Microstructural Design of Fiber Composites

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Chapter

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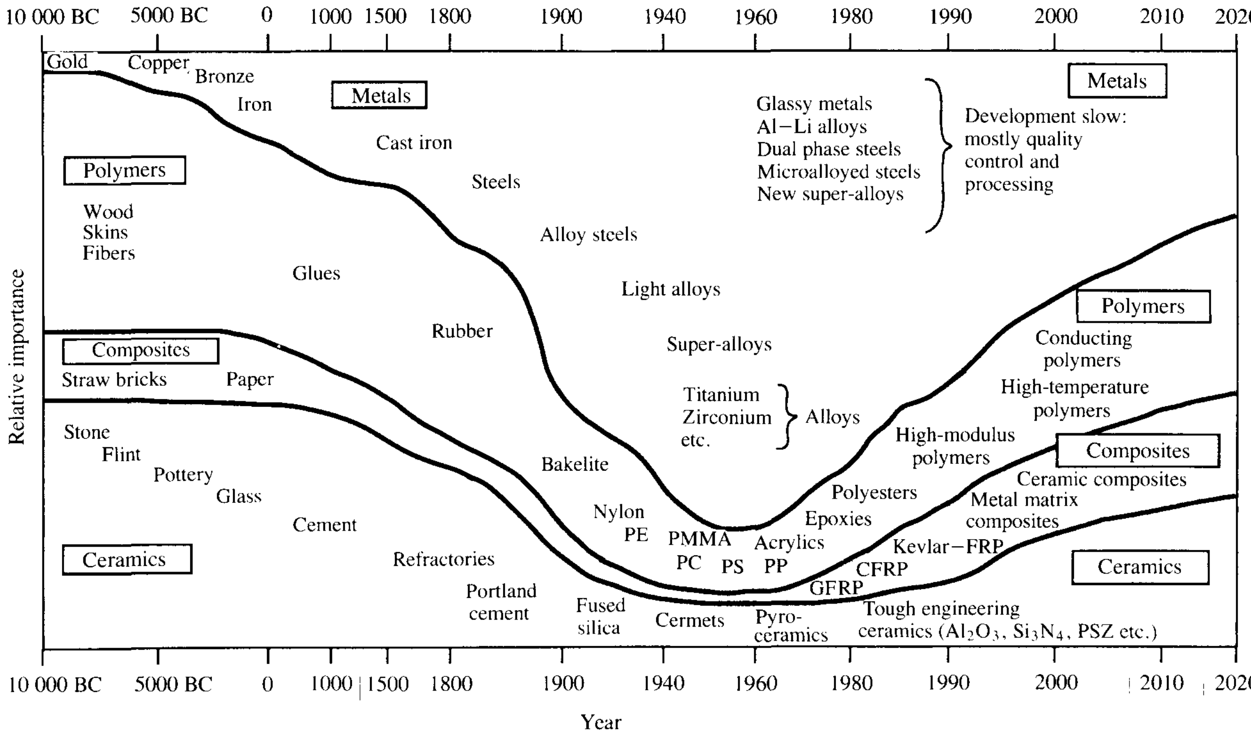
Fig. 1.1. The evolution of materials for mechanical and civil engineering. (After Ashby 1987.)



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 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.

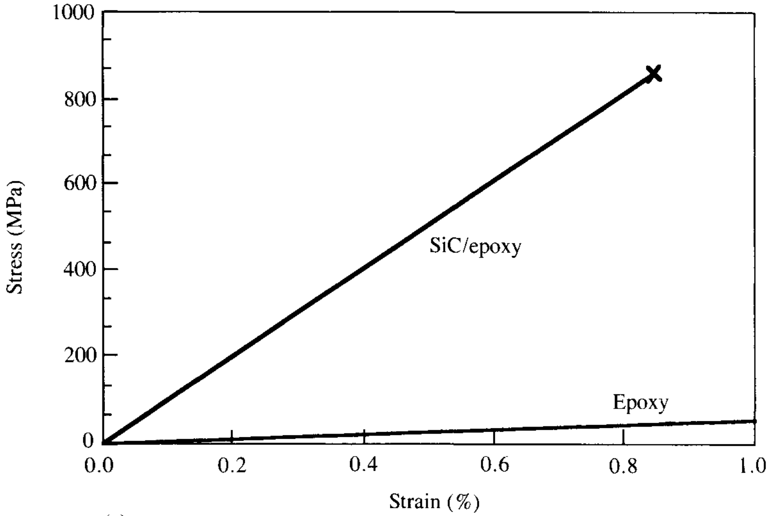
Temperatures high enough to melt or degrade a polymer matrix call for another kind of matrix material, often a metal. Along with temperature resistance a metal matrix offers other benefits. Its higher strength supplements that of the reinforcing fibers, and its ductility lends toughness to the composite. 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.

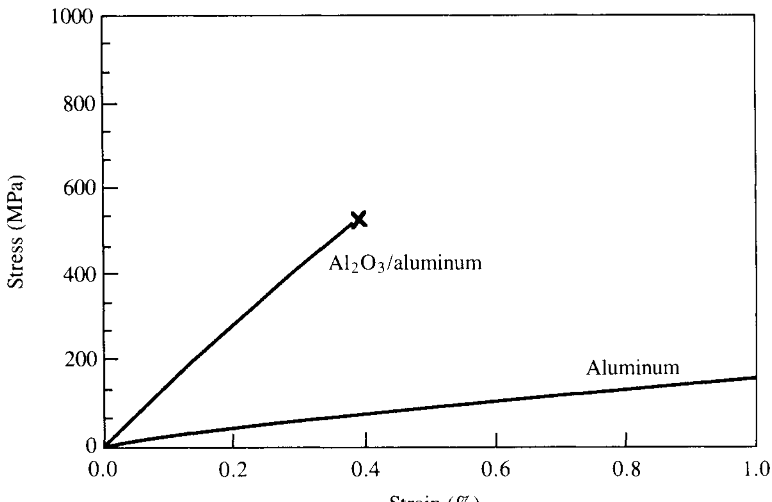
The ceramic matrix gives such composites great temperature resistance. Borosilicate glass reinforced with carbon fibers retains its strength at 600°C. Such matrices as silicon carbide, silicon nitride, aluminum oxide or mullite (a complex compound of aluminum, silicon and oxygen) yield composites that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

