General paper

ROLE OF GRAIN BRIDGING DEGRADATION OF SMALL CRACK ON CRACK PROPAGATION BEHAVIOR IN POLYCRYSTALLINE ALUMINA UNDER CYCLIC LOAD

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Abstract: In order to investigate the effects of grain bridging degradation on the cyclic fatigue in polycrystalline alumina, crack propagation tests were carried out under cyclic load and static load. Two kinds of small semi-elliptical surface crack were introduced by Knoop indenter. Polishing the surface layer, the residual stress around the Knoop indentation was completely removed. The cyclic loading accelerates crack propagation in small crack as the same as in long crack. On the other hand, measuring and analyzing the crack opening displacement (COD) of 350 μ m crack, we determined the net stress intensity factor $K_{I_{tip}}$. Under the cyclic load, the reduction of bridging force resulted in an increase in $K_{I_{tip}}$ which, in turn, accelerated the crack propagation rate. Furthermore, it is found that bridging degradation mechanism under cyclic loading does occur, but that this mechanism is not sufficient to completely account for "fatigue crack growth in ceramics".

Key words: Alumina, Small crack, Crack propagation, Fatigue mechanism, Bridging degradation, Cyclic load

1. INTRODUCTION

There are some reports[1-9] that show life reduction by cycling load for ceramics, such as sintered silicon nitride. To discuss the fatigue mechanism in ceramic materials, many studies have been carried out by using an artificial long cracks. For example, Grathwohl[10] has proposed that enhanced crack propagation under cyclic load is due to the degradation of the stress shielding effect by bridging. Lathabai et al.[11] also have studied wear and micro-fracture processes of the bridging zone under cyclic loads by SEM *in situ* observation. Ritchie[12] has devised how to combine the stress shielding effect with a K -evaluation through the study for considering the "role of crack-tip shielding", and gotten a general idea of the net stress intensity factor at the crack tip $K_{I_{tip}}$. The idea of $K_{I_{tip}}$ is very useful to discuss the grain bridging effect on the crack propagation behavior in ceramic materials. On the other hand, as the fracture in ceramics almost always initiates from inherent defects[13] such as pores or inclusions, the mechanisms of cyclic fatigue should be studied with respect to small cracks. However, there are only a few reports discussing the behavior of small crack propagation [14-19].

In this study, we clarified the effects of crack size on the crack propagation rate for artificial small semi-elliptical surface cracks. Furthermore, we evaluated the bridging effect of artificial small cracks, and the cyclic fatigue mechanism in ceramics was discussed using the net stress intensity factor $K_{I_{tip}}$.

2. SPECIMENS AND EXPERIMENTAL PROCEDURES

The materials used in this study were two types of 99.9 % polycrystalline alumina with distinct average grain size of 1 μ m and 19 μ m[20]. In this study, the former is referred to as 0D, and the latter 5D. These materials were similar in chemical composition and sintering history. Grain size was adjusted through heat-treatment after sintering. The mechanical properties are shown in Table 1. Fatigue specimens were machined into the shape shown in Fig. 1, and then machined surfaces were polished to mirror finish using JIS #2000 mesh and #6000 mesh diamond paste. In order to compare the propagation behavior of small-cracks with that of long cracks, these specimens were cut out from used CT specimens[20].

A small semi-elliptical surface crack was induced at the center of a fatigue specimen by using a Knoop indenter. Two different crack sizes $2a$ of 350 μ m and 200 μ m were induced with indenting loads of 83.3 N and 34.3 N for the case of 0D materials, and 68.6 N and 29.4 N for 5D materials, respectively. The residual stress around the Knoop indentation was measured by the X-ray diffraction method using the V-K α ray. The residual

Table 1. Mechanical properties of the materials used.

Material	Average grain size (μ m)	Young's modulus E (GPa)	Poisson's ratio ν	Fracture toughness K_{IC} (MPa $\sqrt{m}$)	Hardness Hv
0D	1	386	0.23	3.1	1697
5D	19	386	0.23	3.7	—

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Fig. 1. Configuration and dimensions of specimen.

