THERMAL SHOCK FRACTURE BEHAVIOR OF CERAMICS CHARACTERIZED BY DISK-ON-ROD TESTS

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ABSTRACT

New experimental technique for evaluating the thermal shock fracture characteristics of ceramic materials, ***Disc-on-Rod test***, was developed. The specimens have thin disc shape and the 2-dimensional thermal stress field was then obtained. The specimen was heated to high temperature and quenched by means of contacting with the cool metal rod with 4 mm diameter. The temperature distribution of specimen was measured by a high-speed IR camera (30 frames/s) and used for the determination of thermal stress field in specimen using FEM analysis. In order to evaluate the fracture process, AE signals during thermal shock fracture were also detected using an AE sensor attached on the end of the metal rod. It was observed by the video camera system that the maincrack was initiated at the center region subjected to the maximum balanced biaxial stress. On the other hand, the initiated crack was propagated, arrested and re-propagated after several seconds, which showed good agreement with the result of AE analysis.

KEY WORDS

Ceramics, Disc-on-Rod Test, Thermal Shock Fracture, Maincrack Formation, Crack Propagation

INTRODUCTION

The thermal shock fracture behavior of ceramics has been investigated using many traditional thermal-shock-testing methods. One of the most popular thermal shock tests is the water quench [1,2]. The critical temperature difference, where samples are subjected to severe damage, is used as the criterion for the thermal shock resistibility of ceramics. Recently, new experimental methods are proposed and applied to the investigation of thermal shock fracture behavior, based on fracture mechanics [3-5]. However the characterization of microfracture process under thermal shock as well as transient thermal stress field is indispensable, since thermal shock fracture is caused by the accumulation of microscopic damages such as microcrackings due to thermal stress.

In this study, new experimental technique for the investigation of thermal shock fracture behavior, Disk-on-Rod test, is proposed. The temperature fields in the specimen were measured and used to calculate the 2 dimensional thermal stress field. Furthermore, fracture process was evaluated by AE measurement. The formation of maincrack due to propagation and/or microcracks was focused in the present paper. Especially, the critical stress for maincrack formation is evaluated from obtained experimental data and compared with the results of mechanical biaxial bending tests. Consequently, thermal shock fracture process in ceramics was well understood.

EXPERIMENTAL PROCEDURE

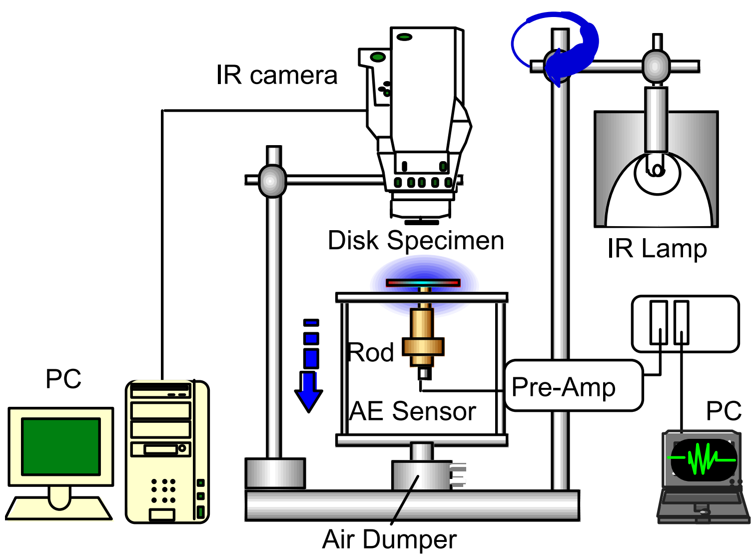
Materials

Two kinds of alumina ceramics (Material A and B) were used in the present study. Material A (own-making) was sintered from high purity alumina powder using a hot-press at 1650 ˚C for 2 hours under the pressure of 40MPa in Ar atmosphere. Material B (ADS-11) was offered from Toshiba Ceramics Co., Ltd. The relative density and mean grain size were 99.3% and 20 μm for Material A, and 97.7% and 6 μm for Material B, respectively. Disk specimens were cut from the rod materials and both surfaces were polished.

