JOURNAL OF MATERIALS SCIENCE 31 (1996) 3535–3539

Cyclic fatigue crack growth of SiC_w/Y-TZP composites: long- and short-crack behaviour

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Cyclic fatigue crack growth behaviour has been investigated for 10 vol % SiC_w/Y-TZP composites with grain sizes varying from 1.50–2.00 μm in a residual stress field. To investigate the effect of precracking procedure, cyclic fatigue tests were performed on unannealed specimens using the four-point bending method under two conditions: (a) with a sharp crack and precracking procedure, and (b) with a natural sharp flaw. For all specimens in both conditions, an overall V-shaped da/dN versus K_{app} relation was obtained. However, for the specimens without precracking, the da/dN had an unusual dependence on the applied stress intensity, giving a zigzag V-shaped curve. Explanations for these different results for the two conditions are discussed in terms of crack-tip shielding effects and residual stress field.

1. Introduction

The importance of fatigue crack growth in engineering ceramics has been recognized in recent years [1, 2]. True cyclic fatigue effects have been observed in Mg-PSZ [3–6], alumina [7–9], Y-TZP [10–13] and Ce-TZP [14–16] ceramics with processing flaws, indentation cracks, and long sharp cracks. The majority of studies reported to date were on bending fatigue using smooth specimens and on fatigue crack growth using compact tension specimens. Efforts have also been made to understand the micromechanisms for this cyclic fatigue effect and the interactions between the fatigue and the crack-shielding effects caused by stress-induced t–m transformation, localized grain, and fibre (or whisker) bridging. It has been realized that the same toughening mechanisms, which lead to the crack-resistance, R, curve behaviour in a ceramic, are also responsible for the weakening in resisting cumulative damage due to cyclic fatigue [17]. In transformation-toughened zirconia-based ceramics, there has also been an attempt to establish the relations between the R-curve and cyclic fatigue [17, 18], although the failure mechanisms are not yet fully understood.

SiC whisker-reinforced yttria-stabilized tetragonal zirconia was selected for the present study. Fatigue behaviour of Mg-PSZ and Ce-TZP, which exhibit extensive plasticity by a mechanically induced phase transformation, have been studied [3, 6, 14, 16]. On the other hand, 3Y-TZP has only rather limited transformation plasticity [13]. However, in the present study, SiC_w/Y-TZP composites had relatively high fracture toughness but very low strength. The cyclic fatigue crack growth and stress-induced transformation were investigated. The effects of residual stress in composites has also been studied. An attempt was made to understand the interrelation between crack shielding and cyclic fatigue crack growth.

2. Experimental procedure

The ceramic composites chosen for the investigation were 3Y-TZP containing 10 vol % SiC whiskers. The SiC whiskers were 0.2–0.8 μm diameter and had an aspect ratio of up to 100, and the whiskers were partially oriented with the longitudinal axis perpendicular to the processing direction. Mechanical properties are listed in Table I.

Fatigue crack growth experiments were conducted using the four-point bending method. The specimen dimensions were as follows: width 8 mm, thickness 5 mm, and length 40 mm. The notch length was 0.25 times the specimen width, and the notch-root radius was 70 μm. The bend fixture had an inner span of 20 mm and an outer span of 30 mm. The notched bend specimens were first subjected to constant amplitude uniaxial cyclic compression loading with a stress range of − 50 to − 500 MPa at a cyclic frequency of 10 Hz to introduce a stable mode I fatigue precrack of up to 300 μm in length. To investigate the effect of precracking procedure with pre-existing t–m transformation, a parallel study was conducted using unprecracked specimens without a preformed transformation zone. All the specimens were unannealed to explore the effects of residual stress on fatigue behaviour.

