tighten up human ecosystems to reduce their interactions with the rest of the earth on whose stability we all depend. This does not require foregoing nuclear energy; it requires that if we must dump heat, it should be dumped into civilization to enhance a respiration rate in a sewage plant or an agricultural ecosystem, not dumped outside of civilization to affect that fraction of the earth's biota that sustains the earth as we know it. The question of what fraction that might be remains as one of the great issues, still scarcely considered by the scientific community.

References and Notes

1. E. P. Odum, *Science* **164**, 262 (1969).
2. Plant nomenclature follows that of M. L. Fernald in *Gray's Manual of Botany* (American Book, New York, ed. 8, 1950).
3. G. M. Woodwell, *Science* **156**, 461 (1967); ——— and A. L. Rebuck, *Ecol. Monogr.* **37**, 53 (1967).
4. G. M. Woodwell and T. P. Gannutz, *Amer. J. Bot.* **54**, 1210 (1967).
5. ——— and J. K. Oosting, *Radiat. Bot.* **5**, 205 (1965).
6. ——— and R. H. Whittaker, *Quart. Rev. Biol.* **43**, 42 (1968).
7. M. F. Buell and J. E. Cantlon, *Ecology* **34**, 520 (1953).
8. G. L. Miller, thesis, Univ. of North Carolina (1968).
9. A. H. Sparrow, L. A. Schairer, R. C. Sparrow, W. F. Campbell, *Radiat. Bot.* **3**, 169 (1963); F. G. Taylor, Jr., *ibid.* **6**, 307 (1965).
10. E. Gorham and A. G. Gordon, *Can. J. Bot.* **38**, 307 (1960); *ibid.*, p. 477; *ibid.* **41**, 371 (1963).
11. F. H. Tschirley, *Science* **163**, 779 (1969).
12. R. H. Whittaker and G. M. Woodwell, *Amer. J. Bot.* **54**, 931 (1967).
13. F. H. Bormann, G. E. Likens, D. W. Fisher, R. S. Pierce, *Science* **159**, 882 (1968).
14. These relationships have been summarized in detail by J. Phillipson [*Ecological Energetics* (St. Martin's Press, New York, 1966)]. See also L. B. Slobodkin, *Growth and Regulation of Animal Populations* (Holt, Rinehart and Winston, New York, 1961) and J. H. Ryther, *Science* **166**, 72 (1969).
15. C. F. Wurster, *Science* **159**, 1474 (1968).
16. G. M. Woodwell, *ibid.* **138**, 572 (1962).
17. Research carried out at Brookhaven National Laboratory under the auspices of the U.S. Atomic Energy Commission. Paper delivered at 11th International Botanical Congress, Seattle, Wash., on 26 August 1969 in the symposium "Ecological and Evolutionary Implications of Environmental Pollution."

Advanced Composite Materials

The mechanical characteristics, constituent materials, and fabrication techniques are reviewed.

Tobey M. Cornsweet

Extensive research and development efforts have produced high-strength, stiff, light-weight "advanced composite materials" (*1*) that are now being used in aircraft systems. Such efforts were originally sponsored by the Air Force Materials Laboratory, but interest and activity gradually spread throughout the aerospace industry. In addition, the Army, the Navy, and NASA are now actively concerned with the development of these materials for use in structural components of aerospace vehicles.

These composites are all combinations of a matrix or binder material and some type of reinforcement, either particles or fibers (*2*). The matrix serves to transfer loads between the reinforcements. The overall properties of the composite are a function of many variables, including the amount and type of reinforcement and matrix, the orientation of the reinforcing particles or fibers, the processing methods used in fabricating the composite, and so on. Some of these materials show isotropic mechanical behavior, others show anisotropic behavior. A concrete block is a particle-reinforced composite that shows isotropic behavior under load—that is, behavior independent of the orientation of the load. The fiber-reinforced composites, such as those used for rocket-motor cases and for some structural components of aircraft, show anisotropic behavior—behavior dependent on the orientation of the load.

Most metal alloys are homogeneous and isotropic. Up to the present, the metal alloys have been the only materials used for primary structural components of aerospace vehicles. Glass-fiber-reinforced composites have, for years, had a wide variety of structural applications. Of major current interest is their use in rocket motor cases for the Minuteman, Polaris, and Poseidon missiles and their use for many secondary structural components of aircraft, such as radomes and aerodynamic fairings. They have been used very little for primary load-carrying structures. The reasons for the wide variation in the uses to which the metal alloys and the glass-fiber-reinforced composites are put is best understood from a comparison of their mechanical properties.

