ICF100996OR

Temperature Dependence of Damage Behavior in a Silicon Nitride for Gas Turbine by Spherical Particles

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ABSTRACT

Model experiment for examining impact damage dependence on temperature is conducted on silicon nitride. It was found that steel and zirconia(PSZ) spheres caused Hertzian cone crack, resulting from the elastic response of the material in accordance with the Hertzian cone crack theory at the room temperature. In contrast, alumina and sialon spheres induced both median-radial crack system at low impact velocity range and Hertzian cone crack at high impact velocity range.

At the elevated temperature, the experimental results indicate that a generated crack system changes from a Hertzian cone crack to median crack in accordance with the experimental temperature change for the case of PSZ spheres. It is explained that the hardness degradation at 1200℃ generated a change in the stress field from elastic/plastic to plastic, resulting from softening of grain boundary glassy layer for silicon nitride. We can conclude response behavior change in the relation of Ht/Hp ratio caused by temperature change.

KEY WORDS

Impact Damage, Elastic Response, Elastic/Plastic Response, Hertzian Cone Crack, Median Crack, Silicon Nitride

1. Introduction

It has been known that in ceramics, owing to its brittle nature, cracks extended under localized load or stress may trigger instantaneous fracture. A typical example of this effect is fracture in a ceramic blade of gas turbine caused by impact of oxide scale particles, which has been recognized as one of serious problems [1,2].

For impacts of the same types of impacting particles, the response behavior and failure behavior of a ceramic target are reported to relate to the properties of the target material such as its hardness [3,4]. Studies have also been presented which described differences in damage behavior according to two types [2] and three types of impactors [4]. The relationship between damage under the impact site and material properties of the impactors and target has not been fully explored. Shockey et al.[5] have used a silicon nitride (Si_3N_4) specimen with a tungsten carbide (WC) spheres, and demonstrated elastic repulsion remaining ring cracks on the surface at the room temperature, which turned into elastic-plastic response impressing radial cracks on the surface at high temperatures, however, they did not mention about internal cracks.

The present study concerns a model experiment in which oxide scales striking at the turbine blade are simulated by four types of particles shot to Si_3N_4 specimen at the room temperature and by zirconia particle at 1200℃. In this way, the temperature dependence of impact damage is evaluated by comparing damage morphology at the room temperature with that at 1200℃.

2. Experiment on Impact Damage with Particles

2.1 Materials Preparation

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 (Shinagawa Refractories Co., Ltd., Tokyo, Japan), and sialon (Shinagawa Refractories Co., Ltd., Tokyo, Japan) spheres 1.0 mm in diameter, the size used in the literature [4], were used as impactors. Silicon nitride specimens, 50x8x3 mm, were polished with diamond paste [6 μ m and 3 μ m] to obtain flat and parallel surfaces by eliminating machining damage. The material properties are listed in Tables 1 were taken from suppliers catalogs.

A disk-shaped specimen of 14 mm diameter and 2.0 mm thickness was used for high temperature test. And its surface was polished with diamond paste [6 μ m and 3 μ m] to eliminate machining damage.

2.2 Particle Impact Experiment

The experimental apparatus used a helium gas pistol and the test procedure was almost the same as that described in the literature[6]. The velocity was measured at each sabot firing based on the time-of-flight principle using piezoelectric sensor. The impact damage was examined by means of the fluorescence flaw detection, followed by morphological observation of surface craters and internal cracks under an optical microscope and by measurement of crater diameter and depth by use of a needle-probe profilometer.

A schematic diagram of the impact apparatus is shown in Fig. 1, which consists of a particle launcher of gas-gun type and a specimen holder installed in a furnace [7]. A target, Si_3N_4 disk, is mounted in the specimen holder within the furnace and the same impact test was conducted at 1200℃. As an impact sensor cannot be used in the high temperature experiment, the impact velocity is to be read from a working curve with velocity calibrated against helium gas pressure. In the present experiment, the impact velocity was available in 500 m/s.

3. Experimental Results

3.1 Surface Damage and Internal Crack

With the steel spheres and PSZ spheres Hertzian cone cracks (Fig. 2B) were initiated high impact velocity range over 330 m/s & 383m/s, respectively. Although alumina and sialon (Figures 2C, 2D) spheres produced Hertzian cone cracks in the high impact velocity range (>500m/s), two types of cracks were observed at intermediate impact velocities (300-500m/s) depending on the response behavior. Median/radial crack (Fig. 3) caused by elastic/plastic behavior [8,9] were observed in the low impact velocity range (<300m/s).