Fig. 1.2. Stress–strain curves for (a) SiC/epoxy, (b) Al_2O_3/aluminum, and (c) SiC/borosilicate glass composites. (From 'Composites,' Chou, McCullough and Pipes). Copyright © (1986) by *Scientific American, Inc.*



(a)



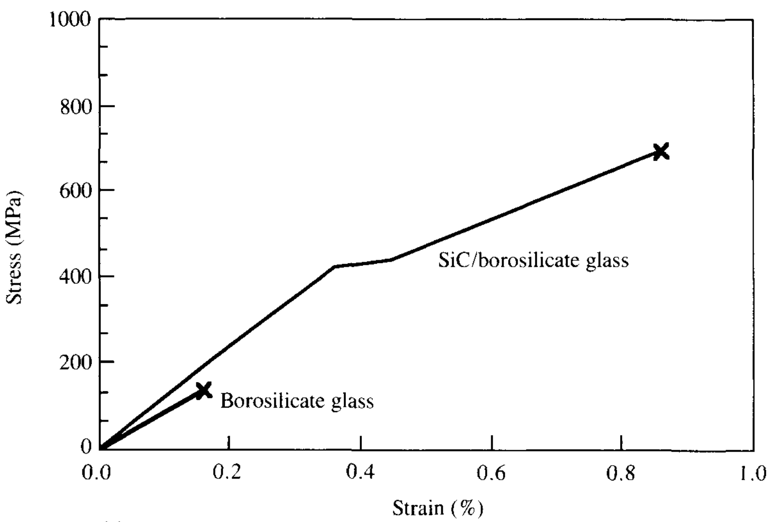
(b)

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)

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.

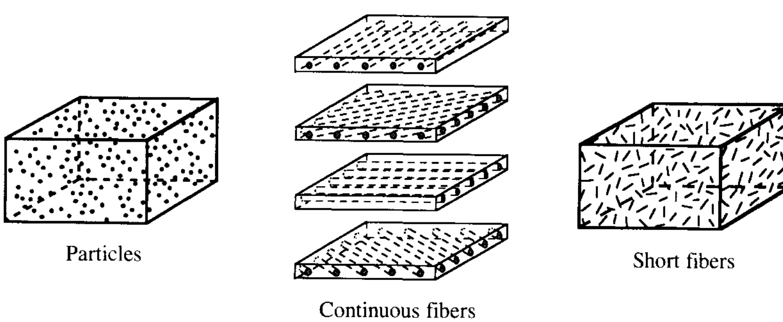
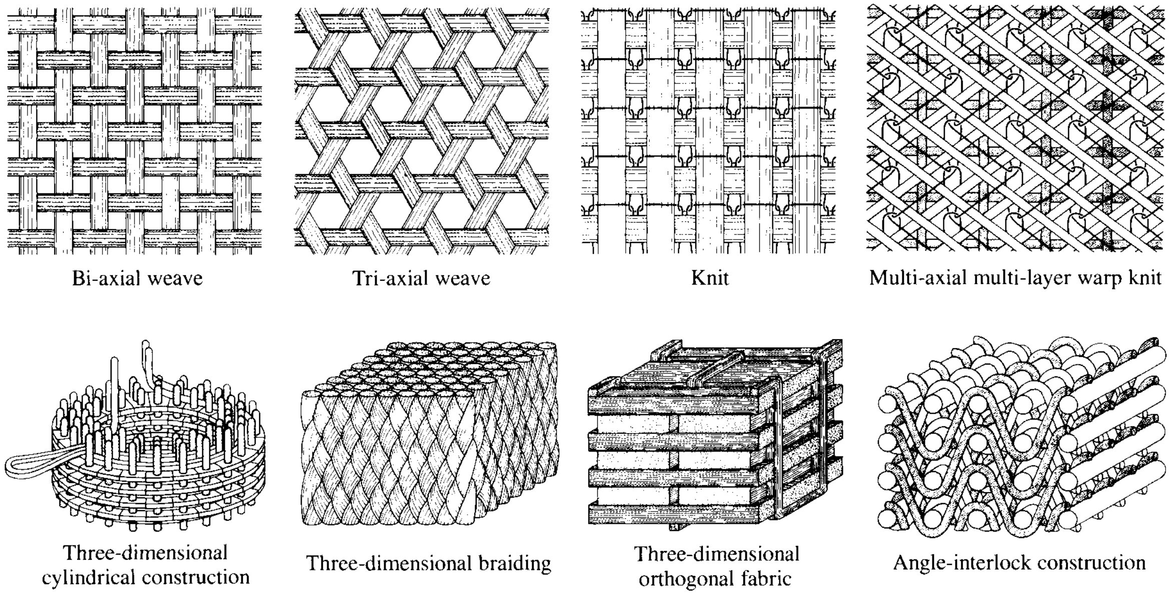


Fig. 1.4. Preforms of textile structural composites. (From 'Composites' Chou, McCullough and Pipes.)



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.

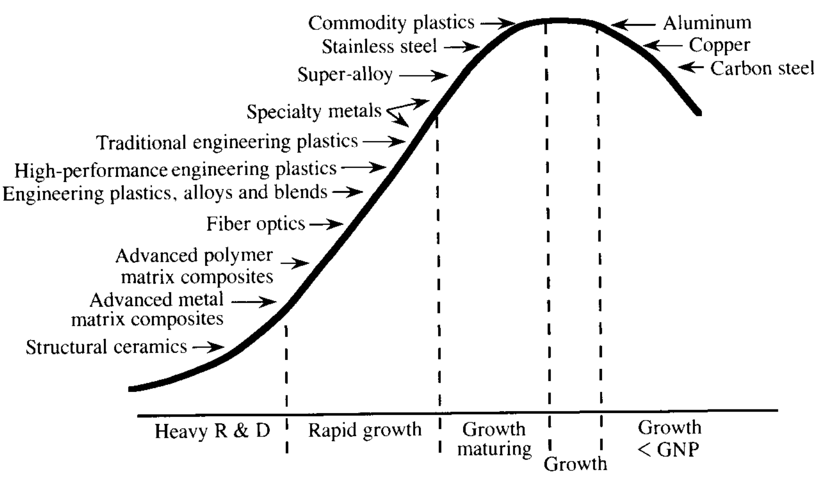
1.3.1 *Economic aspect*

For the discussion of the economic aspect of advanced materials in general and fiber composites in particular, it is worthwhile referring to a recent survey entitled *Problems and Opportunities in Metals and Materials: An Integrated Perspective* by the U.S. Department of the Interior (Sousa 1988). The report asserts that the future growth prospects seem best not in tonnage commodities but rather in materials that are more technology-intensive and more high-value-added. As the economy grows and matures, the rate of growth in consumption of tonnage metals first exceeds, eventually parallels, and finally trails that of the economy as a whole.

