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Thickness Dependence of Impact Damage Behavior in Silicon Nitride Ceramic

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Abstract

The thickness dependence of the impact damage behavior of a silicon nitride ceramic was investigated. For specimens 1·0 mm in thickness, sudden strength degradation occurred over an impact velocity of approximately 250 m/s with Hertzian cone crack or bending fracture. Hertzian cone cracks in 1·0 mm specimens were thought to be enlarged by the scabbing effect. For 1·5–3·0 mm specimens, strength degradation occurred above a 380 m/s impact velocity with Hertzian cone crack. Therefore, the specimen thickness was related to crack initiation behavior resulting in the strength degradation.

Die Dickenabhängigkeit der Schlagbeschädigung von Siliziumnitrit-Keramik wurde untersucht. Für 1·0 mm dicke Proben trat für eine Aufprallgeschwindigkeit von über 250 m/s ein plötzlicher Abfall in der Schlagzähigkeit durch Hertzsche Konusrisse oder Biegebruch auf. Es wird angenommen, daß Hertzsche Konusrisse in 1·0 mm Proben durch einen Splittereffekt vergrößert wurden. Für 1·5–3·0 mm Proben konnte eine Erniedrigung der Schlagzähigkeit bei einer Aufprallgeschwindigkeit von über 380 m/s mit dem Auftreten eines Hertzschen Konusrisses festgestellt werden. Deshalb wurde die Probendicke in Bezug zum Rißeinleitungsverhalten gesetzt, das für die Abnahme der Schlagzähigkeit verantwortlich ist.

L'influence de l'épaisseur sur l'endommagement par impact d'une céramique en nitrure de silicium a été évaluée. Pour des échantillons de 1·0 mm d'épasseur, on note une dégradation soudaine au-dessus d'une vitesse d'impact de l'ordre de 250 m/s, qui so manifeste par la formation d'une cône de fissures Hertzien ou par la rupture en flexion du matériau. La cône de fissures Hertzien pour des échantillons de 1·0 mm d'épaisseur est agrandi suite à un effet d'écaillement. Pour des échantillons d'épaisseur variant entre 1·5 et 3·0 mm, la dégradation de la résistance a lieu au-dessus d'une vitesse d'impact de 380 m/s, également par formation d'un cône de fissures Hertzien. Il résulte de ces considérations que l'épaisseur de l'échantillon est relié au comportement à l'initiation de fissures responsables de la dégradation de la résistance à la rupture.

1 Introduction

Particle impact damage behavior is the most serious problem in ceramics for gas turbine use. Several studies have also focused on impact damage problems in ceramics applied to turbines,[1–6] because fracture is thought to be caused by flying particles which are generated in the combustion chamber. The phenomenon has been studied using Hertzian cone fracture theory based on the elastic stress analysis, and damage behavior is also analyzed based on elastic and plastic coefficients such as Young's modulus and hardness.[2,4]

In impact damage of ceramics, the studies using the Hertzian cone fracture theory attempted to define crack initiation and strength degradation of ceramics analytically.[2,3,7] On the other hand, a design approach defines the stress concentration on turbine vanes by the bending force generated with particle impact using a numerical and/or an analytical solution.[1,6]

From a practical perspective, defining the effective thickness and angle of the turbine vane presents a design problem, which is usually solved by optimizing aerodynamic efficiency. Although recent studies[8,9] have analyzed stress caused by foreign particle impact for different angles and thicknesses of blade, the thickness dependence of the impact damage and fracture behavior is still not fully understood.[9]

In this study, impact damage behavior of a silicon nitride ceramic for turbine use is studied as a model experiment which examines the impact damage for different thicknesses of blade. The thickness dependence of impact damage and fracture behavior shown by turbine ceramics was also examined.

2 Experimental Procedure

2.1 Materials

Commercially available gas-pressure-sintered silicon nitride (EC152; NGK Spark Plug Co., Komaki, Japan) was used in this study. Partially stabilized zirconia (PSZ; Toso Co., Tokyo, Japan) spheres, 1·0 mm in diameter, were used in the spherical impact test. Silicon nitride specimens, 50 mm × 8 mm × t mm (t = 1·0, 1·5, 2·0 and 3·0 mm in thickness), were polished with diamond paste to eliminate machining damage to produce flat and parallel surfaces. Material properties provided by the supplier are listed in Table 1.

2.2 Impact test[4]

The experimental apparatus is shown schematically in Fig. 1. A PSZ sphere was attached to the top of the plastic sabot (ABS plastic) and the sabot was set in the pistol on the apparatus. The gas pressure from an He gas cylinder was then allowed to rise to the specified level (3–5 MPa) in the chamber. The diaphragm was broken by the needle, permitting release of the gas toward the pistol, and thus driving the sabot to the end of the steel pipe, where its immediate stop ejected the sphere toward the target. One impact was made at each condition at room temperature.

