# Fracture Toughness of Silicon Carbide Evaluated Using Pre-Cracked Specimens*

Yoh NOBUTA**, Hiroomi HOMMA**
and Hiroaki HARAGUCHI***

Silicon carbide plate specimens containing a through-thickness crack, on which stress intensity can be calculated using two-dimensional stress analysis, were prepared by a new method developed in the present study, and fracture toughness tests were performed on these specimen. The specimen geometry was quite similar to that of the ASTM Standards compact tension specimen. A compressive load was applied to the upper and lower surfaces of a specimen containing a narrow slit as a crack-starter. This produced a tensile stress near the slit end and a compressive stress far from it. The loading point was changed by the required crack length. Then, the specimen is loaded by 20 μs bending moment at the notch root. The obtained fracture toughness value from the specimen is almost independent of the crack length between 0.5 and 0.7 in the ratio to the specimen width. It is also independent of specimen thickness in the experimental range of 3.0 and 9.5 mm.

***Key Words***: Silicon Carbide, Fracture Toughness, Pre-Cracked Specimen, Three-point Bending, Four-point Bending

## 1. Introduction

Although many methods have been developed to evaluate fracture toughness values, $K_{IC}$, of ceramics, a suitable method has not yet been established. One of the reasons for this is that ceramics are essentially brittle; hence, it is very difficult to introduce a pre-crack in ceramic specimens. With this fact in mind, specimens having a narrow machined notch were used to determine the $K_{IC}$ values. The strength of brittle materials is significantly affected by notch sharpness, however, so use of a machined notch specimen results in evaluation of a greater toughness value than that for a cracked specimen. Thus, indentation[1] and chevron notched specimen[2] methods were developed. However, an elliptical or a fan-shaped crack must be treated in the both methods, and this forces one to deal such questions about an effect of damage zone near the crack caused by the indentation, crack contour shape at the onset of unstable propagation in the chevron notched specimen test, and accuracy of stress intensity factor for the such cracks.

Nose and Fujii[3] determined $K_{IC}$ values of ceramics using a specimen with a crack introduced by a bending moment, as in the ASTM Standards specimen for the plane strain fracture toughness test. The present authors have developed a new method to provide a pre-cracked specimen in which a crack is introduced in a ceramic specimen by a very short-life dynamic loading. Furthermore, the $K_{IC}$ values thus obtained have been used to investigate the effects of notch root radius, specimen thickness and load configuration on fracture toughness, and to compare them with the values obtained by Nose and Fujii[3].

## 2. Experimental Procedure

### 2.1 Material and specimens

The material used in these experiments is commercial silicon carbide, SiC (Ibiceram, Ibiden Co, Ltd.), the chemical composition and mechanical properties of which are shown in Tables 1 and 2, respec-

* Received 18th January, 1988. Paper No. 87-0275 B
** Department of Energy, Toyohashi University of Technology, 1-1 Tempaku-cho, Toyohashi, 440, Japan
*** Yasukawa Electric Mfg. Coz., Ltd., 2346 Hujita, Yahatanishi-ku, Kitakyushu, 806, Japan

tively. As shown in Fig. 1-(a), the specimen in-plane dimensions are $40 \times 50\ mm^2$, and two different thicknesses, 3 and 9.5 mm, were used to examine the effect of specimen thickness on fracture toughness. Each specimen has a 0.2-mm-wide saw-cut notch in the mid-section to serve as crack starter.

Before introducing the pre-crack, each specimen was mirror-surface-finished using diamond liquid and polishing pads. After pre-cracking, the crack length was measured by means of an optical microscope (× 1 000).

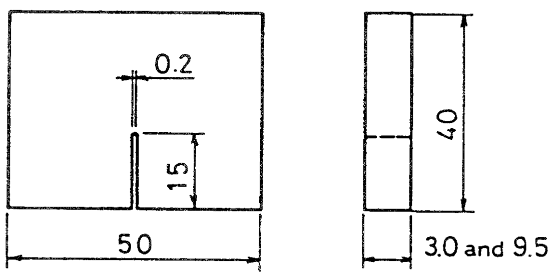
Notched specimens shown in Fig. 1-(b) were cut out from the pre-cracked specimens which had been halved in the fracture toughness test. Since the applied loads to the specimens were very small in the test, it may be considered that there was no damage in the halved specimens except near the fracture surface. During the machining of the specimen, the portion near the fracture surface was cut off. Every notch had the same depth and a different width associated with the diamond wheel thickness. Examination of the notch root through an optical microscope indicated that the shape of the root was approximately semi-circular and its diameter equaled the notch width.

