INVESTIGATION OF BONDING MECHANISM BETWEEN PLASMA SPRAYED Al_2O_3 TOP COATING AND Ti-Al UNDERCOATING ON STEEL SUBSTRATE

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ABSTRACT

Bonding mechanism of plasma sprayed Al_2O_3 top coating onto Ti-Al undercoating made with Ti and Al mixed powders on mild steel substrate was investigated by measuring adhesive strength and observing fractured surfaces of the dual coating system in comparison with single phase undercoatings of Ti or Al. The Ti-Al coating consisted of Al phase and Ti compound phases, but its surface layer was composed mainly of Al splats covered with thin oxide layer of Al_2O. The Al_2O_3 top coating would bond to the Ti-Al undercoating by mechanical anchoring effect.

1. INTRODUCTION

Industrial world of today is required to decrease the usage of hazardous substances for environmental problems. In the surface finishing industry, chrome plating, widely used in many cases, is obtained from the hazardous hexavalent chromium solution. While a plasma spraying is so-called a dry coating process without exhausting any waste solution. And the Plasma sprayed Al_2O_3 coating possesses high hardness, high wear resistance and high corrosion resistance, and also the coating does not contain any hazardous substance.

For the reduction of the environmental burden, we consider applying the Al_2O_3 coating as the alternatives to the chrome plating. However, the Al_2O_3 coating is inferior in quality of adhesive strength, and an undercoating is often deposited on substrate prior to spraying of the Al_2O_3 coating to improve the adhesive strength. Ti and Al are considered to be safe to environment in comparison with heavy metals, so we have developed the Ti-Al coating as the undercoating for the Al_2O_3 coating to achieve highly adhesive and corrosion protection performance. We showed already that the sprayed Ti-Al coating with use of blended Ti-50mass% Al powder consisted of $TiN_{0.3}$, TiNO (TiN-TiO solid solution), Al and small amounts of Ti_3Al by X-ray diffraction, and Ti compound phases of the Ti-Al coating were synthesized during particle flight in plasma jet, and further the adhesive strength of the sprayed Ti-Al coating onto mild steel substrate was 60MPa[1].

As the adhesion mechanism of the sprayed Al_2O_3 top coating on the Ti-Al undercoating, the mechanical and metallurgical bonding would be expected. In this study, as for the mechanical bonding, the effect of surface roughness (*Ra*) of the Ti-Al coating on the bonding strength was examined, and also for the metallurgical bonding the coating surface conditions were characterized by using SEM and ESCA.

2. EXPERIMENTAL PROCEDURE

2.1 PLASMA SPRAYING OF Ti-Al COATING

Ti powder with powder size distributions of 60 - 80μm from Sumitomo Titanium Corporation, and Al powder with powder size distributions of 40 - 60μm from Hikari Sozai Corporation were used as starting materials. The Ti powder was blended uniformly with the 50mass% Al powder in advance, and the blended powder applied for the spraying of Ti-Al coating. The plasma spraying was performed with Argon gas and compressed air as plasma gas in the air atmosphere using an Aeroplasma Limited Company APS7050 system. End face of mild steel bar (JIS SS400, corresponding to ISO E275A) of 25mm diameter was conditioned by grit blasting before the spraying, and then the Ti-Al coatings with thickness of 100-150μm were fabricated. As spray parameters, the input electrical power to the plasma torch of 27kW and the spray distance of 0.1m were selected.

In addition, sprayed Ti coating and sprayed Al coating were fabricated with the same spray parameters. For comparison, the mirror-polished Ti-Al coating surface was prepared by metallographic finish of 0.3μm alumina polishing.

2.2 PLASMA SPRAYING OF Al_2O_3 COATING

Al_2O_3 powder with powder size distributions of 20-40μm from Fujimi Incorporated was used for spraying. The Al_2O_3 coatings with thickness of about 300μm were deposited onto the Ti-Al coating, Ti coating and Al coating, which were formed on the mild steel bar as undercoating. The spraying was performed under the condition of the input electrical power to the plasma torch of 100kW and spray distance of 0.1m using the same spray system as the one used for the Ti-Al coating. Argon gas and carbon dioxide gas were used as plasma gas.