Disk-on-Rod Tests

In this study, for characterizing the thermal shock fracture process, new experimental technique, Disk-on-Rod test was developed. A thin disk specimen was heated to the required temperature by an infrared lamp and only the central part of disk was quenched by means of contacting with a Cu rod. The disk specimens have diameter of 20 mm and thickness of 0.6mm, and a contacting area has 4 mm diameter, therefore 2-D thermal stress field was obtained. The apparatus of Disk-on-Rod test and AE measuring system are shown in Figure 1 schematically. Contacting speed was controlled by an air damper to restrain the generation of AE noise due to contacting. And temperature distributions on disk surface were measured by a high-speed infrared camera (30 frames/s). Then thermal stress was calculated from the measured temperature distribution using FEM analysis.

In order to evaluate the fracture process, AE signals during thermal shock fracture were detected by AE sensor attached on the bottom end of metal rod, which was used for both coolant and wave guide. AE sensor, in which amplifier is instrumented, with resonant frequency of 180 kHz was used, then the initiations of microcracks could be detected with excellent sensitivity. The total gain of the AE system was 75 dB (main amplifier; 20 dB and pre-amplifier with sensors; 55 dB) and the threshold level was 40 dB, i.e.18 μV at the input terminal of the pre-amplifier. AE signals were measured by AE analyzer, sent to a computer and analyzed.



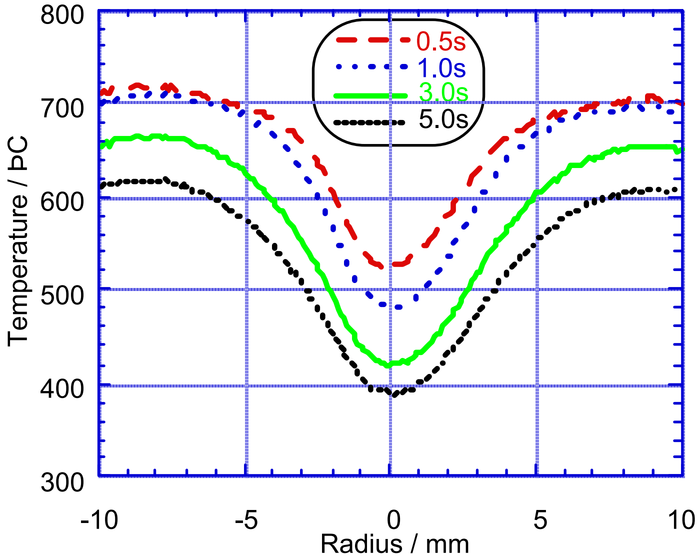


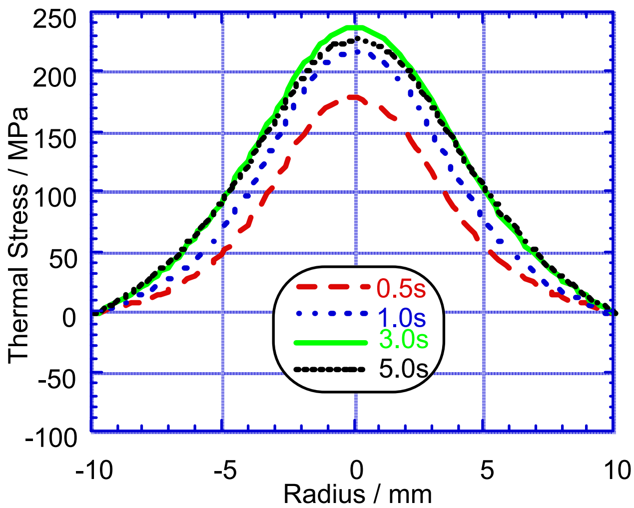
Figure 2: Temperature Distribution during Disk-on-Rod Test of Material B

RESULTS AND DISCUSSION

Determination of Thermal Stress

The temperature on specimen surface was measured by 1/30 s using a high-speed infrared camera system during Disk-on-Rod test and concentric temperature field was obtained. Figure 2 describes the temperature distribution along the specimen diameter for Material B. It can be seen in the figure that there are large temperature gradient in the disk by contacting the metal rod and this gradient becomes maximum at 3s and decreased gradually.

