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Damage behaviour of silicon nitride for automotive gas turbine use when impacted by several types of spherical particles

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Spherical particle impact damage and strength degradation phenomena of silicon nitride by several types of spheres were analysed in comparison with chipping fracture behaviour reported in the literature. It was found that steel and partially stabilized zirconia (PSZ) particles caused Hertzian cone cracks, resulting from the elastic response of the material in accordance with the Hertzian cone crack theory. In contrast, alumina and sialon particles induced both median–radial crack systems at low impact velocity range and Hertzian cone cracks at high impact velocity range. The critical impact velocity for strength degradation, V_c, correlated with the hardness of the spheres and target ceramics, and V_c, for Hertzian cracks and median cracks were higher than that for chipping fracture.

1. Introduction
Particle impact damage is one of the most critical problems displayed by ceramics in actual applications, such as gas turbine use [1, 2]. Several studies [3–6] based on the Hertzian cone crack theory [7] have focused on impact damage problems in silicon nitride ceramics when applied to turbines. Crack initiation and the formation of a plastic zone under the impact site have been studied using both elastic and elastic–plastic approaches for quasi-static and dynamic conditions [8–12]. Studies have also been made of strength degradation due to particle impact [13]. These investigations have led to a better understanding of damage behaviour and its relationship to material properties, and that knowledge has begun to be applied to materials design for ceramic turbines. However, in recent research work on fracture problems in gas turbines, it has been noted that more experimental and analytical data on impact damage are needed to design materials for application to turbine and adjacent components [1, 14].

For impacts of the same types of impacting particles, the response behaviour and failure behaviour of a ceramic target are reported to be related to the properties of the target material, such as its hardness [4, 6]. Studies have also been presented which described differences in damage behaviour according to two [1] and three types of impactors [6]. The relationship between damage under the impact site and material properties of the impactors has not been fully explored. Since Cook and Pharr have implied that there is no general theory to explain response and damage behaviour [12] in designing practical turbine component shapes, it is essential to analyse the impact damage behaviour of a silicon nitride turbine when impacted by several types of particles, under the assumption that adjacent components generate fragments and an oxide scale [14]. In this study, the impact damage behaviour of silicon nitride for turbine components was studied in comparison with earlier research [4, 6, 15] that focused on hardness.

2. Experimental procedure
2.1. Materials
Commercially available gas-pressure-sintered silicon nitride (EC152: NGK Spark Plug Co Ltd Komaki, Japan) was used in this study. Steel, partially stabilized zirconia (PSZ: Toso Co. Ltd, Tokyo, Japan), alumina, sialon (Shinagawa Refractories Co Ltd, Tokyo, Japan) and carbon (GCP: Unitika Co. Ltd, Kyoto, Japan) spheres 1.0 mm in diameter, the size used in the literature [4], were used as impactors in spherical impact tests to obtain consistent results. Silicon nitride specimens, $50 \times 8 \times 3$ mm, were polished with diamond paste [6 and 3 μm] to obtain flat and parallel surfaces by eliminating machining damage. The material properties are listed in Tables I and II, and were taken from suppliers catalogues.

2.2. Impact test and post-impact evaluation
The experimental apparatus used a helium gas pistol, and the test procedure was almost the same as that described in the literature [3, 4]. In this case, the velocity of the PSZ spheres was detected by piezoelectric accelerometers attached to the stopper and specimen holder. The velocity was measured at each sabot firing, based on the time-of-flight principle. This test was conducted at room temperature.

TABLE I Properties of silicon nitride target

Density (g cm^{-3})	3.26
Poisson's ratio	0.26
Hardness (GPa)	15.4 ± 0.4
Young's modulus (GPa)	305
Bending strength (MPa)	912 ± 110
Fracture toughness (MPa m)$^{1/2}$	7.0 ± 0.3

TABLE II Properties of impactors

	Steel	PSZ	Al_2O_3	Sialon	Carbon
Density (g cm^{-3})	7.86	6.05	3.88	3.23	1.5
Poisson's ratio	0.3	0.3	0.23	0.27	0.1
Hardness (GPa)	7.0	12.5	18.0	16.0	3.0
Young's modulus (GPa)	200.0	200.0	370.0	320.0	10.0

