BENEFITS OF FIBER AND PARTICULATE REINFORCEMENT

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Contents

Summary

Fiber and particulate reinforcement of materials is considered. Generic themes addressed include the range of types of reinforcement together with their effects on mechanical properties and processing. The different issues associated with reinforcing various matrices are addressed - the high specific strength and stiffness associated with continuous fiber reinforced polymers, the enhancement of stiffness and strength of

particulate reinforced metals and the increase in toughness associated with reinforcement of ceramics. The disadvantageous aspects of reinforcing different matrices, which may be associated with cost, difficulties in processing and also reduction in some properties, are addressed. Applications of reinforced materials and future trends are also discussed.

1. Introduction

Materials containing fiber or particle reinforcement belong to the class of materials known as *composite* materials. A composite material may be defined as a multi-phase material in which the phase distribution and geometry have been controlled in order to optimize one or more properties. The number of naturally occurring and man-made materials that fall into this category is considerable. Most usually the term "composite" is applied only to systems in which the structure has been deliberately tailored. In a composite one phase is usually continuous and is designated the "matrix" and the other phase (the "reinforcement") is distributed within the matrix and may be fibrous or particulate. In some composites there may be two interpenetrating continuous phases, while in others there need be no continuous phase. Within the present article, attention will focus on materials that are composite in nature, i.e. structural elements/components (such as sandwich panels or bimetallic strips), which comprise more than one material, are not covered. Further, the *scale* of reinforcement, which will be considered, is at the level of micrometers or larger, thereby excluding groups of materials such as rubber particle toughened polymers.

The matrix and reinforcement in a composite can be metallic, ceramic or polymeric in nature. There are rather different mechanical property considerations involved with the introduction of reinforcement into different types of matrix material. For instance, polymer matrix composites, with continuous fiber reinforcement, offer significant improvements in stiffness and strength compared to the unreinforced polymer matrix. Metal matrix composite systems offer enhanced stiffness and temperature capability over the parent matrix, but reduced ductility. The aim in reinforcing ceramic materials is to increase the toughness without compromising the many attractive properties of the parent ceramic such as stiffness, wear resistance and refractoriness. As well as their mechanical properties, composites may be designed to have unique physical properties - for instance metal matrix systems can be produced with almost complete dimensional stability over a wide range of temperature, which is of benefit in space applications.

The intention in producing a composite material is to make a material that combines the best properties of both phases whilst eliminating (or at least minimizing) any poor properties. In fact it is sometimes the situation that a composite can have better properties than either phase individually. This is because of the way in which the phases interact. In particular, there is an interfacial region where the matrix and reinforcing phases bond to each other and improved properties of the composite relative to the constituent materials are often associated with this region, a particular example being the toughness of polymer matrix composites.

The aim of the present article is to provide an overview of reinforced materials. The focus will be on continuous fiber reinforcements since they bring about the largest changes in properties for all categories of matrix material. Since structural applications are the largest application sector at present and polymer composites have by far the largest proportion of the composite market, the emphasis will be on these areas. Firstly, some of the key aspects of using reinforcements will be discussed in a generic way, with sub-sections, which consider types of reinforcement, basic mechanical behavior and processing. The different matrix types (polymer, metal, ceramic) will be covered in more detail later in the article. A final section provides a brief summary and highlights some areas of current interest.

2. Types of Reinforcement

The reinforcing phase in a composite can be present in a number of different formats, e.g. continuous filament, short fiber, platelet, spheroid, sphere or irregular, and is classified by its shape, aspect ratio(s), geometric arrangement and concentration. Continuous fiber reinforcement may be uni-axial, bi-directional in plane, multi-directional in-plane, random planar or three dimensional (see Figure 1).

