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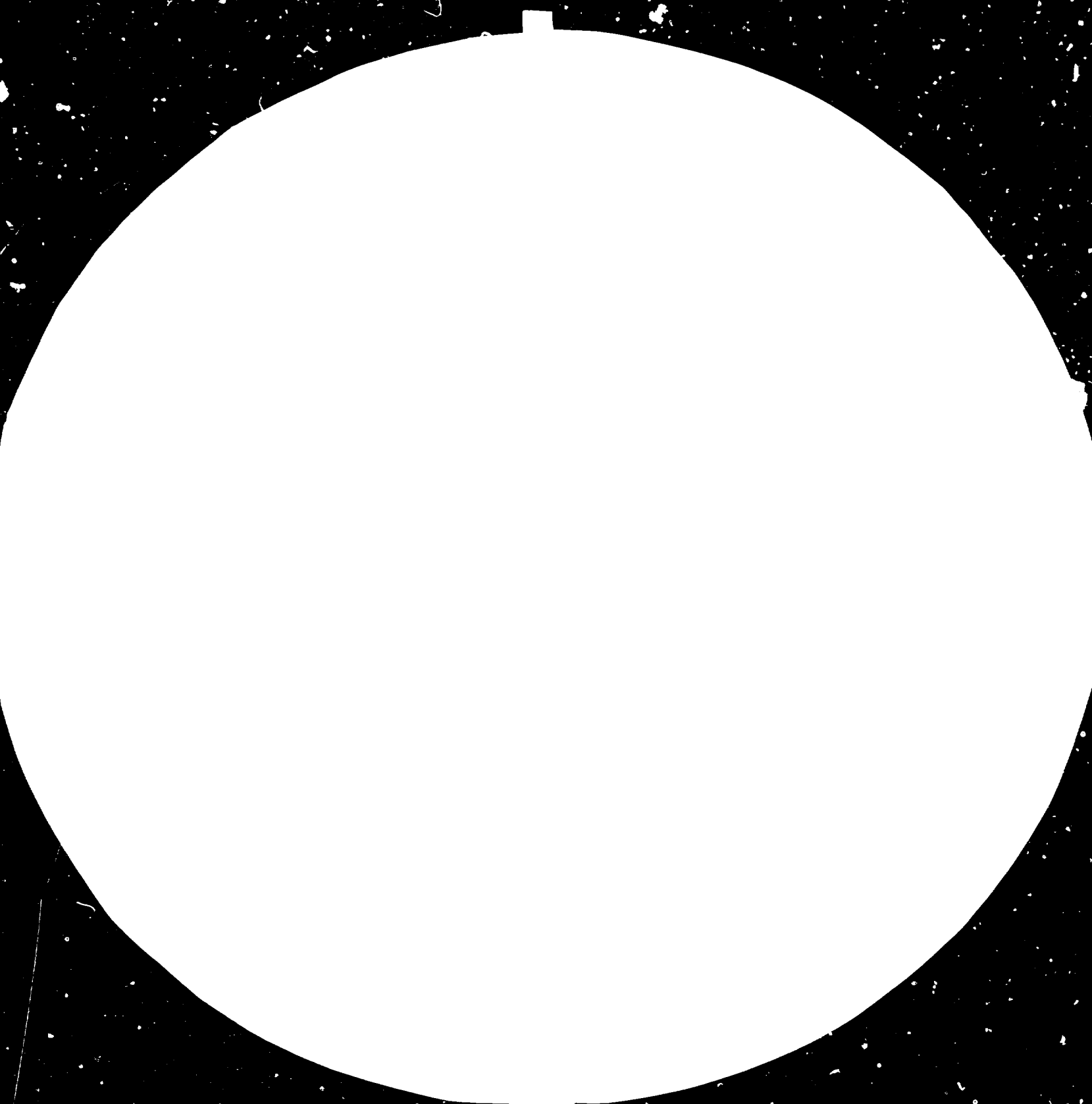
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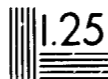
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A COMPARISON OF HIGH MODULUS FIBRES*

by

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Introduction

High modulus fibers are used mainly as fibrous reinforcement in resins, metals, or ceramics to provide strength and stiffness. It is instructive to consider what factors led to the development of composites. Structural designs are as likely to be limited by the stiffness as the strength of the construction material. Hence, engineers have always desired stiffer, stronger, less dense and lower cost structural materials. There are a number of materials in the upper center part of the periodic table, such as boron, carbon, silicon carbide and alumina, which all have significantly higher modulus/weight ratios than the common engineering metals. Theoretically, the high modulus would result in high strength if the material were perfect. Unfortunately, most of the high modulus materials are covalently bonded and are brittle. Small flaws can produce catastrophic failure at drastically reduced stresses. (The flaws may be introduced during manufacture or during service.) Except in some unusual protected environments, primary structural elements can not be made from materials which fail catastrophically. Composite materials offer the potential of using these brittle materials in structures which will not fail catastrophically. The brittle materials are made into fiber form to give redundancy and placed into a matrix. The matrix serves to transfer stress into and out of the fibers. The matrix and matrix/fiber interface must also serve to stop cracks which originate in the fibers from propagating through the solid. Hence, a localized impact may break a few fibers, but the crack can be stopped by a ductile matrix or fiber/matrix debond. Even ceramic fiber/ceramic matrix composites can be made which are relatively tough. The use of composites to attain non-catastrophic failure with brittle materials has penalties. The volume fraction of reinforcing fibers is generally 0.65 or less, and fibers only reinforce in one direction. While fibers can be orientated in three orthogonal directions, composites offer the greatest potential if fibers are oriented predominantly uniaxially or biaxially. Fortunately, many structures are loaded mainly in one direction.