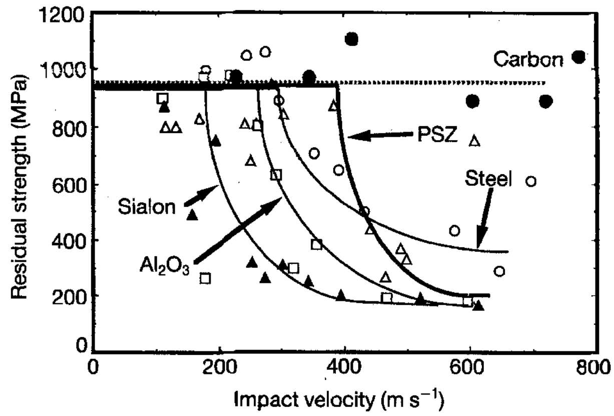

Figure 1 Residual strength of target after impact indicating critical impact velocity for strength degradation: (○) steel, (△) PSZ, (□) alumina, (▲) sialon, and (●) carbon.

Surface damage and subsurface cracks were investigated under a scanning electron microscope (SEM). A four-point bending test (inner span 10 mm and outer span 30 mm) was conducted at a crosshead speed of 0.5 mm min^{-1} to measure the residual bending strength.

3. Results and Discussion

3.1. Strength degradation

Fig. 1 shows the residual strength of the specimens after impact in relation to the impact velocity. Strength plots were connected in order to extrapolate the average strength level. An examination of the fracture surfaces revealed cracks initiation, and the results are shown in Fig. 2a–e. With the steel spheres, a Hertzian cone crack (Fig. 2a) was initiated in strength degraded specimens. The critical impact velocity, V_c, for strength degradation and also for Hertzian cone crack initiation was 330 m s^{-1}. With the PSZ spheres (Fig. 2b), the V_c for strength degradation was 383 m s^{-1}.

Although alumina and sialon (Fig. 2c, d) spheres produced Hertzian cone cracks in the high impact velocity range (> 500 m s^{-1}), two types of cracks were observed at intermediate impact velocities (300–500 m s^{-1}) depending on the response behaviour. Median–radial cracks (Fig. 3a) caused by elastic–plastic behaviour [8, 9] were observed in the low impact velocity range (< 300 m s^{-1}). Median cracks were generated by flaws at the deformation zone boundary [12], extending the boundary and then causing strength degradation behaviour. However, in the intermediate and high impact velocity range, Hertzian cone cracks (Fig. 3a and b) were initiated. With these two impactor materials, the V_c for strength degradation differed from that for Hertzian cone crack initiation. However, no cracks were observed under the impact site for specimens impacted by the carbon sphere (Fig. 2e). The presumed reason for this is that the sphere velocity was less than the critical impact velocity for both bending fracture [1] and Hetzian cone cracking [4] in the case of this target and sphere combination.

The following assumptions have been made regarding crack initiation and response behaviour caused by alumina and sialon spheres.

1. Median cracks (Fig. 3a) were initiated first as a result of the elastic–plastic stress field formed at the sphere indentation at low impact velocities. In this impact velocity range, the stress level at impact was lower than that for Hertzian cone crack initiation [2, 3].

2. At intermediate velocities, a Hertzian cone crack (Fig. 3b) was initiated at a very early stage by the elastic stress field that formed before the sphere entered the target. Subsequently, the stress field changed to an elastic–plastic one resulting in a median crack [11].

3. At high impact velocities, a Hertzian cone crack (Fig. 3c) was initiated at a very early stage by an elastic stress field [8, 14]. The cracks almost reached the back surface and since the stress field could not change to an elastic–plastic one, only Hertzian cone cracks were formed [3, 5].

The velocity calculated for Hertzian cone crack formation using the equation proposed by Wiederhorn and Lawn [13] was compared with the experimental results (Table III), the V_c values for Hertzian cracks were found to be in close agreement. This suggests that an elastic stress field was generated in each material in the intermediate to high impact velocity range. However, median cracks were initiated at lower velocities than Hertzian cracks in the case of the alumina and sialon spheres. Hertzian cone cracks were critical for steel and PSZ spheres, but median cracks were critical for alumina and sialon spheres.