Fig. 2. Residual stress distribution beneath the specimen surface.

stress in 0D materials indented by the load of 83.3 N is depicted in Fig. 2 as a function of the removal δ of the specimen surface. The residual stress tends to decrease with increase in the surface removal until the value of δ reaches 30 μm . The surface length $2a'$ and depth c' of the crack after removing surface[†] were calculated by Eq. (1).

$$\begin{aligned} a' &= a \sqrt{1 - \left(\frac{\delta}{c}\right)^2}, \\ c' &= c - \delta, \end{aligned} \quad (1)$$

in which a and c refer to the surface length and depth of the original crack, respectively. The original crack depth was measured through an ink-penetration technique. The mean values of $2a'$ and c'/a' were 346 μm and 0.61 for indentation by 98 N, 203 μm and 0.61 for indentation by 34 N, respectively.

Fatigue tests were carried out by an electromagnetic bending fatigue testing machine[17] in a chamber at 25 °C and 60 % relative humidity. Cyclic fatigue tests under a sinusoidal wave-form with stress ratio R of 0.1 and

[†]To eliminate the lateral crack around the Knoop indentation, in the case of 0D, 82 μm was removed for the 350 μm crack and 50 μm for the 200 μm crack, respectively. In the case of 5D, 56 μm was removed for the 350 μm crack and 37 μm for the 200 μm crack. Finally, specimen surface was finished again using JIS #15000 mesh diamond paste, to observe the crack more clearly.

(a) Material 0D.

(b) Material 5D.

Fig. 3. Influence of cyclic load on the crack propagation rate.

frequency f of 60Hz, and static fatigue tests were performed. The change in crack length $2a'$ during fatigue tests was measured using a metallographic microscope with a stroboscope and the crack depth c' corresponding to $2a'$ was determined by a graphic simulation[17]. The stress intensity factor was calculated by Newman-Raju's equation[21] into which the measured $2a'$ and estimated c' values were substituted.

3. EXPERIMENTAL RESULTS

3.1. Effects of Cyclic Loading on Crack Propagation Behavior

Figures 3(a) and 3(b) show the relationship between maximum stress intensity factor $K_{I\text{max}}$ and the equivalent crack propagation rate $(da/dt)_{\text{eq}}$ in 0D and

5D materials, respectively. The equivalent crack propagation rate $(da/dt)_{eq}$ is defined as

$$\left(\frac{da}{dt}\right)_{eq} = g \times f \times \frac{da}{dN}, \quad (2)$$

where g is a factor proposed by Evans[22] and values of g are 16.2 for small cracks of 0D, 17.1 for long cracks of 0D, 13.7 for small cracks of 5D and 13.1 for long cracks of 5D, respectively. The crack propagation rate measured through the CT specimen[20] is also represented by straight lines in the figure. Arrows indicate the stress intensity factor when 200 μm cracks started propagating. This value seems nearly equal to the threshold stress intensity factor.

In Fig. 3(a), which shows the results of 0D, cyclic loading accelerates the propagation of small cracks similar to long cracks. As the crack propagation rate decreases, the difference in stress intensity factor $K_{I\max}$ between static and cyclic loading increases. This difference seems larger than that of long crack. Figure 3(b) shows the results of coarse grained alumina 5D, where cyclic loading accelerates crack propagation for both small and large cracks.

3. 2. Effects of Grain Size and Crack Length on Crack Propagation Behavior

Figures 4(a) and 4(b) show the effects of grain size and crack length on the crack propagation rate obtained under static and cyclic load, respectively. At a given da/dt , e.g., 10^{-8} m/s in Fig. 4(a), and at a given da/dN , e.g., 5×10^{-9} m/cycle in Fig. 4(b), the dependence of $K_{I\max}$ values on grain size and crack length is examined. For example, 0D-200 means the result for 200 μm crack in 0D. The result is as follows:

For the cases of static fatigue:

$$0D-200 > 5D-CT > 0D-340 > 5D-340 > 0D-CT.$$

For the cases of cyclic fatigue:

$$\begin{aligned} 0D-200 &> 0D-340 > 5D-CT > 5D-340 \\ &= 5D-200 > 0D-CT. \end{aligned}$$

It is concluded that cracks with higher crack growth resistance under static fatigue also have a higher resistance under cyclic fatigue.

