Delamination property of modeled air plasma sprayed-thermal barrier coatings under shear loading: effect of difference in chemical composition of bond coat

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Abstract

In order to understand the effect of the difference in chemical composition and microstructure of bond coat (BC) layer on delamination properties, pushout tests were performed on modeled air plasma-sprayed thermal barrier coatings (APS-TBCs). Nickel-platinum-aluminides (Ni-Pt-Al), hafnium modified nickel-platinum-aluminides (Ni-Pt-Al-Hf) and NiCoCrAlY alloys were used as BC alloy. Hafnium and aluminum oxide were formed in needle like shape when the Ni-Pt-Al-Hf alloy was used. Vickers hardness of BC alloy decreased up to 50 hours heat exposure and then increased with increasing heat exposure time. Interfacial delamination toughness increased and then decreased with the increase in heat exposure time.

Keywords: modeled APS-TBCs, Vickers hardness, pushout test, interfacial delamination toughness;

1. Introduction

Thermal barrier coatings (TBCs) have been widely used to increase the operating temperature of hot section components in gas turbines blade and vanes. APS-TBCs usually composed of an outer oxide ceramic thermal barrier coating (TBC) layer and an inner intermetallic bond coat (BC) layer to protect the substrate from high temperature and oxidation. During the service in TBCs, oxygen and aluminum diffuses from atmosphere and BC layer,
respectively and formation and growth of the thermally grown oxide (TGO) layer occurs at TBC/BC interface. The main composition of TGO is $\alpha$-Al$_2$O$_3$. In service, the TBC and TGO layers are under nominal biaxial compression condition because of the thermal expansion mismatch among the layers. This compression condition damages TBCs and finally TBC layer spall off from the blades. As reported by Evans et al. (2001) the crack initiates under mode I loading condition (perpendicular to the interface) and then the delamination of TBC layer occurs mainly by mode II loading (parallel to the interface). Thus, evaluating the durability of TBC system under mode II loading is important.

Recently, many types of BC layer are applied to the TBCs by Gell et al. (1999) to improve the delamination life of the coatings. However, the evaluation of interfacial delamination toughness on TBCs has not been still performed enough. In this study, the effect of the difference in chemical composition and microstructure of bond coat on modeled APS-TBCs in interfacial delamination toughness was evaluated.

2. Experimental Procedure

Nickel-platinum-aluminides (Ni-Pt-Al), hafnium modified nickel-platinum-aluminides (Ni-Pt-Al-Hf) and NiCoCrAlY alloy were selected as BC alloy. Chemical compositions of BC alloys were Ni-43Al-9Pt, Ni-42Al-9Pt-0.3Hf and Ni-25Al-19Co-16Cr-0.4Y (mol%). Ni-Pt-Al and Ni-Pt-Al-Hf alloys were processed by argon arc melting and NiCoCrAlY alloy was produced by high velocity oxygen fuel (HVOF) process. The BC alloys were then cut to the plate with the size of 30 x 20 x 4 mm and heat treated in a vacuum at 1413 K for 1 hour. After the treatment, modelled TBCs have been formed by APS process. TBC layer of an 8 mass% Y$_2$O$_3$ partially stabilized ZrO$_2$ was coated on the BC alloy in 250 $\mu$m thick at the both side of the area having 30 x 20 mm. The TBCs were heat exposed in an air at 1323 K from 10 to 200 hours. Changes in microstructure during heat exposure were characterized on the polished transverse section of the TBCs by SEM. Vickers hardness of BC layer in as-sprayed and heat exposed TBCs was measured. The load was applied up to 0.49 N for 5 s and then unloaded. To evaluate the delamination toughness of the TBCs under shear loading condition, pushout tests which were reported by Kim et al. (2007), Tanaka et al. (2008) and Hasegawa et al. (2009) were performed. The surfaces of the pushout test specimens were polished up to 0.5 $\mu$m diamond paste finish. Fig. 1 shows the schematic configuration of the test method. The size of the specimen was 4 mm in height, c, 5 mm in width, w, and 4 mm in thickness, b. WC blocks were used for the specimen support. Only the TBC layers of the specimen came to the specimen support. The pushout tests were performed in an air at room temperature using screw-driven test machine with the constant cross head speed of 0.1 mm/min. After pushout test, fracture surfaces were observed from the side of the specimen using OM and SEM.

3. Results and Discussion

3.1 Microstructural change

Fig. 2 shows a typical polished transverse section of the modeled APS-TBCs under as-sprayed state. TBC layers and BC alloys are clearly seen. Pores and inter-splat boundaries are observed in the TBC layer as black spots and
lines, respectively. The Ni-Pt-Al and Ni-Pt-Al-Hf alloys are composed of β single phase. NiCoCrAlY alloy is composed of fine mixture of bright γ' phase and dark β phase. SEM micrographs of the TGO layer and BC alloy after heat exposure at 1323 K are shown in Fig. 3. TBC layer near the BC alloy is also observed. TGO layer forms at the TBC/BC interface during the heat exposure. The thickness of TGO layer increases with the increase in heat exposure time. Almost the same behavior is observed by Shinmi et al. (2005), Tanaka et al. (2006) and Schulz et al. (2001). Further, in case of the same heat exposure time, TGO thickness of the modeled TBCs with Ni-Pt-Al BC alloy shows thinner TGO layer than the TBCs with Ni-Pt-Al-Hf and NiCoCrAlY BC alloy. The average thickness of TGO layer in the TBCs having Ni-Pt-Al BC alloy which are heat exposed for 50 and 200 hours is 2.2 and 2.7 μm, respectively. In case of TBCs with Ni-Pt-Al-Hf and NiCoCrAlY alloy, the TGO thickness after exposure for 50 and