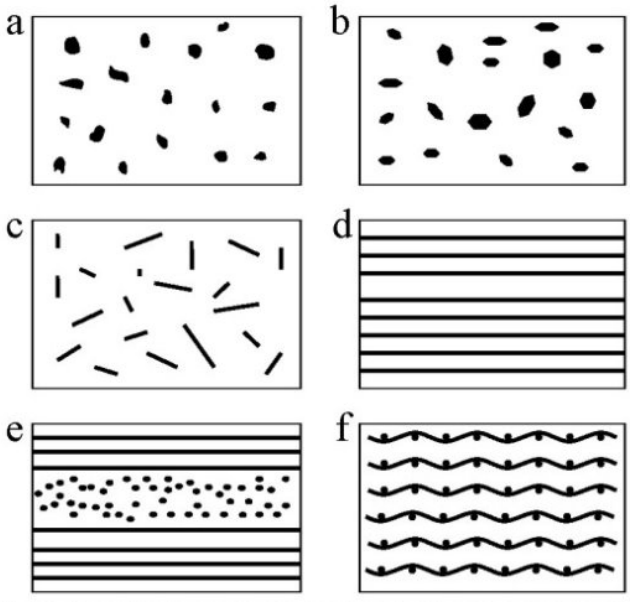

Figure 1. Schematic and not-to-scale diagrams showing the various formats available for the reinforcing phase: (a) particles, (b) platelets, (c) whiskers or short fibers, (d) unidirectional continuous fibers, (e) cross-ply continuous fibers and (f) woven tows of fibers. (a) to (d) show plan views while (e) and (f) are edge views.

Of the various reinforcement types, those based on continuous fibers provide the best mechanical properties, when loaded parallel to the fiber direction. Particulate systems, although locally heterogeneous in nature, remain predominantly isotropic in their physical and mechanical behavior. Short fiber systems are often planar isotropic. Continuous fiber systems exhibit considerable anisotropy, *i.e.* the properties along the fiber direction are very different from those perpendicular to the fiber direction. This anisotropy can be very beneficial in certain applications but if a more isotropic behavior is desired then laminates may be assembled, comprising layers of fibers oriented at a number of different angles. Other types of continuous fiber system are based on woven cloth, which provides reinforcement in two orthogonal directions, or non-crimp fabrics, which comprise layers of fibers at various orientation held together with through-thickness stitches. The stitches present in non-crimp fabrics provide through-thickness reinforcement, which improves the properties (strength and toughness) in this direction. Composites based on woven fabric reinforcement offer greater flexibility in processing (especially with regard to drape), compared to their non-woven counterparts, while maintaining adequate mechanical properties.

As indicated above, fiber reinforcement can be obtained from suppliers in a number of forms, *e.g.* continuous or chopped rovings/tows, chopped-strand mat, swirl mat, woven fabrics, non-crimp fabrics or even knitted pre-forms, tailored to the shape of the eventual component. These fibers then have to be combined with the matrix in some way. Alternatively, for continuous fiber materials, material may be available in an intermediate form, where it has already been combined with the matrix. For polymer matrix composites, "pre-pregs" are an intermediate form, in which the fiber (glass, carbon or aramid) has been combined with a partially cured thermosetting resin. Layers of pre-preg (typically 0.125 mm thick for unidirectional reinforcement, at least twice this thickness for fabric-based pre-preg with orthogonal fibers) can be laid up with the reinforcement at specific orientations and consolidated at temperature and pressure to give a rigid laminate. An analogous processing route has been devised for the processing of fiber reinforced glass and glass-ceramic composite systems such as SiC (silicon carbide) reinforced borosilicate glass and SiC reinforced alumino-silicate glass-ceramics. The process involves drawing bundles of fibers through a slurry. The tows are then wound on to a mandrel to form a tape, which can then be cut and stacked at the required orientations, prior to the burn-out of the binder and hot-pressing. For some metal matrix systems there is also an intermediate form derived from placing arrays of fibers between thin metallic foils (this can be done practically by means of a filament winding operation) prior to hot pressing. This technique is in commercial use for titanium matrices reinforced with SiC.

