Nonlinearity of Uniaxial Compressive Response in Atmospheric Plasma Sprayed Free-Standing CoNiCrAlY Coatings*

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Abstract

CoNiCrAlY protective coatings are used for insulation from corrosion and oxidation of super alloy substrates in gas turbine blades. The life of a gas turbine blade is significantly affected by the mechanical properties of the protective coating. However, the properties of the coatings themselves have not been clarified, because there are few proper measurement methods for thin coatings. In this study, uniaxial stress-strain responses of atmospheric plasma sprayed (APS) free-standing CoNiCrAlY coatings were examined. The coating specimen was tube with the thickness of 0.3 mm. Coating specimens independent of substrates were fabricated by chemically dissolving out the substrates only at the region of gauge area. The stress-strain response was measured using the laser speckle strain measurement method. The coating showed the significant nonlinear stress-strain response. The stiffness increased with an increase of applied compressive stress, and the coating left permanent strain when the compressive stress was released. The nonlinearity of stress-strain response became significant if the surface roughness increased. The nonlinearity was decided by the surface roughness which represented the amount of defects in the coating. On the contrary, the nonlinearity was not proportional to the fraction of oxidized area. As compared with low pressure plasma sprayed (LPPS) CoNiCrAlY, the Young's modulus of APS CoNiCrAlY was low.

Key words: Mechanical Properties, CoNiCrAlY, Protective Coating, Plasma Spray, Thermal Barrier Coating, Laser Speckle

1. Introduction

CoNiCrAlY protective coatings are used for insulation from corrosion and oxidation of super alloy substrates in gas turbine blades. The life of a gas turbine blade is significantly affected by the mechanical properties of the protective coating⁽¹⁾⁽²⁾. However, the properties of the coatings themselves are not clarified, because there are few proper measurement methods for thin coatings. Socie et. al.⁽³⁾⁽⁴⁾ developed the new method to measure the uniaxial stress-strain response of thick circular tube free-standing ZrO₂-8%Y₂O₃ (8YSZ) coating. Authors⁽⁵⁾⁽⁶⁾ modified the method to apply to thin coating, and stress-strain responses of 8YSZ coating and CoNiCrAlY(LPPS) coating were measured. Authors have

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also developed the new easy method to measure the mechanical properties using a lateral compression of circular tube⁽⁷⁾. In this study, stress-strain responses of CoNiCrAlY(APS) coatings were measured at room temperature and 873K by uniaxial compression of the circular tube specimen. The effect of spraying powder on the stress-strain response was discussed with the microstructures.

2. Experimental Method

2.1 Manufacturing Procedure of the Specimens

Specimens of CoNiCrAlY metallic coatings, which were independent of substrates, were manufactured in order to measure stress-strain responses of the coatings. The specimen was the uniaxial cylindrical specimen with the stainless steel screw ends. The manufacturing procedure of the specimen is shown in Fig. 1. First, as shown in Fig. 1(a), a mild steel tube with a thickness of 1mm was fitted into the stainless steel cone jigs which had screws. Next, as shown in Fig. 1(b), thermal spraying was carried out on the center (testing area) of the fabricated substrate after blast processing by alumina grid (WA#24). Finally, the coating specimen which had screw ends as shown in Fig. 1(c) was obtained by dissolving out only the mild steel tube by means of nitric acid. The steel substrate was dissolved out only from the inner surface. Thicknesses of all the coatings were approximately 300 μm . As the section area was large, the loading test was not hard. Furthermore, buckling didn't occur in such a thin coating, because the second moment of the section area was large.

Fig. 1 Manufacturing procedure of the coating specimen: (a) mild steel tube with stainless steel ends before spraying, (b) with sprayed coating, (c) after dissolving out the mild steel tube

Table 1 Plasma-spraying conditions

Pressure (MPa)		0.1
Arc current (A)		500
Arc voltage (V)		60
Arc gas	Ar (MPa)	0.69
	He (MPa)	—
	H ₂ (MPa)	0.41
Spraying distance (mm)		150

Table 2 Specimens used in this study

Abbreviation of coating	Spraying condition	Spraying powder size (μm)
CoNiCrAlY(APS-21)	APS	21
CoNiCrAlY(APS-37)		37
CoNiCrAlY(APS-60)		60

Fig. 2 Experimental setup for surface strain measurement using laser speckle strain measurement system

The coatings were deposited by atmospheric plasma spraying (APS). The spraying powder consisted of 38.5%Co, 32%Ni, 21%Cr, 8%Al and 0.5%Y. The spraying conditions and the three types of the specimens are shown in Table 1 and Table 2, respectively.