Figure 1.5 shows the estimated current relative market maturity of the major metals and other materials. The vertical dimension indicates intensity-of-use (amount/GNP). The potential of polymer, metal and ceramic based composites is obvious. This figure also demonstrates a hard fact of life that eventually catches up with virtually any product – that of market saturation and, as the inexorable evolution of technology proceeds, eventual displacement and decline.

By incorporating different materials into composites, the synthetic class of materials can thus draw on the essential characteristics of diverse materials: the high strength, ductility, thermal–electrical conductivity and formability of metals, the low cost fabrication, light weight and corrosion resistance of polymers, and the strength, corrosion resistance and high-temperature performance of ceramics.

Fig. 1.5. Relative market maturity of materials. (After Sousa (1988).)



The survey of the U.S. Department of the Interior forecasts the total demand for advanced materials in the U.S. in the year 2000 to be approximately $55 billion annually, roughly the same magnitude as the current U.S. steel market. By comparison, a Japanese Ministry of International Trade and Industry report showed that the Japanese annual demand for advanced materials is expected to be about $34 billion. The breakdown of the market in terms of material categories is (1) advanced polymer composites: 22% (U.S.), 7.6% (Japan); (2) advanced metal alloys and composites: 35% (U.S.), 28.3% (Japan); (3) advanced ceramics: 30% (U.S.), 35.9% (Japan); (4) engineering plastics: 13% (U.S.), 28.3% (Japan). Although the rudimentary nature of such forecasts cannot be overemphasized, the transition from a metals economy to a materials economy, and the importance of composite materials to the economy of advanced materials, is unmistakable.

1.3.2 *Technological aspect*

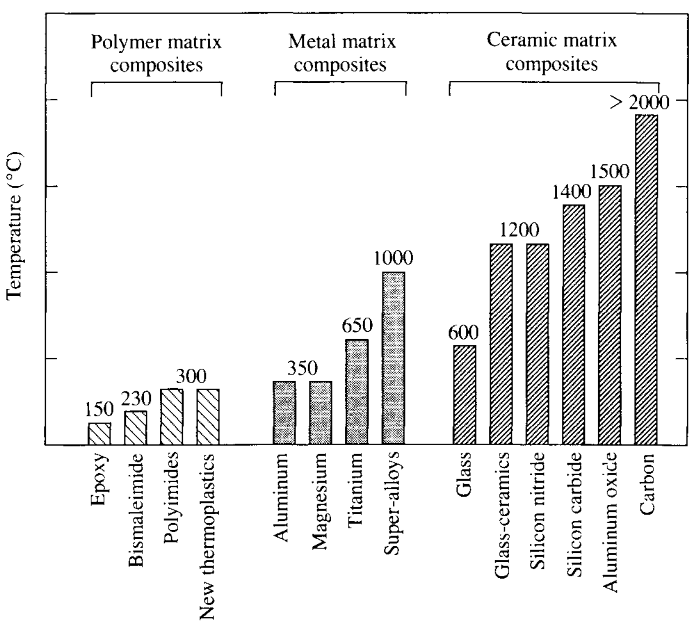
From the technological viewpoint, advanced composite materials can offer a competitive edge in many products, including aircraft, automobile, industrial machinery and sporting goods, provided their overall production costs can be reduced and their performance improved. According to the study *New Structural Materials Technologies* made by the Congress of the United States, Office of Technology Assessment (1988), the broader use of advanced structural materials requires not only solutions to technical problems but also changes in attitudes among researchers and end-users. The traditional approach based upon discrete design and manufacturing steps for conventional structural materials needs to be replaced by an integrated design and manufacturing process which necessitates a closer relationship among researchers, designers, and production personnel as well as a new approach to the concept of material costs. A fully integrated design process capable of balancing all of the relevant design and manufacturing variables requires an extensive database on matrix and fiber properties, the ability to model fabrication processes, and three-dimensional analysis of the properties and behavior of the resulting structure. Knowledge of the relationships among the constituent properties, microstructure and macroscopic behavior of the composite is basic to the development of an integrated design methodology.

To further understand the impacts of advanced structural materials on manufacturing, this report examines the following two possibilities: substitution by direct replacement of metal components in existing products and the use in new products that are made possible by the new materials. Direct substitution of a ceramic or composite part for a metal part is not likely to take full advantage of the superior properties and design flexibility of advanced materials. Substitution of conventional structural metals such as steel and aluminum alloy by composites is highly unlikely. Because of their low cost and manufacturability, these metals are ideally suited for applications in which they are now used. On the other hand, the metal industry has responded to the potential of direct substitution by developing new alloys with improved properties, such as high-strength, low-alloy steel and aluminum–lithium. According to this assessment, significant displacement of metals could occur in four potential markets: aircraft, automobiles, containers and constructions.

In the choice of material substitution, a variety of factors need to be taken into account. Compton and Gjostein (1986) analyzed the weight saving and cost for material substitution for ground transportation. Weight reduction that can be achieved in designing a part by substituting a light-weight material for a conventional one depends critically on the part's function. A unit volume of cast aluminum weighs 63% less than an equal volume of cast iron. Cast iron, however, is stiffer than cast aluminum. Therefore if a hypothetical cast-aluminum part is to be as stiff as a cast-iron one, more aluminum would have to be used and the weight saving would be reduced to 11%. If equal loading carrying capacity is required in the hypothetical aluminum part, the weight saving would be 56%. (In actual design situations the weight saving offered by the substitution of aluminum for cast iron ranges from 35 to 60%.) Similarly, aluminum and fiber-reinforced plastics are much lighter than mild (ordinary) steel by volume. The weight savings, however, are much smaller if equal stiffness or equal collapse load and bending stiffness (a measure of structural strength) is needed. High-strength steel is no lighter by volume than mild steel, nor is it stiffer. Where structural strength is the main concern, however, high-strength steel does offer a weight saving: 18% in the example discussed by Compton and Gjostein.

