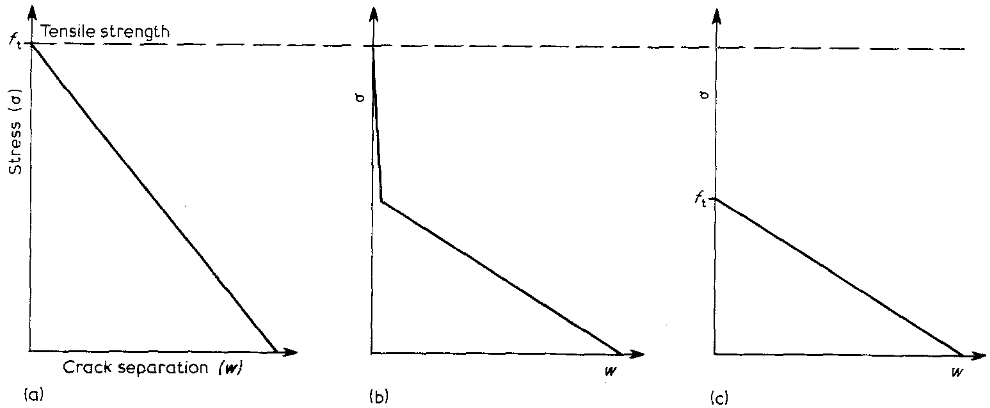

Figure 1 Possible stress–separation relationships for a tied crack.

failure mechanism it is reasonable to suggest that a relatively large force is required to start the fibres or particles slipping and thereafter a smaller "frictional" force resists the subsequent slipping, i.e. a stress–separation relationship of the form shown in Fig. 1b. Since "fracture mechanics" is principally concerned with the area under this curve, i.e. the work required to propagate the crack, we can approximate Fig. 1b with 1c, in which the stress parameter f_t is no longer the strength of the material, but is some lower arbitrary stress. This interpretation suggests that the good fit obtained by putting $f_t = 5\,\mathrm{MN\,m^{-2}}$ is no longer inconsistent with the fact that direct tensile strengths of up to $12.5\,\mathrm{MN\,m^{-2}}$ were experimentally measured.

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Thermal shock resistance of silicon nitride

Silicon nitride (Si_3N_4), silicon carbide (SiC), sialon and aluminium nitride (AlN) have been recognized as leading candidates for high-temperature gas turbine materials [1–9]. Of all the ceramic components in gas turbines, rotor and stator blades have to receive and withstand the most severe mechanical and thermal stresses. Fully densified Si_3N_4 and SiC would be limited materials because of the requirement that components should possess high strength at operating temperatures.

Recent developments have produced a hot-pressed high-strength Si_3N_4 with 5 wt% yttrium oxide (Y_2O_3) and 2 wt% aluminium oxide (Al_2O_3) by applying a new sintering method, the grain-boundary crystallization (GBC) method [9].

A major factor determining the importance of ceramics is their usefulness at high temperatures. Since this often involves rapid heating and cooling of the material, good thermal shock resistance is advantageous. Thermal shock tests currently in use are essentially of two types: determination of the minimum shock to nucleate cracking, and determination of the amount of damage sustained by a fixed shock or series of shocks.

Initiation of fracture determines materials usefulesss in a gas turbine, where a single crack can cause a catastrophic fracture by virtue of the reduction in strength, whereas for a refractory fire brick, the degree of damage is a more important factor.

Cracking is nucleated when the thermal stress, σ_t, reaches fracture stress under shock condition, σ_f. Thermal stress is given by

$$\sigma_t = AE\alpha\Delta T/(1-\nu), \qquad (1)$$

where E is Young's modulus, α the coefficient of linear expansion, ΔT the fall in temperature and ν Poisson's ratio [10]. A is a number between 0 and 1. For an infinitely fast quench, the maximum tensile stress is developed instantaneously and A equals unity.

In the present work, the thermal shock resistance of Si_3N_4 was evaluated by the measurement of critical thermal shock temperature difference ΔT_c by water-quenching method, and for this temperature difference, an abrupt strength reduction occurs in accordance with the crack initiation. ΔT_c measured by the water-quenching method is convenient for ranking materials under rapid heat-transfer conditions.

