

# 1 Introduction

## 1.1 Evolution of engineering materials

Compared to the evolution of metals, polymers and ceramics, the advancement of fiber composite materials is relatively recent. Ashby (1987) presented a perspective on advanced materials and described the evolution of materials for mechanical and civil engineering. The relative importance of four classes of materials (metal, polymer, ceramic and composite) is shown in Fig. 1.1 as a function of time. Before 2000 BC, metals played almost no role as engineering materials; engineering (housing, boats, weapons, utensils) was dominated by polymers (wood, straw, skins), composites (like straw bricks) and ceramics (stone, flint, pottery and, later, glass). Around 1500 BC, the consumption of bronze might reflect the dominance in world power and, still later, iron. Steel gained its prominence around 1850, and metals have dominated engineering design ever since. However, in the past two decades, other classes of materials, including high strength polymers, ceramics, and structural composites, have been gaining increasing technological importance. The growth rate of carbon-fiber composites is at about 30% per year – the sort of growth rate enjoyed by steel at the peak of the Industrial Revolution. According to Ashby the new materials offer new and exciting possibilities for the designer and the potential for new products.

## 1.2 Fiber composite materials

Fiber composites are hybrid materials of which the composition and internal architecture are varied in a controlled manner in order to match their performance to the most demanding structural or non-structural roles. The fundamental characteristics of fiber composites have been summarized by Vinson and Chou (1975), Chou and Kelly (1976), Chou, Kelly and Okura (1985), Kelly (1985), and more recently by Chou, McCullough and Pipes (1986), from which the following is excerpted.\*

On the face of it a composite might seem a case of needless complexity. The makings of ideal structural materials would appear

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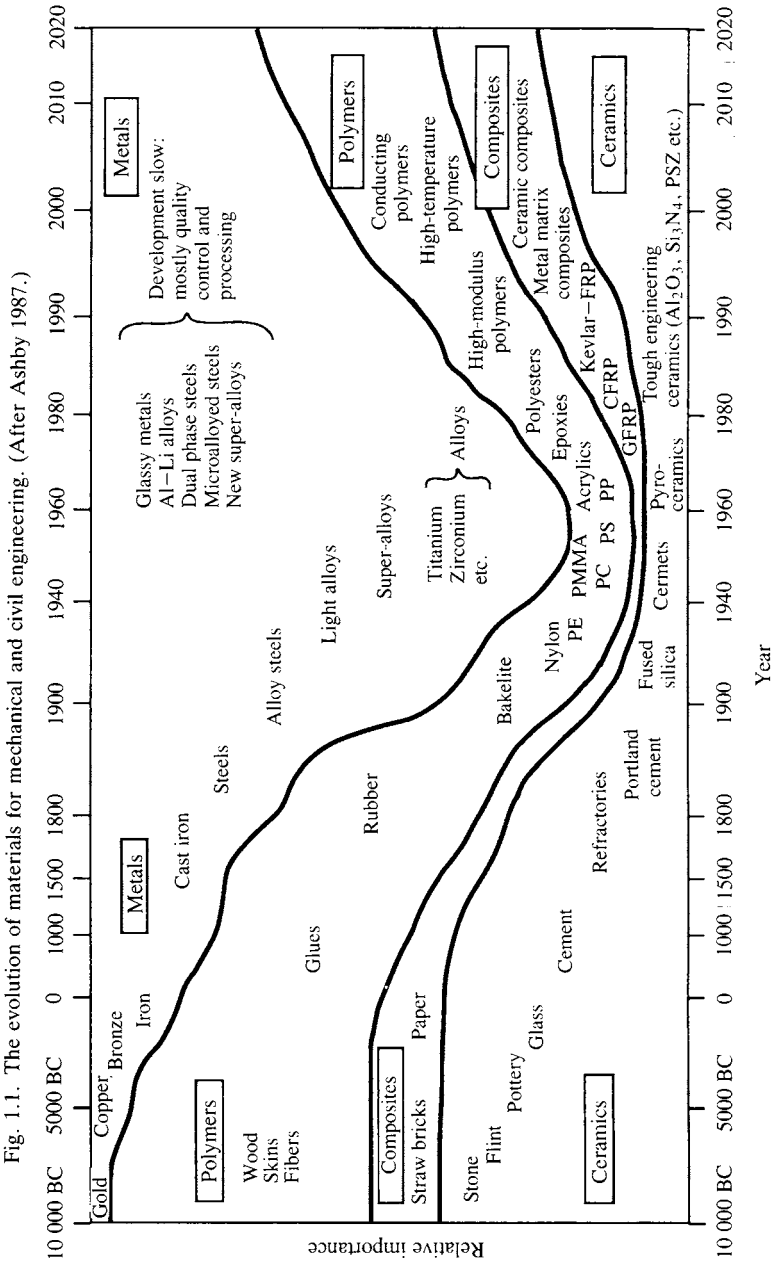