In Fig. 1 the specific tensile strength (tensile strength relative to density) is plotted as a function of the specific tensile modulus of elasticity (tensile modulus relative to density) for a variety of materials—both composites and metal alloys—used in structural components of aerospace vehicles. Theoretically, the more ideal a material's mechanical properties are, the more closely it will approach the upper right-hand corner of the graph, combining high strength and stiffness with low density. To illustrate, 2024 aluminum (an alloy) has a tensile strength of $49.2\ \text{kg/mm}^2$, a modulus of $7500\ \text{kg/mm}^2$, and a density of $2.77\ \text{g/cm}^3$—that is, a specific strength of 17.8×10^6 millimeters and a specific modulus of 25×10^8 millimeters. Values for stainless steel 301 [containing chromium (18 percent), nickel (8 percent), and carbon (<0.15 percent)] and for titanium 6-4 [containing aluminum (6 percent) and vanadium (4 percent)] have been plotted to show the range of the properties of metallic materials in current use in the aerospace industry.

From Fig. 1 it is apparent that, though glass-fiber-reinforced composites are definitely stronger than any conventional structural material, they are not much stiffer. Similarly, beryllium provides greater specific stiffness but very little more specific strength than conventional structural metals.

From these considerations it is apparent that an ideal material would have the properties of high strength, high stiffness, and light weight. The need for a real material with these characteristics provided the impetus for developing the advanced composite materials. These new materials have already demonstrated the combination of greater strength and stiffness and lighter weight than any conventional structural metals.

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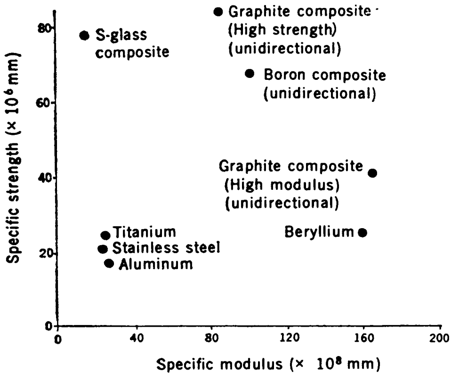


Fig. 1. Graph showing specific tensile strength as a function of specific tensile modulus of elasticity for various structural materials. Two points are shown for the graphite unidirectional composites to illustrate the extremes in properties that would be available from a variety of suppliers. Generally, today a choice must be made between a high-strength or a high-modulus graphite fiber reinforcement.

Most of these improved properties have resulted from the development of new fiber reinforcements.

Of these new fibers, the one most widely used today is the boron fiber, having a tensile modulus of elasticity of 38,500 kg/mm^2, an ultimate tensile strength above 315 kg/mm^2, and a density of less than 2.70 g/cm^3. Composites in which this fiber is used in an epoxy matrix have higher specific strength and stiffness than any of the conventional structural materials (see Fig. 1). Another new reinforcement is the graphite fiber. As shown in Fig. 1, the composite in which this material is used is generally equivalent in physical properties to the boron-fiber-reinforced composite. In the discussion that follows, the "boron composite" is used as an example. The same considerations would apply to all fiber-reinforced composites.

The boron composite of Fig. 1 is, as indicated, a unidirectional composite, one with all the fibers oriented in the same direction. Figure 2 shows what any one layer or ply of the unidirectional composite might look like. The organic matrix material surrounding the fibers is much less strong and much less stiff than the fibers. Thus the composite is much stronger and stiffer when a load is placed parallel to the fibers than when it is placed perpendicular to the fibers and the matrix must carry most of it.

The longitudinal tensile strength (the tensile strength in the direction of the fibers) of a unidirectional composite with equal volumes of boron fiber and epoxy matrix is about 147 kg/mm^2, whereas the transverse tensile strength is only about 10.5 kg/mm^2. Coupled with this decrease in tensile strength is a decrease in tensile modulus, from 22,400 kg/mm^2 in the longitudinal direction to 2100 kg/mm^2 in the transverse direction.

