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Multilayered Thermal Barrier Coating for Land-Based Gas Turbines

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Multilayered thermal barrier coatings (TBC) with different functions were proposed for the hot section components of land-based gas turbines. This article describes a multilayered TBC with an oxidation resistant layer. A conventional duplex TBC and a triplex TBC, in which an aluminized layer was added to the conventional duplex TBC to increase oxidation resistance, were prepared. It was confirmed by a burner rig test that the triplex TBC with the aluminized layer is resistant to oxidation and shows high durability in a thermal cycle test, compared with the conventional duplex TBC. The spalling in the thermal cycle test of each TBC specimen occurred at the same position, when the thickness of the oxidation layer was 11 to 13 μm. The mechanism of spalling of the coating in the thermal cycle test was discussed in terms of stress in the coating. Stress in the direction of spalling occurred by an uneven interface between the bond and top coat and increased with growth of the oxidation layer. It is thought that the high durability of the triplex TBC in the thermal cycle test is derived from suppressing the growth of the oxidation layer and decreasing the stress due to the addition of the aluminized layer.

Keywords multilayered thermal barrier coatings, oxidation layer, stress analysis, thermal barrier coating spalling

1. Introduction

Thermal barrier coatings (TBCs) are used as hot section components of gas turbines, such as blades, nozzles, and combustion chambers. The conventional duplex TBC consists of an *M*CrAlY (where *M* indicates nickel, cobalt, iron, or combinations) bond coat and a CaO-, MgO-, Y_2O_3-, or CeO_2-stabilized ZrO_2 top coat (Ref 1). To increase the thermal efficiency of land-based gas turbines, operating temperatures are being increased, and hence TBCs are becoming more important to achieve high reliability without generating cracks and spalling of the TBC under service conditions. Various studies have therefore been conducted on the improvement of the coating processes or materials of the TBC (Ref 2-4).

Figure 1 shows various factors encountered by the TBC of the hot section components of land-based gas turbines under service conditions (Ref 5). The TBC encounters not only mechanical stress and thermal stress, but also erosion, oxidation, and corrosive environments. Also, interaction between the coating and base metal degrades the base metal.

2. Concept of Multilayered Thermal Barrier Coating

Figure 2 shows a concept of a multilayered TBC with different functions corresponding to the various factors (Ref 6). This coating consists of five layers on a superalloy substrate, and each layer has unique functions. The first layer is a diffusion resistant layer that prevents interaction between substrate and coating materials. The second layer is a thermal stress control layer including crack arrestment that reduces the thermal stresses in the thermal barrier ceramic layer and arrests crack progress from the ceramic layer. The third layer is a corrosion and oxidation resistant layer with improved adhesion. This layer prevents corrosion and oxidation of the substrate material and enhances adhesion between the thermal stress control layer and the following thermal barrier ceramic layer. The fourth layer is a thermal barrier layer that consists of a ceramic with low thermal conductivity and good chemical stability. The thickness of the layer is set such that the temperature of the substrate material becomes less than a critical value. Finally, the fifth layer is an erosion resistant layer that prevents thickness loss of the thermal barrier ceramic layer due to atmospheric impurities such as some kinds of oxides.

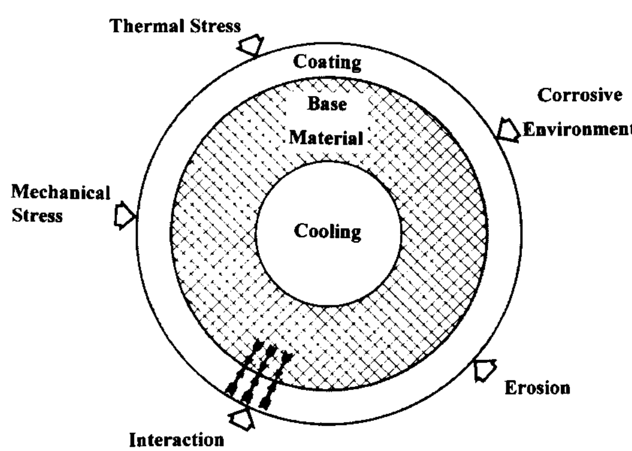

Fig. 1 Various factors encountered by thermal barrier coatings under service conditions (Ref 5)

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3. Experimental Procedure

3.1 Specimen Materials and Preparation

In order to examine the durability of multilayered TBCs, two kinds of TBC specimens were prepared. Table 1 shows the materials of the TBC specimens. The first specimen was a conventional duplex TBC, and the other specimen was a triplex TBC in which an aluminized layer was added to the duplex TBC as an oxidation resistant layer. The thicknesses of the top coat (the thermal barrier layer) and bond coat (the thermal stress control layer) were 250 to 300 μm and 100 to 130 μm, respectively. The thickness of the aluminized layer was 20 to 50 μm.

