Interface Fatigue Crack Propagation in Ceramic Thermal Barrier Coatings

Yoshiharu MUTOH**, Jin-Quan XU**, Yukio MIYASHITA**, Gomez G. BERNARDO*** and Masashi TAKAHASHI****

Failure of thermal barrier coating (TBC) layer, especially spalling of ceramic coating layer, results not only in degradation of thermal barrier properties but also in crucial damage to turbine components. The spalling of ceramic coating layer will follow the crack initiation and propagation along the interface between ceramic top-layer and metal bond-layer. In the present study, fatigue crack growth tests of TBCs with various porosities were carried out at room and elevated temperatures. It is found that an interface crack induced near a pre-introduced notch propagates along the interface under mixed mode condition, and its growth behavior can be well characterized by using the parameter \( \Delta K_c = \Delta K_{ic}^2 + K_c^2 \), which corresponds to the energy release rate. It is also found that the crack propagation resistance decreases with increasing of the porosity of the top ceramic coating. The crack propagation resistance at elevated temperature becomes lower compared to that at room temperature.

**Key Words:** Fatigue, Crack Propagation, Interface Crack, Ceramic Coating, Stress Intensity Factor

1. Introduction

Recently, thermal barrier coating (TBC) technology has been widely used in the gas turbine engineering to elevate the thermal efficiency\(^{(1,2)}\). To insure the reliability and the safety of TBC components, the quantitative evaluation of bonding strength and fatigue resistance of debonding is strongly required. The spaling of coated layer results not only in degradation of thermal barrier properties but also in crucial damage to turbine components. The spalling of TBC follows the crack initiation and propagation along the interface between ceramic top-layer and metal bond-layer. Many studies have been reported on the failure of TBC under thermal loads\(^{(3)-(6)}\). Some experimental methods for determining the bonding strength between the coating layer and the substrate have been also proposed\(^{(7)-(10)}\). Though several studies\(^{(9)-(10)}\) have dealt with the fatigue behavior of TBC, only few research works have been available on the crack propagation behavior in TBC, which is important for evaluating the spalling phenomena. In this study, fatigue tests of TBC with different porosities were carried out at room and elevated temperatures. The fatigue crack propagation behavior was then evaluated based on the interfacial fracture mechanics\(^{(11)}\).

2. Fatigue Experiments

The geometry of specimen is shown in Fig. 1. The specimen was cut from a plate, polished by emery papers of #600, #1000 and #1500, successively, and finally finished two sides of the specimen by diamond paste with particle radius of 3 \( \mu \)m for observing crack propagation behavior. A notch parallel to the interface is introduced by an EDM machine, which causes stress concentration so that an initial crack could be induced at the interface. The initiated crack generally propagates along the interface from both two tips.
Table 1 Material properties

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Material</th>
<th>Young's modulus (GPa)</th>
<th>Poisson's ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>RT (20°C)</td>
<td>FSX-414</td>
<td>194.0</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>NiCoCrAlY</td>
<td>178.0</td>
<td>0.3</td>
</tr>
<tr>
<td>8wt%</td>
<td>Y$_2$O$_3$ZrO$_2$</td>
<td>5%</td>
<td>42.7</td>
</tr>
<tr>
<td>15%</td>
<td></td>
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<td>29.8</td>
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<td>20%</td>
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<td>24.2</td>
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<tr>
<td>HT (900°C)</td>
<td>FSX-414</td>
<td>131.5</td>
<td>0.2</td>
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<tr>
<td></td>
<td>NiCoCrAlY</td>
<td>117.0</td>
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<td>Y$_2$O$_3$ZrO$_2$</td>
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<td>15%</td>
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<td>23.2</td>
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<tr>
<td>20%</td>
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<td>19.3</td>
</tr>
</tbody>
</table>

