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Effects of loading rates, notch root radius and specimen thickness on fracture toughness in bulk metallic glasses

Kazutaka Fujita [a,*], Akinori Okamoto [b], Nobuyuki Nishiyama [c], Yoshihiko Yokoyama [d], Hisamichi Kimura [d], Akihisa Inoue [d]

[a] *Department of Mechanical Engineering, Ube National College of Technology, Ube, Japan*
[b] *Ube National College of Technology, Ube, Japan*
[c] *RIMCOF-Tohoku University Laboratory, Institute for Materials Research, Tohoku University, Sendai, Japan*
[d] *Institute for Materials Research, Tohoku University, Sendai, Japan*

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Abstract

The fracture toughness (K_Q) tests were carried out in order to study the effect of loading rate ($\dot{K}$), notch root radius (R) and specimen thickness (B) on the K_Q in Zr-based bulk glassy alloys (BGAs). The plane strain fracture toughness K_{IC} of the BMG of $Zr_{50}Cu_{40}Ni_{10}$ at.% prepared by an arc tilt casting method showed a large value of 53 MPa m$^{1/2}$ under the conditions satisfying ASTM E399. With $\dot{K}$ of about 0.1 MPa m$^{1/2}$ s^{-1}, there were cases that the K_Q exhibited more than 100 MPa m$^{1/2}$. The K_Q increased with increasing R even for smaller R of 30 μm, and K_Q exhibited more than 120 MPa m$^{1/2}$ with R of more than 90 μm. K_Q decreases a little with decreasing the B from 2.3 to 0.12 mm was shown. In these cases, the estimated plane stress plastic zone sizes agreed well with the length of shear bands near the fatigue crack tips or notch roots on specimen surfaces.

Keywords: Amorphous materials; Casting; Scanning electron microscopy; X-ray diffraction

1. Introduction

It is important for application of the very high strength bulk glassy alloys (BGAs) to machine structural materials to clarify the value of fracture toughness (K_Q), as the conventional very high strength crystalline alloys usually show small K_Q. Therefore, the K_Q tests of BGAs have been carried out according to the standard of ASTM E399 [1–5]. However, the verification of whether the standard is effective for BGAs has not been yet established.

In this report, the influences of the loading rate ($\dot{K}$) and specimen thickness (B) on K_Q were examined using the specimens of Zr-based BGAs with a fatigue crack. The influence of the notch root radius (R) on the notched toughness was also examined. Fracture mechanisms were studied through the specimen surface and fracture surface observations using SEM. The toughness data obtained on specimens which do not satisfy the plane strain condition or contain no fatigue cracks are reported as K_Q instead of plane strain fracture toughness (K_{IC}) because the specimens do not satisfy the standard of ASTM E399.

2. Experimental

The material for examined the influences of $\dot{K}$ and R on the K_Q was a BGA of $Zr_{50}Cu_{40}Ni_{10}$ at.% prepared by an arc melt tilt casting method (tensile strength σ_B: 1.82 GPa) [6], and the material examined for the influence of B on the K_Q was a BGA of $Zr_{65}Cu_{15}Ni_{10}Al_{10}$ at.% prepared by a powder extrusion method (σ_B: 1.44 GPa, a commercial material of YKK Corp.).

K_Q tests were conducted using standard compact specimens in accordance with ASTM E399. The size of specimens used to examine the influence of $\dot{K}$ and R was $B = 2$ and with $W = 8$ mm for the influence of B was $B = 0.12$–2 and $W = 8$ mm, $B = 1$ and $W = 4$ mm, and $B = 2.3$ and $W = 9.2$ mm. Notch was machined by a wire electrical discharge machine (EDM). The notched toughness specimens contained notches with R of about 29, 35 and 95 μm. The root of notch was finished by a diamond wire saw or the wires for EDM pasted with a polishing material in order to remove the heat affected zone after machining the notch by EDM.