Fig. 1.1. The evolution of materials for mechanical and civil engineering. (After Ashby 1987.)

to be at hand, in the midsection of the periodic table. Those elements, among them carbon, aluminum, silicon, nitrogen and oxygen, form compounds in which the atoms are joined by strong and stable bonds. As a result, such compounds, typified by the ceramics, for instance, aluminum oxide, silicon carbide and silicon dioxide, are strong, stiff and resistant to heat and chemical attack. Their density is low and furthermore their constituent elements are abundant.

Yet because of a serious handicap these substances have rarely served as structural materials. They are brittle and susceptible to cracks. In bulk form the substance is unlikely to be free of small flaws, or to remain free of them for long in actual use. When such a material is produced in the form of fine fibers, its useful strength is greatly increased. The remarkable increase in strength at small scales is in part a statistical phenomenon. If one fiber in an assemblage does fail, moreover, the crack cannot propagate further and the other fibers remain intact. In a similar amount of the bulk material, in contrast, the initial crack might have led to complete fracture.

Tiny needlelike structures called whiskers, made of substances such as silicon carbide and aluminum oxide, also contain fewer flaws and show greater strength than the material in bulk form. Whiskers are less likely to contain defects than the bulk material, not only for statistical reasons but also because they are produced as single crystals that have a theoretically perfect geometry. The notion that many materials perform best as fibers also holds for certain organic polymers. Composites are a strategy for producing advanced materials that take advantage of the enhanced properties of fibers. A bundle of fibers has little structural value. To harness their strength in a practical material the designer of a composite embeds them in a matrix of another material. The matrix acts as an adhesive, binding the fibers and lending solidity to the material. It also protects the fibers from environmental stress and physical damage that could initiate cracks.

The strength and stiffness of the composite remain very much a function of the reinforcing material, but the matrix makes its own contribution to properties. The ability of the composite material to conduct heat and current, for example, is heavily influenced by the conductivity of the matrix. The mechanical behavior of the composite is also governed not by the fibers alone but by a synergy between the fibers and the matrix.

The ultimate tensile strength of a composite is a product of the

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synergy. When a bundle of fibers without a surrounding matrix is stressed, the failure of a single fiber eliminates it as a load carrier. The stress it had borne shifts to the remaining intact fibers, moving them closer to failure. If the fibers are embedded in a matrix, on the other hand, fracture does not end the mechanical function of a fiber. The reason is that as the broken ends of the fiber pull apart, elastic deformation or plastic flow of the matrix exerts shear forces, gradually building stress back into the fragments. Because of such load transfer the fiber continues to contribute some reinforcement to the composite. The stress on the surrounding intact fibers increases less than it would in the absence of the matrix, and the composite is able to bear more stress without fracturing. The synergy of the fibers and the matrix can thus strengthen the composite and also toughen it, by increasing the amount of work needed to fracture it.

