

COMPOSITE MATERIALS— REFLECTIONS ON THE FIRST HALF CENTURY

Nature tends to use composites in building strong structures. Timber, for instance, is a composite made up of strong cellulose fibers in soft lignin. Bone consists of hydroxyapatite in collagen. Although people don't always recognize them, composites are everywhere. Only in the last 50 years or so has mankind purposely imitated these natural materials by developing artificial composites.

Consider the automobile tire shown in figure 1. Layers of rubber are interleaved with parallel fiber bundles, "cords," to form a toroidal laminate. The choice of fiber for the cord material depends on several factors. High stiffness is needed so that the fibers will neither stretch under load nor bend when stressed. The cord fiber should also be able to withstand failure under repeated flexural loads—that is, it should have a high resistance to fatigue. It has to be strong and yet lightweight. Then, the cord material must also adhere well to the rubber. Finally, it must be inexpensive. Over the years, tire cords have been made of a variety of materials, including cotton rayon (regenerated cellulose made from trees), nylon, polyester, and glass. Nowadays, either polyaramid fibers (such as Kevlar) or steel wires are typically used.

The bricks that the ancient Egyptians made by adding straw to mud are among the earliest examples of composite materials. Straw, a hollow tubular form of cellulose-based material, has the triple advantage of being cheap, readily available, and easy to handle. But because the cellulose molecules are not aligned very well with one another, straw is neither very stiff nor strong. Far superior fibrous materials have been developed over the past few hundred years, many of the advances during the last half-century. Among them are hemp, steel wires, glass, carbon, and various polymeric fibers.

Today's fibers—and the quest for tomorrow's

High-performance fibers form the basis of many modern composites. What are their characteristics, and how are they designed?

First, let us consider the stiffness of materials in general. Stiffness depends on interatomic forces. A common way to represent such forces is on a plot of energy against interatomic separation, as in figure 2. Because the force is proportional to the gradient of such a plot, stiff materials show up as having deep, steep potentials. Stiffness commonly results when electrons are shared between atoms to form strong, inflexible covalent bonds. When they form between light elements—such as beryllium, boron, carbon,

Advances made in understanding the properties and behavior of composite materials are now powering the exploitation of their immense potential.

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nitrogen, and oxygen—the bonds are often particularly strong. The outer electrons are more tightly bound in the small atoms of light elements than in large atoms, whose outer electrons are shielded from the nucleus by large clouds of inner electrons.

Next, let us consider a material's ability to withstand great heat. Materials that exhibit deep potentials also tend to have tight binding, which causes them to have a high melting point and makes them suitable for use at high temperatures (provided they do not readily oxidize). Furthermore, the deeper wells are usually less asymmetric; lower asymmetry implies less expansion on heating.

A third desirable quality is strength. You might imagine that strength, like stiffness, would also be determined by interatomic bond characteristics. It is true that strong bonds are needed if a material is to be very strong. In practice, however, the presence or absence of flaws in a specimen has an important effect on its strength, particularly in the case of many stiff and strong materials. Flaws will concentrate stress and promote the propagation of cracks through a material. In fact, it is because the fibers of some materials can readily be kept free of large flaws that they are often exceptionally strong. Furthermore, the chemical constitution of the strongest, stiffest, and lightest fibers is such that they always contain at least one of the elements whose atomic number is less than 9.

Advanced fibers have other typical properties that are worth noting. The combination of two qualities—high thermal conductivity and low electron mobility—constitutes a fourth characteristic of in-demand commercial composites. Since advanced fibers tend to be held together by strong covalent or ionic bonds, their long-range electron mobility is usually very limited. That makes many of them very poor electrical conductors. On the other hand, advanced fibers can be excellent thermal conductors, because heat can be transferred by lattice vibrations (phonons), as well as by the movement of electrons. The fact that phonons are easily transmitted in a stiff lattice of light atoms, means that materials made up of carbon, boron, and silicon carbide are excellent thermal conductors. Those elements may conduct heat even more effectively in fibrous form because the low level of structural defects in their fibers keeps the phonons from being readily scattered.