Fatigue pre-cracks were induced by a servohydraulic fatigue machine with a length of more than 1.3 mm at a stress ratio of 0.1 and a test frequency of 10 Hz. The maximum ΔK levels were applied at less than 6 MPa m$^{1/2}$. Fracture toughness tests were performed using the same machine. The $\dot{K}$s of about 0.1, 1.0 and 100 MPa m$^{1/2}$ s^{-1} were used for examining the effect of $\dot{K}$, and $\dot{K}$ of

* Corresponding author.
E-mail addresses: fujita@ube-k.ac.jp (K. Fujita), rimcofnn@imr.tohoku.ac.jp (N. Nishiyama), yy@imr.tohoku.ac.jp (Y. Yokoyama), hisami@imr.tohoku.ac.jp (H. Kimura), ainoue@imr.tohoku.ac.jp (A. Inoue).

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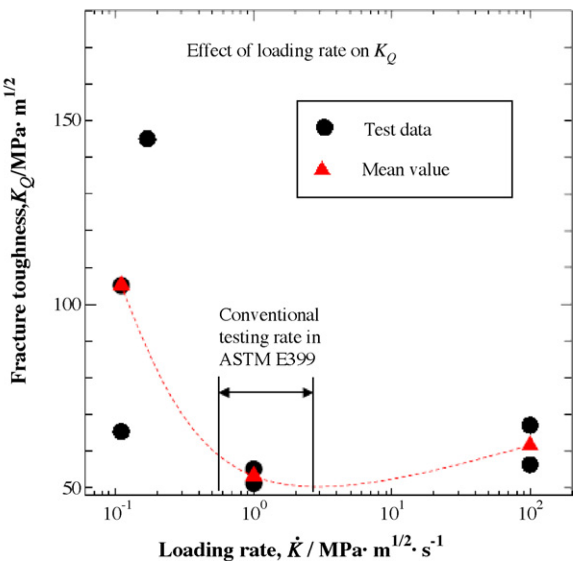

Fig. 1. Relationship between fracture toughness K_Q and loading rate $\dot{K}$.

1.0 MPa m$^{1/2}$ s^{-1} was used in the other tests. Measurements of crack length and the *R*, and observations of specimen surfaces and fracture surfaces were conducted using a metallographic microscope and SEM.

3. Results and discussion

3.1. Effect of loading rate

Fig. 1 shows the relationship between K_Q and $\dot{K}$. For $\dot{K}$ = 1.0 MPa m$^{1/2}$ s^{-1} satisfying the E399, K_Q approximately satisfied the plane strain condition as shown in Table 1, that is $B \fallingdotseq 2.5(K_Q/\sigma_y)^2$, and therefore the K_Q value was considered to be K_{IC} with a value of about 53 MPa m$^{1/2}$.

When $\dot{K}$ is small (0.1 MPa m$^{1/2}$ s^{-1}), K_Q had a very large value more than 100 MPa m$^{1/2}$. In these cases, the plane strain conditions were not satisfied (see Table 1). A clear variation of K_Q in the $\dot{K}$ range of 1–100 MPa m$^{1/2}$ s^{-1} was not observed and remained in the range 51–67 MPa m$^{1/2}$.

Figs. 2 and 3 show shear band morphology near the fatigue crack tips on the specimen surfaces and fracture surface mor-

Table 1
Relationship between fracture toughness K_Q, loading rate $\dot{K}$, slip band length and plane stress plastic zone size r_p

Specimen no. (*B* = 2 mm, *W* = 3 mm)	$\dot{K}$ (MPa m$^{1/2}$ s^{-1})	Slip band length on front and back surfaces		K_Q (MPa m$^{1/2}$)	$2.5(K_Q/\sigma_y)^2$ (mm)	r_p (μm)
		H (μm)	*V* (μm)			
CT-15-L	0.11	611	910	105.0	8.32	1060
CT-13-L	0.17	1735	1940	134.1	13.57	1729
CT-17-L	0.11	340	355	65.3	3.22	410
Mean	0.13	895	1068	101.5	7.8	991
CT-10-L	1	290	290	55.1	2.29	292
CT-18-L	1	294	300	51.2	1.98	252
Mean	1	292	295	53.2	2.1	272
CT-12-L	100	382	357	67.0	3.39	431
CT-16-L	100	353	335	56.3	2.39	305
Mean	100	368	346	61.6	2.9	365

B and *W*: specimen thickness and width, respectively; *H* and *V*: horizontal and vertical directions to the loading axis; r_p: plastic zone size under plane stress condition, $(K_Q/\sigma_y)^2/\pi$.

