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CERAMICS FOR ENGINES

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SUMMARY

The NASA Lewis Research Center's Ceramic Technology Program is focused on aerospace propulsion and power needs. Thus, emphasis is on high-temperature ceramics and their structural and environmental durability and reliability. The program is interdisciplinary in nature with major emphasis on materials and processing, but with significant efforts in design methodology and life prediction.

INTRODUCTION

Structural ceramics have been under nearly continuous development for various heat engine applications since the early 1970's (refs. 1 to 4). These efforts have been sustained by the unique properties that ceramics offer in the areas of high-temperature strength, environmental resistance, and low density, and the large benefits in system efficiency and performance that can result. The results of recent studies of potential ceramic applications in small aeropropulsion engines (ref. 5) have revealed that substantial benefits are possible over current engine technology. As shown in figure 1, small gains can be obtained via improved aerodynamic and cycle efficiency. Much larger benefits are possible by going to a regenerated cycle or by going to an uncooled hot section. Both of these approaches require ceramics (i.e., a ceramic regenerator for weight considerations and ceramic hot section components to overcome the need for hot section component cooling). An engine that uses both a regenerated cycle and an uncooled hot section would achieve optimum fuel efficiency.

But the promise of ceramics has not been realized because of their brittle nature, which results in high sensitivity to microscopic flaws and catastrophic fracture behavior. This has translated into low reliability for ceramic components and thus limited application in engines. For structural ceramics to successfully make inroads into the terrestrial heat engine market, further advances are necessary in net shape fabrication of components with greater reliability and lower cost (fig. 2). The cost constraint as well as technical constraints currently dictate use of monolithic or possibly particulate or whisker-toughened ceramics. Improvements in properties such as toughness, strength, lubricity, and durability may also be needed for specific applications. These advances in technology will lead to very limited use of ceramics in noncritical applications in aerospace engines. For critical aerospace applications, an additional requirement is that the ceramics display markedly improved toughness and noncatastrophic (i.e., graceful) fracture.

STRUCTURAL CERAMICS APPLICATIONS

The engines shown in figure 3 contain ceramic components that were developed in the Advanced Gas Turbine (AGT) Development Project. This program was funded by the U.S. Department of Energy and managed by the NASA Lewis Research Center (refs. 6 and 7). These all-ceramic hot gas flowpath engines are being considered as alternatives to conventional piston engines in automobiles. Complex structural ceramic components were fabricated and tested, and improvements in the areas of design methodology and life prediction were achieved. The technology from this program (which was completed in 1987) and its continuation, the Advanced Turbine Technology Applications Program (ATTAP), will help make it possible for ceramics to ultimately be used in automotive engines and provide part of the technology base for some aerospace applications.

CERAMIC TECHNOLOGY PROGRAM

The Ceramic Technology Program at NASA Lewis is focused on aerospace propulsion and power needs. Thus, emphasis is on high-temperature use of ceramics and on their structural and environmental durability and reliability. The objective of our Ceramic Technology Program is to identify and develop ceramics and ceramic composites with strength, toughness, reliability, and durability sufficient for use at temperatures to 1650 °C (3000 °F) and above in future advanced aerospace propulsion and power systems. The program is interdisciplinary, with major emphasis on materials and processing, but with significant efforts in design methodology and life prediction:

(1) Materials and processing

- (a) Reliable, tough ceramics
- (b) Fiber-reinforced ceramics
- (c) Advanced ceramic fibers
- (d) Wear-resistant and low friction coatings

(2) Design methodology

- (a) Brittle materials design code
- (b) Friction and wear data

(3) Life prediction

- (a) Environmental effects
- (b) Nondestructive evaluation
- (c) Fracture and fatigue
- (d) Time-dependent behavior

About 35 researchers in the Materials and Structures Divisions are involved in the project. Strong interactions between researchers involved in materials efforts and nondestructive evaluation (NDE), corrosion, fracture, and design methodology have led to successful collaborations (refs. 8 to 13).

APPROACHES TO CERAMIC RELIABILITY

Two basic forms of reliability can be defined for ceramics. The first is a statistical reliability, as illustrated in figure 4. Ceramics typically display a broad distribution of strengths. In the inspection approach to reliability, we would separate unacceptable parts by NDE and proof testing and would reject them. A more efficient and cost effective approach lies in improved processing that increases strength and yields no defective parts.

We define the second form of reliability as functional reliability because it relates to how well a component performs its function during system assembly and service. Thus, factors such as fracture toughness, impact resistance, and failure mode (graceful versus catastrophic) need to be considered. Specific approaches to improved functional reliability include the addition of particulate and whisker phases which can improve fracture toughness, and the addition of continuous fibers which can both improve toughness and provide a noncatastrophic failure mechanism. This brings us into the realm of engineered microstructures (i.e., composites).

MONOLITHIC AND TOUGHENED CERAMICS

Current NASA Lewis materials, design, and life prediction research is focused on SiC and Si_3N_4, since these materials offer the desired combination of high-temperature strength, thermal shock resistance, and environmental durability. We are concluding efforts on monolithic SiC and Si_3N_4 reliability improvement. Future efforts are being focused on determining the potential of these materials for use in the 1300 to 1600 °C range. This requires improvements in strength and toughness and an understanding of how these improvements translate into use potential. These efforts are synergistic with our effort in fiber-reinforced ceramics, where our major emphasis is on SiC and Si_3N_4 materials (for matrix and fiber reinforcement applications).