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TABLE I Properties and grain sizes of 10 vol % SiC_w/Y-TZP composites

Materials SiC_w/Y-TZP	HP-temperature (°C)	K_{1c} ($MPa\,m^{1/2}$)	Four-point bending strength (MPa)	Grain size (μm)
I	1600	13.52 ± 0.14	950 ± 40	1.50
II	1650	14.01 ± 0.16	1036 ± 15.1	2.00

Following precracking, the specimens were subjected to four-point bending cyclic loading with a frequency of 10 Hz and a stress ratio, K_{min}/K_{max}, of 0.1. The stress intensity factors were evaluated by means of the following equation

$$K = \beta FB(\pi a)^{1/2} \quad (1a)$$

where

$$\beta = \frac{3(L-1)}{2BW^2} \quad (1b)$$

and $F = 1.122 - 1.40(a/W) + 7.33(a/W)^2 - 13.08(a/W)^3 + 14.0(a/W)^4$, and P is the applied load, L is the length of the lower span, l is the length of the upper span, B is the thickness, and W is the depth.

Electrical resistance measurements were used *in situ* to monitor crack lengths to a resolution better than ± 3 μm.

3. Results

3.1. Crack growth and transformation behaviour in a residual stress field under cyclic loading

Fig. 1 shows the crack growth behaviour of two composites under cyclic loading tests using unannealed specimens. For the SiC_w/Y-TZP(I) composite with grain size of 1.5 μm (Fig. 1a), crack growth took place in an almost continuous fashion under cyclic loading. In contrast, the SiC_w/Y-TZP(II) composite shows a stepwise crack growth behaviour (Fig. 1b) similar to Ce-TZP ceramics [17] caused by "autocatalytic" transformation. X-ray diffraction on composites specimens showed that little monoclinic phase could be detected in the static fatigue specimens, although 10%–20% transformation from t–m was observed for the overall cyclic fatigue specimens. This means accelerated transformation for cyclic fatigue specimens.

In Fig. 2, the crack extension curves of composites I and II are compared. It is evident that the curve shape of the composite I is distinctly different from the composite II, in that although the crack in the pre-cracked specimens initially grew rapidly, it soon ceased to grow over a certain range before it accelerated again at 82×10^3 cycles (Fig. 2a). In contrast, cracks in all the unprecracked specimens grew in a relatively steady way from the beginning. These results agree with the reports of Liu *et al.* [3].

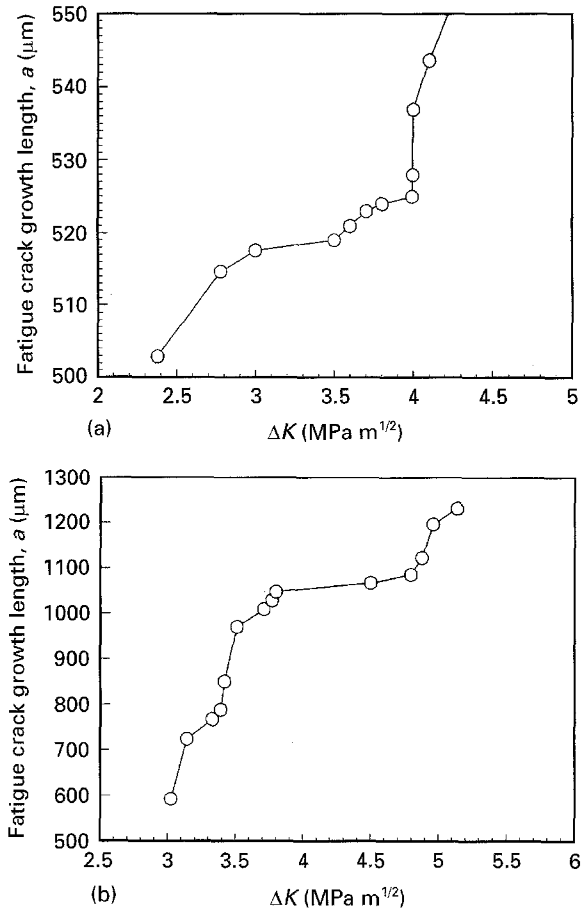

Figure 1 Crack growth behaviour under cyclic loading for (a) SiC_w/Y-TZP (I) and (b) SiC_w/Y-TZP (II) composites.