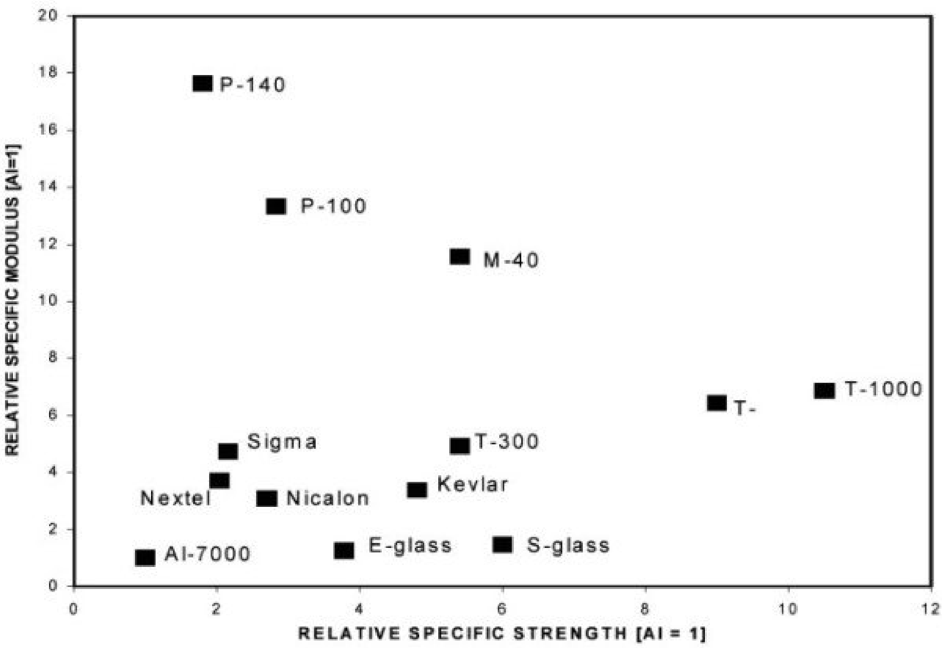

Figure 2. Plot of normalized specific modulus against normalized specific strength for a range of different fiber types (reference material is an aluminum alloy from the 7000 series - Al-7000). The data are for room temperature and may refer to a range of products with the general fiber specification. P-140, P-100 (AMOCO) and M-40 (Torayca) are high modulus, pitch-based carbon fibers; T-300, T-800 and T-1000 are polyacrylonitrile-based carbon fibers from Torayca, Kevlar™ fibers are aramid fibers made by Du Pont, Nicalon™ fibers are SiC fibers from polycarbosilane precursors manufactured by Nippon Carbon, Nextel™ are oxide fibers made by 3M and Sigma SiC monofilaments are manufactured by Sigma Metal Matrix Composites (UK) using chemical vapor deposition. The figure has been adapted from M G Bader 'Polymer Composites in 2000: structure, performance, cost and compromise', Journal of Microscopy, 201[2], 110 - 121 (2001).

The strength and stiffness of continuous fiber composites usually derive from the fiber properties. Figure 2 shows strength plotted against stiffness for a number of fibers and some relevant competitor materials. The excellent properties of the fibers are apparent. Most of the fibers shown are for incorporation into polymer matrices. Details regarding manufacture and properties of the main types of fiber for polymer matrix composites are given in some of the references cited in the bibliography. Rather larger diameter (above 100 μm compared with around 10 μm for fibers) silicon carbide monofilaments, manufactured by chemical vapor deposition processes are the most common continuous reinforcements for metal matrix composites. For ceramic matrix systems, predominantly silicon carbide fibers, produced by pyrolysing a polymer precursor are the most studied reinforcements but interest in oxide fibers is increasing (*see Fiber Production*).

Continuous rovings of fiber can be chopped to give discontinuous fiber reinforcement. Typical lengths of short fiber reinforcement lie in the range 0.1 - 10 mm. Short fiber polymer composites offer modest strength and stiffness increases compared with those provided by continuous fiber composites but other key properties, in particular toughness, are improved dramatically compared with unreinforced polymers. Moreover, short fiber composites provide considerable flexibility in processing.

A limited number of materials are available in whisker form. The most common whiskers are high aspect ratio (i.e. a few micrometers in diameter and tens of micrometers long) highly faulted crystals of silicon carbide and these may be incorporated into matrices, usually ceramics. This type of reinforcement does tend to produce superior toughness properties to lower aspect ratio reinforcements but issues relating to the specific health hazards associated with whiskers and processing difficulties may have prevented more widespread usage of them.

Potentially, any material in particulate form can be used as the second phase in discontinuous composites but compatibility throughout the processing steps leads to many combinations being unsuitable. Further, some combinations do not provide any advantages over the parent matrix material so that in practice, the number of combinations that are available commercially are limited. The most common of these will be discussed in the relevant materials sections.

3. Mechanical Behavior of Composites

3.1. Introduction

In continuous fiber composites, the fibers are normally of higher stiffness and strength than the matrix and provide the mechanical properties of the composite - an exception to this generalization is silicon carbide reinforced silicon carbide in which the matrix has a higher modulus than the fiber. The matrix is the continuous phase in the composite system and as such must support the fiber (especially under compression loading) and provide adequate environmental protection, although this is an issue still being addressed in ceramic matrix systems designed to operate at elevated temperatures. Loads are transmitted to the fibers through the matrix by shear at the fiber matrix interface. The matrix must withstand these shear stresses. The interface controls the transfer of stress from fiber to matrix and has a strong influence on toughness and damage tolerance.

The detailed mechanics of composite materials are complicated and for a formal introduction the reader is referred to standard texts such as those given at the end of this article. A few general observations and principles are discussed here, firstly with regard to the behavior of continuous fiber systems (Section 3.2) and then systems based on short fiber or particulate reinforcement (Section 3.3). A final section considers, briefly, some aspects of mechanical design.