Some recent progress at NASA Lewis in improving the strength of monolithic silicon carbide (ref. 14) is illustrated in figure 5. Materials fabricated by dry pressing or slurry pressing, followed by sintering at 2200 °C for 30 min have four-point flexural strengths of about 345 and 414 MPa, respectively. Hot-isostatic pressing tantalum-encapsulated, green, slurry-pressed specimens at 1900 °C for 30 min under 138 MPa argon pressure improves strength to about 552 MPa while achieving the same density. This densification at a much lower temperature yields a much finer grain size and a shift in the strength-limiting flaw from internal defects, such as pores and agglomerates, to surface machining defects. Improvements are being sought to reduce sensitivity to surface flaws. Annealing in air has proven successful, and improved fracture toughness from the addition of particulates or whiskers is expected to be beneficial.

In the area of monolithic silicon nitride processing, an improved NASA 6Y (6 wt % Y_2O_3) sintered Si_3N_4 composition was realized by iterative utilization of conventional x-radiography to characterize structural (density) uniformity as affected by systematic changes in powder processing and sintering parameters (ref. 15). As shown in figure 6, four-point flexural strength was improved 56 percent, and the standard deviation was reduced by more than a factor of three. Correlated with these improvements were improved microstructures and a change in critical flaw character from processing flaws such as voids to large grains, as shown by the fractographs at the lower left and right of figure 6, respectively.

NASA has supported major contract research efforts to improve the statistical reliability and strength of silicon nitride (Garrett Ceramic Components Division) and silicon carbide (Ford Motor Co.) via improved processing centered about injection molding. Both efforts have made good progress toward the goals of 100-percent improvement in Weibull modulus and 20-percent improvement in strength (refs. 14 and 16). The effort at Garrett is essentially complete. One Garrett accomplishment, as shown in figure 7, was the development of material GN-10, which appears to have significantly advanced the state of the art for Si_3N_4 in terms of both room- and elevated-temperature strength.

An interdisciplinary toughened ceramics life prediction project has been initiated at NASA Lewis. The objective of this research is to understand the room- and high-temperature behavior of toughened ceramics, especially SiC whisker-toughened Si_3N_4, as the basis for developing a life prediction methodology. A major goal is to determine material behavior as a function of time, temperature, and whisker content. A second major objective is to understand the relationship between microstructure and mechanical behavior. These results will be used in materials development and design methodology development. Resultant design codes will be verified.

Fiber-Reinforced Ceramics

Improved strength, toughness, and reliability can be achieved by incorporating continuous ceramic fibers into a ceramic matrix. Reinforcing with ceramic fibers having a modulus and ultimate strength greater than the monolithic ceramic used as the matrix material yields ceramic composites with greater stiffness and greater strength at first matrix cracking. If small-diameter fibers are used, matrix crack propagation can be delayed by the bridging mechanism depicted in figure 8. This results in matrix failure for the composite at a stress and strain level higher than for the monolithic ceramic. If the fiber-matrix interfacial bonding is optimum, matrix cracks propagate around the fibers and not through them. Once matrix cracks start to form, they occur at a regular spacing. The ceramic is then held together by the load carrying capacity of the fibers until they begin to fracture in a statistical manner. The net result for a tough ceramic composite is that a metallike stress-strain curve is displayed with first-matrix cracking stress corresponding to the yield stress of metals and fiber fracture corresponding to the ultimate strength. Thus, fiber-reinforced ceramics fail in a graceful manner, rather than catastrophically.

The processing of fiber-reinforced composites is more difficult than the processing of monolithic ceramics. Also, available fibers for high-temperature (1400 °C) ceramic matrix composites are limited, and the proper fiber-matrix bond must be maintained in fabrication as well as during the life of the composite. Too strong a bond yields a loss in toughness and a reversion to monolithic ceramic behavior, while too weak a bond yields loss in stiffness, strength, and toughness.

The focus of current NASA Lewis research in fiber-reinforced ceramics (FRC) is on the development of fabrication approaches that yield good matrix properties and can be carried out with minimal degradation of fiber strength. Four approaches that are being pursued are listed as follows:

$$\text{Si powder + heat + } N_2 \text{ gas} \longrightarrow Si_3N_4$$
$$\text{SiC polymer + heat} \longrightarrow SiC$$
$$\text{C polymer + heat + Si gas} \longrightarrow SiC$$
$$\text{Al-O sol gel + heat} \longrightarrow Al_2O_3$$

Each process has a specific advantage. The reaction-bonded Si_3N_4 matrix has excellent strength, the use of SiC- or C-yielding polymers can provide low-cost processing (ref. 17) or tailorable matrix capability, and an Al_2O_3 matrix (with oxide fiber reinforcement) would provide excellent oxidation resistance. Extension of the capability of FRC via development of advanced fibers and fiber coatings is a second area of focus. Effort is focused on identifying and developing high-strength fibers (ref. 18), especially those with the potential for use at temperatures greater than 1650 °C (3000 °F). Environmental protection through coatings and control of the fiber-matrix bond are also being evaluated. The third area of focus is assessment of FRC capability to perform in applications such as NASP and rocket propulsion systems. These efforts thus focus on key issues associated with each application, such as process scale-up to enable component fabrication, compatibility with the environment, and resistance to thermal shock.