Table 1 Chemical composition

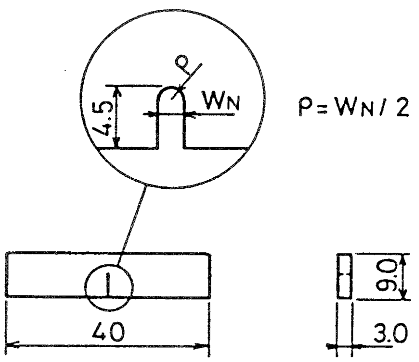
| Compositions | SiC | Total-Al | Total-Fe | Free-$SiO_2$ | Free-C | $H_2O$ |
|---|---|---|---|---|---|---|
| (Weight %) | 98.0 | 0.03 | 0.04 | 0.2 | 0.3 | 0.25 |

Table 2 Mechanlcal properties

| Density | Young's modulus | Poisson ratio |
|---|---|---|
| 3.08-3.15 $g/cm^3$ | 396 GPa | 0.13 |




(a) Geometry and dimensions of pre-cracked specimen




(b) Geometry and dimensions of notched specimen

Fig. 1

### 2.2 A method to introduce a pre-crack in the specimen

A loading apparatus for the pre-cracking is schematically shown in Fig. 2. A projectile of 20 mm in diameter and 30 mm in length is inserted into the barrel from its outlet and placed at a pre-determined position. When a gas gun is fired, the projectile is accelerated in the barrel by the flow of pressurized $N_2$ gas from the reservoir, and undergoes a high-speed collides with the end of the load transfer rod. A compressive stress pulse of about 20 μs duration is generated in the rod by this collision and propagates toward the other end of the rod contacting with the specimen. When the stress pulse arrives at the rod end, it is partially transmitted to the specimen. Then, the specimen is dynamically bent in a period of approximately 20 μs. A crack is initiated at the notch root and stopped within the specimen by the immediate unloading of bending and the compressive stress normal to the crack path exerted by the clamp.

The clamp is shown in detail in Fig. 3. The clamping position was determined so that the stress field in the specimen due to application of the clamping force is tensile near the notch root and compressive far

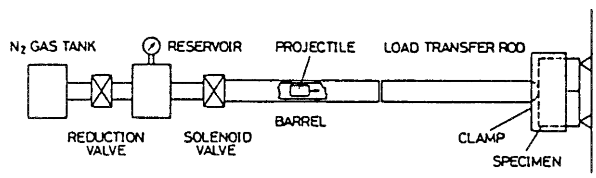



Fig. 2 Apparatus for impact loading

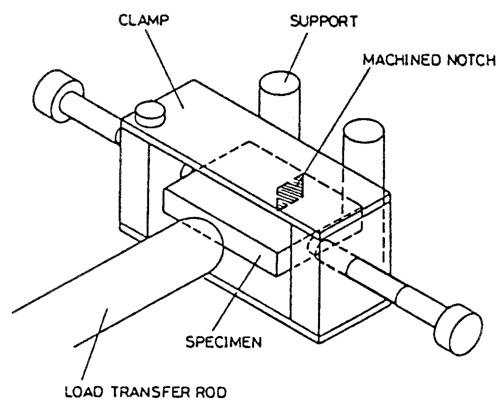



Fig. 3 Schematic view of clamp

away from it. A finite element method (FEM) was used for the stress analysis. The stress field for the chosen position is shown in Fig. 4. If the clamping force is small, an initiated crack runs throughout the specimen. A crack jump distance is significantly dependent on the clamping force. Derivation of their quantitative relationship requires a quite complicated dynamic analysis for a running crack. In this study, the clamping force for the crack jump of about 5 mm was experimentally determined by a trial and error method. The forces are 1 500 and 4 500 N for 3 mm and 9.5 mm thick specimens, respectively.