The velocity of the PSZ sphere was analyzed by piezoelectric sensor attached on the stopper and specimen holder. The velocity was detected at each sabot firing, based on the time of flight principle.

2.3 Post-impact evaluation

After the impact test, surface damage to the silicon nitride was investigated by optical microscope and scanning electron microscope (SEM) analysis and the crater depth and diameter were measured by profilometer. A four-point bending test (inner span 10 mm, outer span 30 mm) with 0·5 mm/min cross-head speed was used to measure the bending strength. The impact site was set in the center of the outer span, so that the maximum tensile stress at bending was imposed on the area of damage. The fractured surface was also examined by optical microscope and SEM.

Table 1. Materials properties (suppliers' data)

Properties	*Target sphere*	
	Silicon nitride	*PSZ*
Density (g/cm³)	3·26	6·05
Poisson's ratio	0·26	0·3
H_v (GPa)	15·4	12·5
Young's modulus (GPa)	310	200
Band strength (MPa) (four-point bend test)	920	1100
K_{IC} (MPa$\sqrt{m}$) (indentation method)	6·0	7·5

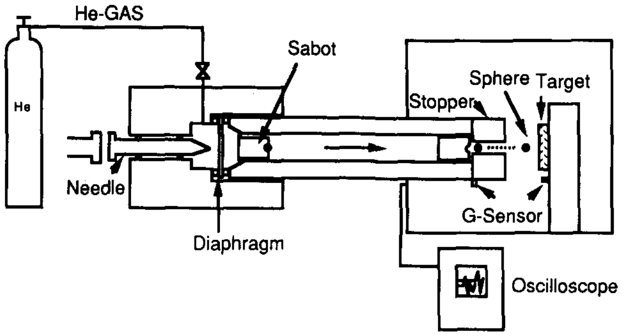

Fig. 1. Impact test apparatus.

3 Results and Discussion

Specimen surface damage after the spherical impact test was examined. Specimens 1·0 mm in thickness showed craters below 200 m/s. However, the specimens failed at an impact velocity above 247 m/s. Specimens 1·5–3·0 mm in thickness displayed craters at low velocity (< 220 m/s), ring cracks at intermediate velocity (220–250 m/s), and ring cracks and radial cracks at high impact velocity (< 350 m/s). These surface damage morphologies suggest that the ceramic response behavior varied according to the impact velocity and specimen thickness.

According to the Hertzian cone fracture theory[3] and other analyses,[2,7] the contact diameter ($2a$) can be calculated as

$$2a = 2(5/4\pi k\rho v^2)^{1/5}r \quad (1)$$

where

$$k = \frac{1-\nu_a^2}{E_a} + \frac{1-\nu_b^2}{E_b}$$

and where ρ, v and r are the sphere mass density, the impact velocity and the sphere radius, respectively, ν_a and ν_b are the Poisson's ratio of the target and sphere, and E_a and E_b are the Young's modulus of the target and sphere, respectively.

The theoretical contact diameter calculated from the Hertzian cone crack eqn (1) are compared with experimental data in Fig. 2. (Crater diameter was measured by profilometer assuming that it is close to contact diameters.[7]) Although the thicknesses of specimens were different, the experimental data for silicon nitride agree with the theoretical values, resulting in the accordance with the Hertzian cone fracture theory. Response behavior is assumed as an elastic, although shallow, crater (1–3 μm).

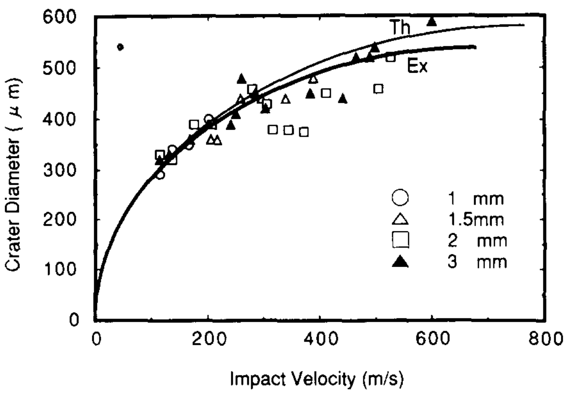

Fig. 2. Crater diameter versus impact velocity.