The fabrication sequence, microstructure, and mechanical properties of a strong and tough SiC fiber-reinforced, reaction-bonded silicon nitride composite recently developed at NASA Lewis are summarized in figure 9. Silicon and SiC fiber monotapes are interleaved and subjected to a mild hot-pressing step to burn out the binder and provide some green strength (ref. 19). The composite is then nitrided to convert the silicon to Si_3N_4. The resultant composite microstructure contains high levels of porosity, particularly between fibers. In four-point flexural testing, the composite exhibits a first matrix cracking strength comparable to typical monolithic reaction-bonded silicon nitride (RBSN) even though the matrix density at 2.0 g/cm^3 is far lower than that of monolithic RBSN. The ultimate strength of the composite is more than twice that of a typical RBSN at both 23 and 40 percent fiber loading. Further, the high-temperature strength of this SiC/RBSN composite exceeds that of various commercial ceramics. In figure 10, four-point bend strengths for the NASA Lewis SiC/RBSN composite at room temperature, 1200 °C (2200 °F), and 1400 °C (2550 °F) are compared with data for the following commercially available ceramic materials: fully dense, hot-pressed Si_3N_4, reaction-bonded Si_3N_4, and SEP SiC/SiC composite (one-dimensional). At elevated temperature, 23 vol % SiC/RBSN is stronger than both monolithics and more than twice as strong as the SEP SiC/SiC composite.

Tensile stress-strain data and fracture behavior of 30 vol % SiC/RBSN composites (ref. 20) are illustrated in figure 11. An additional strain occurs after matrix fracture at about 0.12 percent strain. The stress at failure is much higher than for first matrix cracking. The fracture surface exhibits the moderate fiber pullout required for achieving a strong, tough ceramic matrix composite. It is expected that with the development of high strength, smaller diameter SiC fibers, the fracture properties of the SiC/RBSN will improve significantly.

An example of studies aimed at improved ceramic fibers is a recent in-house study of post-processing of Nicalon SiC fibers (ref. 21). This research involved high-temperature/high-pressure treatments of Nicalon in an attempt to determine if the fiber properties could be improved or stabilized. Results are summarized in figure 12. Treatment under 1360 atm argon results in about a 300 °C increase in the maximum exposure temperature (for avoiding excessive strength degradation). This effect is transitory in nature. Thus, exposure to high temperature at 1 atm after pressure treatment gives the same results as exposure of a virgin fiber. However, if high-temperature exposure is necessary only for processing of the composite, the pressure treatment approach may have significant merit.

CONCLUDING REMARKS

For ceramics to achieve their promise in advanced aerospace applications, reliable and economical fabrication processes must be developed for monolithic, whisker-toughened, and fiber-reinforced ceramics and their constituents. In addition, a basic understanding of the materials science of ceramics is required for the development of processing, design, and life prediction methodologies that will enable ceramics to be used. NASA Lewis is actively pursuing all of these goals through our integrated multidisciplinary Ceramics Technology Program.

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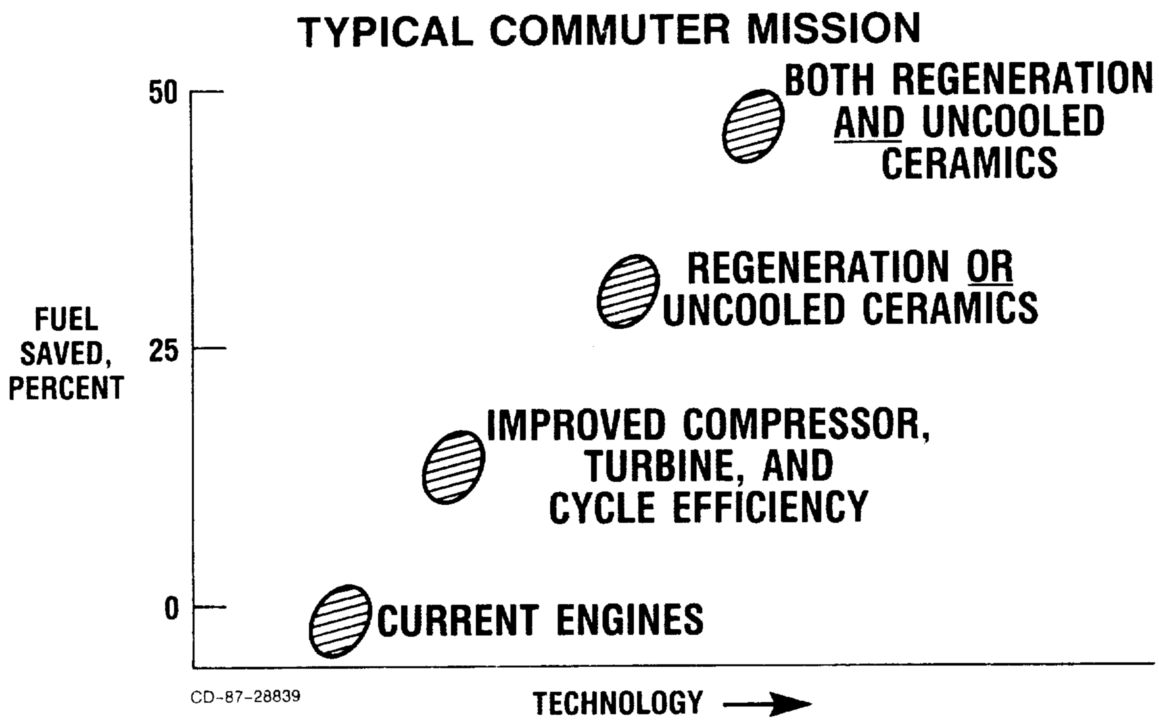

Figure 1. - Technology benefits from ceramics.