### 2.3 Stress intensity factor

For the specimen configuration shown in Fig. 1-(a) which is subjected to three- and four-point bendings tests, values of stress intensity factor are not available in any of the published handbooks. In this investigation, it was calculated from FEM analysis and its relationship with the $J$ integral. In FEM stress analysis, an 8-node isoparametric element was used, and one half of a specimen was divided into 96 elements with 333 nodes. The stress intensity factor-crack length curves for the two types of bending are shown in Fig. 5. Polynomial approximations are shown by the lines. These polynomial equations are, for three-point bending;

$$K_{IC}=\frac{3SP}{2TW^2}(\pi a)^{1/2}F_{3P}(a/W)$$
$$F_{3P}(a/W)=2.64-16.26(a/W)+58.04(a/W)^2-91.97(a/W)^3+58.92(a/W)^4 \quad (1)$$

where

$S=$ span, 40 mm
$P=$ applied load
$a=$ crack length
$W=$ specimen width
$T=$ specimen thickness

and for four-point bending;

$$K_{IC}=\frac{3(S_1-S_2)P}{2TW^2}a^{1/2}F_{4P}(a/W)$$
$$F_{4P}(a/W)=5.03-29.34(a/W)+104.49(a/W)^2-164.81(a/W)^3+106.43(a/W)^4 \quad (2)$$

where

$S_1=$ support span, 40 mm
$S_2=$loading span, 10 mm.

The $K_{IC}$ values were calculated by use of the above equations.

## 3. Results and Discussion

Since every load-deflection curve was linear up to the maximum load in fracture toughness tests of the pre-cracked specimen, the fracture toughness value was defined as the stress intensity for the maximum load and the initial crack length. The fracture toughness values for the two types of bending and the two thicknesses are shown as a function of the crack length in Fig. 6. The obtained data is scattered to some extent. When the data of four-point bending for the 9.5-mm-thick specimen, of which the number is the largest, is taken as the basis of consideration, most of the other results are within the scatter band of the basic data. Statistical analysis indicates that there is no significant difference among the results. This means that the obtained fracture toughness is independent of the specimen thickness, the loading

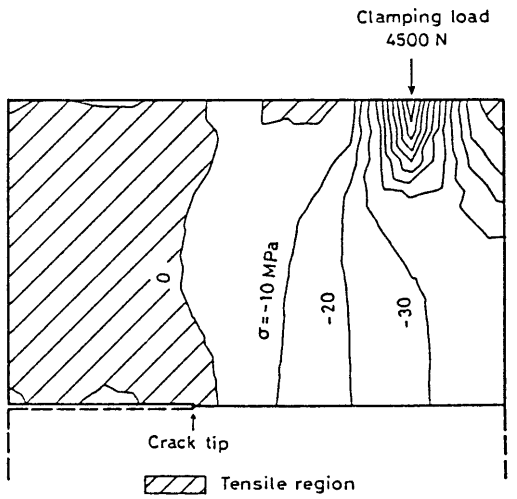



Fig. 4 Stress field in a specimen applied a clamping load

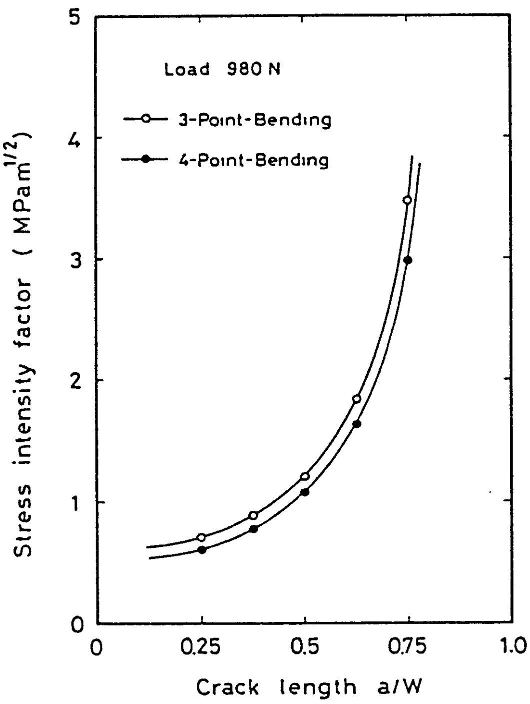



Fig. 5 Stress intensity factor-crack length curve for three-point and four-point bending specimens

