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Composite materials after seventy years

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To celebrate the 40th anniversary of our journal I would like to pen an account of the state, as I see it, of Fibre Composite Materials. My personal involvement in this field started in the very early 1960s. And I remember being asked to join the Honorary Advisory Board of a journal to be entitled Journal of Materials Science, a few years after that, namely in 1965/66. I thought it a very good idea of Robert Cahn at the time and have been pleased to remain associated with the journal ever since. Since those days the field of composite science has expanded enormously and lately with Carl Zweben I edited, as General Editor, a six volume work on the science and technology of composites entitled Comprehensive Composite Materials. In what follows I have set down a summary of the field of composites engendered by my editing of that comprehensive work adding some history of how the field arose and including some pointers to the future. © *2006 Springer Science + Business Media, Inc.*

1. How composites arose

Composite materials are as much an engineering concept as they are a specific material. They represent an idea which to the best of my knowledge was first recognised in engineering in the "composite" construction of the later Clipper ships in the middle of the nineteenth century where wooden planking was set on iron frames. This was a binary composite—some ships carried in addition copper outer sheathing to combat marine organisms—a tertiary composite. The iron was used because it was strong, stiff and durable and being cast to shape could make the frames. Iron was not available at all easily in sheet form—wood of course was—as sawn planks. So to use iron's strength and stiffness a composite was necessary.

The modern term composite arose in the aircraft industry in the early middle part of the last century. Its advent can be viewed either as a means of using plastics in aircraft construction or as a means of utilising the stiffness and strength of fibres which were first made in the late 50s and early 60s of the last century. The first of these views emphasised the desirable properties of plastics which were becoming available in the late 30s. The modern synthetic plastics were first discovered in the early 1900s. The desirable properties were ease of formability, very low density compared with metals, excellent surface finish and lack of corrosion. They lacked stiffness and so some stiffening agent was necessary. The leading idea was to use plastics for aircraft construction. Plastics for aircraft propellers were experimented upon in the early 1920's.

The relevant mechanical properties of fibres and composites available in the thirties of last century are shown in Table I with the exception of those containing glass fibres. Glass fibres were not available then, being produced in quantity only from about 1940 or so. Naturally grown fibres such as flax or jute were tried as additions to stiffen the plastic. Although a great improvement was possible the resulting materials were not superior to aluminium alloy as may be seen from Table I. Note also that glass, while being superior to aluminium alloy in terms of strength does not provide a composite which outstrips it in terms of specific stiffness. Another possible addition would have been asbestos because chrysotile asbestos is very stiff and strong but it is not available in long continuous lengths. A problem of course with natural fibres, as with wood, which is in fact a natural fibre composite of cellulose fibres in lignin, is that moisture attacks the material and degrades the properties. The addition of flax to an organic resin does make a fibrous composite in the modern sense.

Recently there has been renewed interest in such composites since by choice of a suitable matrix resin, based, say on starch, a wholly biodegradable composite may now be made—with the material showing adequate stability during useful life.

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TABLE I Fibres and composites available prior to 1960

Fibre or composite	Modulus, E (GPa)	Tensile strength, σ (MPa)	Specific gravity ρ	Specific stiffness, E/ρ (GPa)	Specific strength σ/ρ (MPa)
Flax	103	690	1.5	69	460
Hemp-wet	34	–	1.5	23	–
Hemp-dried under tension	85	–	1.5	57	–
Ramie-wet	19	–	1.5	13	–
Ramie-dried	51	758	1.5	34	505
Asbestos-chrysotile	159	1379	2.6	61	530
E-glass	69	3447	2.54	27	1357
Unidirec.Flax Phenolic resin (Aerolite)	34	345	1.35	25	256
Unidirec. E-glass/epoxy	41	1241	2.05	20	605
Asbestos/phenolic Part. Align-"Durestos"	17	138	1.27	13	109
Aluminium alloy	70	600	2.8	25	214

Data from: P McMullen, Fibre-resin composites for aircraft primary structures: a short history, Composites, 15, 222–230 (1984).