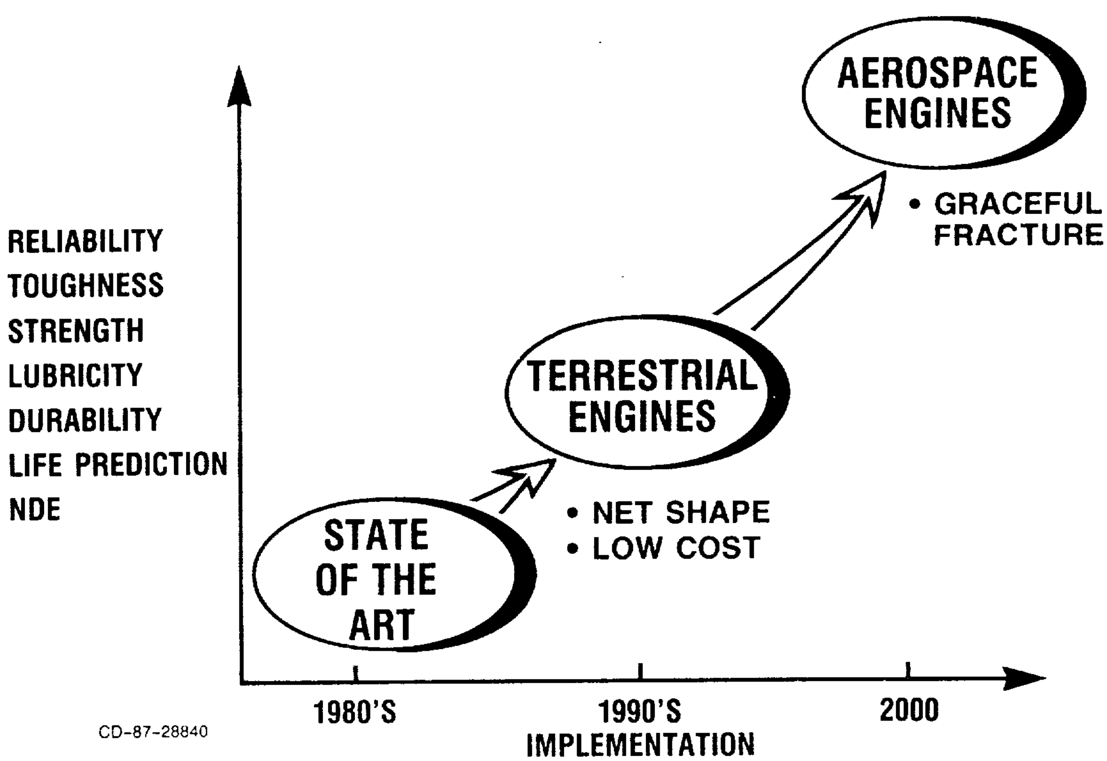

Figure 2. - Ceramic technology needs.

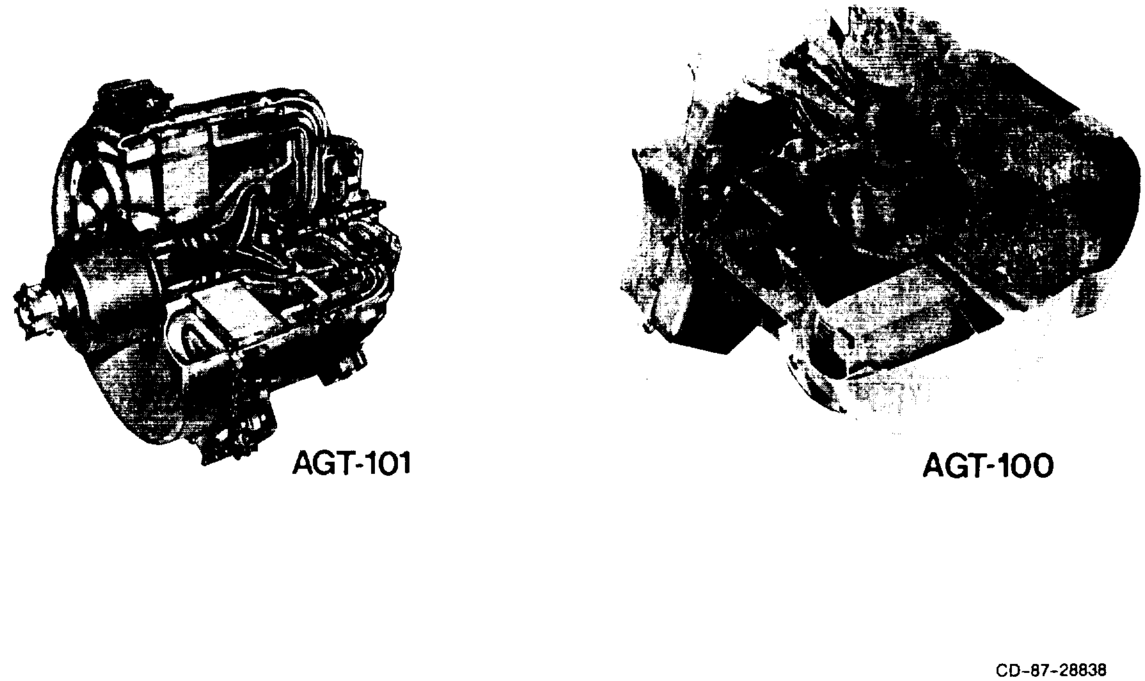

Figure 3. - All-ceramic hot gas flowpath engines are being considered as alternative to conventional piston engines in automobiles.