The data in figure 3, which shows the electrical and thermal conductivities of metals and of various grades of carbon fiber, illustrate some of the points just described. The engineer's scope for microstructurally controlling composites' properties is reflected in the wide range of conductivities that carbon fibers exhibit. The mechanical and thermal properties of fibers can be strongly influenced by such factors as the degree of porosity, the number and size

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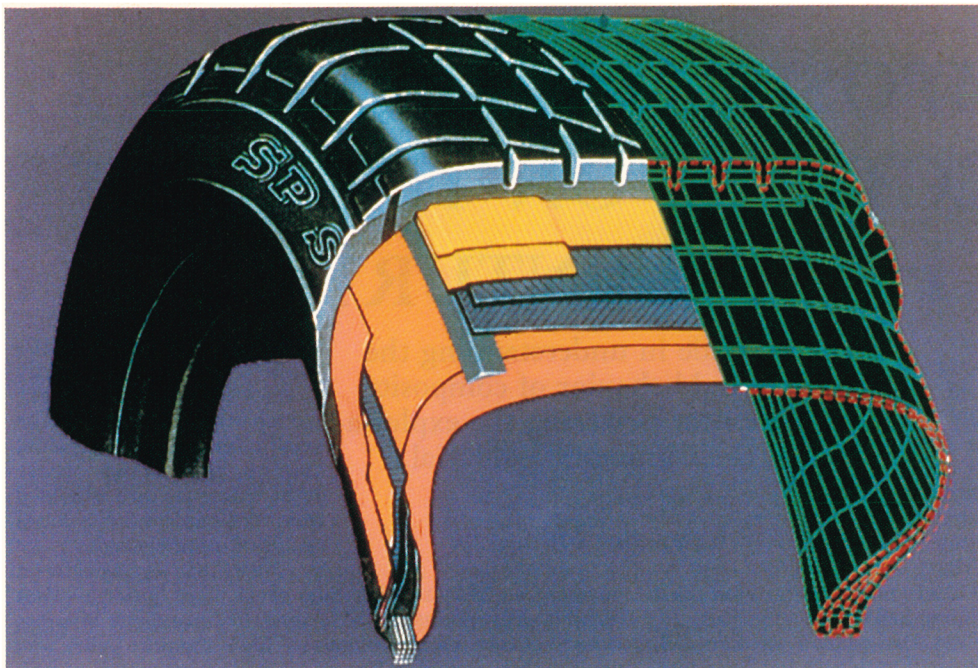


FIGURE 1. A CAR TIRE gains considerable strength from the toroidal laminate formed by the interlaced cords inside the rubber.

of cracks, the ratio of amorphous to crystalline material, the degree of molecular alignment along the fiber axis, and the grain size and shape—and all those factors can be controlled by means of the processing conditions.

The quest for improved fibers continues. Some of today's experimental activities are focusing on diamond fibers and hollow carbon fibers, which are designed to enhance performance in specific areas—bending and compression in particular. Concerted efforts are also being directed at so-called carbon nanotubes—molecular-scale structures like Bucky balls, which are made up of one or more cylindrical graphitic basal plane layers. Nanotubes are predicted to have stiffnesses and strengths greater than those of conventional carbon fibers, whose basal planes lie parallel to the fiber axis but are not especially organized in the radial directions. These tubular struc-

tures call to mind the use of straw for building in ancient Egypt, but coming full circle has been a long haul! tures call to mind the use of straw for building in ancient Egypt, but coming full circle has been a long haul!

Matrix addition

Fibers can be used on their own in bundles for many practical applications. Indeed, this arrangement is the basis of rope, which not only performs well under tension but features the advantage of flexibility as well.