configuration and the crack length in the range of experiment. The average fracture toughness obtained is about 2.2 MPa$\sqrt{m}$. The degree of scatter was 10 percent of the average. This is not large in comparison with that of metals. The insignificant difference between the results for the three- and four-point bending tests suggests that the pre-crack introduced in this study was parallel to the notch flanks, and the loading point of three-point bending was accurately located at the crack line. The $K_{IC}$ value obtained by Nose and Fujii[3] for the identical SiC material, 2.5 MPa$\sqrt{m}$, agrees well with our value. This is due to the fact that since the cracks initiated by both methods are arrested after some growth, their nature is essentially the same. Furthermore, any damage such as microcracks at the crack tip can't be detected by a transmitted electron microscope. Therefore, the pre-cracked specimen prepared by this method is applicable to the $K_{IC}$ tests of ceramics.

Fracture stress for the notched specimen under three point bending is shown as a function of the reciprocal of stress concentration factor in Fig. 7. Fracture stress, $\sigma_0$, is given by

$$\sigma_0=\frac{6M}{T(W-a)^2} \quad (3)$$

where $M$ is bending moment, $W$ is specimen width, and $a$ is crack length.

The broken line was obtained using the assumption that a notched specimen of a brittle material is cracked when the maximum stress at the notch root reaches the strength of the smooth specimen ($K_t=1$). As shown in Fig. 7, it is difficult to explain the experimental results by this line. On the other hand, a solid line was drawn by the criterion that the notched specimen is fractured when the stress at a small distance $R_c$ inside the notch root equals the strength of the smooth specimen. The stress near the notch root is expressed by the following equation[4].

$$\sigma=K_t\sigma_0\left(1-\frac{8(W-a)+\rho}{4\rho(W-a)}R_c\right) \quad (4)$$

where $K_t$ is stress concentration factor, $\rho$ is notch root radius, $a$ is crack length, $W$ is specimen width. Although this can be applied to a hyperbolic notch in a semi-infinite plane loaded by in-plane bending, if $R_c$ is very small, this will also give the stress near a notch root of a finite-width specimen with a moderate degree of accuracy. As shown in Fig. 7, the experimental data of the notched specimens lie near the solid line of Eq. ( 4 ) when $R_c$ is taken as 0.035 mm while all the data of the pre-cracked specimens lie below this line. Fracture of a pre-cracked specimen can't be explained by the above criterion.

Fracture toughness obtained from the pre-cracked specimens and the apparent fracture toughness obtained from the notched specimens are plotted as a function of the notch root radius in Fig. 8. Fracture toughness linearly decreases as $\rho$ decreases. The solid line was calculated by the least-squares method for all the apparent fracture toughness data. The extrapolated value from the solid line with a notch root radius of zero, that is, containing a crack, is 2.64 MPa$\sqrt{m}$, which equals the upper limit of the obtained data for the pre-cracked specimen. This means that when estimation of the fracture toughness from data of notched specimens is used for design of ceramic

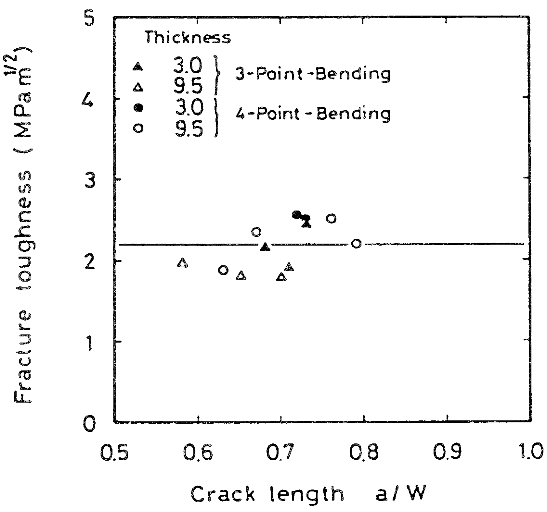



Fig. 6 Fracture toughness as a function of crack length for pre-cracked specimens

