 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,

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T. W. Clyne , D. Hull
Excerpt
More Information

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 the 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. In fact, this is often inaccurate even for conventional materials. For example, metal sheet usually has different properties in the plane of the sheet than 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 created in the component under external load should also be taken into account. The material can thus be produced bearing in mind the way it will be loaded when it is made into a component, with the processes of material production and component manufacture being integrated into a single operation. This happens when biological materials are produced. In fact, the fine-scale structure of a natural material such as wood is often influenced during its creation by stresses acting on it at the time.

There are several different types of composite. Examples of possible configurations with different types of reinforcement are shown in Fig. 1.1. The matrix material may be polymeric, metallic or ceramic, although by far the largest proportion of composites in

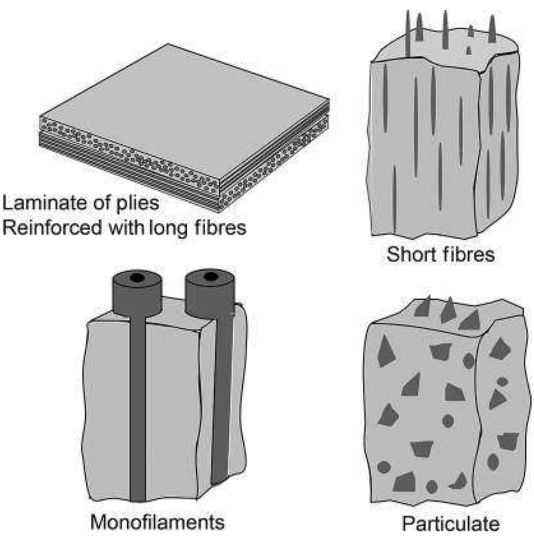

Fig. 1.1 Schematic depiction of different types of reinforcement configuration.

industrial use are based on polymers – predominantly thermosets (resins), although in some cases thermoplastics are used. Reinforcements are usually ceramics of some sort, most commonly long fibres of carbon or glass. It should, however, be appreciated that other types of fibre, including polymeric and metallic forms, are used in commercial composite materials and that there are also materials containing short fibres or particulate reinforcement. Composites with metallic or ceramic matrices (MMCs and CMCs) are also of industrial significance. Furthermore, it should be noted that there is extensive ongoing research into novel types of composite. As might be expected, property enhancements sought by the introduction of reinforcement into metals or ceramics are often less pronounced that those for polymers, with improvements in high-temperature performance or tribological properties often of interest for MMCs. With CMCs, on the other hand, the objective is usually to enhance the toughness of the matrix. With all three types of matrix, there is enormous potential for achieving property combinations that are unobtainable in monolithic materials.

In considering the formulation of a composite material for a particular type of application, a starting point is clearly to consider the properties exhibited by the potential constituents. Properties of particular interest include the stiffness (Young's modulus), strength and toughness. Density is also 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 indicative property data are shown in Table 1.1 for a few engineering materials, including some composites. These values are very approximate, but they immediately confirm that some attractive property combinations (for example, high stiffness/strength/toughness, in combination with low density) can be obtained with

Table 1.1 Overview of properties of some engineering materials, including composites.

Material	Density ρ (kg m^{-3})	Young's modulus E (GPa)	Tensile strength σ_* (MPa)	Fracture energy G_c (kJ m^{-2})	Thermal conductivity K (W m^{-1} K^{-1})	Thermal expansivity α (με K^{-1})
Mild steel	7800	208	400	100	40	17
Concrete	2400	40	20	0.01	2	12
Spruce (// to grain)	600	16	80	4	0.5	3
Spruce (⊥ to grain)	600	1	2	0.2	0.3	10
Chopped strand mat (in-plane)	1800	20	300	30	8	20
Carbon fibre composite (// to fibres)	1600	200	1500	10	10	0
Carbon fibre composite (⊥ to fibres	1600	10	40	0.2	2	30
Al-20% SiC_p (MMC)	2800	90	300	2	140	18

composites. They also, of course, highlight the potential significance of anisotropy in the properties of certain types of composite. An outline of how such properties can be predicted from those of the individual constituents forms a key part of the contents of this book.