However, rope cannot withstand compressive or shear stresses because the fibers will simply buckle or slide over one another. To harness the strength of advanced fibers for materials that are required to resist both compression and shear, the gaps between the fibers must be filled with some material to transmit these stresses from fiber to fiber. In fiber composites, that purpose is served by the matrix.

Many brittle materials—such as ice, hardened clay, porcelain, glass, and plaster of Paris—can be toughened dramatically by having fibers incorporated into them. By forming bridges across cracks, the fibers tend to stop them from widening and spreading. Fiber-reinforced ceramics and reinforced concrete are examples of how combining an otherwise weak material with fibers strengthens it, as is the plaster cast used to set a broken limb. Those uses, though, however valuable, are still not the most important applications of fiber composites. In fact, most of our composite matrices are polymers, like the commonly used polyester or epoxy resins. Relatively soft and pliable, such materials actually exist as liquids before the cross-linking process—the attachment of one polymer chain to another along their length—is complete. If the chemistry is judiciously controlled, polymers can easily be infiltrated between the fibers, to which they will bond well afterward. A metallic matrix (such as aluminum) is stronger, stiffer, and tougher than a polymer but is not so easy to infiltrate into a fibrous array without damaging the fibers. Furthermore, the presence of fibers, unfortunately, degrades the toughness of the metal somewhat. Nevertheless, there is a great deal of interest in metal matrix composites, which are becoming industrially important.

The way to pack fibers most densely is to arrange them parallel to one another—which is just how high-performance fibers are used in composites. Sheets are pro-

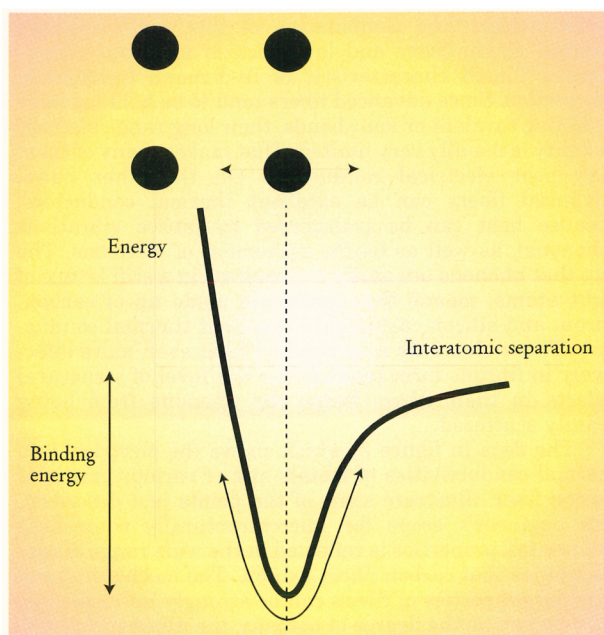


FIGURE 2. POTENTIAL ENERGY versus interatomic separation in a typical solid. Deep, steep potentials indicate stiff materials. Shallow, asymmetric potentials indicate materials with high coefficients of thermal expansion, whose atoms (as indicated by the black balls) oscillate with large amplitude when heated.

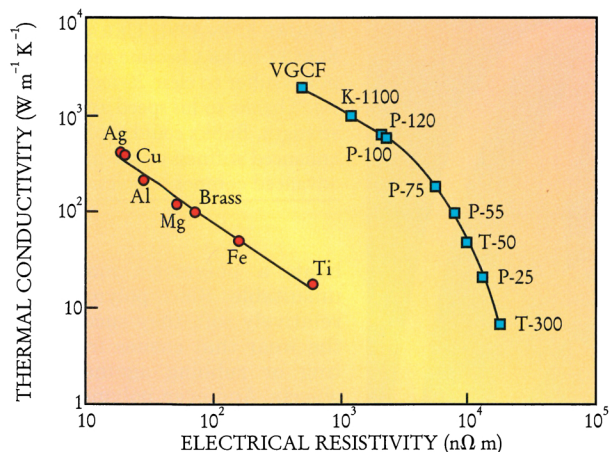


FIGURE 3. THERMAL CONDUCTIVITY and electrical resistivity are two important material properties. By plotting them against each other for different materials, the industrial designer can choose the material that offers the most suitable combination of the two—a metal (as shown on the left) or a carbon fiber (as shown on the right).