In view of materials parameters listed in Table 1, the ratio of target hardness (Ht) to particle hardness (Hp) for steel and zirconia spheres, i.e., Ht/Hp, is >1.25, which is within a range to produce elastic response. The ratio(Ht/Hp) of sialon and alumina, its become less than 1.0, response behavior becomes elastic-plastic response with median crack formation.

On the other hand, when the target was impacted with particles at 500 m/s velocity and at 1200℃, the surface damage consisted of a porous zone and radial cracks (Fig. 4 (A)), while the internal crack was composed of median crack (Fig. 4 (B)) representing the elastic-plastic response. According to the parameter list in Table 1, the ratio Ht/Hp was 0.75, falling in a range of elastic-plastic response (Ht/Hp < 1.0) [5,7].

3.2 Measurement of Impact Damage to Define Response Behavior

3.2.1 Crater Diameter

The morphology of impact damage at the surface of the target was measured by using a needle-probe profilometer.(Fig.5) The good agreement of experimental values at the room temperature with theoretical ones suggests a state of contact where the materials give elastic response. At 1200℃, however, the crater size was somewhat greater than the calculated values, which may be attributed to larger contact diameter associated with deeper penetration of spheres into the materials. The calculation formula derived from Hertz's theory is as shown below [10],

$$D_a = 2R(5\pi V^2 \rho k/4)^{1/5} \tag{1}$$

where D_a stands for contact diameter [m], k is given by $k = (1 - \nu_1^2)/E_1 + (1 - \nu_2^2)/E_2$ [GPa^{-1}], ν_1 is Poisson's ratio of target material, ν_2 Poisson's ratio of sphere, R is sphere diameter (= 500 μm), E_1 is Young's modulus of target material, E_2 Young's modulus of sphere (listed in Table 1), ρ is density of sphere (ρ =6.05 x 10^3 kg/m^3), and V is impact velocity of sphere.

3.2.2 Crater Depth

The crater depth was 1 to 4 μm at the room temperature, while that at 1200℃ was 8 to 13 μm (Fig. 6). Data at the room temperature demonstrates experimentally the occurrence of plastic deformation, though as small as a few μm, in contradiction to Hertzian contact theory, where no plastic change is admitted. While a small plastic deformation may affect the elastic stress field [5], the agreement of ring crack morphology at the surface with the contact area shown in Fig. 5 suggests the formation of elastic stress field just like that predicted from the theory.

On the other hand, the morphology of internal crack at high temperatures (median crack) indicates that the spherule penetrates into the materials by 8 to 13 μm in the course of time from coming in contact with the surface to collapse of sphere, probably owing to softening of glassy phase at the grain boundary of materials. Consequently, the materials take elastic-plastic stress state, forming a median crack and a porous zone immediately below it with intersecting micro-cracks [11].

4. Response Behavior depending on Temperatures

The Hp/Ht ratio [3] determines the response behavior. Elastic response occurred when the ratio was less than 0.8, and both elastic/plastic and elastic responses occurred when it was over 1.0. Response behavior changed according to the Hp/Ht ratio and impact velocity. These ratios differed from the values cited in the literature [4,5], 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.

At high temperatures, as the hardness of materials is reduced, resulting in Ht/Hp ratio smaller than 1.0 median cracks are formed through the elastic-plastic rebound. This effect may be attributed to change in the response behavior of materials softened at high temperatures, into which a sphere of room temperature is shot (Fig. 7).

5. Conclusion

In the present study, damage caused by the bombardment of ceramic sphere was examined in model experiment of impact caused by oxide scale hitting the actual turbine blade. It was found that steel and PSZ particles caused Hertzian cone cracks resulting from the elastic response of the material in accordance with the Hertzian contact theory. In contrast, alumina and 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. When a zirconia sphere was shot into a target of silicon nitride, the damage in the target was Hertzian cone crack at the room temperature, while it turned into median crack at 1200℃. This may be attributed to change in response behavior to impact from elastic to elastic-plastic, owing to reduced hardness caused by softening of glassy phase at the grain boundary of silicon nitride at 1200℃.

