Effect of Powder Particle Size and Spray Parameters on the Ni/Al Reaction During Plasma Spraying of Ni-Al Composite Powders

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Abstract It was known for long that Ni-Al composite powders can be used to deposit self-bonding coating as a bond coat for common ceramic coatings due to the exothermic reaction between Ni and Al. However, it was found that with commercial Ni-Al composite powders with a large particle size, it is difficult to ignite the self-propagating reaction between Ni and Al to form Ni-Al intermetallics by plasma spraying. In this study, Ni-Al composite powder particles of different sizes were used to prepare Ni-Al intermetallics-based coatings by plasma spraying. The dependencies of the exothermic reaction between Ni and Al and the coating microstructure on powder particle size and spray parameters were investigated. The phase composition, microstructure, porosity and oxide content of the coatings were characterized by x-ray diffraction, scanning electron microscope and image analyzing. The results show that particle size of Ni-Al composite powders is the dominant factor controlling the exothermic reaction for the formation of Ni-Al intermetallics during plasma spraying. When the powders larger than about 50 μm are used, the reaction forming aluminide cannot complete even by heating of plasma flame

generated at high plasma arc power. However, when smaller powders less than 50 μm are used, the exothermic reaction can completely occur rapidly in plasma spraying, contributing to heating of Ni-Al droplets to the highest temperature for development of the self-bonding effect. The positive relationship between molten droplet temperature and tensile adhesive strength of the resultant coatings is recognized to confirm the contribution of high droplet temperature to the adhesive or cohesive strength.

Keywords Ni-clad Al · powder particle size · exothermic reaction · Ni-Al intermetallics · plasma spraying · self-bonding

Introduction

Ni-Al intermetallic-based alloys have many excellent properties such as high melting point, low density, high thermal conductivity, high wear resistance and high corrosion and oxidation resistance (Ref 1–3). To utilize the unique properties of the Ni-Al intermetallic-based alloys, many investigations have attempted to use the intermetallic compounds as a protective coating to protect the substrate from oxidation and corrosion (Ref 3–6). NiAl coatings have excellent bonding strength along with the ability to form a dense and continuous Al_2O_3 layer, which plays an important role in protecting the substrate from the corrosion and oxidation environment at high temperature (Ref 7, 8). Therefore, it can be widely used in aerospace and other advanced industries.

Over the past decades, many processes have been developed to fabricate Ni-Al intermetallic coatings, such as electron beam physical vapor deposition (Ref 9), high-velocity oxygen-fuel thermal spraying (Ref 10) and plasma

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Fig. 1 Morphology of three Ni-Al powders in different sizes: (a) S-powder, (b) M-powder, (c) L-powder and XRD pattern of the Ni-coated Al composite powders (d)

spraying (Ref 11). Among these processes, plasma spraying has the advantages of versatility, low cost and simple processing, and meanwhile, it can also be used to prepare coatings of any composition. Therefore, it can be generally utilized to deposit NiAl intermetallic coatings to protect critical components from oxidation and corrosion. During plasma spraying, powder particles are accelerated and heated to fully molten or semi-molten state by a high temperature plasma jet and then projected onto substrate to form the coating through successive stacking of splats after molten droplets impact and spread followed by rapid cooling and solidification processes. Therefore, a conventional plasma-sprayed coating is comprised of splats with various shapes and exhibits a typical lamellar structure (Ref 12). The properties of the coating depend highly on inter-layer interface bonding (Ref 13). Tian et al. (Ref 14) have proved that particle temperature is one of the important factors influencing the properties of thermally sprayed metal coating. Ni-coated Al is well known as a typical self-bond powder material, which will undergo an

exothermic reaction to form Ni-Al intermetallics during spraying (Ref 15). Thus, it is believed that such reaction is capable to raise particle temperature during the spraying process, which can not only induce an impact melting effect of the Ni-based superalloy substrate, but also are possible to cause an impact melting effect to pre-deposited Ni-Al splats in the coating. Accordingly, a metallurgical bonding is also achievable at the inter-lamellar interfaces within coating, being referred to as the self-bonding effect. However, it was found by this study that it is difficult for Ni-coated Al powders with a large particle size to ignite the self-propagating reaction between Ni and Al. It is of considerable significance to re-study how to utilize Ni-Al exothermic reaction to prepare NiAl intermetallic coatings by plasma-spraying traditional Ni-coated Al composite powders.