Comparison of high modulus fibers must necessarily compare their performance in composites. The task is made more difficult by the diverse applications, particularly if non-ambient temperature uses are considered. This paper will be separated

into two parts: firstly, the requirements for fibers which are to be used in resin, metal or ceramic matrix composites will be defined. Secondly, present fiber performances will be compared to each other and the desired composite requirements.

Composite Requirements

The desired properties for fibers are often ranked quite differently for resin, metal and ceramic matrix composites. Also, since metal and ceramic matrix composites commonly are exposed to elevated temperature, (if only for processing), the high temperature characteristics of the fibers must also be considered.

Resin Matrix Composite Reinforcement

Fibers for resin matrix applications would have the highest modulus, lowest density, and highest tensile, compressive, and interfacial bond strength between resin and fiber, while still failing in a non-catastrophic mode. Non-catastrophic failure requires a balance between the values of the tensile strength of the fiber and the interfacial bond strength. Too high an interfacial bond strength for a given fiber tensile strength will produce a more brittle composite which will be flaw sensitive and generally have a lower tensile strength. Too low an interfacial bond strength will produce poorer composite shear and tensile strengths, but the composite will be less flaw sensitive. The exact value of the ratio of fiber tensile strength to interfacial bond strength should be selected for the particular application. Hence, for high damage tolerance, a slightly lower interfacial bond strength might be desirable. Other factors affect the fracture behavior. For example, higher fiber modulus, low fiber strength, higher volume fraction, brittle matrix, low test temperature, and high loading rate will all produce a more brittle fracture. Except for a few applications, fibers are produced with only one surface treatment which is optimum for many applications. Practically, the shear strength of a composite must exceed 35MP/m^2 (5,000 psi) to have any practical application. This requirement forces the strain-to-failure for a fiber to be at least 0.5% for any structural application for two reasons. Firstly, strains in structures often reach 0.2% (a common fatigue limit strain in metals), and local strains, as under rivets, are likely to be several times higher. Secondly, this low strain-to-failure corresponds to low fiber strength, and a brittle composite would result if the shear strength

is maintained at a minimum of 25MN/m^2 . Obviously, for more critical structural applications the strain-to-failure should be several times higher. Boeing, for example, would not use a fiber with less than a 2.0 percent strain-to-failure with a 100MN/m^2 composite shear strength for primary structural applications such as the wing box.

Thermal expansion coefficient is also an important property for reinforcing fibers. In many cases, the thermal expansion of a composite will be lower than the structure to which it is attached. Careful design must be used or binding and warping will result with a temperature change. However, the negative thermal expansion coefficient of some fibers can be used to produce a zero thermal expansion coefficient, provided the fiber modulus is sufficiently high. Finally, stress rupture is important for sustained load applications.

One secondary consideration is the form of the reinforcement. Generally, continuous fiber in the form of tow with zero or a half to one tpi twist is desirable. Fine diameter ($<15\mu$) is desirable to minimize stresses which arise from fiber high curvatures in parts. (However, a large number of fine fibers is harder to handle during fabrication than fewer large diameter ($>100\mu$) filament.) Another consideration is electrical properties. For radar domes, or printed circuit boards for example, an insulating fiber is required. However, for electromagnetic shielding, or static discharge, a conductive fiber is required. Although either insulating or conductive fibers may be used in corrosion resistant composites, conductive fibers may cause corrosion of attached metal parts. Finally, other properties such as thermal conductivity or coefficient of friction may be important for certain applications.

Metal Matrix Reinforcement:

The mechanical requirements for reinforcements for high temperature applications results in many of the same chemical elements and compounds being selected as presently used in resin matrix composites. Materials with high modulus and high strength generally have high melting points, and good high temperature properties. (Exceptions are the high modulus organic fibers.) Hence, most fibers developed for use with resin matrices would appear to be good candidates for reinforcement in high temperature composites.

High temperature stress rupture and creep resistance are the properties of general concern in most high temperature structural material applications. The refractoriness (i.e., melting temperature) of the fiber is often a good indication of these properties because thermally activated slip and creep become dominant at 0.5 of the melting temperature for simple crystal systems. Oxidation resistance must also be thoroughly considered in fiber selection because of the uncertainty of filament exposure to the environment or the possibility of oxygen diffusion through the

matrix. These problems are particularly acute if the fiber also has a fine diameter such as the graphite filaments. Fiber diameter will also affect the choice of processing techniques and subsequent forming operations that can be used. Fine diameter (25μ or less) multi-tow filaments such as FP-alumina and graphite are more conveniently processed by liquid infiltration while filament over 100 microns in diameter can be processed using powder metallurgy techniques.