Table 1 Materials of TBC specimens

	Duplex TBC	Triplex TBC
Top coat	8wt% Y_2O_3-ZrO_2	8wt% Y_2O_3-ZrO_2
Aluminized layer	…	Aluminized layer
Bond coat	NiCoCrAlY	NiCoCrAlY
Substrate	Nickel-base alloy	Nickel-base alloy

TBC, thermal barrier coating

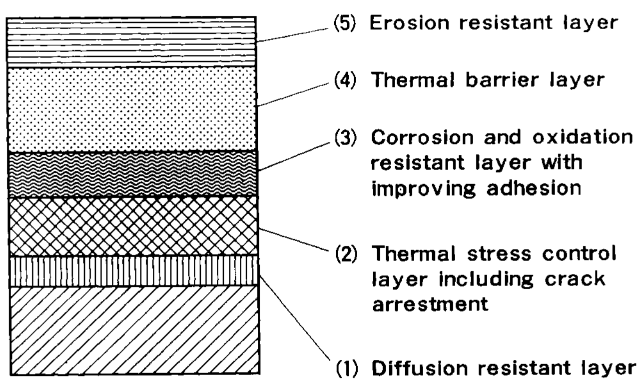

Fig. 2 Concept of multilayered thermal barrier coating with different functions (Ref 6)

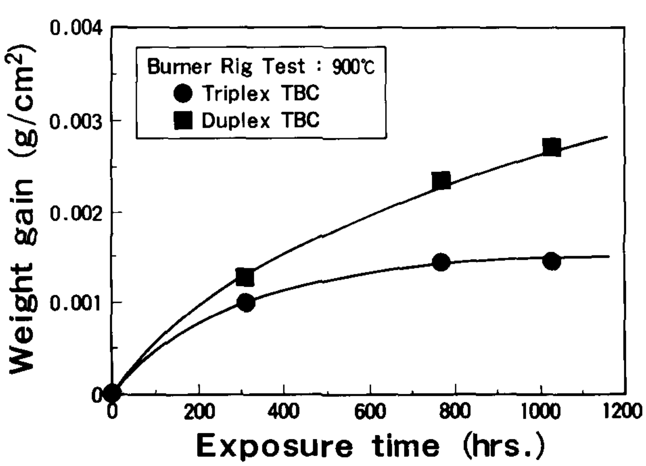

Fig. 3 Weight gain of specimens in burner rig test. Test temperature: 900 °C

3.2 Burner Rig Test

A burner rig test was performed by exposing specimens to gas atmosphere modified combustion gas compositions isothermally at 900 °C by electric furnace and exposing them to combustion gas compositions similar to those of land-based gas turbines. The weight gain of the specimen was measured during the test, and the cross section of the specimen after 1000 h was investigated by scanning electron microscopy (SEM) and electron probe microanalysis (EPMA).

3.3 Thermal Cycle Test

A thermal cycle test was carried out by cyclic heating at 1100 °C for 1.8 ks and cooling to approximately 150 °C in air. The thermal cycles were continued until more than 50% of the coating area of the specimen failed by spalling. The cross sections of the specimen after failure of the coating were investigated by SEM.