TABLE II Some fibres and composites available since 1965

Fibre or composite	Modulus, E (GPa)	Strength, σ (MPa)	Specific gravity, ρ	Specific stiffness, E/ρ	Specific strength, σ/ρ
S-glass	86	4481	2.49	35	1780
Unidirectional S-glass/epoxy	52	1793	2.08	25	862
Boron	379	2758	2.69	141	1025
Unidirectional Boron/epoxy	269	1345	1.97	137	683
Carbon(HM)	379	1724	2.0	189	862
Unidirectional Carbon/epoxy	131	1517	1.55	85	979
Kevlar 49	117	2758	1.45	81	1902
Kevlar/epoxy	83	1931	1.35	61	1430

The view of fibrous composites as a means of greatly improving the mechanical properties of plastics remains a very powerful perspective. Almost all plastics in use contain fillers of various kinds, often particulate which are added to plastic to extenuate the material and hence lower the cost—they are often cheap and plentiful materials such as chalk—and to add stiffness. The addition of fibres is a natural progression.

The normal means of incorporating a filler into plastic involves blending or mixing so as to produce a homogeneous material in which little or no attention is paid to the relative arrangement of the filler particles. While such a procedure will do with roughly equiaxed particles, of spheroidal or cuboidal form it will not do with fibres if the advantages of incorporating fibres are to be maximised; a fibre is strong and stiff in a direction parallel to its axis; so only in one direction. Some examples of modern fibres and composites of high strength and stiffness are shown in Table II.

2. Strength and stiffness of fibres

The breaking strength and stiffness of a fibre of given chemical constitution can be understood in terms of the geometric form which often governs the strength and the molecular construction and internal structure of the fibre which governs the stiffness. For simple chemical substances such as pure silica (SiO_2), or alumina (Al_2O_3) a fibre is in principle, and it can be shown so in practice, no stronger than a large piece, provided that the large piece has smooth surfaces. The stiffness of the fibre—along its axis—can be understood with some precision—say within 50%—from a knowledge of the binding forces between the component atoms. The fibre is strong because the surface is likely to be smooth—in general the thinner the smoother.

For other modern fibres such as carbon (graphite) or aramid the control of the internal constitution (the microstructure) is vital in determining the axial stiffness—the strength follows from this and the method of production, drawing through a die at a crucial stage, ensures surface smoothness. To some extent, in these cases, provided the surface is "fairly smooth" the internal microstructure can also add or subtract from the strength. For metal wires or fibres the axial stiffness can be understood in terms of the binding forces between atoms. High strength demands very close control of the microstructure, besides attention to surface smoothness and perfection.

These factors controlling the strength and stiffness of fibres were recognised in the 1960s and very stiff and strong fibres of boron and of graphite were made for the first time. They were strong and stiff, but also, because made from chemical elements of low atomic weight they are much less dense than most metals.

3. Using the fibres

The second way of looking at composite materials then arises if one asks how to utilise these attractive properties of a fibre; stiffness, strength, and low density. By themselves they can only be used for their mechanical properties in the form of a rope and even for that application some facility for twisting the fibres to form a handleable tow will be necessary. To make them really useful they must be incorporated into some material—a matrix. Clearly one of the most attractive is a resin. They must also be handled before being put into a matrix. Fibres provide the stiffest material when all aligned parallel to one another and this is the form in which they are used in the highest performance applications. Fibres are also used in woven form and if used thus, must be capable of withstanding modern weaving processes.

It is also very important that resin matrices are available which are compatible with the new fibres as these are produced. Glass fibres, for instance cannot be used with phenolic resins. Polyester and epoxy resins have been developed for use with the high performance fibres and modern ones such as vinyl esters provide resins of superior quality to accompany high-performance fibres.

4. Properties of composites

The outlines of the materials science of composite materials are now clear. They are about the properties of strong stiff fibres and how they are made and how and why the fibres affect the properties of the matrices which are used to bind them together. The fibres require a matrix in order to be useful to the engineer. The mechanical properties of the fibrous composite which depend upon properties of the (usually) two components and their relative volume fractions are describable rather generally, and in many cases follow a simple rule of mixtures.

