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Specimen Size and Geometry Effects on Fracture Toughness of Al₂O₃ Measured With Short Rod and Short Bar Chevron-Notch Specimens

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Prepared for the
Symposium on Chevron-Notched Specimens:
Testing and Stress Analysis
sponsored by the American Society for Testing and Materials
Louisville, Kentucky, April 21, 1983
SPECIMEN SIZE AND GEOMETRY EFFECTS ON FRACTURE TOUGHNESS OF $\text{Al}_2\text{O}_3$
MEASURED WITH SHORT ROD AND SHORT BAR CHEVRON-NOTCH SPECIMENS

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SUMMARY

Plane strain fracture toughness measurements were made on $\text{Al}_2\text{O}_3$ using short rod and short bar chevron-notch specimens previously calibrated by the authors for their dimensionless stress intensity factor coefficients. The measured toughness varied systematically with variations in specimen size, proportions, and chevron notch angle apparently due to their influence on the amount of crack extension to maximum load (the measurement point). The toughness variations are explained in terms of a suspected rising R-curve for the material tested, along with a discussion of an unavoidable imprecision in the calculation of $K_{IC}$ for materials with rising R-curves when tested with chevron-notch specimens.

NOMENCLATURE

- $a$: crack length
- $\Delta a$: crack extension
- $a_m$: crack length at minimum of $Y^*$
- $a_{max}$: crack length at $P_{max}$
- $a_0$: initial crack length (distance from line of load application to tip of chevron)
- $a_1$: length of chevron notch at specimen surface (distance from line of load application to point of chevron emergence at specimen surface)
- $a/W$
- $\Delta a/W$
- $a_m/W$
- $a_{max}/W$
\[ a_0 = \frac{a_0}{W} \]
\[ a_1 = \frac{a_1}{W} \]

**B**
- thickness of short bar specimen or diameter of short rod specimen

**b**
- crack front length

**b_m**
- crack front length at minimum of \( Y* \)

**K**
- stress intensity factor

**K_{IC}**
- plane strain fracture toughness

**K_{IR}**
- crack extension resistance

**K_{IR_m}**
- crack extension resistance at minimum of \( Y* \)

**K_{IR_{max}}**
- crack extension resistance at \( P_{max} \)

**P**
- load

**P_m**
- load at minimum of \( Y* \)

**P_{max}**
- maximum load

**W**
- specimen width

**Y***
- dimensionless stress intensity factor coefficient for a trapezoidal crack, \( = KB\sqrt{W/P} \)

**Y_{m*}**
- minimum of \( Y* \) as function of \( \alpha \)

**Y_{max}**
- \( Y* \) at \( P_{max} \)

**INTRODUCTION**

The performance of short bar and four-point-bend chevron-notch specimens in measuring the fracture toughness of aluminum oxide, using experimentally and analytically determined stress intensity factor calibrations, has been previously reported upon by the authors [1] to [3]. The measured fracture toughness varied systematically with variations in specimen size, proportions, and chevron notch angle apparently due to their influence on the amount of crack extension to maximum load (the measurement point). Similar effects would be expected for the short rod chevron-notch specimen, first used by Barker [4].

Experimentally determined stress intensity factor calibrations of the short rod specimen have recently been made by the authors to enable calculation of fracture toughness from maximum test load [5] and [6]. These calibrations were used for the short rod specimens in this study. Fracture toughness tests were made on the same Al₂O₃ stock that was used in the investigations reported upon in references [1] to [3]. The short bar specimen results of references [1] and [3] are combined with the short rod specimen results newly reported here for the sake of generalizing conclusions on size and geometry effects for the chevron-notch type of fracture toughness specimen.
EXPERIMENTAL MATERIAL, SPECIMENS, AND PROCEDURE

The experimental material used in this investigation of the short rod chevron-notch specimen was from the same production of 3M Company Alsiain®-614 sintered aluminum oxide (Al₂O₃) as that used in the studies of references [1] to [3]. Short rod specimens were machined to the dimensions shown in figure 1 from cylindrical blanks 12.7 mm and 25.4 mm in diameter. Width-to-diameter (W/D) ratios of both 1.5 and 2.0 were examined. The chevron notch length at the specimen surface (a₁) was always made equal to the specimen width (W), (i.e., a₁ = 1). The chevron angle was varied by varying the length to the chevron tip (a₀). The notches were introduced by diamond wheel slotting with kerfs (slot width, N) of either 0.4 mm or 1.0 mm depending on the specimen diameter.

Results for the short bar specimens reported in references [1] and [3] are repeated here. Those specimens were machined to the dimensions shown in figure 2 from rectangular blanks of 12.7 mm and 25.4 mm square cross section. Like the short rod specimens, proportions (width-to-height, W/2H ratios) of both 1.5 and 2.0 were produced. Chevron angles were varied by varying either a₀ or a₁. The notches were introduced either by diamond coated wire sawing or diamond wheel slotting. Slot widths in the 12.7 mm thick specimens were 0.25 mm. Those in the 25.4 mm thick specimens were either 0.25 mm or 0.70 mm. As pointed out in references [1] and [3], no effect of slot width was observed for these 25.4 mm thick specimens.