Relevant studies (Ref 16, 17) have demonstrated that the performance of plasma-sprayed coatings strongly depends on feedstock powder's characteristics (such as structure, size and distribution of powder particles) and spray

Table 1 APS parameters

Materials	Spray parameters					
	Current, A	Power, kW	Ar (SLPM)	Secondary gas (H ₂) (SLPM)	Spray distance, mm	Coatings
S-powder	600	25	40	1.4	120	S0
		33		4.5	60	S1
		33		4.5	90	S2
		33		4.5	120	S3
		33		4.5	150	S4
		42		10	120	S5
M-powder		25		1.4	120	M0
		33		4.5	60	M1
		33		4.5	90	M2
		33		4.5	120	M3
		33		4.5	150	M4
		42		10	120	M5
L-powder		25		1.4	120	L0
		33		4.5	60	L1
		33		4.5	90	L2
		33		4.5	120	L3
		33		4.5	150	L4
		42		10	120	L5

parameters (Ref 18). This paper aims to examine how to control the powder particle size and spray parameters to effectively utilize the exothermic reaction between Ni and Al to prepare the coatings with enhanced properties. Ni-coated Al composite powders with different particle sizes were used in this study. Plasma jet was used as external heat source to cause the exothermic reaction between Ni and Al elements.

Experimental Procedures

Materials

Commercially available Ni-coated Al composite powder (Ni/Al:80/20 wt.%; Metco 404NS) was used as the feedstocks. To investigate the effect of powder particle size on the exothermic reaction of Ni and Al elements and the coating microstructure, the powders were sieved into two size ranges: 53–75 μm , and 75–90 μm , which were labeled as M-powder and L-powder, respectively. Moreover, a Ni-coated Al composite powder with a particle size range of 30–50 μm (Ni/Al:80/20 wt.%; BGRIMM, China) was also used for comparison, which was labeled as S-powder. Figure 1 shows the morphologies of three powders and the XRD pattern of the Ni-Al composite powder. It can be

found that all powders have a near spherical shape with Al core clad by Ni.

Deposition of the Coatings

In this study, the IN738 Ni-based superalloy substrate with dimensions of $\phi 25.4 \times 3$ mm was used as the substrate. The Ni-Al intermetallic alloy was deposited on IN738 Ni-based superalloy substrate, which was sandblasted with corundum grits before spraying. The Ni-Al intermetallic coatings were prepared by atmospheric plasma spraying (APS) with Ar-H₂ as plasma gases. During plasma spraying, the arc current was fixed to 600 A and the flow of the primary plasma gas of Ar was fixed as 40 SLPM, while the flow of H₂ gas was changed to alter the arc voltage for changing plasma arc power. To examine the evolution of the exothermic reaction, the coatings were deposited at different spray distances from 60 to 150 mm. To ensure the effective heating of spray particles an internal injector for powder feeding was adopted. The typical APS spray parameters are shown in Table 1.

Characterization of the Coatings

The morphology of powders and the microstructure of the coatings were characterized by scanning electron microscopy (SEM, MIRA 3 LMH, TESCAN, Czech). EDS was

Fig. 2 Cross-sectional backscattered electron images of the APS Ni-Al coatings prepared by three different particle sizes at a plasma arc power of 33 kW and spray distance of 120 mm: (a) and (b) S3; (c) and (d) M3; (e) and (f) L3

Table 2 Elements percentage in different regions of coatings in Fig. 2

Regions color	Ni, at. %	Al, at. %	O, at. %
White	97.08	2.92	...
Light gray	89.01	10.99	...
Gray	55.79	44.21	...
Dark gray	8.52	87.88	3.60
Dark	1.75	32.48	65.77

used to analyze the elemental compositions of the coatings. X-ray diffraction (XRD, D8 ADVANCE) was utilized to identify the phase structure of the powder and coatings. The porosity and oxide contents of the coatings were estimated through image analyzing using SEM images of polished cross sections of coatings. Coating tensile adhesion test was conducted at a loading rate of 0.5 mm/min with an universal INSTRON1195 testing machine. The temperatures of Ni-coated Al particles during in-flight were measured by a commercial thermal spray particle property

Fig. 3 XRD patterns of APS Ni-Al coatings prepared by three different particle sizes at a plasma arc power of 33 kW and spray distance of 120 mm

diagnostic system (DPV-2000, Tecnar Automation Ltd., Canada) against spray distance.