The obvious initial conclusion is that only unidirectional composites should be used and that the fiber direction and the load axis should be kept parallel. Just as obvious, however, is the fact that most structures have multiple load paths, requiring the use of combinations of ply orientations that will provide high strength and stiffness in various directions. The ability to select desired mechanical properties in designing a structure is giving the design engineer new freedom and removing many of the constraints he formerly faced. However, before the improved properties can be fully exploited, the behavior of advanced composites must be fully characterized.

Mechanical Behavior and Design

Conventional homogeneous metallic materials have uniform properties in all directions, and determination of a mechanical property does not require any special geometric information. With a continuous-fiber-reinforced composite the situation is generally much more complex. The composite is inhomogeneous and anisotropic, and thus its properties are a function of the type, amount, and orientation of the reinforcing fiber and of the type and amount of matrix material.

Characterization of the mechanical behavior of an isotropic material is greatly simplified by the fact that axial stresses may cause only axial elongations or strains and shear stresses may cause only shear strains. These simplifications, plus one relating to the modulus of elasticity of the material (*3*), reduce the complex three-dimensional generalized equations for the state of stress and strain to the simplified strength-of-materials equations given in undergraduate textbooks.

A fiber-reinforced composite, however, cannot generally be represented by these reduced equations, for it exhibits the property called "shear coupling"—that is, an axial load can produce a shear strain and, conversely, a shear stress can produce an axial strain. This is illustrated by the comparison in Fig. 3 between the response of an isotropic and an anisotropic sheet to a uniform axial load. The distortion, as indicated by the shear strain γ, is a result of the fibers' trying to align themselves in the direction of the applied load. To eliminate this distortion due to shear coupling, the composite is normally "cross-plied"—that is, equal numbers of plies are aligned at a given angle to the load axis and at the supplement of that angle. Another way of describing this is to say that the ply angles are $\pm\theta$ degrees from the load axis. This cross-plying balances the distortion of one layer against the distortion of its complement.

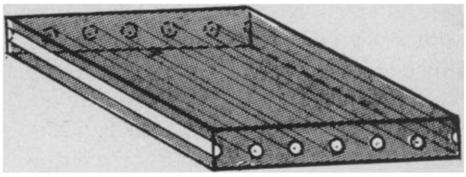


Fig. 2. Appearance of a single layer of a unidirectional composite.

Another problem is, however, created by this cross-plying. As the load is imposed upon the composite, the ends of the plies tend to distort in opposite directions. This is the balancing force that would solve the problem if the composite were not a three-dimensional material. The actual result of the cross-plying is an elimination of distortion in the plane of the composite but a distortion of the ends of the composite out of plane as the plies try to average out the different distortions of the plies. In order to eliminate this three-dimensional distortion the minimum number of plies in the composite is kept to four, and these are cross-plied, with a plane of symmetry through the mid-plane of the composite; that is, $+\theta°/-\theta°/-\theta°/+\theta°$ or $-\theta°/+\theta°/+\theta°/-\theta°$. The result is that the plies above the midplane tend to twist in a direction opposite to the direction of twist of the plies below it and distortion is eliminated.

Figure 4 shows the tensile strength of a boron-fiber-reinforced epoxy composite as a function of the angle between the direction of orientation of the fibers and the direction of load (the "reinforcement angle"). The curve, except at 0° and 90°, represents properties of symmetrically cross-plied composites with no two-dimensional or three-dimensional distortion. The highly anisotropic mechanical behavior, shown by longitudinal tensile strength of 147 kg/mm^2 and the transverse tensile strength of 10.5 kg/mm^2, is characteristic of any continuous-fiber-reinforced composite. This change in strength points to the key concept to be grasped in designing with composites—the concept that one may "tailor" the composite to match the anticipated structural load levels and load directions, using the high strength and stiffness of the fiber reinforcements by changing the orientation and number of fibers rather than merely by varying the total amount of load-carrying material, as must be done in the case of metals.

To effectively utilize the composite's properties the designer will not look up in a handbook a single tensile strength representative of the material in general, as he would do in the case of aluminum, but, rather, will turn to a series of graphs, like those of Fig. 5. The graphs of Fig. 5 illustrate only the general concept of initial design techniques. In actual practice a somewhat different family of curves might be used. The graph at left in Fig. 5 shows the variation in the tensile strength of the boron-fiber-reinforced epoxy composite as a function of the percentage of fibers oriented at 0°, ±45°, and 90° to the load axis. The graph at right shows the corresponding relationship for tensile modulus of elasticity. All the values are for a composite with equal volumes of boron fiber and epoxy matrix.

