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Ceramic Composites–Enabling Aerospace Materials

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applications, and (2) the status and needs for materials development in the areas of fibers, fiber coatings or interfaces, and matrices with illustrative material drawn from some of the research being carried out at NASA Lewis Research Center.

APPLICATIONS AND BENEFITS

The limitations of superalloys and other advanced metallics with regard to high temperature strength capability and strength-to-density set a lower bound goal for ceramic materials properties and define the potential application windows for fiber reinforced ceramic matrix composites. Other attributes such as high stiffness, low thermal expansion coefficient, and environmental resistance also contribute to CMC desirability in many cases.

The benefits of ceramic materials for numerous current and proposed aerospace applications have been discussed elsewhere (ref. 2). For space structures and aerospace vehicle airframe applications, reductions in vehicle weight are most readily quantifiable. In some instances, e.g., hypersonic or re-entry vehicle thermal protection systems and control surfaces, improved temperature capability is a primary consideration. The primary competitive material is carbon/carbon which offers advantages in tensile strength-to-density and temperature capability. However, reliable resistance to oxidation and across-ply and interlaminar strength properties that are strongly dictated by the matrix in two-dimensional architectures tend to tip the balance toward ceramic matrix composites. Table I illustrates some of these property comparisons for an advanced carbon/carbon material and two state-of-the-art ceramic matrix composites (ref. 3).

Additional aerospace vehicle applications combine high-temperature capability with a requirement for transparency in certain regions of the spectrum e.g., visible light for windows and radar radio frequencies for radomes.

Perhaps the most demanding and highest pay-off areas for ceramic matrix composites are in space power and aerospace vehicle propulsion systems. Here, gains related to weight reduction and improved temperature capability not only affect the efficiency of energy conversion, but are also multiplied throughout the system. The most obvious direct impact is in reduced fuel or propellant mass requirements and thus smaller tankage. This then impacts related structure and overall vehicle size and mass. Further gains are attained as a direct and multiplicative result of reductions in the mass of the energy conversion or propulsion system itself. The bottom line is a reduction in overall vehicle acquisition and direct operating cost. These payoffs for CMC's will now be illustrated with several specific examples drawn from possible future advanced rocket engine and aircraft propulsion systems.

Several studies of the potential benefits possible from application of ceramics in rocket engine turbopumps have been carried out. Current performance of staged combustion and gas generator cycles are limited by the temperature capability of superalloys. Pump sizes are such that blade and vane cooling are impractical. Therefore, cycle temperatures are limited to about 850 °C. State-of-the-art CMC, as listed in table I, offer the capability for more than a 300 °C increase in cycle temperature. This can be used to provide increased performance and payload capability and improved durability via improved resistance to thermal shock and thermal fatigue. Additionally, increased turbopump design flexibility can result from the reduction in rotational mass. Performance and payload gains are most readily quantified. For example, a two-stage, Earth-to-orbit gas generator cycle advanced launch system, a payload gain of over 10 000 lb is calculated for a baseline vehicle payload of 160 000 lb (ref. 4).

Advanced aircraft gas turbine engines are another potential application where ceramic matrix composites can yield major performance benefits. A recent paper study of an early 21st century subsonic transport using ultra-high bypass turbofan engines wherein CMC are used in the combustor and first two turbine stages in conjunction with advanced polymer, metal and intermetallic matrix composites throughout the rest of the engine has recently been reported (ref. 5). In a related study reductions of about 10 to 12 percent in direct operating cost were projected for a 400 °C increase in turbine inlet temperature (ref. 6).

Another aircraft engine application of great current interest is that of a second generation supersonic transport. A study of such a vehicle and its propulsion system has been completed (ref. 7). For such a vehicle to be viable, it must be environmentally acceptable and economically competitive. The former requirement mandates that the emissions of noise throughout the vehicle operational envelope be at acceptable levels and that emissions of nitrous oxides while at a cruise altitude be at less than about 8 gm/kg of fuel to avoid damage to the ozone layer. For the noise requirement, the engine component can be addressed via exhaust nozzle design. Since a larger nozzle near the tail of the aircraft is required, it is essential that lightweight, advanced high-temperature intermetallic matrix composites and ceramic matrix composites be developed. Such advanced materials could yield a 50 percent weight reduction compared to the use of current materials in a mixer/ejector nozzle design.