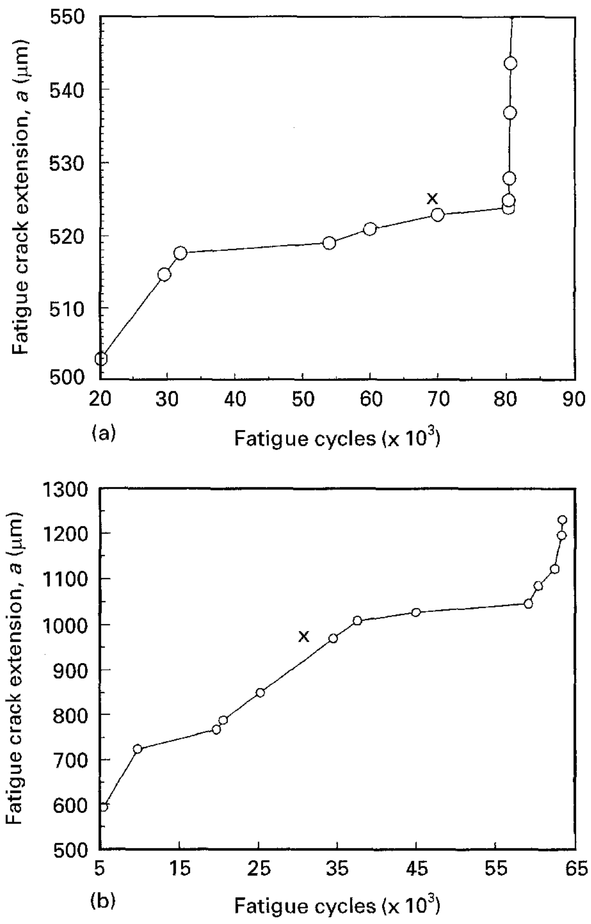

Figure 2 Crack extension versus fatigue cycles for (a) SiC_w/Y-TZP (I) and (b) SiC_w/Y-TZP (II) composites.

3.2. Crack growth rates versus ΔK curves

The crack growth rate in unannealed specimens has an unusual dependence on the applied stress intensity. This is shown in Fig. 3, where the growth rate is plotted against the stress intensity factor ranges, ΔK (or K_{max}), giving a V-shaped curve. The negative slope found for shorter cracks corresponds to the data to the left side of the inflection point "x" in Fig. 2. Such behaviour has been reported in the past and is generally termed "short-crack behaviour" [19]. Beyond a certain stress intensity factor, corresponding to a minimum crack growth rate, the normal fatigue crack growth behaviour gradually resumed and the positive dependence on the applied stress intensity factor is again obeyed. The fatigue crack growth can be described by the Paris power-law equation: $da/dN = A(\Delta K)^m$. However, there are some unusual aspects of the fatigue crack growth results for unprecracked specimens. The results indicate that for the SiC_w/Y-TZP(II) composite without precracking, "zigzag". V-shaped da/dN versus ΔK curves were observed, which is caused by the interaction between the "autocatalytic" shielding effect and the residual stress field. The values of m and A in the Paris-law equation are 16 and 9.04×10^{-19}, respectively.

