Interface fracture toughness of TBCs at high temperature

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ABSTRACT

Thermal barrier coatings (TBCs) have been utilized in order to increase the turbine inlet temperature and hence increase the efficiency of turbine engines. There are some important effects on TBC operating life. Defects such as delamination, spallation, or cracking due to thermal stress in TBC are critical events disrupting continuous operations. During studies of life prediction and failure mechanism of TBCs, many researchers have found that due to mismatch of mechanical and thermal properties, interfacial defects experience severe stresses during operation and tend to be planes of weakness. Previous research has studied the interface fracture toughness at room temperature by using the Suo-Hutchinson model based on experimental data for uniaxial tensile and four-point bending tests. However, thermal stress must have influence on the interface fracture toughness of TBCs for its high working temperature. In this paper, uniaxial tensile tests at different high temperatures were conducted on plane rectangular samples. Cracks normal to the loaded axis initially appeared on the surface of the top ceramic layer, then these transverse crack manifolded and saturated in top coat with an increase in tensile strain. When the surface crack tip is close to the ceramic/bond coat interface, the crack kinks and propagates along this interface and results in eventual spallation of the top ceramic layer, exposing the bare metal to rigorous working condition. In this study, the high temperature interface fracture toughness evaluated by the Suo-Hutchinson model was decreased from about 7.6MPa $m^{1/2}$ to 3.6 MPa $m^{1/2}$ when temperature increased from room temperature to 800^{o}C.

1 INTRODUCTION

Thermal barrier coatings (TBCs) have been utilized in order to increase the turbine inlet temperature and hence increase the efficiency of turbine engines. TBCs system consists typically of an oxidation-resistant metallic bond coat on a superalloy substrate and a heat-insulating ceramic attached on the bond coat. An yttria-stabilised zirconia (6-8wt.% Y_2O_3 stabilized ZrO_2) is usually employed as the top material because of its low thermal conductivity and relatively high coefficient of thermal expansion coefficient compared to other ceramics, hence minimizing the CTE mismatch with the substrate alloys. Normally, the bond coat alloy is an MCrAlY (M=Ni/Co), which protects the superalloy substrate from oxidation by forming a continuous protective oxide scale (usually α-Al_2O_3) at the interface of meta/ceramic.

Under service condition, once cracks initiate and propagate in the top ceramic layer, coating would be prone to spallation or delamination and the operation becomes impossible. Those reported studies on the damage behavior of TBCs all emphasize that due to the presence of defects the interfaces experience severe stresses during service and tend to be planes of weakness (Rabiei [1]). Fracture mechanics specimen with sandwiched four point bending was also applied to measure the near-interface fracture toughness. However it was used without considering the effect of high temperature thermal stress. Previous research (Zhou [2]) has studied the interface fracture toughness at room temperature by using the Suo-Hutchinson model based on experimental data for uniaxial tensile test. In this paper, uniaxial tensile tests were conducted on election beam physical vapor deposited TBCs at different high temperatures. The high temperature interface fracture toughness is then evaluated by the Suo-Hutchinson model.

2 EXPERIMENTAL PROCEDURE

A well-polished Ni-based superalloy DZ125 of 2mm in thickness was used as the substrate material. NiCrAlY was election beam physical vapor deposited onto the substrate as a bond coat. A partially stabilized ZrO_2 with 8 wt.% Y_2O_3 was selected as the top layer and deposited on the bond coat by election beam physical vapor deposition method. The thickness of the bond coat and ceramic coat were $150\mu m$ and $350\mu m$, respectively. The shape and dimensions of the specimens were shown in Figure 1. Specimens were loaded along their longitudinal axis with displacement measured using a displacement sensor (Type NS-WY03, TM Automation Instruments Co. Ltd., Shanghai). The span of displacement measured was 20mm. Tests were done at 20°C, 200°C, 400°C, 600°C, 800°C, respectively.

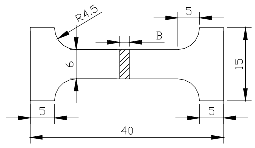

Figure1: Dimensions of TBC specimens in tensile test.

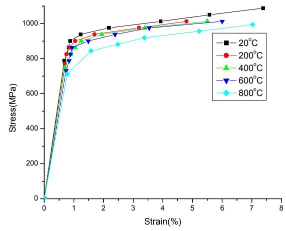

Figure 2: Stress-strain curves at different high temperature.

Figure 3: Morphologies of surface (a) before tensile test and (b)after tensile test.

3 RESULTS AND DISCUSSION

Figure 2 shows the stress-strain curves for the coating/substrate measured at different temperature. It can be seen that elastic limit decreased only about 80MPa when test temperature increased from room temperature to 800°C. Previous research (Zhou [2]) also demonstrated that cracks normal to the loaded axis initially appeared on the surface of the top ceramic layer and saturated with an increase in tensile strain. When the surface crack tip is close to the ceramic/bond coat interface, the crack kinks and propagates along this interface and results in eventual spallation of the top ceramic layer. Figure 3 shows the morphologies of ceramic surface before and after tensile test. There are obvious parallel and large cracks developed perpendicular to the tensile strain axis after test.

The interface fracture toughness is discussed by Suo-Hutchinson analysis(Suo [3]) on interface cracking between two elastic layers. Their model related mechanical and thermal loading induced interface cracking to bi-material fracture mechanics.