The important thing to note in the graphs of Fig. 5 is that 2024 aluminum is represented on each graph by the single point shown, whereas the boron composite may be fabricated to have many strengths and stiffnesses, so that the composite could be represented by many points, all falling within the shaded portions of the graph. Any point above the dashed lines would represent a composite having higher strength or modulus than 2024 aluminum. Any point below the dashed lines would represent a composite having lower strength or modulus than 2024 aluminum, but in all cases the composite would be 30 percent lighter than 2024 aluminum. A composite represented by points *A* of Fig. 5 has 80 percent of its plies oriented at 0°, 20 percent of them oriented at ±45°, and none oriented at 90°. This composite would be both stronger and stiffer than aluminum. Points *B* represent a composite stiffer but not stronger than the aluminum. It has 60 percent of its plies oriented at 0°, 20 percent at ±45°, and 20 percent at 90°. Points *C* represent a composite which is neither stronger nor stiffer than aluminum. It has no plies oriented at 0°, 20 percent at ±45°, and 80 percent at 90°. Clearly, the composite has been altered significantly in each case, but this in no way alters the overall thickness or density or the technique of fabrication necessary to obtain reproducible data.

The plots shown are for only three (0°, ±45°, and 90°) of an infinite variety of possible combinations of fiber orientations. The structural designer would use charts of this type to provide initial design information; then a computer would be used to select the best fiber orientation for optimum structural performance. Many properties other than strength and stiffness must be considered in designing with advanced composite materials. For example, it was found, from repeated load-fatigue tests, that boron-fiber-reinforced epoxy composites retained as much as 80 percent of their initial ultimate tensile strength even after 10 million load cycles. Use of these new materials for helicopter rotor blades may completely eliminate the need to replace blades for reasons of fatigue.

Numerous other matters of significance in design are under investigation: crack propagation, nondestructive inspection techniques, bearing strength, variations in thermal coefficient of expansion, and lightning strike and other environmental effects. Typical of such investigations are the programs throughout the government and the aerospace industry that have developed boron-fiber-reinforced composites for use in aircraft components to the point of flight-testing.

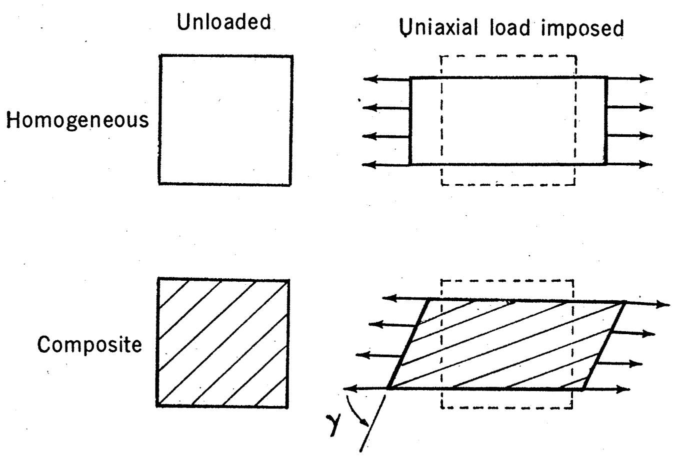
Boron-Fiber Production

The most widely used method for producing boron fibers is by chemical vapor deposition. This technique consists of passing a moving, electrically heated tungsten wire through a sealed reaction chamber containing a gaseous mixture of boron trichloride and hydrogen. The tungsten wire substrate (diameter, 0.0125 millimeter) is heated to about 1070°C, at which temperature the boron trichloride is reduced by way of the following reaction scheme:

$$2BCl_3(\text{gas}) + 3H_2(\text{gas}) \rightarrow 2B(\text{solid}) + 6HCl(\text{gas})$$

If the tungsten wire is passed through mercury gas seals at each end of the reaction chamber, it may also be resistance-heated through use of these same seals as electrical contacts.