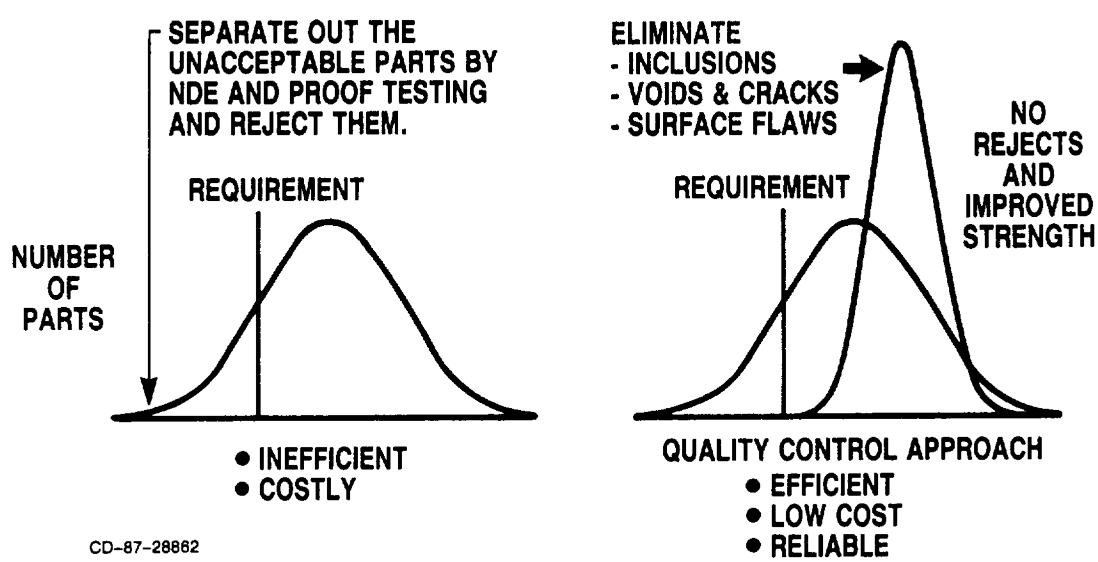

Figure 4. - Approaches to ceramic reliability.

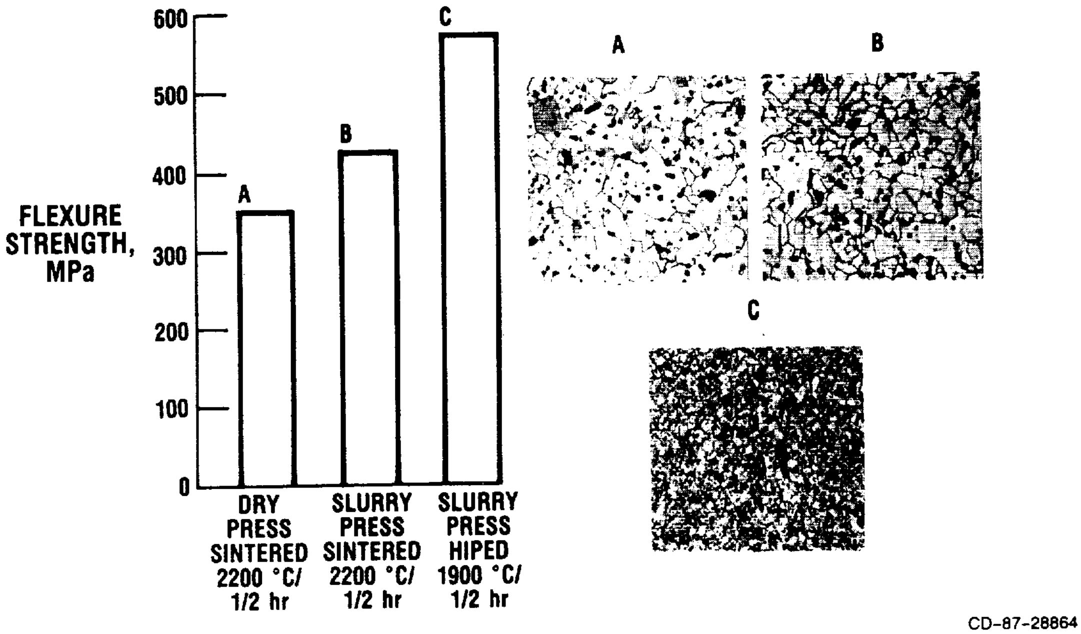

Figure 5. - Improved silicon carbide by hot-isostatic pressing.

