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Influence of the mechanical properties of CoNiCrAlY under-coating on the high temperature fatigue life of YSZ thermal-barrier-coating system

Hiroyuki Waki [a,*], Akira Kobayashi [b]

[a] Department of Mechanical Engineering, Faculty of Engineering, Osaka Electro-Communication University, 18-8 Hatsu-cho, Neyagawa, Osaka 572-8530, Japan
[b] Joining and Welding Research Institute, Osaka University, 11-1 Mihogaoka, Ibraki, Osaka 567-0047, Japan

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A B S T R A C T

Yttria-stabilized zirconia (YSZ) thermal-barrier-coatings (TBC) have been used for insulating and protecting the components from high temperature. However, the mechanical properties of the coatings are not well known, because the characterization of thin coatings is difficult. Consequently, how should we choose the mechanical properties, which is very important, is unsolved problem. In this paper, the effects of the mechanical properties of under-coatings, CoNiCrAlY, on the fatigue life of YSZ coating system were examined. First, the strength of three types of CoNiCrAlY coatings were examined by lateral compression of circular tube free-standing coating. The residual stresses of CoNiCrAlY coatings were also measured by X-ray diffraction method. Furthermore, the adhesive strengths of CoNiCrAlY coatings were measured by indentation method. Subsequently to the systematic understanding of mechanical properties of the CoNiCrAlY coatings, fatigue tests were carried out for the TBC systems at both room temperature and 893 K. The results indicated an improvement of the fatigue life because of the restriction of crack initiation into the substrate. It was found that the under-coating with proper mechanical properties could significantly extend the fatigue life of the TBC system.

1. Introduction

Yttria-stabilized zirconia (YSZ) thermal-barrier-coatings (TBC) have been used for insulating and protecting the components from high temperature. CoNiCrAlY alloy was coated on the substrate as under-coating for YSZ. However, the mechanical properties of the coatings are not well known, because the characterization of thin coatings is difficult. Consequently, how should we choose the mechanical properties, which is very important, is unsolved problem [1].

In this paper, the effects of the mechanical properties of under-coatings, CoNiCrAlY, on the fatigue life of YSZ coating system were examined. There are some studies about mechanical properties of CoNiCrAlY [2–4]. Authors have developed a new method for measuring the bending strength of a thin plasma sprayed coating by lateral compression of circular tube free-standing coating [5]. First, the strengths of three types of CoNiCrAlY coatings were examined by the method. The residual stresses of the CoNiCrAlY coatings were also measured by X-ray diffraction method. Furthermore, the adhesive strengths of the CoNiCrAlY coatings were measured by indentation method. Subsequently to the systematic understanding of mechanical properties of the CoNiCrAlY coatings, fatigue tests were carried out for the TBC systems with three types of CoNiCrAlY. The obtained relationship between the fatigue lives of TBC systems and mechanical properties of CoNiCrAlY coatings was discussed.

2. Experimental procedure

2.1. Specimens

Hourglass-shaped specimens were used for the fatigue testing of TBC system. The shape and dimensions of the substrate are shown in Fig. 1. Type 304 stainless steel was used for the substrate. This substrate specimen was denominated an AN specimen. Before spraying, blast treatment was applied to the AN specimen. The blasted substrate specimen was denominated a BS specimen. CoNiCrAlY alloy and ZrO_2-8%Y_2O_3 (YSZ) ceramic were deposited on the hatching area in Fig. 1. The thickness of the alloy coating and the ceramic coating was about 150 μm and 300 μm, respectively. Three types of TBC specimens shown in Table 1 were manufactured. The CoNiCrAlY alloy was deposited by either atmospheric plasma spraying (APS) or low pressure plasma spraying (LPPS). The CoNiCrAlY(LPPS) coating with thermal aging for diffusion treatment was also manufactured. The diffusion thermal treatment consisted of heating for 3 h at 1323 K in vacuum followed by furnace cooling. YSZ was deposited by APS. Spraying powders are listed in Table 2.

