RECENT ADVANCES AND KEY ISSUES ON STRUCTURAL CERAMICS FOR ADVANCED HEAT ENGINES

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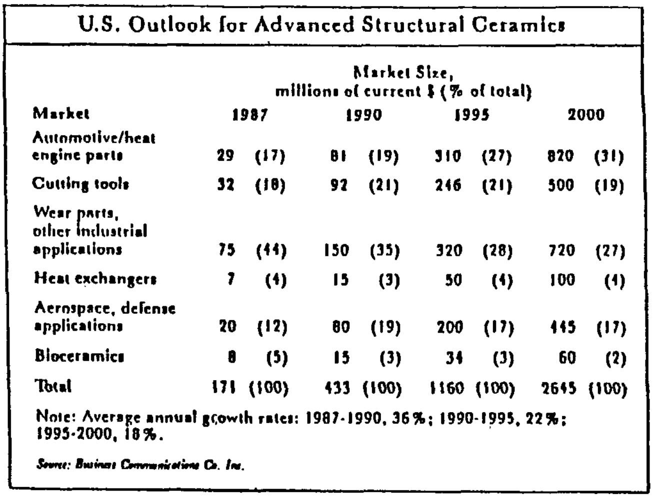
The role of advanced structural ceramics such as Si_3N_4 and SiC in automobile and aerospace applications is continuously growing since its inception more than two decades ago. Among the specific advantages recognized are turbine efficiencies, specific fuel consumption, multifuel capabilities, and less dependence on costly superalloys. Therefore, a significant potential exists for a large growth for these ceramics between 1995 and 2000. Table 1 shows the U.S. outlook for advanced structural ceramics by the year 2000[1]. Major market segments are automotive heat engine components, wear parts, cutting tools, and aerospace defense applications. Ceramic parts currently in production are glow plugs, pre-combustion chamber inserts, wear pads, wear plates, pistons, wrist pins, valves, valve seats, turbocharger rotors, etc., in automotive applications.

Table 1



U.S. Outlook for Advanced Structural Ceramics

	Market Size, millions of current $ (% of total)							
Market	1987		1990		1995		2000	
Automotive/heat engine parts	29	(17)	81	(19)	310	(27)	820	(31)
Cutting tools	32	(18)	92	(21)	246	(21)	500	(19)
Wear parts, other industrial applications	75	(44)	150	(35)	320	(28)	720	(27)
Heat exchangers	7	(4)	15	(3)	50	(4)	100	(4)
Aerospace, defense applications	20	(12)	80	(19)	200	(17)	445	(17)
Bioceramics	8	(5)	15	(3)	34	(3)	60	(2)
Total	171	(100)	433	(100)	1160	(100)	2645	(100)

Note: Average annual growth rates: 1987-1990, 36%; 1990-1995, 22%; 1995-2000, 18%.

Source: Business Communications Co. Inc.

In the area of aerospace, components such as igniters, turbine rotors and stators, hot flow path ducting and valves, bearings, and seals, etc., are being considered. Nissan Motor Co. already has developed ceramic turbocharger rotors and rocker arms using mainly silicon nitride and has been working on the development of ceramic parts which can provide improved thermal resistance and anti-abrasion properties. Ceramic turbocharger rotors (62 mm) were first used in the "Fairlady" sports car in October 1985; and in 1986, installation of ceramic rotors was begun in the "Skyline", a passenger sedan. In June 1987, Nissan adopted a Si_3N_4 based turbocharger rotor (55 mm) in a new V-6 engine for use in passenger models such as the "Cedric" and the "Gloria"[2]. In 1990, skyline, a two-door medium-size sport passenger car, had been equipped with twin ceramic (Si_3N_4) turbochargers, supplied by Garret turbo, Inc[3]. Further, Toyota motor mass-produced turbochargers with Si_3N_4 ceramic rotors since October 1989. These turbochargers have been introduced into Celica and MR-2 models, which are sport type passenger cars[3].

In the area of World progress in structural ceramics, Japan has already provided Ceramics (Si_3N_4) rotors to the AGT (Advanced Gas Turbine) program by U.S. DOE/NASA. The AGT program was successfully ended, and further program expansion is being continued under ATTAP (Advanced Turbine Technology Applications Project). The objective of the ATTAP is (1) to demonstrate structural ceramic component technology potential for competitive automotive engine life cycle cost, and (2) to operate for 3500 hours in a turbine engine environment at temperatures up to 2500°F. Figure 1 shows the overall ATTAP approach. This is a 5-year program (1988-92), and is being carried out by Allison Gas Turbine Division of General Motors, the prime contractor. Similarly, Japan, after a 2-year of feasibility study, has initiated a full-scale 7-year program (1990-96), to develop a base metallic gas turbine engine to evaluate and test ceramic components, (2) to develop a 1200°C ceramic gas turbine engine, and (3) to develop final target 1350°C ceramic gas turbine engine[4].