Advanced concepts for control of NO_x emissions in an HSCT require innovative combustor designs wherein conventional through-the-wall film cooling is not possible. Only back-side cooling is permissible. This results in a requirement for higher temperature materials with reasonable levels of thermal conductivity (ref. 7). It appears that silicon-based ceramic matrix composites offer the greatest promise for such design concepts.

STATUS AND NEEDS FOR FIBER REINFORCED CERAMIC MATRIX COMPOSITES

Some of the key issues that need to be resolved for fiber reinforced ceramics to have major impact on aerospace systems by offering use temperatures significantly beyond that of metals are outlined in table II along with primary solutions and secondary contributors. The majority of the issues are materials related and the primary solutions relate to either the fibers or their coatings (i.e., interphases). Matrix properties and environmental durability are of secondary importance at this time because of the fiber and interface limitations.

Fibers

The main goals for fibers for CMC are high use temperature, high as-produced strength and stiffness, and compatibility with high-potential matrix materials. High use temperature requires oxidation and creep resistance and good strength retention. This can be achieved through thermochemical and microstructural stability. High as-produced strength is process as well as materials driven while specific stiffness is purely a materials property. Two factors are key to matrix compatibility. The first is a good match in thermal expansion coefficient. The second requirement is chemical compatibility. Since high CMC toughness often requires interface tailoring via a coating, it then becomes the role of that coating to provide the required fiber-matrix chemical compatibility as well as a weak mechanical interface. In addition, small fiber diameter is highly desirable for optimum toughening effectiveness as well as to allow fabrication of multidimensional woven structures.

The primary nonoxide fibers are based on silicon carbide or silicon nitride with the former preferable from a higher modulus standpoint. One approach for judging the thermomechanical potential of various fibers is the bend stress relaxation test wherein a length of fiber is constrained to a curved shape, heat-treated and then unconstrained. If the fiber retains curvature (i.e., stress relaxation ratio $m < 1$), then creep has occurred. Figure 2 illustrates that contemporary silicon-based fibers undergo significant stress relaxation at 1200 and 1400 °C (ref. 8). However, at 1400 °C, SiC whiskers do not relax thus showing that SiC does have potential for creep resistance at 1400 °C. Further analyses of these and other results indicates that optimization of fiber chemistry and microstructure can yield creep resistant polycrystalline fibers at 1400 °C.

The oxide fibers of serious interest can be grouped into polycrystalline fibers and single crystals. Figure 3 shows strength retention at room temperature after 1-hr heat treatments and strength at temperature for advanced polycrystalline Al_2O_3 fibers (PRD-166 and Nextel 480) and a single crystal Al_2O_3 fiber (Saphikon) (ref. 9). While all three fibers show reasonable strength retention, only Saphikon displays reasonable strength for use in composites above 1200 °C. Various alloying approaches for enhancing the capability of single crystal oxide fibers are being pursued such as cation doping and eutectic microstructures.

Interfaces

Several approaches can be taken to achieve high toughness in continuous fiber reinforced ceramic matrix composites. The most straightforward approach is to produce a composite wherein the matrix is quite porous and weak and depend solely on the fiber properties for strength (ref. 10). If all constituents are oxidation resistant, i.e., oxides, and the fibers are not degraded in properties by contact with the matrix phase, no interphase is required. Such composites generally offer low strength and stiffness and the limited temperature capability associated with polycrystalline oxide fibers and weak matrices.

To achieve higher strength, stiffness, and temperature capability, fully dense matrices are desirable with single crystal oxides and polycrystalline SiC as the preferred fibers. Tailored interfaces (interphases) are required to provide the properties necessary for strong, tough composites. This subject is concisely reviewed by Evans (ref. 11). Key interface properties include low toughness of the interface relative to that of the fiber and an interfacial sliding stress ~20 MPa upon interface debonding in Nicalon fiber reinforced FRC. These, along with the thermal expansion mismatch strain between fiber and matrix, the matrix toughness, and the fiber volume fraction, strength and Weibull modulus govern the stress-strain behavior (ref. 11). In this context, the approach outlined above succeeds because an effectively low toughness interface exists.