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Table.1. Material Properties

	Si3N4		PSZ	Steel	Al2O3	Sialon
	RT	1200 ℃	RT	RT	RT	RT
Density ($\times 10^3$ Kg/m^3)	3.26	3.26	6.05	7.86	3.88	3.23
Poisson's Ratio	0.25	0.25	0.3	0.3	0.23	0.27
Young's Modulus (GPa)	318	296	200	200	370	320
Vicker's Hardness (GPa)	15.0	9.0	12.0	7	18	16

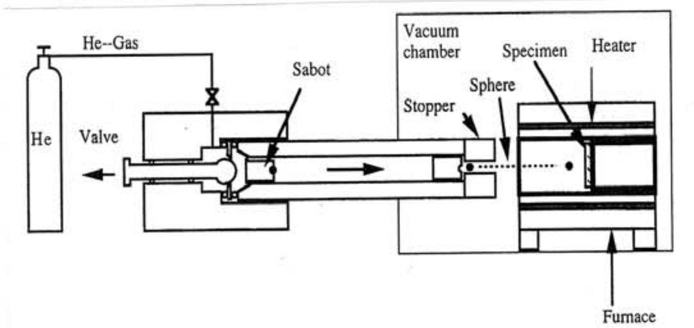
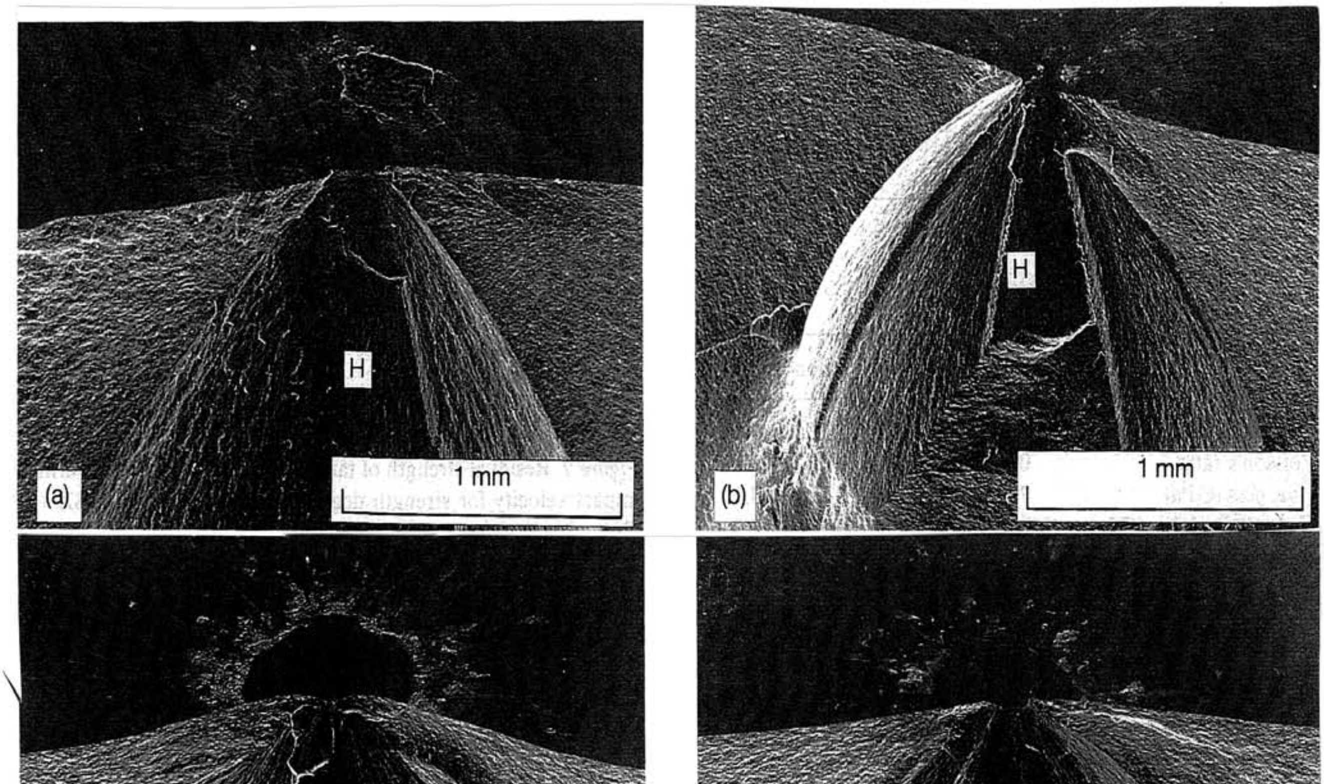


Fig.1. Experimental apparatus for high temperature test.