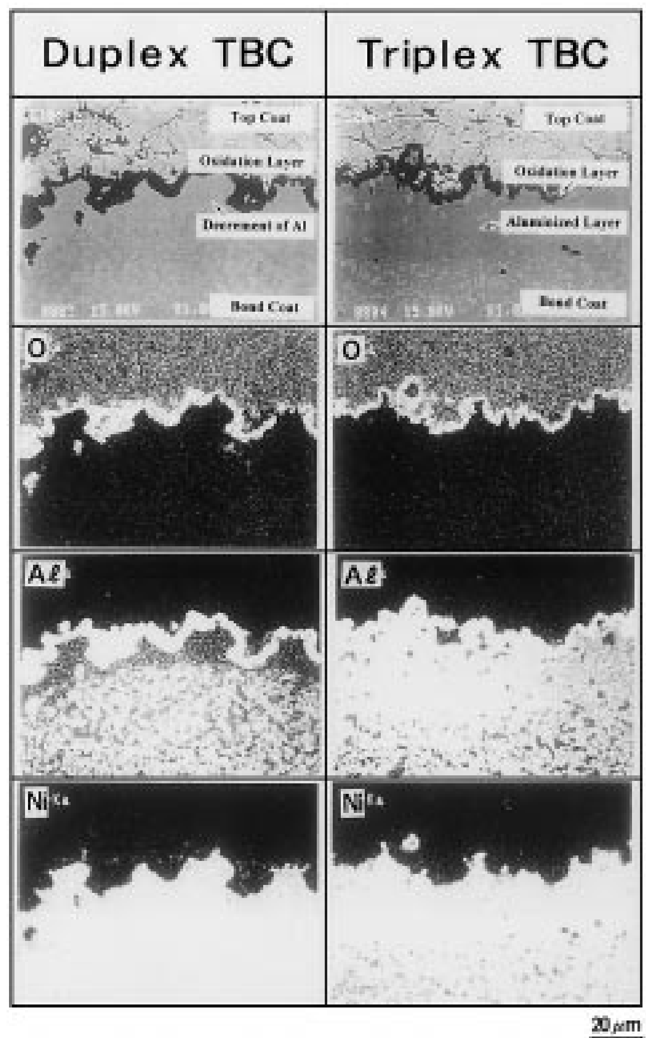

Fig. 4 Scanning electron microscopy image and electron probe microanalyzer of a cross section after burner rig test. Bond coat/top coat: 900 °C, 1000 h

4. Results

4.1 Burner Rig Test

Figure 3 shows the weight gain of the duplex and triplex TBC specimens in the burner rig test. The weights of both TBC specimens increased during the burner rig test, and the weight gains obeyed the parabolic law of diffusion. The weight gain of the triplex TBC was about half that of the duplex TBC.

Figure 4 shows SEM images and EPMA results of specimens after the burner rig test adjacent to the interface between the bond coat and top coat. An aluminum-rich layer and an aluminum-deficient layer was formed on the bond coat surface in the duplex TBC. A nickel oxide was probably also formed because insufficient aluminum was supplied from the bond coat.

Conversely, an oxidation layer was formed on the aluminized layer in the triplex TBC, but the aluminum-poor and nickel oxide layers could not be confirmed.

The thicknesses of the duplex and triplex TBC specimens were 6.3 and 4.8 μm on average, respectively. The difference of the thickness probably relates to the previously mentioned weight gain.

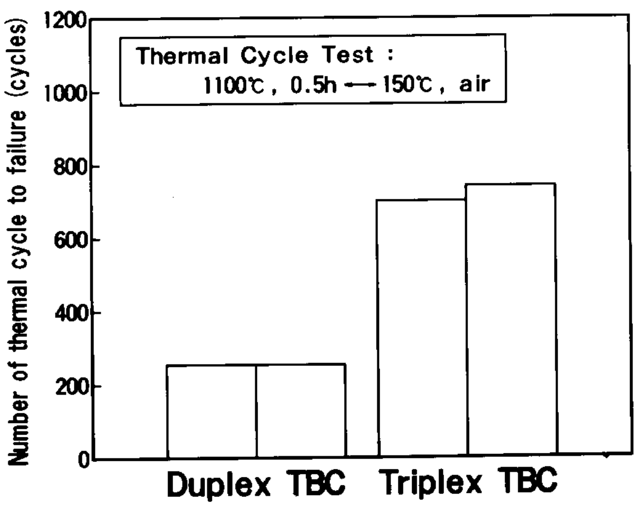

Fig. 5 Comparison of duplex and triplex thermal barrier coatings in a thermal cycle test

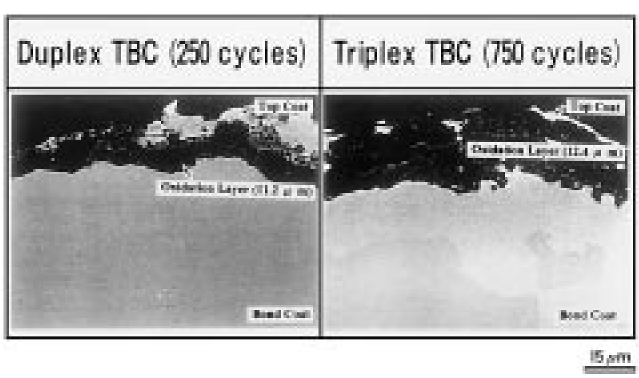

Fig. 6 Scanning electron microscopy images of cross section after the thermal cycle test

It was confirmed that the addition of an aluminized layer to the duplex TBC increased oxidation resistance compared with the duplex TBC due to the difference of the oxidation formed on the bond coat surface.

