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Experimental Study and Numerical Simulation of the Tensile Test for GH4169 Coated with YSZ Coating at High Temperature

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Abstract. In this study, high temperature tensile test was conducted on the specimen of superalloy GH4169 coated with wt8%-YSZ under the conditions of 950℃ and 80MPa. By using finite element (FE) simulation method, the failure initiation and evolution of the metal substrate and YSZ coating were predicted. It was found that stress concentration originally occurred in the YSZ ceramic top coating, causing an axial stress and triggering severe debonding failure in the center region of the specimen at t=180s. With increased load, further interfacial debonding failure of the residual coating occurred due to the presence of oblique tensile stress and at t=900s, and only a few residues can be seen at the arc transitional region. Subsequently, the metal substrate was subjected to uniform tensile deformation and finally ruptured at t=76min with apparent necking. In addition, it was notable that YSZ coating can relieve stress significantly (nearly 40% lower), thus helping prolong the substrate's service life in the same environment. Simulated results were consistent with observed behavior.

Introduction

Thermal barrier coatings (TBCs), a kind of multi-layer material, are widely used in aerospace, engines and marine vehicle propulsion system. They can improve the work temperature of turbine blades effectively and also help prolong the hot end components' service life, thus playing an increasingly important role in the aeroengine field [1].

The high temperature performance of thermal barrier coatings is directly related to their service life, which has attracted many researchers in recent years. As we know, thermal barrier coatings may fail under the conditions of thermal fatigue or high temperature oxidation, which, in general, is because of the thermal stress caused by the difference in thermal expansion coefficients between coating and superalloy substrate [2], the stress developed by the bond coating oxidation and TGO thickening, the transformation stress and sintering shrinkage stress of YSZ ceramic coating as well as the hot corrosion damage caused by the fused salt deposition [3]. However, in the engine's actual working environment, hot end components not only bear the high temperature, but also the centrifugal force developed by high-speed rotating. In this case, the role of mechanical load cannot be ignored. Some studies have found that high temperature oxidation resistance of metal coating can be greatly changed when subjected to external forces. On the other hand, since the strain tolerance of ceramic coating of TBCs is much less than that of metal substrate, the effect of external forces on TBCs will be more significant. It can be predicted that with or without mechanical load, the failure mode and mechanism of coatings will be different. In this paper, the fracture behaviour and underlying mechanism of a TBC coated superalloy specimen prepared by plasma spraying process subjected to high temperature tensile are studied systematically using both test method and FE numerical simulation.

Material and Methods

High Temperature Tensile Test. The investigated TBC system consists of zirconia partially stabilized with about 8 wt.% yttria (wt8%-YSZ) ceramic top coating and Ni-38.5Co-21Cr-8Al-0.5Y bond coating. The nano-structured YSZ top coating with 150 μm thickness was produced by atmospheric plasma spraying (APS). The bond coating with 100 μm thickness was deposited onto a Ni-based superalloy GH4169 substrate, as shown in Fig. 1, by vacuum plasma spraying.

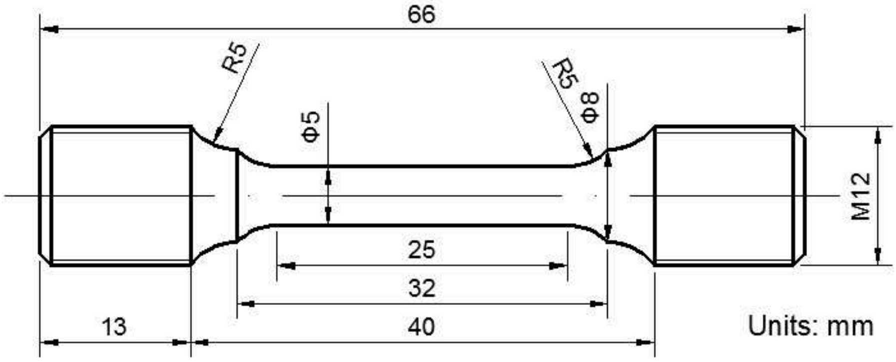

Fig. 1 The shape and dimension of Ni-based superalloy GH4169 substrate

The specimen was subjected to uniaxial tensile loading using an INSTRON8803 universal testing machine. The displacement rate was fixed at 0.22 mm/min and the test was performed at 950°C and 80MPa.

Finite Element Numerical Simulations. To understand and explain the underlying failure mechanisms and test results, FE numerical simulations using ANSYS LS-DYNA software were performed to simulate the spalling failure process of YSZ ceramic coating as well as the rupture of substrate.