Although there are very few surprises, some among the thermomechanical properties are quite striking: e.g., negative thermal expansion coefficient and negative Poisson ratio both in plane and through the thickness. This last can be quite useful, e.g., when dome shaped objects are required to be produced by bending, since a negative Poisson ratio will avoid anticlastic curvature. In addition a smooth variation of physical property can be obtained, which is useful in matching components, e.g., glass to metal seals or in prosthetic devices—see Fig. 1. Very large values of Poisson's ratio e.g. up to a value of nearly three may be found in laminated composites—such a value lies well outside that of either of the components. Matching of acoustic inpedance at interfaces is also a very useful advantage. Acoustic wave velocity provides an additional example where a well-known physical property has a value lying outside that shown by either component.

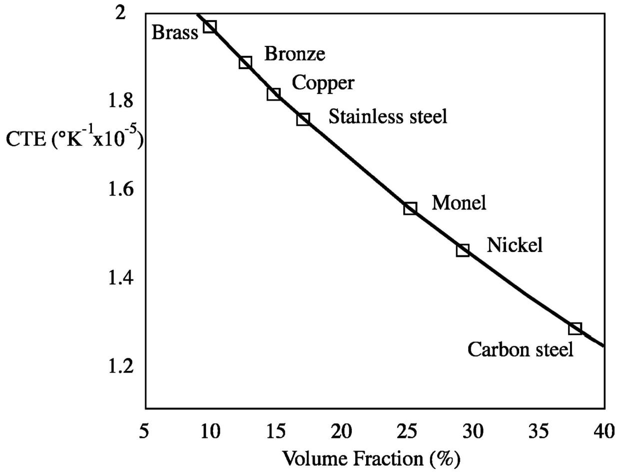

Figure 1 Room temperature thermal expansion coefficient of SiC spheres in aluminium compared with other materials.

Of course the idea of using a pair of materials each of known properties in order to obtain an effect shown by neither alone is a very general one and one would hope, would occur to any competent engineer. The bimetallic construction devised by Harrison to eliminate the effects of differential thermal expansion in a chronometer is an obvious example. Reinforced concrete is another where steel bars are introduced into concrete in order to bear tensile loads which cement concrete or other masonry cannot. Such examples are not referred to as composite materials primarily because the two components are clearly recognisable as distinct from one another and the size of the pieces of each large enough so that one is considering an engineering "structure".

5. Size and nomenclature

The principles of interaction of the two material pieces in the above examples are however composite principles. And the latter example of "reinforced concrete" behaves very similarly to some of the ceramic composites I will describe later. A material is usually described as being a composite material when the size of the individual units is so small, usually less than 100 μm (0.1 mm), so they are not visible to the naked eye. Here, importantly, they are so small that a useful material—one handleable by the engineer—contains many millions of units.

The size of the units here are crucial. The thermomechanical properties of composites—resins and rubbers—metals—ceramics and glass, depend on the microstructure—sometimes called the mesoscopic phase—of the materials. This is on a scale of size between atomic dimensions (i.e. up to a few nanometres at most) and several microns (ten thousand nanometres). Over these length scales metals, ceramics etc. are not homogeneous. Conventional processing (heating, drawing, dissolving, precipitating) of such materials alters this microstructure and redistributes the constitutive chemical elements so as to produce different phases (metals and ceramics) or different conformation (plastics). However, such materials are not usually to be regarded as composites.

However, when particles, be they fibres, whiskers or voids or other shapes, of a completely different material are introduced extraneously on a similar scale of size i.e. much smaller than the diameter of the fibres described here, the resulting material may quite rightly be described as a nanocomposite. Discussion of Whiskers and Particulates might be described as discussing nanocomposites. The engineering idea of the nanocomposite is of growing importance for two reasons; materials processing capability based on modern microscopes, micromanipulators and sensitive transducers is now carried out on this scale of size which was not possible a few years ago—nanotechnology—microlithography—and so the principle of combining two (or more) materials in order to obtain new properties shown by neither alone can now be applied on a much smaller scale of size. The non-mechanical, physical properties of such nanocomposites (e.g. magnetic and electrical) will, I believe, be perhaps more important than the thermomechanical ones. Carbon nanotubes, an important recently discovered form of carbon, are an exemplar.

