Journal of the European Ceramic Society 17 (1997) 1587-1590

PII: S0955-2219(97)00022-8
0955-2219/97/$17.00

Fatigue Crack Growth Rate of Zirconia Ceramics

Jiun-Ren Hwang, Jiunn-Long Shih & Ming-Chang Jeng

Department of Mechanical Engineering, National Central University, Chung-Li, Taiwan 320

(Received 10 July 1996; accepted 3 February 1997)

Abstract

This paper investigates the fatigue crack growth behaviours of 3 mol% Y_2O_3 partially stabilized zirconia (Y-PSZ). Stable fatigue crack growth rate under tension-tension loading was measured from the indentation flaw under three-point bending. The influence of stress ratio on the fatigue crack growth rate was also studied. The results show that the relation between fatigue crack growth rate and effective stress intensity factor for Y-PSZ can be expressed as: $dc/dN = C(K_{eff})^n$. Under a given K_{eff} level, the fatigue crack growth rate decreases with increasing stress ratio for Y-PSZ ceramics. © 1997 Elsevier Science Limited.

1 Introduction

Linear elastic fracture mechanics (LEFM) is widely used in the analysis of the mechanical behaviours of ceramics. Fracture toughness, K_c, and fatigue crack growth rate, dc/dN, are the two most important material properties in LEFM. However, no ASTM standard test method has been established for evaluating such properties. Various types of specimens and precracking methods have been adopted. Among these, the indentation-microfracture method[1] is the most convenient one to evaluate the fracture toughness of ceramics. As a consequence of different analyses, numerous equations have been proposed and applied to both the Palmqvist and the radial median crack systems.[2–6] However, there is little literature on the fatigue crack growth as compared to the fracture toughness. Sglavo and Green[7] used an interrupted static fatigue test to evaluate the threshold stress intensity factor in ceramic materials. Zhang and Edwards[8] studied the small, short and long fatigue crack growth behaviours in silicon nitride. They found that the anomalous growth of small cracks may be attributed to reduced grain bridging which occurs along the wake. Raghuraman and Stubbins[9] investigated the effects of grain size and stress ratio on the subcritical crack growth of two monolithic ceramics. In this study, fatigue crack growth rate from the indentation flaw was investigated for Y-PSZ. The indentation crack was analyzed using fracture mechanics to take into account of the residual stress component. Also, an effective stress intensity factor for crack growth was evaluated.

2 Experimental procedure

The bulk density of the sintered specimens used in this study was 6·097 g cm^{-3} (99% of theoretical), and the bending strength was 895 MPa. The dimensions of specimen were 3 mm × 4 mm × 18 mm. Pre-cracked specimens were prepared by using Vickers diamond pyramid indenter. The indentation was made at the center of the polished face of each specimen so that one of the pyramid diagonals was aligned with the longitudinal axis of the specimen. The indentation load was 196 N and the holding time at the peak load was 15 s. The tensile faces of all specimens were polished with 1 μm diamond paste to remove the residual compressive stress due to initial grinding and also to facilitate the measurement of crack length.

Fatigue tests were conducted under three-point bending with span 16 mm. A sinusoidal wave of 40 Hz and stress ratios, R, of 0·1, 0·3 and 0·5 were used. The crack length was measured intermittently at the end of every hundred or thousand cycles with an optical microscopy at a magnification of 200×. In the calculation of the stress intensity factor, the shape of the crack was approximated as a semi-elliptical type based on the fractographic observation (see Fig. 1). The fractographs were examined with scanning electron microscopy. The

Fig. 1. Fatigue fractograph.

average grain size is 0·5 μm which is determined by the linear intercept method.

3 Results and discussion

The crack growth rates, dc/dN, versus K_{max} of Y-PSZ at various stress ratios are plotted in Figs 2–4. They show that the growth rate reduces with increasing stress intensity factor in the lower K_{max} region and reaches the minimum value K_t in every test condition. However, the stress intensity factor exceeds the value of K_t; the growth rate increases with increasing stress intensity factor. For the test with $R = 0{\cdot}5$ and $P_{max} = 176$ N, no reflection point is observed. It means that the crack propagation stops if stress intensity factor reaches the threshold value. These crack growth characteristics shown in Figs 2–4 do not agree with Dauskardt *et al.*'s results.[10] It is due to the residual stress effect around the indentation-induced crack on the maximum stress intensity factor.