As shown in Fig. 2(a), to reduce the computing burden, a two-dimensional 1/4 axial section FE model of test specimen including YSZ ceramic top coating, bond coating and metal substrate (Fig. 2(b)) was used to calculate and simulate the stress field during high temperature deformation by an implicit axisymmetric method. In order to avoid the effects of rough interface on the stress distribution of coating, smooth interface was adopted. In addition, plane strain elements were chosen for the FE mesh of the model and the total number of elements was 17250.

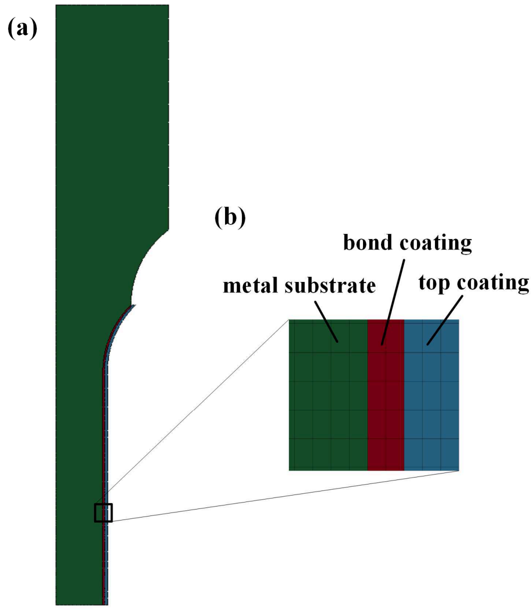

Fig. 2 The FE model of test specimen:
(a) the whole model; (b) drawing of partial enlargement

In this paper, piecewise linear models were chosen for both the bond coating and the metal substrate. The values of tensile stress and strain in stable plastic deformation stage of superalloy GH4169 at 950℃ were obtained through relevant literatures and data [4]. For the YSZ ceramic top coating, a linear elastic model was selected. In addition, the *MAT_ADD_EROSION routine in LS-DYNA was employed to define the failure criteria of the materials. The properties of the three materials are listed in Tables 1 and 2, in which σ_{max}, ε_{max} are respectively the maximum principal stress and maximum principal strain at failure.

Table 1 Parameters for piecewise linear plastic hardening model

Material	Density, ρ [g/cm³]	Elastic modulus, E [GPa]	Poisson's ratio, ν	Yield strength, σ_s [MPa]	Tangent modulus, E_{tan} [MPa]	Failure strain, ε_{max}
GH4169	8.24	7.276	0.3	156	—	3
NiCoCrAlY	7.32	100	0.35	66	500	3

Table 2 Parameters for linear elastic model

Material	Density, ρ [g/cm³]	Elastic modulus, E [GPa]	Poisson's ratio, ν	Failure stress, σ_{max} [MPa]
YSZ	4.58	38	0.2	215

In addition, a displacement rate of 0.22 mm/min was prescribed on the upper surface to be consistent with the experimental procedure and vertical displacement restrictions were added on both the bottom surface and the axis side, shown in Fig. 3.

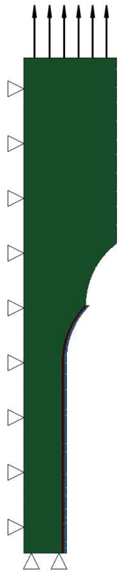

Fig. 3 Schematic of boundary conditions

Results and Discussion

The Test Results. In the experimental test, the rupture of substrate occurred at t=80 min and the specimen after that was shown in Fig. 4. It is clearly seen that, after high temperature deformation of metal substrate, there is obviously coating spalling failure between YSZ and bond coating with only a few residues at the arc transitional region. There are two main reasons for this: Firstly, when subjected to a continuous high temperature load, thermal stress is caused by the difference in thermal expansion coefficients between YSZ and bond coating, thus inducing the breaking-off of coating; Secondly, deformation difference under mechanical load due to the elastic mismatch between YSZ and bond coating also plays an important role.

In addition, tensile fracture partially occurs in the middle of the metal substrate, with apparent necking.