1.2 Property Maps and Merit Indices for Composite Systems

Selecting the constituents and structure of a composite material for a particular application is not a simple matter. The introduction of reinforcement into a matrix alters all of its properties (assuming that the volume fraction, f, can be regarded as significant, which usually means more than a few per cent). It may also be 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 (for example, 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 with different composite systems. This can be visualised using *property maps*. Two examples are presented in Fig. 1.2. These shows plots of: (a) Young's modulus, E; and (b) hardness,[1] H, against density, ρ. A particular material (or type of material) is associated with a point or a region in such maps. This is a convenient method of comparing the property combinations offered by potential matrices and reinforcements with those of alternative conventional materials.

Of course, in general, attractive combinations of these two pairs of properties will lie towards the top-left of these diagrams, although in the case of hardness it should be appreciated that this is a relatively complex 'property' that depends to some extent on microstructure (whereas both stiffness and density are more or less independent of microstructure for a particular type of material). Once the properties of a particular type of composite have been established, then they can, of course, be included in maps of this type. An example is shown in Fig. 1.3, which compares approximate combinations of E and ρ expected for some composite materials with those for materials such as steel, titanium and alumina.

This concept can often be taken a little further by identifying 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 manipulations was set out in Ashby's seminal work [3], which he also oriented specifically towards composites [4]. An example is shown in Fig. 1.4 for three different fibres and a polymer matrix. The shaded areas joining the points corresponding

[1] Hardness is not really a 'genuine' property, although it is a measure of the resistance that the material offers to plastic deformation and is related to the yield stress, σ_Y, and the work-hardening characteristics. It is obtained from the size of an indent produced by an applied load. This is a simple and quick procedure, but hardness values vary with indenter shape and load, since these affect the plastic strains induced. If work-hardening is neglected, then the (Vickers) hardness is expected to have a value of around $3\sigma_Y$.

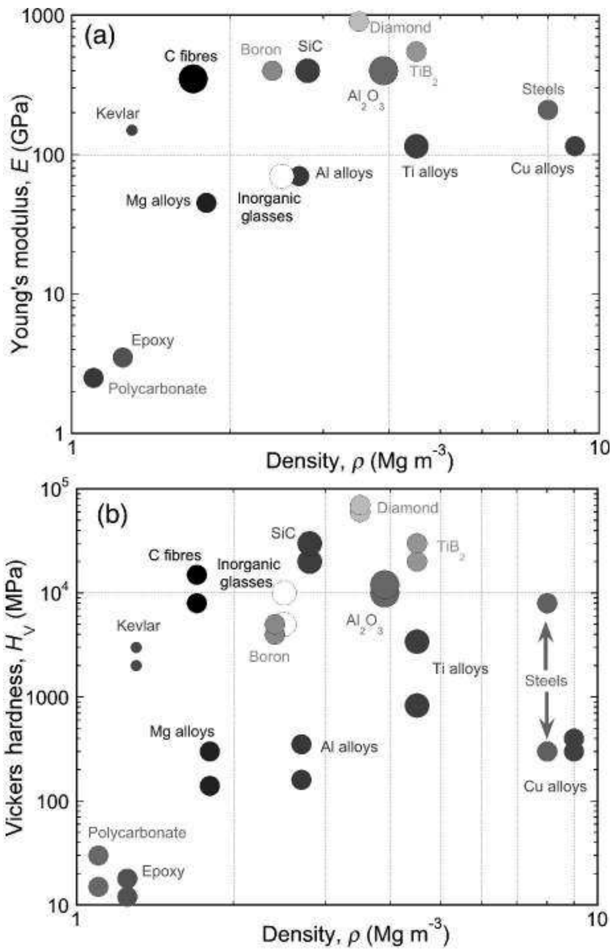

Fig. 1.2 Maps of (a) stiffness and (b) hardness against density, for a selection of metals, ceramics and polymers.

to a fibre to that of the matrix (epoxy resin) 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.) As can be seen in the figure, it is also possible to carry out this operation with the 'reinforcement' being holes – i.e. to consider the creation of foams. As with fibres, the architecture of the porosity is important, and could be such as to cause anisotropy.