Figure 3 illustrates the post-impact bending strength of the silicon nitride for several specimen thicknesses. For specimens 1·0 mm in thickness, sudden fracture occurred at an impact velocity over 247 m/s. For 1·5–3·0 mm thick specimens, strength degradation occurred above a 380 m/s impact velocity. Since original strength data from supplier were measured using $4 \times 3 \times 40$ mm specimens, the average strength shown in Fig. 3 was decreased by the volume effect. Impact damage and strength degradation were found to be related to specimen thickness and resulted from crack initiation at impact.[8,9]

No small cracks under the impact site were observed, and therefore, the residual strength was maintained until the impact velocity approached a certain value which is denoted the critical impact velocity (V_c) for Hertzian cone crack initiation. It is supposed that the Hertzian cone crack abruptly expanded from a surface ring crack above V_c. Below V_c, a shallow crater (depth was 1–3 μm) was generated, but it is thought not to influence the residual strength.

Hertzian cone cracks under the impact site were detected (Fig. 4(A)–(C)) for all strength-degraded specimens.[4–8] For 1·0 mm thick specimens, the Hertzian cone crack radius was larger than that of 1·5–3·0 mm specimens. It is thought that the stress wave was reflected at the back face of the specimen and affected the stress level, resulting in sudden crack propagation near the back face.[10] For 1·0 mm thick

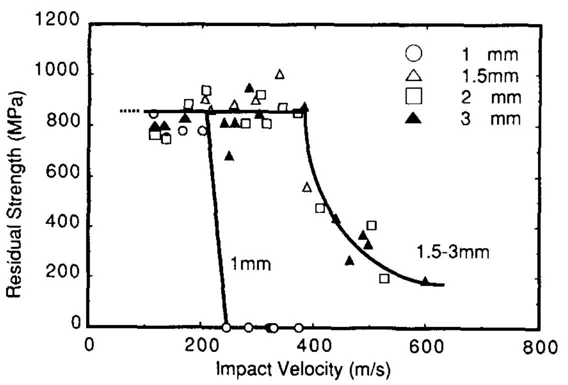

Fig. 3. Residual strength of impacted specimen.

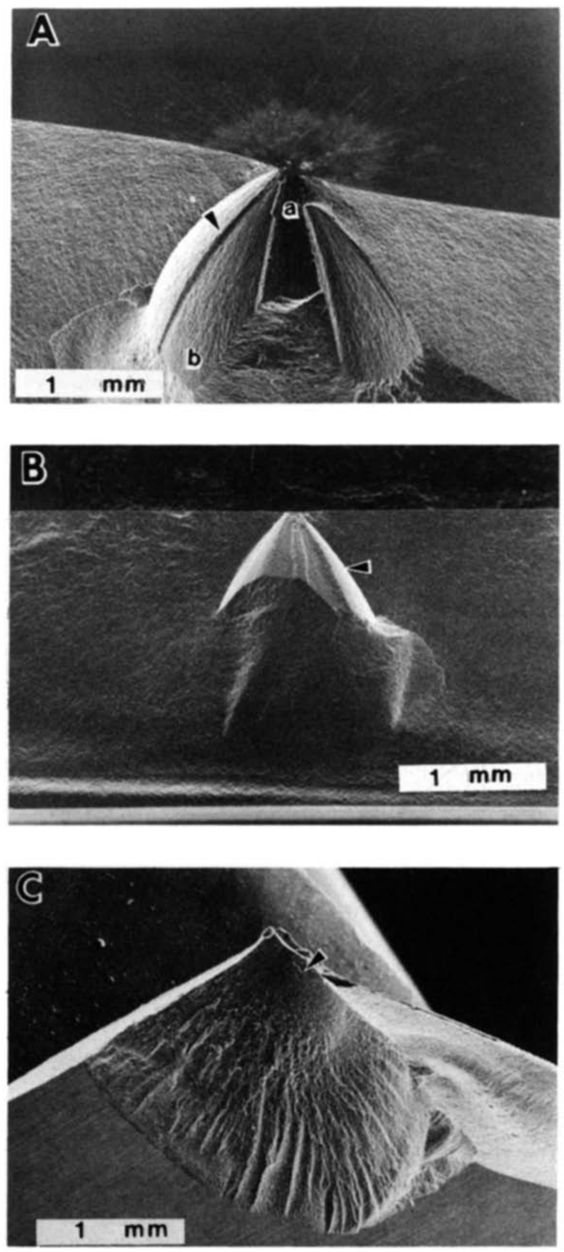

Fig. 4. Scanning electron micrographs of fractured surface (arrow: cone crack). (A) 3 mm thick specimen, $v = 600$ m/s; (B) 2 mm thick specimen, $v = 504$ m/s; (C) 1 mm thick specimen, $v = 320$ m/s.

specimens, bending fracture was also observed over 247 m/s impact velocity (Fig. 5), caused by the bending zone occurring on impact.[9] On the other hand, Hertzian cone cracks were arrested in specimens having a thickness of 1·5–3·0 mm.

