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Estimation of foreign-object damage to silicon carbide plates by silicon nitride spherical projectiles

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Abstract

This study experimentally and numerically investigated the damage extension of a brittle monolithic silicon carbide plate in response to the high speed impact of a projectile. An out-of-plane impact of a silicon nitride sphere with a velocity of 50 to 600 m/s induced multiple ring cracks on the contact surface. A crater, a cone crack, and a median crack were observed in the cross section under the contact point. The generation and extension of the damage were numerically studied based on linear fracture mechanics. A dynamic stress analysis using the finite element method demonstrated that the distribution of the principal axis corresponding to the maximum principal stress aligned radically from the contact point to induce a circular crack on the surface.

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1. Introduction

Monolithic ceramics have superior mechanical properties such as high temperature strength, corrosion resistance, and wear resistance compared to conventional metals and have been employed in roller bearings [1]. However, the brittleness of ceramics has restricted other practical applications.

Recently, research and development projects have been conducted on ceramic gas turbines to improve their

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efficiency [2,3]. A higher turbine inlet temperature achieved higher efficiency in a turbine engine, and silicon nitride was employed in high temperature components such as turbine nozzles and blades. To practically use these ceramic components, reliability should be ensured to support the various loadings that occur in gas turbines. Previous studies [4,5] pointed out that foreign object damage (FOD), along with low creep and corrosion resistance, were critical issues for a ceramic turbine. Certain particles (foreign objects) are generated in the combustion gas and strike the ceramic components. Cracks can then be generated because of the brittleness of ceramics. Furthermore, the notch sensitivity of brittle materials is extremely high, and even minor damage could cause catastrophic failure of the component. Accordingly, FOD resistance became the key parameter for ceramic components.

Various experiments have been reported on impact damage in ceramics. Ceramic plates were impacted by small spheres, and the impact damage and the degradation of the residual strength were discussed [6,7]. Sherman and Ben-Shushan [8] investigated the effect of the restriction conditions and the plate thickness on FOD in alumina plates. Choi et al. [9,10] studied the relationship between FOD and the residual strength in some types of silicon nitrides, and suggested that fracture toughness is the key parameter for resistance to FOD. Moreover, they indicated that typical FOD consisted of ring cracks, radial cracks, and cone cracks, and that the combination of these cracks was independent of the impact velocity. Impact (point load) induced damage in ceramic coatings has also been investigated, and ring cracks and cone cracks were observed in the coating [11,12]. This damage pattern is similar to that caused by quasi-static contact with a sphere. In the case of indentation, the stress distribution and the damage pattern were discussed based on Hertz's contact theory [13,14]. Licht et al. [15] investigated generation of cone cracks based on the energy release rate during the extension of preexisting defects. In recent years, numerical simulations on ballistic impact have been analyzed based on the finite element method. Espinosa et al. [16] discussed the influence of the material parameters of ceramic/steel laminates on their penetration characteristics. Ballistic impact behavior was also predicted in steel plates [17] and ceramic matrix composites [18]. Zuo et al. [19] studied the impact damage in a ceramic plate wrapped with titanium. They predicted the generation of some micro cracks and damage like cone cracks in the ceramic.

However, to our knowledge, few studies have reported on dynamic extension of FOD in monolithic ceramics. Moreover, the previous studies on ballistic impact focused on the penetration and the impact energy at the penetration limit. The damage extension in the target has been overlooked, although this damage extension is essential for quantitatively evaluating the absorbed impact energy. Thus, the mechanisms of damage extension in ceramics due to high speed impact still remain unclear.

The purpose of this study is to clarify the mechanisms of FOD in monolithic ceramics. To this end, we experimentally and numerically investigated the damage process in silicon carbide plates impacted by silicon nitride spherical projectiles. Generation and extension of cracks near the impact point is predicted based on a criterion involving linear fracture mechanics. Second, the predicted FOD pattern clearly correlates with that observed in the experiment, a result that had not been reproduced in previous studies. The mechanisms of FOD are discussed through these experiments and simulations.

2. Experiment

2.1. Materials and experiment procedures

The material used was pressureless sintered silicon carbide (SiC). The plate specimen was 20 mm long, 10 mm wide and 5 mm thick. The specimen surface was polished with diamond slurry to achieve a roughness of less than 1 μm. A silicon nitride (Si_3N_4) sphere with a diameter of 1.58 mm was used as a projectile. The mechanical properties of the plate and the sphere are listed in Table 1. Here, the fracture toughness was evaluated by the indentation fracture method, where a crack was induced by a Vickers hardness test and the fracture toughness was calculated

Table 1 Material properties of the silicon-carbide plate specimen and silicon-nitride projectile

Material	Young's modulus (GPa)	Poisson's ratio	Density (kg/m3)	Fracture toughness (MPa·m0.5)
SiC	410	0.17	3313	4.0
Si_3N_4	194	0.25	3265	7.6

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