Also shown in Fig. 1.4 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

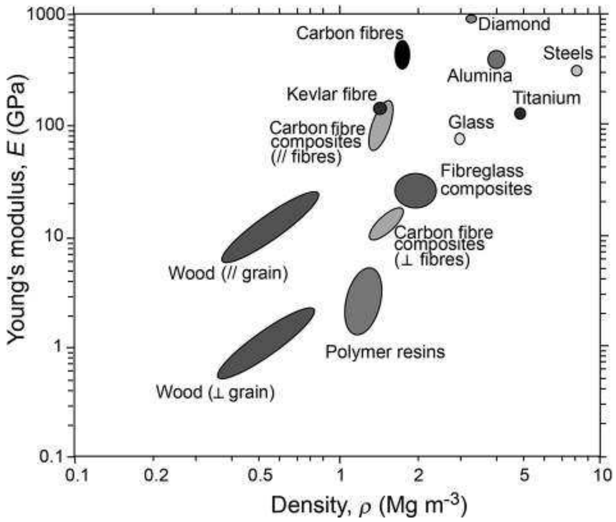

Fig. 1.3 Map of stiffness against density for some common materials, including some fibres and composites.

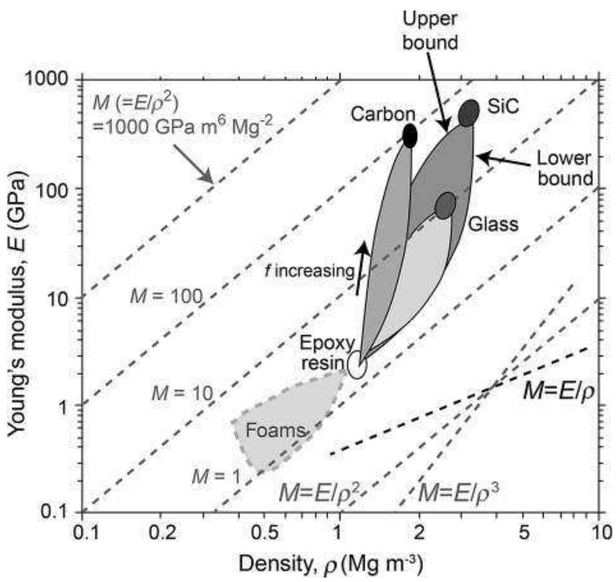

Fig. 1.4 Predicted map of stiffness against density for composites of glass, carbon or SiC fibres in a matrix of epoxy resin. Also shown is the effect of introducing porosity (to create foams). The shaded areas are bounded by the axial and transverse values of E predicted for these composite systems. The diagonal dotted lines represent constant values of three merit indices (E/ρ, E/ρ^2 and E/ρ^3). For E/ρ^2, several lines are shown corresponding to different values of the ratio.

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section beam able to support a given load without exceeding a specified deflection is 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. Also notable is that a foam could perform better (i.e. give a lighter component capable of bearing a certain type of load) than the monolithic matrix, particularly if the loading configuration is such that the merit index is E/ρ^3.

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 the constituents (e.g. the matrix and the fibre).[2] This gives rise to the condition

$$f\bar{\sigma}_{\mathrm{f}} + (1-f)\bar{\sigma}_{\mathrm{m}} = \sigma_{\mathrm{A}} \tag{1.1}$$

governing the volume-averaged matrix and fibre stresses ($\bar{\sigma}_{\mathrm{m}}$,$\bar{\sigma}_{\mathrm{f}}$) 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 fibres and the remainder will be carried by the matrix. Provided the response of the composite remains elastic, this proportion will be independent 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 that occurs in a composite is central to an understanding of the mechanical behaviour of composite materials.

The above concept constitutes an important criterion for distinguishing between a genuine composite and a material in which there is an additional constituent – for example, there might be a fine dispersion of a precipitate – that is affecting the properties (such as the yield stress and hardness), but is present at too low a volume fraction to carry a significant proportion of an applied load.

[2] 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 each another according to Eqn (1.1).

References

1. Currey, JD, The many adaptations of bone. *Journal of Biomechanics* 2003; **36**: 1487–1495.
2. Currey, JD, The structure and mechanics of bone. *Journal of Materials Science* 2012; **47**: 41–54.
3. Ashby, MF, *Materials Selection in Mechanical Design*. Pergamon Press, 1992.
4. Ashby, MF, Criteria for selecting the components of composites: overview No. 106. *Acta Metallurgica et Materialia* 1993; **41**: 1313–1335.