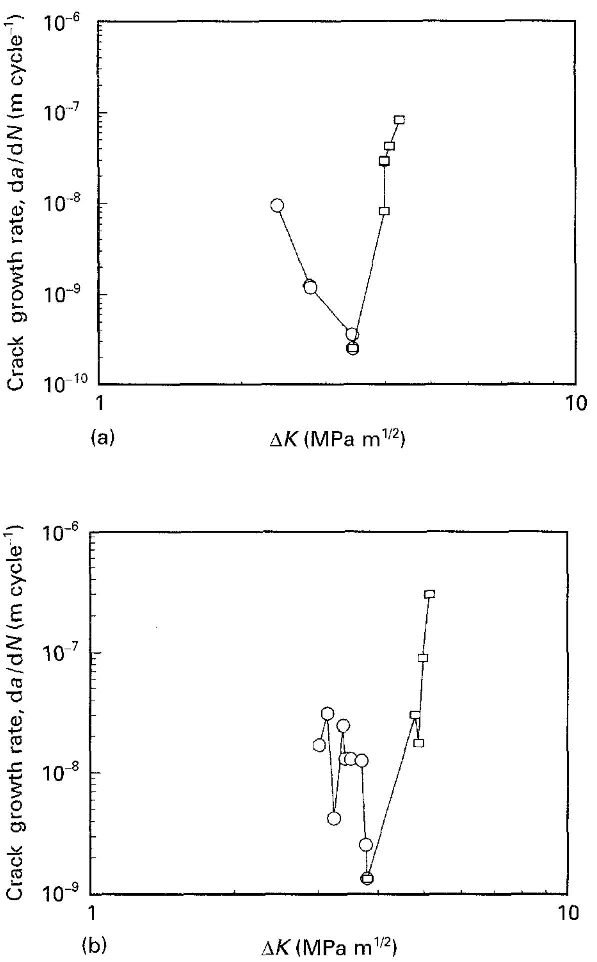

Figure 3 Fatigue crack growth rates versus applied stress intensity factor ranges for (a) SiC_w/Y-TZP (I) and (b) SiC_w/Y-TZP (II) composites. $R = 0.1, f = 10$ Hz. (○) Short cracks, (□) long cracks.

4. Discussion

4.1. Interrelations between crack shielding and cyclic fatigue crack growth in a residual stress field

4.1.1. Specimens without precracking

For SiC_w/Y-TZP(II) without precracking, and therefore no preformed t–m transformation zone, but in contrast with a pronounced "autocatalytic transformation behaviour" [17], the cyclic fatigue damage may be initially accumulated at the crack tip within the t–m transformation zone. When the damage reaches a critical state, the crack jumps forward with further "autocatalytic" t–m transformation. Damage accumulates again at the new crack tip, and unstable crack growth occurs, subsequently being arrested within the newly formed "autocatalytic" transformation zone. The results lead to a series of discontinuous fatigue crack growths with possible formation of striations. These fatigue striations have been reported in Y-TZP ceramics [13]. Similar discontinuous fatigue crack growth behaviour associated with "zigzag" da/dN versus ΔK curves have also been observed in Ce-TZP [17] and many polymeric materials [20].

4.1.2. Specimens with precracking

For SiC_w/Y-TZP(I) with the preformed t–m transformation zone after compression–compression fatigue tests, the continuous fatigue crack growth behaviour associated with "smooth" V-shape da/dN versus ΔK curves corresponds to the fatigue crack growth in a residual stress field. The presence of residual stress will alter the growth mechanics, as discussed as follows.

4.2. Cyclic fatigue crack growth mechanisms

For ceramics, the crack tip effective stress intensity factor, K_{eff}, can be described by the following equation

$$K_{eff} = K_{app} + K_{res} - K_s \quad (2)$$

where K_{res} is a stress intensity factor due to the residual stress, K_s is the shielding effect due to the stress-induced t–m transformation developed under cyclic loading [4]

$$K_s = \beta K_{max} \quad (3)$$

As recognized by Hoshida *et al.* [21], the V-shaped growth behaviour can be qualitatively understood using linear elastic fracture mechanics developed for indentation fracture. The residual stress intensity factor is customarily represented as

$$K_{res} = \alpha P a^{-3/2} \quad (4)$$

where P is the indentation load and α is a material and geometrical constant. Equation 4 can be further simplified by noting that

$$K_{1c} = \alpha P a_0^{-3/2} \quad (5)$$

where K_{1c} is the fracture toughness and a_0 is the crack length determined from the initial indentation