2.2 Stress-Strain Measurement Method

In order to investigate the uniaxial stress-strain responses of sprayed coatings, a quasi-static monotonic compression test was carried out. The tests were carried out at 873K and room temperature. The electro-hydraulic servo fatigue testing machine (± 2 kN) were used for loading the specimen. Loading speed was approximately 5 MPa/sec under the condition of load control. A laser speckle strain / displacement gauge (SSDG) developed by authors was used for measuring a strain of the specimen. The details of SSDG were described in previous papers⁽⁸⁾⁽⁹⁾. The gauge length was selected as 1 mm. In case of high temperature test, specimens were heated by an electric furnace. The schematic illustration of the experimental setup is shown in Fig. 2. The resolution in the strain measurement depends on both the arrangements of CCD cameras and the number of pixels of an image processing board. The measurement system used in this study had a resolution of 0.06 % strain.

3. RESULTS AND DISCUSSIONS

3.1 Microstructures

The plasma-spraying produced the coatings which had complicated microstructures. Longitudinal-sections of coatings were observed using a scanning electron microscope (SEM). The composition images of the coatings are shown in Figs. 3(a)~(c). In addition, the coatings are laminated in the lateral direction of the Figs, and the loading directions of specimens are the vertical direction of the Figs. As shown in Figs. 3(a)~(c), CoNiCrAlY coatings deposited by APS have the laminated structures with much oxide which look black in the Figs.

The fraction of oxidized area was measured by image processing. The composition images, Figs. 3(a)~(c), were converted into black and white images, and the black ratio, fraction of oxidized area, was estimated. Figure 4 shows the fraction of oxidized area plotted against the spraying powder size. The fraction of oxidized area increases with a decrease of spraying powder size. It is also found from Figs. 3(a)~(c) that there are much small size of oxidation in CoNiCrAlY(APS-21). Small spraying powder had larger oxidized surface than large spraying powder. It was the reason of high fraction of oxidized area in CoNiCrAlY(APS-21).

Surface roughness, R_a , was also measured from longitudinal section images by image processing. R_a is also shown in Fig. 4. R_a increases with an increase of spraying powder size. It was reported that the porosity of CoNiCrAlY coating was directly correlated with

Fig. 3 Microstructures of CoNiCrAlY(APS) coatings

Fig. 4 Fraction of oxidized area and surface roughness of each coating

surface roughness⁽¹⁰⁾. In this study, R_a was used as a representative parameter instead of the amount of pores or cracks between platelets.

3.2 Stress-Strain Response

The typical examples of the compressive deformation behaviors of CoNiCrAlY coatings at room temperature and 873K are shown in Figs. 5(a) and (b), respectively. The loading method of a specimen was as follows: First, compressive load was applied along the line from point O to point A. Next, the compressive load was removed along the line from point A to point B. After that, a compressive load was applied again along the line from point B to point C. Next, the compressive load was removed along the line from point C to point D. Finally, a compressive load was applied again along the line from point D to point C. In short, the compressive load was stepwise increased by -50MPa. It is found from Figs. 5(a) and (b) that CoNiCrAlY(APS) coating shows nonlinear stress-strain response.

Next, stress-strain responses are quantitatively investigated. The stress-strain curve

Fig. 5 Compressive stress-strain response under stepwise loading

loaded with compressive load at the first time is named initial-load-line, and the curve at the part of removing compressive load toward a zero stress is named unload-line, and the curve loaded with compressive load once again is named reload-line. As shown in Figs. 5(a) and (b), the unload-line AB which has the larger slope is different from the initial-load-line OA both at R.T. and 873K. It means that a permanent strain appears both at R.T. and 873K. There is also a tendency at R.T. that the tangent of stress-strain is higher at high stress region than at low stress region. On the contrary, the tangent of stress-strain is nearly linear at 873K. The difference of the stress-strain form was because creep was high in high compressive stress region at high temperature. The reload-line BC passes near the unload-line AB both at R.T. and 873K. When stress exceeds the maximum compressive stress undergone, the strain increases and the stress-strain line follows the extension line of the initial-load-line OA. Then, when compressive load is given stepwise, the coatings show the similar deformation behavior. It was found that the coatings remembered a loading history, and that a permanent strain appeared by undergoing compressive load. It was the same deformation behavior as the nonlinear stress-strain response of the uniaxial compressive load in a thick thermal barrier ZrO_2 -8% Y_2O_3 coating which Socie et. al. ⁽³⁾⁽⁴⁾ had reported.

Next, total strain range was investigated. Figure 6 shows the total strain range generated under $\Delta\sigma=100$ MPa plotted against a spraying powder size. It is found that the total strain range increases with an increase of the powder size. Figure 7 shows the total strain range plotted against the surface roughness R_a . R_a is a representative parameter instead of the amount of pores or cracks between platelets. It is found that the total strain range increases with an increase of R_a . Itoh et. al. had also reported that CoNiCrAlY coating with high density had high Young's modulus and high strength ⁽¹¹⁾. It is also found from Fig. 7 that the total strain range of CoNiCrAlY(APS-21) at 873K is not significantly different from that at

Fig. 6 Total strain range generated under $\Delta\sigma=100$ MPa plotted against the spraying powder size

Fig. 7 Total strain range generated under $\Delta\sigma=100$ MPa plotted against the surface roughness

Fig. 8 Permanent strain range generated under $\Delta\sigma=100$ MPa plotted against the surface roughness

R.T.