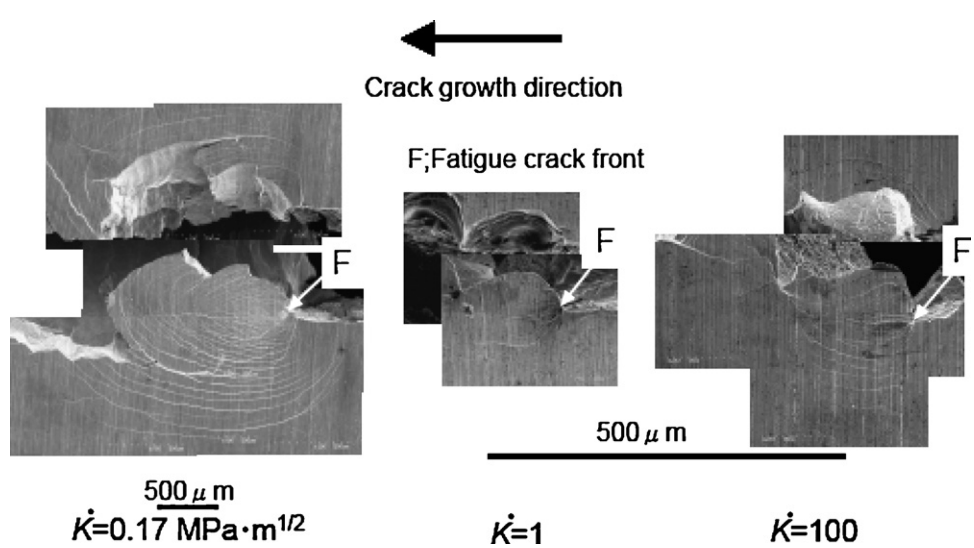

Fig. 2. Slip bands morphology near the fatigue crack tips on the specimen surfaces in different loading rates $\dot{K}$s.

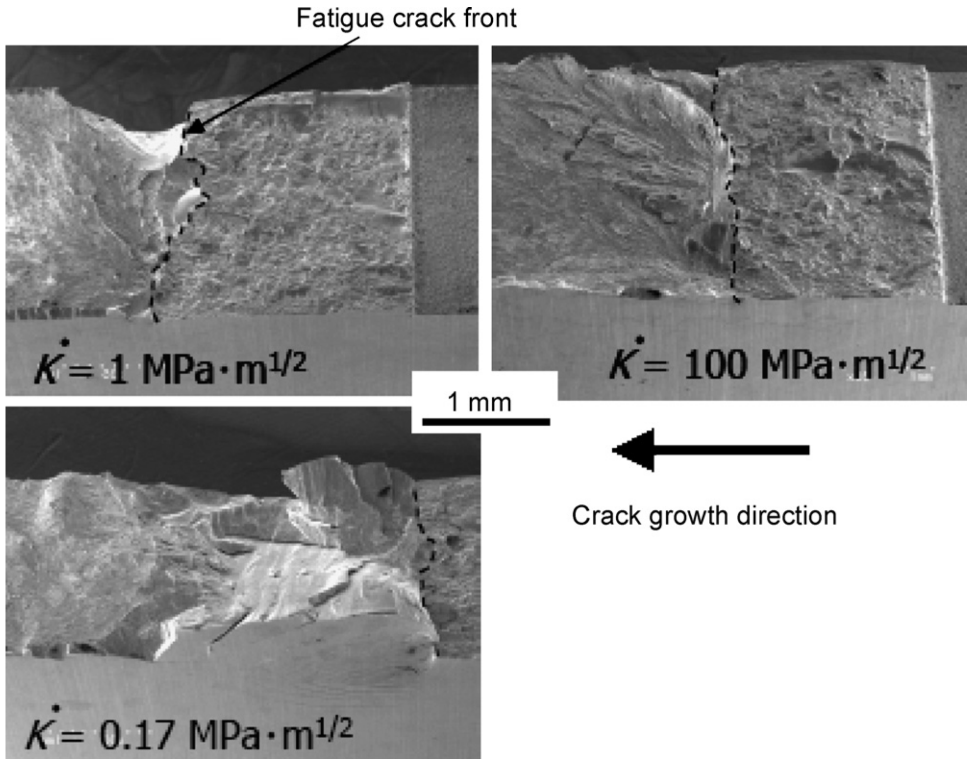

Fig. 3. Fracture surface morphology in different loading rates $\dot{K}$s.