The thermal stress field was computed from the obtained 2-dimensional temperature distribution using FEM code (ANSYS; isoparametric structural shell, 2977 elements, 6082 nodes). The obtained stress field was axi-symmetric according to the concentric temperature distribution. The determined temperature fields were shown in Figure 3 (a), radial stress, and (b), tangential stress. It is understood from the figure that equi-biaxial maximum stress is subjected at the center of the disk and the stresses decrease to the outer region along the radial direction. It is important that radial stress is tension in the whole of disk specimen, while tangential stress has the transition point from tension to compression at 4mm from the center of the disk. Both stresses show the maximum at 3s.



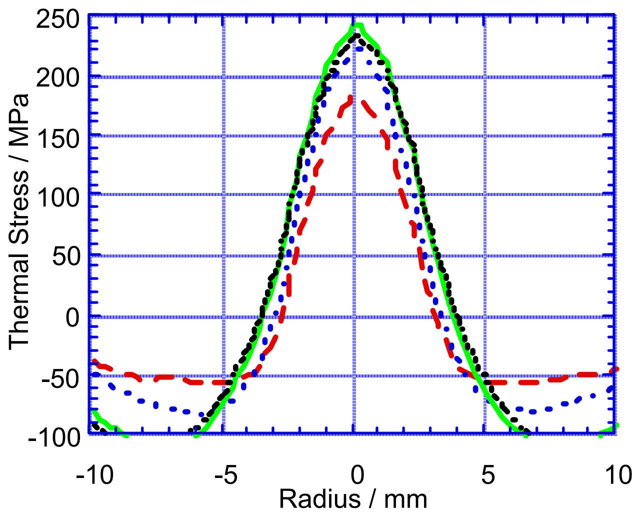


Figure 3: Thermal Stress during Disk-on-Rod Test of Material B.

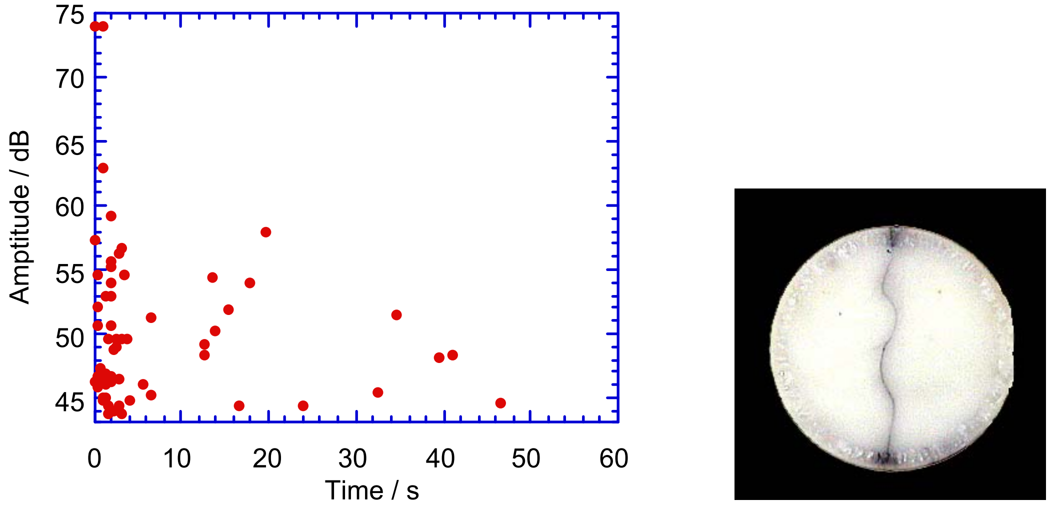


Figure 4: Thermal Stress and AE Behavior during Disk-on-Rod Test and Fractured Specimen.(Material A)

(a) Thermal Stress and AE Behavior (b) Fractured Specimen

Fracture Behavior during Disk-on-Rod Tests

AE behavior during Disk-on-Rod test of Material A and fractured specimen are shown in Figure 4. In Figure 4 (a), each plot indicates the detected time and amplitude of each AE event. A large number of AE events were detected at 0 – 7s as thermal stress increased. It is important that there are incubation period at 7 – 12s and secondary generation after 12s. AE activity before incubation period is higher than secondary AE. It is then suggested that the crack propagation rate before incubation period is higher. The disk specimen (Material A) after Disk-on-Rod test is shown in Figure 4 (b). It is observed in the figure that maincrack was formed along radial direction at the center of the disk and propagated to the outer region with the deflection to tangential direction, which shows good agreement with the thermal stress field (Figure 3).