Although the general requirement that the matrix be ductile provides some guidance for choosing a matrix material, the most common determinant of the choice is the range of temperatures the composite will face in its intended use. Composites exposed to temperatures of no more than between 100 and 200°C usually have a matrix of polymer. Most composites belong to this group.

Polymer matrices are often thermosets, that is polymers in which bonds between the polymer chains lock the molecular structure into a rigid three-dimensional network that cannot be melted. Thermosets resist heat better than most thermoplastics, the other class of polymeric materials, which melt when they are heated because no bonds cross-link the polymer chains. Epoxies are the most common thermosetting matrix for high-performance composites, but a class of resins called polyimides, which can survive continuous exposure to temperatures of more than 300°C, have attracted considerable interest. If the resin is a thermoset, the structure must then be cured, subjected to conditions that enable the polymer chains to cross-link. Often the composite must be held at high temperature and pressure for many hours.

In part to shorten the processing time, thermoplastic matrix materials are attracting growing interest; one promising example is a polymer called PEEK (polyetheretherketone). Consolidating a composite that has a thermoplastic matrix requires only relatively short exposure to a temperature that is sufficient to soften the plastic. The melting temperature of some thermoplastic matrices is so high that they rival thermosets in heat resistance: PEEK, for example, melts at 334°C. Thermoplastics have the additional advantage of being tougher than most of the thermosets.

Temperatures high enough to melt or degrade a polymer matrix call for another kind of matrix material, often a metal. Along with temperature resistance a metal matrix offers other benefits. Its higher strength supplements that of the reinforcing fibers, and its ductility lends toughness to the composite. A metal matrix exacts two prices: density that is high in comparison with polymers, even though the light metals such as aluminum, magnesium and titanium are the most common matrices, and complexity of processing. Indeed, whereas the production of many advanced polymer matrix composites has become routine, the development of metal matrix composites has progressed more slowly, in part because of the extreme processing conditions needed to surround high strength fibers with a matrix of metal.

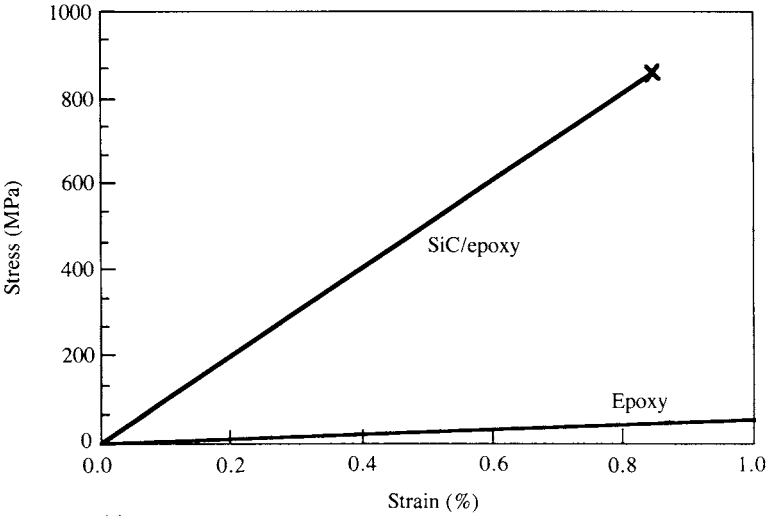
Metal matrix composites might assume a place in the cooler parts of the skin of a hypersonic aircraft, but at the nose, on leading edges of the wings and in the engines temperatures could exceed the melting point of a metal matrix. For those environments, there is growing interest in a class of composites that have matrices as resistant to heat as the fibers themselves, and also as lightweight and potentially as strong and stiff, namely, ceramics. Because they are brittle, ceramics behave differently from other matrices. In metal and polymer matrix composites the fibers supply most of the strength, and the ductile matrix acts to toughen the system. A ceramic matrix, in contrast, is already abundantly stiff and strong, but to realize its full potential it needs toughening. The fibers in a ceramic matrix composite fill that need by blocking the growth of cracks. A growing crack that encounters a fiber may be deflected or may pull the fiber from the matrix. Both processes absorb energy.