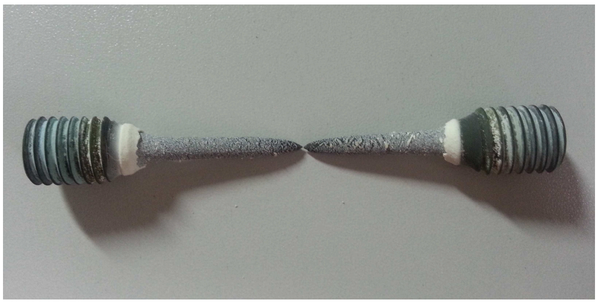

Fig. 4 The specimen after rupture

Simulated Results and Discussion. Fig. 5(a) shows that at time t=120s from initial application of the load, stress concentration mainly occurred in the YSZ ceramic top coating where the maximum tensile stress reached about 200 MPa. The maximum principal stress vectors at this moment in Fig. 5(b) (inset in Fig.5(a)) show the presence of an axial stress of typical elements parallel to the loading direction, which is equally distributed through the thickness. Simultaneously, coating material was subjected to a radial stress (the intermediate principal stress which was much lower), which increased toward the interface between YSZ and bond coating, where the failure of coating was more liable to occur, shown in Fig. 5(c). As the applied load continued to increase, at t=180s, the maximum tensile stress eventually exceeded the tensile strength of YSZ, triggering severe debonding failure in the center region of the specimen, as shown in Fig. 5(d).

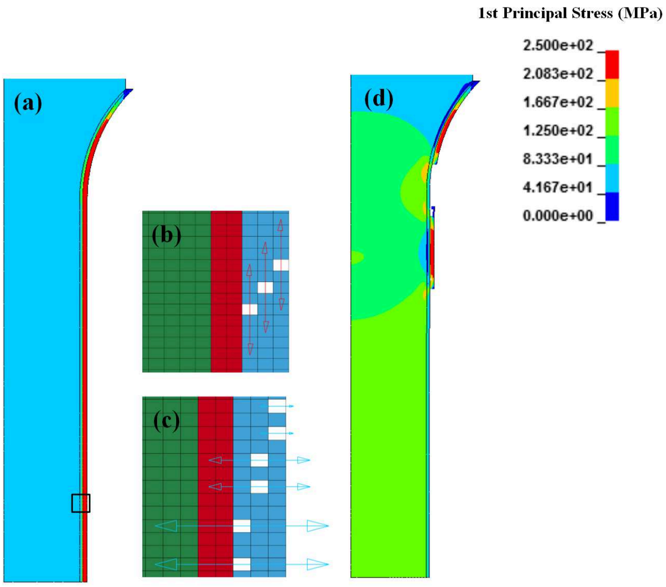

Fig. 5 The initial debonding failure of YSZ coating:
(a) stress contours of the model at t=120s; (b) the maximum principal stress vectors inserted in Fig.5(a); (c) the intermediate principal stress vectors inserted in Fig.5(a); (d) coating delamination in the center region of the specimen

With increased load, Fig. 6(a) shows the maximal principal stress contours of the model at t=660s, and the stress vectors at this time in Fig. 6(b) (inset in Fig.6(a)) show the presence of an oblique tensile stress in the residual coating, thus inducing the delamination phenomenon subsequently, shown in Fig. 6(c).

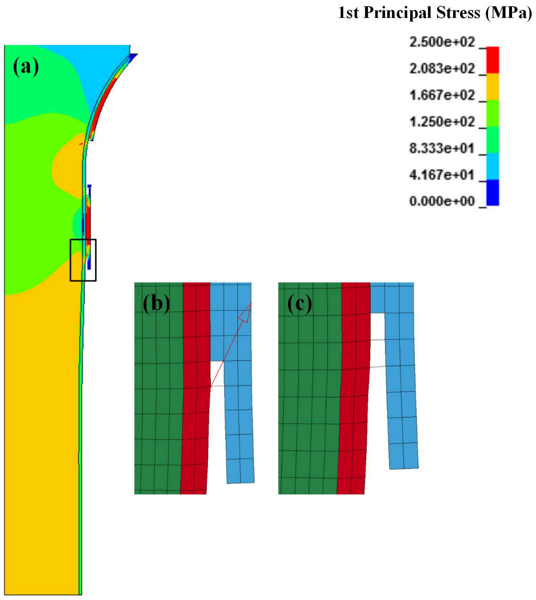

Fig. 6 Further debonding failure of YSZ coating:
(a) stress contours of the model at t=660s; (b) the maximum principal stress vectors inserted in Fig.6(a); (c) the residual coating delamination

Fig. 7(a) shows the stress contours at t=780s, where it is seen that the residual coating (in the wireframe) can apparently change the stress distribution inside the metal substrate. The tensile stress of substrate with coating was nearly 40% lower than that without coating. Therefore, it can be conclude that YSZ coating can relieve stress significantly, thus helping prolong the substrate's service life in the same environment. As we can see from Fig. 7(b), residual YSZ coating near the interface was subjected to a vertical or oblique tensile stress, which induces further interfacial debonding failure, shown in Fig. 7(c). With the increase of external loading, at t=900s, only a few residues can be seen at the arc transitional region (Fig. 7(d)), which is in close agreement with the test results (Fig. 4).