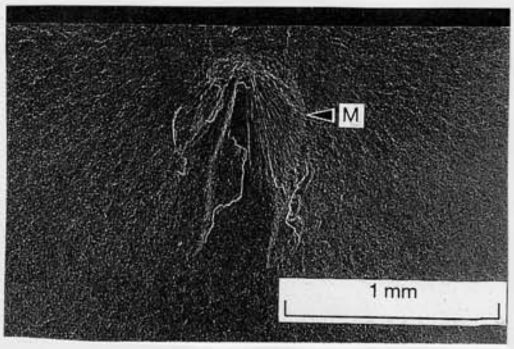


Fig.3. Medial/Radial cracks

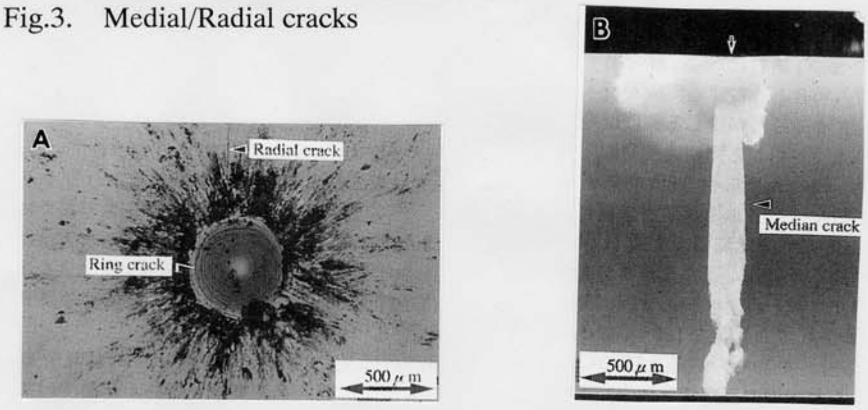


Fig.4. Surface Damage tested at 1200℃ (A Radial Crack, B: Median cracks)

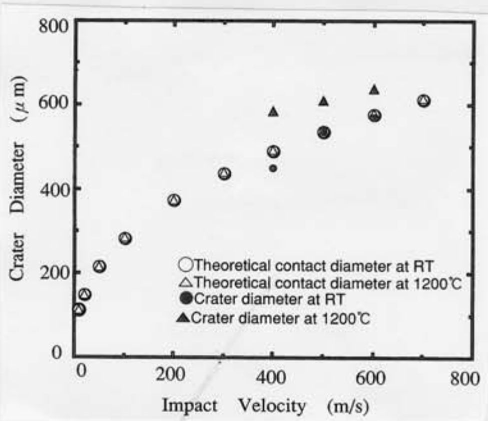


Fig.5. Crater Diameter

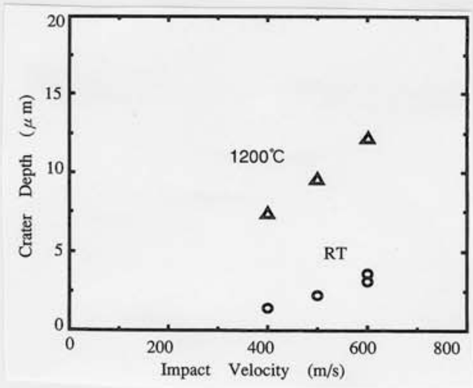


Fig.6. Crater Depth

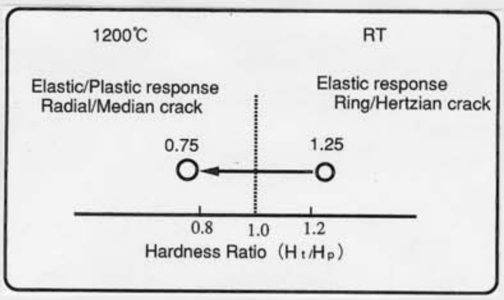


Fig.7. Response Behavior Change with temperature