Strength Evaluation of Sintered Silicon Nitride Ceramics by means of a New Test System at Elevated Temperatures*

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A test system for precisely evaluating the tensile strength of ceramics at elevated temperatures was newly developed. Four-point bending and tensile tests were performed on sintered silicon nitride ceramics in the temperature range from room temperature to 1300°C. The track of a ductile fracture was observed on the fractured surfaces of the tensile specimens tested at temperatures above 1100°C, suggesting the occurrence of plastic deformation. The fracture stress of bending specimens was about 1.18 ~ 1.43 times as large as that of tensile specimens. The test temperature dependency, however, was very similar in both the fracture stresses throughout the entire test temperature range. The fracture toughnesses from tensile and bending specimens were almost the same in the test temperature range from R. T. to about 800°C. The fracture toughness obtained from the chevron-notch-type specimen was almost coincident with that from the Knoop-indented specimen in the temperature range from R.T. to 900°C. There was, however, some difference at temperatures above this, suggesting the occurrence of adhesion at the crack tip in the Knoop-indented specimen.

Key Words: Silicon Nitride Ceramics, Laser-Beam-Type Extensometer, Elevated Temperatures, Flexural Strength, Fracture Toughness

1. Introduction

The application of engineering ceramics to the components of machines operated at high temperatures such as gas turbines and diesel engines, cannot be extensively promoted until their mechanical properties can be precisely evaluated at temperatures over 1000°C. Nevertheless, at present, reliable data on these are greatly lacking. This seems mainly due to the difficulty of the stress/strain measurements in such a temperature range.

The fracture toughness has been evaluated by means of a variety of test methods. Chevron-notch-type specimens⁽¹⁾, specimens⁽²⁾ precracked with the hardness tester's indenter and double torsion-⁽³⁾ and double cantilever-⁽⁴⁾ type specimens were developed for ceramics.

Bending tests using specimens precracked with the hardness tester's indenter have been extensively per-

formed for measurement of the fracture toughness since they are quite simple⁽⁵⁾⁽⁶⁾. The size of the precrack is commonly small, and indentation-induced residual stress is produced in the specimen; therefore the reliability of the indentation-test method is problematic in obtaining correct fracture toughness. The bending test using a chevron-notched specimen^{(1)(7)~(11)} is recognized as a fairly simple and reliable method for the fracture toughness measurement. The correlation between the fracture toughnesses measured by means of the two tests has not been adequately elucidated.

Ceramics inherently contain numerous small inclusions and pores, and fractures nucleate at these sites. Fractures caused by self-contained defects have therefore been discussed in connection with the fracture toughness^{(6)(12)~(14)}.

The phenomena mentioned above have not been sufficiently elucidated at room temperature, much less at elevated temperatures. In the present study, we developed a new test system for engineering ceramics which enables us to evaluate their mechanical properties in the temperature range from 700°C to 1500°C. It is constituted of a closed-loop-type loading system,

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a laser-beam-type displacement measuring system, and a heating system composed of an electric-resistance-type heating furnace and its precise control unit. Bending tests were performed for a smooth specimen with self-contained defects, a specimen precracked with the Knoop hardness tester's indenter, and a chevron-notched specimen, which were machined from sintered silicon nitride ceramics. Four-point bending tests were performed for these specimens at room and elevated temperatures using this test system. Then, the flexural strength and the fracture toughness were discussed in comparison with the data obtained from respective specimens at elevated temperatures.

2. Test System and Test Procedures

2.1 Newly developed test system

Figure 1(a) shows the general view of the test system which was newly developed for evaluating the deformation and strength of engineering ceramics at elevated temperatures up to 1500°C. The closed-loop-type electrohydraulic test system was employed for loading. The present test system was characterized by

(a) General view

(b) Detailed view of jig and specimen set up for four-point bending test

Fig. 1 Newly developed test system

the laser-beam-type displacement measuring system with which it was equipped.

The electric-resistance-type heating furnace has two windows; the laser beam enters the furnace through one of them, reaches the set-up specimen, and then exits through the second window. The temperature variations were kept within one percent of the set-up temperature in the range of 1.0 cm above and below the center of the mounted specimen, and within a radius of 1.5 cm.