The ceramic matrix gives such composites great temperature resistance. Borosilicate glass reinforced with carbon fibers retains its strength at 600°C. Such matrices as silicon carbide, silicon nitride, aluminum oxide or mullite (a complex compound of aluminum, silicon and oxygen) yield composites that remain serviceable at temperatures well above 1000°C. The heat resistance of a ceramic matrix composite, however, complicates its fabrication.

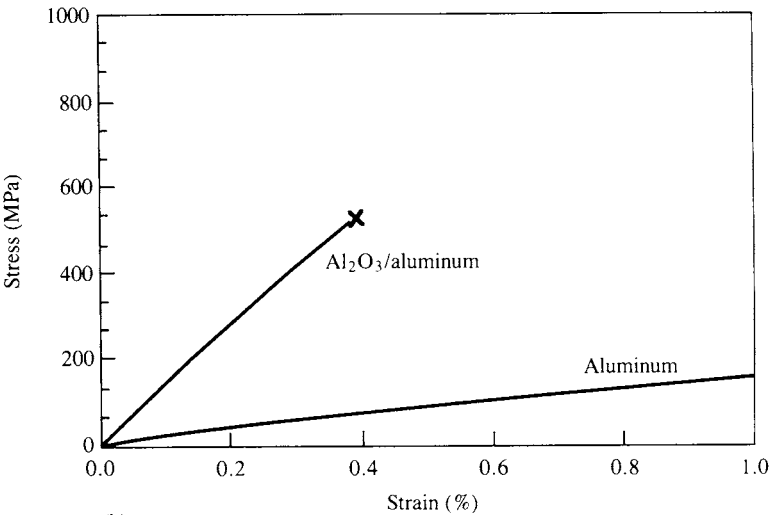
The characteristics of these three classes of composites can be exemplified by the relation of stress and strain for the unreinforced polymer, metal and ceramic as compared with curves for the corresponding composites. Whereas unreinforced epoxy stretches easily, an epoxy matrix composite containing 50% by volume of silicon carbide fibers is far stiffer (Fig. 1.2a). In an aluminum matrix the same volume of reinforcement, in this case aluminum oxide fibers, also improves stiffness dramatically (Fig. 1.2b). Because the

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Fig. 1.2. Stress–strain curves for (a) SiC/epoxy, (b)  $\text{Al}_2\text{O}_3$ /aluminum, and (c) SiC/borosilicate glass composites. (From 'Composites,' Chou, McCullough and Pipes). Copyright © (1986) by *Scientific American, Inc.* All rights reserved.



(a)



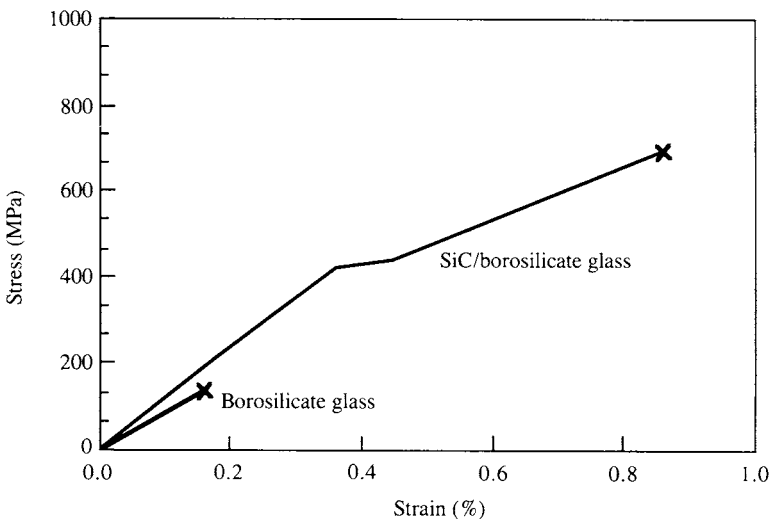
(b)

fibers are brittle, the composite fails at a much lower strain than unreinforced aluminum does. A similar fraction of silicon carbide fibers stiffens a matrix of borosilicate glass only slightly but toughens it considerably, increasing the percentage by which it can be strained without breaking (Fig. 1.2c). The fibers do so by restraining the growth of matrix cracks that might otherwise lead to fracture.

