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EFFECT OF NOTCH ROOT RADIUS ON THE FRACTURE BEHAVIOUR OF MONOCRYSTALLINE SILICON

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INTRODUCTION

The fracture behaviour of solids has frequently been studied by investigating the behaviour of highly brittle materials. This reduces the influence of plastic deformation of the material near the crack tip on understanding the fracture process. Because some crystals approach the behaviour of perfectly elastic materials, it is possible to use these materials to investigate the fracture process. Several investigators have studied fracture behaviour using monocrystalline silicon, a highly brittle material. Gilman [1], Gilman and Gillis [2], Wiederhorn, et al [3] and Jacodine [4] determined the surface energy of silicon crystals by applying cleavage techniques. St. John [5] measured the plane strain fracture toughness of silicon.

In this study, the influence of the notch root radius on the fracture behaviour along the {111} plane of monocrystalline silicon was investigated.

EXPERIMENTAL INVESTIGATION

Fourteen notched beam specimens loaded in four point bending were tested. The test specimen configuration is shown in Figure 1 with the dimensions listed in Table 1. To investigate the effect of crack tip radius, specimens with five different crack tip radii were tested. The material was Czochralski [6] grown crystals whose growth direction coincided with the <111> direction. The cleavage plane of this diamond structured material is also the {111} plane. All notches were machined parallel to the {111} plane. Since silicon exhibits no measurable plasticity at room temperature, plane strain conditions existed. While two specimen sizes were used in this investigation, the specimens were proportioned the same with spans of L = 101.6 mm and 50.8 mm. The 101.6 mm specimens had a V-shaped notch with different tip radii as given in Table 1. The other radii used were made using various diamond impregnated cutting wires or wheels. The dimensions of the notches for each specimen were measured using an optical comparator.

RESULTS

The stress intensity factor, K_I, for the four point bend specimens is

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$$K_I = \frac{3PL\, f\left(\frac{a}{w}\right)}{4B(w-a)^{3/2}} \qquad (1)$$

where f(a/w) is the geometry factor and the P,L,B,w and a are as shown in Figure 1 [7]. By evaluating equation (1) using the test results for each notch root radius, the value of an effective stress intensity factor, $K_I(\rho)$, at fracture can be determined. These results are presented in Table 1.

Since silicon does not exhibit any plastic deformation prior to fracture, the stress distribution at the notch is elastic. As a result, the elastic stress concentration factor can be used to determine the maximum stress at the notch root when fracture occurs. Using the stress concentration factor for this geometry [8], the fracture stress, σ_f, was determined for the eight smaller sized specimens. These results are presented in Table 1. The average value of the fracture stress, σ_f, is 128 MPa.

These results can be compared using the elastic stress field equations developed by Creager and Paris [9]. For the geometry of the specimens used in this study the stress at the notch root is

$$\sigma_y = \frac{2K_I(\rho)}{(\pi\rho)^{1/2}} \qquad (2)$$

where $K_I(\rho)$ is the stress intensity factor for a given notch root radius, ρ. Assuming that at fracture σ_y is equal to the fracture stress, σ_f, then equation (2) can be solved for $K_I(\rho)$,

$$K_I(\rho) = \frac{\sigma_f(\pi\rho)^{1/2}}{2} \qquad (3)$$

The average value of the fracture stress, $\sigma_f = 128$ MPa, was determined from the theoretical stress concentration factor. Substituting this into equation (3) gives $K_I(\rho)$ as a function of $\sqrt{\rho}$. This equation is compared with the experimental results in Figure 2. The experimental results for $K_I(\rho)$ were determined from the test results using equation (1). As can be seen there is good agreement between the two methods of determining $K_I(\rho)$ for the larger notch radii.

CONCLUSIONS

Based on this investigation, monocrystalline silicon can be used to investigate the fracture behaviour of nearly perfectly brittle materials. The stress intensity factor at fracture for finite radius notches compares favourably with that determined from the stress field equations developed for blunt notches.