In addition to the requirements for interphases outlined above, it is also necessary for the interphase material to be: oxidation resistant in the composite; applicable in a continuous manner to monofilaments, multifilament tows, or performs; chemically compatible with the fiber and matrix, and be nondegrading to fiber mechanical properties in processing and in service.

In silicon-based matrix and glass-ceramic matrix composites, successful composites have relied upon carbon or BN to provide the proper interface. As illustrated by data in figure 4 for a reaction-bonded silicon nitride matrix reinforced by ~140 μm silicon carbide fibers, carbon fiber coatings (in this case supplied with the fiber) suffer from oxidation (ref. 12). In this example, the oxidation attack occurs via the ~25 percent open porosity present in the matrix. In fully dense matrices, oxidation of C interphases has been observed to occur via the interphase path as well (ref. 13).

Oxidation of the interphase is clearly an unacceptable situation for FRC use in an oxidizing environment. A solution to this problem via identification of oxidation resistant materials or via protection of C or BN is necessary.

CONCLUSION

Fiber reinforced ceramic matrix composites have much to offer to advanced aerospace systems because of their potential for high strength and specific strength at use temperatures above that of superalloys. Two critical issues must be resolved to enable these materials to attain their potential. First, strong, stable, creep-resistant fibers must be developed. Polycrystalline silicon carbide and alumina-based single crystals offer the most promise. Carbon, of course already fills these requirements, but oxidation imposes a severe limitation. Second, stable, oxidation-resistant interphases are required for successful use of FRC in oxidizing environments. This can be approached via use of composite designs which require no special interphase because the matrix is weak and porous; by identification of oxidation resistant interphase materials and microstructures; or by protecting BN or C from oxidation via a nonpermeable, dense matrix phase in combination with surface coatings and sealants. From the status of these issues and the slow pace of progress over the past decade, it is apparent that short of major breakthroughs, FRC are not going to have a large role in aerospace propulsion and power systems in the next 10 years.

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TABLE I.—COMPARISON OF KEY PROPERTIES FOR CARBON-CARBON AND CERAMIC MATRIX COMPOSITES

	Two-dimensional advanced carbon/carbon		Two-dimensional reinforced SiC CMC		Two-dimensional Nicalon reinforced SiC CMC	
	Property	Specific property	Property	Specific property	Property	Specific Property
Density, g/cm^3	1.55-1.65		2.1		2.5	
Elastic modulus, GPa	70-90	38	90	43	230	92
Ultimate tensile strength, MPa	150-200	109	350	167	200	80
Elongation, percent	0.2-0.4		0.9		0.3	
Interlaminar shear strength, MPa	8-12	6	35	22	40	16
Flexural strength, MPa	150-200		500		300	
Fiber content, vol %	55-65		45		40	

[a]Based on mid-range values.

TABLE II.—KEY ISSUES FOR CERAMICS IMPACT ON AEROSPACE SYSTEMS

Issue	Primary solution	Other contributors
Reliability	Fiber reinforcement	Fiber/interphase stability Matrix reliability
Toughness	Fiber reinforcement	Small diameter fibers Tough matrix
High-temperature capability	Stable fibers	Matrix strength Environmental durability
Environmental durability	Fiber coatings (interphases)	Matrix Surface coating
Design		
Joining		
Manufacturing base		