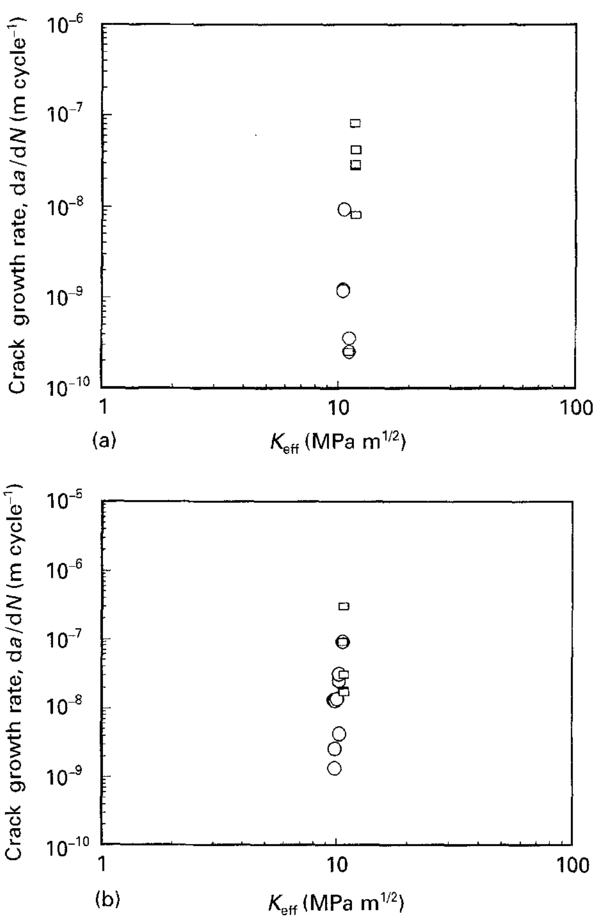

Figure 4 Fatigue crack growth rates versus effective stress intensity factor for (a) SiC_w/Y-TZP (I) and (b) SiC_w/Y-TZP (II) composites. $R = 0.1, f = 10$ Hz. (○) Short cracks, (□) long cracks.

experiment. Thus

$$K_{res} = K_{1c}(a_0/a)^{3/2} \tag{6}$$

For the present study, where a_0 is the precrack length or the notch length, a is the crack extension under cyclic loading. With those derivations, Equation 2 can be written as

$$K_{eff} = (1 - \beta)K_{max} + K_{res} \tag{7}$$

According to Equation 7, a universal curve is obtained, shifting the data for each material. The result of normalizing the data in this manner is shown in Fig. 4a and b.

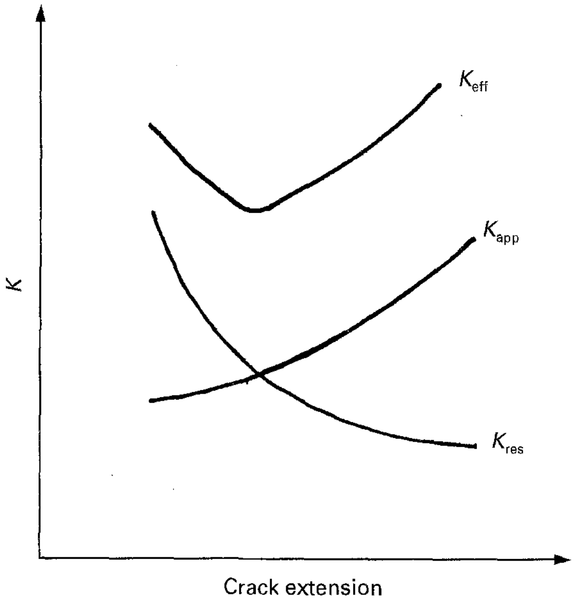

Figure 5 Schematic curves of K_{eff}, K_{app}, and K_{res} versus crack extension for SiC_w/Y-TZP (I) composite.

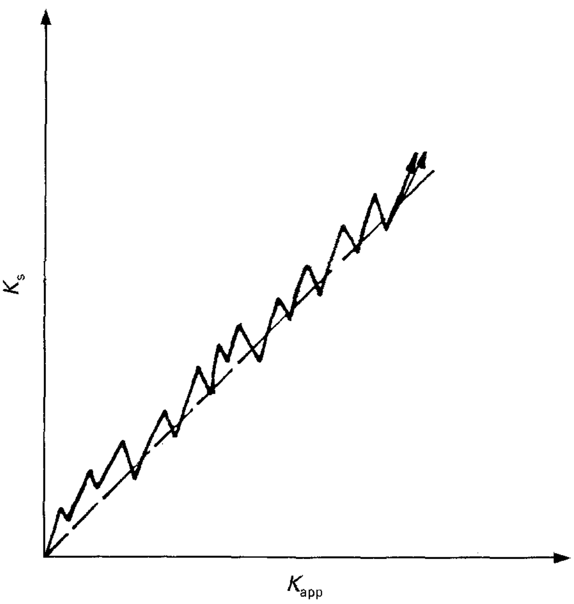

Figure 6 (a) Dependence of shielding K_s on K_{app} under cyclic loading for specimens without precracking.