4.2 Thermal Cycle Test

Figure 5 compares the duplex and triplex TBC specimens in the thermal cycle tests. Both coatings failed to spall. The number of thermal cycles to failure of the triplex TBC was about three times as many as that of the duplex TBC. It was confirmed that the addition of the aluminized layer increased the number of thermal cycles to failure.

Figure 6 shows SEM images of a cross section adjacent to the spalling position after the thermal cycle test. The spalling of both the duplex and triplex TBCs occurs at the interface between the bond coat and the top coat or in the top coat adjacent to the interface. The thickness of the oxidation layer was almost constant at 11 to 13 μm for each TBC, though the numbers of thermal cycles to failure were different.

5. Discussion

5.1 Effect of Oxidation on Spalling of Coating

It is well known from observation of the cross sections after spalling that formation of an oxidation layer has an effect on the thermal cycle lifetime (Ref 7, 8). To investigate a change in the coating before spalling, the thermal cycle test was stopped prior to spalling. Figure 7 shows cross sections of the coating. Many transverse cracks occurred in the top coat at a concave region of the uneven interface between the bond coat and the top coat. These transverse cracks probably cause spalling because such cracking occurs at the same position as the spalling.

5.2 Effect of Oxidation Layer on Stress

Although thermal stress due to mismatch (Ref 9, 10) could not cause spalling, it was reported that the thermal stress caused failure adjacent to the uneven interface (Ref 11). In order to investigate the relation between spalling of the coating and stress

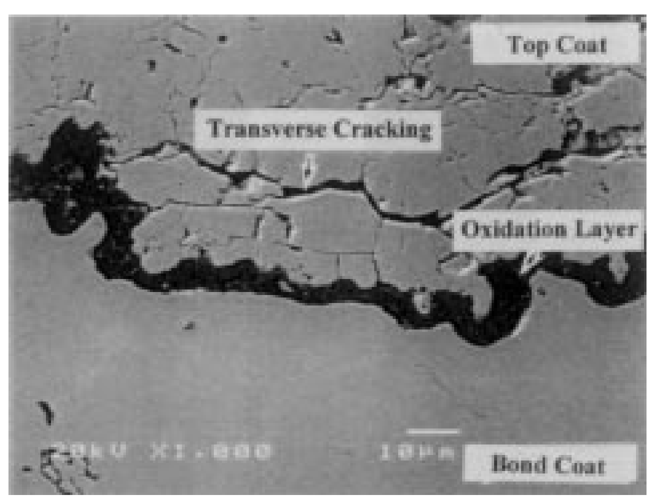

Fig. 7 Cracking in top coat before spalling. Thermal cycle: 100 cycles

in the direction of spalling, the stress due to formation of the oxidation layer was analyzed by finite element method (FEM). Figure 8 shows the stress distribution adjacent to the interface where the thickness of the oxidation layer is 3 μm, and the roughness of the interface is assumed to be a sine wave, R_a 10 μm. It should be noted, however, that Fig. 8 shows a stress that has been standardized with reference to a maximum value, following conversion to a dimensionless value based on four-point bending strength. A compressive stress occurred in the oxidation layer by the decrease in density when the oxide was formed. Conversely, a tensile stress in the direction of spalling occurred locally in the top coat adjacent to the interface, and the stress became maximum at the concave part of the bond coat. A distribution of this stress adjacent to the uneven surface is the same as that of thermal stress (Ref 11). It is estimated that these local stresses at the same position as that of transverse cracking might cause cracking.

Figure 9 shows the relation between maximum stress in the direction of spalling and thickness of the oxidation layer. The maximum stress became higher with increasing thickness of the oxidation layer. It is thought that the maximum stress increased with growth of the oxidation layer in the thermal cycle test, and that maximum stress was one of the causes of coating spallation.

Figure 10 shows the relation between thermal cycles and thickness of the oxidation layer. The curve of the thickness of the oxidation layer was obtained from the results of the thermal cycle test. The thickness of the oxidation layer obeys the parabolic law of diffusion, and the thickness of the triplex TBC was thinner than that of the duplex TBC. The spalling in the thermal cycle test occurred when the oxidation layer grew to the critical thickness of about 11 to 13 μm. It is thought that spalling is related to the stress. As shown in Fig. 9, stress in the top coat is adjacent to the interface between the bond coat and top coat. Namely, the high durability of the triplex TBC in the thermal cycle test was due to the addition of the aluminized layer, which suppressed the growth of the oxidation layer and, therefore, decreased the stress.

