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Effect of Plasma Spraying Parameters on Anisotropic Feature of the Mechanical Property of Plasma Sprayed Al_2O_3 Coating

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Abstract. The effects of the plasma spraying parameters on the strength of an Al_2O_3 coating were investigated by changing the input electrical power to the plasma torch, the spray distance and the Al_2O_3 powder size as the spraying parameters. The anisotropic feature of the coating strength is also discussed. The strength of the Al_2O_3 coating in a direction perpendicular to a substrate plane was dominated by the layered structure of Al_2O_3 splats, and was affected by all the parameters. The strength of the coating in a direction parallel to the substrate plane was not affected by the input electrical power. The strength of the former was lower than that of the latter, in the coating containing many cracks. The anisotropy of the coating strength would be caused by the cracks propagating along the lines of the laminated layer.

1. Introduction

Recent growing demand of a plasma sprayed Al_2O_3 coating, applied to various applications, requires the coating to possess higher reliability and mechanical property. Some researchers have reported mechanical properties of the plasma sprayed Al_2O_3 coating [1-3]. The effects of the mass flow rate of plasma gas on the structure and mechanical properties of the plasma sprayed Al_2O_3 coating have also been reported by the author [4].

The structure and mechanical properties of the plasma sprayed Al_2O_3 coating are anisotropic perpendicular or parallel to the substrate plane, since the coating consists of flattened Al_2O_3 particles stacked on a substrate. And also, the strength of the coating in a direction perpendicular to the substrate plane would be different from the strength in a direction parallel to the substrate.

In this work, Al_2O_3 coatings were made by changing several parameters; such as, input electrical power to the plasma torch, the spray distance and the Al_2O_3 powder size. The effects of these parameters on the strength of the coating in different directions were investigated.

2. Experimental Procedure

Fused and crushed powders of α- Al_2O_3 with average powder sizes of 10 μm, 30 μm and 60 μm from FUJIMI INCORPORATED were used for the atmospheric plasma spraying, which was performed using Aeroplasma Limited Company APS7050 system. The input electrical power to the plasma torch and the spray distance were varied in the range of 20, 26 and 31 kW, and 0.1, 0.15 and 0.2 m, respectively, with the plasma gases (argon gas of 8.3×10^{-5} m^3/sec and compressed air of 16.7×10^{-5} m^3/sec) as the ordinary condition. In addition, the high power plasma spraying was performed with the input electrical power of 100 kW at a spray distance of 0.1 m and with plasma gases of Ar (67×10^{-5} m^3/sec) and CO_2 (117×10^{-5} m^3/sec). Al_2O_3 coating was formed on a mild steel substrate, which was pre-coated by a Ni-20 mass%Cr coating of about 100 μm thickness as an under-coating.

By using an Instron type-testing machine, the strength measurement of the Al_2O_3 coating was carried out with test samples, whose end face was coated with the plasma spraying of Al_2O_3 on the Ni-Cr undercoating and bonded to the end face of an uncoated bar, with the same diameter, by an epoxy resin adhesive. In this work, the Al_2O_3 coatings delaminated from the layered Al_2O_3 splats due to this test, with the exception of the coating at the high power plasma spraying. The measured strength should correspond to the bond strength of the coating in a direction perpendicular to the substrate plane, as shown in Fig. 1, and is described as σ_B in this paper.

The other strength of the Al_2O_3 coating, which corresponded to the fracture strength of the coating in a direction parallel to the substrate plane (σ_F), was measured using a dumbbell shape sample made of the Al_2O_3 coating with about 400 μm thickness, separated from the substrate.

To observe the micro cracks in the Al_2O_3 coating, the coating was dipped in the chromic acid (CrO_3) solution to fill up the cracks heated at 723 K for 1 h to seal the cracks by forming chromia (Cr_2O_3) [5].

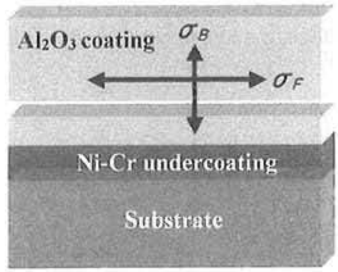

Fig. 1 Schematic diagram of measured strength of Al_2O_3 coating; (σ_B) perpendicular to the substrate plane, (σ_F) parallel to the substrate plane.

3. Results and Discussion

3. 1. Effects of input electrical power and spray distance

3.1.1. Coating microstructure

The surfaces of the sprayed Al_2O_3 coatings are shown in Fig. 2. Al_2O_3 powder of 30 μm size was used for making these coatings. The Al_2O_3 splat morphology changes with input electrical power and spray distance. The splat is more flattened with higher input electrical power and shorter spray distance. The splats of the coating at 31 kW - 0.1 m in Fig. 2(c) are well spread, having faded boundaries.

