Tribological Performance of Al_2O_3/NiCr Coating

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The tribological performance of Al_2O_3/NiCr coating deposited on steel(SM45C) was investigated under lubrication. The parameters of sliding wear consist of normal load and coating thickness. Test result showed that there was no evidence of an improved bonding strength in the coating. However, the wear resistance of the Al_2O_3/NiCr coating was significantly greater than that of the Al_2O_3 coating. It was eviclent that the residual stress for the Al_2O_3 coating was higher than that of the Al_2O_3/NiCr coating from the scratch test failure of coating. The bond coating played an important role in decreasing the residual stress. Also, it was found that the residual stress had a notable influence on the wear mechanism.

Key Words : Plasma Spray, Alumina Coating, Bond Coating, Wear, Friction, Residual Stress

1. Introduction

A considerable number of investigations have been conducted on the tribological behavior of plasma sprayed coatings. The application of ceramic coatings by plasma spray has become essential in tribosystems to attain high wear resistance and long life in severe conditions. However, the problem of coating failure during operation needs to be solved.

To make a coating structure by APS(Air Plasma Spray) method the coating process and material properties of the substrate and powders must all be considered. Many papers have reported various coating failures, such as the mismatch of the TEC(Thermal Expansion Coefficient) or the elastic modulus between the coating and the substrate(Holmberg et al., 1994; Pawlowski, 1995; Heimann, 1996; Tekeuchi et al., 1991; Wang et al., 1988). The defaults include cohesive failure, spallation of the coating, and weak adhesive strength of the interface, all of which influence the wear resistance characteristics of the coating.

Many researchers have tried to solve the problem of the mismatch of the TEC and thereby improve the cohesive strength between the coating and the substrate. Recently, it has been identified that compatible bond coating has advantages in its mechanical and tribological characteristics (Wang et al., 1988; Vijande-Diaz et al., 1991; Lugscheider, 1987). Improved plasma-sprayed coatings require certain tribological properties including the wear resistance of the coating and solidification of residual stress in the microstructure.

In this work wear testing of alumina under lubrication conditions with various coating thicknesses and normal loads was performed to evaluate the correlation between the residual stress and the wear mechanism. It was observed that the wear of coating was influenced by the residual stress and thickness of the coating.

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2. Experimental Detail

The substrate material used for the experiments was a low carbon steel(SM45C). The uniform thickness of all specimens was ensured by grinding to less than 0.1mm of tolerance from both sides of the disc surfaces. The surface of the substrate was degreased and sand blasted with alumina grit to create a better adhesion and remove any contaminants on the surface.

The chemical composition of the coating powder was 98wt.% Al_2O_3 and NiCr of 80wt.% Ni 20wt.% Cr. The spray equipment selected was the Hexa plasma system. The shape and size of the coating powder are shown in Fig. 1. The coating process parameters are shown in Table 1. Plasma spraying was carried out in air using an argon and helium mixture as the plasma-forming gas. The bond layer, NiCr, had an average thickness of 50μm, and the thickness of the alumina coating is shown in Table 2.

Table 1 The spraying parameters and properties for Hexa plasma

Parameters	Al_2O_3 coating	NiCr bond coating
Current [A]	630	650
Primary gas [l/min] (Ar)	60	60
Secondary gas [l/min] (H_2)	12	3
Powder carrier gas [l/min]	8(Ar)	8(Ar)
Powder inlet position	internal	external
Feed rate [g/min]	30	30
Stand-off distance [mm]	80	100

The tensile testing standard ASTM C633 was used to measure the bonding strength between the ceramic coating and the substrate(adhesive failure) or the bond failure(cohesive failure). A high performance epoxy adhesive, ARALDITE, was used to combine the surfaces of the two stubs. The bonding strength was determined as the maximum tensile strength, which was measured using an Instron 1342 tester at an across-head speed of 0.013mms^{-1}.