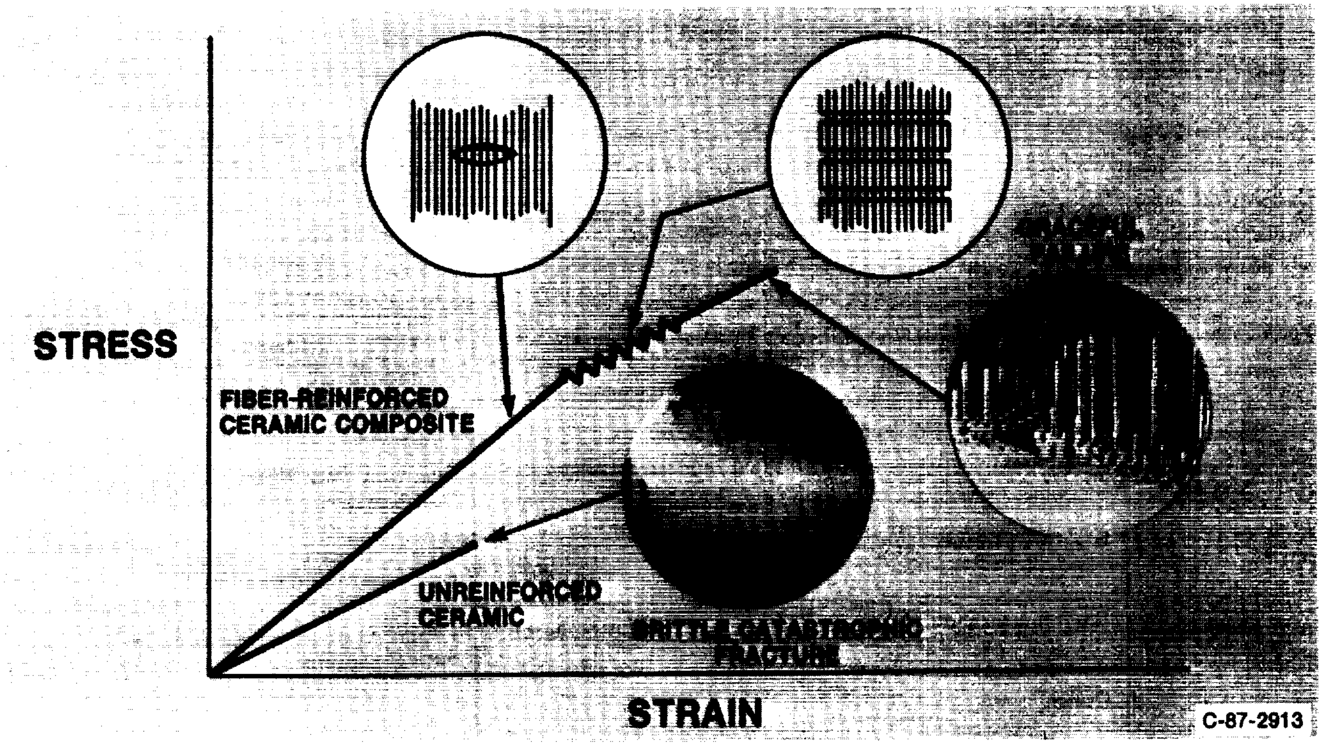
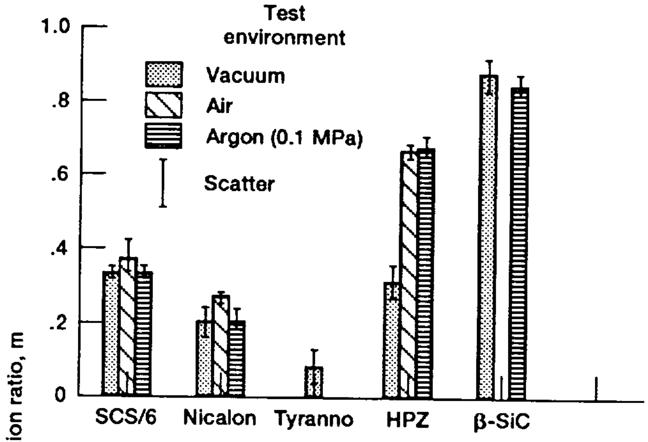
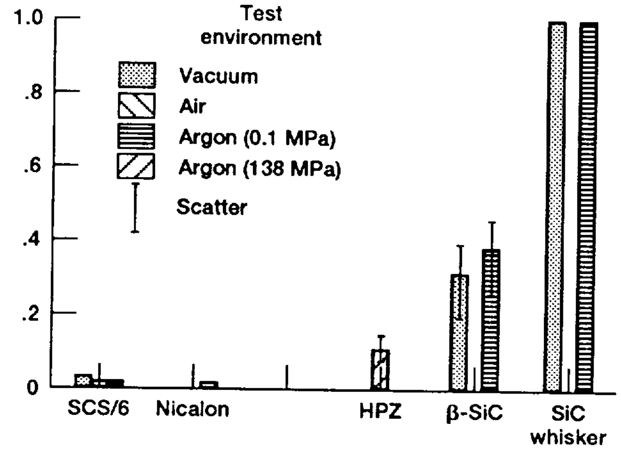