Results and Discussion

Effect of Powder Particle Size on Ni-Al Intermetallic Formation and Coating Microstructure

In order to study the dependence of coating microstructure on powder particle size, Ni-Al coatings were prepared by Ni-coated Al composite powders of three different size ranges at a plasma arc power of 33 kW and a spray distance of 120 mm. The SEM backscattered image is sensitive to atomic weight, and any change of the image in contrast could show chemical variation of the coating composition (Ref 19). Figure 2 shows the cross-sectional backscattered electron images of S3, M3 and L3 coatings. It can be observed that all coatings present a typical lamellar structure which indicates that the melting of spray particles is sufficient. However, the coating composition is not uniform. As can be seen in Fig. 2, four distinct regions with different white, light gray, gray and dark gray contrasts were present on the coating cross-sectional microstructures besides oxide with a dark contrast. The results of EDS analysis in the individual regions as shown in Table 2 indicate that the coatings contain various phases. The regions with a gray contrast have the composition corresponding to NiAl intermetallic compound. The regions with a white contrast contain mainly Ni, indicating the existence of pure Ni phase without any reaction with molten Al. The regions with bright contrast have high Ni content, and the regions with dark contrast have high Al content. From Fig. 2, it was recognized that S3 coating mainly consisted of light gray and gray phases corresponding to possible Ni₃Al and NiAl, being resulted from variation of exothermic reaction degrees during in-flight

and splat deposition during plasma spraying. This is because in-flight time of spray particles is about 1 ms in order and the solidification time after molten droplet impact on a substrate is about several tens of microseconds (Ref 20, 21). Compared to the coating shown in Fig. 2(a) and (b) with those in Fig. 2(c), (d), (e) and (f), much more unreacted Al element was retained in L3 coating than that observed for M3 coating. This fact can be attributed to the difference of powder particle sizes, since larger particles need more time to reach fully molten and complete the exothermic reaction by the diffusion between Ni and Al elements during plasma spraying. The exothermic reactions were promoted with decreasing powder size, less Al-rich and Ni-rich alloy phases were observed in S3 coating, and this coating showed a homogeneous structure and high density. Therefore, the powder particle size is the most significant parameter affecting the phase formation of plasma-sprayed coatings through the exothermic reaction between Ni and Al elements. If the high amount of Ni and Al cannot be fully reacted in the plasma jet, the self-bonding effect from the exothermic reaction cannot be achieved. Therefore, particle sizes must be controlled to facilitate the reaction of Ni and Al during plasma spraying.

The XRD patterns of S3, M3 and L3 coatings are shown in Fig. 3. From the XRD patterns shown in Fig. 1(d), it can be seen that the original Ni-coated Al composite powder consisted of pure Ni and Al phases without any intermetallic phase, while XRD patterns of the coatings indicate the formation of different intermetallic compounds during spraying. It was also recognized that the peaks of pure Al phase remained in the XRD patterns of M3 and L3 coatings. The intensity of Al peaks is higher for L3 coating as compared to M3 coating. This fact is consistent with that observed from coating microstructure. Therefore, the diffusion reaction was more limited and the formation of Ni₃Al and NiAl intermetallic compounds was decreased with increasing particle size.

Effect of Spray Distance on Ni-Al Intermetallic Formation and Coating Microstructure

In order to further reveal the relationships between coating microstructure and powder particle size and spray parameters, Ni-Al coatings were prepared by Ni-coated Al composite powders with three different sizes at different spray distances and a plasma arc power of 33 kW to examine the evolution of the reaction. Figure 4 shows the cross-sectional backscattered electron images of S1, S2 and S4 coatings. It was found that dense coatings were deposited. As shown in Fig. 4(a) and (b), when the S-powder was used to prepare the coatings, almost no pure Ni and Al phases were present in the coating even at a short distance. The EDS analyzing results at typical regions on

Fig. 4 Cross-sectional backscattered electron images of Ni-Al coatings prepared by S-powder at a plasma arc power of 33 kW and different spray distances: (a, b) S1; (c, d) S2; (e, f) S4