* Corresponding author. Fax: +81 72 820 9000.
E-mail address: waki@isc.osakac.ac.jp (H. Waki).

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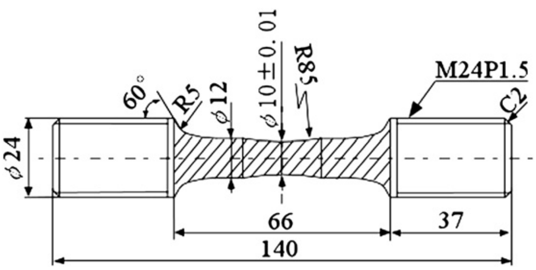

Fig. 1. Shape and dimensions of the TBC specimen.

2.2. Test conditions

An electro-hydraulic-servo fatigue test machine (max. load = 100 kN) was used for tension–compression fatigue testing. The fatigue tests were carried out under the condition of constant nominal stress range $\Delta\sigma_n$ with a stress ratio of $R = -1$ at a frequency of 10 Hz. Testing temperatures were both 893 K and room temperature. The specimens were heated by furnace heating.

3. Mechanical properties of CoNiCrAlY coatings

3.1. Microstructures of CoNiCrAlY coatings

Fig. 2 shows the longitudinal sections of the three types of the CoNiCrAlY coatings shown in Table 1. The black regions in the figures are oxides of Al, Cr, Ni or Co. There are much oxides in CoNiCrAlY(APS) coating. On the contrary, there are little oxides in CoNiCrAlY(LPPS) and CoNiCrAlY(LPPS-T) coatings. CoNiCrAlY(LPPS-T) coating has a homogenized structure with intermetallic compounds, (Ni, Co)Al [3,6]. The difference of microstructure may affect the mechanical properties and fatigue life of TBC system.

3.2. Bending strengths of CoNiCrAlY coatings

The strengths of three types of CoNiCrAlY coatings shown in Table 1 were examined. These mechanical properties were measured by the lateral compression tests of the cylindrical coating specimens whose thickness were approximately 250 μm. The inner diameter of the cylindrical coating specimen was 12.7 mm and the length was 5 mm. The manufacturing procedure of the coating specimen independent of a substrate was as follows. First, CoNiCrAlY was sprayed on the cylindrical substrate made of mild steel. Last, the substrate was dissolved out by means of nitric acid. The load–displacement curves during the lateral compression test were measured. Bending strength was estimated by the broken load of the free-standing cylindrical coating. The details of the lateral compression test were described in other paper [5].

Fig. 3 shows the bending strengths of three types of CoNiCrAlY coatings. The strength of the CoNiCrAlY(APS) coating was lowest among the three types of specimens. As shown in Fig. 2, the CoNiCrAlY(APS) coating contained much oxidation which looks black in the figure and defects among the platelets. This is the reason for low strength of CoNiCrAlY(APS) coating. On the contrary, the CoNiCrAlY(LPPS) coating is precise and has almost no internal defect as shown in Fig. 2. It is also found from Fig. 3 that the heat treatment is effective in improving the strength.

Table 1
Three types of thermal-barrier-coated specimens used in this study

Specimen	Top-coating	Under-coating
AN	No	No
BS	No	No (only blasting)
APS	ZrO_2-8%Y_2O_3(APS)	CoNiCrAlY(APS)
LPPS	ZrO_2-8%Y_2O_3(APS)	CoNiCrAlY(LPPS)
LPPS-T	ZrO_2-8%Y_2O_3(APS)	CoNiCrAlY(LPPS) with thermal treatment

Table 2
Spraying powders used in this study

	Chemical composition (mass%)	Powder size (μm)
YSZ	ZrO_2, 8%Y_2O_3	45 ~ 75
CoNiCrAlY	Co, 32%Ni, 21%Cr, 8%Al, 0.5%Y	5 ~ 37

3.3. Residual stresses of CoNiCrAlY coatings

The plate type stainless specimens with CoNiCrAlY coatings were prepared. The residual stresses of three types of CoNiCrAlY coatings on stainless steel were examined using an X-ray diffraction method. The $2\theta_\psi - \sin^2\psi$ method was selected. The details of the method were described in other paper [7]. The measured residual stresses in CoNiCrAlY coatings are shown in Fig. 4. There is no significant difference between CoNiCrAlY(APS) and CoNiCrAlY(LPPS) coatings. On the contrary, the compressive residual stress significantly increases for CoNiCrAlY(LPPS-T) coating. It was found that diffusion thermal treatment was effective in generating the high compressive residual stress.