Related to ceramic matrix composites in character but distinctive in manufacture is a composite in which both the matrix and the reinforcing fibers consist of elemental carbon. Carbon-carbon composite is reinforced by the element in a semicrystalline form, graphite; in the matrix the carbon is mostly amorphous. A carbon-carbon composite retains much of its strength at 2500°C and is used in the nose cones and heat shields of re-entry vehicles. Unlike most ceramic matrix composites, it is vulnerable to oxidation at high temperatures. A thin layer of ceramic is often applied to the surface of a carbon-carbon composite to protect it.

The combination of fiber and matrix gives rise to an additional constituent in composites: an interface (or interphase) region. Chemical compatibility between the fibers and the matrix is most crucial at this region. In polymer and metal matrix composites a bond must develop between the reinforcement and the matrix if they are to act

Fig. 1.2. (cont.)



(c)

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in concert. A prerequisite for adhesion is that the matrix, in its fluid form, be capable of wetting the fibers. Fibers that would otherwise not be wetted by their matrix can be given a coating that fosters contact by interacting with both the fibers and the matrix. In some cases varying the matrix composition can also promote the process. Once the matrix has wetted the fibers thoroughly, intermolecular forces or chemical reactions can establish a bond.

The properties of an advanced composite are shaped not only by the kind of matrix and reinforcing materials it contains but also by a factor that is distinct from composition: the geometry of the reinforcement. Reinforcing geometries of composites can be grouped roughly by the shape of the reinforcing elements: particles, continuous fibers or short fibers (Fig. 1.3). Sets of parallel continuous fibers are often embedded in thin composite layers, which are assembled into a laminate. Alternatively, each ply in a laminate can be reinforced with continuous fibers woven or knitted into a textile 'preform'. Recently developed geometries dispense with lamination: the fibers are woven or braided in three dimensions (Fig. 1.4), a strategy that in some cases enables the final shape of the composite to be formed directly.

Progress toward managing the many variables of composite design has encouraged investigators to contemplate new complexities. An ordinary composite reinforced with stiff, straight fibers usually displays a nearly constant value of stiffness. New composites designed to display specific non-linear relations of strain and stress are now attracting interest. One such example, a flexible composite consisting of undulating fibers in an elastomeric matrix, can

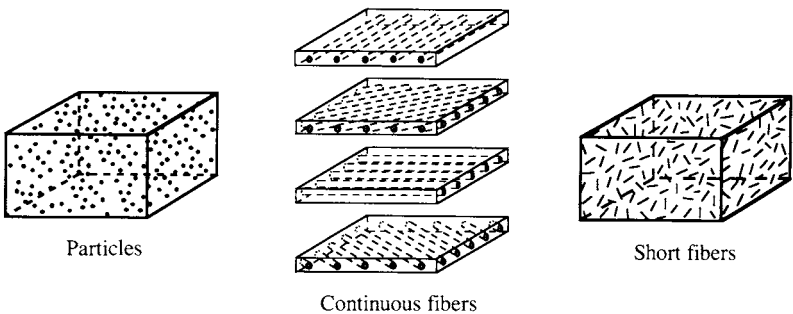
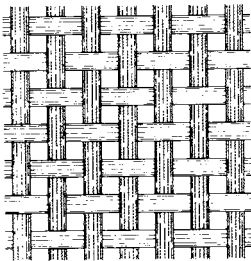


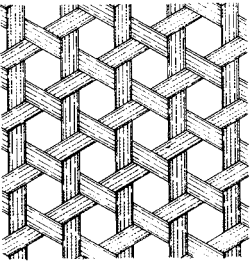
Fig. 1.3. Particle- and fiber-reinforced composites. (From 'Composites' Chou, McCullough and Pipes.) Copyright © (1986) by *Scientific American, Inc.* All rights reserved.