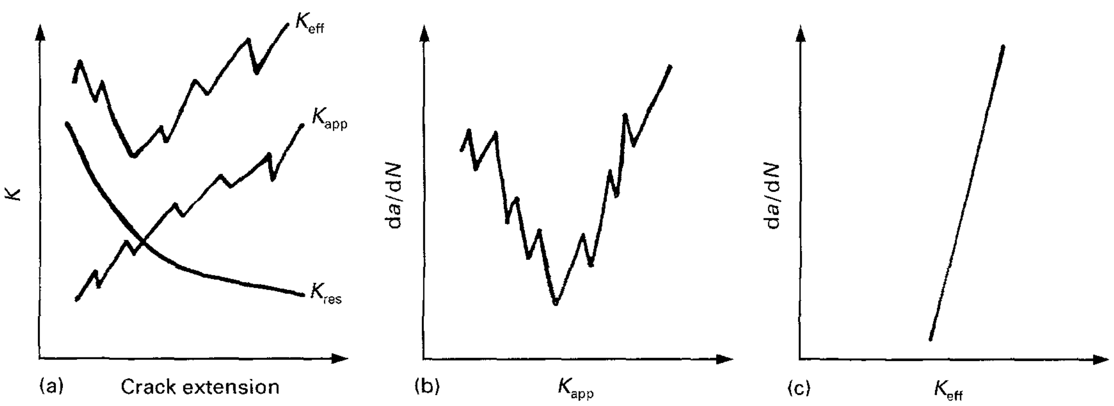

Figure 7 Schematic curves of (a) K_{eff}, K_{app}, and K_{res} versus crack extension, (b) da/dN versus K_{app}, and (c) da/dN versus K_{eff} relations for SiC_w/Y-TZP (II) composite.

The effective stress intensity factor in unannealed specimens is ($K_{app} + K_{res}$). These contributions are schematically plotted in Fig. 5, which clearly demonstrates that while K_{app} increases monotonically with crack extension, K_{eff} experiences a minimum because of the rapid decay of K_{res}. Thus, the V-shaped behaviour in the presence of a residual stress can be conceptually understood.

It must be cautioned, however, that for SiC_w/Y-TZP(II) composite, the value of β in Equation 3 is a variable. Fig. 6 shows schematically the shielding, K_s, on applied stress intensity under cyclic loading. From Fig. 6 and Equation 2, we can obtain the K_{eff} versus crack extension and hence da/dN versus K_{app} and K_{eff} relations, as shown schematically in Fig. 7.

5. Conclusion

Cyclic fatigue crack growth behaviour of composites has been investigated in this study. The study shows a strong interaction between the cyclic fatigue damage and the crack-shielding effect in a residual stress field. For the composites without precracking, the stress-induced t–m transformation under cyclic loading was characterized by the "autocatalytic" behaviour. This "autocatalytic" transformation and residual stress lead to a stepwise fatigue crack growth behaviour under cyclic loading. The cyclic fatigue growth relation for these materials was then characterized by a "zigzag" V-shaped da/dN versus K_{app} curve. For these composites with preformed transformation zone after compression–compression fatigue tests, the residual stress can be directly responsible for a V-shaped da/dN versus ΔK curve. The apparent "short-crack behaviour" of unannealed specimens, which exhibited an abnormal dependence of growth rate on the applied stress intensity factor in the composites, was found to be an artefact. By considering the residual stress contribution, the growth rate is shown to be in accordance with the other growth data of pre-existing flaws free from residual stress.

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Received 22 December 1994
and accepted 15 December 1995