The density of the fiber, as well as the material property of interest, will determine the potential specific properties of the composite. From this consideration ceramic and carbon fibers could offer a greater potential as reinforcements in metal matrix composites if not precluded by stability and other limitations. The over-riding consideration in selecting a metal matrix for composites is its chemical and physical compatibility with the reinforcing fiber.

A major requirement for the reinforcements is that they be compatible with their environment. Ideally, the reinforcement would be oxidation resistant and compatible with all potential matrices. Only the oxides are truly oxidation resistant, but some compounds have adequate oxidation resistance if they form an adherent glassy coating.

Compatibility with matrices is also required. Numerous fiber and matrix combinations have been proposed as potential high temperature composites based on their unique mechanical, physical and chemical properties. The record of successful development of such composites has been disappointingly low because of chemical or physical incompatibility between fiber and matrix.

Chemical compatibility must be of two types. One is sufficient interaction between the fiber and the matrix to assure strong bonds necessary for off-axis strength of continuous reinforced composites or for stress transfer between reinforced composites. The other is the ability of the matrix and fiber to co-exist without mutually induced disintegration by interdiffusion and reaction. The dilemma faced in composite development is that the conditions which result in both types of compatibility are mutually exclusive. Useful composites can be produced only if a successful compromise between bonding and disintegration can be established. Two principal techniques used to achieve this result are applying a protective coating to the filament, and adding constituents to the matrix that restrict interaction.

The carbides, nitrides, and borides all react with most potential metal matrices, and the question of importance is how fast. The most kinetically stable are the carbides of niobium and hafnium, although silicon carbide is also attractive for lower temperatures. Coating, however, is not an ideal solution to compatibility problems because of two critical considerations. The first is the obvious economic penalty incurred by the

addition of the coating step during composite fabrication. Second is the criticality of optimum coating thickness. Too thick a coating can result in sources of brittle failure while too thin a coating results in insufficient protection.

Mechanical compatibility of the fiber with the metallic-matrix requires consideration of the thermal expansion properties of the fiber, especially if cyclical thermal excursions are expected in service. Exact matching of thermal expansion properties of fiber and matrix is neither practical nor absolutely always necessary. However, the particular operating conditions and the performance requirement will determine the criticality of this variable. For example, a macrodimensionally stable large structure can be achieved in a graphite-copper composite, but when the surface quality must meet optical standards the thermal mismatch between fiber and matrix precludes this material for use.

Finally, corrosion couples may be generated between electrically conductive fibers and the matrix. In turbine applications the thermal conductivity of the fiber as well as the matrix can be utilized for heat dissipation and therefore must be considered when designing cooled components. In this case metal fibers are preferable to ceramic fibers. Conversely, ceramic fibers could be more advantageous for applications where heat retention or insulation is desired.

Finally, compatibility is not the only consideration. For metal matrices, no single matrix alloy will be optimum for all desired properties and the development of suitable materials invariably involves compromises for one or more of the significant properties. The question that remains to be settled is whether sufficient properties can be retained after such a trade-off to render the alloy useful and economical for composite application. While lower melting point metals, such as aluminum, can form useful composites with certain fibers, it is not apparent that suitable systems exist for higher melting point matrices.

Ceramic Matrix Composite Reinforcements

Brittle materials, while often having superior high temperature properties, are limited by inadequate fracture toughness at near ambient temperature. The problem then is to increase fracture toughness while not sacrificing strength. In ceramic matrix composites the emphasis is on toughening at lower temperature, <1000°C, so that they may survive heating or cooling. This is in contrast to metal matrix composites where the emphasis is on improving high temperature behavior.

The general principles for toughening ceramic composites are similar to those for other types of composites: (1) to increase the local driving forces necessary to propagate cracks to failure; (2) to locally increase the amount of mechanical energy consumed per unit area of propagation of any crack; or (3) to decrease the local strain by crack-

ing which reduces the stress concentration. However, the mechanisms by which these principles are realized in ceramic matrix composites may be the same or very different from other composites. The differences in mechanisms manifest themselves in two important ways. First, in most other composite systems, applying the first two principles above would generally increase the strength of the body. However, in ceramic composites this is not necessarily the case. In some, toughening may be obtained at the sacrifice of some strength rather than increasing it, due to the introduction of larger effective flaws and/or lower Young's moduli. In other ceramic composites, strength may either be unaffected or may be increased. An important difference between ceramic and other composites is the temperature regime in which toughening is emphasized.

While ceramics can be toughened by incorporating fibers having a higher Young's modulus than the ceramic matrix, e.g. as illustrated by the work on use of ceramic fibers in glass or crystallized glass matrices, its applicability to ceramics is much more limited. The limitation arises because of Young's moduli of most matrices and fibers of interest are similar and the descriptive terms matrix and reinforcement lose much of their meaning except geometrically.