A view of the specimen set up for the four-point bending test is shown in Fig. 1(b). The loading device is constructed of two blocks and four pins machined from silicon-nitride and silicon-carbide ceramics, respectively.

The displacement, δ , of the specimen tested under four-point bend loading at a test temperature over 1000°C was precisely measured using the laser-beam-type extensometer. Figure 2 is the schema showing the method of this measurement. The laser beam emitted from the irradiator (A) passes through the aperture between the top of the specimen and the bottom of the upper jig, and then reaches the receiver (B). The size of the aperture decreases as the applied load increases, decreasing the amount of the laser beam passing through the aperture. Thus, the receiver (B) continuously picks up the change in the amount of the laser beam passing through the aperture and transforms this into the displacement. We can calculate the strain generated at the top and bottom surfaces of the rectangular cross-sectional bar specimen from the displacement through the following equation obeying the elementary mechanics:

$$\epsilon = (3 \cdot \delta \cdot h) / (3l^2 - l_1^2), \quad (1)$$

where h is the height in the rectangular cross section of the bar specimen, and l_1 and $2l$ are the distances

Fig. 2 Arrangements of specimen and laser-beam-type displacement meter for measuring displacement yielded under four-point bend loading. The arrangement of loading and supporting pins for four-point bend testing of smooth and indented specimens is also described

between the loading and supporting points, and between the two supporting points, respectively, which are schematically given in Fig. 2. In the present test, h , l_1 , and $2l$ are 3, 10, and 30 mm, respectively. The laser-beam-type displacement meter is set up so that the laser beam passes through the aperture prepared just above the midpoint of the specimen, as shown in Fig. 2.

The fluctuation of air inside the furnace influences the stability of the stream of the laser beam, and causes an error in the displacement measurement in high-temperature tests. In order to minimize this, the following means were adopted. The loading rod machined from a nickel-base heat-resisting super alloy was designed so that its diameter was close to the inner diameter of the furnace. In addition, the openings produced around the loading rod at the top and the bottom of the furnace were closed with asbestos. Before high-temperature testing, the stability of the laser beam stream was checked by making sure that the displacement meter showed the stable indication under unloaded conditions at elevated temperatures.

The precision of the present displacement meter was examined by performing the four-point bending test at room temperature. The flexural displacement at the midpoint of the specimen, δ_1 , and the strain at the specimen surface were simultaneously measured by the laser-beam-type displacement meter and the strain gauge, respectively. Then, the strain was transformed into the flexural displacement, δ_2 , through Eq. (1). The comparison between δ_1 and δ_2 is shown in Fig. 3. This figure shows that the present displacement meter detects the flexural deflection of about 200 μm , which is generated in engineering ceramics loaded under four-point bending, with sufficient accuracy.

2.2 Test material and specimens

Silicon-nitride ceramic sintered at ambient pressure was used for the present study. Specimens were

Fig. 3 Comparison between displacements measured by means of laser-beam-type displacement meter and through strain gauge method

machined from disc-shaped material into the following two sizes shown in Figs. 4 and 5; rectangular cross-sectional bars of 4.0, 3.0 and 45 mm, and 3.0, 6.6 and 45 mm in width, height and length, respectively. The indenter of the Knoop hardness tester was pushed into the former bar by applying loads of 49, 98, 196, 294, and 490 N. Consequently, five kinds of precracked specimens were prepared. The latter is the one for the chevron-notched specimen, details of which are shown in Fig. 5.

It is known that the tensile residual stress is produced around the tip of the precrack prepared in the manner mentioned above. In order to eliminate the residual stress, the following two methods were adopted; removal of the dent formed on the specimen surface by grinding, and annealing of the precracked specimen at 1000°C for 1.0 hour.

2.3 Four-point bending test

The temperature dependencies of Young's modulus, flexural strength and fracture toughness were examined by performing four-point bending tests at room temperature, 800°, 900°, 1000°, 1100°, 1200°, 1250° and 1300°C in an ambient atmosphere. The temperature was raised at the rate of 5°C per minute, and the test machine was run at the cross-head speed of 0.1 mm per minute after the tempera-

Fig. 4 Shape and dimensions of smooth specimen and specimen precracked with Knoop hardness tester's indenter

Fig. 5 Shape and dimensions of chevron-notched specimen. The arrangement of loading and supporting pins in four-point bending test, and the value of Y^* in Eq. (4) are also presented

ture was kept at the targeted level for 30 minutes. Incidentally, the same cross-head speed was adopted in the test at room temperature.