2.3 ADHESIVE TEST

Tensile adhesive strength measurements of the coatings were carried out with an Instron type testing machine at cross head speed of 1mm/min. Coated face of the test specimen was bonded to the end face of the same diameter mild steel bar by an epoxy resin adhesive. Self-aligning device was used for applying the tensile load to the assembly of the coating and fixtures[1].

Number of test samples was 3 to 5.

2.4 CHARACTERIZATION OF COATING

Surface roughness of the sprayed Ti-Al coating, Ti coating and Al coating was evaluated with use of Form Talysurf S5, (Taylor Hobson Limited Company).

Electron Spectroscopy for Chemical Analysis (ULVAC-PHI, INC, ESCA5700) was used to detect the elements and their bonding states on the surface of the sprayed Ti-Al coating with the analysis area of 2mm in diameter.

The Ti-Al coating surface and the cross-section of the Al_2O_3 coating on the Ti-Al undercoating were observed by SEM.

3. RESULTS AND DISCUSSION

3.1 SURFACE STRUCTURE OF Ti-Al COATING

Fig. 1 shows surface images of the sprayed Ti-Al coatings by SEM. Point A with bright contrast was the Ti compound phase, and point B with dark contrast was the Al phase. That is,

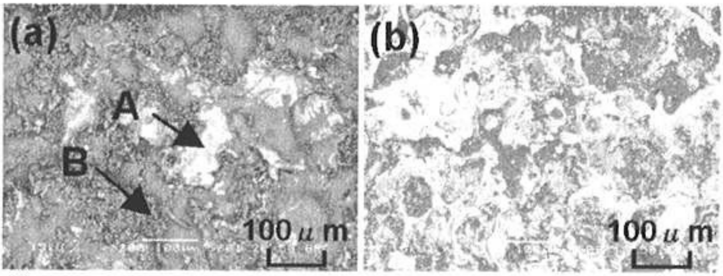

Fig. 1. SEM images of sprayed Ti-Al coating surfaces;
(a) As-sprayed Ti-Al; (b) Mirror-polished Ti-Al.

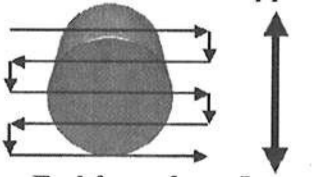

Fig. 2. Traverse of plasma torch on end face of sample bar.

the coating surface (a) composed of mainly Al splats. This phenomenon would be caused by considered that the separation of blended powders of Ti particle and Al particle by difference in particle mass during spraying. The plasma torch traversed on the end face of the sample bar from side to side in horizontal direction, and moved down from the upper to the lower area of the face as shown in Fig. 2. Since the Al particle was smaller mass than the Ti particle, the particles deposited lastly on the coating surface should be mainly the Al particles.

Fig. 3 shows the depth profiles of Ti, Al, O and N by ESCA. From the compositional concentrations at etching time near 0, the top surface of the sprayed Ti-Al coating would be seen to consist mainly of Al_2O.

3.2 STRUCTURE OF INTERFACE BETWEEN Al_2O_3 COATING AND Ti-Al COATING

Fig. 4 shows cross-sections of interface between the Ti-Al coating and the Al_2O_3 coating by SEM. Dual phase structure of Ti-Al coatings is clearly seen in (a). At the interface between the both areas of the Al phase (b) and the Ti compound phase (c), glaring cracks or pores were not observed.

By Suganuma et al, at the interface between pure Al and α- Al_2O_3, reaction layer was not formed[2] even after the heating at 923K for 1h. In this work, thin Al oxide layer covered the Al splat surface, and Ti splat consisted mainly of Ti oxide and Ti nitride. Therefore, it would be reasonable to consider that the reaction layer would not be synthesized at the interface between Al_2O_3 top coating and Ti-Al undercoating.

