CREEP DEFORMATION IN THERMAL BARRIER COATINGS DUE TO THE EFFECT OF THERMAL GROWTH OXIDATION AND TEMPERATURE GRADIENT

Y. C. Zhou, D. Wu
Institute of Fundamental Mechanics and Materials Engineering, Xiangtan University,Hunan, 411105, China

Summary In the paper, the creep deformation in thermal barrier coatings due to the effect of thermal growth oxidation and temperature gradient were theoretically and experimentally studied. In the theoretical investigation, the residual stress in the thermal barrier coating were analytically obtained for a plane rectangle sample. It was found that the temperature gradient and TGO have great effect on the residual stress. In the experiment, the samples were heated in high temperature furnace at different temperature and with different time. The oxidized and non-oxidized samples were again heated by a laser beam and in this case there was a high temperature gradient along the thickness direction of TBCs. It was found that the failure modes would be surface crack or interface crack for different thickness TGO and different temperature gradient. The experimental results were good agreement with the theoretical results.

INRODUCTION

Thermal barrier coatings (TBCs) have been utilized in order to increase the turbine inlet temperature and hence increase the efficiency of turbine engines. A TBCs system consists typically of an oxidation-resistant metallic bond coat on a superalloy substrate and a heat-insulating ceramic top coat attached on the bond coat. An yttria-stabilised zirconia (6-8wt.% Y_2O_3 stabilized ZrO_2) is usually employed as the top material. Due to the fact that the TBCs system was working at high temperature, a thermal growth oxidation(TGO) would form at the interface of top ceramic coating and bond coat and the deformation of the TBCs system would be creep. The creep deformation and TGO, especially their nonlinear effect would induce the failure of the TBCs. In the paper, the creep deformation in thermal barrier coatings due to the effect of thermal growth oxidation and temperature gradient were theoretically and experimentally studied.

THEORETICAL MODEL

In the theoretical investigation, the stresses fields in the thermal barrier coating due to the effect of creep deformation and thermal growth oxidation at the condition of temperature gradient along the thickness direction of TBCs were first studied for a plane rectangle sample as shown in Fig.1. The histories of temperature cycles in thermal barrier ceramic coatings system is sketched Fig.2. T_1 and T_0 are the steady state heating temperature and room temperature in the coating. The deformation of ceramic coating, bond coat and substrate are regarded as creep and that of TGO is regarded as elastic.

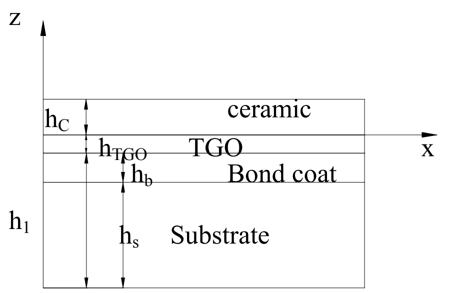

Fig.1 Crossing-section of thermal barrier ceramic coating system

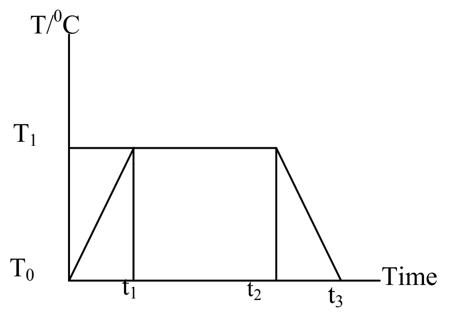

Fig.2 The histories of temperature in the TBCs

The temperature histories and temperature gradient along coating thickness direction could be expressed as in the following,

$$T(z,t)=\begin{cases}\dfrac{T_1(z)-T_0}{t_1}\times t+T_0 & (0\le t\le t_1)\\ T_1(z) & (t_1\le t\le t_2)\\ T_1(z)-\dfrac{T_1(z)-T_0}{t_3-t_2}\times(t-t_2) & (t_2\le t\le t_3)\end{cases}\qquad T_1(z)=\begin{cases}\dfrac{T_s-T_i}{h_c}\times(z-h_1)+T_i & 0\le z\le h_c\\ T_i & -h_1-h_{TGO}\le z\le 0\end{cases}\qquad(1)$$

The residual stress in the thermal barrier coating at the end of every cycle were analytically obtained as,

$$\sigma_c^{residual}=\sigma_c(z,t)+\sigma_c^{elastic}(z,t)\qquad(2)$$

In the above expression, the first one on the right side is due to the contribution of thermal stress at the end of loading, the second one is the contribution of the elastic unloading.