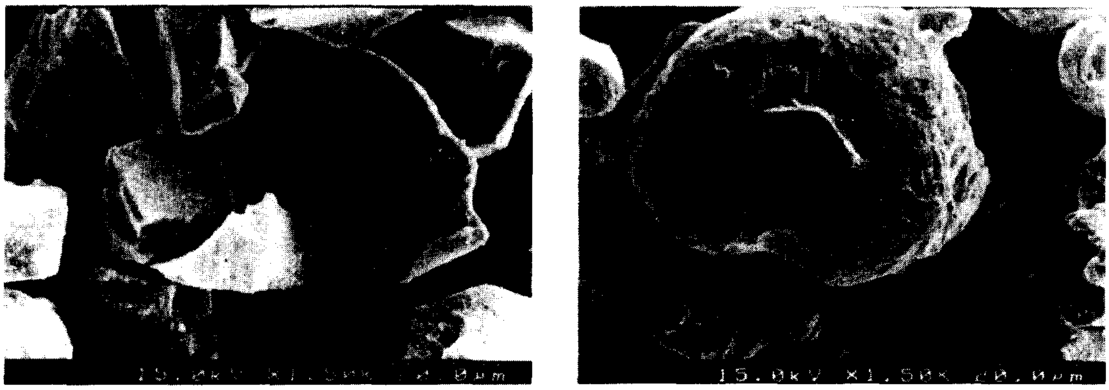
The wear volume was calculated from the sur face profile using a profilometer(Mitutoyo Surftest 500). The roughness value, *Ra*, was obtained by averaging four sets of data. The surface roughness values of the specmees are shown in Table 3.

Table 2 The structure of coating specimen

Specimen	Al_2O_3/NiCr	Al_2O_3
Coating thickness, μm (Bond coating)	250 (50) 300 (50) 400 (50)	300

Table 3 Result of surface roughness for specimens

Specimen	Roughness Ra(μm)
As-ground	0.6
After sand blasting	6.4
As-spray coating	6.8
After ground coating	1



(a) Al_2O_3 powder (b) NiCr powder

Fig. 1 SEM photographs of coating powder

The wear test was carried out under lubricated sliding conditions using a ball-on-disc-type apparatus as shown in Fig. 2. The normal loads used in this experiment were 50N, 80N and 110N and the sliding speed was constant at $0.1ms^{-1}$. Scanning Electron micvoscopy was performed to clarify the wear mechanism of the coating and observe the tribological behavior of the bonding mechanism.

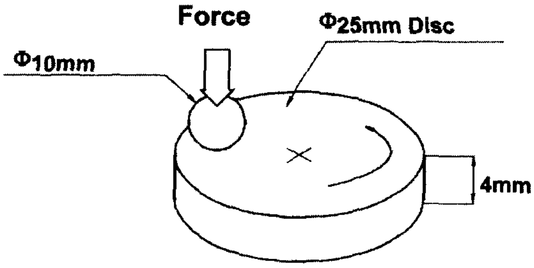
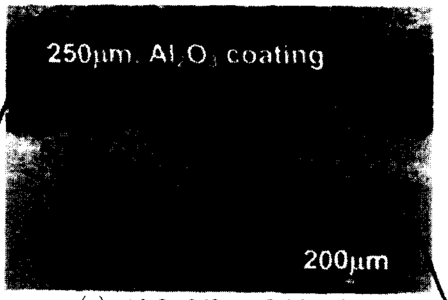