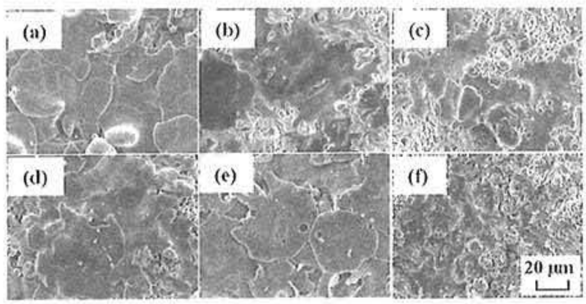

Fig. 2 Al_2O_3 coating surfaces at various input electrical powers and spray distances; (a) 20 kW 0.1 m, (b) 26 kW 0.1 m, (c)31 kW 0.1 m, (d) 31 kW 0.15 m, (e) 31 kW 0.2 m, (f) 100 kW 0.1 m.

The fractured cross-sections are shown in Fig. 3. The horizontal bands and cracks are present at the boundary of the laminated layer, and these defects become less clear with increasing input electrical power and decreasing spray distance.

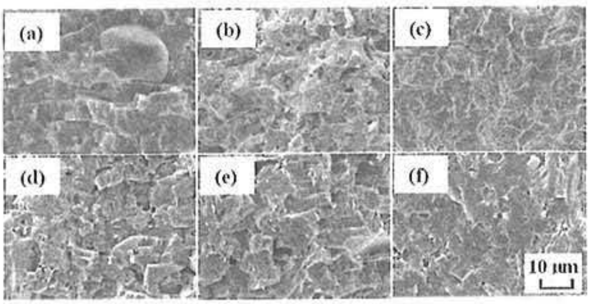

Fig. 3 Al_2O_3 coating cross-sections at various input electrical powers and spray distances; (a) 20 kW 0.1 m, (b) 26 kW 0.1 m, (c)31 kW 0.1 m, (d) 31 kW 0.15 m, (e) 31 kW 0.2 m, (f) 100 kW 0.1 m.

When α-Al_2O_3 is cooled rapidly from a molten state, α-Al_2O_3 transforms to a metastable γ-Al_2O_3. In this work, X-ray diffraction spectra of the Al_2O_3 coatings revealed the coexistence of α-Al_2O_3 and γ-Al_2O_3. The ratio of γ-Al_2O_3 increased with increasing input electrical power.

This suggests that the sprayed Al_2O_3 particles fused well during plasma spraying at higher input electrical power and shorter spray distance, and consequently the Al_2O_3 coating came to have a denser microstructure.

At the high power plasma spraying (100 kW), the surface and the cross-section as shown, in the Figs. 2 and 3, indicate that the Al_2O_3 splats fused well, and the laminated layer is less in comparison to the coatings by the low power plasma spraying.

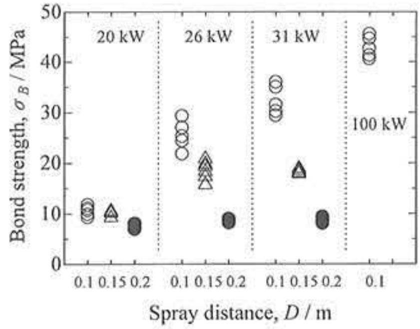

Fig. 4 Effect of input electrical power and spray distance on bond strength (σ_B) of Al_2O_3 coatings.

3.1.2. Bond strength of the coating in a direction perpendicular to the substrate plane (σ_B)

The σ_B of the Al_2O_3 coatings, made with 30 μm powders, as a function of input electrical power and spray distance are shown in Fig. 4. The σ_B increased with increasing input electrical power, and decreased with increasing spray distance. For the high power plasma spraying case, the coating delaminated from the interface between the Ni-Cr undercoating and the Al_2O_3 coating, or from the splitting of undercoating, by the bond test. This means that the bond strength of the flattened Al_2O_3 splats deposited by the high power plasma spraying would be higher than the measured strength.

The low bond strength of the Al_2O_3 splats would be attributed to the porous structure of the coating, including large cracks and pores. In contrast, the densely sprayed Al_2O_3 coating, having well-flattened splats, would have the high bond strength.

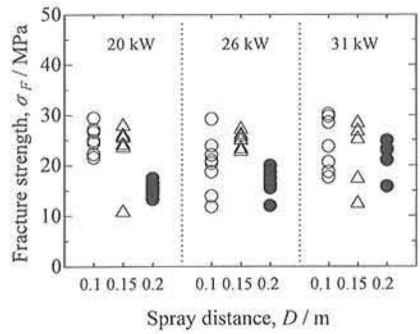

Fig. 5 Effect of input electrical power and spray distance on fracture strength (σ_F) of Al_2O_3 coatings.