The upper size limit at which one speaks of a composite material is also important. This arises for two reasons both ultimately connected with design of structures. Firstly, as has been pointed out for many years most living structures of animals and plants are composites in the sense used here, strong fibres (cellulose in the case of wood, hydroxyapatite in the case of animals' bony structures) surrounded by a matrix, lignin or collagen. The matrix fulfils the mechanical properties necessary, and in biological structures also permits passage of fluids and so its transport properties are essential. The strong fibres bear the load. Composite mechanics can explain some of the properties of biological materials and since many biological structures e.g. birds' wings or fishes bodies, are found to be extremely well designed in terms of lightweight or aerodynamic efficiency, there is a desire to copy them. But one does not refer to the biological entity as a composite.

They, like an engineering structure, particularly the civil engineering structure are grown into place; they develop the composite material as a structure. Hence the second reason for the upper limit. The composite material has become a structure. Conceptually the fibres are placed first in the most economical way (least weight) to carry the load. There are various theorems, Michells' famous one is well known, concerning the arrangement of fibres necessary to bear the loads. The matrix should then be placed around the fibres to fulfil other tasks. In order to proceed like this, in more than a rather superficial sense, for a structure with varying and dynamic loads and possibly many degrees of freedom, the designer needs efficient computer codes to define and work out the problem—codes which define the response of the structure and of the component materials. These are available.

Composite materials can claim to be the first materials to be designed in the sense of building together the two components of a structure and (due to its size) calling it a material. The application of the computer codes referred to above require some material properties as input. Sufficient is now known so that one can be quite definitive in reviewing how these may be obtained and used in a large number of cases.

6. Processing and manufacture

Of course the properties of real composites depend on how each is made. Processing is of paramount importance because whether or not the desired properties can be attained must depend on the processing procedure. If this is complicated or expensive the properties may not be achieved. Usually, but certainly not always, fibre composites are manufactured by making the fibres separately from the matrix and then combining the two, usually with some additive, in order to ensure the two come together properly.

So composites are finding increasing use in the form of both plastics *and* metals containing long strong fibres, thus providing a combination of high stiffness, high strength, low density, good corrosion resistance, and the possibility of manufacturing large complex shapes in a single operation with relatively little material wastage. The last advantage is particularly true of the plastic matrix composite. However, it is only true for short production runs and when in competition with metals where the latter must be extensively machined. For large production runs metal pressing remains the cheaper option. This fact is limiting the penetration of composites into carrosserie (car bodies) for volume production cars, but they are penetrating the bicycle market, often allied with carbon fibres—particularly for the more expensive type of bike.

However cheap the matrix is made in a composite, fibres remain an inherently expensive form of material from which to manufacture an engineering artefact. There are some naturally occurring fibres which can be very cheap. Jute attracts attention at present, as I have said, because it has properties which rival those of flax and is incinerable (while glass is not). It may displace glass in some applications because protection of the environment demands destruction of a structure after use—glass will not burn and forms an intractable slag.

However, where a realistic cost comparison can be made between (essentially) the same material in bulk sheet and fibre form, the fibre form always emerges as the more expensive. For instance, taking the case of high performance polyester, which is commercially produced in equivalent production tonnage and with equivalent commercial uptake (sales) in the three forms of bulk, high performance film (with various coatings), and textile filament, the relative costs (bulk to film to filament) are 1:2.6:3-4.6. For steel or glass the ratios are a little smaller but of the same order.

The cost of a composite could be reduced if fibre were produced directly *in situ*. Many techniques to do this have been tried over the years but none is particularly promising so far as I know. Of the thousands of tonnes of composite material manufactured today, the great majority is with a polymer matrix. The manufacturing techniques used with thermosetting resins are different from those with thermoplastic substances. The composite fabrication industry is, like other materials manufacturing industries, much concerned to measure property evolution during manufacture and to control this—the concept of smart or intelligent processing is a developing area.