The degree of acceleration in the crack propagation by cyclic loading is also examined. The degree of acceleration is determined as the difference between $K_{I\max}$ under static load and $K_{I\max}$ under cyclic load in the range of $(da/dt)_{eq}$ between 10^{-5} m/s and 10^{-7} m/s. The magnitude of acceleration in order is:

$$0D-200 > 5D-CT > 0D-340 > 5D-340 > 0D-CT.$$

This order completely coincides with the order in the

(a) Static load.

(b) Cyclic load.

Fig. 4. Influence of grain size and crack size on the crack propagation rate.

Fig. 5. Example of SEM microphotograph of crack path (0D material).

case of static fatigue given above. It seems that the bridging effect, which varies depending on grain size and crack size, brings about difference in crack propagation resistance.

3.3. COD Measurements and Evaluation Method of SIF

Figure 5 shows an example of SEM microphotograph of a crack path at the central region of OD material. The crack propagated along the grain boundary, and the grain bridging site was observed apparently as indicated by arrow. Since it is well known that the grain bridging shields the crack tip from the applied stress, the net stress intensity factor $K_{I_{tip}}$ is expressed by the following equation [12].

$$K_{I_{tip}} = K_{I_{max}} - K_S, \quad (3)$$

where $K_{I_{max}}$ is the applied nominal stress intensity and K_S is the stress intensity factor concerned with stress shielding by bridging. The correlation among the K_S value, cyclic loading and the crack propagation behavior in relation to the grain size is discussed in the following.

In order to verify the effect of grain bridging, the crack opening displacement (COD) of 350 μm cracks was observed in SEM and measured. Figure 6 shows an example of COD in OD before cyclic loading. The COD was measured on the surface of a cracked specimen, to which $K_{I_{max}}$ of 1.61 $\text{MPa}\sqrt{\text{m}}$ was applied during observation in SEM. Torii et al.'s method using measured COD[23] was applied to estimate the stress intensity factor of small cracks affected by grain bridging. This procedure is summarized as follows:

- (1) Measured COD was approximated by a function which is composed of a polynomial of third degrees V_1 and V_2 as

$$\begin{aligned} V_1(x) &= A + Bx + Cx^2 + Dx^3, \\ V_2(x) &= \alpha(a' - x)^{1/2} + \beta(a' - x)^{3/2}, \end{aligned} \quad (4)$$

in which a' is the half surface length of the crack, x is the distance from the center of the crack, $A \sim D$ and α, β are constants.

- (2) The crack opening stress σ_{yy} was calculated by

substituting the function V_1 and V_2 into the following equation

$$\sigma_{yy}(t) = \frac{1}{4\pi} \int_{-a'}^d \frac{E'}{x-t} \left(\frac{\partial V_i}{\partial x} \right) dx, \quad (5)$$

[$i = 1, 2$]

in which E' is the modified Young's modulus, which is equal to $E/(1 - \nu^2)$ for plane strain.

- (3) The stress intensity factor of the surface crack was calculated by using Eq.(5) as

$$K_I = \frac{1}{\sqrt{\pi a'}} \int_{-a'}^d \sigma_{yy}(x) \sqrt{\frac{a' + x}{a' - x}} dx. \quad (6)$$

In Fig. 6, a solid line shows the approximation of V_1 and V_2 . Providing functions V_1 and V_2 are symmetrical to the origin, and substituting V_1 and V_2 into Eq.(5), we obtained the crack opening stress σ_{yy} . For the cases of 5D material, as the number of COD data points was not enough to completely determine the approximated function of V_1 and V_2 , data on the both sides from the crack center were pooled and then analyzed.