3.1.3. Fracture strength of the coating in a direction parallel to the substrate plane (σ_F)

The σ_F of the Al_2O_3 coatings measured with the dumbbell shape samples is shown in Fig. 5. Changes in the σ_F with spraying parameters showed the different feature observed from the σ_B. The σ_F slightly decreased with increasing the spray distance, and was hardly affected by the input electrical power. The coatings were fractured mainly inside the splat, and therefore the strength of the splat itself would dominate the σ_F.

The coating at 20 kW-0.1 m has many cracks propagating along the lines of the laminated layer, as shown in Fig. 3(a), and the σ_B of its coating was much lower than the σ_F. Whereas, the coating at 31 kW-0.1 m has a fewer cracks, as in Fig. 3 (c), and the σ_B was higher than the σ_F. The cross-section of the coating by the sealed treatment of chromia, as shown in Fig. 6, shows the cracks propagate in both directions; i-e parallel and perpendicular to the substrate. The cracks parallel to the substrate would affect the σ_B, and the perpendicular cracks would affect the σ_F. The sprayed Al_2O_3 coating, which has a few cracks along the lines of the laminated layer due to well-fused Al_2O_3 splats, would have the anisotropy of high σ_B compared to σ_F. In contrast, the coating containing many cracks would have the anisotropy of low σ_B compared to σ_F.

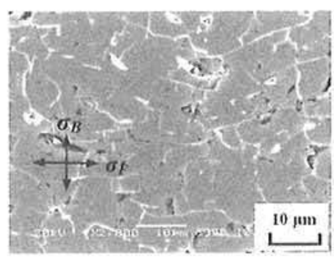

Fig. 6 Microstructure of cross-section of Al_2O_3 coating sealed by chromia; plasma sprayed at 20 kW - 0.1 m.

3.2. Effects of Al_2O_3 powder size

In the coating of powder, having mean diameter of 10 μm, the sprayed particles were not well fused, since the splat shape on the surface and the boundary in the laminated structure were clearly visible. However, this coating consisted of mostly of γ- Al_2O_3, based on X-ray diffraction analysis. This result suggests that the sprayed particles melted perfectly and solidified during flight, before depositing on the substrate.

In the coating of the 60 μm powder, the splat shape and the boundary are well defined, in comparison to the coating of 30 μm powder. The ratio of the γ- Al_2O_3 is lower than those of the coating with the 10 μm and 30 μm powders. It is considered that the sprayed particles with the 60 μm powder were not fully fused in the plasma jet, and the inner part of that could have remained α- Al_2O_3.

Fig. 7 shows the σ_B of the coatings at 31 kW. The σ_B decreased with increasing spray distance. However, in case of coating with the 60 μm powder, σ_B hardly decreased with increasing spray distance. This could be due to that the fact that large sprayed particle showed resistance to cooling during flight and the deposited splats bonded tightly with each other despite long spray distance. The σ_F of the coating decreased with increasing powder size, as shown in Fig. 8.

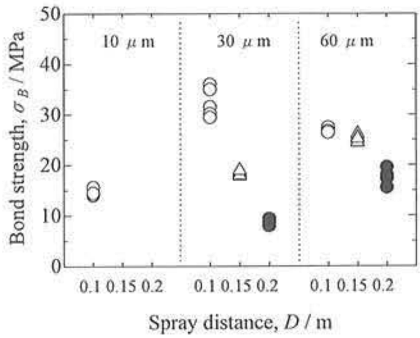

Fig. 7 Effect of spray distance on bond strength (σ_B) of Al_2O_3 coatings with various powder sizes at 31 kW.

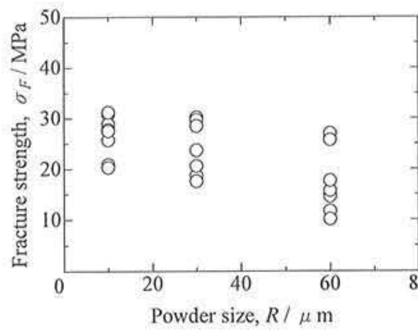

Fig. 8 Effect of powder size on fracture strength (σ_F) of Al_2O_3 coatings at 31 kW - 0.1 m.

4. Conclusion

The bond strength of the Al_2O_3 coating in a direction perpendicular to the substrate plane (σ_B) is dominated by the bond strength of the layered Al_2O_3 splats. This strength correlates evidently with the cracks propagating along the lines of layered splats; the input electrical power to the plasma torch, the spray distance, and also the Al_2O_3 powder size affected them.

The fracture strength of the coating in a direction parallel to the substrate plane (σ_F) does not correlate with the input electrical power, but is affected by the Al_2O_3 powder size and the spray distance.

The coating containing many cracks propagating along the lines of the laminated layer has the anisotropy of lower σ_B than σ_F. In contrast, the coating containing a few cracks has the anisotropy of higher σ_B than σ_F.

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