The energy release rate in the Suo-Hutchinson formula is given:

$$G = \frac{c_1}{16}\left[\frac{P^2}{Ah} + \frac{M^2}{Ih^3} + 2\frac{PM}{\sqrt{AI}h^2}\sin\gamma\right] \tag{1}$$

where G is energy release rate, P, M, A, I and angle γ are defined in Suo [3], h is thickness of ceramic. Young's modulus, Poisson's ratio and thermal expansion coefficient for ceramic coating, bond coat and substrate are quoted from Zhou [4]. In this paper, the combination of bond coat and substrate is regarded as a substrate.

The energy release in terms of the complex stress intensity factor K is:

$$G = \frac{c_1 + c_2}{16\cosh^2 \pi\varepsilon}|k|^2 \tag{2}$$

By comparing eqn (1) and eqn (2) the magnitude of the complex stress intensity factor can be obtained:

$$|k|^2 = \frac{p^2}{2}\left[\frac{P^2}{Ah} + \frac{M^2}{Ih^3} + 2\frac{PM}{\sqrt{AI}h^2}\sin\gamma\right] \tag{3}$$

where

$$p = \sqrt{\frac{1-\alpha}{1-\beta^2}} \tag{4}$$

α and β are Dundurs' parameters. The stress intensity factor of the interface crack associated with tensile experiments at high temperature for thermal barrier ceramic coating is equivalent to that induced by combination of applied tensile stress and residual stress due to uniform tensile "misfit" stress in the ceramic coating.

First consider the applied tensile stress induced stress intensity factor of the interface crack. It is equivalent to that induced by the following load and moment:

$$P_1 = 0\,,\quad M_1 = 0\,,\quad P_3 = -Q\,,\quad M_3 = 0\,. \tag{5}$$

The stress Q is known from Figure 2.

Next the effect of high temperature thermal stress is considered. Here σ^T is the uniform tensile "misfit" stress in the ceramic coating relative to the substrate. Note that σ^T is the misfit stress and not the residual stress in the ceramic coating:

$$\sigma^T = 8\Delta\alpha(T - T_0)/c_1 \tag{6}$$

where $\Delta\alpha$ is the coefficient of thermal expansion of ceramic coatings minus that of substrate. T is test temperature and T_0 is room temperature. The stress intensity factor of the interface crack associated with residual stressing due to σ^T is equivalent to that induced by the following load and moment:

$$P_1 = P_3 = \sigma^T h\ , \quad M_3 = \sigma^T h(H - \delta + h/2)\ , \quad M_1 = 0\ . \tag{7}$$

From Suo [3] the load parameters P and M are given by:

$$P = P_1 - C_1 P_3 - C_2 \frac{M_3}{h}, \qquad M = M_1 - C_3 M_3 \tag{8}$$

hence

$$P = \sigma^T h\left[1 - C_1 - C_2(\frac{1}{\eta} - \Delta + \frac{1}{2})\right] + C_1 Q\ , \quad M = -\sigma^T h^2 C_3(\frac{1}{\eta} - \Delta + \frac{1}{2})\ . \tag{9}$$

The phase angle ψ is given by:

$$\psi = \tan^{-1}\left[\frac{\lambda \sin\omega - \cos(\omega+\gamma)}{\lambda \cos\omega + \sin(\omega+\gamma)}\right] \tag{10}$$

where $C_1, C_2, C_3, \eta, \Delta, \lambda$ and γ are defined in Suo [3]. The stress intensity factor for high temperature tensile experiment can be obtained from eqn (3) and eqn (9) and the results are shown in Figure 4.

Under the protection of TBCs systems, the inner temperature of substrate usually maintain about 700^{o}C. Hence we choose 800^{o}C as maximal test temperature. The stress intensity factor for complete spallation is regarded as the fracture toughness of the interface and was decreased from about 7.6MPa m$^{1/2}$ to 3.6MPa m$^{1/2}$ when temperature increased from room temperature to 800^{o}C. During calculation for stress intensity factor, it was found that M induced by σ^T have little influence on final results of $|K|$. Whether $|K|$ change similarly or adversely with temperature is mainly decided by P. Although young's modulus decreased with increase of temperature, this decrease is eliminated by augment of difference of room temperature and test temperature. Hence magnitude of misfit stress σ^T is bigger than that of lower temperature. Furthermore, the stress for complete spallation slowly decreased which results in reduce of Q. The above two aspects lead to final shrinkage of $|K|$.

Table 1: Phase angle under high temperature.

Temperature	200^{o}C	400^{o}C	600^{o}C	800^{o}C
Phase angle ψ	56.82^o	56.68^o	56.51^o	56.31^o

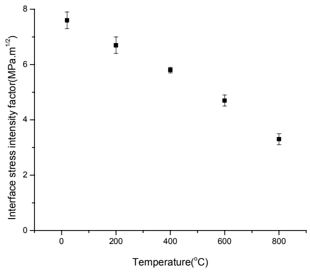

Figure 4: Stress intensity factors at high temperature.

The phase angle ψ obtained from eqn (10) is listed in Table 1. It can be seen that the phase angle, or the relative contribution that K_1 and K_2 made is almost the same for different temperature.

4 CONCLUSIONS

Uniaxial tensile tests were conducted on thermal barrier ceramic coatings at different high temperature. Based on those experimental data the interface fracture toughness was evaluated by the Suo-Hutchinson model considering the effect of thermal "misfit" stress at high temperature. Temperature has a notable effect on the fracture characteristics of TBCs. Samples exhibited decreased interface strength at high temperature compared to room temperature. Higher the temperature is, lower the interface strength is. It is mainly caused by increase of misfit stress and decrease of stress for complete spallation.

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