3 mm × 3 mm × 30 mm bar specimens were used for the strength measurement. The surface of each specimen was finished with diamond wheel (40 μm grit size). Round edges were obtained with use of SiC water-proof abrasive paper (40 μm). The strength measurement for quenched specimens was carried out by means of three-point bend test with a span length of 20 mm and a stress rate of about 33.3 MN m^{-2} sec^{-1}.

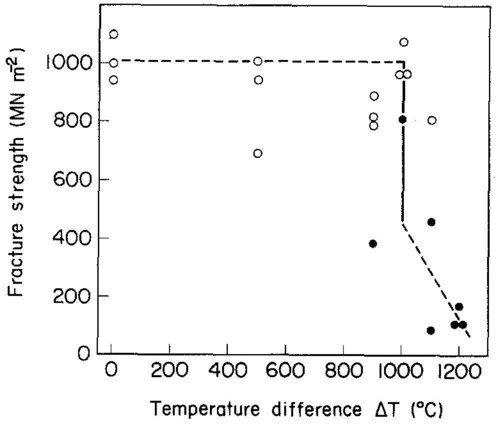

Figure 1 Fracture strength of the specimen after water quenching; ○ no cracks after quenching, ● cracked after quenching.

Fig. 1 shows the fracture strength of the GBC-Si_3N_4 quenched from various temperatures into flowing water kept at 20° C. Strength dropped suddenly, accompanied by crack generation, at the temperature difference of 1000° C. The critical thermal shock temperature, ΔT_c, was thus determined to be 1000° C. Exceptional cracking was observed at a temperature difference of 900° C, however the crack ran longitudinally to the specimen and was extraordinarily large compared to the other ones. These aspects seem to show that the crack was due to a local inhomogeneity in the specimen microstructure attributed to the

TABLE I Measured and calculated resistances of various ceramics to thermal fracture under severe quenching

Materials	$\sigma_t \times 10^8$ (N m^2)	$E \times 10^{11}$ (N m^2	$\surd$	$\alpha \times 10^{-6}$ (° C^{-1})	R (° C)	ΔT_c (° C)	Description
SiC–1*	1.161	2.361	0.14	4.8	88	265	Recrystallized
SiC–2*	2.128	3.593	0.15	4.0	126	305	Reaction sintered
Si_3N_4–1*	1.225	1.258	0.27	3.2	222	460	Reaction sintered
B_4C–1*	4.515	4.109	0.26	2.4	339	160	Hot-pressed
B_4C–2*	4.515	4.012	0.24	2.4	356	200	Hot-pressed
SiC–3*	6.127	4.160	0.15	3.4	368	415	Hot-pressed
Si_3N_4–2*	5.160	2.973	0.25	2.8	465	>900	Hot-pressed
AlN†	7.42	2.79	0.25	4.9	407	250	Hot-pressed
GBC–Si_3N_4	10.10	3.13‡	0.26‡	2.6	918	1000	(This work)

Dimensions; *6.35 mm × 3.175 mm × 6.35 mm; †and this work 3 mm × 3 mm × 30 mm.
*C. C. Seaton [11].
†K. Komeya and F. Noda [3].
‡H. Iwasaki (to be published).
§A. Tsuge *et al.* [12].

sintering processes. It should be noted that no cracks were initiated in any of three specimens subjected to thermal shock of $\Delta T = 1100^\circ$ C. This fact suggests the possibility of a ΔT_c of over 1100° C in the GBC-Si_3N_4.

Values of ΔT_c for the present GBC-Si_3N_4 and some various structural ceramics [3, 11] measured by a similar method, are shown in Table I. It is clear that ΔT_c values of Si_3N_4 ceramics, especially GBC-Si_3N_4, are higher than others, and that the GBC-Si_3N_4 is an excellent thermal shock-resistant material. This is based on both high strength value and low thermal expansion coefficient [9].

Calculated thermal resistances of some structural materials are also listed in Table I, where resistance R is calculated using [11].

$$\Delta T_c \propto R = \frac{\sigma_f(1-\nu)}{E\alpha} \qquad (2)$$

Except for the case of GBC-Si_3N_4, where measured ΔT_c is approximately equal to the calculated R, the relationship between ΔT_c and R is not precise. However, it seems to be apparent that, whereas ΔT_c values of both B_4C and AlN are smaller than respective R values, SiC and Si_3N_4 have larger ΔT_c than R values respectively. It should be noted that $R/\Delta T_c$ ratio approaches 1, i.e. $R = \Delta T_c$, wish increasing ΔT_c, but the explanations of this phenomenon is not yet available.

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