3.2. Mechanical Behavior of Continuous Fiber Composites

For a unidirectional laminate, the modulus parallel to the fiber direction is given by the simple rule-of-mixtures expression:

$$E_1 = V_f E_f + (1 - V_f) \qquad (1)$$

where E_f and E_m denote the fiber and matrix modulus, respectively, and V_f is the fiber volume fraction. The modulus E_1 is referred to as a fiber-dominated property.

If a unidirectional laminate is loaded perpendicular to the fiber direction, then the modulus can be *estimated* from:

$$E_2 = \frac{1}{\left[\left(\frac{V_f}{E_f}\right) + \frac{(1 - V_f)}{E_m}\right]} \qquad (2)$$

While this expression is fairly approximate, it shows that the modulus E_2 is a matrix-dominated property at practical fiber volume fractions, as is the in-plane shear modulus, G_{12}.

The strength of a unidirectional composite parallel to the fiber direction (σ_{1U}) is governed largely by the fiber strength, but this cannot be readily be expressed in a simple way because of the statistical nature of fiber fracture and the role of the matrix and/or the interface during fracture. The transverse strength (σ_{2U}) also cannot be determined from a simple analysis. Like the transverse modulus, the transverse strength is a property, which depends not only on the matrix properties, but also the nature of the interface.

For glass or carbon fibers reinforcing an epoxy matrix, at a fiber fraction of 0.6 typical values of E_1 and E_2 for glass fiber/epoxy would be 42 GPa and 13 GPa and for high strength carbon/epoxy 140 GPa and 10 GPa. Strength values would be around 1200 MPa (σ_{1U}) and 40 MPa (σ_{2U}) for glass fiber/epoxy and around 2000 MPa (σ_{1U}) and 70 - 80 MPa (σ_{2U}) for a high strength carbon fiber/epoxy. The shear modulus G_{12} would normally be in the range 4 - 6 GPa and the shear strength in the range 50 - 100 MPa. These values emphasize the benefits of reinforcement with regard to the stiffness and strength in the fiber direction, but demonstrate also the anisotropy of the unidirectional material properties. This anisotropy is seen in a range of other properties of fiber-reinforced polymers, such as the electrical and thermal conductivities, diffusion coefficients, etc. Other fiber-matrix combinations also show significant anisotropy, although that associated with carbon fiber reinforced plastics or polymers (CFRPs) is amongst the most extreme in terms of the property ratios.

As indicated in Section 2, a consequence of the anisotropy of unidirectional material is that in practice multi-directional reinforcement is usually required. Typically such laminates may contain fibers at 0^o, $\pm45^o$ and 90^o to a reference loading direction. In constructing such laminates, it is usual to keep the laminate lay-up balanced and symmetric. This simplifies the laminate deformation under applied load. A balanced laminate (one in which there are an equal number of off-axis plies oriented at + θ^o and - θ^o to the reference direction) shows no coupling between in-plane extension and shear while a symmetric laminate (one in which the laminate lay-up is symmetric about the laminate mid-plane) shows no coupling between extensional and bending deformation. The basic elastic response of laminates under in-plane and bending loading can be analyzed using laminate theory, a technique explained in many texts, some of which are given in the bibliography at the end of this article. In overcoming the anisotropy by laminating there is an associated reduction in the material properties. For instance a CFRP laminate from the XAS/914 system (a high strength fiber in a modified epoxy matrix) based on 25 % 0^o plies, 50 % $\pm45^o$ plies and 25 % 90^o plies has a modulus about 56 GPa and a strength of 600 MPa compared to the unidirectional material values of 145 GPa and 1750 MPa.