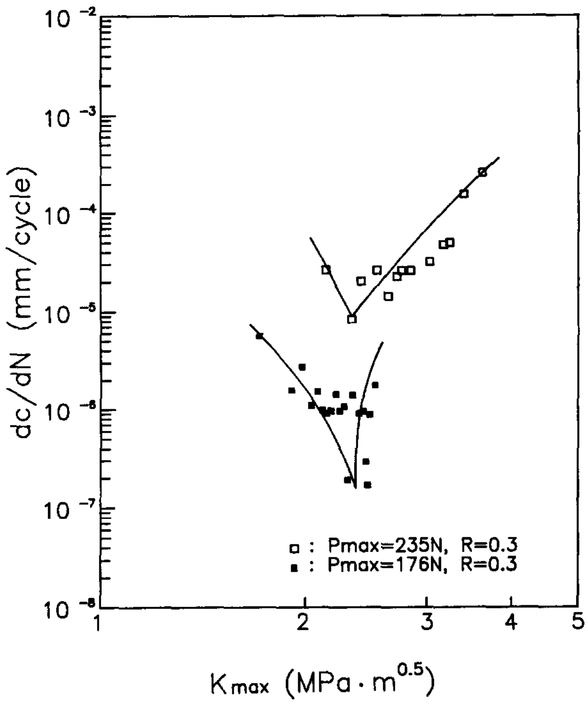

Fig. 3. Plots of dc/dN versus K_{max} for $R = 0{\cdot}3$.

The maximum stress intensity factor for a semi-elliptical crack occurs at the intersection of the

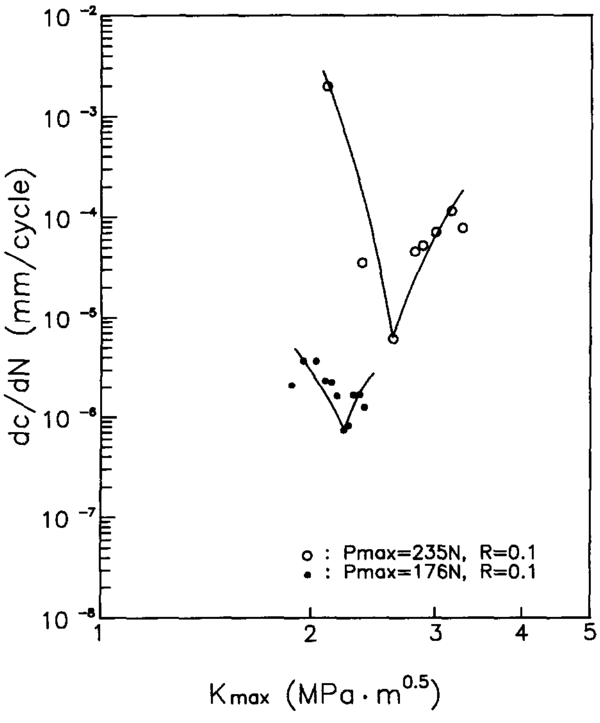

Fig. 2. Plots of dc/dN versus K_{max} for $R = 0{\cdot}1$.

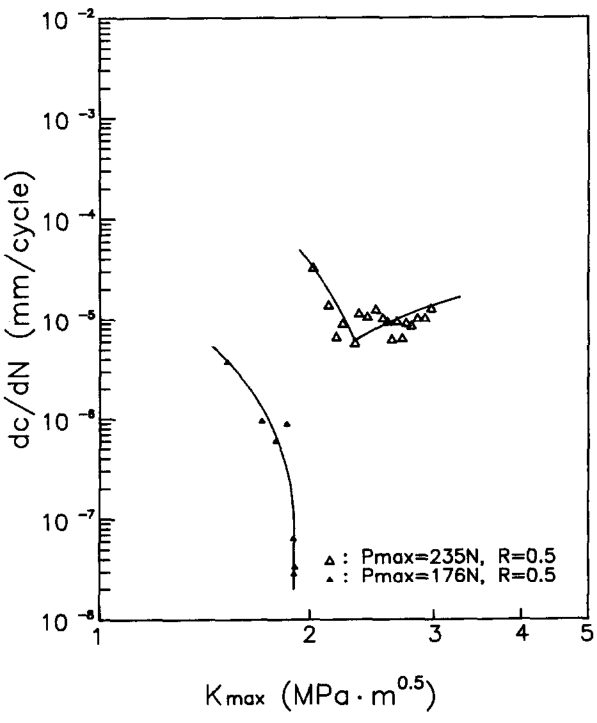

Fig. 4. Plots of dc/dN versus K_{max} for $R = 0{\cdot}5$.