7. Metal matrix composites

Metal matrix composites (MMCs) are the most recent to be developed—if one omits, as is usually done, to consider cutting tools made of so called "hard metal" and its derivatives. Metal matrix composites have arisen since the 1960s. The reason for the technological interest in metal matrix composites at that time, and since, arose because the really stiff fibres of low density only became available in the very late 50s and early 60s of the last century. Boron discovered in 1958, and graphite fibre discovered in 1963 were not in fact stiffer than wires of tungsten but the density is almost an order of magnitude less. This predicated advantage to the aerospace industry who were eager to receive the fibres in order, among other things, to make aluminium—the principal aircraft construction material—stiffer. Naturally the early composites made with the much stiffer and lighter fibre used a resin as the matrix. However boron in aluminium was experimented with extensively in the USA and USSR and very large pieces were made. When carbon fibres were first discovered they were difficult to make compatible with aluminium due to electro-chemical effects and this is still the case to some extent. The advent of silicon carbide fibres in the early 1970s, which were quite compatible with aluminium, has led to a developing interest in MMCs.

Particles of a very stiff inclusion in a weak elastic matrix, if present in sufficient volume fraction, can of course give a very stiff composite and so in the case of the metallic matrix particulate composites are produced in larger quantities than those containing fibres.

An additional point is that the metallurgist or materials scientist specialising in metals is very used to dealing with particles inside his metals. So particulate composites with a metal matrix seem a natural development. In the case of the metal matrix there is then a case for adding both forms of stiff material to a metal matrix and indeed some composites contain both stiff fibres and stiff particles. The fibres are not usually continuous.

The principal advantages conferred upon a metal by the addition of materials such as silicon carbide, boron or other strong solid are: increased stiffness, decreased coefficient of thermal expansion and better resistance to wear. Whether or not the breaking strength of the material is increased is not the most important factor.

The reinforcement of metals though leading to much smaller market sizes than polymer matrix composites has played an important part in the development of the field of composite materials generally. In the years after World War II although the advantages of a composite material were well known to some people, metals dominated the construction market, particularly for aerospace and defence, which are often the drivers of new developments. Work at NASA initially intended to provide metals of higher temperature performance e.g., by putting tungsten wires into nickel alloys, led to the understanding of some principles of reinforcement and this understanding was picked up by the metallurgical community.

This community formed the principal group of engineers and scientists concerned with the development of new and improved materials. Experiments in universities and other research institutes led to a wider dissemination of the knowledge of how composite materials could show improved properties compared with metallic monoliths. When the stiffer fibres became available the materials engineering community was therefore much better able to appreciate quickly the possible advantages of the composite approach.

I referred earlier to the fact that making the fibres and matrix separately and then combining them into the composite material is not the only way to fashion a composite. In some alloy systems e.g. cobalt, chromium alloys containing carbide fibres of a stiff strong phase may be produced *in situ* in a matrix. This is done by various forms of heat treatment and can produce aligned and very regular fibres. Work on such systems, aimed at replacing metal alloy for high temperature service did not produce commercially useful products but was again of importance in demonstrating the advantages of "thinking composites".

We now know how to grow *in situ* reinforcements in all three of the matrix types, polymer, metal and ceramic.

Returning to the point that composite materials are as much an engineering concept as they are a specific material one can think of introducing voids into a matrix, i.e. using empty space as the second material. Doing so automatically lowers the density and greatly reduces the thermal conductivity while in some cases altering the transmission of sound and the sound velocity. Foam can be a very useful form of material in many cases and metallic foams are much researched at present.

8. Brittle matrices and brittle fibres

The very strong and stiff fibres which I am discussing contain principally the chemical elements occurring early in the Periodic Table, B, C, N, O, Si, Al—the chemicals which form the basis of the inorganic solids—see Table III. Of course carbon is always a special case, forming the backbone of the strong organic fibres, polyamide, polyester, aramid, besides providing itself a stiff fibre—maybe the stiffest possible—and being a constituent of some strong inorganics. The six elements just listed comprise indispensable chemical elements in the constitution of carbon, cement and ceramic matrices. So in this case fibres of very similar chemical composition to that of the matrix are being introduced into it. The reason is that in these cases the introduction of fibres is often, though not always, in order to ameliorate a failing of the matrix rather than to realise a property of the fibre. The principal "failing" of the matrix is of course its brittleness.