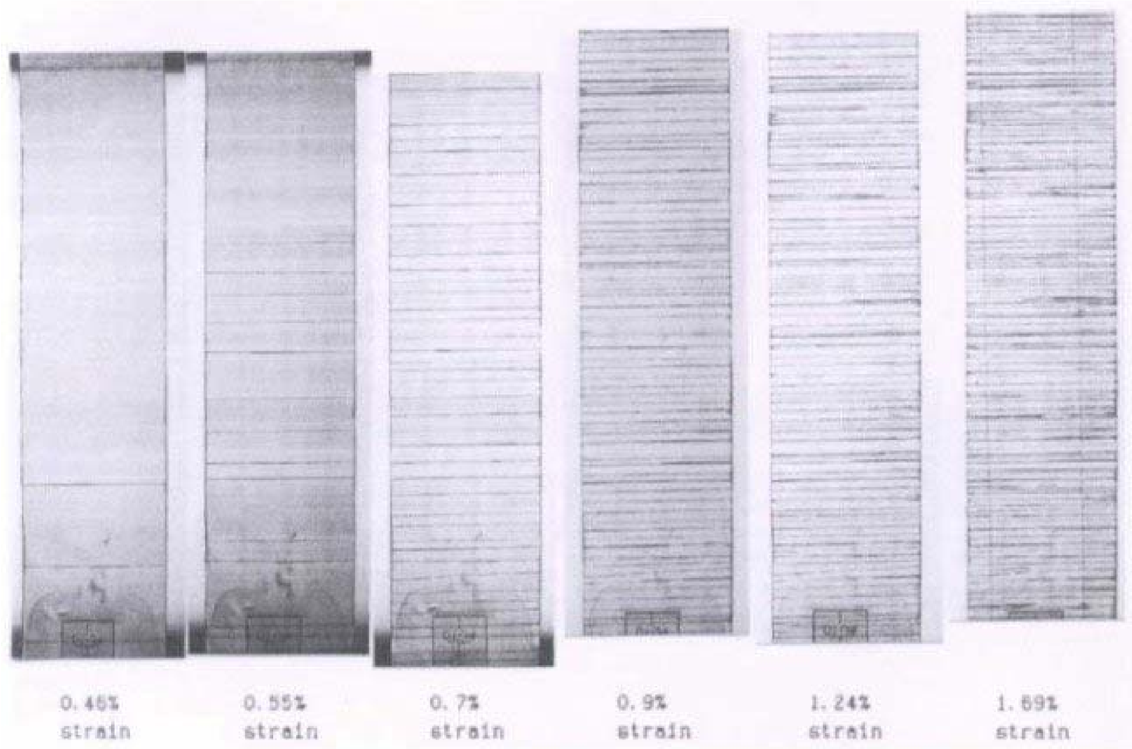

Figure 3. Matrix cracking in a glass fiber reinforced plastic/polymer of cross-ply, i.e. $(0/90)_s$, lay-up. As the level of strain in the coupon increases, the number of cracks in the plies oriented at 90° to the applied loading increases. The fibers are not apparent as the refractive index of the matrix and the fibers are matched so as to produce a transparent laminate, which enables easier observation of the cracks. Each coupon is 20 mm wide. (Figure courtesy of Dr Lynn Boniface).

It is difficult to predict the complicated sequence of failure events, which occur in a laminate as it is loaded. Initially, the response will be elastic. In polymer matrix and ceramic matrix composites the fiber and matrix, which make up the composite are essentially "brittle" materials (and would normally fail in a catastrophic manner), but laminated composites do not generally behave in such a brittle way. Beyond the elastic limit, normally damage develops prior to catastrophic failure, in particular in the form of matrix cracking (within and between layers) (see Figure 3), but also fiber breakage and debonding. This damage (which is loosely analogous to plasticity in metals) can be of great benefit in redistributing load at stress raisers, thereby extending the life of a component. If the laminate is loaded in compression, somewhat different behavior may be seen and in current polymer composite systems it is established that plies containing fibers parallel to the load will fail eventually by micro-buckling. Developing analytical models to describe these various failure processes is an area of much research and important for increasing confidence in using composites in critical load bearing applications. In laminated metal matrix composites failure processes are rather different and will generally involve matrix plasticity, although the ductility is reduced compared to unreinforced metals.

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Biographical Sketches

Paul Smith is Professor of Composite Materials in the School of Engineering at the University of Surrey. His first degree was in Engineering from the University of Cambridge and his PhD (also from Cambridge) was concerned with understanding the mechanical behavior of composite bolted joints. He joined the University of Surrey in 1986. His research interests are concerned with understanding the deformation and fracture of engineering materials, especially polymer composites, with a view to developing physically-based models of their behavior for incorporation into the design process. He is a Chartered Engineer and a Fellow of the Institute of Materials. He is currently European Editor and Editor-in-Chief of 'composites Part A: applied science and manufacturing'.

Julie Yeomans is a Senior Lecturer in Ceramic Materials in the School of Engineering at the University of Surrey. Following a degree in Natural Sciences, she remained in the Department of Metallurgy and Materials Science of the University of Cambridge to study ceramic tool materials for her PhD. After a brief spell as a ceramist with BP she joined the University of Surrey in 1988. Her research interests have focused on localized damage processes, which result from wear and/or thermal shock, in ceramics, including both particulate and continuous fiber reinforced materials. Currently, she is an Associate Editor of 'Journal of Materials Science'.