In terms of innovative designs and new products based upon advanced composites, the automotive industry undoubtedly provides an excellent paradigm. The use of polymer matrix composites for primary body structures and chassis/suspension systems is under evaluation by the major automobile manufacturers. The potential advantages of using composites are: weight reduction and resulting fuel economy; improved overall quality and consistency in manufacturing; lower assembly costs due to parts consolidation; lower investment costs for plant, facilities, and tooling; improved corrosion resistance; and lower operating costs. The major barriers to the large-scale applications of composites are the lack of high-speed, high-quality, low-cost manufacturing processes; uncertainties regarding crash integrity and long-term durability; and lack of adequate technologies for repair and recycling of polymer composite structures. According to Compton and Gjostein, glass fiber reinforced composites are capable of meeting the functional requirements of the most highly loaded automotive structures. Candidate fabrication methods include resin transfer molding, compression molding, and filament winding. Among these methods, resin transfer molding seems the most promising, although none of these methods can satisfy all of the production requirements at this time. There is no doubt that the large-scale adoption of polymer matrix composites for automotive structures would have a major technological impact on the fabrication and assembly of automobiles.

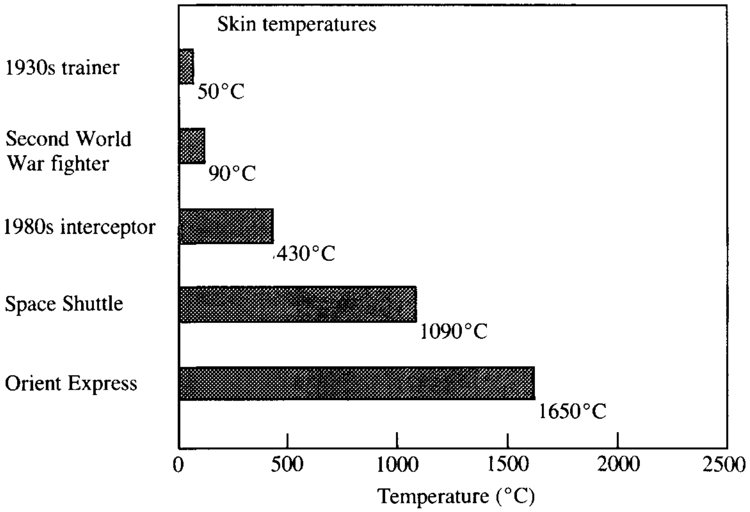
Fig. 1.6. Temperature capabilities of polymer, metal and ceramic matrix materials. (After Mody and Majidi 1987, with permission from the Society of Manufacturing Engineers.)



Another technological aspect that motivates the use of fiber composites pertains to the demand of an elevated temperature environment (Steinberg 1986). Temperature capabilities of polymer, metal and ceramic matrix materials are shown in Fig. 1.6 (Mody and Majidi 1987). The demand for high-temperature applications of composites is best exemplified by the need for aerospace materials. The U.S. goals for subsonic, supersonic and hypersonic flight and for space explorations require alloys and composites with superior strength, light weight and resistance to heat. According to Steinberg, the evolution of aircraft has required continual improvements in materials because increased speed raises the heating of the skin from friction with the air and increased power raises the temperature of the engine. Figure 1.7 shows the changes in skin temperatures from aircraft of the 1930s to the proposed Orient Express which is a transatmospheric craft capable of cruising at great speed in space. The skin materials have progressed from wood and fabric to advanced alloys of aluminum, nickel and titanium and graphite fiber reinforced polymer composites.

Figure 1.8 shows the changes in engine temperature from engines cooled by water to those of scramjets. The need for composites in engine components can be understood from the evolution in engine

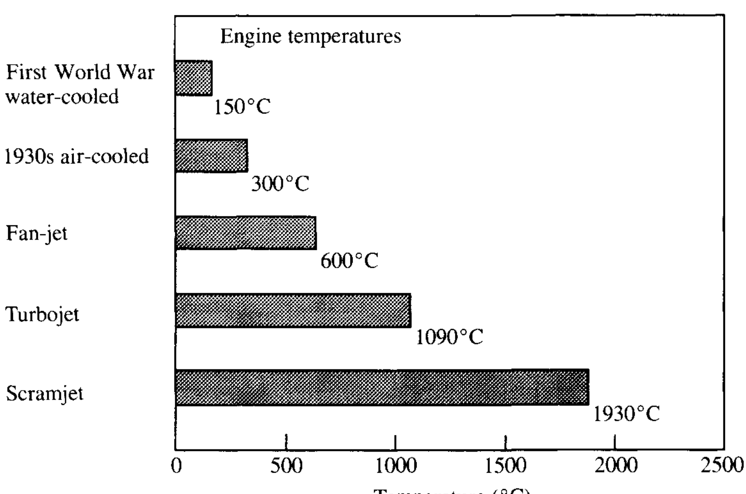
Fig. 1.7. Evolution of aircraft skin temperatures. (From 'Materials for Aerospace', Steinberg). Copyright © (1986) by *Scientific American, Inc.* All rights reserved.



performance. According to Steinberg, the thrust delivered by a big jet engine for transport and cargo aircraft has increased about six fold over the past 30 years, approaching 294 000 newtons (66 000 pounds) now. During the same period the weight of the engine has increased by a factor of only two or three. The thrust-to-weight ratio of the military aircraft may approach 15:1 by the year 2000. The performance of jet engines has been made possible partially with improvements in turbine blades. It is predicted that with the further improvements in blades and other aspects of aircraft propulsion, a typical propulsion system in the year 2000 will be likely to contain about 20% each of composites, steel, nickel and aluminum, 15% titanium, 2% ordered alloys (aluminides, e.g. titanium–aluminum or nickel–aluminum) and 1% ceramics (Steinberg 1986).