Fig. 2 Schematic illustration of ball on disk type wear test

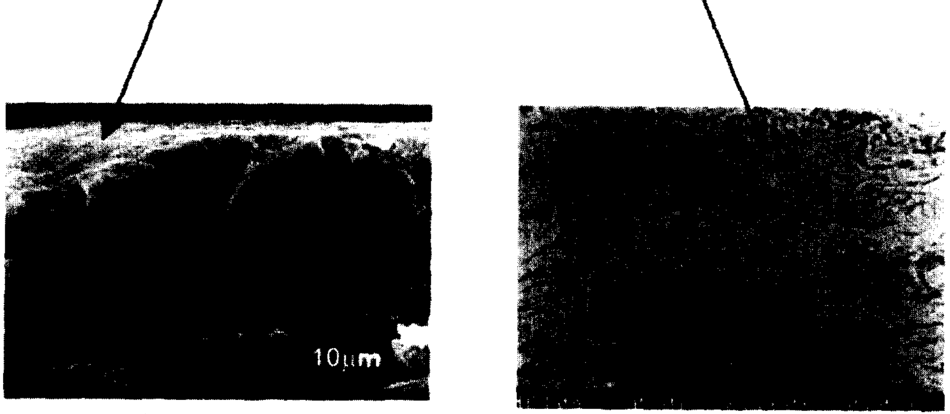
3. Results of Test

3.1 Microstructure of coating

Figure 3(a) shows the cross-sections of the Al_2O_3/NiCr structure in which the thickness of the NiCr bonded coating is 50μm. Therefore, the coating of the specimen has a total thickness of 300μm. The condition of the plasma coating has an influence on the microstructure and the shape of the splats in the coating. Columnar grains that result from the stress caused by the contraction of the lamellae are formed during the solidification cooling process. Pawlowski, 1995; Heimann, 1996; Ahn et al., 1993). The results of this study indicate that the wear behavior of coating depends on the microstructure of the coating. Wear occurs when wear debris is formed by the crack propagation within the columnar grains. Figure 3 (c) shows the cross-section of the NiCr bond coating.



(a) Al_2O_3 250μm, NiCr 50μm



(b) Al_2O_3 top coating (c) NiCr bond coating

Fig. 3 SEM photographs of cross-section for coating

3.2 Adhesion of coatings

As shown in Fig. 4, the bonding test results indicate that the surface roughness has an effect on the bonding strength. It has been previously reported that bond coating has an important influence on the cohesive strength and adhesive failure(Tekeuchi et al., 1991 ; Wang et al., 1988 ; Vijande-Diaz et al., 1991 ; Lugscheider, 1987). Mechanical properties are, therefore, improved due to an anchor mechanism at the interface between the substrate and the coating.

In this study, the adhesion strength of the Al_2O_3/NiCr coating was generally lower than that of the Al_2O_3 coating except when the surface roughness was 100μm R_{max}. This result suggested that the adhesion strength of the interface related not only to the material combination but also to the roughness of the surface.

3.3 Results of wear test

3.3.1 Effect of bond coating

Figs. 5, 6 and 7 show the variations in the specific wear rates of 300μm thick Al_2O_3 and Al_2O_3/NiCr coatings as a function of the sliding distance under 50N, 80N and 110N, respectively. As the sliding distance increased the specific wear rate of the Al_2O_3/NiCr coating remained constant, whereas the wear resistance of the Al_2O_3 coating decreased. The wear resistance of the Al_2O_3/NiCr coating was observed two times greater than that of the Al_2O_3 coating.

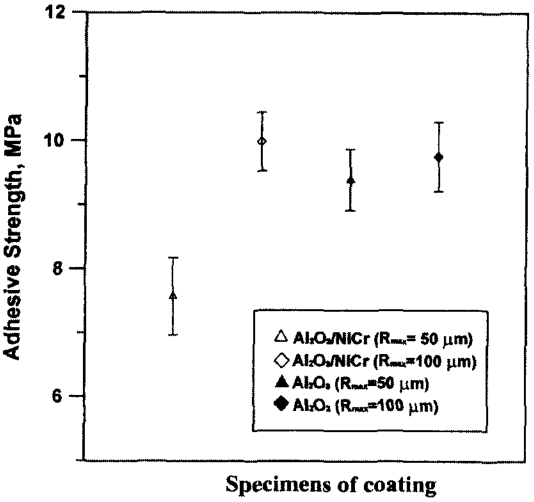


Fig. 4 Adhesive strength for various specimens

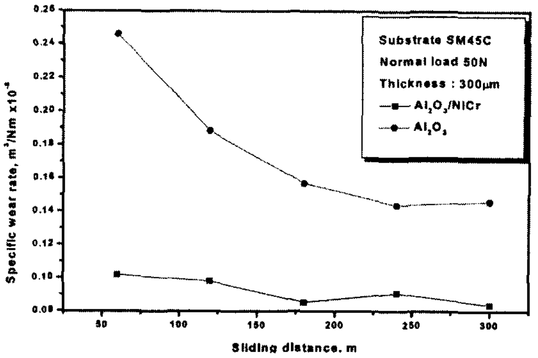


Fig. 5 Variation of specific wear rate for Al_2O_3/NiCr and Al_2O_3 coating as a function of sliding distance at 50N under lubrication