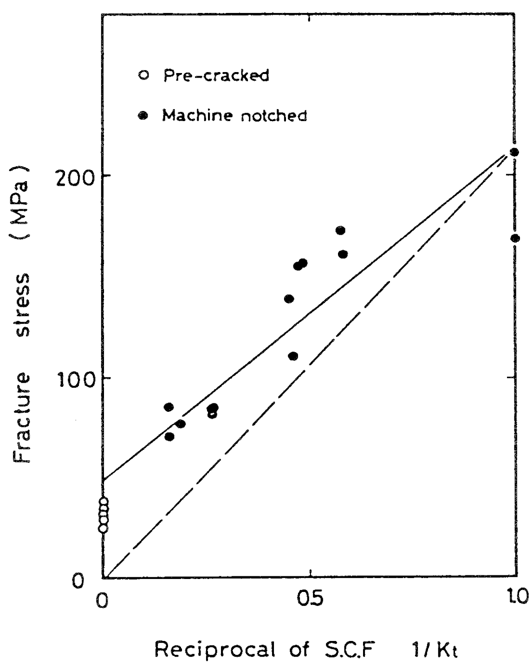



Fig. 7 Fracture stress as a function of reciprocal of S. C. F. for pre-cracked and notched specimens

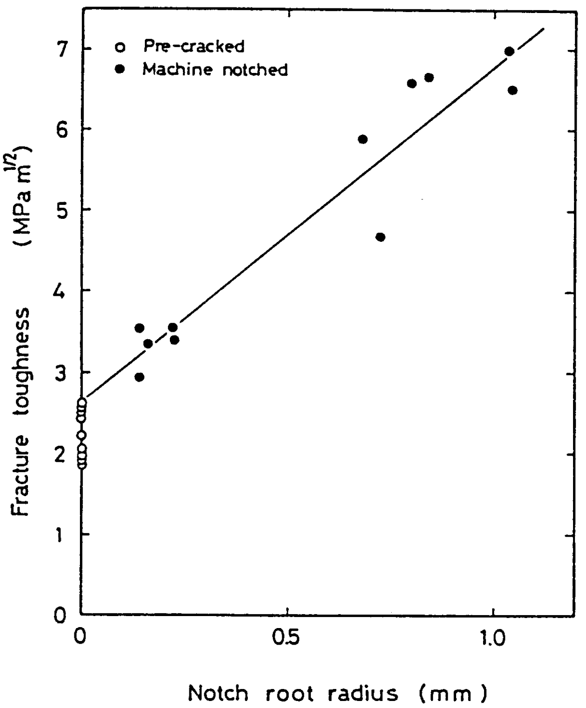



Fig. 8 Fracture toughness as a function of notch root radius

components, the components will suffer premature fracture. This also suggests that since the sharpest notch in this test had a root radius of 0.1 mm, an experiment should be carried out for a notch root radius of less than 0.1 mm to make a better estimation of the fracture toughness. However, considering the difficulties of providing the very narrow notched specimens and the lack of accuracy in the extrapolated values, the pre-cracking method proposed in this study is reasonably applicable to evaluating the fracture toughness of brittle materials such as ceramics.

## 4. Conclusions

To obtain the true fracture toughness of ceramics, a new pre-cracking method was developed. The obtained fracture toughness of SiC was compared with the apparent fracture toughness obtained for the notched specimens. The conclusions are as follows.

1. A new method which easily introduces a pre-crack to a ceramic specimen was developed.
2. The fracture toughness of SiC obtained for the specimens prepared by this method is independent of crack length, loading configuration and specimen thickness; hence, it may be considered to represent the true plane strain fracture toughness of this type of ceramic.
3. The fracture toughness for a crack, extrapolated from the apparent toughness values for notch root radius of 0.1 to 1.0 mm, is larger than the experimental value for a pre-cracked specimen.

## References


(1) Evans, A. G. and Charles, E. A., J. Am. Ceram. Soc., 59 (1976), p. 371.
(2) Munz, D., Bubsty, R. T. and Shannon, J. L., J. Am. Ceram. Soc., 63 (1980), p. 300.
(3) Nose, T. and Fujii, T., Evaluation of Fracture Toughness for Ceramic Materials by Single Edge Pre-cracked Beam Method, Prepr. of J. Ceram. Soc. Jpn., (jn Japanese), 1(1986), p. 363.
(4) Nishida, M., Stress Concentration, (in Japanese), (1976), p. 88, Morikita Publishing Co, Ltd.