Clark and Flemings (1986) have also examined the present and future material systems for meeting the engine operating temperature requirements. In Fig. 1.9 the lowest band on the graph indicates the temperature increase that has been achieved so far through improvements in nickel-based super-alloys, the standard turbine material. It is believed that in the coming decades alloy turbine blades made of metal strengthened by directional crystal structures, and blades protected by a coating of ceramics or special

Fig. 1.8. Evolution of aircraft engine temperatures. (From 'Materials for Aerospace' Steinberg). Copyright © (1986) by *Scientific American, Inc.* All rights reserved.

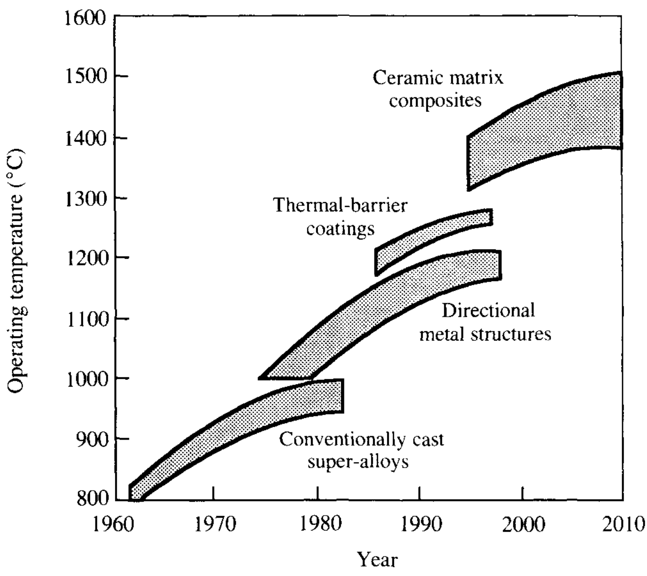


alloys, will allow an increase in turbine-inlet temperatures. However, ultimately, the demand for very-high-temperature material can only be met by ceramic matrix composites and carbon–carbon composites.

1.4 Trends and opportunities

Kelly (1987a&b), in a recent outline of the trends in materials science and processing, examined the status of fiber composites. It was concluded that the development of this field has been mainly driven by the aerospace industry. This development has contributed to the growth of a relatively small body of new science which related the colligative properties of fiber composites to the properties of the individual components. There have been interesting combinations of properties not hitherto available in single phase materials, for example, a negative thermal expansion and a negative Poisson's ratio. However, there have not been large non-linear synergistic effects. There is perhaps not much new science of the colligative properties of composites. However, in Kelly's view, the studies of design of fiber composites are critical for

Fig. 1.9. Rise in the operating temperature of jet engines with time. (From 'Advanced Materials and Economy' Clark and Flemings). Copyright © (1986) by *Scientific American, Inc.* All rights reserved.



their applications. Furthermore, there may be much new science on how to produce composites.

The significant trends in structural composites point to the direction of low-temperature metal matrix, resin matrix, metal–resin matrix, rubber matrix, cement–ceramic matrix and elevated-temperature composites. Non-structural composites are increasingly being recognized for their unique opportunities in electric, magnetic, superconducting and biomedical applications. A brief summary of those trends follows (see Kelly 1987a).

A major motivation behind the development of low-temperature metal matrix composites in the U.S. has been for the utilization of high-stiffness continuous fibers in a matrix material without the disadvantage of thermosetting resins of low thermal conductivity, high thermal expansion, dimensional instability, hygrothermal degradation, material loss in high vacuum, susceptibility to radiation damage, and lower temperature brittleness. The lighter metals do not possess these disadvantages; their low atomic number (Z) is important in a neutron-rich environment. It is useful to bear in mind that five out of the 13 lowest-Z solids are metals. Some of these metals, together with their atomic number and density, are listed below: lithium ($Z = 3$, density $= 0.53\,\mathrm{Mg\,m^{-3}}$), sodium (11, 0.97), potassium (19, 0.86), calcium (20, 1.55), magnesium (12, 1.741), beryllium (4, 1.85), and aluminum (13, 2.7).

Reinforcement of a light metal, e.g. aluminum and magnesium, is attractive in the automobile industry in reducing creep at moderate temperatures and improving wear resistance. Coating for carbon fibers is necessary for incorporation into aluminum and magnesium matrices.

Thermoplastic resins have certain advantages over thermosets in their infinite shelf life, good resistance to water and solvents, and ductility. Thermoplastics are attractive particularly from the viewpoint of composites manufacture because they are rapidly processable, and are better adapted to automated manufacturing. Also, they can be recycled and joined by welding.

Laminates formed by bonding metal sheets to fiber–resin composites take advantage of the synergistic effects of hybrid composites. For instance, the combination of aluminum foil with Kevlar/epoxy composite results in enhanced fatigue resistance and compressive strength.

Rubber (elastomeric) matrix can be reinforced with short and continuous fibers and can provide the capability of large non-linear elastic deformation. Automobile tires and coated fabrics are examples in this category.

Contrary to the large deformation of rubber type flexible composites, ceramic based composites offer the other extreme on the scale of deformation. The brittle nature of ceramic solids requires a new way of thinking in 'reinforcement'. Fibers are added for the purpose of improving toughness against fracture and ductility in terms of energy absorption and deformation range.

Ceramic matrix composites, directionally solidified eutectics, intermetallic solids, certain types of metal based composites, and carbon–carbon composites are the candidate materials for elevated-temperature applications. Among these, carbon–carbon composites present the ultimate in high-temperature materials under reducing conditions. They have many tribological applications. Protection against oxidation and densification of the matrix are major challenges to carbon–carbon composites.

Finally, the potential of non-structural composites has not been fully explored. Kelly (1987a) cited the examples in making special devices. For example, a magnetoresistive device obtained by coupling a metal rod with a semiconductor matrix provides a contactless potentiometer or a fluxmeter, or coupling a piezoelectric and magnetostrictive material gives a magnetoelectric material. The potential for biomedical applications of flexible composites also exists (see Chou 1989).

1.5 Microstructure–performance relationships

Chapters 2–9 examine the stiffness, strength and failure behavior of several types of composites: laminated composites composed of continuous fibers; composites reinforced with short fibers in biassed or random orientations; composites with two types of fibers in intermingled, interlaminated or interwoven forms; composites reinforced with textile preforms; and flexible composites exhibiting large deformations. The mathematical tools for analyzing their thermomechanical properties have been presented. Most significantly, an effort has been made to delineate the relationship between the behavior and these composites.