phology, respectively. In the case where K_Q exhibited very large value for $\dot{K}$ nearly equal 0.1 MPa m$^{1/2}$ s^{-1}, many long shear bands of plane stress type are observed on the specimen surfaces, and plane stress type fracture is also observed through the thickness. When $\dot{K}$ is in the range of 1–100 MPa m$^{1/2}$ s^{-1}, short shear bands of plane stress type are observed on the specimen surfaces, and in the inner region of the specimen a crack propagated a short length by plane strain type, followed by unstable fracture perpendicular to the loading axis by tearing and showed equiaxed vein patterns. The length of shear bands on specimen surfaces corresponds well to the plane stress plastic zone size (rp) (see Table 1).

From these observations, the cause of the BGA's large K_Q with slow loading rate $\dot{K}$ (0.1 MPa m$^{1/2}$ s^{-1}) is thought to be related to the ease of cooling at the viscous shear regions. The lower temperature increased the viscous shear resistance; the number of shear bands increased long shear bands were formed. Slip bands of plane stress type cut each other in the inside of the specimen, producing many small steps which become obstacles for shear. This is how we explain the very large K_Q at small $\dot{K}$.

3.2. Effect of notch root radius

Fig. 4 shows the relationship between K_Q and R. The K_Q increases with increasing R, to more than 120 MPa m$^{1/2}$ for radius of more than 90 μm. The K_Q for R of 30 μm shows larger value compared with that on fatigue cracked specimen. In crystalline alloys K_Q is not affected by the notch root radius below about 150 μm [7,8]. In comparison with this result, the Zr-based BGA can be considered to be a material sensitive to R compared with the crystalline alloys.

Shear bands occur more widely and numerously along the notch root and propagate deeper in the plane stress direction with increasing R as shown in Fig. 5. Fig. 6 shows the fracture surface morphology for different Rs. In the inner region of the specimen, shear of plane stress type becomes larger with increasing R.

Table 2 shows the relationship between the K_Q, R, shear band length and plastic zone size r_p. The r_p was calculated using

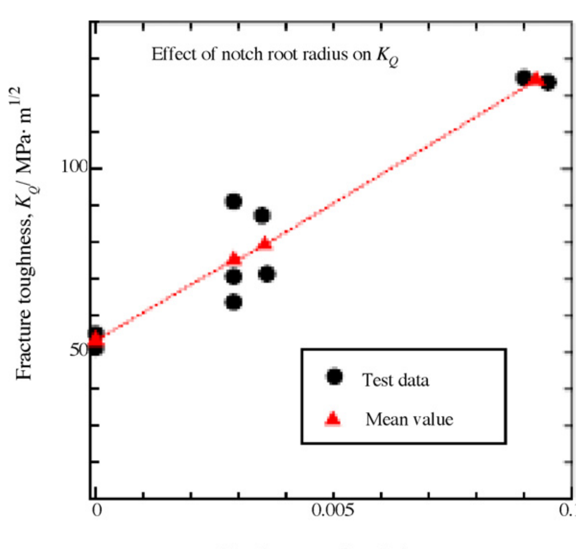

Fig. 4. Relationship between fracture toughness K_Q and notch root radius R.