duced, each with a common fiber direction. The sheet is stiff and strong along its length but pliable and weak sideways. The sheets are stacked with the fibers in successive sheets lying in different directions, then bonded together, so that the extreme anisotropy (different behavior in different directions) of the single sheet is avoided. Overall, strength, stiffness, and other marketable properties are reduced, but they are more uniform—at least in the plane of the sheet.

With that stacking technique, high-performance fiber-based materials are made for aerospace and other transport applications, as well as for many of today's sporting goods. Properties such as the degree of stiffness along different directions can be predicted for a stack of sheets with specified fiber alignment directions (see figure 4).

The matrix, because it both binds the fibers together and also protects them from the environment, is as essential to a good composite as the fibers are. The interaction of fiber and matrix provides toughness—a property (difficult to define exactly) that generally means the energy, not the force, required to break something. A well-designed fiber composite shows breakage behavior resembling that of the hardest wood and is very tough.

Practical uses for composites

Unlike many other industrial materials, composites are often produced during the manufacture of the artifact they

are to be used for. This feature, which has been exploited in many different fields, allows the industrial designer to match the properties of the material to the performance requirements of the component being produced. For a number of applications, components must be elastic and remain very stiff. Composite vaulting poles are one example.

For some 80 years before composite poles were introduced in the 1970s, vaulters used bamboo poles and then, after World War II, aluminum poles, and the world pole-vaulting record rose only slowly, from about 3 m to about 5 m. Why? Top pole-vaulters weigh about 80 kg and can clear a bar 6 m off the ground, to attain a maximum potential energy of about 5 kJ. With a rigid pole, most of the energy has to come from the kinetic energy of the vaulter's forward motion. Even at 100% efficiency, such a conversion scheme would require a velocity of more than 10 m/s, a speed that is virtually impossible for a person to attain while carrying a pole. It is also just as difficult to make up the energy deficit by springing upward at the last moment like a high jumper.

The advent of the fiberglass pole significantly changed the dynamics of pole vaulting. With such a strong and flexible pole, a vaulter can store the energy necessary to clear 6 m or more by bending the pole. The energy comes partly from the vaulter's forward motion and partly from the muscle power applied when the pole is planted in the ground, and it is released as the pole straightens. Pole-vaulters do not need much in the way of springing. A rough calculation of the energy stored in the bent pole shown in figure 5 indicates that it is more than enough to propel a skilled vaulter over a bar 6 m high.

A good pole must, therefore, have a reasonably high axial stiffness. More important, it must also have a high elastic limit, so that the energy stored in the bent pole can be recovered without any loss due to plastic deformation or—more crucially—without any danger of fracture. The minimum radius of curvature during use of the pole is about 1 m (see figure 5), typically generating a peak strain of 1 to 2% in the surface layers. A fiberglass composite has an elastic limit of about 2 to 3%, whereas even a high-strength aluminum alloy has an elastic limit of less than 1%, and wooden beams fail at even lower strains (usually on the compression side). Finally, to keep the pole from flapping excessively during the vaulter's run-up—which is crucial—requires a minimum beam stiffness. The marvel is that varying the amount and type of glass in the composite creates variation in the stiffness and strength of the beam, so that it is possible nowadays to design the ideal pole for each individual vaulter.