The scanning electron micrograph (Fig. 6(A)) of the fractured surfaces of silicon nitride at an impact velocity of 504 m/s show that Hertzian cone cracks formed just under the craters, although the cone angle differed from the theoretical value (136°[11]). Figure 4(A) shows the origin of the cone crack produced by impact and the surface of the cone crack. The fractured surface on the cone crack changes from an intragranular fracture (Fig. 6(A)) to an intergranular fracture (Fig. 6(B)) when compared to the microstructure of failure during the bending

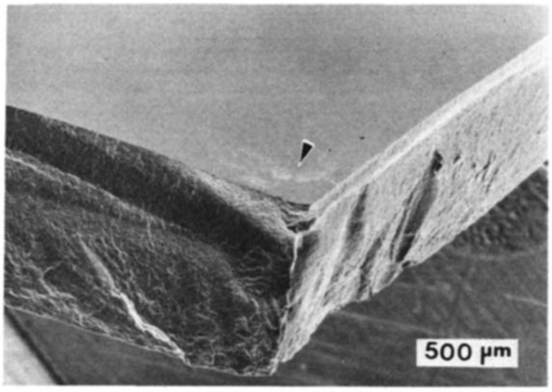

Fig. 5. Fractured surface by bending force of 1 mm thick specimen (impact velocity is 320 m/s; arrow: impacted site).

test. This result suggests that cone cracks formed catastrophically by impact were arrested in the specimen. In the figure, the fracture by bending test begins near the bottom of the cone, producing an intergranular fracture followed by an impact fracture. Since the bending test caused the failure of the specimen, which included the cone crack, the fracture produced by the bending test must have originated around the cone crack.

Crack size also affects residual strength and its effect can be evaluated using a standard equation of fracture mechanics ($\sigma_f = K_{IC}/\sqrt{\pi C_f}$). The cone crack diameter at the basal plane and cone angle (θ) of the strength-degraded specimens were measured (Fig. 7)

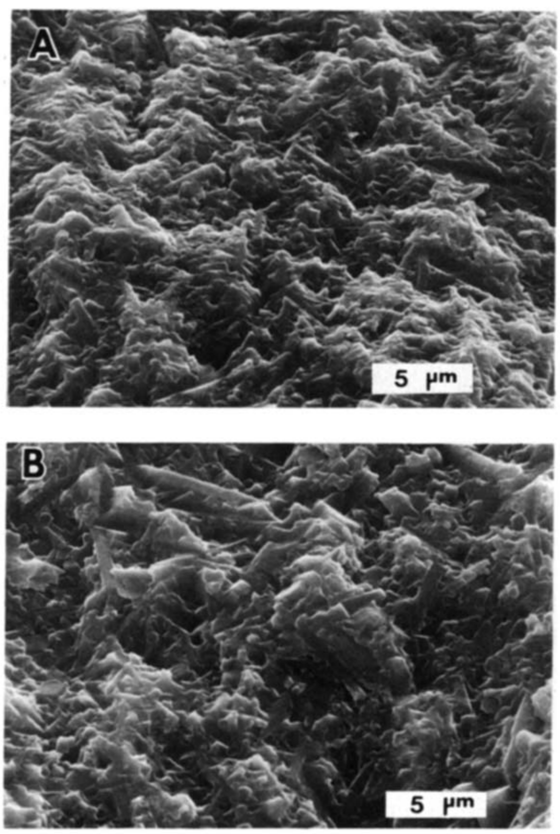

Fig. 6. Scanning electron micrographs of microstructure of the same cone as Fig. 4(A): (A) at the beginning of crack propagation; (B) at the end of crack propagation.

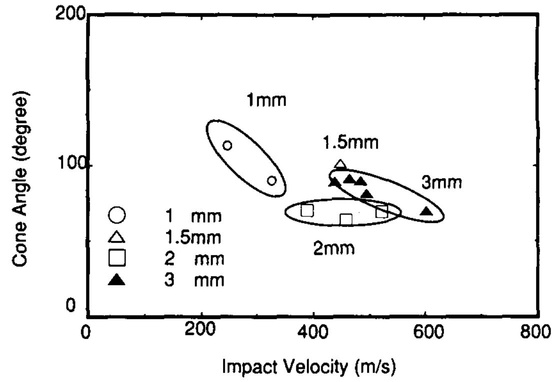

Fig. 7. Cone crack angle versus impact velocity.