3.2. Relation between material properties and damage behaviour

Response behaviour (Fig. 4) resulting in strength degradation due to crack initiation has been shown to be related to the contact situation using the hardness ratio between the spheres and the target, H_p/H_t, [2, 3, 6, 15]. The H_p/H_t ratio [3] determines the response behaviour. Elastic response occurred when the ratio was less than 0.8, and both elastic–plastic and elastic

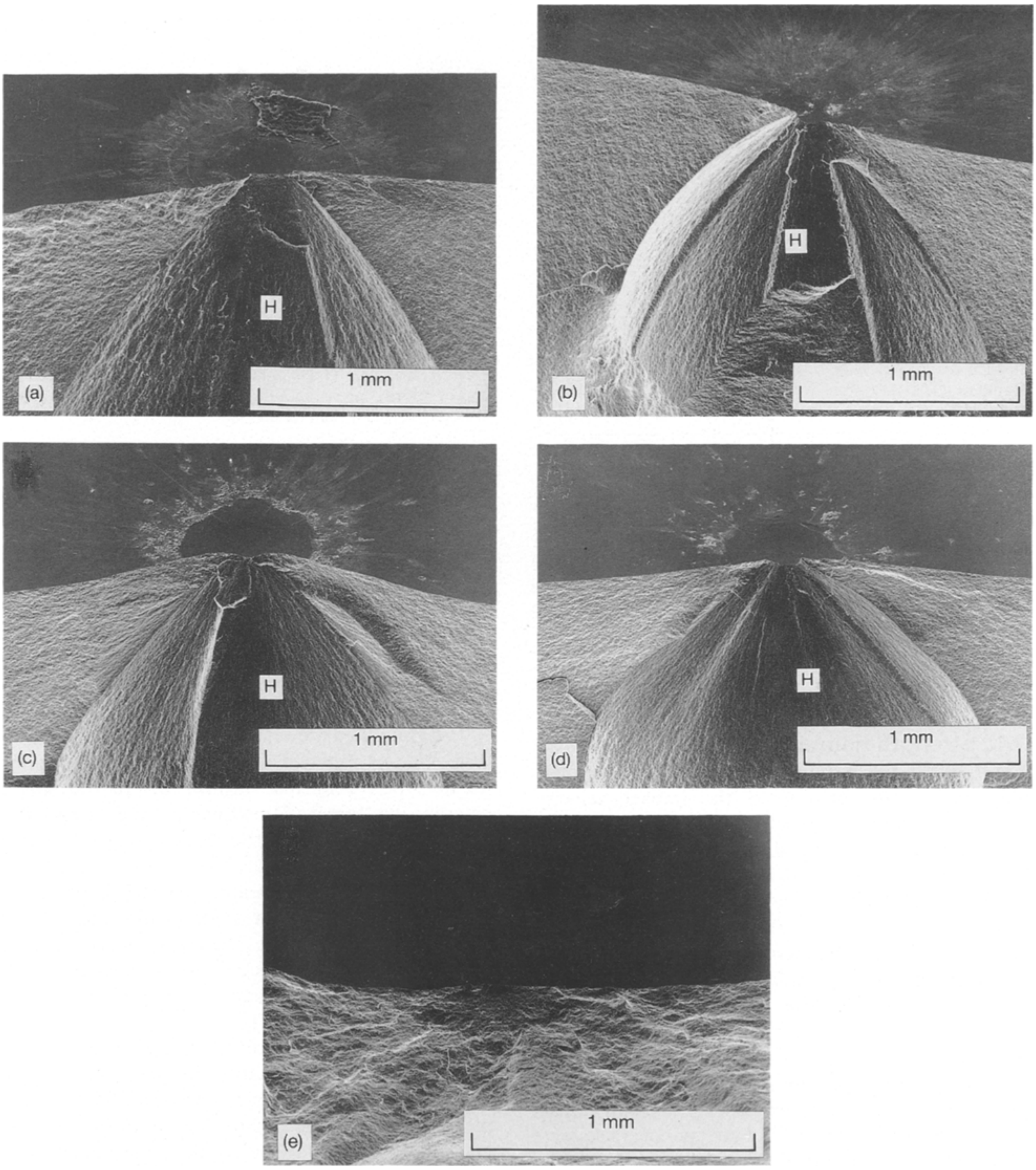

Figure 2 Fractured surfaces after high speed impact showing Hertzian cone cracks except (e). (H: Hertzian cone crack under the impact site.) (a) steel sphere, $V = 646\ \mathrm{m\,s^{-1}}$; (b) PSZ sphere, $V = 600\ \mathrm{m\,s^{-1}}$; (c) alumina sphere, $V = 595\ \mathrm{m\,s^{-1}}$; (d) sialon sphere, $V = 520\ \mathrm{m\,s^{-1}}$; (e) carbon sphere, $V = 728\ \mathrm{m\,s^{-1}}$.

responses occurred when it was over 1.0. Response behaviour changed according to the H_p/H_t ratio and impact velocity. These ratios differed from the values cited in the literature [6, 15]; but as suggested by Cook and Pharr [12], crack and damage morphologies are completely material dependent and correlate closely with the ratio of Young's modulus and hardness. Therefore, further study is needed to define this relationship more accurately.

A comparison with results from the literature [6] is shown in Fig. 4. As reported in the literature [6], chipping caused a half size Hertzian cone crack, when the whole sphere was impacted within the target. Contact behaviour differences causes a different stress state, and the stress level resulted in different crack initiation velocity. Chipping fracture may be generated by a lower load and impact velocity resulting from stress concentration. Therefore, half Hertzian cracking (chipping crack) is assumed to be generated at a lower velocity level than that of complete Hertzian cracking.

4. Conclusions

A silicon nitride ceramic was impacted by spherical particles of steel, PSZ, alumina, sialon and carbon to investigate its impact damage behaviour. It was found that steel and PSZ particles caused Hertzian cone