The market for composites with a matrix of this type is very much larger than that for metal matrix composites and is of two types. Fibres introduced into cheap widely used materials e.g. cement, or clays which have a big market or fibres introduced into specialist materials, such as various ceramics e.g. silicon nitride (Si_3N_4).

We should distinguish in passing between reinforced concrete introduced in the early part of the nineteenth century, where steel wires and or bars are used to enable concrete to bear tensile loads and fibre reinforced cements. In the former case we are dealing with a structure, and the wires may be variously stretched and then anchored in place as in the so called Freysinnet system. Although some of the theory may be read over, and has relevance for composite theory when prestressing of the fibres, either by accident or by design occurs, reinforced concrete is not a composite material. Asbestos cement and cement containing polypropylene or carbon fibres is.

TABLE III Elements forming strong solids

H	Be	C	N	O	F
(Li)	Mg	Si	P	S	(Cl)

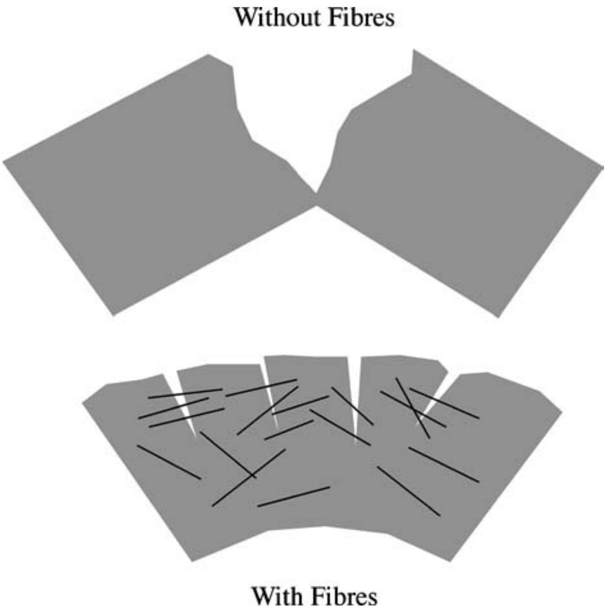

Figure 2 How fibres impede crack growth.

Here the fibres are introduced into the cement, usually Portland cement, in order to prevent its cracking under tensile loads. The use of fibres to prevent otherwise brittle materials from cracking has been recognised for millennia. The Holy Bible (Exodus, Chapter 5) refers to the need to introduce straw into clay to make bricks and many early building materials are of this type and are still made. Some of the earliest ancient Egyptian vessels were built from glass fibres wound by hand round a core of shaped clay. Eskimos are familiar with the important fact that ice containing moss is safe to stand on because although it may crack locally under pressure the cracks do not extend as they do in ice containing no vegetation. The effect is quite dramatic and during World War II a large project concerned with the introduction of wood fibres (sawdust) into ice in order to build artificial islands yielded much important data. The theory which explains this type of behaviour, namely how it is that fibres prevent the spreading of cracks is now quite sophisticated and used in the understanding of the design of personal and of other types of armour. The physical reason for the toughness conferred on a brittle material by the incorporation of fibres is illustrated diagrammatically in Fig. 2.

9. Using ceramics at high temperatures

Ceramics and glasses are the materials which do not burn in air at very high temperatures. To prevent oxidation at high temperature one must use either a noble metal or something already oxidised so that the process can go no further. The material must be either a stable oxide or one which is covered with an oxide (a nitride) or some sort of impervious cover itself stable against oxidation (and nitridation). Many ceramics fulfil these conditions. SiC for instance resists oxidation under many conditions due to the formation of a very stable film of silica. Fibres of silicon carbide—almost stochiometric silicon carbide—were produced due to the efforts of Yajima in Japan in the mid 1970s. At the same time a fibre of aluminium oxide was produced. Such fibres like carbon and boron fibres are very stiff and although somewhat denser than the first two are nonetheless much less dense than all metals capable of high temperature service (with the possible exemption of beryllium, which is toxic).