3.4. Delamination energies of CoNiCrAlY coatings

The plate type stainless specimens with CoNiCrAlY coatings were manufactured. Delamination energies of three types of CoNiCrAlY coatings on stainless steel were examined using an indentation method. The load–displacement curves during the indentation were measured, and the given energy per unit area of delamination was estimated. The details of the indentation method were described in other paper [8]. It is found from Fig. 5 that the delamination energies of CoNiCrAlY(APS) and CoNiCrAlY(LPPS) coatings are approximately the same. The delamination energy of the CoNiCrAlY(LPPS-T) coating is widely scattered as compared with the other two coatings, however, that of the CoNiCrAlY(LPPS-T) coating is found to be about three times higher than those of the other two coatings. It was found that diffusion thermal treatment was effective in improving the adhesive strength. High compressive

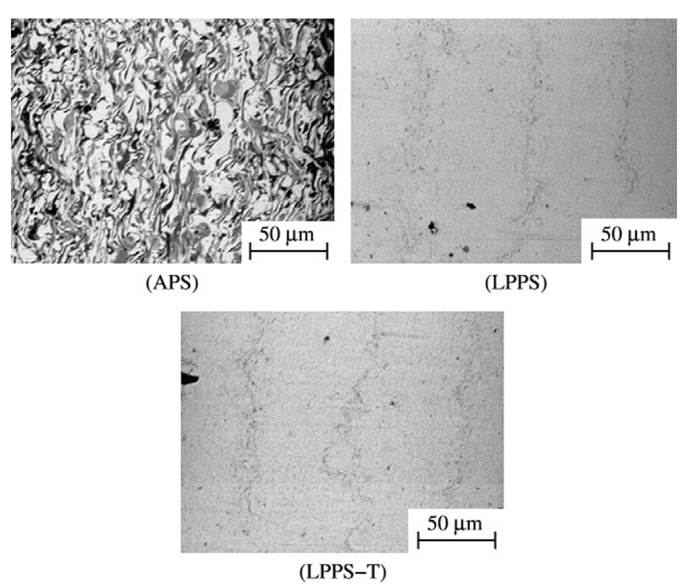

Fig. 2. Longitudinal sections of the three types of CoNiCrAlY coatings.

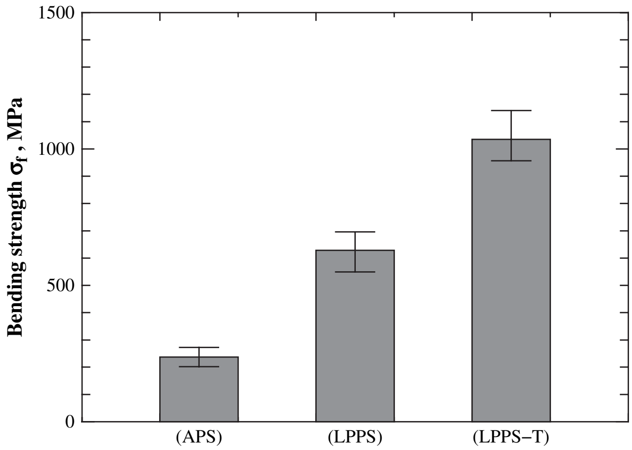

Fig. 3. Bending strengths of three types of CoNiCrAlY coatings.

residual stress is one of the reason why CoNiCrAlY(LPPS-T) coating has high adhesive strength.