Since 1963, stronger and stronger boron fibers have been produced by this process; the strength has been increased



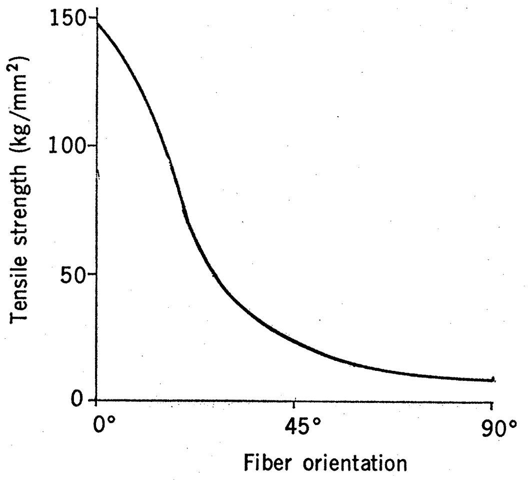


Fig. 3 (left). "Shear coupling" induced in a composite. Fig. 4 (right). Graph showing variation in the tensile strength of a boron-fiber-reinforced epoxy composite as a function of the reinforcement angle.

from about 175 kg/mm^2 to over 315 kg/mm^2. The tungsten core is very dense, and the boron coating must be thick enough to ensure an overall fiber density low enough to maintain high specific strength and modulus. The best balance of density, production rate, and materials properties results at present in production of a fiber with an overall diameter of 0.100 millimeter. This means that 45,000 meters of boron fiber weigh 1 kilogram. The original production speed was only 3 meters per minute, but the speed has been increased to almost 36 meters per minute. While the strength and modulus and the production rate have been increasing, the cost has been decreasing, from almost $13,200 per kilogram in 1963 to less than $550 per kilogram today. Obviously the use of boron-fiber-reinforced composites in cost-sensitive aerospace structures requires that the cost of producing the boron fiber be reduced as much as possible.

The latest step in efforts to reduce this cost is to replace the dense, expensive tungsten wire substrate with a graphite fiber substrate. The tungsten substrate is formed by drawing the material through successive diamond dies. Production of the substrate contributes $200 per kilogram to the current cost of the fiber. Replacement of the tungsten with a graphite fiber substrate, which is much cheaper, is expected to lower the total cost of the boron fiber below $220 per kilogram when it is produced in quantity. In addition, with the light-weight graphite core it should be possible to produce boron fiber of smaller diameter for special applications.

New Reinforcing Materials

Through research, other fibers which have the high strength, high stiffness, and low density needed in advanced composite materials are being developed. The boron fiber of today should be considered only the first member of a family of materials that will be increasingly used in the future.

Of these new materials, the one most widely used today is the graphite yarn mentioned above. The yarn is composed of very fine graphite fibers formed by heating and stretching an organic precursor fiber such as polyacrylonitrile. The graphite fibers thus formed have a tensile strength of 280 kg/mm^2, a modulus above 25,000 kg/mm^2, and a density of only 1.50 g/cm^3. The epoxy composite reinforced with graphite yarn has properties comparable to those of the epoxy composite reinforced with boron fiber and will have many uses once the cost of producing the yarn can be reduced below today's figure of $770 per kilogram. Graphite-yarn-reinforced composites are being used today in aerospace-vehicle structures, and experience in both design and fabrication is being gained as a result. Several American companies have entered into licensing agreements with British firms, and it is anticipated that one or more of these composites will be in commercial production in the near future. It is anticipated that graphite reinforcing fibers will be produced in large volume at a cost of less than $100 per kilogram.

Other reinforcing materials are being made in limited quantities. The most commonly used of these is the silicon-carbide-coated boron filament. The thin coating serves to protect the boron filament at high temperatures in a metal-matrix composite. Continuous silicon carbide and alumina fibers have potential uses in metal-matrix composites for high-temperature applications.

The use of very fine single crystals—very short discontinuous fibers called "whiskers"—may provide an entirely new family of composites. The whiskers may be used as a reinforcement in their own right, but their major potential appears to be that of improving the properties of continuous-fiber composites. When some of these whiskers are mixed into the matrix, the load-transfer characteristics of the matrix seem to be greatly improved. Whether or not the use of coated boron or silicon carbide or alumina fibers and of whiskers increases will depend heavily on whether the cost of producing these materials can be reduced; in any case they are examples of the many reinforcing materials that are being developed.