ATTAP APPROACH

1. ITERATE BETWEEN DESIGN / MATERIALS / PROCESSING
2. IMPROVE MATERIALS PROCESSING
3. ESTABLISH TOUGHER COMPONENTS
   - COMPOSITES
   - MONOLITHICS
4. DEVELOP COST EFFECTIVE COMPONENTS
   - MATERIALS
   - PROCESSES
5. EVALUATE CERAMIC COMPONENTS IN AN AUTOMOTIVE GAS TURBINE ENVIRONMENT

Figure 1

MONOLITHIC SILICON NITRIDE (Si_3N_4)

Numerous investigations in the last 10 years in the USA, Japan and W. Germany, have resulted in significant improvement in material properties such as strength, creep, oxidation, thermal shock, and fracture toughness. Figure 2 shows significant improvements in both room temperature and high temperature flexure strengths (4-point bend) of Si_3N_4 material obtained by various manufactures in the USA and Japan. For example, Garrett Engine Co. improved the baseline strength of Si_3N_4 material from $\sim$ 500 MPa to $\sim$ 900 MPa in a NASA sponsored "Improved Silicon Nitride" program, within 3 years. Similarly, GTE has developed an improved Si_3N_4 with an average flexure strength of $\sim$986 MPa and Weibull as high as 20, (Fig. 3)[5]. In Japan, NTK has developed Si_3N_4 with room temperature strength $\sim$ 1100 MPa and high temperature (2500° F) strength 650$\sim$ MPa. A summary of current status in baseline flexure strength of Si_3N_4 materials is listed in Table 2. The improvement in strength is the result of extensive research and developmental work during the last 4-5 years.

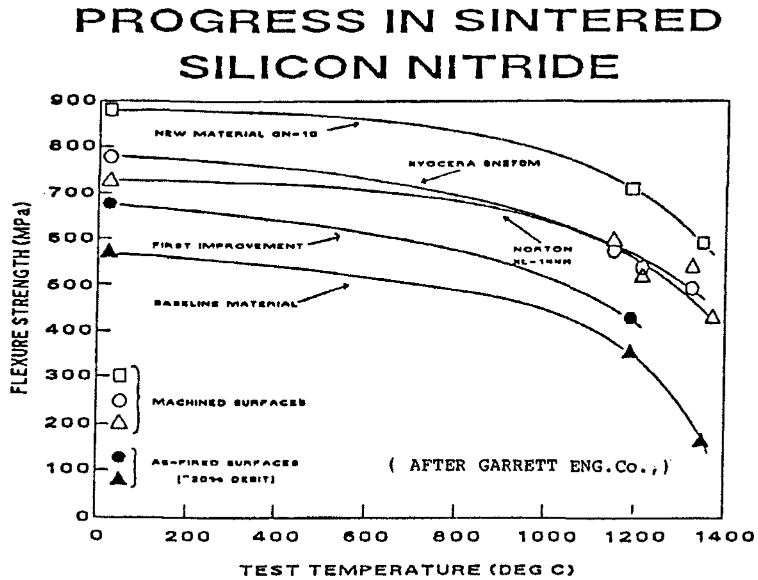


Figure 2

Weibull probability plot for the strength of samples produced by the identified routes. The average strength and Weibull moduli are: IP-697 MPa and 9; SC-834 and 20; IM-897 and 14; IM+HIP-956 and 20.