2.4 Observations of fracture surface

The trace of the semielliptical crack can be found on the fracture surface of the precracked specimen. The shape and size of the precrack were measured by observing the trace through an optical microscope; these were used for estimating the fracture toughness, K_{IC} .

Meanwhile, the defect from which the fracture originated was detected on the fracture surface of the smooth specimen through a scanning electron microscope, where only the defect located in the near-surface layer was made the object of the observation. Then, the mirror formed around the origin was approximately profiled by the semielliptical shape, and its size was determined. The fracture toughness was tentatively estimated on the basis of the self-contained defects using the above measurements.

3. Analysis

The fracture toughnesses, K_{IC} of the smooth and the precracked specimens were determined through the following equations, using the shapes and sizes of the precrack and defect-related mirror, which were measured as stated in the previous section:

$$\left. \begin{aligned} \text{i) in the case of } a \leq c, \\ K_{IC} = 1.12\sigma\sqrt{\pi a}/\Phi \\ \Phi = \int_0^{\pi/2} \{1 - (1 - a^2/c^2)\sin^2\theta\}^{1/2} d\theta \end{aligned} \right\}, \quad (2)$$

and

$$\left. \begin{aligned} \text{ii) in the case of } a > c, \\ K_{IC} = 1.12\sigma\sqrt{\pi a/c}/\Phi \\ \Phi = (a/c) \int_0^{\pi/2} \{1 - (1 - c^2/a^2)\sin^2\theta\}^{1/2} d\theta \end{aligned} \right\}, \quad (3)$$

where a and $2c$ are the crack depth and the crack length on the specimen surface, respectively, and σ is the stress imposed on the specimen surface.

The K_{IC} of the chevron-notched specimen was calculated in accordance with Bluhm's slice model^{(15)~(17)}. According to this model, the specimen is divided into n thin slices of ΔZ in thickness, m and $(n-m)$ of which are situated in the straight-through portion of the trapezoid and in the tapered portion of the chevron notch, respectively, as shown in Fig. 5. Then, the compliance of each thin slice is estimated. The whole compliance of the chevron-notched specimen, C_{tr} , is calculated by totalling the compliances of the respective thin slices. The fracture toughness, K_{IC} , is obtained from the following equation including C_{tr} :

$$K_{IC} = \frac{P}{B\sqrt{W}} \frac{1}{2} \frac{dC_{tr}}{da} \frac{a_1 - a_0}{a - a_0} = \frac{P}{B\sqrt{W}} Y^*, \quad (4)$$

where P is the load; a is the A -to- W ratio, A/W ; a_1

$= A_1/W$ and $a_0 = A_0/W$. The quantities of A , A_1 , A_0 , B and W are given in Fig. 5. The parameter, $Y^* = (1/2)(dC_{tr}/da)\{(a_1 - a_0)/(a - a_0)\}$ in Eq. (4), which is needed for calculating the K_{IC} , is plotted against the ratio, a , in Fig. 6.

Equation (4) means that Y^* becomes the minimum when P assumes the maximum value, where the maximum P is the fracture load of the chevron-notched specimen under four-point bend loading. We can obtain the minimum value of Y^* from Fig. 6, which is noted in Fig. 5. Thus, the K_{IC} of the chevron-notched specimen can be calculated by measuring only the fracture load in the four-point bending test.

4. Test Results and Discussion

4.1 Effect of annealing on flexural strength and fracture toughness at room temperature

Figure 7 shows the fracture toughness, K_{IC} , plotted against the equivalent crack length, a_e , for three types of specimens indented by the Knoop-hardness tester: the one in which the indentation was preserved as it was, the one in which it was followed by annealing at 1 000°C for 1 hour, and the one in which the

Fig. 6 Y^* -versus- a relationship, where Y^* is included in Eq. (4) and a is presented in Fig. 5, respectively