Some benefits accrue at higher temperature, if fibers have a higher modulus and/or a lower rate of decrease of their modulus with temperature. Hence, some modulus transfer of load may also occur at temperatures reasonably in excess of 1000°C. In addition to improved toughness at ambient temperatures, ceramic matrix composites will require a combination of properties to accommodate particular high temperature applications including: creep rupture strength, oxidation/hot corrosion resistance, and good mechanical and thermal fatigue characteristics. The challenge is to design a ceramic composite with a balance of properties superior to competitive materials. The development of composites faces additional problems which include chemical and mechanical compatibility between matrix and reinforcement, and anisotropy of properties. Chemical instabilities, such as interdiffusion at elevated temperatures, may degrade the properties of the reinforcements or interface, yet some reaction may be required to provide adequate stress transfer between the reinforcement matrix interface. The compatibility problems of reinforcements with ceramic matrices can be severe. The oxides begin to react with the elements, carbides, nitrides, and borides in the temperature range of interest, but would be attractive combinations for lower temperature use. The nitrides and the element carbon are also marginal in the desired temperature range. The various carbides, nitrides, and borides appear to be mutually compatible from a reactivity view in the lower end of the temperature range of interest.

High temperature atmospheric oxidation can be

a problem with ceramic matrix composites. Carbon fiber/carbon matrix composites, while having good mechanical properties, must be completely protected from oxidizing gases. The problem is particularly difficult as the anisotropy of the composite (local or global) makes application of protective surface coatings very difficult. The coefficient of thermal expansion can not be matched to the different coefficients of thermal expansion of a carbon/carbon composite in its different directions. Although various designs similar to those used in early glass to metal seals may minimize problems, the surface coating is usually in tension at ambient temperature and can act as a crack initiator to the whole composite. Microcracking of the protective coatings are common. At temperatures above the application temperature of the coating, the coating will be in compression and may present an effective barrier, even though microcracked, to oxidation for short times. The leading edges of the space shuttle rely on this behavior.

An important consideration of brittle reinforcement/brittle matrix systems is residual stresses arising from mismatch in coefficient of thermal expansion upon fabrication or use. (In addition, stresses generated from processing may also be high.) These stresses can provide beneficial prestresses for applications, but generally they result in deleterious internal stresses. Interestingly, sometimes these stresses are so high that extensive microcracking occurs within the composite and this can produce a tough material. Carbon fiber/carbon matrix composites are a good example.

In summary, carbon, oxides, carbides, nitrides, and borides all appear attractive for ceramic matrix composite applications. Several ternary oxides (mullite) provide improved creep resistance and could be desirable for reinforcements. A potential important advantage of developing oxide ceramic matrix composites would be the inherent oxidation resistance. In general, the distinction between matrix and reinforcement in ceramic systems is less well defined. The major reason for using composite technology in ceramic systems is to improve toughness.

Reinforcement Fibers

Fibers are available for a fair range of materials over a wide range of diameters. However, it should be realized that all fibers that might be desired are not presently available in appropriate diameters. Generally, some processes produce fine diameter (<25 μ m) only, while others can only produce large diameter fibers economically. Similarly, some processes are sufficiently versatile to produce almost any of the desired materials, while others are specific to one. Fine diameter fibers are desirable for: 1) high strength, 2) large surface area for bonding, and 3) the ability to be bent in a sharp radius of curvature. Fine diameter fibers do appear to be desirable,

and even required, for ceramic matrix composites.

Fiber/matrix compatibility studies for high temperature composites appear to indicate that relatively large amounts of reaction will usually occur in many potential systems. The implication is that large diameter fibers would be required for these systems whether diffusion barriers are used or not. The result is that the fiber reinforcement should have a minimum diameter of 15 μ , and preferably larger for many composite systems. However, present processes designed to produce fine diameter fibers at low cost may not be attractive for many of the high temperature composites, since the processes are not easily modified to produce large diameters. Processes which produce large diameter fibers, such as chemical vapor deposition, are very versatile but unfortunately expensive.

Fiber Processes

Generally, reinforcement fibers must have very high strength to be useful, since limited volume fractions and plying of uniaxial layers drop the potential strength rapidly. While high strength reinforcement could be single crystalline, the high strength is usually obtained by a very fine or elongated grain microstructure. The problem is to find and develop processes which will produce the very fine grain sizes desired.