Fig.3 illustrates the characterization of stress as a function of interface temperature, surface temperature and position. Above the curved surface, the thermal stress in ceramic was compressive, while below the curved surface, the stress was tensile. The numerical results for thermal stresses and residual stresses illustrated that the temperature gradient and TGO have great effect on the residual stress. In some cases, the residual stresses in ceramic coating are compressive, but in other cases the residual stress are tensile. As we know, the failure mode is very different for different residual stresses. For compressive residual stresses, the ceramic coating would fail due to the buckling of the ceramic coating, however, for tensile residual stresses, the ceramic coating would fail due to the surface crack in the ceramic coating. In the paper, we obtained the failure map in the general space of ceramic surface temperature, the substrate surface temperature and heating time.

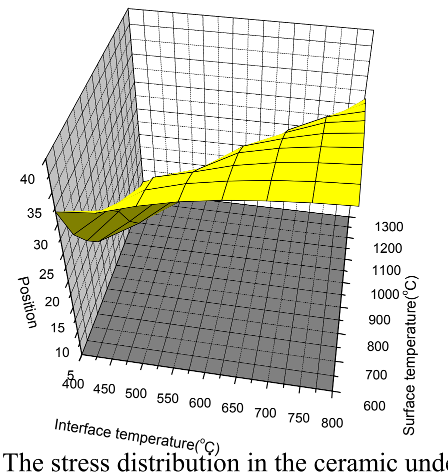

Fig.3 The stress distribution in the ceramic under different temperature gradient.

EXPERIMENT

In the experiment, the samples were heated in high temperature furnace at different temperature and with different time. In this case, the uniform high temperature in TBCs induced the formation of thermal growth oxidation at the interface of top ceramic coating and bond coat and the thickness was measured by two methods, such as scanning electron microscopy (SEM), impedance spectroscopy. The oxidized and non-oxidized samples were again heated by a laser beam and in this case there was a high temperature gradient along the thickness direction of TBCs and the schematic of the experimental setup for CO_2 laser heating method is shown in Fig.4.

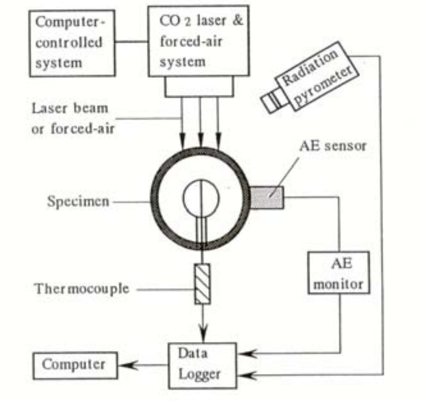

Fig.4 Schematic of the experimental setup for CO_2 laser heating method

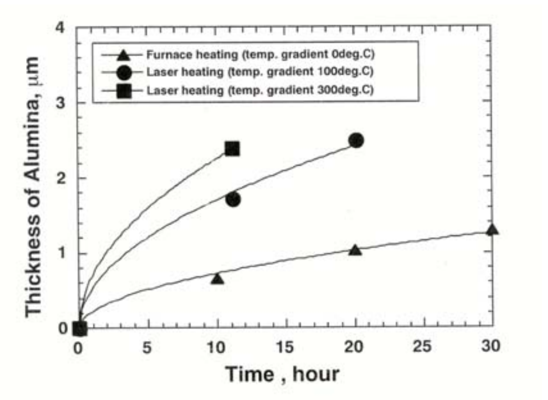

Fig.5 The effect of temperature gradient on the thickness of thermal growth oxidation, i.e., alumina

The effect of temperature gradient on the thickness of thermal growth oxidation, i.e., alumina is shown in Fig.5, where the temperature at interface was same. As the result, in spite of equal YSZ/NCrAlY interface temperature between the non-uniform heated specimen and uniform heated one, the alumina thickness are markedly different. The alumina is thicker for non-uniform heated case than that for uniform heated case. Namely, larger temperature gradient forms thicker alumina than smaller temperature gradient. The reason of the phenomenon is that the diffusion of oxygen through the YSZ accelerates in order to being high temperature concerning YSZ surface in case of laser heating as local heat. Moreover, due to the fact that the laser heated specimen has many porosity accompanied by formation of microcracks by virtue of larger thermal stress, oxygen rapidly penetrates interface through microcracks. Accordingly, laser heating which has temperature gradient is more effective condition to evaluate oxidation behavior of real plants. In our experiment, it was also found that the failure modes would be surface crack or interface crack for different thickness TGO and different temperature gradient. The experimental results were good agreement with the theoretical results.

References

[1] Zhou Y.C., Hashida T.: Coupled Effects of Temperature Gradient and Oxidation on Thermal Stress in Thermal Barrier Coating System, *Int. J. Solids and Structures*, **38**: 4235-4264,2001.
[2] Freborg A.M., et al.:, Modeling Oxidation Induced Stresses in Thermal Barrier Coatings, Mater. Sci. Eng. , **A245**: 182-190, 1998.