Fig. 7 Relationship between fracture toughness estimated from different types of specimens and equivalent crack length

indentation was removed by grinding. The average value of K_{IC} obtained from the chevron-notched specimens, $5.4 \text{ MPam}^{1/2}$, is shown by the dotted line as the reference data in this figure. Now, the size of the defect or semielliptical surface precrack contained in the ceramics is transformed into $2a_e$, the length of the through-thickness center crack included in an infinitely scaled plate by the following equation:

$$a_e = (1/\pi)/(K_{IC}/\sigma)^2, \quad (5)$$

where σ and K_{IC} are fracture stress and fracture toughness of the smooth specimen containing defects or the specimen with a semielliptical surface precrack. This figure shows that the K_{IC} is larger in the annealed indented specimens than in the one that was unannealed. This seems to be due to the effect of the tensile residual stress on K_{IC} , which was introduced around the precrack tip by the indentation. It has been pointed out that such a residual stress is eliminated, and additionally, that the precrack tip becomes dull or adhered, due to the annealing⁽¹³⁾. Since the K_{IC} of the annealed precracked specimen increases with decrease in the crack length in the range of $a_e \leq 0.15 \text{ mm}$, as shown in Fig. 7, such a phenomenon might intensively occur around the tip of a small precrack. Meanwhile, the K_{IC} of the unannealed precracked specimen decreases in the range of $a_e < 0.15 \text{ mm}$, compared with that in the range of $a_e \geq 0.15 \text{ mm}$. This might be caused by the characteristics of a small crack⁽¹³⁾; the size of the precrack in this region is almost the same as that of the microstructure such as a grain of ceramic material.

The K_{IC} estimated on the basis of the defect contained in the smooth specimen, whose size is in the range of $a_e < 0.1 \text{ mm}$, is almost coincident with that of the annealed precracked specimen in the same crack-size range. Moreover, it should be noted that the K_{IC} of the indentation-removed specimen almost coincides with that of the annealed precracked specimen in the crack-size range of $a_e > 0.15 \text{ mm}$. The K_{IC} of the chevron-notched specimen is situated between the two K_{IC} values of the annealed and unannealed precracked specimens.

The indented silicon nitride ceramic specimen was annealed to eliminate the tensile residual stress introduced around its precrack tip at temperatures from 1000°C to 1200°C . Iseki et al.⁽⁹⁾ showed that annealing at temperatures less than 1000°C hardly causes any change in the shape or size of the precrack and weight loss due to oxidization in silicon nitride ceramics. Meanwhile, in Takahashi et al.'s experiment⁽¹³⁾ the precracked silicon nitride ceramic annealed at temperatures over 1200°C exhibits higher flexural strength than the unannealed precracked one at room temperature, since an adhesion occurs around

the precrack tip during annealing at these temperatures.

The precracked specimen annealed at 1000°C for 1 hour exhibits almost the same fracture toughness as the indentation-removed one, as shown in Fig. 7. Since it is considered that the removal of the indentation relieves the tensile residual stress around the precrack tip, the annealing at 1000°C for 1 hour seems to be appropriate for elimination of the residual stress without an adhesion of the precrack tip.

Figure 8 shows the σ_f -vs.- a_e relationships obtained from replotting the data presented in Fig. 7 on double logarithmic scales. The solid line describes the $\log \sigma_f$ -vs.- $\log a_e$ relationship estimated using $K_{IC} = 5.4 \text{ MPam}^{1/2}$, which was measured in the chevron-notched specimen. It is known from this figure that the data of the annealed and unannealed precracked specimens form the respective bands having the slope of about $-1/2$ in the crack-size range of $a_e > 0.15 \text{ mm}$. On the other hand, the $\log \sigma_f$ -vs.- $\log a_e$ relationships of the annealed and unannealed precracked specimens separate from the extensions of these bands on the upper and the lower sides in the crack-size range of $a_e < 0.15 \text{ mm}$, respectively. The levelling-off phenomenon appearing in $\log \sigma_f$ plotted against $\log a_e$ in the unannealed precracked specimen was interpreted as a characteristic of small cracks, which was reported by Takahashi et al.⁽¹³⁾.