Figure 1.—Graceful failure of fiber reinforced ceramic composites by fiber bridging of matrix cracks.



(a) 1200 °C



(b) 1400 °C

Figure 2.—One hour stress relaxation ratio comparison for various fibers and environments. Between 4 and 8 fibers were treated for each bar. Surface strain was ~0.3 percent for all fibers except for the SiC whisker (0.05 to 0.15 percent) (ref. 8).

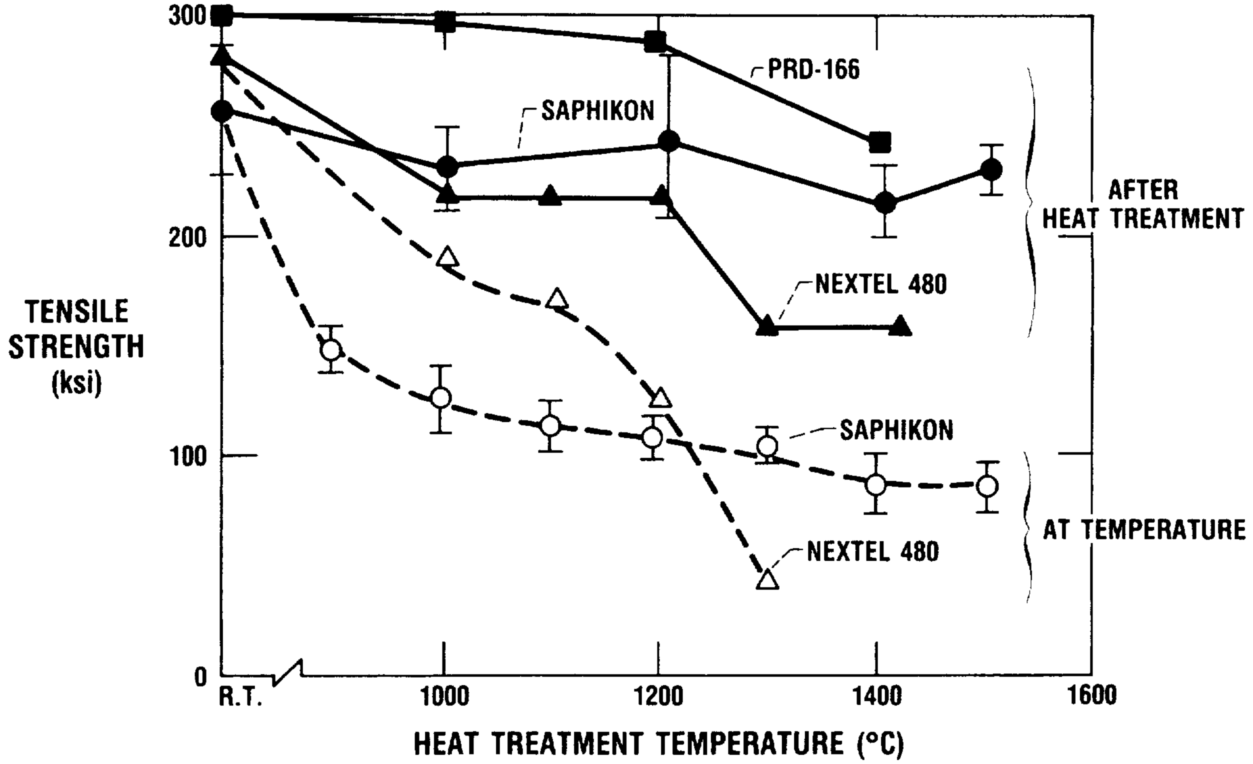


Figure 3.—Tensile strength of Saphikon, Nextel 480 and PRD-166 after heat treatment and at temperature.