Such high-technology vehicles as the

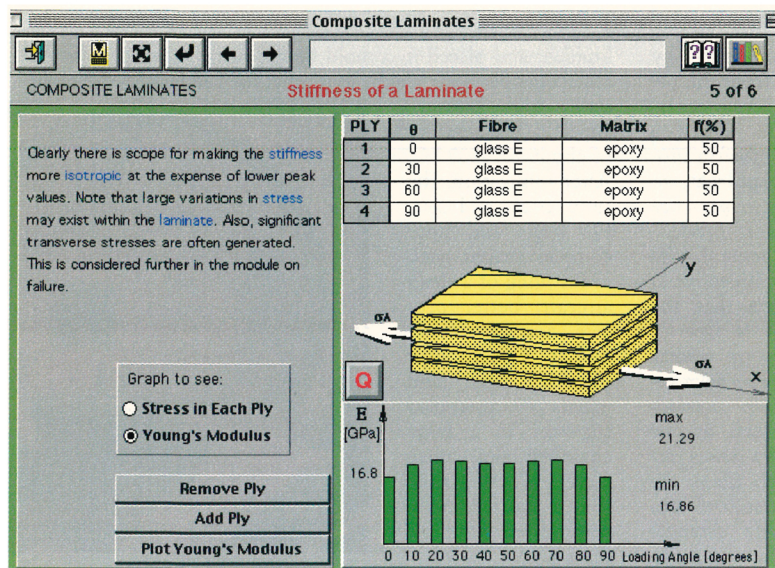


FIGURE 4. THE STIFFNESS of composite laminates—which depends in part on how the sheets are arranged—is routinely predicted with the help of software, as shown here.

Formula One car depicted in figure 6 are veritable test beds for advanced composites. Why are carbon fiber composites the material of choice for the cars' main structural members? We already know some of the reasons: stiffness, lightness, and strength (which are critical), as well as good resistance to fatigue and to corrosion from all the oil, gasoline, and other fluids used in the cars.

But the composite body shell, it turns out, is also mechanically safer than a body shell made of conventional materials. Under impact conditions, a composite material can often absorb significantly more energy per unit weight than a metal can. Metals absorb energy by undergoing plastic deformation—that is, they change shape because of the movement of atomic-scale defects called dislocations. The motion of dislocations absorbs energy, which is released as heat.

A fiber composite behaves quite differently. The material disintegrates, but in a very controlled way. Although the fibers and matrix do break up, they also consume energy by frictional processes, such as the pulling out of fibers from their sockets in the matrix. The modes of energy dissipation in a composite material, which make it possible to create a tough material from two essentially brittle ones, can be even more efficient in terms of energy absorption than the motion of dislocations in metals. When a modern racing car crashes, its kinetic energy is efficiently absorbed as the body shell disintegrates, slowing it progressively and thus limiting the deceleration forces transmitted to the driver. Deaths in Formula One racing are now quite rare, largely thanks to scientists' and engineers' improved understanding of how composites deform and consequent advances in the design of microstructures and components.

For applications that entail repetitive friction or great

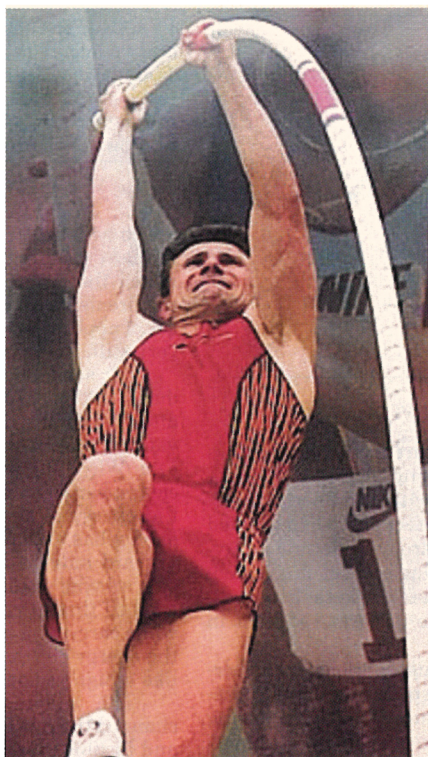


FIGURE 5. IN 1991, UKRAINIAN SERGEI BUBKA became the first pole vaulter to clear 20 feet (6.1 m). Thanks to his speed and strength, Bubka could exploit the enhanced stiffness of the most advanced composite poles.