At about this time the feasibility of developing materials for service at elevated temperatures under substantial loads in air was assuming great industrial significance. This significance remains today. The advent of the fibres just mentioned, however, gave impetus to the concept of producing a strong composite of very high temperature capability. Ceramics were the natural matrix.

A good deal of research effort has therefore gone into understanding in further detail the mechanics of ceramic matrix composites containing ceramic fibres. The motivation here is to improve the properties of prime movers requiring the use of very high temperatures. Aeroengine requirements are outlined in Table IV and the conditions of operation of high-pressure turbine blades in an advanced jet engine are shown in Table V. Important, though it is in advancing understanding, no new material of high temperature capability superior to that of the nickel alloys—about 1000°C see Fig. 3—has yet emerged until recently, mainly because of the lack of a fibre with a high strength at that temperature which can be maintained for many hours. There are at least two promising approaches. One is based on a silicon carbide fibre with a very coherent coating (based on mullite-a ceramic oxide). The other is the emergence of novel crystalline oxide fibres invented by Mileiko and his team in Russia. The progress towards attainment of the goal is shown in Fig. 3.

TABLE IV Aero engine requirements

	1940	1987	2000+
Thrust/weight	3:1	10:1	20:1
Compression ratio	4:1	30:1	40:1
Turbine entry temperature	800°C	1400°C	2000°C

TABLE V Conditions of operation of advanced gas turbine blades.

Operating temperature	850–1750°C (Melting temperature of Ni 1453°C)
Gas velocity	1800 km/s = Mach 1.6
Rotation	1000 rpm = 1000 mph
Stress	20 t/in^2 = 300 MPa
Life	1000 h = 5 M miles of flying

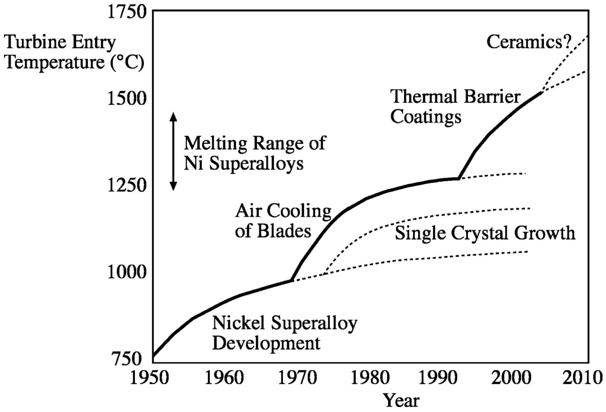

Figure 3 Progress towards achievement.

A feature of many ceramic materials not shared by metals and thermoplastics is that they do not melt, but rather sublime e.g. C, SiC, and BN. Consequently it is usually very difficult to form them into solid pieces without voids. The difficulty of diffusion in many ceramics and the wish to avoid a matrix full of holes (say by using vapour deposition) means, in general that the processing of ceramic composites is very slow compared with others and this adds to the cost of production. Strenuous efforts are being made to change this situation.

10. Testing

Long fibre composites differ from most other materials of engineering construction in being anisotropic and comprising at least two distinct phases or materials. The tensile testing and particularly the compressive testing of very anisotropic materials has demanded the evolution and general acceptance of new test methods for composite materials. In addition standardised test methods concerned with the detailed interaction between fibre and matrix are necessary.

Composite materials, made with a resin matrix are usually susceptible to moisture uptake, which does not occur in metals. Durability tests are therefore of special significance for polymer composites.

