K_R-CURVE MEASUREMENTS WITH CERAMIC MATERIALS

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K_R-curves are measured at room temperature in air for three different alumina materials in a load-controlled experiment with high loading rates. SENB specimens were used and precracked in a displacement controlled experiment. The K_R-curves calculated from these specimens with different sharp crack lengths proved to be independent on crack lengths. The results are in contradiction to the normally measured rising K_R-curve behaviour.

INTRODUCTION

Normally ceramic materials have a completely brittle behaviour. Therefore, crack resistance curves, which show the dependency of critical stress intensity as a function of crack length, should be constant and independent of crack length. In contradiction to these presumptions some results given by Kleinlein (1), Krohn (2), Hübner, Jillek (3) and Bornhauser et al (4) indicate a rising crack resistance curve even at room temperature. The effect is normally explained by a "process zone" developing at the tip of a sharp crack and increasing with growing crack length (Buresch (5), Hockey (6), Pratt (7), Buresch (8), Pabst et al (9)). Other explanations are owing to errors in crack length measurements or adhesive forces on the fracture surfaces (2). In the literature the stress intensity factor forming the K_R-curve is measured normally in a displacement controlled test using the maximum value K_{max} of a load-displacement curve. These kinds of experiments give opportunity to make a "zone" of secondary crack formation and microcracks, which reveals that a rising crack resistance curve is related to the experimental conditiones employed.

Therefore load controlled experiments are used for these measurements performed at high loading rates to suppress subcritical crack extension and crackbranching. The load-displacement curves behave completely linear elastic and the stress intensity K_I is really critical. Three alumina qualities are used

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to account for different material behaviour. Special attention was given to an exact crack length measurement.

MATERIALS

In order to study the K_R-curve effect, two commercial pure aluminas Al_2O_3-bio and Al_2O_3-fk were used and compared with a debased alumina Al_2O_3-S which contains nearly 3% SiO_2. Al_2O_3-fk is very small grained and therefore susceptible to secondary crack formation, which should cause a rising "R-curve effect". More data are given in table 1.

TABLE 1 - Materials.

Material	Composition	$\bar{d}$ (μm)	E (MNm^{-2})	ρ (gcm^{-3})	K_{IC} ($MNm^{-3/2}$)
Al_2O_3-bio	99.7% Al_2O_3 +0.3% MgO	3	3.91×10^5	3.95	3.8±0.6 (10)
Al_2O_3-fk	99.7% Al_2O_3 +0.3% MgO	<1	3.78×10^5	3.94	4.2±0.1 (12)
Al_2O_3-S	97% Al_2O_3 +3% SiO_2	9	3.6×10^5	3.82	3.1±0.1 (11)

EXPERIMENTAL

The measurements were performed in three point bending (30 mm span) at room temperature in air using specimens with a sharp precrack and a nominal 7 x 2.5 mm^2 cross section. Precracking to various a/W ratios were obtained by first notching with a 50 μm width diamond saw and then loading the specimens in a stiff closed-loop testing machine at a displacement rate of 1 μm/min. When the desired crack length was obtained the specimens were unloaded and the crack length measured by three different methods:

1) direct visual observation with a travelling microscope (4, fig. 1)
2) by side light technique after precracking (fig. 2)
3) observation of the transition region inter- to transgranular fracture at the broken surfaces (fig. 3, 4).

Then the precracked specimens were fractured in a load controlled test at a very high loading rate. The measured critical stress intensities K_{IC}^* were plotted against the normalized crack length a/W and a linear regression analysis was made forming the K_R-curve. The critical stress intensities K_{IC}^* were calculated using the formula

$$K_{IC} = \frac{3.P_c.s}{2.B.W^2} \cdot \sqrt{a} \cdot Y(a/W) \quad \ldots\ldots\ldots\ldots\ldots (1)$$

where

$$Y(a/W) = Y(\alpha) = \frac{1.99 - \alpha(1-\alpha).(2.15 - 3.93\alpha + 2.7\alpha^2)}{(1 + 2\alpha)\ (1 - \alpha)^{1.5}}$$

$0 < \alpha < 1$ (Srawley (13)).

The critical load P_C was taken from a load controlled test at a loading rate of 1ooo N/min. Table 2 gives two examples where the three methods of crack length measurements are compared (specimen 1 as an example of mean scatter, specimen 2 as an example of maximum scatter). The corresponding measured K_{IC}^*-data are also listed.