The estimated stress intensity factors $K_{I_{esti}}$ before cyclic loading obtained by Eq.(6) are about 0.47 $\text{MPa}\sqrt{\text{m}}$ in OD and 0.65 $\text{MPa}\sqrt{\text{m}}$ in 5D. The applied stress intensity factors $K_{I_{max}}$ calculated by Newman-Raju's equation were 1.56 $\text{MPa}\sqrt{\text{m}}$ in OD and 1.70 $\text{MPa}\sqrt{\text{m}}$ in 5D, respectively. The difference between $K_{I_{max}}$ and $K_{I_{esti}}$ is thought to mainly attribute to the stress shielding effects of grain bridging K_S . Therefore, $K_{I_{esti}}$ is believed to be the net stress intensity factor $K_{I_{tip}}$. It is worth notice that the ratio of K_S to $K_{I_{max}}$ is as large as 70 % in OD and 62 % in 5D, respectively. Grain bridging takes over many portion of crack growth resistance of these materials.

4. DISCUSSION

4.1. Effects of Cyclic Load on Grain Bridging Degradation

In order to discuss the grain bridging degradation, the method as stated above was applied to analyze the crack behavior under cyclic loads. To be sure that any COD change was solely due to bridging deterioration and not due to crack advance, the cyclic load with $K_{I_{max}}$ below the threshold stress intensity $K_{I_{max,th}}$ was applied. Fatigue tests were carried out with $K_{I_{max}}$ of 1.61 $\text{MPa}\sqrt{\text{m}}$ for OD and 1.70 $\text{MPa}\sqrt{\text{m}}$ for 5D, respectively. COD was measured under $K_{I_{max}}$ of 1.61 $\text{MPa}\sqrt{\text{m}}$ for both materials, after 10^6 cycles of cyclic load and again after 5×10^6 cycles. The approximated curves of COD are shown in Figs. 7(a) and 7(b). COD increased as number of stress

Fig. 6. Example of COD measurements in OD before cyclic loading and the approximated function.

Fig. 7. The approximated curves of COD before and after cyclic load.

 Fig. 8. Relationship between the $K_{I\text{tip}}$ and number of cycles N .

cycles increased. Figure 8 shows the relationship between $K_{I\text{tip}}$ and number of cycles. On the semi-logarithmic paper, least-square lines fit the data points over six orders of number of cycles. As compared with the $K_{I\text{tip}}$ values before cyclic load, $K_{I\text{tip}}$ increased by 0.23 MPa√m after 5×10^6 cycles for 0D, 0.07 MPa√m after 5×10^6 cycles for 5D.

 Fig. 9. The normalized $K_{I\text{tip}}$ as a function of number of cycles N .

 Fig. 10. Relationship between the $K_{I\text{tip}}$ and $(da/dt)_{\text{eq}}$ under various conditions.

$K_{I\text{tip}}$ increases with increase in the number of cycles. This means that K_S decreases with the number of cycles. The decrease in K_S is deduced to be concerned with the degradation of the bridging effect by cyclic load[11]. The degree of degradation of the bridging effect, which is reflected to the slope of the linear regression lines in Fig. 8, is dependent on both the grain size and number of cycles. It is concluded that the degradation of the grain bridging effect with cyclic fretting was responsible for the $K_{I\text{tip}}$ increase which, in turn, accelerated the crack propagation rate under cyclic loads.

4.2. The Role of $K_{I\text{tip}}$ on Crack Propagation Behavior

As is generally recognized, the crack tip stress intensity factor $K_{I\text{tip}}$ is the most important driving force for crack propagation. However, there are only a few reports discussing the role of $K_{I\text{tip}}$ on crack propagation behavior. In this section, we discuss the role of $K_{I\text{tip}}$ on the crack propagation behavior.

Table 2. Summary of results.