Glass Melt Spinning

In the sense that a glass is the limit of a fine grained microstructure, glass drawing is a useful process when systems with suitable viscosities exist (Figure 1). Silica is the basis for high strength glass fibers, although the composition is usually modified by the additions of boron, aluminum, magnesium calcium oxides. Generally, the modulus of glass fibers is mainly determined by the silicate network, although S type glasses have a higher specific modulus than E glass because of a slightly higher modulus and lower density (Table I). Higher moduli have been obtained by adding beryllium oxide to the glass, but the improvement is partially negated by a higher density. In any case, the toxicity and cost of beryllium glasses have generated little interest in the slightly higher modulus. Most elements and binary compounds with high modulus have low viscosity and would require extremely high quench rates to produce a glassy structure. Even with the very complex crystal structure of boron, only very limited success has been achieved in obtaining short lengths of boron filament from quenching a melt. Hydrodynamic instabilities from low viscosity and crystallization both caused problems with boron. More complex melts, particularly eutectics, might allow some useful systems to be discovered, but it should be realized that melt containment may be difficult. Furthermore, devitrification of the glasses may limit usage. No suitable systems to give high modulus glasses that might be melt spinnable have been identified.

The other processes that produce fine grained high strength fibers all are carried out well be-

low the recrystallization temperature.

Chemical Vapor Deposition

Chemical vapor deposition is the formation of a solid by the decomposition or reduction of one or more gaseous molecules upon a heated substrate. Fine grained materials may be formed at one-third or less of the melting point of the material for simple crystal structures and somewhat higher for more complex crystal structures. The crystallite size also depends on the rate of deposition and back etching, and the surface mobility. For fiber production, the deposition geometry shown in Figure 2 is typical. Tungsten or carbon filament is run through a chamber where the filament is resistance and RF heated and suitable gases decompose on the heated wire. Although the linear deposition rate is quite high by plating process standards, the contact time required to deposit the necessary coating thickness is tens of seconds or more. Hence, for any appreciable production rate, many reactors must be run in parallel. The cost for the substrate and deposition gases, and the capital equipment for the reactors and gas handling is quite high. Hence, the filament tends to be quite expensive. However, CVD can be used to deposit almost any type of large diameter fiber or coating. A problem arises from the kinetic nature of the deposition process. Compounds may be deposited off stoichiometry or even with second phases, and the composition may vary within the fiber. While these variations may give improved room temperature properties, high temperature properties may be severely degraded or vice-versa. (An example is SiC deposited with excess silicon.) CVD is used at present to produce boron and silicon carbide filament (Table I).

Precursor Polymeric Fiber Decomposition

Carbon, silicon carbide and alumina fibers can be made by careful pyrolysis of a polymeric or gel precursor fiber. The use of a polymeric precursor allows the fiber to be spun using the procedures, modified as required, of the synthetic fiber industry. The result is generally a bundle of fine diameter fibers which upon a controlled heat-treatment decompose to the product fiber. The most well known examples are the carbon fibers whose processes are shown in Figure 3. Most carbon fiber is produced from a special polyacrylonitrile (PAN) copolymer fiber. In this process, the PAN is stretched to align the polymer chains parallel to the fiber axis, and these linear backbones are converted into ribbons of continuous hexagonal rings of carbon and nitrogen by an oxidation. These ribbons have a sufficiently high glass transition temperature that part of the orientation is retained after a carbonization cycle to 1000°C. Most of elements other than carbon are removed in the carbonization cycle, while the orientation of these ribbons are generally parallel to the fiber axis, this alignment can be improved by heat-treating to higher temperatures which improves the modulus of the fiber. Recent

improvements in lower modulus PAN precursor carbon fibers promise two percent tensile strain to failure by year's end. Unfortunately, similar improvements in tensile strength have not been made in the high modulus PAN precursor fibers.

The second major process for producing carbon fibers uses liquid crystalline fractions of coal tar or petroleum pitch as precursors. The sheet-like aromatic hydrocarbons are easily oriented parallel to fiber axis upon melt spinning of these liquid crystalline materials. The pitch fibers are made infusible by a thermosetting oxidation step and then carbonized. Just as the ribbons in PAN can be more perfectly aligned through higher temperature heat-treatments, these sheets undergo rearrangement to form a more aligned and higher modulus fiber. Fiber properties for both precursors are reported in Table I.

Silicon carbide fiber has been developed by Yajima and Nippon Carbon Co. in Japan (Fig. 4). As the polymer has a Si/C ratio of one-half, excess carbon is present in the fiber and this often leads to variable properties. The values are shown in Table I. Dow Chemical is developing SiC fiber in the U.S. The preliminary mechanical properties are reported to be about equal to Yajima's better values.

Although some work was performed in the 1960's in the U.S. to make inorganic fibers via a polymeric route, only alumina fiber has reached a production stage. The properties for these fibers are reported in Table I. (More complete properties are detailed in another paper.) While the strength is only of the order of 200,000 PSI at room temperature, it maintains most of its short time tensile strength to 1000°C. However, at high temperatures required for turbine service applications, alumina would not have the creep resistance necessary. Also, compatibility problems limit its use in high temperature metal matrices, but it is attractive for lower temperature use. It also may be of interest in ceramic matrix systems.

Host Conversion

In one embodiment of this process, a precursor fiber is converted by reaction with a gas phase species to form the new fiber (Fig. 5). Carborundum Company (Division of SOHIO) has made both boron and silicon carbide filament by reacting a rayon precursor carbon fiber with boron or silicon chlorides at elevated temperature. In the case of boron carbide, the room temperature modulus was 410 GPA (60×10^6 PSI), while the strength was 1.2 GPA (180×10^3 PSI). Obviously, this process could be used to produce other carbide fibers, or coatings on carbon fibers if desired with relative ease.