TABLE 2 - Comparison of crack length measurements

No	crack length (mm)			K_{IC}^* $(MNm^{-3/2})$		
	dir.	s.l.	f.sf.	dir.	s.l.	f.sf.
1	2.282	2.432 2.3o4	2.398 2.339	4.o	3.94	4.23
2	2.367	2.688 2.528	2.8o7 2.749	3.17	3.51	4.12

dir. = direct measurements
s.l. = side light technique, both sides
f.sf.= fracture surface, both sides

RESULTS AND DISCUSSION

Al_2O_3-bio. The K_R-curve reveals a linear dependency on measured K_{IC}^* and the normalized crack length a/W. The initial saw cut had a depth of 2.1 mm or a/W ~ 0.3. The slope of the curve remains roughly constant with a slope of 0.13 (RMS regression error 0.0197, fig. 5). The mean K_{IC}^* is 4.3 ± 0.6 $MNm^{-3/2}$, in good agreement with values obtained from narrow notched specimens by Bornhauser (1o).

Al_2O_3-fk. The initial saw cut had a depth of 1.4 or 3.5 mm (a/W~ ~0.2 or ~0.5). The regression line of the measured K_{IC}^* vs a/W gives a slope of 0.68 (RMS regression error 0.195, fig. 6). Omitting the K_{IC}^*values with a/W>0.92, the slope changes to 0.34 which indicates a flat K_R-curve. These data are omitted, because the correction function becomes infinite as a/W→1 small errors in crack length measurements lead to large errors in the measured K_{IC}^*

The mean $K_{IC}^*$of 4.3 ± 0.8 $MNm^{-3/2}$ is in good agreement with data measured by Popp (11) and Li (12) using specimens with narrow notches.

Al_2O_3-S. The initial notch depth was 1.4 mm or a/W~0.2. The regression line forms a slope of 1.18 resulting in a rising K_R-curve. If data of a/W>0.95 are omitted, the slope becomes 0.61, which now appears to be independent of a/W (fig. 7). The mean measured K_{IC}^* value for a/W<0.95 is $3.o \pm 0.4$ $MNm^{-3/2}$, which is somewhat lower than those measured using narrow notches (12).

The above results show that a K_R-curve, measured in a load controlled test at high loading rates, is flat. It is assumed that the rising crack resistance curves reported from (1), (2) and (4) are due to the displacement controlled test procedure. If sharp cracks are extended in a controlled manner a "process zone" of crack branching and/or microcracking could be formed depending on the growing crack length ((1) and Evans, Rana (15)). In consequence, the measured K_R-curves must increase.

Naturally, the "process zone" also developes in the precracking process used here. But the subsequent load controlled test at high loading rates gives no opportunity for energy dissipation in that zone. The critical fracture process could be attributed to the weakest point within the energy dissipation zone.

The measured mean values of K_{IC}^* are equal or below those reported from measurements with narrow notched specimens. This is consistent with the assumption that K_{IC}-data depends on the crack root radius ((11),(12),Bertolotti(14) and Pabst (16)).

CONCLUSION

The K_R-curves measured in a load controlled testing device at high loading rates do not show any dependence on normalized crack length a/W. Therefore the above measured stress intensity K_{IC}^* is a real fracture toughness K_{IC}. So single K_{IC}-values measured in a load controlled test, where a completely linear elastic behaviour is guaranteed, may be used to characterize the materials behaviour at least at room temperature.

SYMBOLS USED

a = crack length (mm)

B = thickness of specimen (mm)

$\bar{d}$ = grain size (μm)

E = Young's modulus (MNm^{-2})

K_I = stress intensity ($MNm^{-3/2}$)

K_{IC} = fracture toughness ($MNm^{-3/2}$)

K_{IC}^* = critical stress intensity ($MNm^{-3/2}$)

P_c = critical force (N)

s = span (mm)

W = width of specimen (mm)

Y = correction function

α = a/W

ρ = density (gcm^{-3})