4.2 Deformation behavior and temperature dependence of Young's modulus

The relationship between the load, P , and the displacement, δ , was examined in the four-point bending test at elevated temperatures, where δ was measured at the midpoint of the specimen by the laser-beam-type extensometer. The test data on the specimens indented by loads, 294 N and 490 N, and the smooth specimen are presented in Figs. 9 (a), (b) and (c), respectively. The linear relationship holds

Fig. 8 Effect of annealing of indented specimen and removing of dent formed by the Knoop indentation on fracture toughness

between P and δ in the range of temperature less than 1200°C for the three specimens. Meanwhile, the P -vs.- δ relationship curves in a convex manner, deviating from the linear relationship held in the small deflection range as δ increases in the temperature range over 1200°C . Moreover, the curvature of the P -vs.- δ curve becomes large with increase in test

(a) Specimen indented by Knoop hardness tester at load, 294 N

(b) Specimen indented by Knoop hardness tester at load, 490 N

(c) Smooth specimen

Fig. 9 Relationship between load and displacement of specimen in four-point bending test

temperature. In addition, the displacement at the fracture point is larger in the smooth specimen than in the indented ones, as was expected. The laser-beam-type extensometer can detect such characteristic deformation behaviors of the silicon nitride ceramic specimens under four-point bend loading. Thus, the present silicon nitride ceramic yields inelastic deformation at temperatures over about 1200°C , while this material behaves elastically at temperatures less than about 1200°C .

Figure 10 shows the test temperature dependence of Young's modulus, E , which was obtained from the P -vs.- δ relationships at temperatures less than 1200°C . A fairly large scatter can be observed in the data presented in this figure; for instance, Young's moduli at room temperature range from 200 GPa to 330 GPa. Their average value, however, is 265 GPa, corresponding to the values 230 to 290 GPa reported previously in other papers⁽¹⁴⁾⁽¹⁸⁾. It is also known from this figure that Young's modulus remained almost unchanged in the temperature range from room temperature to 1100°C and tends to decrease slightly around 1200°C .

The existence of precracks in the indented specimens was disregarded in the present measurements of Young's modulus. Incidentally, their sizes, $2c$ and a , are an average of 710 and 310 μm and 1010 and 470 μm in the specimens indented by loads, $P=294$ and 490 N, respectively, where $2c$ and a are precrack length on the specimen surface and precrack depth.

4.3 Test temperature dependences of flexural strength and fracture toughness

Figure 11 shows the flexural strength of the smooth and the indented specimens plotted against test temperature. According to this figure, the flexural strength of the smooth specimen remains nearly unchanged in the temperature range from room temperature to about 900°C , and this decreases as temperature increases over about 900°C . The rate of decrease in the flexural strength is much greater in the temper-

Fig. 10 Temperature dependence of Young's modulus

ature range over 1200°C than in the temperature range from 900°C to 1200°C.

Generally, silicon nitride ceramics are composed of a polycrystal structure. Then, a glass layer constituted of impurity ingredients exists in its grain boundary. Since the viscosity of the glass layer decreases with the increase in the temperature, grain-boundary slip readily occurs at elevated temperatures. The crack originating at self-contained defects seems to grow slowly along the grain boundary with the aid of the grain-boundary sliding. The decrease in the flexural strength in the temperature range over 900°C might be due to the slow crack growth occurring in this temperature range. The optical microscope observation of the fracture surface obtained at temperatures over 1200°C clearly revealed the boundary between the slow crack growth area and the region in which the crack was quickly growing just before the complete failure occurred. This boundary was detectable on the fracture surface obtained from the specimen tested at 1300°C even with the naked eye. The great decrease in the flexural strength, σ_f , in the temperature range over 1200°C might be due to the inelastic deformation occurring in this temperature range in addition to the slow crack growth.

Meanwhile, the test results of the indented specimens show the following: The annealed ones have greater flexural strength than the unannealed ones at room temperature. In addition, the flexural strength remains almost constant in the temperature range from room temperature to 900°C, attaining the maximum values at temperatures of around 1100°C to 1200°C. Then, the flexural strength of the indented specimen almost coincides with that of the smooth specimen in the temperature range of 1250°C to 1300°C.

The residual tensile stress introduced around the precrack tip by indentation might be relieved during

an annealing at 1000°C for 1 hour. Consequently, the indented specimen which was annealed might exhibit greater flexural strength than the unannealed one at room temperature, as shown in Fig. 11. The maximum flexural strength attained at temperatures of 1100°C to 1200°C in the same figure might be caused by blunting and/or adhesion as well as the relief of the tensile residual stress, which occurred at or around the precrack tip. The adhesion enhanced in the vicinity of the precrack tip might lead to a nearly coincident flexural strength of the smooth and the indented specimens around temperatures of 1250°C to 1300°C, as shown in Fig. 11.