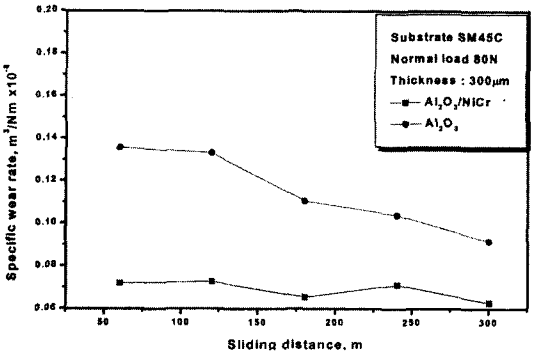


Fig. 6 Variation of specific wear rate for Al_2O_3/NiCr and Al_2O_3 coating as a function of sliding distance at 80N under lubrication

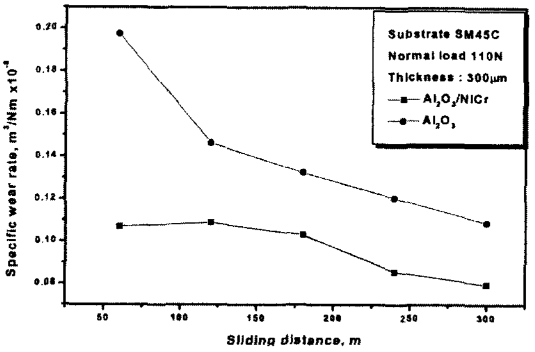


Fig. 7 Variation of specific wear rate for Al_2O_3/NiCr and Al_2O_3 coating as a function of sliding distance at 110N under lubrication

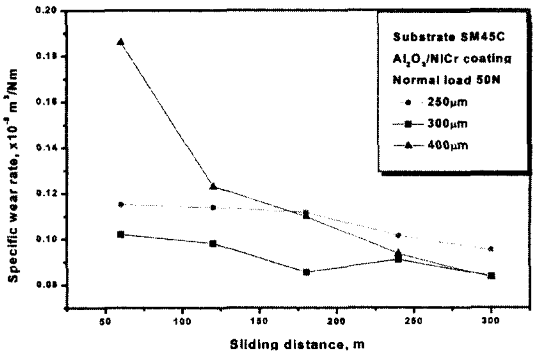


Fig. 8 Variation of specific wear rate for specimens of various coating thickness in Al_2O_3/NiCr coating as a function of sliding distance at 50N under lubrication

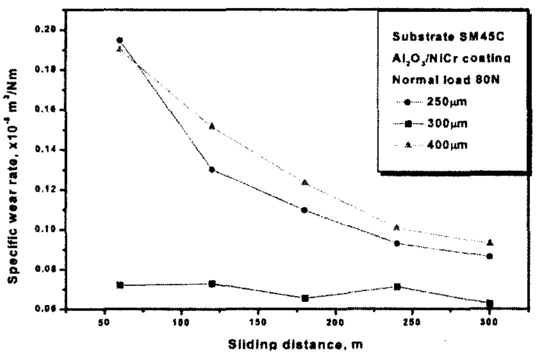


Fig. 9 Variation of specific wear rate for specimens of various coating thickness in Al_2O_3/NiCr coating as a function of sliding distance at 80N under lubrication

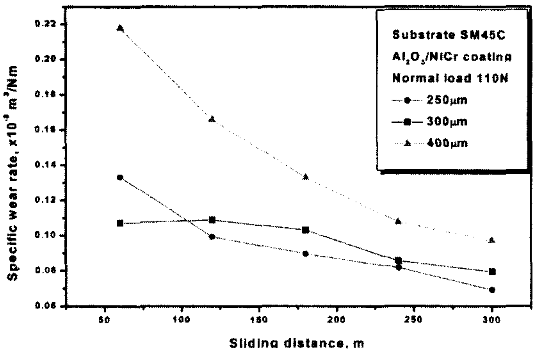


Fig. 10 Variation of specific wear rate for specimens of various coating thickness in Al_2O_3/NiCr coating as a function of sliding distance at 110N under lubrication

