Development of Lateral Compression Method of Circular Tube Thin Coating for Mechanical Properties of Plasma Sprayed CoNiCrAlY

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CoNiCrAlY coatings have been developed to protect gas turbine blades from oxidation and corrosion at high temperature. However, the mechanical properties of the thin CoNiCrAlY coatings used in actual turbine system were unknown, because there was not a proper measurement method of thin sprayed coatings. Lateral compression test for the circular tube coatings of plasma-sprayed thin coating was newly developed. In considering the deformation of the tubes, the elastic contact with a flat plate jig and a tube surface was taken into account as well as the bending of the curved beam of the tube. Young’s moduli of well known materials obtained from the lateral compression tests agreed well with the true values. CoNiCrAlY tube specimens independent of substrates were manufactured by dissolving out the substrates by nitric acid. The thickness of coatings were selected from 150 to 700\,\mu m. The effects of spraying particle size, spraying atmosphere and thermal treatment on mechanical properties, such as Young’s modulus and bending strength, of CoNiCrAlY were examined. It was found that Young’s modulus and a fracture stress increased with an increase of the coating thickness. Young’s modulus was sensitive to the spraying powder size and increased with a decrease of the size. It was found that spraying with small spraying powder was the most effective in increasing the Young’s modulus. It was also found that Young’s modulus was governed by the porosity if thickness and process were given. It was found that thermal treatment was the most effective in increasing the bending strength. [doi:10.2320/matertrans.47.1626]

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1. Introduction

As an increase of turbine inlet temperature, the efficiency in gas turbine system increases. MCrAlY, where M means Co and/or Ni, coatings have been developed to protect gas turbine blades from oxidation and corrosion at high temperature.\textsuperscript{1} Itoh et al.\textsuperscript{2,3} systematically investigated the mechanical properties of MCrAlY coatings by both four points bending test and resonance method. However, the mechanical properties of the thin MCrAlY coatings used in actual turbine system were unknown, because there was not a proper measurement method of thin sprayed coatings. Authors have developed the uniaxial loading specimen of thin plasma sprayed coatings and examined the stress-strain response of plasma sprayed coatings.\textsuperscript{4,5} However the method needed the greatest carefulness in specimen chucking. In this paper, the simple measurement method for the mechanical properties of thin coatings by lateral compression of a circular tube plasma sprayed coating was proposed. Next, the effects of spraying particle size, spraying atmosphere and thermal treatment on mechanical properties, such as Young’s modulus and bending strength, of CoNiCrAlY were examined.

2. Lateral compression for a circular tube coating

2.1 Manufacturing procedure of a thin specimen independent of a substrate

The circular tube specimen used in this study is shown in Fig. 1. Manufacturing procedure was as follows: First, blasting was carried out over the pipe made of SS400 with the thickness of 1\,mm. Subsequently, CoNiCrAlY (Co, 32\%Ni, 21\%Cr, 8\%Al, 0.5\%Y) was coated over the pipe using plasma spraying, as shown in Fig. 1(a). The pipe with the coating was cut to the pieces with the length of 5\,mm using a diamond disk cutter. The cut surface was polished by a sand paper of #2000. Last, only the mild steel pipe was dissolved out by nitric acid, as shown in Fig. 1(b).

2.2 Deformation mechanism of a circular tube

Lateral compression was applied to a circular tube speci-
men using an electro-hydraulic fatigue test machine with the load cell of 1 kN as shown in Fig. 2. Deformation of a forcing plate jig, \( \delta \), was measured using an eddy current displacement sensor with the resolution of 3 \( \mu \)m. In considering the deformation of the tubes, the elastic contact with a flat plate jig and a tube surface, \( \delta_{Hz} \), was taken into account as well as the bending of the curved beam of the tube, \( \delta_b \). Where \( \delta_{Hz} \) was calculated by the Hertz’s contact between elastic column (Young’s modulus \( E_1 \), Poisson’s ratio \( \nu_1 \)) and elastic plate \( (E_2, \nu_2) \),\(^6\) when load \( P \) was applied.

\[
\delta_{Hz} = \frac{8\delta}{\pi} \left[ 0.1535 + \frac{1}{2} \ln \left( \frac{\pi L^2}{R_0 \delta} \right) \right]
\]

\[
\delta = \frac{P}{L E}, \quad 2 = \frac{(1 - \nu_1^2)}{E_1} + \frac{(1 - \nu_2^2)}{E_2}
\]

Where \( L \) and \( R_0 \) are the length and outer radius of the tube, respectively. The elastic plate jig was made of stainless steel with \( E_2 = 198 \text{ GPa} \) and \( \nu_2 = 0.3 \).