The test setup, shown schematically in figure 3, was the same as that used in references [1] and [3]. Care was exercised in aligning the loading rods according to a procedure previously used by the authors for compliance calibrations of the short bar [7] and short rod [5] specimens. A double-cantilever displacement gage (ASTM Standard Method of Test for Plane-Strain Fracture Toughness of Metallic Materials E-399-81) was inserted into knife edges integral with the loading rods, as shown in figure 3. The displacement gage force was tared from the load measurement, and the specimen was installed by pressing it firmly against the loading rods to seat the loading knife edges in the corners of the recessed notch mouth of the specimen.

Specimen load was applied at a constant test machine crosshead speed of 0.05 mm/min. A typical load versus displacement record is shown in figure 4. The slope of the record trace is initially depressed because of local surface damage to the specimen at the loading knife edge line of contact, but increases continuously to become linear, and thereafter decreases with stable crack extension. After passing through its maximum, the trace suddenly drops because of rapid specimen fracture.

For material with a flat crack growth resistance curve (R-curve), the chevron-notch specimen fracture toughness is proportional to the maximum load as expressed in the following:

\[ K_{IC} = \frac{P_{max}}{B\sqrt{W}} Y_m^* \]  
(see footnote 2)  

where \( Y_m^* \) is the minimum value of the dimensionless stress intensity factor coefficient as a function of relative crack length for the particular specimen used (i.e., for the particular specimen proportions W/B for the short rod specimen and W/2H for the short bar specimen, and chevron notch parameters \( a_0 \) and \( a_1 \)). From the experimental compliance calibrations of references [5] and [6], the
following polynomial expression for $Y^*_m$ for short rod chevron-notch specimens with $a_1 = 1$ was developed for use in the present investigation:

$$Y^*_m = 19.98 - 9.54(W/B) + 6.80(W/B)^2 + [-118.7 + 125.1(W/B) - 22.08(W/B)^2]a_0$$

$$+ [379. - 363.6(W/B) + 84.4(W/B)^2]a_0^2$$

RESULTS AND DISCUSSION

As expected, the short rod specimen results of this investigation (Figure 5) closely resemble the short bar specimen results previously obtained by the authors [1]. There is little if any perceptible influence of $a_0$ on $K_{IC}$ within the range investigated, but a measurable effect of specimen size and proportions, $B$ and $W/B$. As explained previously for the short bar specimen [1], these effects can be ascribed to a rising $R$-curve for the aluminum oxide material tested. Specimen size, proportion, and chevron notch angle all affect the amount of crack extension to maximum load (the measurement point), and therefore $K_{IC}$ as dictated by the shape of the $R$-curve.

As the crack proceeds down the chevron shaped ligament, the test load passes through a smooth maximum. For materials with flat $R$-curves, this maximum occurs at the same relative crack length where the corresponding dimensionless stress intensity factor calibration curve ($Y^*$ versus $a$) exhibits a minimum, namely $a_m$. This value of $Y^*$ is designated $Y^*_m$ and is used in equation (1) to compute $K_{IC}$ directly from maximum load.

For any flat $R$-curve material, the crack extension to maximum load is $(a_m - a_0)$. $a_m$ is not measured on the specimen, but is computed as $W$ times $a_m$, where $a_m$ is read from the $Y^*$ versus $a$ curve for that specimen at $Y^*_m$.

For materials with rising $R$-curves, maximum load and $Y^*$ do not occur coincidentally at $a_m$. The load peaks, instead, at a relative crack length greater than $a_m$. This results in some error in the calculation of $K_{IC}$ at maximum load because we do not know the corresponding value of crack length. Nevertheless, a plot of $K_{IC}$ versus $(a_m - a_0)$ should be a reasonable approximation of the basic trend of the fracture resistance versus crack extension to maximum load curve and serve as an indication of whether the material has a flat $R$-curve or not.

Figure 6 is the $K_{IC}$ versus $(a_m - a_0)$ curve for the short rod specimen, and Figure 7 is the corresponding curve for the short bar specimen reported upon previously [1]. These curves are not $R$-curves, but rather the loci of points lying on a family of $R$-curves, with each $R$-curve being specific to the particular chevron-notch specimen involved. In effect, the chevron-notch is a variably side-grooved specimen. As the crack proceeds down the chevron, the constraint provided by the notch varies, and how it varies will depend on the particular geometry of the chevron. Thus we can imagine that the data in Figure 7, for example, are specific
points on a family of R-curves as shown schematically in figure B.