4. Effects of under-coating on the fatigue life of thermal-barrier-coating system

4.1. Fatigue life of TBC system

Fatigue tests were carried out for YSZ coated stainless steel specimens shown in Table 1. The relationships between a nominal stress range $\Delta\sigma_n$ and a fatigue fracture life N_f at room temperature and 893 K are shown in Fig. 6. $\Delta\sigma_n$ was defined as a load divided by the cross-section area of a substrate. As shown in Fig. 6, the N_f of a LPPS-T specimen is the longest among the all specimens in all stress regions at both high temperature and room temperature.

On the other hand, in the case of the specimens except for the LPPS-T specimen, there is no remarkable difference in the life under a high stress region more than 500 MPa at room temperature. It is generally known that the influence of surface treatment on the fatigue life is insignificant in such a high stress region, in other words, short life region. In this study, the influence of a coating will be discussed in a low stress region in which the influence appears notably. It is found from Fig. 6 that the N_f of an APS specimen is shorter than the other two types of coated specimens both at 893 K and room temperature, while it is longer than those of un-coated specimens, AN and BS specimens. Since the damage of the alloy and the ceramic coating was insignificant in a low stress region, the

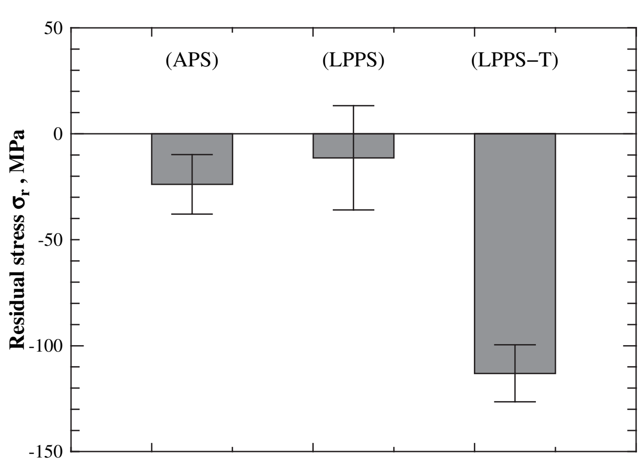

Fig. 4. Residual stresses of three types of CoNiCrAlY coatings.

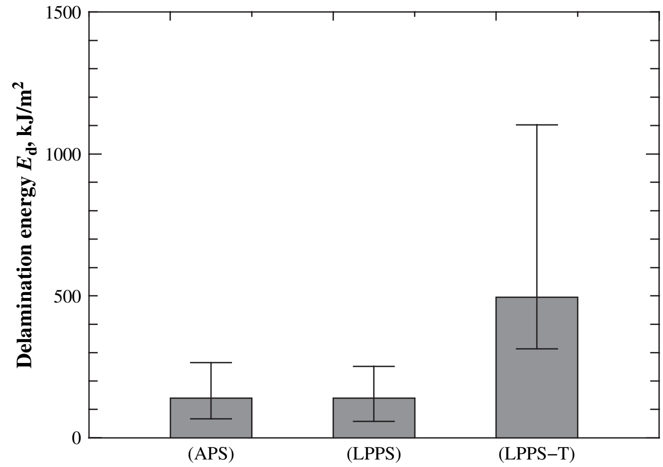

Fig. 5. Delamination energies of three types of CoNiCrAlY coatings.

coatings paid the stress of a substrate. This meant that N_f didn't become short by the APS coating with low strength.

4.2. Fatigue fracture process of TBC system

In order to examine the fatigue fracture process of thermal-barrier-coated stainless steel, the longitudinal sections of the coated specimens after fatigue tests were observed by SEM. The specimens were cut at the point of crack initiation in a substrate. Fig. 7 shows the typical images obtained under long life conditions at high temperature.

