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Contact strength and crack formation in monolithic ceramic materials

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ABSTRACT

The paper deals with the strength meaurement and characterization of strength data of monolithic Si_3N_4 and SiC ceramics using unconventional contact tests between opposite rollers and opposite spheres. The results are compared to the results of conventional four-point-bending test. Ceramographic and fractographic methods are used for the characterization of strength degrading defects represented by processing flaws and by cracks of different types arising during the loading. The processing flaws influenced the Weibull parameters mainly in the bending mode, and the strength and its scatter in contact modes was influenced by lateral, median and contact end cracks, originating during the contact test using rollers, and by cone cracks originating during the contact test using spheres. The influence of the radius of the spheres on length and an angle of the cone cracks has been determined too.

1. Introduction

Silicon nitride and silicon carbide based ceramics are promising materials for a wide range of practical applications due to a unique combination of mechanical properties (e.g. hardness, wear resistance, high-temperature strength, corrosion resistance, etc.) [1]. These materials have been developed for the last few decades with the aim to optimize their final mechanical properties such as strength, fracture toughness, creep behavior, etc. [2,3]. The relationship between the processing, microstructure and fracture/mechanical properties, reliability and lifetime was investigated in detail at different mechanical loading configuration and in different environments using different testing methods [4,5].

Strength of ceramic materials is usually determined by three- or four-point-bending tests representing standard experimental techniques to induce a quasi-uniaxial stress state with insignificant stress gradients [6–8].

On the other hand, mechanical loading within practical applications is often represented by a multi-axial and non-homogeneous stress state with significant stress gradients. During the last decades numerous authors investigated the character of the damage introduced during the Hertzian indentation in glasses and different monolithic and composite ceramics [9–15]. A great advantage of the Hertzian indentation test is that the deformation in the substrate produced by the indenter is wholly elastic until fracture occurs and the complications associated with the residual stresses do not exist. Various forms of cone cracks are observed and analyzed in brittle materials when conical, spherical, or cylindrical indenter are used the so-called ‘Hertzian cone crack’. Lawn has investigated cone cracks developing from the free surface in spherical indentation [10,11] and method for determination of the fracture toughness of brittle materials based on the length of the induced cone cracks from a spherical indentation tests was suggested in [12,13]. Hertzian indentation technique was used to measure surface flaw sizes on polished ceramics and fracture toughness of different ceramics [14]. The finite element method has been used by Kocer and Collins [15] to model the growth of cracks in the Hertzian stress fields and was found that the angle of the cone crack, as grown in the model, is in excellent agreement with observations on experimentally grown cone cracks in glass, with the same Poisson’s ration.

The multi-axial and non-homogeneous stress state can be induced by line or point contact loading obtained by two opposite rollers or spheres, respectively. Application of symmetric sphere loading leads to even better defined mechanical boundary conditions compared to the flat supported specimen loaded by one sphere only. Fett et al calculated the stress solution for loading between opposite rollers and successfully applied the rollers on

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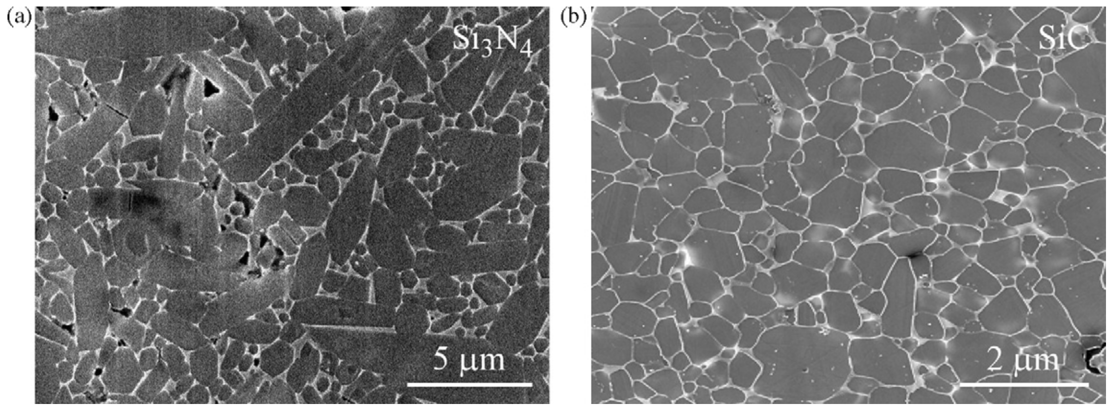

Fig. 1. SEM micrographs of microstructure of Si_3N_4 plasma etched (a) [21,22], and SiC plasma etched (b).

rollers and spheres on spheres contact strength techniques for the characterization of the strength and fatigue of brittle materials, mainly based on alumina [16–20].