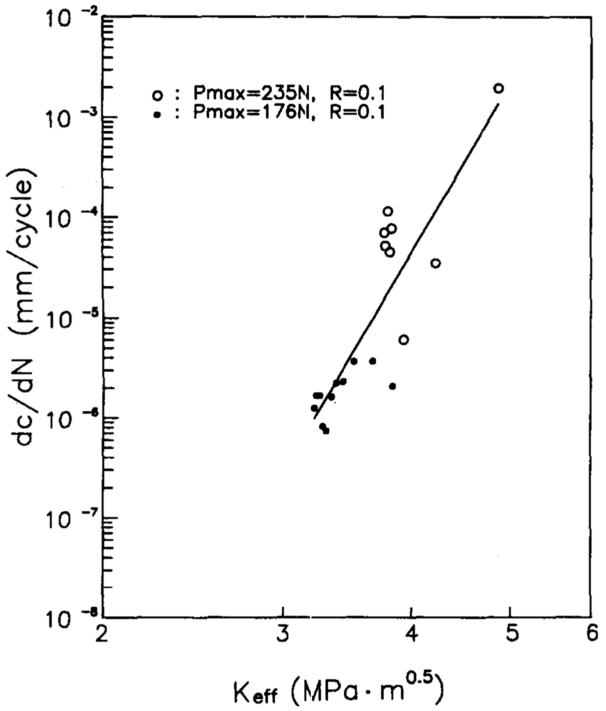

Fig. 5. Plots of dc/dN versus K_{eff} for $R = 0{\cdot}1$.

minor axis and the crack front. The stress intensity factor K_{max} can be calculated as follows:[11]

$$K_{max} = M_b \sigma_b \sqrt{\pi d}/\phi \tag{3}$$

where d is the crack depth, ϕ the complete elliptic integral of the second kind, and M_b is a correction factor. The plastic deformation formed by a Vickers

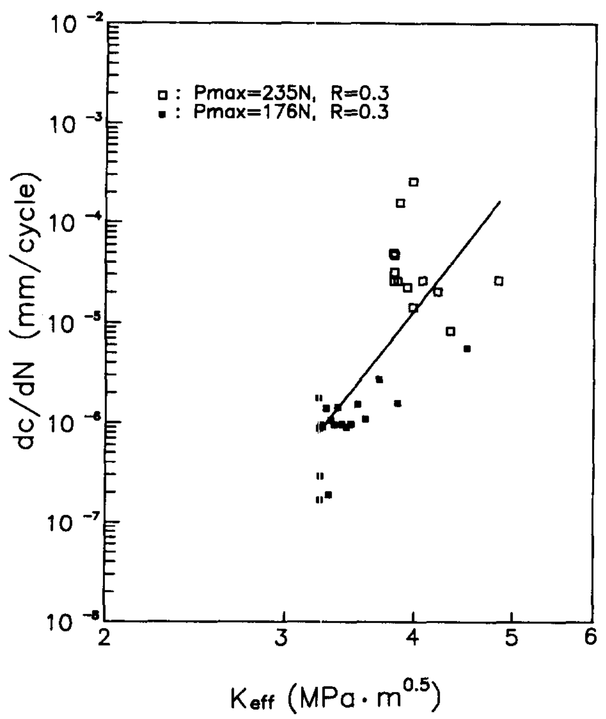

Fig. 6. Plots of dc/dN versus K_{eff} for $R = 0{\cdot}3$.