As shown in Fig. 7(a), there are a few crack in the alloy layer in an APS specimen. On the contrary, the crack in alloy layer doesn't occur in LPPS-T and LPPS specimens as shown in Fig. 7(b) and (c). This is because the strength of CoNiCrAlY(LPPS) and CoNiCrAlY(LPPS-T) coatings was high as shown in Fig. 3. Moreover, delamination doesn't occur and the fracture surface is continuous in the APS specimen. It was suggested that the crack occurred at the surface of a ceramic layer propagated into the alloy layer, and subsequently propagated into a substrate in APS specimen. In the case of the APS specimen, although the crack of the ceramic layer, which occurred at an early stage of the fatigue test, grew up to be the crack of a substrate, the fatigue fracture life didn't decrease as compared with a BS specimen as shown in Fig. 6. It was suggested that the crack

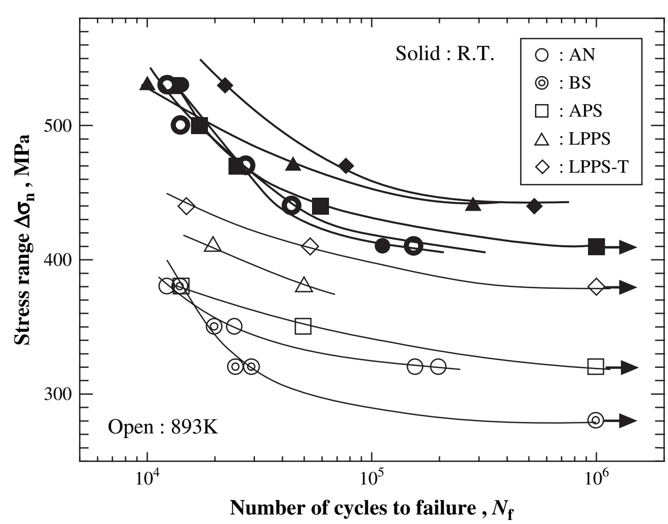

Fig. 6. Relationships between the nominal stress range, $\Delta\sigma_n$, and the fatigue fracture life of TBC stainless steel, N_f.