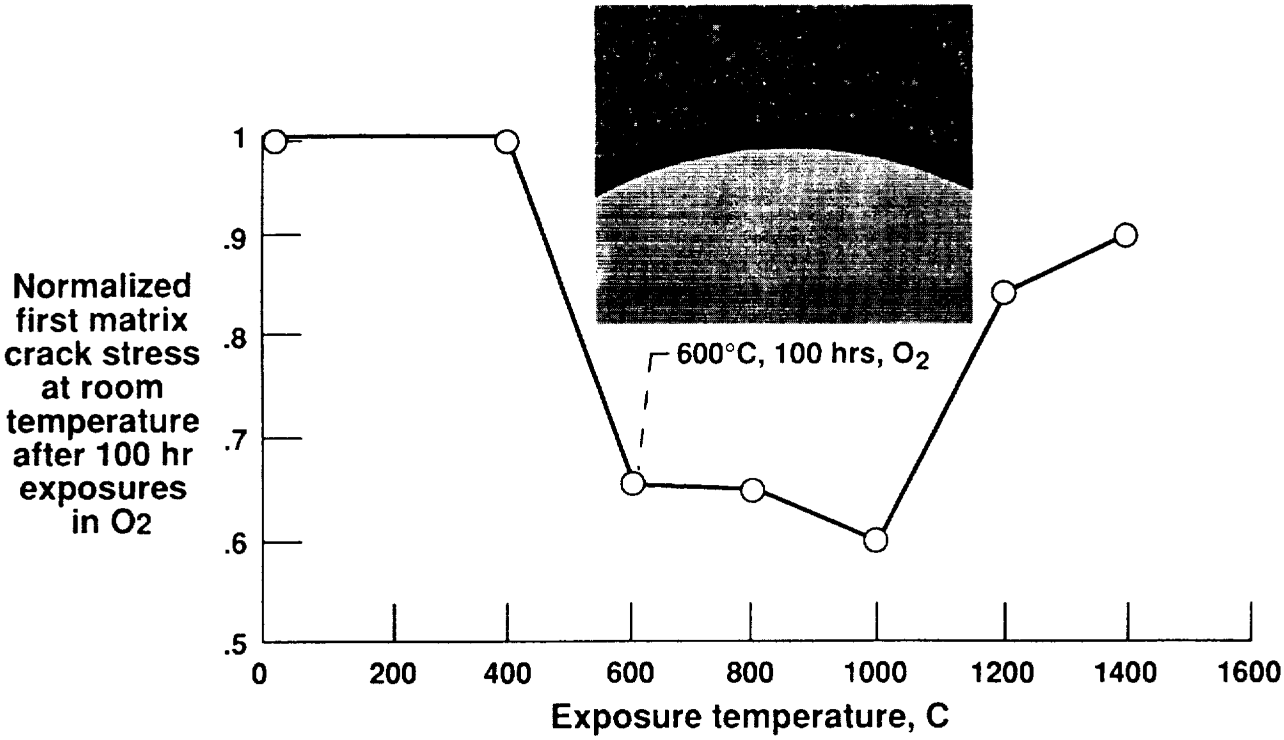


Figure 4.—Oxidation of carbon from interphase degrades SiC/RBSN at intermediate temperature.

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13. ABSTRACT ***(Maximum 200 words)***

Ceramics and ceramic matrix composites (CMC) have the potential for significant impact on the performance of aerospace propulsion and power systems. In this paper the potential benefits are discussed in broad qualitative terms and are illustrated by some specific application case studies. The key issues in need of resolution for the potential of ceramics to be realized are also discussed.

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