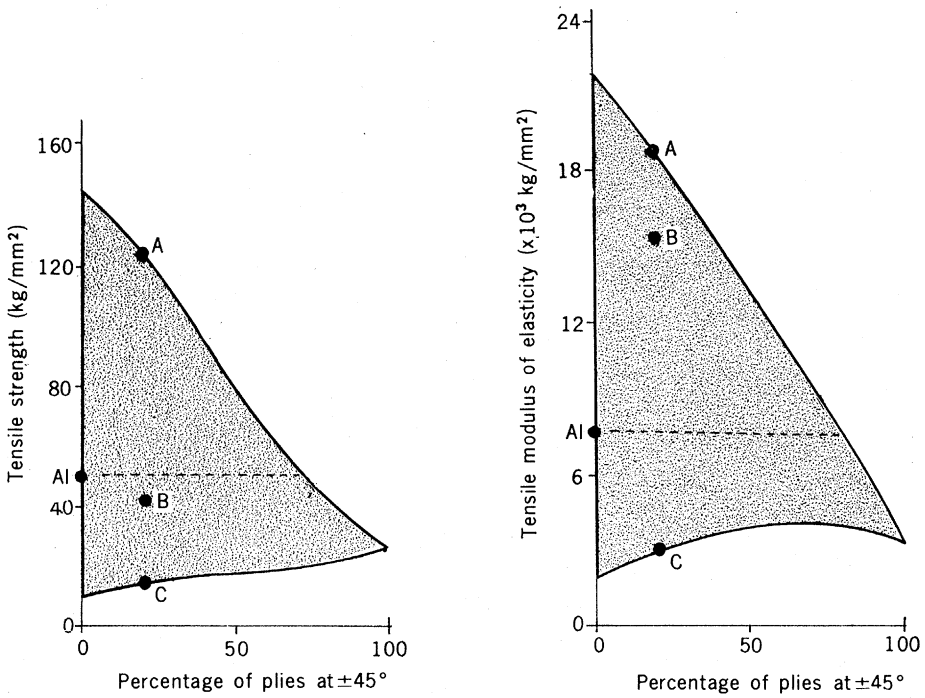


Fig. 5. (Left) Graph showing variation in the tensile strength of a boron-fiber-reinforced epoxy composite as a function of the percentage of fibers oriented at 0°, ± 45°, and 90° to the load axis. (Right) Graph showing the corresponding variation in the tensile modulus of elasticity.

Matrix Materials

Many organic-matrix and metal-matrix composites had been studied prior to the development of advanced composites. The most common of the fiber reinforcements is the glass fiber, drawn from molten glass at very high speeds. The fiber thus formed is extremely small in diameter and is used almost exclusively as a bundle of continuous fibers. The noncritical nature of the secondary structural uses to which it has been put and the averaging effect of the many fibers have made it unnecessary to maintain very precise spacing or orientation of the individual fibers.

With the development of high-performance fibers such as the boron fiber there has suddenly been a reemphasis on the importance of maintaining very precise placement and spacing of fibers.

This has resulted in alterations in the epoxy resin systems that were developed for use with glass fibers—primarily in an increase in the viscosity of the resins. These more viscous epoxy resins are still of the thermosetting type, with high bond strength and toughness and relatively moderate temperature capability (<230°C). When the structural temperature and performance requirements are changed from those for a helicopter rotor or a subsonic aircraft to those for a propulsion system, a reentry vehicle, or a supersonic cruise aircraft, much higher structural temperatures (270°C and above) are involved. Up to about 350°C the epoxy matrix may be replaced by a high-temperature organic matrix, but above these temperatures the use of a metallic matrix such as aluminum or titanium is required. Work is continuing toward the development of improved organic and metallic matrix systems. Both types of materials have been used in actual components, but the costs must be greatly reduced and the fabrication processes simplified before these materials find widespread application.

Techniques for Fabricating Composites

The technique most commonly used today for fabricating high-performance composite structures is "filament winding." This is the technique currently used for fabricating rocket motor cases and other pressure vessels reinforced with glass fibers. It consists of slowly rotating some sort of preshaped mandrel and then laying resin-coated glass fibers onto the mandrel's outer surface, very much as a fishing line is distributed on a reel as the line is wound in. In the filament-winding technique, however, there is generally a fiber-payout head that rotates around the mandrel at the same time that the mandrel itself is rotated. By means of this process, interwoven layers of glass fibers are uniformly distributed onto the mandrel. Once the filament winding is complete, the entire assembly, mandrel and all, is put into the oven and "cured." The mandrel is then removed. Sometimes it is disassembled internally and the pieces are removed through the ends of the part; or sometimes the mandrel is made of water-soluble materials and thus is simply washed out after the cure has been completed.