Fig. 1 Shape and dimensions of the specimen

Fig. 2 A schematic of the fatigue test
during the testing. For the convenience, we call the crack tip at the left side from the notch tip as left tip and at the right side as right tip, and denoting corresponding crack lengths as $a_l$ and $a_r$, respectively. The superalloy FSX-414 was used as a substrate and CoNiCrAlY as a bond coating. The top coating was 8 wt% Y$_2$O$_3$-ZrO$_2$ with three levels of porosity as 5%, 15% and 20%. Mechanical properties at room and elevated temperatures are shown in Table 1. Special jigs as shown in Fig. 2 were adopted to increase the rigidity of loading system so that the stable crack propagation condition could be created. The thicknesses of top coating and bond coating were 600 μm and 100 μm respectively. The fatigue test was carried out under the stress ratio of $R=0.1$ with the frequency of 10 Hz by using a servo-hydraulic fatigue test machine. Relatively large load amplitude was applied at first to induce an initial interface crack. After an initial crack was detected, the load amplitude was reduced so that the stable crack propagation state could be realized for long time. For the observation of crack initiation and propagation, the fatigue test was interrupted at different numbers of cycles. The crack was observed by using a traveling microscope with reading accuracy of 10 μm. Crack lengths $a_l$ and $a_r$ as shown in Fig. 1 were measured at different cycles, and crack growth rates from two tips were then calculated separately. Figure 3 shows an example of a propagating interface crack. It can be found that length of the left crack is longer than that of the right crack.

3. Boundary Element Analysis

To analyze the stress distribution and stress intensity factors, the elastic boundary element method program BEM2D$^{19}$ was used, which is especially effective and accurate for the analysis of interface problems. The analysis was carried out under the plane strain condition. An example of the element division is shown in Fig. 4.

3.1 Stress distribution and crack initiation

For an analysis of crack propagation, the important problems are how to introduce an initial crack, and how to propagate the crack. We carried out at first the analysis for the case without any interfacial crack. Typical stress distribution along the interface between top and bond coatings is shown in Fig. 5. It can be seen that stress concentration is induced just beneath the notch tip. Considering that the shear strength of an interface is usually stronger than the debonding strength$^{19}$, we assume that the initial crack is induced mainly by the debonding stress $\sigma_d$. From a certain stress level selected for introducing an initial crack as shown in Fig. 5, it is possible to determine the crack location and its lengths $a_l$, $a_r$. The debonding stress $\sigma_d$ was determined to make the introduced initial crack length coincided with the observed crack length, which might have some effect of crack propagation due to the observation interval. In this analysis, such an initial crack is introduced.

3.2 Stress intensity factor of an interface crack

It is well known that the stress near the tip of an interface crack indicates oscillatory singularity$^{14}$. Though this behavior leads to a physical contradiction of crack face overlapping, it is proposed that fracture
behavior of the interface crack can be characterized by the stress intensity factors (SIF) defined as:

$$\sigma_y + i\tau_{xy} = \frac{K_1 +iK_2}{\sqrt{2\pi r}} (\frac{r}{2a})^\nu$$

(1)

Here, 2a is the crack length, and $\nu$ is the bimaterial constant defined as:

$$\nu = \frac{1}{2\pi} \log \left[ \frac{\kappa_1/\mu_1 + 1/\mu_2}{\kappa_2/\mu_2 + 1/\mu_1} \right]$$

(2)

where $\mu$ is the shear modulus, $\kappa$ is the elastic constant related to Poisson's ratio as $\kappa = 3 - 4\nu$ for plane strain and $\kappa = (3 - \nu)/(1 + \nu)$ for plane stress, and suffixes 1 and 2 denote the corresponding materials. Coordinate for the definition of SIF is shown in Fig. 6. It should be noted that this definition, Eq. (1), is different from that for a crack in homogeneous materials. Based on the definition shown in Eq. (1), the stress intensity factors $K_1$ and $K_2$ can be determined by the following extrapolation method from numerical results.

$$K_i = \lim_{r \to 0} \sqrt{2\pi r} (\sigma_{xy} \cos Q + \tau_{xy} \sin Q)$$

$$K_i = \lim_{r \to 0} \sqrt{2\pi r} (\tau_{xy} \cos Q - \sigma_{xy} \sin Q)$$

(3)

$$Q = \epsilon \ln(r/2a)$$

These stress intensity factors are related to the energy release rate as:

$$G = \frac{1}{16 \cosh^2(\epsilon \pi)} \left[ \frac{1}{\mu_1} + \frac{1}{\mu_2} \right] (K_1^2 + K_2^2)$$

(4)

Figure 7 shows an example of the extrapolation. It can be found that the extrapolation method of Eq. (3) has a good linearity.

