FUNCTIONALLY GRADED COATINGS PREPARED BY PLASMA ELECTRODE TYPE SPRAY GUN

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SUMMARY
With the use of the thermal plasma reactor (i.e. Plasma Electrode Type Spray Gun) based on the forced constricted type plasma jet generator, multi-layer coatings of Ti-Al are tried to be formed from a view point of fabricating functionally graded materials. The hardness and the adhesion strength of the films, and the microstructure and the composition gradation of the coating are studied experimentally.

Keywords: functionally graded material, plasma spray gun, plain bearings, titanium alloy, hardness

1 INTRODUCTION
Functionally graded materials are a new class of advanced materials, which exhibit a progressive change in the composition, structure, and properties as a function of position within the materials. Due to the increasing demand of high power and high-speed automotive engines, the engine plain bearings have to be improved in tribological characteristics. Three layer copper-alloy bearings with 20 ~ 30 µm overlay are widely in use. The overlay, which provide seizure and corrosion resistance and conformability, is usually made by electroplating of 10 ~ 30 µm thick lead alloy including In, Sn and Cu [1]. The lead matrix is soft and has relatively low fatigue resistance under high-pressure conditions. New materials and new deposition procedures are needed to improve tribological and mechanical characteristics of the overlay.

There are mainly four methods to produce functionary gradient materials, i.e. chemical or physical vapor deposition, powder metallurgy, plasma spraying and self-propagating high-temperature synthesis. Among these methods, plasma spraying has many advantages of easily controlling the mixing ratio of the powder materials, depositing the films at a high rate, spraying on the complex shaped objects and so on. But it is conversely difficult to control the composition and structure precisely in the materials and to spray uniformly on the large surface.

The purpose of this study is to produce the high quality coating of functionally graded materials and to realize large area deposition with high rate by using thermal plasma jet. We previously reported the spray coating of alumina mono-layer [2, 3] with the new type of the reactor [4] based on the forced constricted type plasma jet generator. In this paper, we study further the multi-layer coatings of Ti-Al [5] by using the new-type spray gun (i.e. the plasma electrode type spray gun) [6].

2 EXPERIMENTAL PROCEDURES
Schematic drawing of the plasma electrode type spray gun is shown in Figure 1.

![Figure 1: Sectional view of the plasma electrode type spray gun.](image_url)

The spray gun consists of the rod anode, the insulated constrictor disk and the rod cathode. They have the nozzle structure with the same diameter. The arc in this system is maintained at a constant length, and strongly constricted by the insulated disk, the local constricting ring and the working gas (Ar). As a result, a stable and high power plasma jet is produced under various operating conditions.

In this system, powder particles are injected into the arc column from the upper left side. So, the whole arc column and the plasma jet region work as the interaction region with the injected powder particles. Injected powder particles are efficiently heated and melted and are ejected from the nozzle symmetrically. (See Figure 1)
Figure 2 shows the experimental set-up. In the present experiment, the plasma spray gun is fed with Al and Ti powders of 20 μm in mean diameter. Typical processing conditions were: Ar flow rate; 50 l/min, plasma arc power; 8 ∼ 13 kW, powder feeding rate; 0.1 ∼ 0.2 g/min, deposition time; 10 min, substrate position from nozzle; 25 ∼ 110 mm, pressure; 102 ∼ 104 Pa. The films were characterized by electron probe microanalysis (EPMA), scanning electron microscopy (SEM), optical microscopy (OM), atomic force microscopy (AFM) and micro Vickers hardness.

3 RESULTS AND DISCUSSION

The arc voltage-arc current characteristics of the present arc is a rising characteristics for various operating conditions although the conventional arc has a drooping one. The present plasma jet generator can increase the input power effectively and has high thermal efficiency (see Fig.3).

Measurements on the velocity and size of the in-flight powder particles were found to be essentially Gaussian for all experimental conditions [6]. At the arc power above 10 kW, the mean particle velocity 230 ∼ 270 m/sec, increases slightly (2 ∼ 10 m/sec) with increasing arc power and decreases linearly with increasing distance from the nozzle exit. The size distribution of the heated particles is nearly Gaussian too and has a mean value of 50 μm and a standard deviation of 14 μm. The size of the in-flight particles is larger than that of the raw material powder. This trend can be correlated with the behavior of injected particles in the arc plasma jet.