![Fig. 2: SEM micrographs showing the transverse section of the modelled APS-TBCs in different BC alloy (as-sprayed state).
(a) Ni-Pt-Al, (b) Ni-Pt-Al-Hf and (c) NiCoCrAlY BC alloy.](image)

![Fig. 3: SEM micrographs of modelled TBCs observed from transverse section. Heat exposed at 1323 K for 50 hours (a), (c) and (e) and 200 hours (b), (d) and (f).](image)
200 hours is $2.6$ and $3.5 \, \mu m$ and $3.3 \, \mu m$ and $3.8 \, \mu m$, respectively. After 200 hours heat exposure, cracks can be seen at the TBC/BC interface and at the TBC layer near the interface. The $\beta$ phase of NiCoCrAlY BC alloy near the TGO/BC interface disappears during heat exposure due to the formation and growth of the TGO. Needle like regions are seen at the TGO layer when the modeled TBCs with Ni-Pt-Al-Hf alloy are heat exposed. Fig. 4 shows the result of EPMA analysis where the TBCs with Ni-Pt-Al-Hf BC alloy are heat exposed for 100 hours. Ni and Pt are not detected at the needle like region. However, Al, O and Hf are detected at the region. Thus, the needle like region should be the mixed oxide of Hf and Al. The change of Vickers hardness of BC alloy near TBC layer in different heat exposure time is indicated in Fig. 5. Independent of chemical composition, the Vickers hardness decreases up to 50 hours heat exposure and then increases with the increase in heat exposure time. However, the decreasing rate of the hardness in Ni-Pt-Al and Ni-Pt-Al-Hf BC alloy are low compared to that of NiCoCrAlY alloy. The Vickers hardness of Ni-Pt-Al and Ni-Pt-Al-Hf BC alloy near TBC layer which were as-sprayed or heat exposed for 50 and 200 hours at 1323K was 396, 351 and 370, and, 414, 392 and 410, respectively. As for NiCoCrAlY alloy, hardness of as-sprayed and 50 and 200 hours heat exposed specimen is 389, 298 and 370.

![Fig. 4 Results of EPMA analysis near TGO layer of the modelled TBCs having Ni-Pt-Al-Hf BC alloy. The specimen was heat exposed at 1323 K for 100 hours.](image)

![Fig. 5 Change of Vickers hardness in different heat exposure time.](image)
3.2 Delamination property

A typical load-displacement curve obtained by pushout test is shown in Fig. 6. In this case, pushout test was done at the TBCs with Ni-Pt-Al alloy which were heat exposed at 1323 K for 50 hours. At the initial stage of loadings, non-linear regime originates due to the change of compliance in the entire testing system. After non-linear regime, the load increases almost linearly. Then, the slope of the curve decreases till maximum load. Finally, the maximum load drop to zero indicating the delamination of the coating. Independent of chemical composition of BC alloy and heat exposure time, delamination of the modeled TBCs occurred mainly at TBC/TGO interface and slightly at TBC layer under shear loading.

All the constitute materials are assumed to show perfect linear elastic deformation up to coating delamination, in order to measure interfacial delamination toughness of TBCs by pushout method. Further, it is assumed that all the elastic strain energy stored to the specimen at a maximum load is supplied to form new delamination surfaces. In these assumptions, interfacial delamination toughness can be decided from the energy balance before and after delamination of TBCs shown by Kim et al. (2007), Tanka et al. (2008) and Hasegawa et al. (2009). Fig. 7 shows the change of interfacial delamination toughness under different heat exposure time. All the TBCs having different

![Fig. 6 A typical example of load-displacement curve of pushout test.](image1)

![Fig. 7 Change of interfacial delamination toughness in different heat exposure time.](image2)
chemical composition of BC alloy show the increase of the interfacial delamination toughness up to 50 hours heat exposure. Further increase of the exposure time decreases the delamination toughness. Regarding to the same heat exposure time, in most case, modelled TBCs with Ni-Pt-Al and Ni-Pt-Al-Hf BC alloy shows higher delamination toughness than that of the TBCs with NiCoCrAlY alloy. The decrease of the delamination toughness after 50 hours heat exposure will be due to the increase of the residual stress by the formation and growth of the TGO layer. The reason of the increase of the delamination toughness by the heat exposure up to 50 hours may be due to the sintering of the TBC layer reported by Yamazaki et al. (2006) and/or due to the decrease of the hardness of the BC alloy which may increase the toughness by plastic dissipation at the plastic zone of the alloy near TBC/TGO interface indicated by Hasegawa et al. (2009).

4. Conclusions

Interfacial delamination properties in modeled air plasma-prayed thermal barrier coatings (APS-TBCs) have been studied experimentally by pushout tests. The thickness of TGO where the main composition is $\alpha$-Al$_2$O$_3$ increases with increasing heat exposure time. When the Ni-Pt-Al-Hf BC alloy is used for the modelled TBCs, hafnium and aluminum oxides are formed in needle like shape during the heat exposure. All the TBCs having different chemical composition of BC alloy show decreasing of Vickers hardness and increasing of the interfacial delamination toughness up to 50 hours heat exposure. After 50 hours heat exposure, Vickers hardness increases and delamination toughness decreases with the increase in heat exposure time. The increase of the delamination toughness may be due to the increase of the plastic dissipation by decreasing of the hardness of BC alloy. Delamination toughness decreases because of the increase in residual stress by increasing the thickness of the TGO layer due to the increase in exposure time.

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