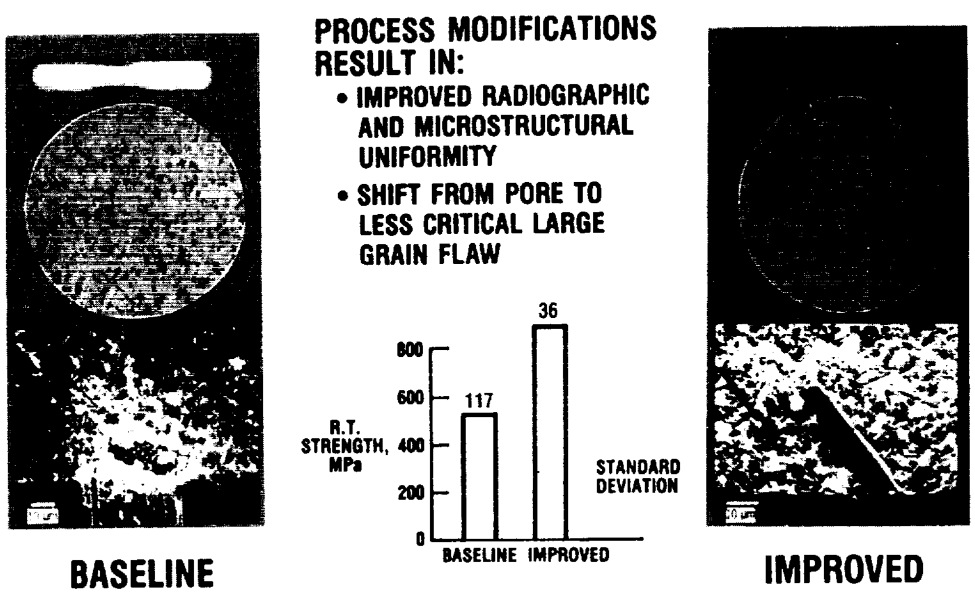

Figure 6. - NASA 6Y sintered silicon nitride improved by radiographically-guided processing changes.

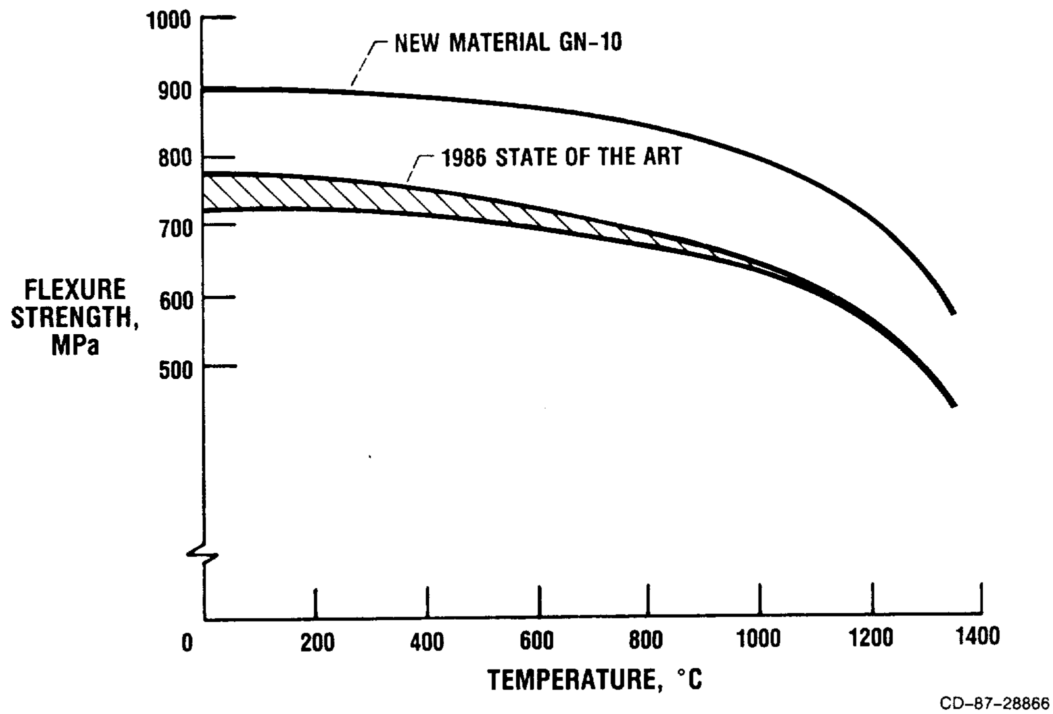

Figure 7. - Improvements in sintered silicon nitride.

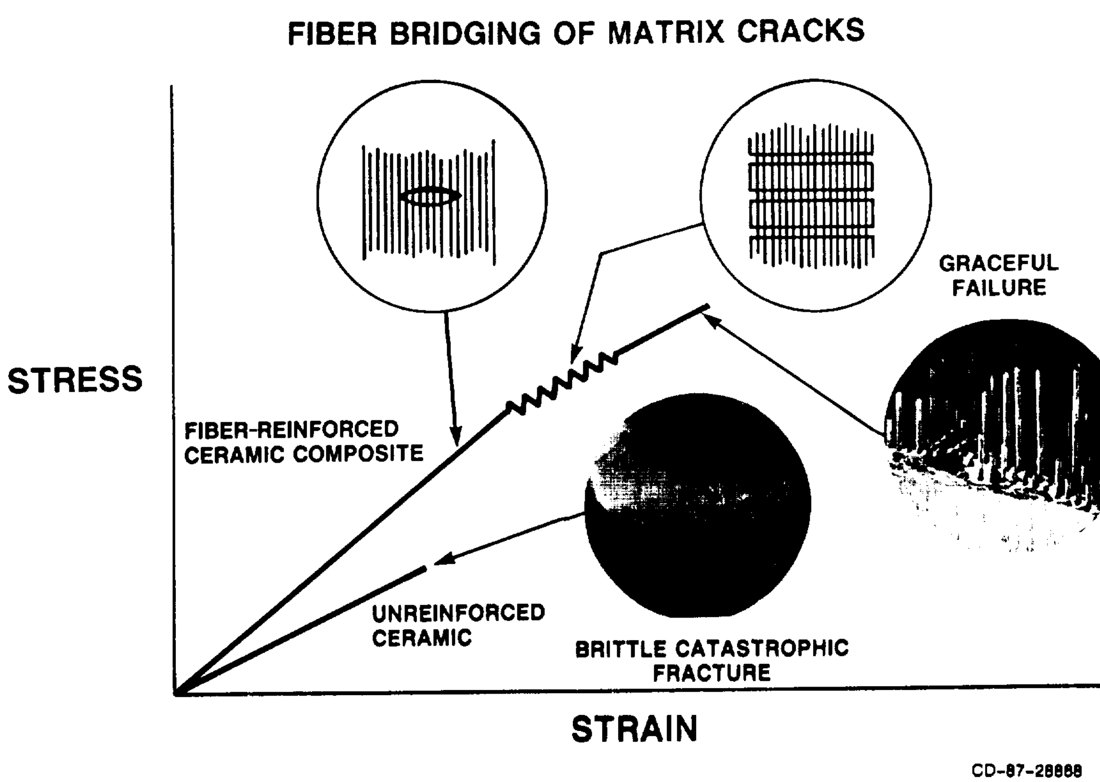

Figure 8. - Graceful failure of ceramic composites.