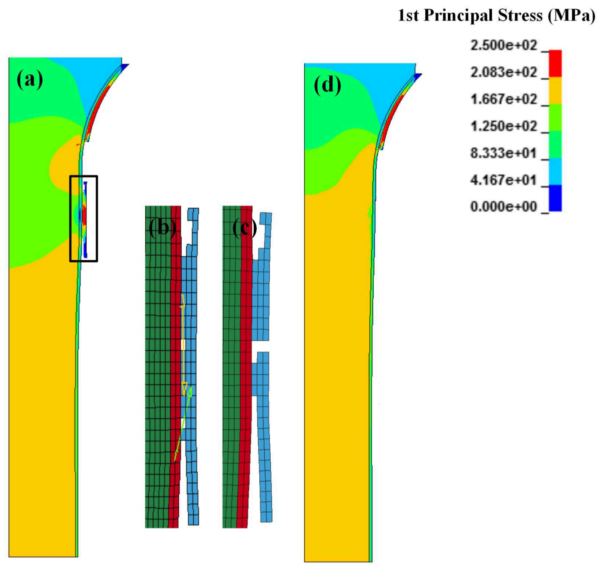

Fig. 7 The final debonding failure of YSZ coating:
(a) stress contours of the model at t=780s; (b) the maximum principal stress vectors inserted in Fig.7(a); (c) the interfacial debonding failure of the residual coating; (d) residues at the arc transitional region

Subsequently, the metal substrate was subjected to uniform tensile deformation as loading increased. Fig. 8(a) shows the maximal principal stress contours of substrate material at t=63min. It was observed that an obvious stress concentration developed in the center region of the substrate, such that apparent necking could be seen from t=72min (Fig. 8(b)) until the specimen ruptured at high stress at t=76min, shown in Fig. 8(c). Simulated results were consistent with observed behavior.

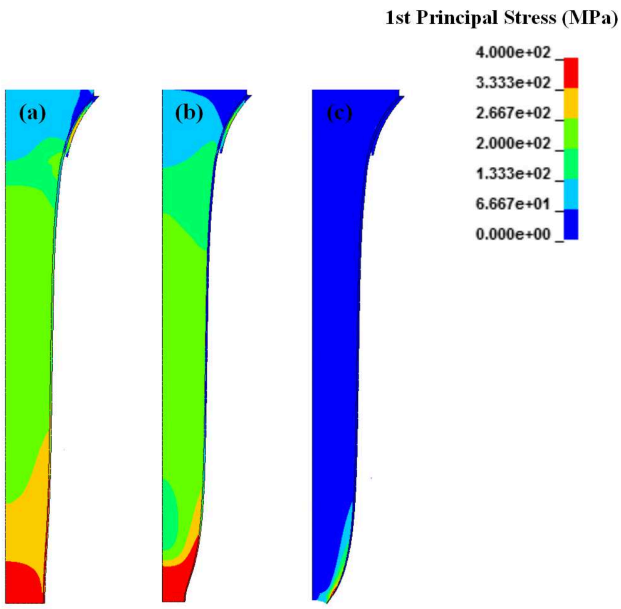

Fig. 8 The tensile deformation and rupture of metal substrate:
(a) stress contours of the substrate at t=63min; (b) the necking of metal substrate; (c) the rupture of metal substrate

Conclusions

The high temperature tensile performance of superalloy GH4169 coated with wt8%-YSZ was investigated under the conditions of 950°C and 80MPa. Simultaneously, a finite element model was also used to simulate and predict the failure initiation and evolution of the metal substrate and YSZ coating under the same circumstances. The numerical simulation results were consistent with the observed experimental results.

It was found that stress concentration originally occurred in the YSZ ceramic top coating, where the maximum tensile stress reached about 200 MPa, causing an axial stress and initiating severe debonding failure in the center region of the specimen at t=180s. As loading increased, the residual coating was subjected to a vertical or oblique tensile stress, which induced further delamination and interfacial debonding failure. Then at t=900s, only a few residues can be seen at the arc transitional region of the specimen. Subsequently, as the applied load continued to increase, the metal substrate was subjected to uniform tensile deformation and an apparent necking was developed in the center region of the substrate from t=72min until the specimen finally ruptured at high stress at t=76min. In addition, it was seen that YSZ coating can relieve stress inside the metal substrate significantly and the tensile stress of substrate with coating was nearly 40% lower than that without coating, thus helping prolong the substrate's service life effectively.

Acknowledgements

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