On the other hand, Figure 5 shows AE behavior during Disk-on-Rod test of Material B and a fractured specimen. It is recognized in Figure 5 (a) that both cumulative AE events and energy increase remarkably at 1.5 s. Since the formation of maincrack was observed at the AE increasing point, it is understood that the critical stress for maincrack formation during thermal shock fracture, σ_{th}, can be determined by Disk-on-Rod test. Those values for Material B ranged from 250 to 300 MPa. It is worth noting that the incubation period and secondary activity in AE behavior was not observed for Material B.

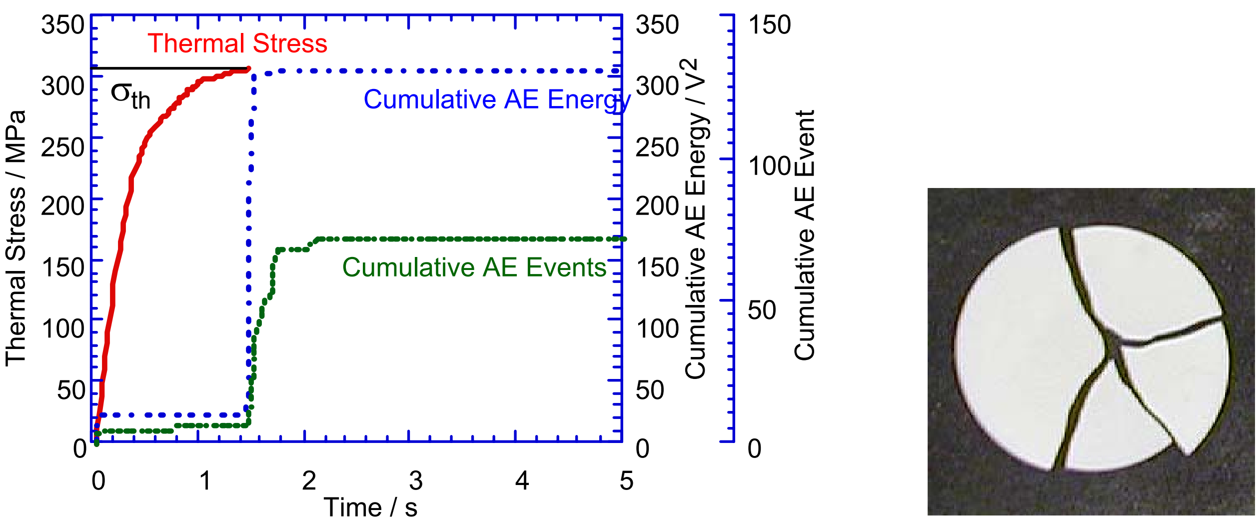


Figure 5: Thermal Stress and AE Behavior during Disk-on-Rod Test and Fractured Specimen.(Material B)

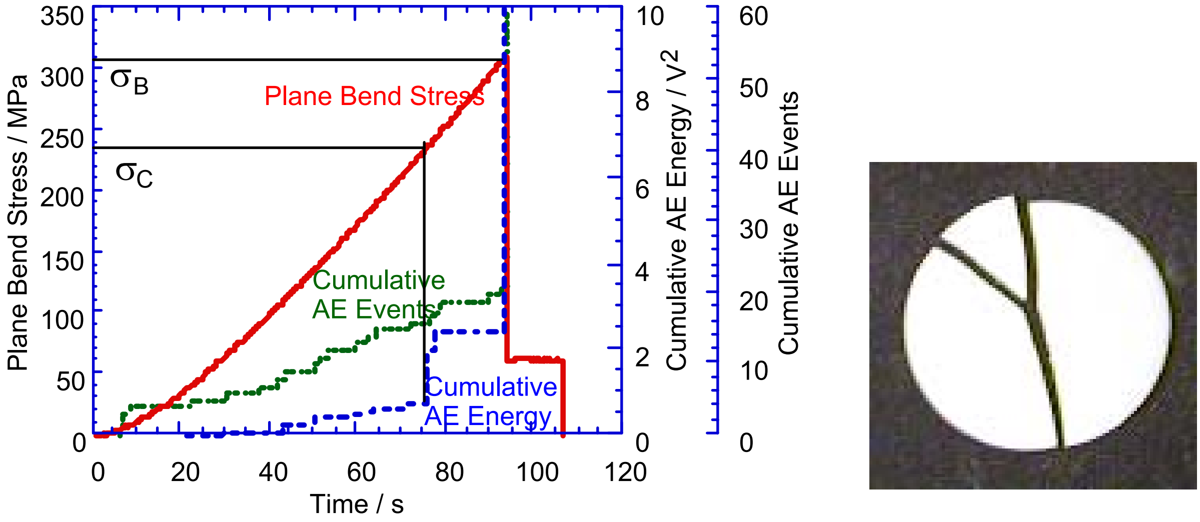


Figure 6: Result of Plane Bending Test and Fractured Specimen.(Material B)