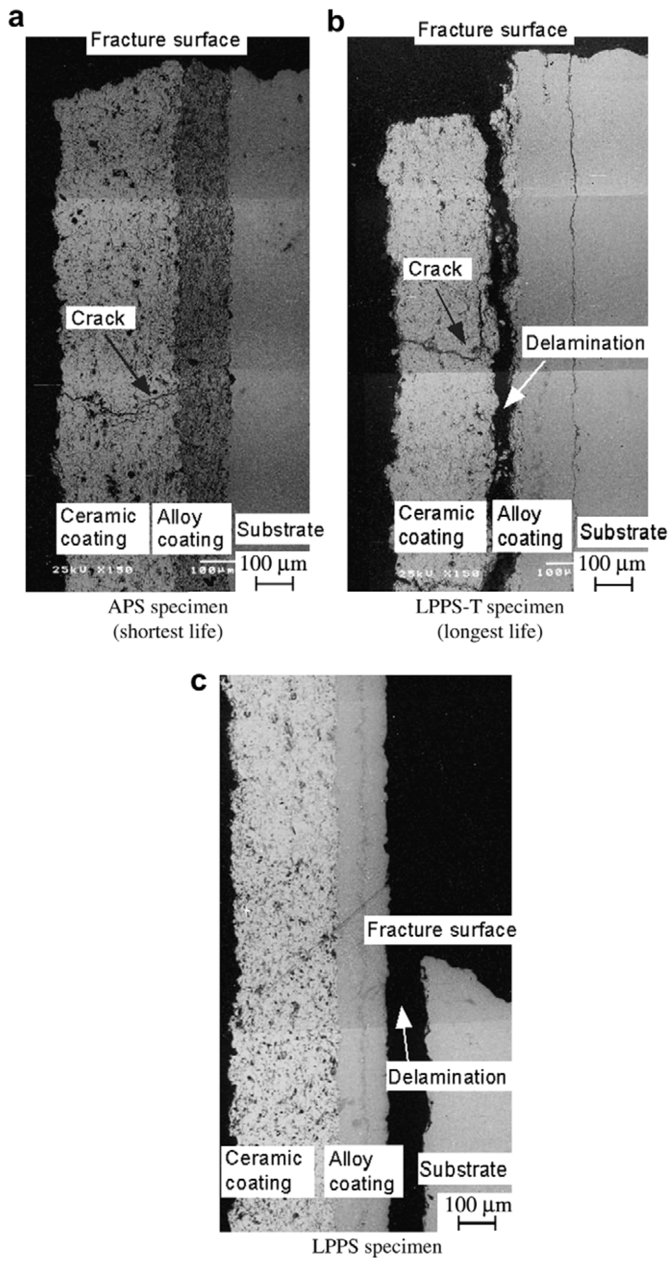

Fig. 7. Longitudinal sections of the typical specimens after fatigue tests.

occurred at the ceramic layer stopped at the interfaces, and the crack initiation life of the substrate was almost the same as that of the BS specimen. Young's modulus of ZrO_2-8%Y_2O_3 coating and CoNiCrAlY(APS) coating was about 20 GPa [4] and 55 GPa [5], respectively, and those were quite low as compared with that of the substrate, 200 GPa. Consequently, the effect of the crack in coating layers on crack initiation of the substrate was insignificant.

Next, the fatigue fracture process of a LPPS-T specimen is discussed. As shown in Fig. 7(b), the crack of the ceramic layer doesn't propagate into the alloy layer, and the delamination between a ceramic layer and an alloy layer occurs. A new crack, which isn't identical with that initiated in the ceramic layer, occurs from the delaminated interface, and the crack propagates into a substrate. From the difference of fatigue fracture process between APS and LPPS-T specimen, it was suggested that the fracture strength of under-coating significantly affects the fatigue fracture process. Consequently, it is desirable that under-coating has high strength.

Last, the fatigue fracture process of a LPPS specimen is discussed. As shown in Fig. 7(c), the crack of the ceramic layer doesn't propagate into the substrate, and the delamination between an alloy layer and a substrate occurs. It was suggested that the crack of the substrate propagated from the free surface of the substrate after the delamination occurred. From the difference of fatigue fracture process between LPPS and LPPS-T specimen, it was suggested that adhesive strength between the alloy layer and the substrate significantly affects the fatigue fracture life. Consequently, it is desirable that the delamination strength between an alloy layer and a substrate is high.

In summary of this section, the improvement of N_f was caused by the restriction of crack initiation into the substrate due to a CoNiCrAlY(LPPS) coating with high strength and high adhesive strength.

5. Conclusion

The effects of CoNiCrAlY under-coatings on the fatigue strength of YSZ thermal-barrier-coated stainless steel were described. First, the mechanical properties of CoNiCrAlY coatings were examined. Next, fatigue tests were carried out at room temperature and 893 K for YSZ thermal-barrier-coated stainless steel. The obtained results are summarized as follows:

(1) the bending strength of a CoNiCrAlY(APS) coating was low. On the contrary, that was high for a CoNiCrAlY(LPPS-T) coating. The strength was effectively improved by the diffusion aging;
(2) there was no significant difference in residual stress between CoNiCrAlY(APS) and CoNiCrAlY(LPPS) coatings. On the contrary, the compressive residual stress was significantly increased for CoNiCrAlY(LPPS-T) coating. Diffusion thermal treatment was effective in generating the high compressive residual stress;
(3) the delamination energies of CoNiCrAlY(APS) and CoNiCrAlY(LPPS) coatings were approximately the same. On the contrary, that of CoNiCrAlY(LPPS-T) coating was three times higher than those of other two coatings. Diffusion thermal treatment was effective in improving the adhesive strength;
(4) the fatigue life of the LPPS-T specimen was the longest, and that of the APS specimen was shortest among the TBC specimens;
(5) it was found that a CoNiCrAlY(APS) coating with low strength didn't shorten the fatigue fracture life of a TBC stainless steel than that of a bared stainless steel;
(6) it was found that an under-coating with high strength and high adhesive strength was effective in improving the fatigue fracture life of TBC stainless steel.

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