3.3 BONDING STRENGTH OF SPRAYED Al_2O_3 TOP COATING ONTO Ti-Al UNDERCOATING

Table 1 shows average roughness (*Ra*) of the undercoating surfaces and adhesive strength of sprayed Al_2O_3 coatings. Fig. 5 shows fractured surfaces of the undercoating by the adhesive test, which consists of 3 areas; point A with bright contrast is the Ti compound phase, and point B with half dark contrast is the Al phase, and point C is Al_2O_3 flake.

In case the Al_2O_3 coating delaminated at the interface between the Al_2O_3 coating and the undercoating by adhesive test, the measured adhesive strength should correspond to the bonding strength between them. Whereas the Al_2O_3 coating delaminated inside the undercoating, the measured adhesive strength should correspond to the tensile strength of the undercoating itself. The adhesive strength of the sprayed Al_2O_3 coating onto the Ti-Al undercoating was 50MPa. The Al_2O_3 coating delaminated mainly at the interface between the Al_2O_3 coating and the Ti-Al coating. And some flakes of Al_2O_3 coating adhered to the Ti-Al coating as shown in (a). Therefore the measured adhesive strength 50MPa should correspond to the bonding strength between the Al_2O_3 coating and the Ti-Al coating.

Bonding mechanism of the sprayed Al_2O_3 coating onto metal substrate is generally

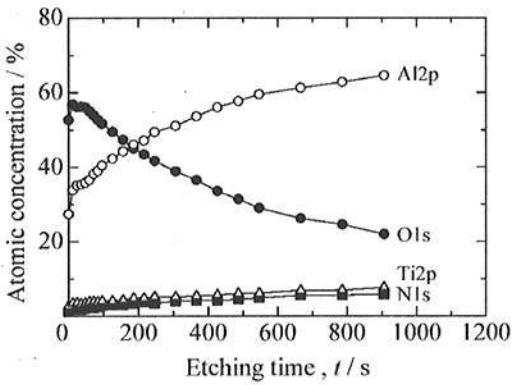

Fig. 3. Depth profiles of compositional elements of sprayed Ti-Al coating surface by ESCA.

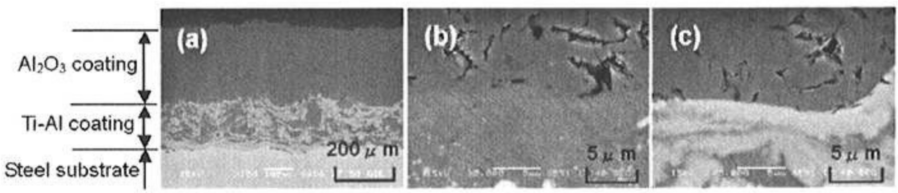

Fig. 4. Cross sections of the interface between Al_2O_3 coating and Ti-Al coating; (a) Overall view; (b) Al_2O_3 / Al phase; (c) Al_2O_3 / Ti compound phase.

Table 1 *Ra* and adhesive strength of samples.

Undercoating sample	Surface state	*Ra* (μm)	Adhesive strength (MPa)	Fracture location
Ti-50mass%Al	As-sprayed	12	50	Al_2O_3/Ti-Al
Ti-50mass%Al	Mirror-polished	0.5	14	Al_2O_3/Ti-Al
Ti	As-sprayed	13	12	Ti coating
Al	As-sprayed	10	43	Al_2O_3/Al
Al	Mirror-polished	0.2	28	Al_2O_3/Al

considered to the mechanical anchoring effect[3]. As for the mirror-polished Ti-Al undercoating, the adhesive strength of the sprayed Al_2O_3 coating onto it was very low to be 14MPa, and the coating delaminated at the interface between the Al_2O_3 coating and the Ti-Al coating as shown in (b). And also, the adhesive strength of the Al_2O_3 coating on the mirror-polished Al undercoating was lower than that of the Al_2O_3 coating on the as-sprayed Al undercoating. These results suggest apparently that the mirror-polished undercoating would not contribute to bond the Al_2O_3 coating by mechanical anchoring due to small *Ra*.