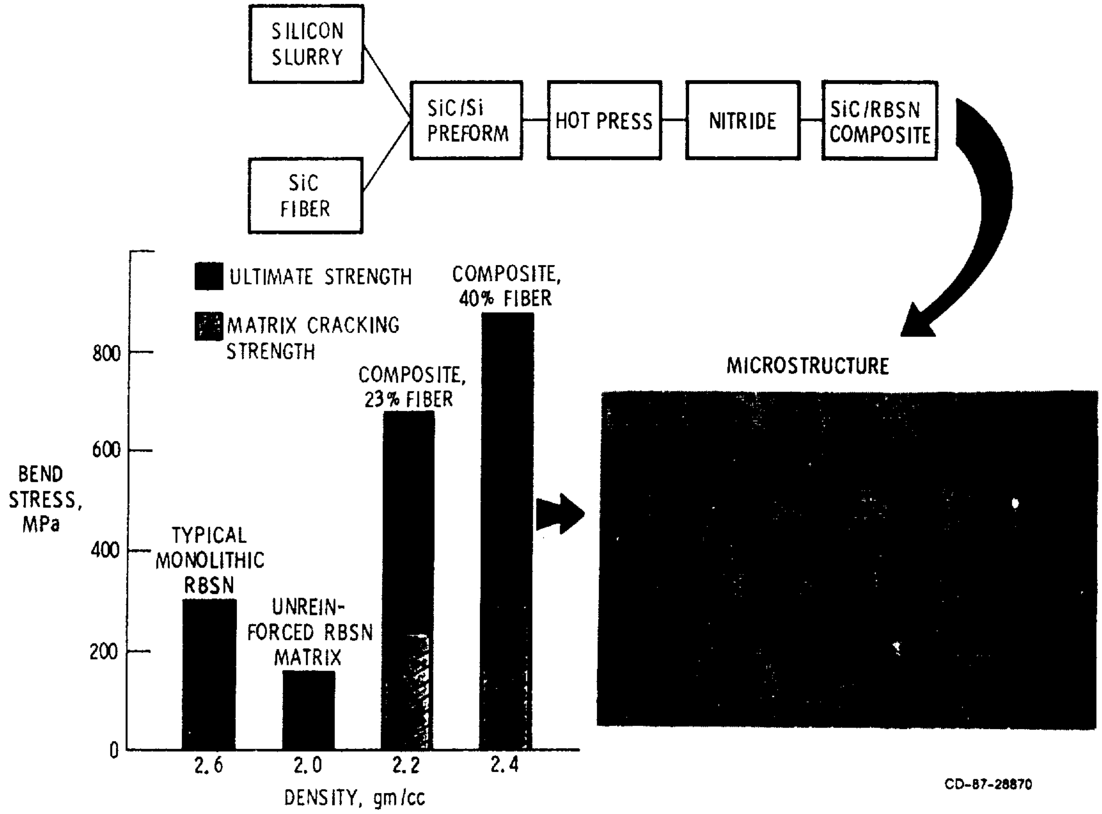

Figure 9. - SiC fibers strengthen and toughen reaction-bonded Si_3N_4.

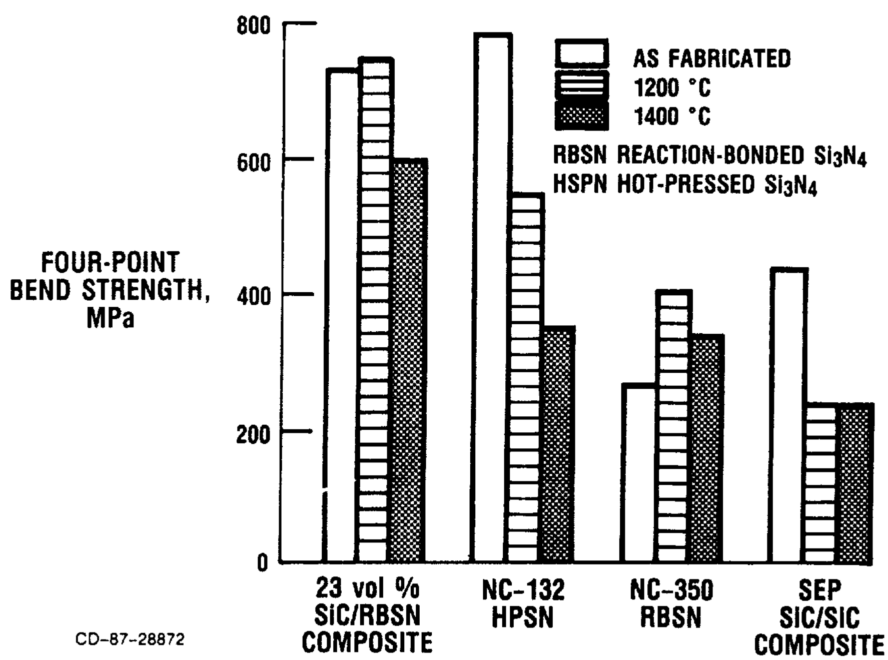

Figure 10. - High-temperature strength of SiC/RBSN composites is better than that of commercial ceramics.