In the following, a comparison is first made among the stress–strain behaviors of three composite systems. The purpose is to demonstrate the versatility in composite performance through the design of microstructure. This is followed by specific examples of tailoring the material performance through microstructural design. Lastly, the emerging field of 'intelligent composites' is introduced.

1.5.1 *Versatility in performance*

For the purpose of demonstrating the versatility of the performance of composites, the stress–strain relationships of three types of composites are examined. Figure 1.10 shows the stress–strain curves of a unidirectional carbon fiber reinforced glass matrix composite (Nardone and Prewo 1988). The behavior is typical for brittle matrix composites based upon polymer and glass/ceramic matrices. The knee phenomenon of the stress–strain curve resembles the yield behavior of metallic alloys.

Figure 1.11 gives the stress–strain curves of interlaminated carbon/glass hybrid composites. The ability of the low elongation phase (carbon) in developing multiple fractures enables the hybrid composites to sustain deformations at a level much higher than that of the all-low elongation fiber composite. The energy absorption capability as indicated by the area under the stress–strain curve is also much higher than that of the all-carbon fiber composite. The shape of this stress–strain curve resembles those of ductile metals with strain-hardening behavior.

The stress–strain data of a flexible composite (Fig. 1.12) show rapid increase in stress and stiffness at large deformation (Chou 1989). It resembles the behavior of certain biological materials such as soft animal tissues (Humphrey and Yin 1987; Gordon 1988).

Fig. 1.10. Tensile stress–strain curves of a carbon/borosilicate glass composite. (After Nardone and Prewo 1988).

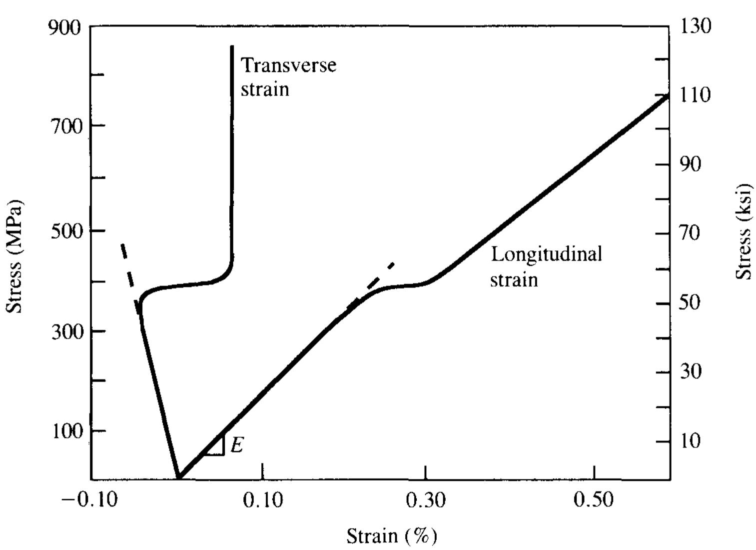


Fig. 1.11. Tensile stress–strain curves of a carbon/glass/epoxy interlaminated composite. (After Bunsell and Harris 1974).

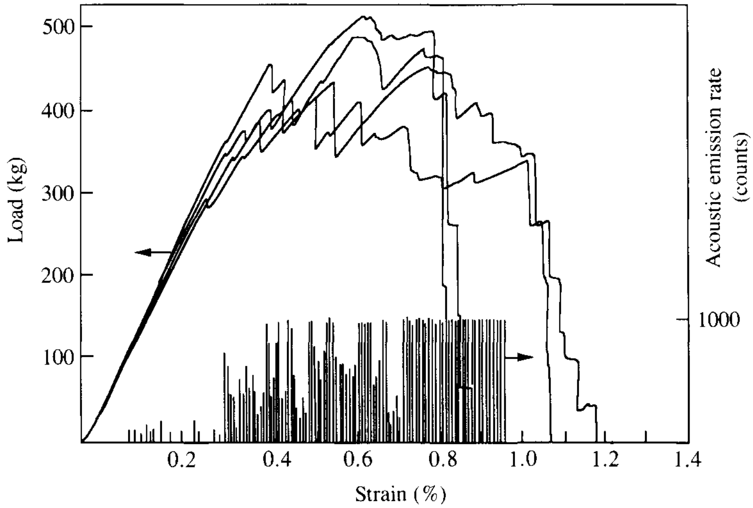
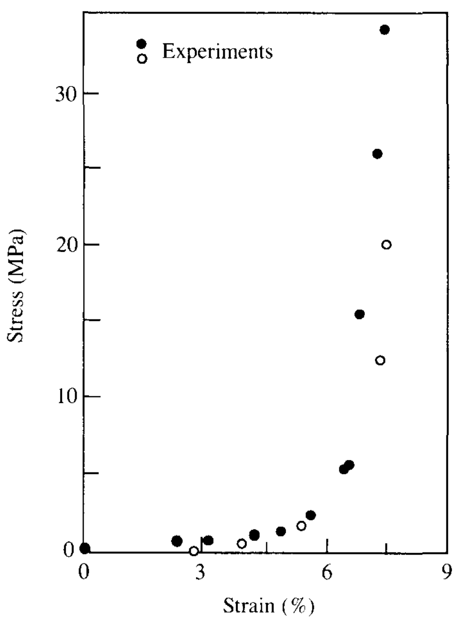


Fig. 1.12. Tensile stress–strain data of a flexible composite. (After Chou 1989.)



It is interesting to note that through the selection of fiber and matrix materials, as well as their geometric arrangements, a broad spectrum of material performance can be accomplished. It is feasible to design the physical and mechanical properties of composites which not only duplicate the performance of some existing materials but also fulfil the most demanding structural roles not envisioned before.