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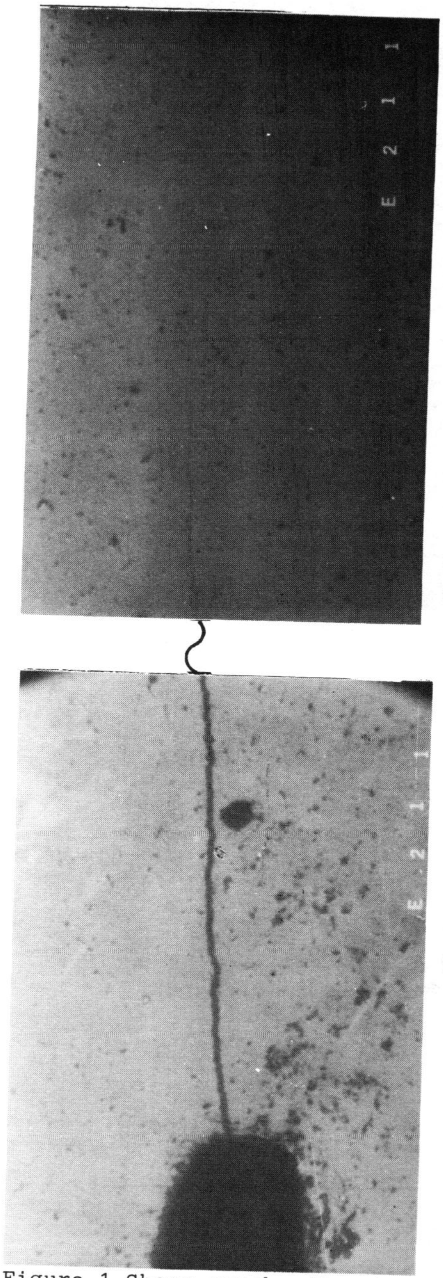