The first advanced composites were formed from flat unidirectional sheets (plies) made by uniformly winding one layer of boron fiber onto a cylindrical drum. The "drum-wound broad goods" thus formed were cut parallel to the axis of the drum and removed in the form of sheets. These sheets formed the individual plies in the composite. The end product was a material that could be used, on a batch basis, for fabricating test specimens and specially shaped pieces. However, an excessive amount of scrap was left if these rectangular sheets were used to make pieces of irregular shape. Also, structural members of complex shape, such as spars, fittings, and compound contoured skins, cannot readily be made by the technique of filament winding. The requirement that such members be fabricated and that hand labor be eliminated in making composites from sheet material, coupled with the need to keep waste to a minimum, forced the development of continuous flat "tapes," 3.1 and 75 millimeters wide, containing the reinforcing and the matrix materials, respectively, in a readily usable form.

These flat tapes provide the working material from which most composites are now being fabricated. The tape is composed of many continuous fibers running parallel to its long axis and spaced uniformly across it. (The glass-fiber-reinforced tape commonly used to seal boxes gives an excellent idea of what the boron fiber tape looks like.) The tape is wrapped on a reel for shipment and storage. A nonadherent separator paper prevents it from sticking to itself while it is on the reel; the paper is removed as the tape is used. The boron-fiber tape itself has two distinct layers. The first layer is a very thin "scrim cloth," a woven glass cloth that provides just enough strength to keep the boron fibers from pulling apart when the tape is handled without the supporting separator paper. The second layer is made up of the boron fibers and the epoxy resin coating given them during fabrication of the tape, in a process called resin preimpregnation. This preimpregnated tape is extremely tacky. During fabrication of the multilayer composite the paper is stripped away and the exposed surface provides all the adhesion necessary to maintain the correct orientation of the tape in the composite, even though as many as 100 layers or plies may be placed one upon another at different angles.

After the composite has been built up layer by layer, the entire skin is cured through the application of heat and pressure in prescribed ways. Use of a common epoxy resin would require a pressure of 0.0595 kg/mm^2 throughout the cure cycle; the temperature would be slowly raised to 177°C and held there for 1 to 4 hours. The cured composite would then be cooled, the pressure released, and the composite removed from the mold. The plies would be of uniform thickness—0.132 millimeter per ply; that is, a composite containing ten layers of boron fibers would be 1.32 millimeters thick. This is the average thickness of a composite with equal content (by volume) of boron fiber and epoxy matrix, the composition that provides the best overall properties.

The use of continuous tapes has made possible a return to the machine fabrication techniques originally feasible only with filament winding, and has eliminated the need for expensive hand techniques, required until very recently in assembling the layers. The tape-laying machines will eventually be computer-controlled and will lay tape at a speed of more than 18 meters per minute, with an overall fabrication rate equivalent to that at present attainable for metals, and with no need for heavy, slow, waste-removal equipment of the type metal fabrication requires. The use of light-weight, high-speed tape-laying machinery will bring a distinct decrease in the amount of waste material. In most of the current metal-fabrication processes, 70 to 90 percent of the raw material must be scrapped, whereas, for boron-fiber-reinforced composites, scrappage rates as low as 9 percent have already been achieved, and several simple techniques now under consideration would reduce this figure to around 3 percent. In addition, it is possible that the scrap material, chopped into short pieces, could be used to make components through compression molding techniques.

Improvements in machining techniques are also being emphasized in connection with the fabrication of boron-fiber-reinforced composites. The emphasis upon machining is due to the extreme hardness of the boron fibers, which approaches that of diamond. So far, the only acceptable means of cutting, trimming, or drilling the material has been with diamond-coated or diamond-impregnated tools or with ultrasonic cutting devices. The diamond tooling results in machine-operation rates roughly equivalent to those typical of aluminum machining today. Even though the costs will continue to be higher than those for comparable aluminum machining, the costs today are no greater than those now being paid for the difficult machining of high-strength steel or titanium. The use of graphite-fiber-reinforced composites will allow greatly simplified machining procedures.