The observation of crack path in fractured specimen shown in Figure 5 (b) demonstrates that the deflection of maincrack in Material B is much smaller than Material A and specimen separated into 4 pieces. Therefore it is suggested that the crack propagation in Material B is unstable, while that in Material A is stable (Figure 4 (b)), that might be resulted from the difference in the strength of both materials as mentioned in the following section.

(a) Plane Bending Stress and AE Behavior (b) Fractured Specimen

Facture Process under Thermal Shock

In order to investigate the critical stress for maincrack formation, the plane bending tests were carried out using same geometry specimens and a loading rod with 4mm diameter. Figure 6 shows the result of plane bending test of Material B and a fractured specimen. Similarly to the thermal shock fracture, it is observed in Figure 6 (b) that the maincrack was initiated at the center region of the specimen subjected to equi-biaxial stress. In Figure 6 (a), the AE increasing point can be observed before maximum bending stress, therefore it is understood that the critical stress for maincrack formation under mechanical loading, σ_C, can be determined. Those critical stresses for Material B were evaluated as 180 – 240 MPa; those are lower than the critical stress for maincrack formation under thermal shock as mentioned above. Considering the influence of stress corrosion cracking due to water during bending test at room temperature, it can be concluded that the critical stresses for maincrack formation under thermal shock and mechanical loading are equivalent to each other.

On the other hand, the critical stress for maincrack formation under biaxial mechanical loading was estimated as 80 – 150 MPa elsewhere [6]. Therefore, the strain energy released at the formation of maincrack during thermal shock fracture in Material B may be higher than Material A, which result the deference in crack propagation behavior during Disk-on-Rod tests; stable for Material A (Figure 4) and unstable for Material B (Figure 5).

In the case of Material A, the crack path in outer region is parallel to radial direction although the calculated tangential stress in the outer region was compressive (Figure 3 (b)). Therefore, stress field must be redistributed. It was considered from the incubation period of AE from 7 s to 12 s in the Figure 4 (a) that stress redistribution was not caused by mechanical stress redistribution because mechanical stress redistribution might be caused instantaneously. Therefore, it caused by the redistribution in temperature due to the disturbance of heat flow by maincrack. Consequently, thermal shock fracture process in Material A was understood as followings.

(1) Microcrackings were initiated at the center of the disk due to the thermal shock. Maincrack was then formed by equi-biaxial maximum stress due to the coalescence and propagation of the microcracking.

(2) The maincrack was deflected to the tangential direction due to the radial stress as the maximum principal stress and propagated at high speed.
(3) The crack arrested by the tangential compressive stress at the outer region of the disk.
(4) The temperature and the thermal stress were redistributed and maincrack re-propagated to radial direction by redistributed tangential tensile stress.

It is expected that larger specimen yield the similar fracture process for Material B. Consequently, it should be emphasized that the whole process associated with thermal shock fracture suggested by the unified theory of Hasselman [2], i.e. crack initiation, arrest and propagation, can be characterized during simple Disk-on-Rod test.

CONCLUSIONS

In the present study, new experimental technique, Disk-on-Rod test, was developed and applied to the characterization of thermal shock fracture process in ceramics. The thermal stress fields were computed from temperature distributions measured by high-speed IR camera and fracture process was evaluated by AE measurement, both of which are significant for understanding the thermal shock fracture behavior. From these results, the following conclusions were obtained.

(1) The maincrack was formed at the center of disk specimen subjected to maximum equi-biaxial stress.
(2) The critical stress for maincrack formation was evaluated and it was almost equivalent to the critical stress for maincrack formation in plane bending test.
(3) Thermal shock fracture process consisting of crack initiation, propagation and arrest was well understood.

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