Figure 1 Sharp crack, direct visual observation

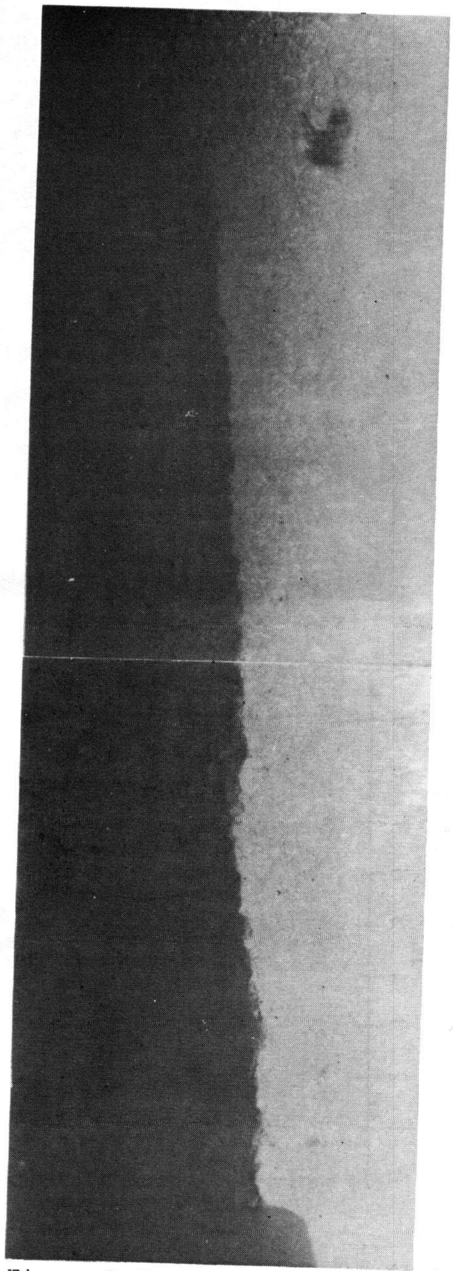

Figure 2 Sharp crack, side light technique

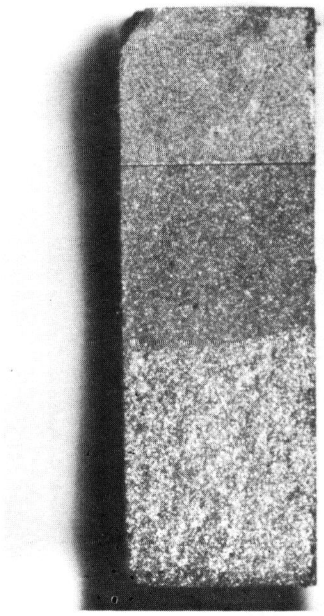

Figure 3 Fracture surface

Figure 4 Transition region inter-to transgranular crack growth

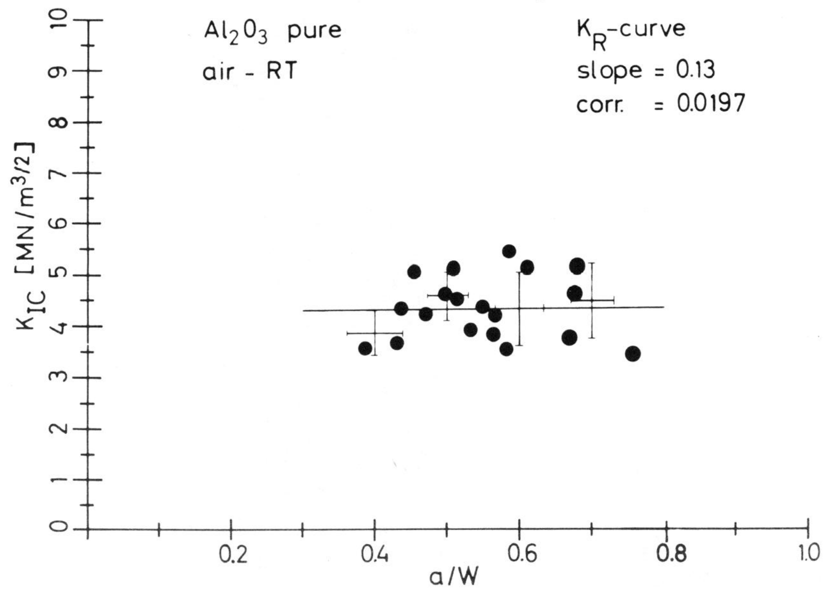

Figure 5 K_R-curve for Al_2O_3-bio

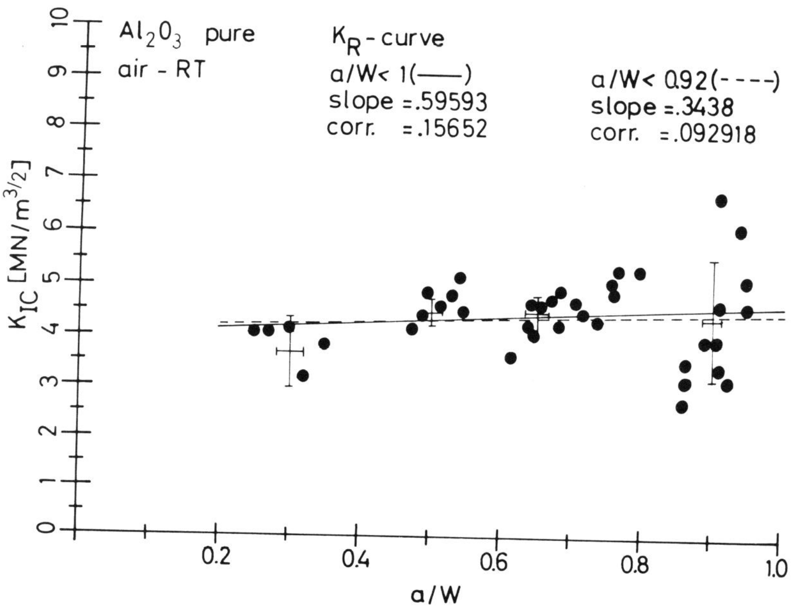

Figure 6 K_R-curve for Al_2O_3-fk

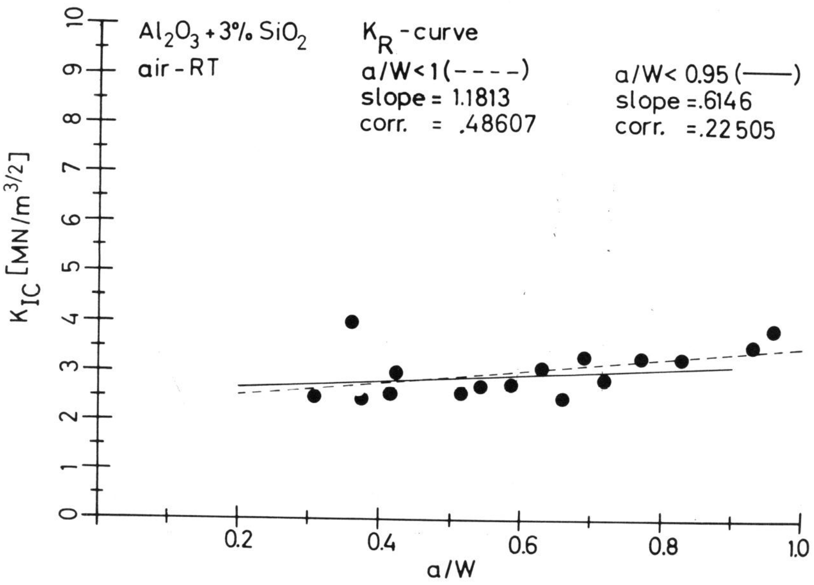

Figure 7 K_R-curve for Al_2O_3-S