In an extension of this concept, Carborundum has converted B₂O₃ glass fiber to either boron nitride or boron carbide fiber. The resulting, boron nitride fiber generally has about a 27 GPA

$\times 10^6$ PSI) modulus and 0.34 GPa (50×10^3 PSI) strength which is too low for most reinforcement applications. Strain annealing this fiber at high temperature increases the mechanical properties to those shown in Table I. Individual fibers have tested as high as 480-550 GPa ($70-80 \times 10^6$ PSI) in modulus and 2.4 GPa (350×10^3 PSI) in strength. A big advantage of boron nitride filament is its excellent dielectric properties. However, its behavior in metal matrices is very similar to high modulus carbon fibers, e.g. it is hard to wet, and is reactive.

A process somewhat different in concept is the use of a rayon fiber to absorb metallic nitrate salt and then to carefully pyrolyse to a salt laden carbon fiber. The carbon is then oxidized and the remaining oxide carefully sintered. Several oxide fibers were prepared by Union Carbide Corporation in this manner, the most notable being stabilized zirconia. Fiber strengths were in the 0.7-1.4 GPa ($100-200 \times 10^3$ PSI) range. Although mainly used for insulation, some ceramic matrix composites were made from these fibers, and the strengths were as high as 0.35 GPa (50×10^3 PSI). Unfortunately, the fibers are no longer available commercially.

Organic Fibers

The ultrahigh modulus of graphite results from the strong sp^2 bonding in the basal plane. High modulus organic fibers are possible if a portion of the multifused aromatic rings in graphite can be incorporated into a polymer. Highly oriented parapolymers or polyacene ladder polymers provide attractive specific moduli. The problem is how to get these intractable polymers into a highly oriented fiber form. A major breakthrough came with the development of Kevlar^(R) aramid fiber (Fig. 6a). The enhanced solubility due to good solvents and the amide linkage in polyphenylene-terephthalamide (PPT) allowed formation of an easily oriented liquid crystalline polymer solution. This solution could be spun into a highly oriented fiber, whose properties could be further enhanced by a high temperature crystallization heat-treatment. Properties are listed in Table I. (A more detailed description of the fiber is presented in an accompanying paper.) As might be expected from a rigid rod polymer structure with relatively low bonding between adjacent polymer molecules, these rods might be expected to buckle at relatively low compressive stresses. Also, the offset which is introduced by the amide linkage produces a slightly kinked structure along the rod (Fig. 6a). This might be expected to further reduce the load required for buckling as well as decrease the modulus. A truly straight rigid rod polymer such as polybenzothiazole (PBT) might be expected to provide a higher modulus which it does (Fig. 6b/Table I). However, the compressive failure load is the same as for PPT, although the failure mechanism is quite different.

Linear chain type polymers would also give high modulus if the chains were fully extended

parallel to the fiber axis. For example, fully extended polyethylene has a theoretical modulus of 250 GPa with a density slightly less than unity. Values of modulus as high as about 1/3 the theoretical have been observed experimentally, which is about the same as aluminum. Compressive strength of fully extended polyethylene parallel to the fiber axis have not been measured experimentally, but can be estimated from the elastic constants to be about 18 MPA. This low value which can be expected for a flexible chain in compression would limit the structural use of fully extended polyethylene severely, as would the low melting point of the polymer. Other linear chain polymers with higher chain-to-chain interaction would improve compressive and transverse properties, but would be harder to process. No fibers have been reported for these other polymers.

Whiskers

After Galt and Herring's discovery of high strength tin whiskers, much research on whisker growth and properties was performed in the 50's and 60's. Many problems exist in growing whiskers in large quantity with good quality at an economically viable price. Because of this, interest in whisker technology has waned, except for SILAG and TOKAI SiC whiskers which are made from rice hulls or similar by-products. The main application of these whiskers has been to aluminum and other low-melting metallic matrices with relatively good results. SiC whiskers would be too reactive for higher melting metallic matrices, except with prohibitively thick (relatively) protective coatings. However, the application of these whiskers to ceramic systems, even just for model systems, appears attractive. The fine dimensions of the whiskers could allow for additional toughening mechanisms to apply.

Comparison of Fibers

Many of the fibers described in the previous sections are experimental fibers which are not produced in quantity. Comparison of fibers which are primarily used for resin matrices will be limited to glass, Kevlar^(R) 49, carbon and boron. Similarly, only boron, silicon carbide, and alumina fibers will be compared with respect to application to metal matrix composites.