\( \delta_\delta \) was calculated from the bending of a curved beam theorem.\(^7\)

\[
\delta_\delta = \frac{3\pi R_3}{E_1 L h^3} \left[ 1 - H + 2\alpha(1 + \nu_1)H - \frac{8}{\pi^2} (1 - H^2) \right] P
\]

Where, \( H = h^2/(12R^2) \), \( \alpha = 1.2 \), \( h \) and \( R \) are the thickness and mean radius of the tube, respectively. The measured displacement was obtained from the next equation.

\[
\delta = \delta_{Hz} + \delta_b \quad (3)
\]

Young’s modulus of the specimen \( E_1 \) was numerically decided as the value if the measured \( \delta \) correspond with the addition of \( \delta_b \) and \( \delta_{Hz} \).

Figure 3 shows the relationship between deformation ratio, \( \delta_{Hz}/\delta_b \), and normalized thickness, \( h/R \). Where the constants are a certain CoNiCrAIY’s. The \( \delta_{Hz}/\delta_b \) increases with an increase of the thickness of the specimen as shown in Fig. 3. Figure 4 shows the Young’s moduli of some kinds of well known materials obtained from the lateral compression tests and true values.

\[
\delta = \delta_{Hz} + \delta_b 
\]

\[
\frac{\delta_{Hz}}{\delta_b} \quad \text{Fig. 4 Comparison between Young’s moduli of some kinds of well known materials obtained from the lateral compression tests and true values.}
\]
study, Young’s modulus and stress was obtained from the curved beam theorem of eqs. (4) and (5). Poisson’s ratio of the CoNiCrAlY was assumed to be 0.29.

\[
E = \frac{3\pi R^2}{8Lh^3} \left( 1 - H + 2.4(1 + \nu)H - \frac{8}{\pi^2} (1 - H)^2 \right) \cdot P \quad (4)
\]

\[
\sigma = P \frac{R - e}{\pi Lhe} \left( R - \frac{h}{2} \right)^{-1}, \quad e = R - h \left( \ln \left( \frac{R + \frac{h}{2}}{R - \frac{h}{2}} \right) \right) \quad (5)
\]

3. Results and Discussions

3.1 Microstructures of CoNiCrAlY coatings

The plasma-spraying produced the coatings which had complicated microstructures. Axial-sections of coatings were observed using a scanning electron microscope (SEM). Axial-sections of CoNiCrAlY(APS-21), CoNiCrAlY(LPPS-21), CoNiCrAlY(LPPS-T21) and CoNiCrAlY(LPPS-60) are shown in Figs. 5(a)–(d), respectively. In addition, the coatings are laminated in the lateral directions of the figures, and the axial directions of specimens are the vertical directions of the figures. As shown in Fig. 5(a), CoNiCrAlY(APS) coating deposited by APS has the laminated structures with oxides which look black in the figures. On the other hand, oxides and defects are few in CoNiCrAlY coating deposited by LPPS. Especially, in CoNiCrAlY(LPPS-21) and CoNiCrAlY(LPPS-T21) coating, oxides and defects aren’t almost recognized. If CoNiCrAlY(LPPS-T21) coating is compared with CoNiCrAlY(LPPS-21) coating, oxides are found to precipitate a little at the boundary of particles and become to be a homogenized structure in CoNiCrAlY(LPPS-T21) coating.

The relations between the porosities of CoNiCrAlY coatings and the mean particle diameters of thermal-spraying powders are shown in Fig. 6. Porosities were measured by water absorption method. The pore meant the boundary between particles similar to a crack. It is found from Fig. 6 that porosity becomes high with increasing the diameter of a spraying powder for all the coatings. The area of contact-
surface between particles is known to become small with increasing the diameter of a spraying powder. If a spraying powder with a large diameter was used, the contamination of atmosphere during a solidification process increased, so that defects and pores increased. It is also understood from Fig. 6 that thermally treated CoNiCrAlY coating has a higher porosity than that of non-thermally treated CoNiCrAlY coating. As shown in Fig. 5(c), oxides grew a little at the boundary by thermal treatment, so that the porosity increased. Porosities of CoNiCrAlY(APS) coatings are higher than those of CoNiCrAlY(LPPS) and CoNiCrAlY(LPPS-T) coatings as shown in Fig. 6. It was confirmed that the precise coating with few defects and little contamination of atmosphere was produced by low pressure plasma spraying. Thus, the microstructure of a coating was significantly dependent on the spraying environment, the diameter of spraying powder and thermal treatment.