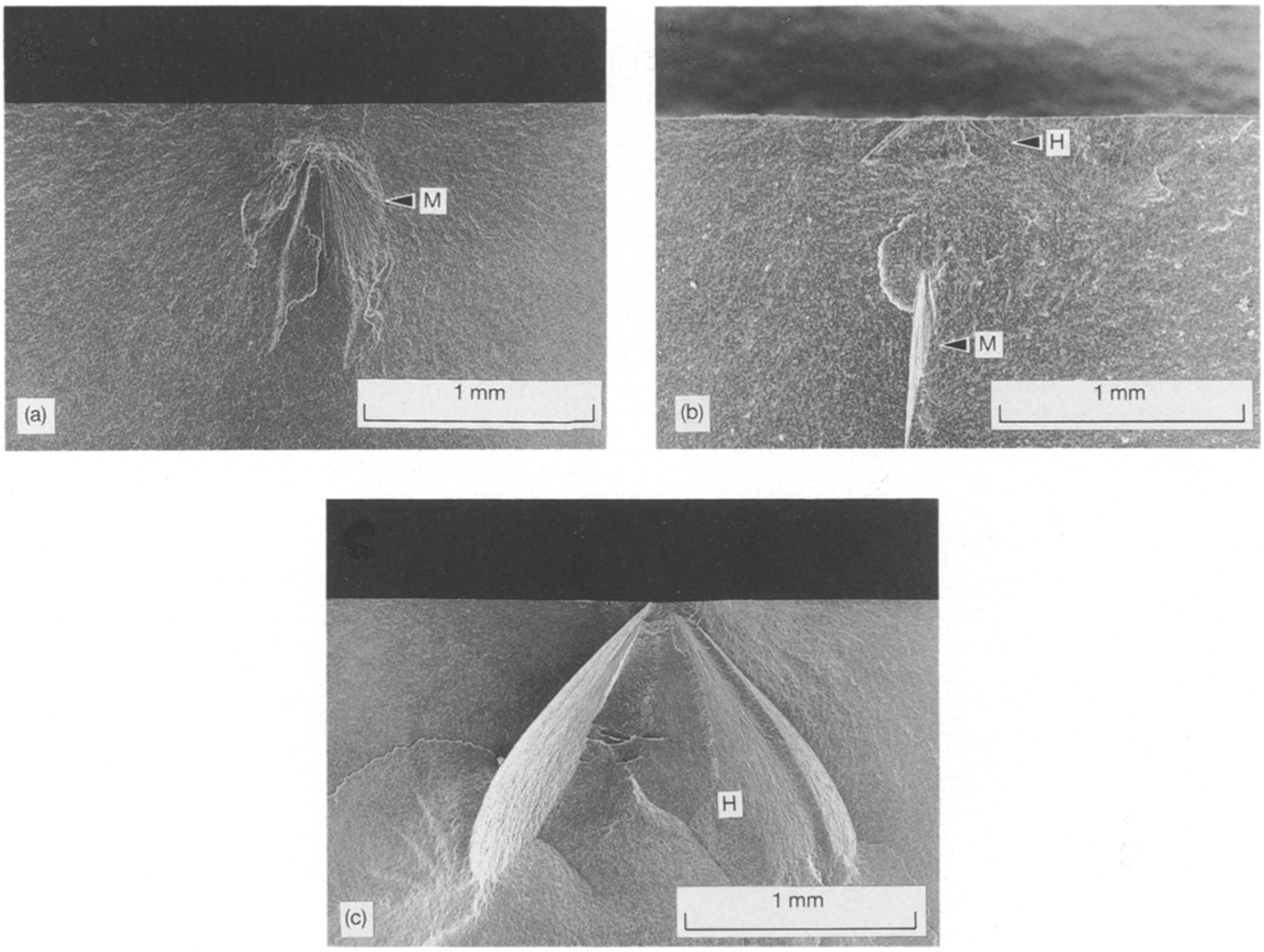

Figure 3 Crack morphology change with impact velocity for alumina spheres: (a) median M, crack at $V = 319\ \mathrm{m\,s^{-1}}$, (b) Hertzian, H, and median cracks at $V = 356\ \mathrm{m\,s^{-1}}$, (c) Hertzian crack at $V = 467\ \mathrm{m\,s^{-1}}$.

TABLE III Comparison of calculated and experimental critical impact velocities

	Critical impact velocity, V_c (m s^{-1})		
Sphere material	Hertzian crack (calculated)	Hertzian crack (experimental)	Median crack (experimental)
Steel	334	330	–
PSZ	360	383	–
Al_2O_3	327	356	275
Sialon	400	394	190
Carbon	960	–	–

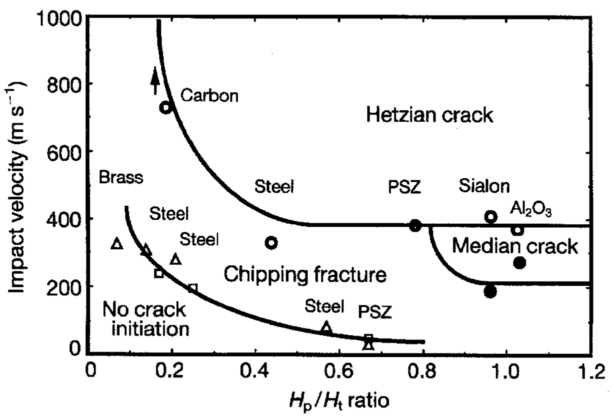

Figure 4 Response behaviour in relation at H_p/H_t and impact velocity: (○) Hertzian cracking, (●) median cracking, and (△, □) chipping cracking from Tsuruta *et al.* [6].

cracks resulting from the elastic response of the material in accordance with the Hertzian contact theory. In contrast, alumina was sialon particles induced median–radial crack systems showing elastic–plastic response in the intermediate velocity range, and also induced Hertzian cone cracks resulting from elastic response in the high impact velocity range. Differences in response behaviour were related to the material hardnesses of the spheres and the ceramic target. The critical impact velocity for Hertzian cracks and median cracks was found to be higher than that of chipping fracture.

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