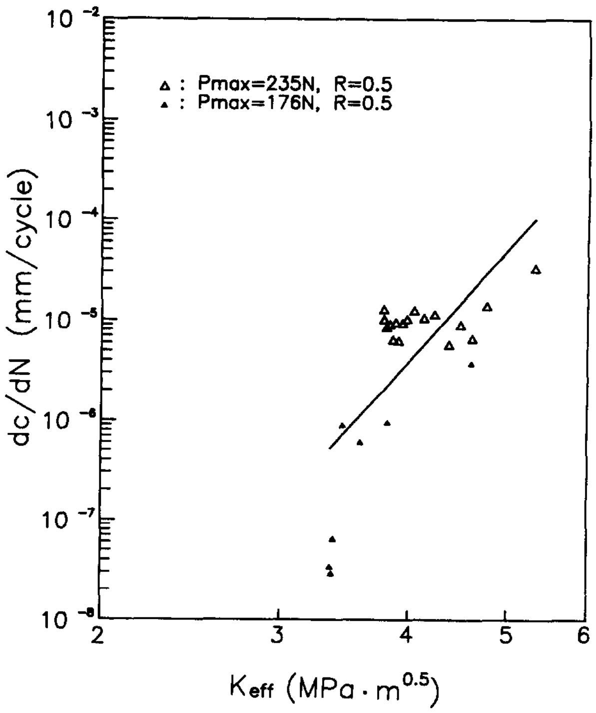

Fig. 7. Plots of dc/dN versus K_{eff} for $R = 0{\cdot}5$.

indentation produces a residual stress field around an induced crack. The stress intensity factor associated with the residual stress, K_r, is given as:[12]

$$K_r = X_r P_i / c^{1{\cdot}5} \tag{4}$$

where P_i is indentation peak load, c is half crack length and X_r is a material constant depending on

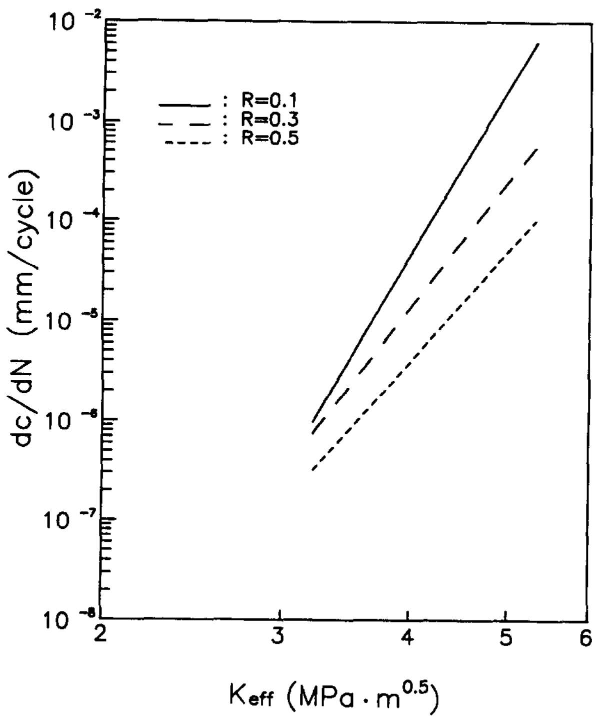

Fig. 8. Plots of dc/dN versus K_{eff} for various stress ratios.

Table 1. C and n value of fatigue crack growth rate $dc/dN = C(K_{eff})^n$

Stress Ratio	C	n
0·1	1·27E-15	17·5
0·3	1·55E-13	13·2
0·5	4·83E-13	11·5

the ratio of Young's modulus to hardness. In all, the peak value of an effective stress intensity factor for crack growth is represented by

$$K_{\rm eff} = K_{\rm max} + K_r \quad (5)$$

The crack growth curves reploted as dc/dN versus $K_{\rm eff}$ are shown in Figs 5–8. It is observed that the data can be correlated approximately by a linear relationship with some scatter. This phenomenon agrees with the results of Hoshide.[13] The lines in Figs 5–7 are expressed by the following form

$$dc/dN = C(K_{\rm eff})^n \quad (6)$$

where the coefficient C and the power n are determined by the least square method and the values are shown in Table 1. Comparisons of the experimental results obtained for various stress ratios show that the crack growth rate increases as stress ratio decreases (see Fig. 8).