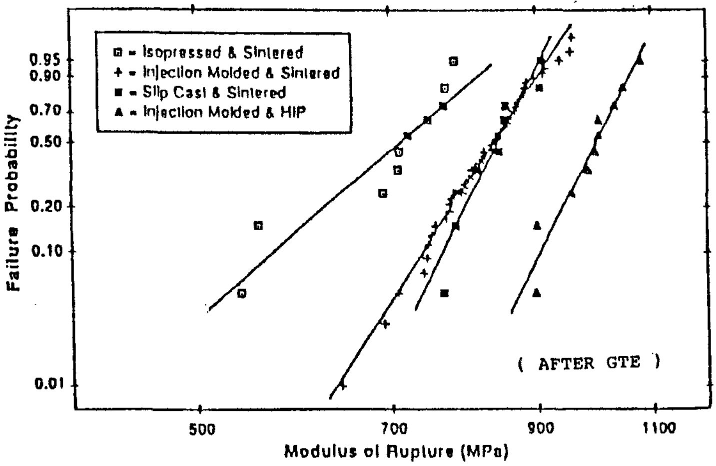


Figure 3

Table 2

Vendor	Strength(R.T.) (MPa)	Strength (2500°F) (MPa)
NTK EC 152	1,053	650
NORTON/TRW	1,000	635
NGK	963	-
GTE PY 6	880	590
GCCD GN-10	880	580
KYOCERA 252	640	550

MONOLITHIC SILICON CARBIDE(SiC)

In the area of SiC, a significant strength improvement was achieved in both α -SiC and β -SiC materials. For example, Fig. 4 shows a gradual strength improvement in

ROOM TEMPERATURE FLEXURE STRENGTH OF SINTERED VERSUS HIPed SILICON CARBIDE

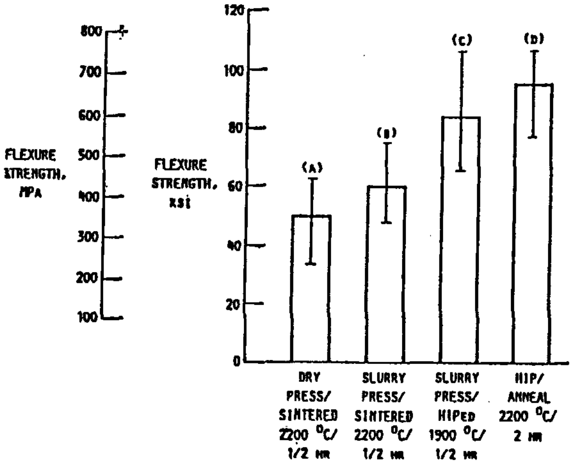
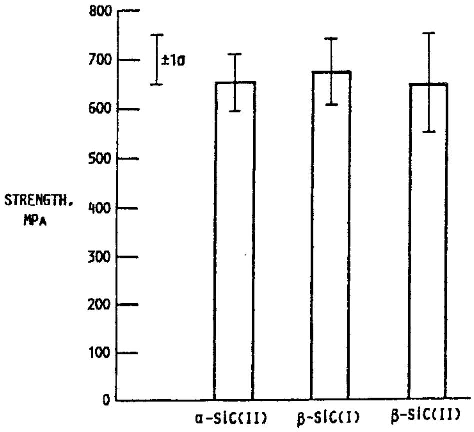


Figure 4

α-SiC by improved processing techniques[6]. Similarly, a significant progress has been made in developing high strength β-SiC by improved processing[7]. Flexure strength (4-point bend) as high as∿ 700 MPa was achieved in both α-and β-SiC materials. This is shown in Fig.5. Recently, Carborundum has developed fine-grained α-SiC by pressureless sintering with an average strength as high as∿600 MPa[8]. The above results clearly indicate a significant improvement in baseline strength (∿600-700 MPa) for SiC materials as compared to 350-450 MPa, a few years ago.

CERAMIC MATRIX COMPOSITES

Although significant improvement in room temperature and high temperature strength had been achieved in commercially produced Si_3N_4 and SiC materials, a critical factor which still limits the widespread application of these ceramics in heat engines, is their high sensitivity to microstructural flaws and



ROOM TEMPERATURE FLEXURE STRENGTH OF α-SiC AND β-SiC HIPed AT 1900 °C FOR 60 min

Figure 5

catastrophic (brittle) failure behavior. It was anticipated that improvement in fracture toughness of these materials would considerably expand their applicability in high performance automobiles and aerospace engines. In order to overcome the brittle nature of ceramics, considerable R&D work is underway to improve toughening in Si_3N_4 and SiC matrix composites. This include particulates and/or transformation toughening, whisker toughening, and continuous fiber-reinforced toughening. Figure 6