However in this work, it's necessary to consider the effect of the phase of the undercoating surface on the bonding strength. The Ti-Al coating was covered with Al splat layer, in contrast the mirror-polished Ti-Al coating surface consisted of the Ti compound phases and the Al phase

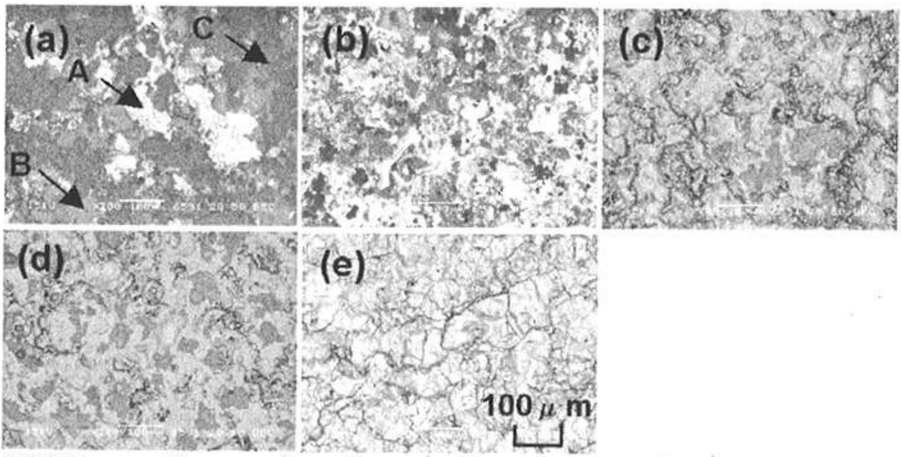

Fig. 5. SEM images of fracture surfaces of sprayed Al_2O_3 coatings onto various undercoating; (a)As-sprayed Ti-Al; (b) Mirror-polished Ti-Al; (c) As-sprayed Al; (d) Mirror-polished Al; (e) As-sprayed Ti.

as shown in Fig. 1 (b).

Since the sprayed Al_2O_3 coating onto the Ti undercoating fractured inside the Ti coating as shown in Fig.5 (e), the measured adhesive strength of 12MPa should correspond to the tensile strength of the Ti coating. Therefore it is difficult to discuss the effect of the surface phase of the Ti-Al coating on the bonding strength by comparing with the adhesive strength of the Al_2O_3 coating on as-sprayed undercoating of Al or Ti.

In Fig. 5 (b) and (d), the sprayed Al_2O_3 coatings onto the mirror-polished undercoating of Ti-Al and Al were delaminated at the interface between the Al_2O_3 coating and the undercoating by the adhesive test. The adhesive strength of the Al_2O_3 coating on the mirror-polished Al undercoating was higher than that of the Al_2O_3 coating on the mirror-polished Ti-Al undercoating as shown in Table 1. These results suggest that the Al phase would bond to the Al_2O_3 coating with higher bonding strength than the Ti compound phases bonding.

4. CONCLUSION

The sprayed Ti-Al coating surface consisted mainly of Al splats covered with thin oxide layer of Al_2O by SEM and ESCA. And the bonding strength of the Al_2O_3 coating on the mirror-polished Al undercoating was higher than that of the Al_2O_3 coating on the mirror-polished Ti-Al undercoating. This indicates the Al phase would have higher affinity with the Al_2O_3 coating than the Ti compound phases.

In addition, bonding strength of Al_2O_3 coating on the mirror-polished undercoating was much lower than that of the Al_2O_3 coating on the as-sprayed undercoating with large roughness for each undercoating. This result suggests that the mirror-polished coating surface would not contribute to bond the Al_2O_3 coating by mechanical anchoring effect due to small *Ra*.

5. REFERENCES

[1] S.Adachi and K.Nakata, "Improvement of adhesive strength of Ti-Al plasma sprayed coating" *Surf. Coat. Technol*, (in press).

[2]K.Suganuma, E.Saiz and A.P.Tomisa, "Microstructure and strength of interface between pure aluminum and α-alumina" *J.Japan Inst.Metals*, **62**, 92-97 (1998).

[3]M.Mellali, P.Fauchais and A.Girmaund, "Influence of the surface roughness and temperature on alumina coating adhesion" *VDI Ber (Ver Dtschlng)*,**1166**, 387-393 (1995).