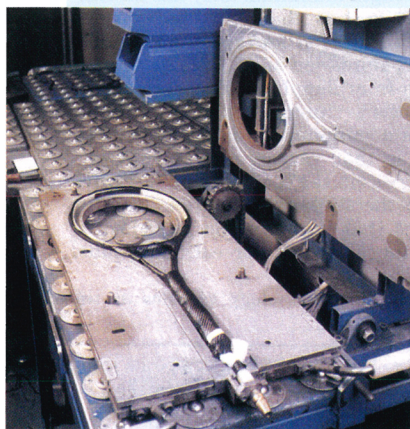
heat, a polymeric matrix is unsuitable. Since polymers are relatively soft, they succumb to the wear that ensues from hitting or rubbing against hard objects. And even polymers specially designed to withstand high temperatures cannot normally be used much above about 200 °C, at which point they tend to soften or degrade chemically, or do both. When resistance to wear and heat is needed, composites based on metallic matrices look far more attractive.

A brake disk used in a high-performance sports car (figure 7) is made from aluminum reinforced with silicon carbide particles. Because it is a light and relatively soft metal, aluminum on its own is not suitable for brake disks, which are usually made of cast iron. The presence of the ceramic reinforcement not only raises the resistance to wear dramatically, but also reduces the thermal expansion coefficient, a result that is beneficial for this application. Since SiC is also a good thermal conductor, the high thermal conductivity of the aluminum is retained. This property of the Al-SiC composite, combined with the introduction of cooling fins in the disk, prevents overheating. Furthermore, replacing cast-iron disks with Al-SiC disks saves several kilograms in weight per car.

When tolerance to very high temperatures is required, it may be necessary to resort to using ceramic materials and compensate in some way for their inherent

Fabrication of Artifacts

Components are produced from composite materials by means of various techniques. They range from simple



manual lay-up operations, in which a resin is brushed into a fiberglass mat, to complex pressure infiltration processes. In general, the primary objective is to ensure that the material is free of porosity or similar defects. For relatively simple components, such as the frame of a tennis racket, the fibers are often assembled into a suitable arrangement (for example,

braided) and placed in a mold before being injected with the matrix (a polymeric resin). Typically, the resin enters the mold under high pressure and at a temperature of about 100–200 °C. After infiltration, the resin cools and sets. For larger and more complex shapes, such as the wing of a small aircraft, better process control is required. Constituents of both fiber and matrix are assembled together in a large chamber (an autoclave), which is then heated and internally pressurized with an inert gas.

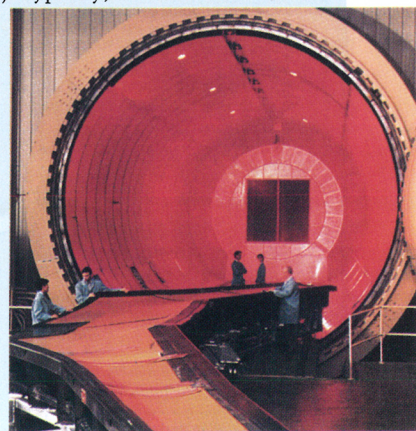




FIGURE 6. MODERN FORMULA ONE racing cars, like the Ferrari shown here, are safer than their predecessors because of the energy-absorbing composites used in their construction.

brittleness. But here, too, composite materials are making significant advances. For example, most aircraft brakes (and also those in many Formula One cars) are now made of so-called carbon/carbon—a material made by depositing a carbon matrix throughout an array of carbon fibers. The presence of the matrix–fiber interfaces within the material is important for deflecting cracks and toughening the material.