The aim of this paper is the measurement and characterization of strength data of monolithic Si_3N_4 and SiC ceramics using unconventional contact tests between opposite rollers and opposite spheres and to compare the character of the fracture origins in these ceramics during the different types of applied loades.

2. Experimental

Two monolithic ceramics have been investigated. Silicon nitride, with additives of 3% Al_2O_3 and 3%Y_2O_3, sintered in atmosphere of N_2, produced by CeramTec (Plochingen, Germany) [21,22]. Silicon carbide SiC, prepared as a mixture of the commercially available β-SiC powder (HSC-0.59, Superior Graphite) with additives of 3%Al_2O_3, and 6%Y_2O_3, hot pressed at 1870°C/1 h in atmosphere of N_2, and subsequently annealed at 1650°C/5 h, prepared at the Institute of Inorganic Chemistry, Slovak Academy of Sciences, in Bratislava.

The microstructure of the investigated materials has been studied using scanning electron microscopy of the polished and etched samples.

Specimens used for mechanical tests were cut by diamond tools, ground and consequently polished to 1 µm finish and the specimen edges were chamfered to the radius 0.15 mm to minimize the stress concentration effect. The number of the specimens used for the strength tests varied from 10 to 30. All mechanical tests were performed in air, at room temperature, and at crosshead speed of 0.5 mm/min.

The contact test using rollers was performed with standard hardened steel rollers with the diameter $D = 3$ mm applied to specimens with the dimensions $W = 3$ mm, $B = 4$ mm, L = 10–15 mm in such way that the load P increased up to a critical value to cause failure of the specimens. The strength σ_{cont} was determined by the equation [16,17]

$$\sigma_{cont} = \frac{0.98P}{tW}. \tag{1}$$

At some specimens the load was stopped at the level of approximately 90% of maximum load and the specimens were examined with the aim to study indentation damages.

The contact test using standard hardened steel spheres with the radius $R = 2, 2.5, 3.5$ mm was applied to specimens with dimensions $W = 3$ mm, $B = 4$ mm, $L = 25$ mm. Two types of tests have been used. In the first, specimens were tested by increasing load to a critical value which causes the failure of specimens. In second, specimen were tested by an increasing load which was stopped at $P = 4.9$ kN before the critical value, i.e. before failure of specimens, with the aim to investigate the character of cracks originating during the applied load. These specimens after the test were cut through a centre of a contact surface, ground and polished for the determination of the crack length c and the angle α of the cone crack.

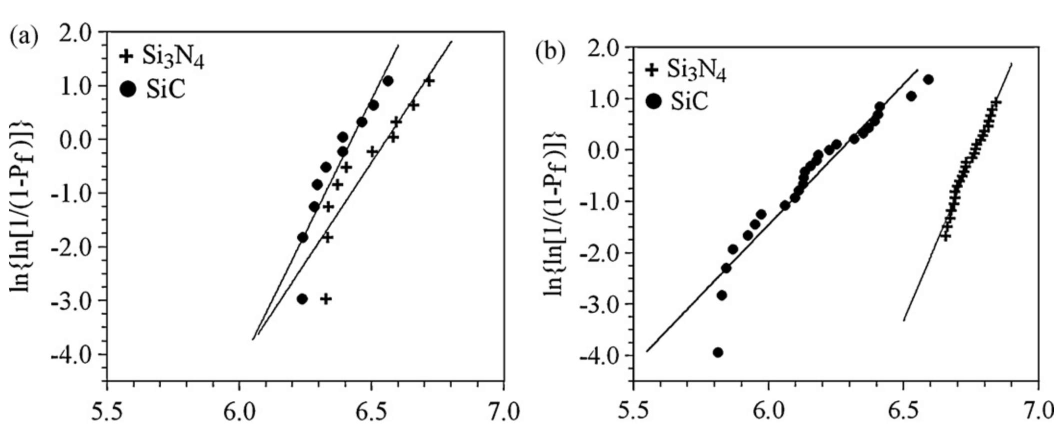

Fig. 2. The Weibull distribution of the strength σ_{cont} [MPa] (a) and σ_{bend} [MPa] (b) related to the contact test using opposite rollers and to the four-point-bending test for the investigated materials, respectively.