Material	Estimated ΔK_S (MPa $\sqrt{m}$)	$K_{Istatic} - K_{Icyclic,lowest}$ (MPa $\sqrt{m}$)	ΔK_S
			$K_{Istatic} - K_{Icyclic,lowest}$
0D	0.23	0.35	66 %
5D	0.07	0.45	16 %

To evaluate the relation between K_{Itip} and the crack propagation rate, we reconstruct Fig. 8 to Fig. 9. The left-hand ordinate indicates the K_{Itip} normalized by K_{Imax} , and the right-hand ordinate shows the K_S normalized by K_{Imax} . Assuming the ratio K_{Itip}/K_{Imax} to keep constant at the whole K_{Imax} range in Fig. 3, K_{Itip} corresponding to all data points in Fig. 3 can be calculated. In the cases of cyclic loading, K_{Itip} values associated with the K_{Imax} for all data points in Fig. 3 can be determined, since the K_{Imax} vs. N relation was determined using the applied stress and the a' vs. N relations obtained during the crack propagation tests. In cases under static load, K_{Itip} are obtained by multiplying the value of K_{Itip}/K_{Imax} before cyclic loading and K_{Imax} for all data points in Fig. 3.

Figure 10 is a revised diagram of Fig. 3. The abscissa is replaced by K_{Itip} . When comparing Fig. 10 with Figs. 3(a) and (b), it is seen that the deviation along the abscissa reduced remarkably. Especially, in the range that $(da/dt)_{eq}$ is lower than approx. 5×10^{-6} m/s, it is worth notice that the crack propagation behavior of the small cracks in polycrystalline aluminas under each stress condition and grain size can be almost well arranged by the net stress intensity factor K_{Itip} . It is considered that the K_{Itip} is seemed to be a good fracture mechanics parameter to describe the crack propagation behavior.

4.3. Limitation of Grain Bridging Degradation Mechanisms

As shown in Figs. 8 and 10, it is apparent that $\log K_{Itip}$ is in proportion to $\log N$ and that the crack propagation rate is also in proportion to $\log K_{Itip}$. In this section, the role of K_{Itip} on the fatigue mechanism is verified in the following.

From data plots of 0D-340 and 5D-340 in Figs. 3(a) and 3(b), we can obtain the stress intensity factor with the lowest $(da/dt)_{eq}$ under cyclic load $K_{Icyclic,lowest}$. We can also define the stress intensity factor with the same $(da/dt)_{eq}$ under static load $K_{Istatic}$. The difference between $K_{Istatic}$ and $K_{Icyclic,lowest}$ means cyclic load effect expressed by the stress intensity factor. As mentioned in a previous section, degradation of K_S , ΔK_S , is deduced to be concerned with the degradation of the bridging effect by cyclic load. Therefore, if the value of $K_{Istatic}$ minus $K_{Icyclic,lowest}$ is equal to the change in K_S during cyclic loading, the fatigue crack growth mechanism may be related to the grain bridging deterioration. The predicted

results are summarized in Table 2. In the case of 0D, the predicted ΔK_S is somewhat lower than the value of $K_{Istatic}$ minus $K_{Icyclic,lowest}$. In the case of 5D, it is noted that the ΔK_S is far lower than the value of $K_{Istatic}$ minus $K_{Icyclic,lowest}$. These mean that the cyclic degradation of the bridging effect is not the unique fatigue mechanism in these materials. The same results has been obtained through the same technique[17] and a compliance change in silicon nitride[24]. Therefore, it is concluded that bridging degradation mechanism under cyclic loading does occur in the crack wake region, but that this mechanism is not sufficient to completely account for "fatigue crack growth in ceramics". Other mechanisms, which may occur in the vicinity of a crack tip, should be considered in this regard.

5. CONCLUSIONS

The major results of this study are summarized as follows:

(1) As the propagation rate of a small crack decreases, the difference in stress intensity factor K_{Imax} between static- and cyclic loading increases. This tendency is similar to that of a long crack.

(2) The degree of acceleration in the crack propagation by cyclic loading was examined and they are summarized as follows:

$$0D-200 > 5D-CT > 0D-340 > 5D-340 > 0D-CT.$$

This order completely coincides with the order in the case of static fatigue. The bridging effect, which varies depending on grain size and crack size, brings about difference in crack propagation resistance.

(3) K_{Itip} was shown to be a good fracture mechanics parameter to describe the crack propagation behavior.

(4) The predicted degradation of K_S is lower than the value of $K_{Istatic}$ minus $K_{Icyclic,lowest}$. It is concluded that bridging degradation mechanism under cyclic loading does occur, but that this mechanism is not sufficient to completely account for "fatigue crack growth in ceramics".

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