Figure 12 shows the dependence of the temperature, T , on the fracture toughness, K_{IC} , which was obtained from the indented, chevron-notched, and smooth specimens. As a matter of course, the K_{IC} -vs.- T relationship of the indented specimens behaves in a manner similar to the σ_f -vs.- T relationship, which is shown in Fig. 11. The K_{IC} evaluated from the smooth specimen is fairly close to the ones obtained from the indented and chevron-notched specimens at room temperature. The difference between the two becomes more marked in the temperature range from about 800°C to 1000°C. Thus, the fracture toughness measurements based on the self-contained defects of the smooth specimen are much more inaccurate at elevated temperatures than at room temperature. This might mainly result from the experimental problem that the profile of the mirror formed around the defects becomes quite difficult to be found on the fracture surface obtained at elevated temperatures. Meanwhile, the K_{IC} of the chevron-notched specimen remains nearly constant in the temperature range from room temperature to 1000°C, being almost coincident with the K_{IC} of the unannealed indented specimen. This is followed by gradual decreasing of K_{IC} with an increase in test temperature, with the mini-

Fig. 11 Variations of flexural strength with increase in test temperature

Fig. 12 Variations of fracture toughness with increase in test temperature

imum value reached at around 1 200°C. The temperature at which K_{Ic} assumes the minimum corresponds well to the one at which σ_f assumes the maximum in Fig. 11. The K_{Ic} of the chevron-notched specimen increases as test temperature rises over 1 200°C. This might be due to the inelastic deformation occurring at temperatures over 1 200°C. Thus, fracture toughness evaluated in this temperature range seems to be incorrect owing to the inelastic deformation effect included in it.

The fracture toughness estimated at elevated temperatures exhibits the marked test-mode dependence, specifically in the temperature range from 1 000°C to 1 300°C, as shown in Fig. 12. Discussion of the reason for this will be left for future studies.

5. Conclusions

A new test system equipped with a laser-beam-type displacement measuring system was developed for evaluation of the high-temperature strength of engineering ceramics. Four-point bending tests were performed for silicon nitride ceramics using this test system. The main results obtained can be summarized as follows:

(1) The present displacement measuring system made it possible to detect the displacement of 200–300 μm with the precision of about 2% at test temperatures ranging from room temperature to 1 300°C.

(2) The specimen precracked with the Knoop indenter, which was annealed at 1 000°C for 1 hour, exhibited almost the same fracture toughness as that of the specimen in which the dent was removed by grind-machining. This test result might show that the above annealing treatment is sufficient to eliminate the tensile residual stress introduced around the pre-crack tip by the indentation.

(3) It was suggested that the indentation method for measuring fracture toughness is useful for specimens with the precrack larger than 0.15 mm in the equivalent crack length.

(4) The silicon nitride ceramics exhibited a linear relationship between load, P , and displacement, δ , at test temperatures below 1 200°C. The P -vs.- δ relationship deviated from the linear relationship at temperatures above 1 200°C, showing the occurrence of the inelastic deformation.

(5) The flexural strength of silicon nitride ceramics remained unchanged in the test temperature range from room temperature to about 900°C, and then this decreased gradually with further increase in the test temperature.

(6) The fracture toughness obtained from the chevron-notched specimen is nearly constant in the test temperature range from room temperature to

1 000°C. This is followed by gradual decrease with further increase in the test temperature, and attains the minimum around 1 200°C.

(7) The fracture toughness measured using the indented specimen was nearly coincident with that obtained from the chevron-notched one in the test temperature range from room temperature to 1 000°C.