The properties of a real material depend on the structure of it after it has been processed—the properties obtained usually differ from the ideal required—the real properties must be measured and that without dismantling the piece—non destructive evaluation (NDE) is required. Some of the methods used are similar to those used in evaluating structural metals—but many are different, or so qualitatively different, that they require different apparatus. For example eddy current testing of a metal is commonplace because of the high electrical conductivity. For composite materials based on a resin containing a non electrically conducing fibre the technique is of much less importance. This is not because of the low conductivity, because this leads to a larger penetration depth in a composite, but due to the ambiguity of the response.

Of course the development of composite materials as an engineering concept and its realisation has advanced at the same time as the development of other engineering materials. Until recently NDE was used almost exclusively for the detection of microscopic flaws (usually cracks) after a material had been created and was in service. Nowadays it embraces all aspects of materials production and application.

11. Smart materials

One very big concomitant advance contemporaneous with the development of composite materials has been that of optical fibre communication. This highly developed technique evolved very rapidly since the discovery of very low loss optical fibres in the mid 1970s. Optical fibres produced for long distance telecommunication are so important because the methods used to check them and those proposed for this task, make the fibres themselves extremely sensitive sensors. Since fibre composites by definition contain fibres, it seems natural to incorporate these into a material so that it might be able to tell one "how it feels". Optical fibre sensing techniques and the ways of integrating optical fibres into composites (the fibres are usually of much greater diameter than the stiff fibres used in the composite) are becoming very important.

The use of fibres embedded in a composite so as to monitor structural change can be described as the passive use—producing a perceptive material. A fully intelligent material or "smart material" might try to correct a defect in itself or to alter its form in response to external stimuli. This involves self measurement of its condition and an active response. Again the bimetallic strip is an extremely simple example. To produce an active response an actuator must be incorporated. The three forms of these, piezoelectric, magnetostrictive and that based on what are called shape memory alloys (an imposed shape change is accomplished by means of a crystal transformation which may be reversed) are all being developed. The Piezoelectric actuators are often composite materials themselves.

12. Applications

Society's drive to develop modern composite materials arose from a military imperative as we have briefly seen. Hence many of the leading applications of composite materials are in military hardware of some form. It is clear from the foregoing that component design involving composites will inevitably be *sui generis* due to the anisotropy of the material and to the fact that it contains, at least, two components.

Composite materials provide, stiff strong lightweight materials of high corrosion resistance, excellent fatigue resistance and may be electrically conducting. Provided they can be fashioned to shape at acceptable cost there are many applications emerging. They are gaining ground in civil engineering where the light weight and excellent corrosion resistance makes them the preferred materials for repair of the transportation infrastructure: bridges, roads, tunnels, etc.

Cost is of less importance in areas such as military hardware, highly competitive high publicity sports activities, and in medical devices. These are areas where new composite materials have been developed and tried. As happens with all "new" materials their availability enables the making of some artefacts which would be impossible without them. An example of this type for composite material would be a man powered aircraft. More usually, the development enables much improved performance of a given artefact so that the performance could not be obtained without the use of an improved material. The increase in performance becomes so great that eventually one considers it natural to use that material. The chassis of formula I racing cars, some aspects of stealth aircraft, and vaulting poles are examples of this type of development using composite materials.

Composite materials are an engineering concept that is now becoming widely accepted. The composite idea though at present mainly of relevance for constructional materials has great pregnancy for functional materials; for example in the manufacture of computers, particularly of substrate and packaging materials for silicon chips. Composites provide the possibility of varying combinations of thermal expansion, thermal conductivity and dielectric constant, which are not possible with a single material.

13. Summary

The remarks above were initially engendered in the course of my editing as General Editor the volumes listed below. I have added a few remarks relevant to what has happened since the publication.

Comprehensive Composite Materials, Pergamon (2000), A Kelly and C Zweben Editors in Chief. A six volume work of 5161 pages.

Volume 1 Fiber Reinforcements and General Theory of Conposites-824 pages
Volume 2 Polymer Matrix Composites-1129 pages
Volume 3 Metal Matrix Composites-866 pages
Volume 4 Carbon/Carbon Cement and Ceramic Matrix Composites-715 pages
Volume 5 Test Methods Non-destructive Evaluation and Smart Materials-653 pages
Volume 6 Design and Applications-974 pages