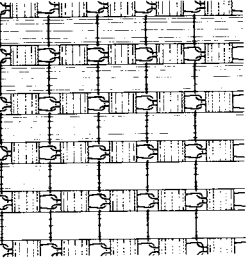
Fig. 1.4. Preforms of textile structural composites. (From 'Composites' Chou, McCullough and Pipes.)  
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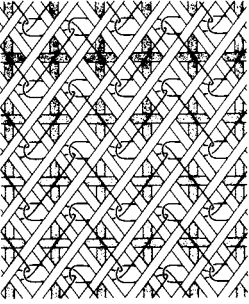
Bi-axial weave



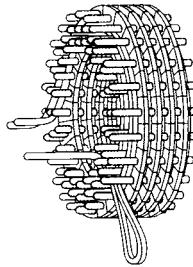
Tri-axial weave



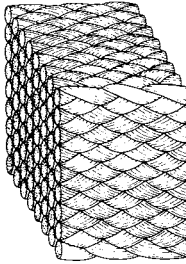
Knit



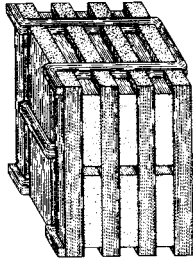
Multi-axial multi-layer warp knit



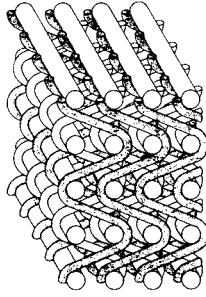
Three-dimensional cylindrical construction



Three-dimensional braiding



Three-dimensional orthogonal fabric



Angle-interlock construction

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elongate readily at low stresses but stiffens when the fibers become fully extended. A hybrid composite strengthened with two kinds of fibers, some of them brittle and inextensible and the others ductile and tough, can display the opposite behavior. The stiff fibers cause stress to increase very sharply at low strains, but when the strain is sufficient to break the stiff, brittle fibers, the curve of stress over strain flattens. The ductile fibers come into play, and as a result the composite becomes more extensible. The hybrid design can yield a material that combines much of the stiffness of an ordinary composite containing only stiff fibers with increased toughness.

Overall, the opportunity in the engineering of fiber composites is the potential to control the composition as well as internal geometry of the materials for optimized performance.

### 1.3 Why composites?

The question of ‘Why composites?’ was raised in the 1975 text by Vinson and Chou (1975). The rationale provided then focussed on

- (a) the limitations in strength and ductility for metallic alloys from the viewpoints of theoretical cohesive strength of solids and the arrangement of crystalline defects,
- (b) the need of a balanced pursuit in strength and ductility and the potential of achieving both in fiber composites, and
- (c) the strength limitation of metallic alloys at elevated temperatures and the potential of carbon–carbon composites and refractory metal wire reinforced super-alloys.

The field of fiber composites has witnessed drastic changes and advancement since the mid-1970s because of the availability of several ceramic fibers, high-temperature thermoplastics, glass–ceramic matrices, and intermetallic solids for composites. Although the fundamental physical principles governing the synergism of the component phases in composites should not change, the advancement in materials technology coupled with that in processing, surface science and instrumentation has greatly changed the perspective of composite technology. In the following, the answer to the question of ‘why composites?’ is re-examined from both economic and technological points of view.

#### 1.3.1 Economic aspect

For the discussion of the economic aspect of advanced materials in general and fiber composites in particular, it is