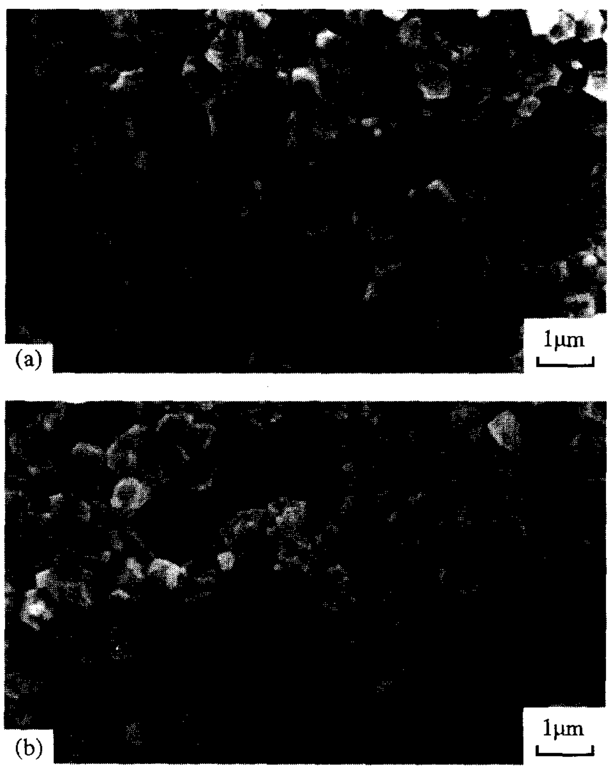

Fig. 9. Fracture surfaces of fatigue specimens: (a) fatigue region, (b) unstable fracture region.

The fatigue fracture surfaces of Y-PSZ material tested under various stress ratios show no significant difference. In the fatigue growth region shown in Fig. 9(a), transgranular fracture is predominant. However, intergranular fracture shown in Fig. 9(b) is responsible for unstable fast fracture.

4 Conclusions

1. The relation between fatigue crack growth rate and effective stress intensity factor for Y-PSZ can be expressed in the following form: $dc/dN = C(K_{\rm eff})^n$.
2. Under a given $K_{\rm eff}$ level, the fatigue crack growth rate decreases with increasing stress ratio for Y-PSZ ceramics.

References

1. Palmqvist, S., Method att bestamma segheten hos sproda material, sarskilt hardmetaller. *Jernkontorets Ann.*, 1957, **141**, 300–307.
2. Binner, J. G. P. and Stevens, R., The measurement of toughness by indentation. *Trans. Journal of British Ceram. Soc.*, 1985, **83**, 167–172.
3. Ponton, C. B. and Rawlings, R. D., Vickers indentation fracture toughness test part 1: review of literature and formulation of standardized indentation toughness equations. *Mater. Sci. Tech.*, 1989, **6**, 865–872.
4. Niihara, K., A fracture mechanics analysis of indentation-induced Palmqvist crack in ceramics. *Journal of Mater. Sci. Let.*, 1983, **2**, 221–223.
5. JIS Standard R1601. *Testing method for flexural strength (modulus of rupture) of high performance ceramics.* Japanese Standards Association, 1981.
6. Lankford, J., Indentation microfracture in the Palmqvist crack regime: implications for fracture toughness evaluation by the indentation method. *Journal of Mater. Sci. Let.*, 1982, **1**, 493–496.
7. Sglavo, V. M. and Green, D. J., Interrupted static fatigue test for evaluating threshold stress intensity factor in ceramic materials: a numerical analysis. *J. Europ. Ceram. Soc.*, 1995, **15**, 777–785.
8. Zhang, Y. H. and Edwards, L., Small, short and long fatigue crack growth in an advanced silicon nitride ceramic material. *Scripta Metall. et Mater.*, 1996, **34**, 1561–1566.
9. Raghuraman, S. and Stubbins, J. F., Fatigue crack growth in advanced in ceramic materials. In *Ceramic Engineering and Science Proceedings*. Am. Ceram. Soc., 1993, **14**, 237–245.
10. Dauskardt, R. H., Yu, W. and Ritchie, R. O., Fatigue crack propagation in transformation-toughened zirconia ceramic. *Journal of Am. Ceram. Soc.*, 1987, **70**, C248–252.
11. Shah, R. C. and Kobayashi, S. S., Stress intensity factor for an elliptical crack approaching the surface of a plate in bending. In *Stress Analysis and Growth of Cracks, Proceedings of the 1971 National Symposium on Fracture Mechanics*. ASTM STP 513. American Society for Testing and Materials, Philadephia, 1972, pp. 3–21.
12. Anstis, G. R., Chantikul, P., Lawn, B. R. and Marshall, D. B., A critical evaluation of indentation techniques for measuring fracture toughness: I, direct crack measurements. *Journal of Am. Ceram. Soc.*, 1981, **64**, 533–538.
13. Hoshide, T., Ohara, T. and Yamada, T., Fatigue crack growth from indentation flaw in ceramics. *Int. Journal of Fracture*, 1988, **37**, 47–59.