3.3.2 Effect of the coating thickness

The variations of the specific wear rates of the Al_2O_3 and Al_2O_3/NiCr coatings versus the coating thickness under 50N, 80N and 110N are shown in Figs. 8, 9 and 10, respectively. It was found that the wear rate for the coating of thickness of 300μm was lower than those of 250μm and 400μm thickness cootings under the normal load of 50N as shown in Fig. 8. It was observed that the wear rate varied considerably with the coating thickness under 80N normal load as shown in Fig. 9. Particularly, the wear rate of the coating thickness of 300μm was lower than those of other coating thicknesses. However, as shown in Fig. 10, the wear rate for the coating thickness of 250μm was the lowest under the normal load of 110N. Also, it was found that the wear rate of coating thickness of 400μm was the highest in the wear test. That is, the large coating thickness resulted in the higher wear rate in this test. From this study, it seems that the optimum coating thickness for the wear rate was between 250μm and 300μm.

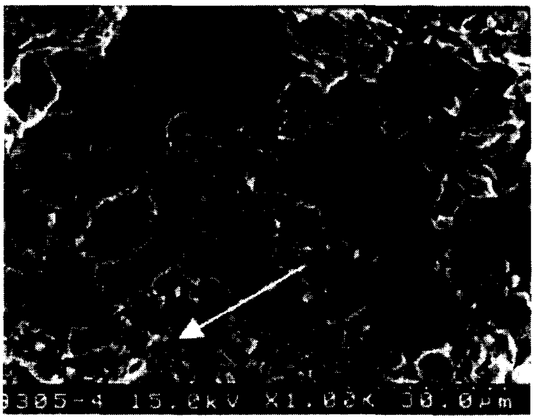
4. Discussion

It has been previously reported that bond coating improves the anchor mechanism of the interface in a coating system(Tekeuchi et al., 1991 ; Wang et al., 1988 ; Vijande-Diaz et al., 1991 ; Lugscheider, 1987). The bond strength of the coating and substrate increased as the rough interface improved the anchor mechanism in the plasma spray. In this study, particularly there was no evidence of an improved bonding strength in the coating(Fig. 4). According to the wear performance results, coating systems with bond coating have a better wear resistance. Also, it is possible that coating systems with bond coating have an influence on the wear mechanism of the coatings.

Residual stress, whichis one of the typical problems in thermal spray coating, has an influence on the adhesive or cohesive strength of the coating, such as the coating failure due to debonding from the substrate, spalling or cracking as a result of the contraction solidification of the as-spray. Consequently, a coating system with a mismatch in the thermal expansion between the splat and the substrate plays an important role in the wear performance (Holmberg et al., 1994; Pawlowski, 1995; Heimann, 1996; Pina et al., 1991; Bull et al., 1996; Chae et al., 1997; Chae et al., 1999; Chae et al., 2000).

The Al_2O_3 and Al_2O_3/NiCr coatings exhibited different wear mechanisms, as shown in Figs. 11 (a) and (b). In Fig. 11(a) spallation and abrasion marks were both generated on the worn surface of the Al_2O_3 coating with a mismatch of the TEC of the coating structure formed during the cooling to room temperature from 1400K. In contrast, the wear mechanism of the Al_2O_3/NiCr coating did not include spallation and abrasion on the worn surface but instead plastic flow was evident (Fig. 11(b)). Lugscheider et al. also reported an improved coating wear resistance resulting from the bond coating which complemented the mismatch of the TEC of the coating system (Lugscheider, 1987; Pina et al., 1991; Kvernes et al., 1991; Ahn et al., 1993; Fernandez et al., 1995; Bull et al., 1996).