Next, we show the example of the multi-layer coating, i.e. the Ti-Al structurally graded films. In this case, five kinds of powder materials are used. They are Ti only, three mixed powders of Al and Ti, and Al only. The effect of jet power Wj on the microstructure and the composition of the coating is studied.

Figure 4 shows a typical example of structurally graded Ti-Al coating films, i.e. a cross-sectional SEM photograph.

One can observe that near substrate where the Al was fed as 100 % appear high concentration Ti points with a diameter of 20 - 30 μm. Ti melted droplets with such diameter were able to penetrate the deposited Al layer.
At any rate, the dense coatings are successfully obtained when $W_j$ is higher than 7 kW.

Figure 6: Titanium distribution analyzed by EPMA of the same cross-section presented in Figure 4

![Figure 6](image)

Figure 7: Vickers hardness map of the 500 µm x 500 µm cross-sectional area. Ti-Al coating film. Indentation load: 0.0025 N, the distance between the position on the surface; 50 µm.

Figure 7 shows a hardness map of a 500 µm x 500 µm cross-sectional area of the Ti-Al coating as a function of the distance from the substrate surface. Figure 8 shows an OM image of the indentation pattern of the same cross-sectional area. Hardness of different zones starting with substrate shows increasing values. The hardness of the coating adjacent to the substrate, measured using an indentation load of 0.025 kg, was 18-20 HV and determined only by the Al layer. The influence of increasing Ti concentration was the increasing hardness as an average value between Al layer and the dispersed Ti droplets (100 - 200 HV).

When appropriate relative concentrations of Ti and Al were provided into the reactor, due to the long residence time of the powders in the plasma stream, an intermetallic Ti-Al compound was formed. This fact is proved by high hardness (300 - 400 HV) and the indentation pattern that shows cracks characteristic to the brittle Ti-Al intermetall as can be seen in the medallion of the Figure 8.

Figure 8: OM photograph of the indentation patterns corresponding to the Figure 7. The medallion shows the indentation pattern with cracks.

![Figure 8](image)

Higher values of hardness (500 - 700 HV) may be assigned to TiAlN formation due to the presence of N2 in the reactor as the residual gas. Figure 9 shows the distribution of hardness measured across the Ti-Al layer and a part of substrate. At 25 µm depth from the substrate surface, the stainless steel hardness was increasing from 200 - 225 HV$_{0.025}$ to about 350 HV$_{0.025}$. As is shown clearly in the figure structurally graded coating enhances the hardness of the substrate materials and then realizes functionally graded materials.

Figure 9. Hardness distribution across the Ti-Al layer and substrate.

![Figure 9](image)

The surface of the spayed layer analyzed by AFM showed rough morphology. Figure 10 shows the 3-d AFM image of the surface and corresponding height profile. One can identify structures having “corn” shapes of few µm in height suitable to produce appropriate morphological structures for tribological applications.

Figure 10: 3-d AFM image of the surface and corresponding height profile.
4 CONCLUSIONS

In order to demonstrate the application feasibility of the plasma electrode spray gun reactor based on the forced constricted type plasma jet generator to fabricate functionally graded materials, we have tested the multi-layer coating. The powder particles injected into the arc were efficiently heated and melted and were ejected from the nozzle symmetrically. Measurements on the velocity and size of the in-flight powder particles were found to be essentially Gaussian for all experimental conditions. At the arc power above 10 kW, the mean particle velocity 230 ~ 270 m/sec, increases slightly (2 ~ 10 m/sec) with increasing arc power and decreases linearly with increasing distance from the nozzle exit. The size distribution of the heated particles was nearly Gaussian too and has a mean value of 50 µm and a standard deviation of 14 µm. The size of the in-flight particles was larger than that of raw material powder. This trend can be correlated with the behavior of injected particles in the arc plasma jet. With the use of this plasma jet, the dense film without pores was obtained, and the hardness and the adhesion strength of the films were improved. Then, we have confirmed that well controlled thermal plasma is very useful for formation of structurally graded films. By mean of the AFM, structures with “corn” shapes of few µm in height were identified, as appropriate morphological structures for tribological applications.

5 REFERENCES