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References

- (1) Munz, D., Himsolt, G. and Eschweiler, J., Effect of Stable Crack Growth on Fracture Toughness Determination for Hot-Pressed Silicon Nitride at Elevated Temperatures, ASTM STP No. 745(1980), p. 69.
- (2) Srinivasan, M. and Seshadri, S. G., Application of Single Edge Notched Beam and Indentation Techniques to Determine Fracture Toughness of Alpha Silicon Carbide, ASTM STP No. 745(1980), p. 46.
- (3) Michalske, T. A., Singh, M. and Frechette, Experimental Observation of Crack Velocity and Crack Front Shape Effects in Double-Torsion Fracture Mechanics Tests, ASTM STP No. 745 (1980), p. 3.
- (4) Rice, R. W., Test-Microstructural Dependence of Fracture Energy Measurements in Ceramics, ASTM STP No. 745 (1980), p. 96.
- (5) Miyoshi, T., Sagawa, N. and Sasa, T., A Study on Fracture Toughness of Structural Ceramics, Trans. Jpn. Soc. Mech. Eng., (in Japanese), Vol. 51, No. 471, A (1985–11), p. 2489.
- (6) Tanaka, K., Mutoh, Y. and Niwa, T., Fracture Strength, Fracture Toughness and Their Scatter Characteristics at High Temperature in Silicon Nitrides Produced by Several Sintering Methods, Trans. Jpn. Soc. Mech. Eng., Vol. 54, No. 501, A (1988–5), p. 1086.
- (7) Miyoshi, T., Ebihara, Y. and Sasa, T., Study on the Strength Evaluation of Structural Ceramics, Trans. Jpn. Soc. Mech. Eng., (in Japanese), Vol. 52, No. 476, A (1986–4), p. 1177.
- (8) Kobayashi, H., Nakamura, H., Kitayama, A. and Ohote, S., Evaluation of Fracture Toughness for Ceramics by Chevron-Notched Specimen, Jour. Soc. Mat. Sci., Japan, (in Japanese), Vol. 35, No. 395, (1986–8), p. 892.
- (9) Iseki, T., Mori, M. and Suzuki, H., Fracture of Hot-Pressed Silicon Nitride in Bending, Yogyo-Kyokai-Shi, (in Japanese) Vol. 86, No. 12, (1978), p. 597.
- (10) Homma, K. and Tohyama, M., Geometry Effects on Fracture Toughness of Ceramics with Chevron

- Notched Specimens, *Trans. Jpn. Soc. Mech. Eng.*, (in Japanese), Vol. 54, No. 503, A (1988-7), p. 1445.
- (11) Newman, J. C. Jr., A Review of Chevron-Notched Fracture Specimens, ASTM STP No. 855 (1984), p. 5.
 - (12) Kishimoto, H., Ueno, A., Kawamoto, H. and Ura, S., Tensile Test of Sintered Si_3N_4 and the Influence of Process Defects Such as Pores on Fracture Strength, *J. Soc. Mat. Sci., Jpn.*, (in Japanese), Vol. 38, No. 424 (1989-1), p. 32.
 - (13) Takahashi, I., Usami, S., Nakakado, K., Miyata, H. and Shida, S., Effect of Defect Size and Notch Root Radius on Fracture Strength of Engineering Ceramics, *Yogyo-Kyokai-Shi*, (in Japanese), Vol. 93, No. 4 (1985), p. 186.
 - (14) Kimoto, H., Usami, S. and Miyata, H., Relationship between Defect Size and Strength in Glass and Polycrystal Ceramics, *Trans. Jpn. Soc. Mech. Eng.*, (in Japanese), Vol. 51, No. 471 (1985-11), p. 2482.
 - (15) Bluhm, J. I., Slice Synthesis of a Three Dimensional Work of Fracture Specimen for Brittle Materials Testing, *Eng. Fract. Mech.*, Vol. 7 (1975), p. 593.
 - (16) Munz, D., Bubsey, R. T. and Srawley, J. E., Compliance and Stress Intensity Coefficients for Short Bar Specimens with Chevron Notches, *Int. J. Fract.*, Vol. 16, No. 4 (1980), p. 359.
 - (17) Munz, D., Bubsey, R. T. and Shannon, J. L., Jr., Fracture Toughness Determination of Al_2O_3 Using Four-Point-Bend Specimens with Straight-Through and Chevron Notches, *J. Amer. Ceramic Soc.*, Vol. 63, No. 5-6 (1980), p. 300.
 - (18) Miyoshi, T., Ebihara, Y. and Sasa, T., Strength of Structural Ceramics with Micro Cracks, *Trans. Jpn. Soc. Mech. Eng.*, (in Japanese), Vol. 53, No. 486, A (1987-2), p. 267.
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