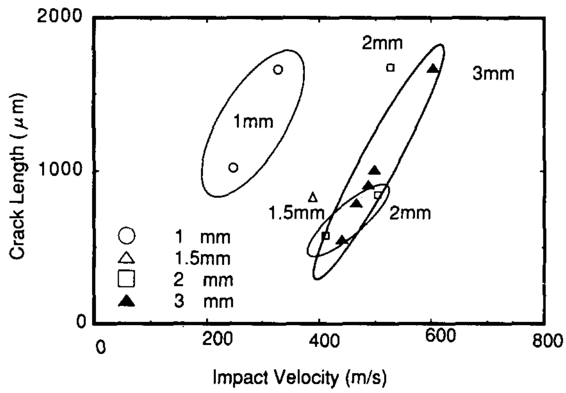

Fig. 8. Critical crack length calculated from cone crack shape for four types of specimens.

and converted to the critical crack length using the approximate solution of Lawn *et al.*[11] denoted as

$$C_f = \Omega(\alpha) \times R \tag{2}$$

$$\alpha(\text{degree}) = 90 - \theta/2$$

where C_f is critical flaw size for strength degradation, $\Omega(\alpha)$ is the conversion factor, α is the angle between the cone perimeter and the specimen surface, and R is the radius of the cone at the basal plane. The critical crack length depending on the thickness is shown in Fig. 8. It is thought that the differences in the critical crack length between the 1·0 mm thick specimen and the others is related to the scabbing effect resulting from reflection of the stress wave.[10]

4 Summary and Conclusions

The thickness of dependence of the impact damage behavior of a silicon nitride was investigated. For specimens 1·0 mm in thickness, sudden fracture occurred at an impact velocity of approximately 250 m/s with Hertzian cone crack and bending fracture. For 1·5–3·0 mm specimens, strength degradation occurred above a 380 m/s impact velocity with Hertzian cone crack. Hertzian cone crack geometry was converted to the critical flaw size for fracture, and it is thought that the scabbing effect occurs for 1·0 mm thick specimens because of the wide cone crack shape. Therefore, impact damage and strength degradation were found to be related to specimen thickness.

References

1. Cuccio, J. S. & Fang, H., Impact damage study of silicon nitride. In *Proceedings of the 26th Automotive Tech. Development Coordination Meeting*. Society of Automotive Engineers, PA, 1988.
2. Dao, K. C., Shockey, D. A., Seamon, L., Curran, D. R. & Rowcliff, D. J., Particle impact damage in silicon nitride. Annual Report, Part III, Office of Naval Research, Contract No. N00014-76-057, May 1979.
3. Hertz, H. R., *Hertz's Miscellaneous Papers*. Macmillan, London, England, 1896, Chapters 5 and 6.
4. Akimune, Y., Katano, Y. & Matoba, K., Spherical impact damage and strength degradation in ceramics for automobile turbocharger rotors. In *Proceedings of the 3rd International Symposium of Ceramic Materials and Components for Engines*, ed. V. J. Tennery. The American Ceramic Society, OH, 1989, pp. 1495–507.
5. Suzuki, A., Natsumura, T., Sugiyama, M., Teramae, T. & Hamada, S., Particle impact damage in silicon carbide. *Trans. Japan. Soc. Mech. Eng. (A)*, **56**(532) (1990) 2431–6.
6. Teramae, T. & Hamada, S., Fracture analysis of ceramics impacted by solid particles. *Trans. Japan. Soc. Mech. Eng. (A)*, **55**(520) (1989) 2423–6.
7. Liaw, B. M., Kobayashi, A. S. & Emery, A. F., Theoretical model of impact damage in structural ceramics. *J. Am. Ceram. Soc.*, **68**(8) (1983) 544–8.
8. Akimune, Y., Oblique impact damage of spherical particle on silicon nitride. *J. Am. Ceram. Soc.*, **73**(12) (1990) 3607–10.
9. Tsuruta, H., Masuda, M., Soma, T. & Makino, M., Foreign object damage resistance of silicon nitride and silicon carbides. *J. Am. Ceram. Soc.*, **73**(6) (1990) 1714–18.
10. Field, J. E., Sun, Q. & Townsend, D., Ballistic impact of ceramics. In *Proceedings of the 4th Int. Conf. Mech. Prop. Materials at High Rate of Strain*, ed. J. H. Haeding. Oxford, UK, 1989, pp. 387–94.
11. Lawn, B. R., Wiederhorn, S. M. & Johnson, H. H., Strength degradation of brittle surfaces: blunt indenters. *J. Am. Ceram. Soc.*, **58**(9–10) (1975) 428–32.