For each of the two curves in figure 7, one chevron notch parameter (either \( \alpha_0 \) or \( \alpha_1 \)) was fixed while the other was varied. \( K_{IC} \) at a given value of crack extension to maximum load is different in the region of lesser extensions due to the different constraint afforded by the two manners of adjusting the chevron angle. The data can be normalized to account for the variable side grooving effect by multiplying the crack extension by \( (B - b_m)/B \) as shown in figure 9, where all the data falls on a common curve.

The difficulty in calculating \( K_{IC} \) for materials with rising R-curves can be understood as follows. From an energy consideration, crack extension in the chevron-notch specimen occurs so as to satisfy the following relation [7]:

\[
K_{IR} = \frac{P}{B \sqrt{W} Y^*}
\]  

For a given material the \( K_{IR} \) versus \( \Delta a \) curve is fixed, and for a given specimen geometry the \( Y^* \) versus \( \Delta a \) curve is fixed. The \( P \) versus \( \Delta a \) curve then follows directly from equation (3).

The consequence of a rising R-curve is not just to raise the load for continued crack extension compared to that dictated by a flat R-curve, but also to shift the load maximum with respect to the \( Y^* \) curve minimum as shown schematically in figure 10. As seen for a hypothetical rising R-curve, and a typically shaped \( Y^* \) curve, \( P_{max} \) occurs at a relative crack length \( \alpha_{max} \) greater than \( \alpha_m \) corresponding to the \( Y^* \) curve minimum. Referring still to figure 10, \( K_{IR_m} \) and \( K_{IR_{max}} \) are computed using the following combinations of load and stress intensity factor coefficients:

\[
K_{IR_m} = \frac{P_{m} \cdot Y^*_m}{B \sqrt{W}} \quad \text{and} \quad K_{IR_{max}} = \frac{P_{max} \cdot Y^*_{max}}{B \sqrt{W}}
\]

Calculation of \( K_{IC} \) is conventionally done on the assumption of a flat R-curve using the following combination of \( P \) and \( Y^* \):

\[
K_{IC} = \frac{P_{max} \cdot Y^*_m}{B \sqrt{W}}
\]

\( K_{IC} \) calculated in this way yields a value which lies on the R-curve between \( K_{IR_m} \) and \( K_{IR_{max}} \), this uncertainty being greater the steeper the R-curve. Since it is reasonable to assume that \( K_{IR} \) depends on the absolute amount of crack extension \( \Delta a \) and not the relative amount \( \Delta a \), \( K_{IC} \) from proportionate chevron-notch specimens can be expected to increase with increasing specimen size.
FOOTNOTES

1 Plot of crack extension resistance $K_{IR}$ versus crack extension $\Delta a$.

2 The authors recognize that the designation $K_{IC}$ is customarily reserved for that value of plane strain fracture toughness determined in strict accordance with ASTM Standard Test Method for Plane-Strain Fracture Toughness of Metallic Materials (E-399). For materials with flat crack growth resistance curves, we believe the chevron-notch specimen would yield a plane strain fracture toughness value fully equivalent to $K_{IC}$ of the E-399 test and without the encumbrances of posttest crack length measurement and secant-line construction on the test record. For materials with nonflat crack growth resistance curves, as suspected for the Al$_2$O$_3$ material tested here, the measured $K_{IC}$ will be different from the E-399 value, but is nevertheless designated $K_{IC}$ in this paper for convenience.
REFERENCES


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ALL DIMENSIONS IN mm.

Figure 1. - Chevron-notch short rod fracture toughness test specimen.

DIMENSIONS OF SPECIMENS TESTED IN INVESTIGATIONS OF REFERENCES (1) AND (3)

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ALL DIMENSIONS IN mm.

Figure 2. - Chevron-notch short bar fracture toughness test specimen.
Figure 3. - Test setup.

Figure 4. - Typical load versus displacement record for chevron-notch short rod specimen test of sintered aluminum oxide (Alsimag-6141).
Figure 5. - Effect of $a_0$ on $K_{lc}$ of sintered aluminum oxide (Alsimag-614) determined with chevron-notch short rod specimens.

Figure 6. - Variation in $K_{lc}$ of sintered aluminum oxide (Alsimag-614) with amount of crack extension to maximum load for short rod chevron-notch specimens of $a_1 = 1$ in two diameters and W/B proportions, and variable chevron-notch angle as obtained by varying $a_0$. 
Figure 7. - Variation in $K_{ic}$ of sintered aluminum oxide (Alsimag-614) with amount of crack extension to maximum load for short bar chevron-notch specimens in two thicknesses and W/2H proportions, and variable chevron-notch angle obtained by selectively varying either $a_0$ or $a_1$. 

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Figure 8. - Same as Figure 6 but with family of $R$-curves schematically overlaid.
Figure 9. - Data of Figure 7 replotted with abscissa normalized to account for variable side grooving effect of the chevron notch.

Figure 10. - Lack of coincidence between the load maximum and the stress intensity factor coefficient minimum values as functions of relative crack length for rising R-curve materials.