Next, permanent strain was investigated. Figure 8 shows the permanent strain generated under $\Delta\sigma=100$ MPa. The permanent strain of CoNiCrAlY(LPPS) which had reported in previous paper ⁽⁶⁾ is also plotted in Fig. 8. CoNiCrAlY(LPPS-T) means the CoNiCrAlY(LPPS) specimen with thermal treatment which consisted of 1327K 3 hours in vacuum. It is found that the permanent strain increases with an increase of R_a , and the permanent strain of CoNiCrAlY(APS) is the highest among the coatings. It is also found that the permanent strain at 873K is higher than that at R.T.

Next, the strain range ratio of the average strain of unloading-strain range and reloading-strain range to initial-strain range, R_m , is shown in Fig. 9. The strain ranges generated under $\Delta\sigma=100$ MPa shown in Fig. 6 were used for estimating the R_m . If R_m is

Fig. 9 The strain range ratio of the average strain of unloading-strain range and reloading-strain range to initial-strain range, R_m

lower than 1.0, it means the coating shows hardening. The R_m of CoNiCrAlY(LPPS) coating⁽⁶⁾ is also plotted in Fig. 9. It is found that R_m decreases with an increase of R_a and the R_m of CoNiCrAlY(APS) is the lowest among the coatings. It is also found that the R_m at 873K is lower than that at R.T. It is found from these results that the compliance of the stress-strain curve decreased by undergoing monotonic compressive load.

In short of this section, CoNiCrAlY(APS) showed significant nonlinear stress-strain response. The nonlinearity was decided by the surface roughness which represented the amount of defects in the coating and it was significant if the surface roughness increased. On the contrary, the nonlinearity was not proportional to the fraction of oxidized area. There were not significant differences between the stress-strain response of CoNiCrAlY(APS-21) at 873K and that at R.T.

3.3 Apparent Young's Modulus

The tangent modulus of stress-strain curve obtained was investigated quantitatively. Tangent modulus of an initial-load line at each stress is shown in Fig. 10. The value of modulus increases with increasing compressive stress at R.T. as shown in Fig. 10. This means that the stress-strain curves are convex curves at R.T. On the contrary, the modulus is nearly constant at 873K. This means the stress-strain curve is nearly linear at 873K. Since the compaction of micro pores was the one of the deformation mechanism, the stress-strain responses at R.T. showed convex curves. At high temperature, the nonlinearity was canceled by creep, so that it showed nearly linear stress-strain response.

Next, tangent modulus of initial-line at near zero stress, apparent Young's modulus, was investigated. It is understood from Fig. 11 that apparent Young's moduli of coatings are low as compared with bulk alloy. It is also found that apparent Young's modulus of CoNiCrAlY

Fig. 10 Tangent modulus at each stress

Fig. 11 Apparent Young's modulus

(APS) is the lowest, and those of CoNiCrAlY (LPPS) and CoNiCrAlY(LPPS-T) are almost the same. It is the same results by lateral compression of circular tube coating⁽⁷⁾. The apparent Young's modulus increases with a decrease of R_a . It is also found that apparent Young's modulus at 873K is a little higher than that at R.T. Authors confirmed that Young's modulus does not decrease until at 873K and that at 873K was a little higher than that at R.T. by lateral compression of circular tube CoNiCrAlY(APS).

4. Conclusion

Free-standing CoNiCrAlY sprayed coating specimens whose thicknesses were approximately 300 μm were developed. The uniaxial stress-strain response of CoNiCrAlY(APS) were measured using the laser speckle strain / displacement gauge at R.T. and 873K. The results obtained are summarized as follows:

- (1) The coatings had much oxide if the coatings were sprayed using small diameter of spraying powder. On the contrary, the coatings had low surface roughness.
- (2) CoNiCrAlY(APS) coating showed significant nonlinear stress-strain response. The stiffness increased with an increase of applied compressive stress, and the coating left permanent strain when the compressive stress was released.
- (3) The total strain range and permanent strain increased with an increase of the surface roughness which represented the amount of defects in the coating.
- (4) Nonlinearity of stress-strain response became significant if the surface roughness increased. The nonlinearity was decided by the surface roughness which represented the amount of defects in the coating. While, the nonlinearity was not proportional to the fraction of oxidized area.
- (5) Apparent Young's modulus of CoNiCrAlY(APS) was lower than that of CoNiCrAlY (LPPS). The Young's modulus increased with a decrease of surface roughness.

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