3.2 Relationship between load and displacement of a circular tube

The typical relationship between the load per unit length, \( P/L \), and the displacement, \( \delta \), of CoNiCrAlY is shown in Fig. 7. Almost all the case, at first, the tube broke at inner surface in vertical direction, point A or B, as shown in Fig. 7. The load doesn’t drop to zero in spite of breaking. At second, it broke at point B or A. Subsequently, it broke at outer surface in horizontal direction, point C or D. Last, it broke at point D or C. The tube specimen was finally divided into 4 pieces. In this study, the relationship between the load and displacement in elastic deformation before first breaking was used for the calculation. Bending strength was calculated from the load that the tube initially broke at point A or B. Of course, as taking account of breaking in deformation formula, the relationships after breakings are able to be used for obtaining the mechanical properties.

3.3 Young’s moduli of CoNiCrAlY coatings

The relationship between Young’s modulus and the thickness of the coating is shown in Fig. 8. The numbers in the figure represent the types of the specimens shown in Table 1. The deformation behaviors of plasma sprayed coatings in tension were different from those in compression. The Young’s modulus obtained by the lateral compression test was affected by both tension and compression similar to the traditional bending test of a plate type specimen. Young’s modulus increases with an increase of the thickness as shown in Fig. 8. It was found that Young’s modulus of sprayed coating was dependent of the thickness. This meant that mechanical properties must be measured for thin coatings used in real turbine blades. Compared among the coatings with the same size of spraying powder in Fig. 8, it is found that the values of CoNiCrAlY(LPPS-T) and CoNiCrAlY(LPPS) coatings are higher than that of CoNiCrAlY(APS) coating. It was the reason that the coating with fine microstructure had the high rigidity. Next, compared among the same type of coatings in Fig. 8, the value increases with a decrease of the spraying powder size. It was the reason that the coating with small powder size had the fine microstructures as shown in Fig. 5. It is found from Fig. 8 that Young’s modulus is sensitive to the spraying powder size and spraying with small spraying powder is the most effective in increasing the Young’s modulus. It was also found that Young’s modulus of CoNiCrAlY(APS) was pretty low.

Figure 9 shows the relationship between Young’s modulus and the porosity. The thickness of the coating is divided into three regions as shown in Fig. 9. It is also confirmed from Fig. 9 that Young’s modulus is high when the thickness is large. Young’s modulus increases with a decrease of porosity as shown in Fig. 9 in spite of the difference in spraying powder size. Compared with the same porosity, Young’s modulus of CoNiCrAlY(LPPS-T) is highest and that of CoNiCrAlY(APS) is lowest. It is found form Fig. 9 that Young’s modulus is governed by the porosity if thickness and process are given.
3.4 Bending strengths of CoNiCrAlY coatings

The relationship between the bending strength and the thickness of coating is shown in Fig. 10. The numbers in the figure represent the types of the specimens shown in Table 1.

The bending strength also increases with an increase of the thickness as well as the Young's modulus. The values of CoNiCrAlY(21) and CoNiCrAlY(37) coatings are pretty higher than that of CoNiCrAlY(60) coatings as shown in Fig. 10. The value of CoNiCrAlY(LPPS-T) is the highest and that of CoNiCrAlY(APS) is the lowest among the three types of coatings. It was found that thermal treatment was the most effective in increasing the bending strength. This was different from the results of Young’s modulus on which the spraying powder size was the most effective. This also meant that there was not great relationship between bending strength and porosity.

4. Conclusions

Lateral compression test for the circular tube coatings of plasma-sprayed thin coating was newly developed. In considering the deformation of the tubes, the elastic contact with a flat plate jig and a tube surface was taken into account as well as the bending of the curved beam of the tube. CoNiCrAlY tube specimens independent of substrates were manufactured by dissolving out the substrates using nitric acid. Mechanical properties of CoNiCrAlY were measured by the lateral compression test. The obtained results are as follows:

1. Young’s modulus of thin coating was able to be measured by the developed lateral compression method using the circular tube coating.
2. It was found that spraying with small spraying powder was the most effective in increasing Young’s modulus.
3. It was found that Young’s modulus was governed by the porosity if thickness and process were given.
4. It was found that thermal treatment was the most effective in increasing the bending strength.

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