3.3 Analysis of crack propagation

It is easily understood that the crack location (that is, the lengths of left and right cracks) has a
very great effect on the stress intensity factor. The next step of analysis after introducing an initial crack is how to propagate the crack. In this study, the crack propagation analysis was carried out according to the following approach.

1) Calculate \( \Delta K_i = K_{i1}^2 + K_{i2}^2 \) for both right and left crack tips from the stress intensity factors obtained by the extrapolation method as shown above.

2) If the difference of \( \Delta K_i \) between two crack tips is within 0.3 MPa√m, then propagate two tips by 50 μm each, otherwise propagate only for the larger stress intensity factor side by 50 μm.

3) Repeat 1), 2).

Figure 8 shows the simulated and measured crack lengths for the specimen with 15% porosity at room temperature. It can be found that the partial rate of the right and left crack lengths is well simulated, which can be observed for all the cases under different porosities and temperatures. This fact means that the interface crack propagation is mainly dominated by the parameter \( \Delta K_i \), which corresponds to the strain energy release rate as shown in Eq. (4).

This result indicates that the crack growth behavior in the porous coating can be macroscopically assumed as that in continuum with the same macroscopic elastic modulus, while the local crack growth behavior may be microscopically influenced by inhomogeneity of porosity.

4. Crack Growth Curve

Based on the simulation of crack propagation proposed above, the stress intensity factor can be calculated for different crack lengths. Figure 9 shows the relationship between stress intensity factor and crack length for the specimen with 15% porosity at the load of \( P = 100 \) N. It is easy to obtain the \( K_i \) values corresponding to any load of \( P_{\text{max}}, P_{\text{min}}, \) and \( \Delta P \) from this result based on the linear elastic nature. Such relationships have been prepared for all the cases under different porosities and temperatures by the BEM analysis with the material constants shown in Table 1. It can be found Fig. 9 that the crack propagates always under the mixed mode condition, and the mode ratio changes complicatedly during the crack propagation. Moreover, each side of the crack propagates under different mode ratios \( K_i/K_c \). It can be seen from the figure that the maximum stress intensity factor direction is in the bond coating layer, which means that the interface crack should kink into the bond coating layer\(^{(19)}\). However, the interface crack propagated along the interface because toughness of the metallic bond coating layer was much higher than those of the interface and the ceramic top coating layer. On the contrary, in homogeneous media, a crack propagates to following the maximum tangential stress theory\(^{(18)}\).

Figures 10 to 12 show the crack growth curves.
for porosities of 5%, 15% and 20%, under room temperature, respectively, by using the parameter $\Delta K_i$. Figures 13 to 15 show the similar growth curves at 900°C. It can be found that the crack growth properties can be well characterized by the parameter $\Delta K_i$, for both right and left crack tips under different mode ratios. It can be also found that the crack growth resistance reduces with increasing the porosity, and it is much lower at elevated temperature compared to room temperature.

If the intrinsic crack growth resistance would not be changed between room and elevated temperatures, the apparent crack growth resistance will become higher at elevated temperature due to reduction of tensile residual stress vertical to the interface. However, the test result inversely indicated that the crack growth resistance became lower at elevated temperature. The residual stress of plasma-sprayed porous ceramic layer is known to be small due to occurrence of microcracks in sprayed particles during spraying process. The detailed investigation on the effect of residual stress and thermal stress on crack growth resistance along the interface will be made in the next step, while the effect is assumed to be small in the present study.

5. Conclusions

Fatigue crack growth tests were carried out for
TBC with various porosities at room and elevated temperatures. Boundary element method was adopted for the analysis of the stress intensity factors for the interface cracks. The main conclusions are summarized as:

1) The interface crack propagation is basically under mixed mode condition; the mode ratio varied depending on crack length and crack tip location.
2) The crack growth rate of interface crack can be controlled by the parameter \( \Delta K_i \).
3) The crack propagation resistance reduces with increasing porosity and temperature.
4) The simulated crack lengths agreed well with the measured crack lengths.

References