Resin Matrix Composites

The properties of composites depend not only on fiber and matrix properties and the interfacial bond between them, but on the fabrication and test techniques as well. Furthermore, mechanical test data are usually obtained from relatively small well made test specimens. For composites that are not flaw sensitive, the test results from small specimens may adequately describe larger scale hardware. However, for more brittle composites, the application of small specimen test data to a large structure will overestimate the strength of the structure, for the structure is more likely to have strength reducing flaws. The property data

is for small test specimens and only for uniaxial laminates (Table II). For the newer carbon fibers, the tensile strength of the composite is increased although not as much as might be expected from the fiber strength. Similarly, it is not apparent whether the improved composite strengths observed in test specimens will be carried over to structures. Although the composite tensile strength for these newer carbon fiber is higher, no increase in compressive strength has been observed. It may be that the fiber itself is failing internally just as Kevlar^(R) and the higher modulus carbon fibers do. (The very high modulus pitch fibers with very high alignment of the graphite basal planes parallel to the fiber axis fail at less than 1/2 the value of the tensile strength in compression.)

Perusal of Table II shows that boron and high modulus carbon fiber are most desirable for high stiffness applications. Boron filament also has good tensile and compressive strength properties. The major disadvantages of boron filament are cost, machining and limited allowable laminate curvature. Lower modulus carbon fibers have "balanced properties" and moderate impact strength. Cost is also moderate. Kevlar^(R) has good tensile strength, moderate stiffness, is tough, but is relatively poor in compression. Cost is moderate. For specific strength (strength/density) applications, Kevlar^(R) and the new carbon fibers are attractive. Glass is hard to beat for pure strength limited applications because of low cost, strength and toughness. Finally, very high modulus carbon fibers have a sufficiently negative coefficient of thermal expansion that a zero thermal expansion coefficient laminate can be produced. (Kevlar also has a negative thermal expansion coefficient but its modulus is too low to produce a zero thermal expansion coefficient.) Obviously, depending on the relative importance of the design and cost requirements, a different high modulus fiber would be selected.

Metal Matrix Composites

The data is more fragmentary for metal matrix composites, especially because of the lack of high temperature data. Data are shown here for the reinforcement of aluminum at room temperature (Table II.) (More complete data is presented in another paper.) All fibers give a good increase to the stiffness and strength of aluminum parallel to the fiber axis. Good transverse properties are observed with boron and alumina fiber, but not with carbon. Also, corrosion in the aluminum/graphite may be a problem in some environments.

Conclusions

A wide range of fibers is available and more will be developed in the near future. The widely varying properties of the fibers and differing requirements for applications means that no one fiber will completely dominate the others, at least in the near future. Each fiber with its unique characteristics tends to be optimum for

particular uses.

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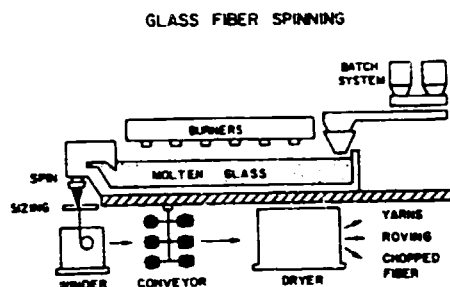


Fig. 1: Glass fiber process. Molten glass is spun at high speeds into fiber which is rapidly quenched. The fiber surface is protected by a size and processed into suitable textile forms.

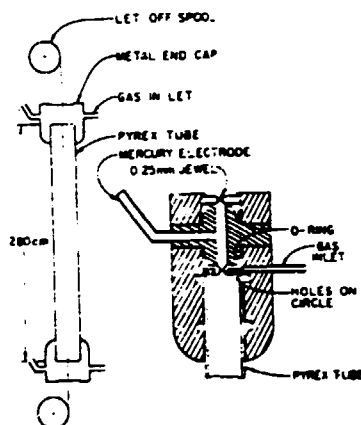


Fig. 2: Chemical vapor deposition of filament. A conductive substrate is passed through a cylindrical chamber where reactive gases deposit the desired material on the heated substrate.

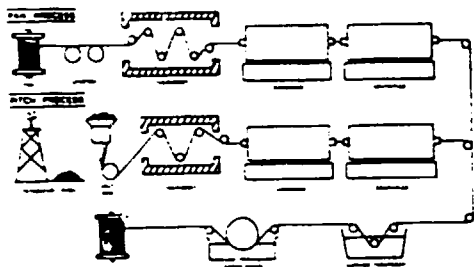


Fig. 3: Carbon fiber processes. Pitch or polyacrylonitrile are spun into oriented fibers, are thermoset, and carbonized to carbon fibers. The modulus of the carbon fibers is increased by subsequent heating to a high temperature, and the surface of the fiber is etched for improved bonding to the resin matrix.

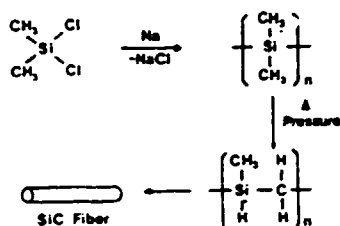


Fig. 4: Silicon carbide fiber process. Dichlorodimethylsilane is polymerized and then thermally treated to form a polycarbosilane polymer which can be spun into a fiber. The polycarbosilane is then pyrolysed to a silicon carbide fiber.