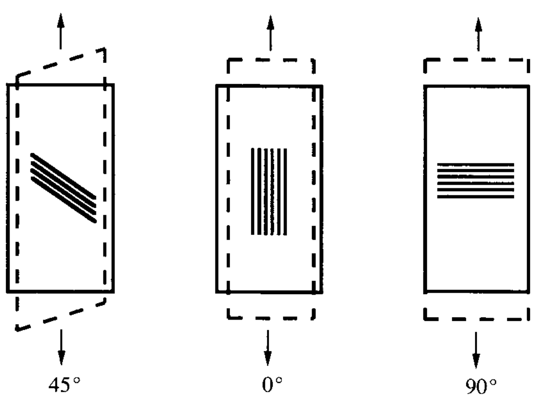
1.5.2 *Tailoring of performance*

The structure–performance relationships of the various types of fiber composites are further demonstrated in this section. First, for continuous fiber composites, the problem of edge delamination is used as an example. Next the variation of composite electric properties with the configuration of reinforcements is demonstrated.

Consider the $[\pm 45°/0°_2/90°_2]_s$ laminate. The effect of fiber orientation on the deformation of each individual lamina is highly anisotropic (Fig. 1.13). The compatibility of displacements among the laminae induces interlaminar stresses through the thickness direction of the laminate. Sun (1989) has demonstrated that the opening mode of delamination can be minimized through fiber hybridization, stitching, the use of adhesive layers, ply termination, and modification of edge geometry.

Figure 1.14 shows the free-edge interlaminar normal stresses in the all-carbon composite and the hybrid composite formed by replacing 90° plies with a glass/epoxy composite. A significant

Fig. 1.13. Effect of fiber orientation on the deformation of composite laminae. (After Sun 1989.)

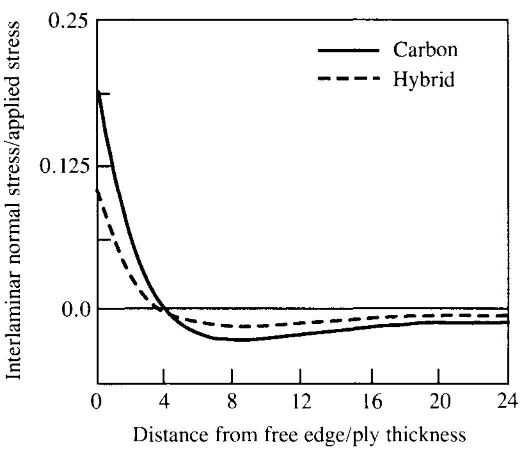


reduction in interlaminar normal stress is achieved with hybrid laminates. The experimentally measured delamination initiation stress and failure stress are 324.3 MPa and 800.4 MPa, respectively. The corresponding stresses for the hybrid laminate are 800.4 MPa and 883.2 MPa, respectively. Thus, the addition of the glass/epoxy plies significantly improves the delamination stress. The gain in failure stress is not as significant since the 0° plies in both laminates dominate the ultimate strength.

Reinforcements in the thickness direction can suppress interlaminar failure. Figure 1.15 shows the X-ray radiographs of $[\pm 45°/0°_2/90°]_s$ laminates under uniaxial tension. The specimen with through-the-thickness stitches along the free edges experiences much less delamination than the specimen without stitches.

Besides relying on textile performing techniques such as stitching, weaving and braiding, delamination in brittle resin matrix composites can be remedied by adding a ductile matrix in the form of thin adhesive layers. The resulting composite has a hybridized matrix. It has been demonstrated in $[0°/90°/45°/-45°]_s$ carbon/epoxy laminates that by reducing the free-edge effect the laminate strength can be greatly improved. Furthermore, the laminate strength becomes an isotropic property which can be predicted by the classical failure theory. The use of adhesive layers in laminates subject to low-velocity impact also proves to be effective in suppressing the development of matrix cracking and delamination.

Fig. 1.14. Free-edge interlaminar normal stresses on the mid-surface in carbon/epoxy and carbon/glass/epoxy laminates. (After Sun 1989).

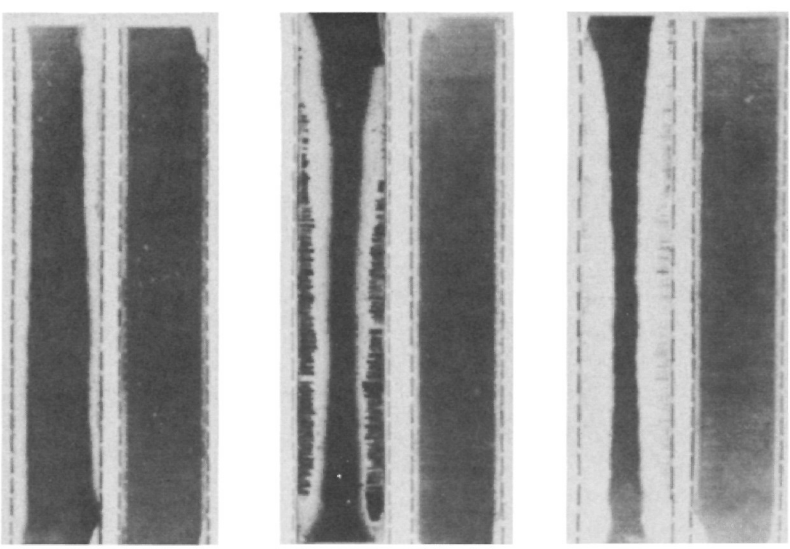


The transport properties, e.g. electrical conductivity, thermal conductivity, dielectric constants, magnetic permeability and diffusion coefficients of composites, are also sensitive to the microstructure of the reinforcements. McCullough (1985) has demonstrated the importance of structural features that promote transport along the preferred path, i.e. percolative mechanisms. Consider, for instance, the electrical behavior of metal-filled polymers. The effective resistivity changes sharply from non-conducting to conducting behavior upon crossing a 'percolation threshold'. Figure 1.16 illustrates such a transition for a composite containing conductive fillers ($\rho_f = 10^{-6}\ \Omega$ cm) in an insulating polymer matrix ($\rho_m = 10^{16}\ \Omega$ cm). The decrease in resistivity with the increase in filler volume fraction is attributed to the enhancement in probability of particle–particle contact. McCullough has concluded that these contacts promote the formation of continuous conduction paths that mimic the behavior of conducting fibers.