(a) Al_2O_3 coating



(b) Al_2O_3/NiCr coating

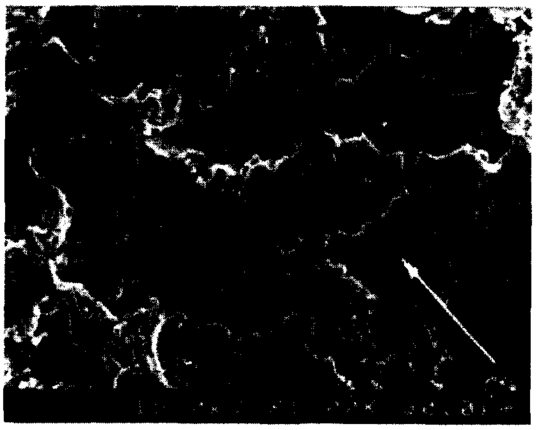
Fig. 11 SEM photograph of worn surface (Coating thickness: 300μm, Load: 50N)
Arrow is sliding direction

The TEC of the SM45C (substrate), alumina (top coating), and NiCr (bond coating) are $12\times10^{-6}K^{-1}$, $8\times10^{-6}K^{-1}$, and $10\times10^{-6}K^{-1}$ respectively. The bond coating played the role of reducing the residual stress in the interface of the coating system.

Coating thickness is also another factor which affects the wear performance of the coating. It was found that thin coating could not support high load owing to the bending stress, and resulted in high wear of the coating (Figs. 8 and 12(a)). To improve the wear resistance of the coating, it is important to control the coating thickness to within an optimal range. The value of residual stress increased as the thickness of a thermally-sprayed coating increased. It was observed that wear characteristics of the coating having a high level of residual stress showed spallation and micro-fractures (Figs. 8 and 12(c)).

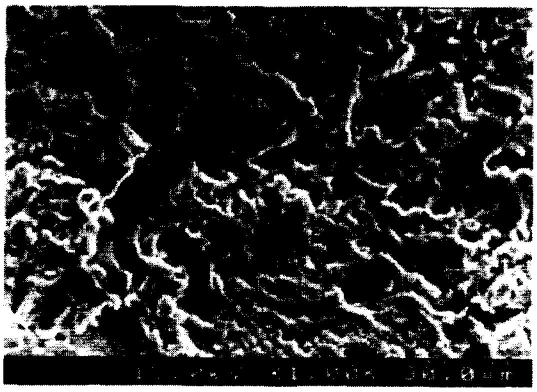
The level of residual stress which affects the wear performance depends on the cooling process of the coating and the mismatch between the thermal properties of the coating and the substrate. Failure modes, such as interfacial decohesion, can be identified using a scratch adhesion test. The failure mode of interfacial decohesion is usually observed in a thick coating applied by a thermal spray. A scratch adhesion test often reveals spallation when the level of residual stress in the coating is high (Bull, 1991). It was found that the scratch on the Al_2O_3 coating showed spallation, during the scratch test. Therefore, it was evident that the residual stress of the Al_2O_3 coating was higher than that of the Al_2O_3/NiCr coating as shown in Fig. 13.

Consequently, bond coating plays an important role in decreasing the residual stress. Residual stress has a significant influence on the wear mechanism. There is an optimal coating thickness



(a) 250μm

(b) 300μm



(c) 400μm

Fig. 12 SEM photograph of worn surface for Al_2O_3/NiCr coating (Load : 50N)
Arrow is sliding direction

for a given coating system. In this study, it was observed that coating thickness of 300μm exhibited good wear resistance (Fig. 8).

(a) Al_2O_3 coating

(b) Al_2O_3/NiCr coating

Fig. 13 SEM photograph of surface test failure for Al_2O_3 coating (a) and Al_2O_3/NiCr coating. Arrow is sliding direction

5. Conclusions

The experimental results and observations from this study have lead to the following conclusions:

(1) The sliding wear resistance of the Al_2O_3/NiCr coating is better than that of Al_2O_3 coating.

(2) Bond coating decreases the residual stress of the coating system. Residual stress has a significant influence on the wear mechanism.

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