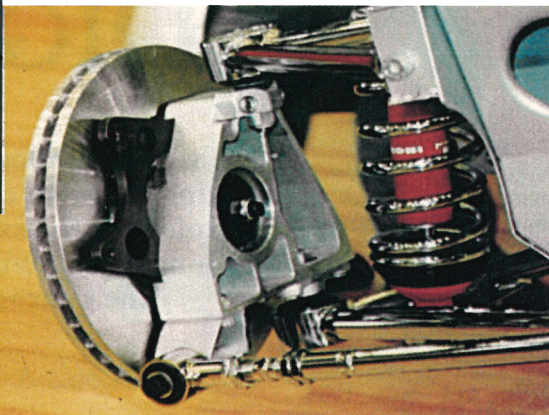
Metals are inherently unsuited to some applications because of their high electrical conductivity, which can turn metallic components into radio antennas, electromagnetic shields, etc. Indeed, for such military hardware as the hulls of minesweepers and the structural members of stealth aircraft, metals are clearly undesirable. As alternatives, polymer-based composites can combine very low electrical conductivity with suitable mechanical properties, while at the same time offering the possibility of achieving other desirable aims, such as relatively high thermal conductivity. From the data in figure 3, it can be seen that the choice of fiber is crucial in achieving the right combination of sought-after properties.

Although certain details of how they manage to elude detection do remain classified, stealth aircraft are clearly designed to give the most minimal possible response to all the searching radiations that an enemy might use—such as sound, heat, light, and, of course, radar. Radar reflectivity is reduced by preventing the incoming radio waves from encountering metallic parts in which they can induce electron motion and thus produce a mini-antenna that radiates back to the detector. To be invisible to radar, all metal components must be screened from the incoming waves by an electrical insulator. For this application, carbon fibers conduct electricity too well (although their conductivity depends on the fiber type—see figure 3). Instead, oxide fibers are commonly used. But although oxide fibers can and do prevent re-radiation, they do not absorb radiation well in the first place. To enhance their absorption capacity, they are mixed with aramid fibers that are chopped up to be a quarter of the wavelength of the incoming radiation. (Aramid is a polyamide fiber, similar to nylon but stronger.) Carbon fiber composites are also used in stealth aircraft—in screened positions, where they perform important structural functions.

Expectations for the next half-century

Looking back over the development of composites since the end of World War II, one feature is particularly striking: the extent to which various improvements in the materi-

FIGURE 7. ORDINARILY, ALUMINUM would be too soft to use in car brakes. But, with the ceramic silicon carbide (shown here), it forms a durable composite that is much lighter than the cast iron customarily used for brake disks.



als and their manufacture have followed advances in the understanding their mechanical behavior. As a result, a wide range of material and component types has been developed and tailored for various applications.

New and subtly evolving challenges now face the composite-materials industry. Cost is often more important than ever. Reinforcement materials, particularly fibers, are inherently somewhat expensive to manufacture (both financially and energetically), and composites are often difficult to recycle. On the other hand, the scope offered by composite systems for achieving tailored sets of properties, both mechanical and functional, is increasingly important for many advanced technical applications and is often worth the price.

The further matching of materials to functions will surely continue, and will probably be coupled with innovations—for example, in the exploitation of both natural and biomimetic composite systems, aimed in some cases at biomedical applications. Fibers could be combined with foamed or hollow elements, perhaps containing structural passageways that double as conduits for various fluids. Of course, such intricate combinations are commonplace in plants and animals, and no doubt nature has more to teach us.

In any event, although we cannot foresee exactly how composite materials will develop, it is clear that they will remain a focus of attention for innovative materials scientists. And, as it has during the past half-century, the field will continue to draw from, and benefit from, physics, chemistry, biology, and engineering.

Further reading

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