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Table 1 Specimen Dimensions and Test Results

ρ (mm)	L (mm)	W (mm)	B (mm)	a (mm)	P_f (N)	$K_I(\rho)$ ($MPa \cdot m^{1/2}$)	σ_f (MPa)
0.08	101.60	25.43	12.78	10.92	551.55	1.34	—
0.08	101.60	25.45	12.70	10.69	667.20	1.58	—
0.08	101.60	25.50	12.75	10.90	542.65	1.30	—
0.13	101.60	25.53	12.57	10.79	515.97	1.24	—
0.15	50.80	12.49	6.38	2.41	458.14	1.57	118
0.15	50.80	12.49	6.17	2.34	564.90	2.01	150
0.15	50.80	12.49	6.65	2.29	453.70	1.46	112
0.18	101.60	25.53	12.80	10.92	716.13	1.71	—
0.18	101.60	25.35	12.88	10.87	751.71	1.81	—
0.18	50.80	12.49	6.48	2.39	551.55	1.88	142
0.18	50.80	12.49	6.35	2.06	582.69	1.84	142
0.56	50.80	12.59	6.10	3.76	511.52	2.56	117
0.56	50.80	12.59	5.97	3.71	480.38	2.41	110
0.58	50.80	12.59	6.10	3.81	569.40	2.85	130
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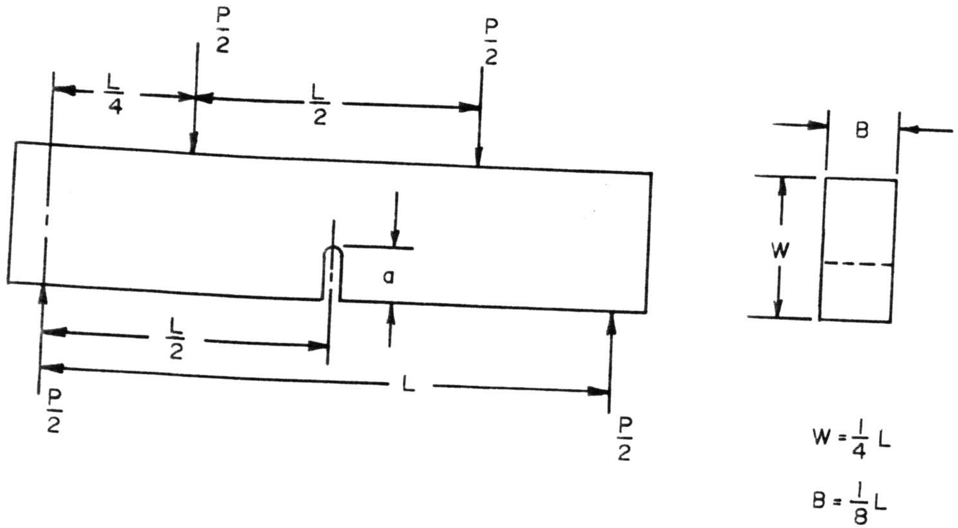

$$K_I = \frac{3PL\, f(\frac{a}{W})\, (W-a)^{-\frac{3}{2}}}{4B}$$

Figure 1 Specimen Geometry

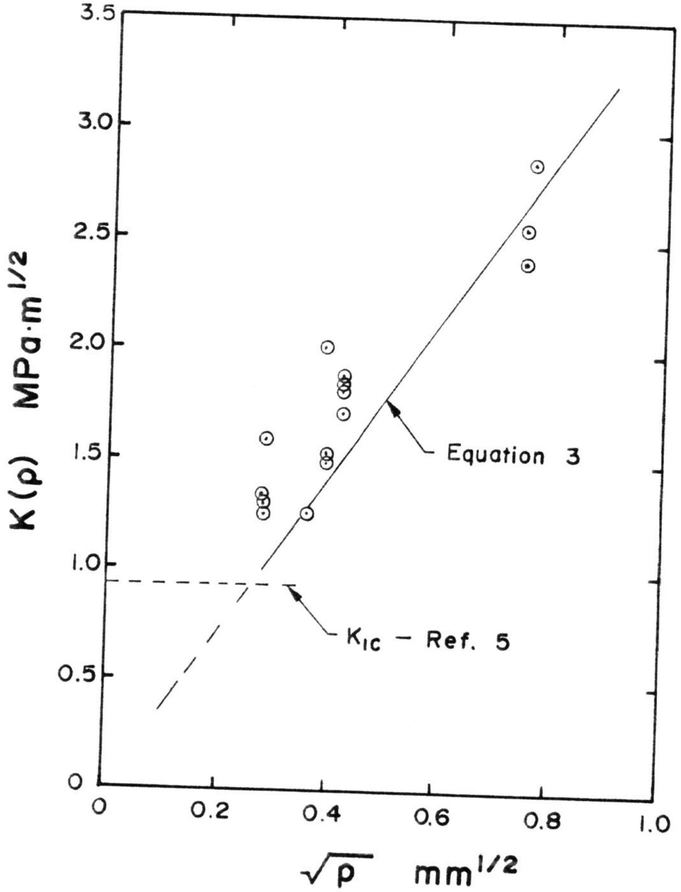

Figure 2 Stress Intensity as a Function of Notch Radii