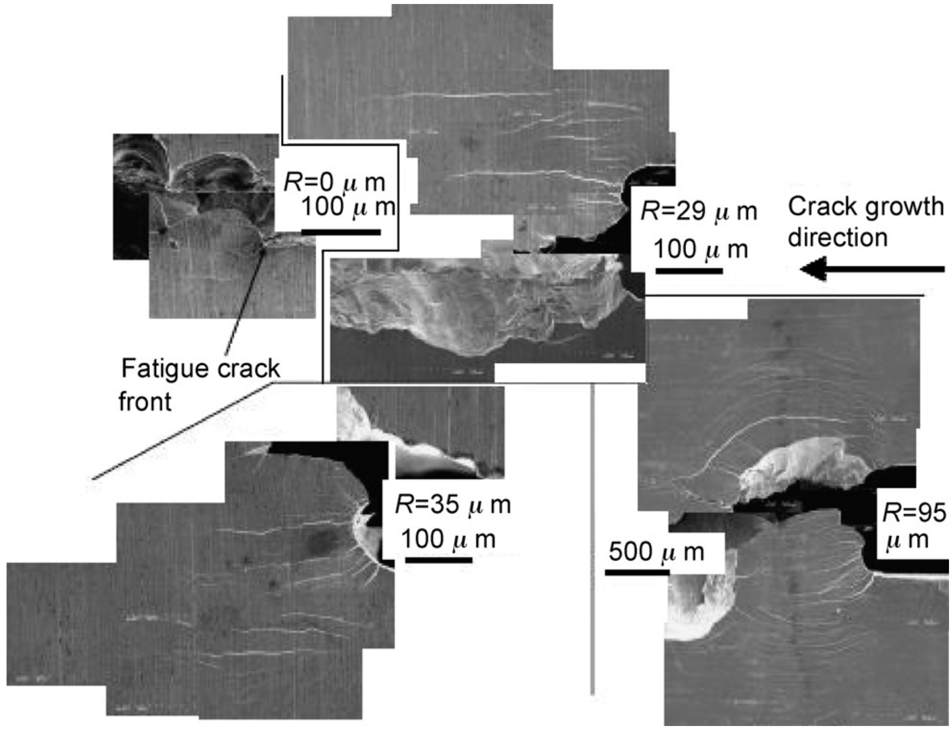

Fig. 5. Slip band morphology near fatigue crack tips on specimen surfaces for different notch root radii *R*.

K_Q obtained by treating a notch length as a crack length. The shear band length on specimen surfaces corresponds with r_p for different $\dot{K}$s.

It is thought that K_Q increased with increasing *R* is due to decrease of the stress concentration. As a result, many shear bands occur along the notch root and grow gradually. Consequently the heating in each shear band was repressed and the specimen with a large *R* as those with low $\dot{K}$, that is, low temperature at shear regions, and the specimen tolerating larger load.

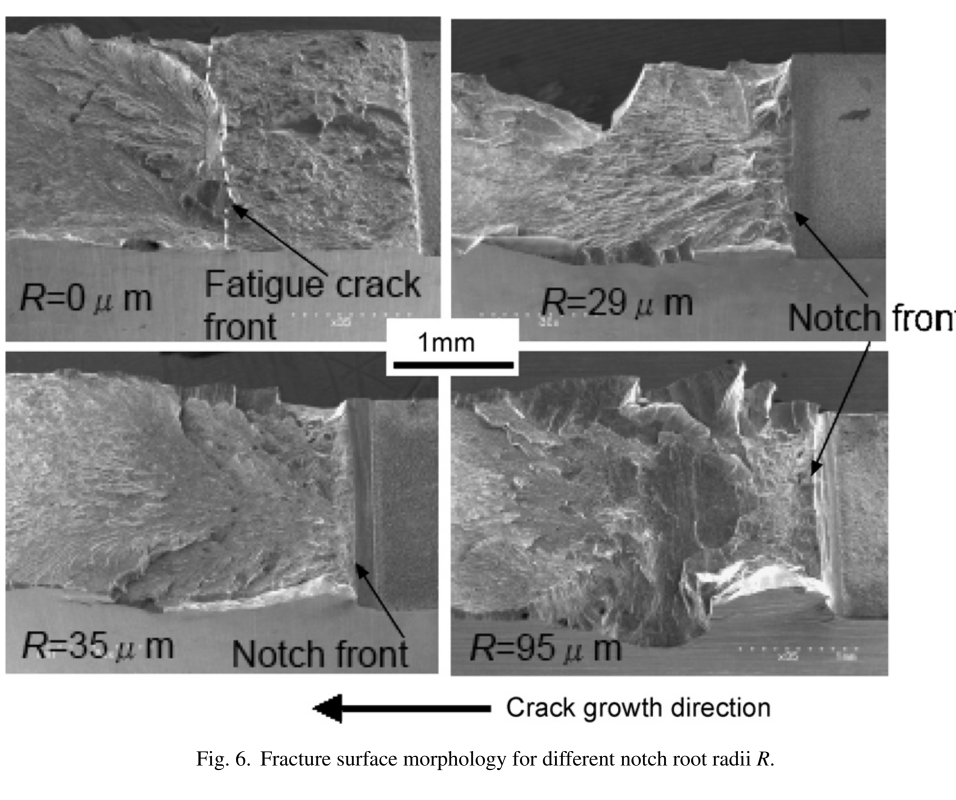

Fig. 6. Fracture surface morphology for different notch root radii *R*.