1.5.3 *Intelligent composites*

Traditionally, fiber composites have been designed and manufactured with the purpose of serving very specific functional

Fig. 1.15. X-ray radiographs showing delamination in unstitched (left) and stitched (right) [±45°/0°$_2$/90°]$_s$ laminates under uniaxial tension. (After Mignery, Tan and Sun 1985.)



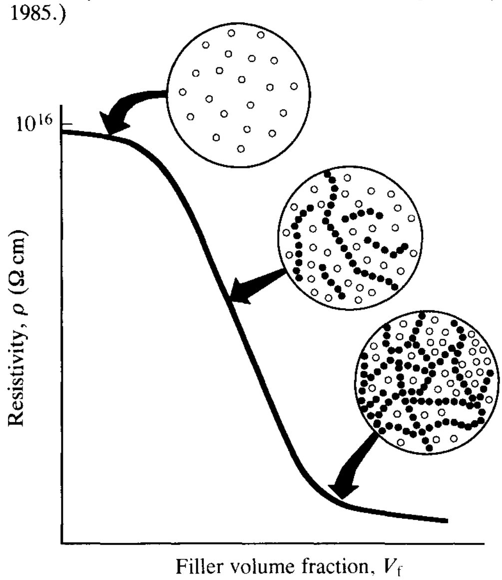
551 MPa (80 ksi) 641 MPa (93 ksi) 689 MPa (100 ksi)

goals. Such goals and considerations may include stiffness, fracture toughness, fatigue life, impact resistance, electromagnetic shielding, corrosion resistance, and biocompatibility, just naming a few. With the expansion in available material systems for composites, advancements in fabrication technologies, and improvements in analysis and design techniques, it becomes increasingly feasible for developing *multi-functional* fiber composites for which a number of functional goals are satisfied simultaneously, and the performance can be optimized.

A new breed of multi-functional composites is dubbed 'smart composites' or 'intelligent composites'. Takagi (1989) has defined intelligent materials as 'those which can manifest their own functions intelligently depending on environmental changes'. Thus, intelligent composites can react to the thermal, electrical, magnetic, chemical or mechanical environment and adjust their performance accordingly. It should be borne in mind that intelligent composites are made possible only through the design of their microstructures.

There are two basic requirements for intelligent composites to 'think' for themselves. First, the ability to detect the change in the environment, such as pressure, strain, temperature, and electro-

Fig. 1.16. Illustration of chain formation in a particulate filled composite. Open circles and closed circles indicate, respectively, isolated particles and contacting particles participating in chain formation. ρ and V_f denote resistivity and filler volume fraction, respectively. (After McCullough 1985.)



magnetic radiation is necessary. Next, the ability in feedback and control is also needed so corrective actions can be taken.

An example of intelligent composites under consideration by researchers is the skin of an aircraft wing (see Port, King and Hawkins 1988). The resin-based composite skin in this case has built-in optic-fiber sensors which through the pulses of laser light can detect internal defects and damages, the weight of ice or incoming electromagnetic radar waves. Signals from the sensors would be analyzed by patches of chips mounted on a flexible printed circuit board bonded over the skin.

It has been suggested that implanting monolithic microwave integrated circuit chips around an airplane's surface would produce a huge, omnidirectional antenna that would be far more effective than the small forward looking units now mounted on its nose. Other applications of intelligent composites have been envisioned for the purpose of in-flight damage assessment capability on airplanes and orbiting spacecrafts, prelaunch checks for leaks and structural integrity of the casing around rockets, altering the stiffness of sporting equipment such as golf club and fishing rods in response to the changing operating conditions, and monitoring the sway of high-rise buildings induced by hurricane winds or earthquakes so measures to compensate such deformations can be activated (Port, King and Hawkins, 1988). Some of the issues of intelligent structures have been discussed by Rogers (1988).

In summary, the challenges of intelligent composites are manifested by the following factors: (a) development of sensing, feedback and control systems as well as the technologies for fabricating composites imbedded with such devices, (b) implementation of the required changes in the shapes of the structural components, for example the change of the angle and shape of an airplane's wing, and (c) perhaps the most challenging task, the ability of a material to change its performance, for example the stiffness or transport properties.

The combination of the structural and non-structural roles of a composite in an integrated manner will undoubtedly change the performance of fiber composites in a way not envisioned in the past.

1.6 Concluding remarks

Having examined the evolution of engineering materials, and the role of fiber composites in materials technology, it is perhaps useful to put in perspective the research and economic opportunities of advanced composites.

First, from the viewpoint of materials research, it is important to recognize that the distinction between the three classes of materials, i.e. metals, ceramics and plastics, is disappearing. As observed by Kelly (1987a), there are now plastics as strong as metals which show some electrical conductivity. Metals are being made which are super-plastic and can be subjected to deformations in processing like conventional polymeric materials. Also the three classes of materials are beginning to show the same limits of strength and stiffness; fibers made from all three can attain stiffness and strength close to the theoretically predicted values. Furthermore, the properties of all three classes of materials can be modified and improved by the use of surface coatings.

As the distinction between the three classes of materials disappears, new possibilities and opportunities arise. One of these, according to Kelly, is the possibility of designing materials not so much for final properties but equally in terms of processability. These thoughts have profound implications for the future technology of fiber composites:

(1) The commonality in processing shared by the three classes of materials, e.g. super-plastic forming of metal and polymers, injection molding of polymers and ceramic powders, will enable more extensive and effective transfer of know-how among the three basic disciplines and effect efficient processing technology for fiber composites.
(2) The commonality in performance shared by the three classes of materials, e.g. stiffness, strength, thermal expansion, enables the material scientist to engineer composites with a broad spectrum of component materials. Consequently, hybridizations of materials, e.g. glass and low-melting-point metal, ceramics and thermoplastics, and polymer and metal in laminates or other interdispersed composite forms can be achieved and the properties optimized (e.g. composites composed of metal and polymer components of nearly the same stiffness but different fatigue resistance, or thermal expansion coefficient).
(3) The similarity in material property and behavior implies that analytical and design methodologies originally developed for a specific class of composites may be transferable to others. A notable example is the fracture and failure behavior of ceramic and polymer based composites.

(4) The complex task inherent in conceiving components and their materials and developing the proper design methodology will grow increasingly dependent on computers and multi-disciplinary teams. Such an approach will harness the full potential of composites for the technologies of the future.