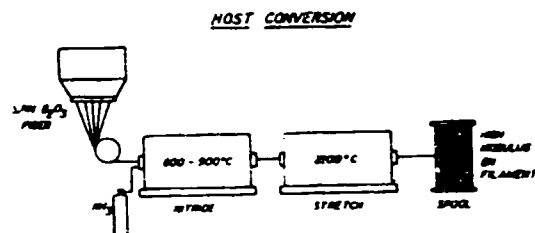


Fig. 5: Boron nitride filament. Boric oxide fiber is spun into a fiber, converted to the nitride by heating in ammonia, and stretched at high temperature to produce high modulus boron nitride fiber.

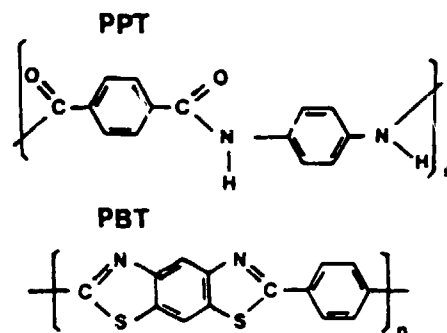


Fig. 6: High modulus organic fibers. PPT: polyphenyleneterephthalamide. PBT: polybenzothiazole.

TABLE I: Fiber Properties

	Modulus		Strength		Strain %	Density gm/c.c.
	GPA	MSI	GPA	KSI		
GLASS						
E-HTS	69	10	3.5	510	3.5	2.55
S-2	82.7	12	4.5	660	4.5	2.4
CVD FILAMENT						
Silicon Carbide						
tungsten substrate	418	61	3.1	450	.8	3.3
carbon substrate	418	61	3.9	575	.9	3.1
Boron	397	58	3.4	500	.9	2.6
CARBON FIBER						
PAN Precursor						
Low Modulus (AS, T-300, XA, CELION, etc.)	220-240	32-35	3.0-3.3	435-480	1.3-1.4	1.75
High Modulus (HMS)	330-350	48-51	2.3-2.6	335-375	0.7	1.91

TABLE I: Fiber Properties (Cont'd.)

	Modulus		Strength		Strain %	Density gm/c.c.
	GPA	MSI	GPA	KSI		
<u>TYPICAL NEW GRADES</u>						
<u>Union Carbide</u>						
T-300A	230	33	3.6	520		
T-700	230	33	4.5	660		
T-800	267	39	5.3	780	2.0	
T-40	294	43	4.2	620		
<u>Hercules</u>						
AS4	233	34	3.6	520	1.5	
AS6	246	36	4.1	600	1.65	
IM6	288	42	4.2	620	1.6	
<u>PITCH PRECURSOR</u>						
<u>Union Carbide</u>						
P-55S	380	55	2.1	300	.5	2.02
P-75S	500	75	2.1	300	.4	
P-100S	685	100	2.2	325	.3	
P-120S	822	120	2.7	400	.3	
<u>INORGANIC FIBER</u>						
<u>Silicon Carbide</u>						
	200	29	2.7	400	1.3	2.8
<u>Alumina</u>						
duPont (FP)	340-375	50-55	1.7	250	.4	3.7
Sumitomo	210	31	1.8	260	.8	3.2
Boron Nitride	310	45	2.1	300	.8	2.1
<u>ORGANIC FIBER</u>						
Kevlar (R) 49 (PPT)	124	18	3.6	525	2.5	1.44
PBT	304	44	2.7	400	.9	

TABLE II: Typical Fiber Reinforced Composite Properties

RESIN MATRIX	E-GLASS	S-2 GLASS	BORON	AS, T-300 CELIOM TYPE CARBON	BMS CARBON	KEVLAR (R)
0° Tensile Modulus (GPA)	47	54	210	150	210	76
0° Tensile Strength (GPA)	1.15	1.31	1.73	1.6	1.12	1.38
90° Tensile Modulus (GPA)		25	23	6.9	8.5	5.5
90° Tensile Strength (GPA)		.046	.06	.041	.037	0.3
0° Compressive Modulus (GPA)	47	54	28	150	210	76
0° Compressive Strength (GPA)	.54	.69	3.1	1.6	.99	.276
Short Beam Shear Strength (GPA)	.105	.090	.103	.131	.072	.04-.08
Density (gm/c.c.)	2.18	2.13	2.0	1.55	1.6	1.38
Impact Strength (ft. lb.)		280	40	100	30	150
Thermal Coefficient of Expansion x 10 ⁶ 1°C		3	4		-2	-6
<u>ALUMINUM MATRIX</u>						
	Sumitomo Al ₂ O ₃	duPont (FP) Al ₂ O ₃	Nippon SiC	Carbon	Boron	
0° Tensile Modulus (GPA)	150	200	100-110	140	230	
0° Tensile Strength (GPA)	.86	.6	.8	.7	1.5	
90° Tensile Modulus (GPA)		106			180	
90° Tensile Strength (GPA)		.09	.08	.02	.28	