Summary

Advanced composite materials offer the potential for major savings in weight for a variety of aerospace and other structural systems. Weight savings of 10 to 50 percent have been demonstrated in comparisons of components made of these materials with corresponding metal components now used in space vehicles, aircraft, missiles, and gas turbine engines. These savings were realized through understanding of the properties and complex mechanical behavior of the basic constituents and through development of special techniques for fabricating fiber-reinforced composites.

Despite the current emphasis on boron- and graphite-fiber-reinforced epoxy composites, these materials should be considered only the first of a family or class of advanced composite materials. Various types of fiber reinforcements are either already available or rapidly becoming available, and this makes it necessary to understand the processes and economics of producing the reinforcements and matrix materials and to weigh the costs associated with the fabrication of composite structural components.

Through effective utilization of one or more of the advanced composites and an increased understanding of their inherent characteristics, improvements in performance will undoubtedly continue to be demonstrated. It seems certain that high-strength, stiff, light-weight advanced composites will come into at least limited use in the near future, their potential for general use being limited only by the eventual costs of producing them in quantity.

References and Notes

1. "Advanced composite materials," although something of a misnomer, has become a generally accepted phrase. "Improved composite materials" would be more precise.
2. For a general discussion, see G. Lubin, *Handbook of Fiberglass and Advanced Plastic Composites* (Van Nostrand, New York, 1969).
3. J. E. Ashton, J. C. Halpin, P. E. Petit, *Primer on Composite Materials: Analysis* (Technomic, Stamford, Conn., 1969).
4. I thank R. C. Tomashot, J. R. Rhodehamel, F. M. Wilson, and R. L. Rapson for their assistance in the preparation of this article.

The Evolution of Photosynthesis

Hypothesis: Photosynthetic bacteria and blue-green algae shared a common photoheterotrophic ancestor.

John M. Olson

On the basis of cell morphology, bacteria and blue-green algae form a single class of prokaryotic organisms that are characterized by the absence of a nuclear membrane, the absence of plastids, and the absence of a mitotic figure during cell division (*1*). Echlin and Morris (*2*) summarize the morphological features and the similarities in cell wall chemistry, which distinguish the bacteria and blue-green algae from eukaryotic organisms, that is, those whose cells are characterized by a well defined nucleus, presence of organelles, and division by mitosis. Of the various types of modern bacteria, the blue-green algae are obviously related most closely to the photosynthetic bacteria. Blue-green algae and photosynthetic bacteria both contain chlorophylls and carotenoids and convert light energy into chemical free energy. Based on this fundamental similarity in pigment content and function, it is postulated that present-day blue-green algae and photosynthetic bacteria have evolved from a common, chlorophyll-containing, prokaryotic ancestor.

The fundamental difference between the photosyntheses of blue-green algae and of photosynthetic bacteria is the oxygen evolution accompanying carbon dioxide fixation by the algae. The ability of the algae to produce molecular oxygen from water can be understood in terms of two photochemical steps connected in series, as first suggested by Hill and Bendall (*3*) (Fig. 1). The evidence for the series formulation is sufficiently compelling that it is now the generally accepted theory of oxygen-evolving photosynthesis (*4*).

Until 1967 it was generally thought that bacterial photosynthesis operated on the basis of one photochemical reaction analogous to system 1 in the series formulation. The inability of the bacteria to evolve oxygen was explained by the absence of the second photochemical step (system 2). It now appears that at least two species of bacteria, *Chromatium* (*5*, *6*) and *Rhodospirillum rubrum* (*7*), may carry out two photochemical reactions in parallel; one photochemical reaction center driving a cyclic electron transport chain for the production of adenosine triphosphate (ATP), and the other driving a noncyclic electron transport chain linked to substrate oxidation (Fig. 2). Thus, the fundamental requirement for oxygen evolution appears to be two reactions connected in series.

Basic Assumptions

My hypothesis for the physiology of the common ancestor and the subsequent evolutionary development of the various types of photosynthetic bacteria and algae is based on three assumptions in addition to those already mentioned.

1) The heterotrophic hypothesis. At the time the ancestral photobacterium existed, its aqueous environment contained organic compounds left over from the prebiotic phase of chemical evolution (*8*).

2) The Berkner-Marshall theory for the origin of oxygen in the atmosphere. The present amount of oxygen in the air is due to the photosynthesis of blue-green algae and eukaryotic green plants

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