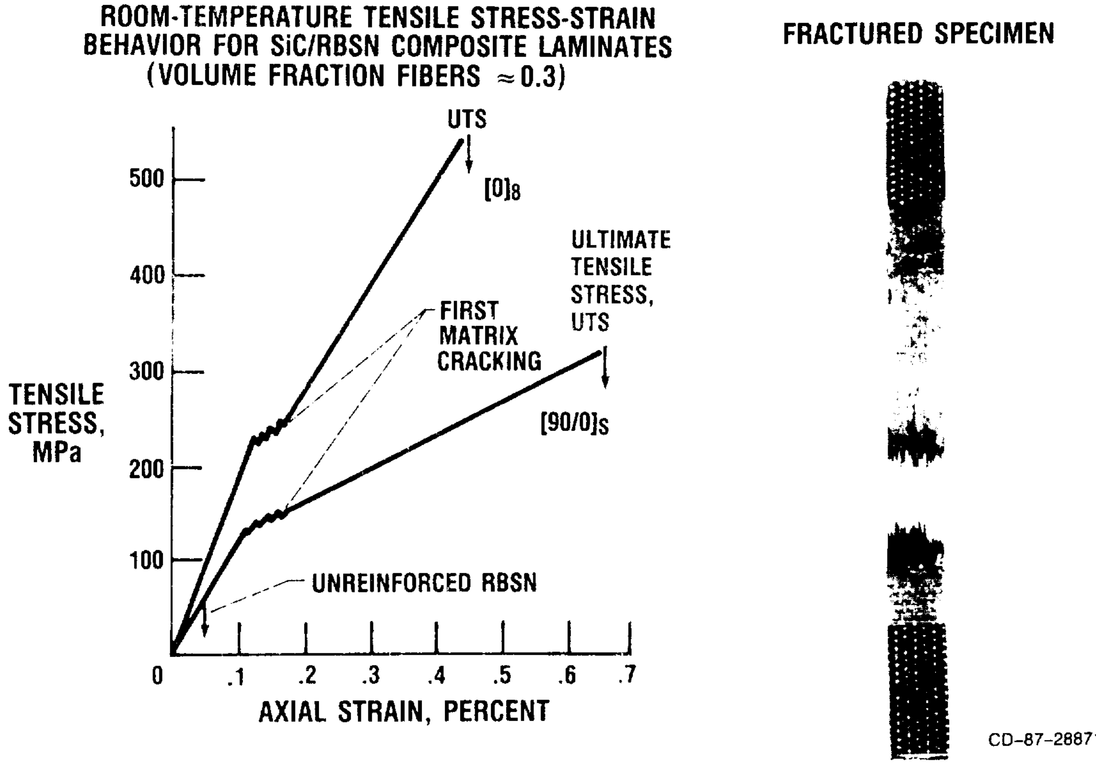

Figure 11. - SiC/RBSN composites fracture gracefully.

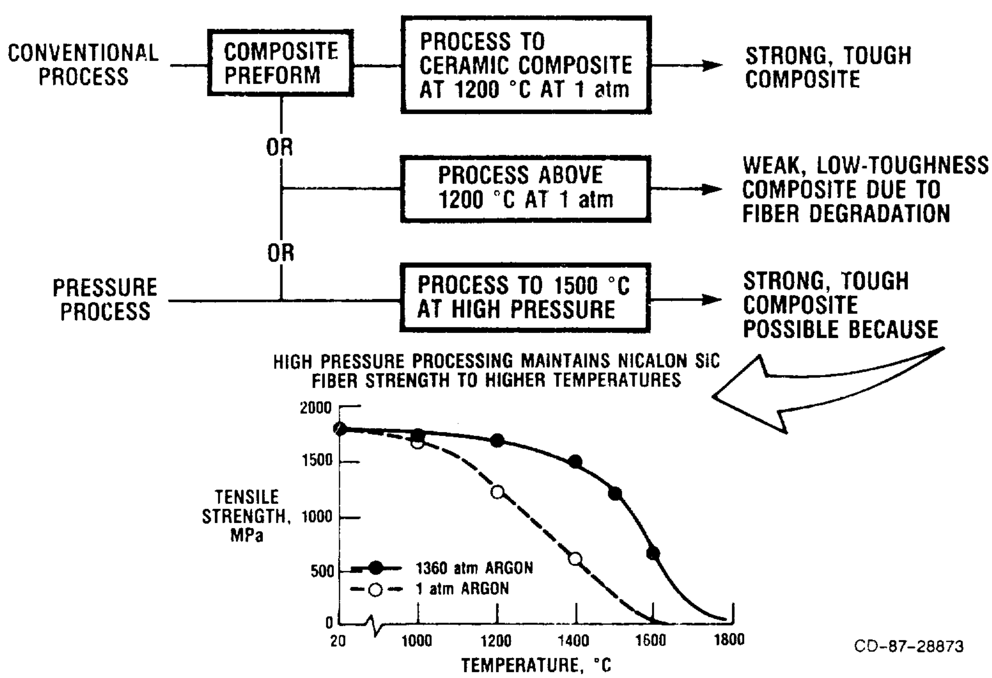

Figure 12. - High pressure extends processing window for ceramic matrix composites.