Table 2
Values fracture toughness K_Q, notch root radius R, slip band length and plane stress plastic zone size r_p

Specimen no. ($B = 2$ mm, $W = 8$ mm)	R (μm)	Slip band length on front and back surfaces		K_Q (MPa m$^{1/2}$)	$2.5(K_Q/\sigma_y)^2$ (mm)	r_p (μm)
		H (μm)	V (μm)			
CT-10-R	0	265	288	55.1	2.29	292
CT-18-R	0	294	300	51.2	1.98	252
Mean	0	280	294	53.2	2.13	272
CT-04-R	29	435	320	70.7	3.77	481
CT-05-R	29	343	293	63.7	3.06	390
CT-06-R	29	823	397	91.2	6.28	800
Mean	29	534	337	75.2	4.37	557
CT-07-R	36	480	460	71.4	3.85	490
CT-08-R	35	524	548	87.3	5.75	733
Mean	36	502	504	79.4	4.80	611
CT-01-R	90	1385	1825	124.9	11.77	1500
CT-03-R	95	1325	1960	123.7	11.55	1471
Mean	93	1355	1893	124.3	11.66	1486

3.3. Effect of specimen thickness

Fig. 7 shows the relationship between K_Q and B. The K_Q decreases a little with decreasing the B from 2.3 to 0.12 mm. The same thickness effects had been reported for metallic amorphous ribbons by Ocelik et al. [9].

The average K_Q of this BGA is as small as 11 MPa m$^{1/2}$ and B satisfies the plane strain conditions (more than 0.15 mm). In this experiment the B was varied from 2.3 to 0.12 mm. For B of 0.12 mm (less than 0.15 mm) plane strain condition was still satisfied because K_{IC} decreased further. Since the K_{IC} of the BGA was small and every result satisfied plane strain conditions, the thickness effect on the K_{IC} is not necessarily clear. The effect of B on K_{IC} must be re-examined using a BGA having large K_{IC}.

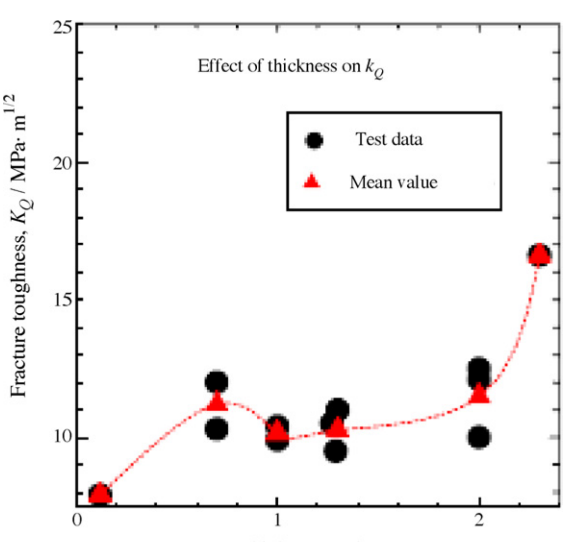

Fig. 7. Relationship between fracture toughness K_Q and specimen thickness B.

4. Conclusions

In the Zr-based bulk glassy alloys (BGAs), fracture toughness was examined using different loading rates ($\dot{K}$) and specimen thickness (B), and notched toughness was also examined using different notch root radii (R). The results obtained are as follows:

1. The BGA of $Zr_{50}Cu_{40}Ni_{10}$ at.% synthesized by arc tilt casting exhibited a large plane strain fracture toughness K_{IC} of 53 MPa m$^{1/2}$.
2. Fracture toughness was more than 100 MPa m$^{1/2}$ when $\dot{K}$ was slow (0.1 MPa m$^{1/2}$ s^{-1}).
3. The notched toughness increased with increasing R from about 30 μm, and reached more than 120 MPa m$^{1/2}$ for R of more than 90 μm.
4. There was a tendency for fracture toughness to decrease with decreasing thickness B.

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