6. Conclusions

The following conclusions were obtained from the thermal cycle test and burner rig test using a conventional duplex TBC and a triplex TBC with an aluminized layer:

- The burner rig test shows that the triplex TBC resists oxidation better than the conventional duplex TBC.
- The triplex TBC showed excellent durability in the thermal cycle test, compared with the conventional duplex TBC. The spalling in the thermal cycle test of both TBCs occurred at the interface between the bond coat and top coat or in the top coat adjacent to the interface when the thickness of the oxidation layer was 11 to 13 μm.
- It was confirmed by FEM stress analysis that stress in the direction of spalling occurred locally due to an uneven interface between the bond coat and top coat, and the stress increased with growth of the oxidation layer. It is thought that the high durability of the triplex TBC in the thermal cycle test is derived from suppressing the growth of the oxidation layer and decreasing the stress due to the addition of the aluminized layer.

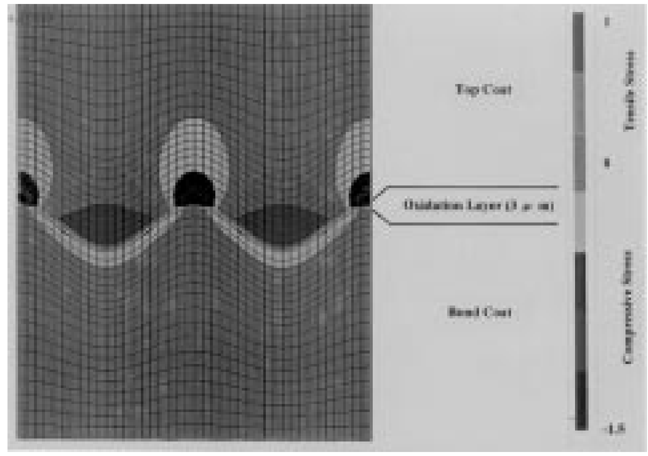

Fig. 8 Stress distribution occurred adjacent to uneven interface between bond coat and top coat

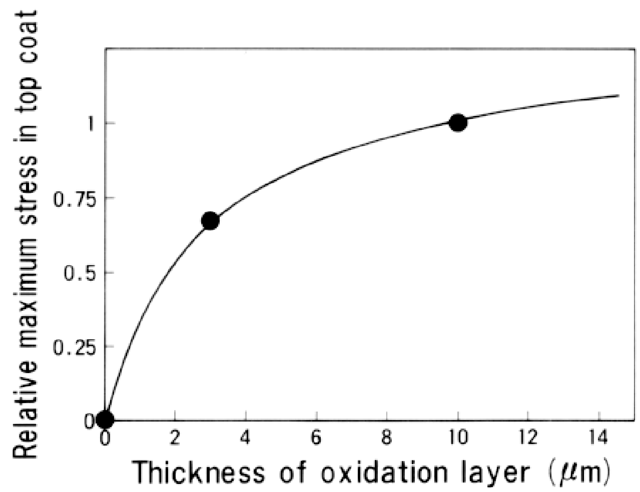

Fig. 9 Relation between maximum stress and thickness of oxidation layer

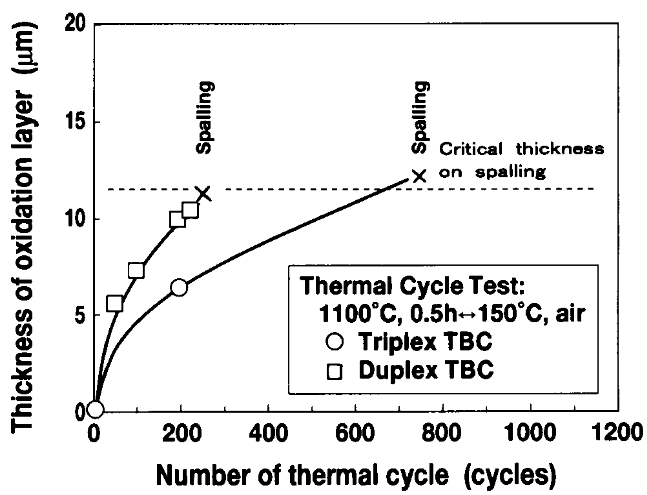

Fig. 10 Growth of oxidation layer in a thermal cycle test and critical thickness of spalling

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