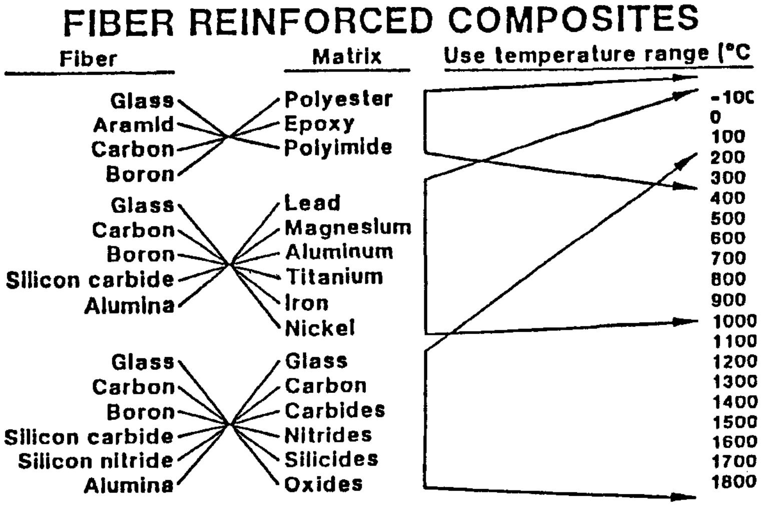


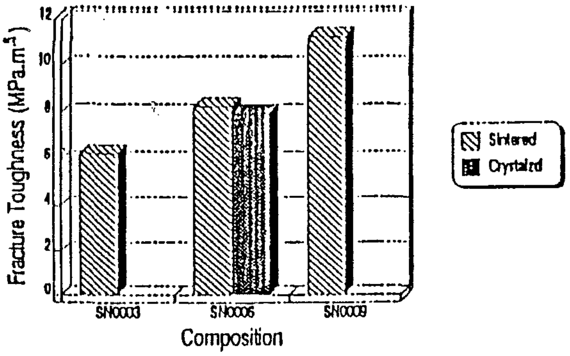
Figure 6

shows various composites systems currently under investigation for various use-temperature applications. Considerable progress has already been made to improve toughening of the Si_3N_4 matrix with SiC-whisker reinforcement. For example, fracture toughness values of $\sim$6-8 MPa$\sqrt{m}$, are routinely produced (as current state-of-the-art) in SiC-whiskers reinforced Si_3N_4 matrix, while in-situ β-Si_3N_4 grain enlargement, having high aspect ratios, yielded fracture toughness values[9], ranging between 8-11 MPa$\sqrt{m}$. This is shown in Fig. 7. Similarly, SiC composites with high fracture toughness (K_{IC}) have been achieved with the incorporation of sintering additives, and through microstructural engineering, e.g. grain size and shape. Recently Carborundum Co. has developed fine-grained α-SiC material with a fracture toughness[8] ranging between

8-10 MPa$\sqrt{m}$, as compared to 3-3.5 MPa$\sqrt{m}$ in conventionally processed SiC . Also, in SiC-whiskers reinforced SiC matrix, MER Corporation has improved the fracture toughness (K_{IC})[10] values ranging between 6-7 MPa$\sqrt{m}$.

SUPER-TOUGH SILICON NITRIDE[8]

(AFTER ALLIED SIGNAL Co.,)



TECNIQUE	TOUGHNESS
Short Bar Chevron Notch	9.45
3-pt Bend Chevron Notch	9.55

Figure 7

In the area of continuous fiber-reinforced composites, the incorporation of continuous ceramic filamens having greater stiffness than matrix has the major advantages such as improved toughness imparted by crack deflection and crack bridging, increased modulus and stress to failure, metal-like stress-strain behavior, improved creep and thermal shock resistance and tailorable thermal conductivity. Significants improvements were made in SiC fiber-reinforced glass matrix composites. In contrast, very limited progress has been made to date in fiber-reinforced Si_3N_4 and SiC matrix composites for high temperature (2500° F) applications. In developing such composite systems, key technical issues have been identified. These include:

1. Preparation of optimum matrix precursors, uniform precursor infiltration into fiber array, and matrix consolidation and densification (without fiber strength degradation, large shrinkage cracks or porosity, and nonuniform fiber distribution).

2. Availability of high performance ceramic fibers with high strength and stiffness and thermal stability above 1200° C.

3. Fiber coatings for fiber strength retention during composite processing and use.

In order to overcome the above barriers, investigations are now underway in USA, Japan, and W. Germany to develop fiber reinforced Si_3N_4 and SiC matrix composites with significant high toughness and strength for high temperature automobile and aerospace engines.

CONCLUDING REMARKS

Structural ceramics technology for high temperature automobile and aerospace applications has progressed dramatically during the past 20 years for both materials processing and design. Application is feasible and probably inevitable, although the exact time phasing is difficult to predict. Further development is required to obtain improved material properties, improved processing, and further understanding of design/material interrelationships.

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