Table 3 Elements percentage in different regions of coatings in Fig. 4b

Regions color	Ni, at. %	Al, at. %	O, at. %
Light gray	77.33	22.67	...
Gray	44.80	55.20	...
Dark gray	6.86	81.36	11.78

the coating cross section corresponding to typical different contrasts on the microstructure as shown in Fig. 4(b) are summarized in Table 3. All Ni reacted with Al elements to form certain Ni-Al intermetallics in the coating. It can be considered based on the EDS results in Table 3 that the light gray regions correspond to Ni_3Al , while the gray region corresponds to NiAl . Moreover, the regions with a dark gray contrast correspond to the mixture of NiO and Al_2O_3 . With the increase in the spray distance, it can be seen that the oxidation of the coating became more severe

Fig. 5 Cross-sectional backscattered electron images of Ni-Al coatings prepared by M-powder at a plasma arc power of 33 kW and different spray distances: (a, b) M1; (c, d) M2; (e, f) M4

due to long in-flight distance (Fig. 4(c), (d), (e), (f)). Thus, more oxides were present in S4 coating.

Figure 5 and 6 shows the cross-sectional backscattered electron images of Ni-Al coatings plasma-sprayed by M-powder and L-powder, respectively. It can be recognized from lamellar structure that the melting of spray particles during in-flight is sufficient. For M1 coatings and L1 coatings, a large amount of unreacted Al can be observed in the coatings, and it is due to a short residence time of particles in the plasma flame at a short spray

distance. Because the exothermic reaction between Ni and Al is time-dependent (Ref 22), the formation of the intermetallic phases was not finished at a short spray distance. However, the unreacted Al was still observed in M4 and L4 coatings (Fig. 5(c), (d), (e), (f)). Besides, the amount of unreacted Al in the coatings prepared by L-powder is much higher than the coatings prepared by M-powder irrespective of spray distance. This means that maybe it is impossible to prepare intermetallic coating through

Fig. 6 Cross-sectional backscattered electron images of Ni-Al coatings prepared by L-powder at a plasma arc power of 33 kW and different spray distances: (a, b) L1, (c, d) L2, (e, f) L4

sufficient reaction between Ni and Al when large size powders are employed.

XRD patterns of APS Ni-Al coatings are shown in Fig. 7. For the coating prepared by S-powder, the XRD results illustrated that the coatings include NiAl, AlNi₃ intermetallic phases. Whereas when the spray distance was increased to 90 mm, the oxidation product (NiO) was detected from the XRD spectrum of the sprayed coating. The oxide content in the coating increases with the increase in the spray distance. Because the content is low, the peaks

of Al₂O₃ phase were not detected by the XRD. This result is consistent with the SEM result in Fig. 4. Besides, even if the spray distance was increased to 150 mm, Al phase was still detected in M4 and L4 coatings. These results further show that the reduction of the particle size is beneficial to facilitate exothermic reaction between Ni and Al elements and the formation of Ni₃Al and NiAl intermetallic compounds.

Figure 8 shows the porosity and oxide content of the coatings. As shown in Fig. 8(a), the oxide content in the

Fig. 7 XRD patterns of APS Ni-Al coatings were deposited by three powders at a plasma arc power of 33 kW and different spray distances

Fig. 8 Oxide content (a) and porosity (b) of the coatings prepared by three powders at a plasma arc power of 33 kW and different spray distances

coatings increased with the increase in the spray distance deposited by three different sizes of powders. The oxide content was increased from about 4% for M1 and L1 coatings to over 10% for S4 coating. Moreover, spray powder particle size has a significant effect on the oxide content in the coating. With the decrease in the powder particle size, the oxide content in the coating was significantly increased. The oxidation behavior of spray powder

particles during thermal spraying has been well documented (Ref 23). The main reason for particle size effect on the oxidation can be attributed to the larger specific surface area of smaller powders. Thus, the oxide content of the coating deposited by S-powder is higher than that of M-powder and L-powder. As shown in Fig. 8(b), the porosity of the coating increased with increasing the spray distance. The formation of pores in the coating is determined by filling of spreading molten melt into the cavities on the rough surface and the wetting of molten melt to splat surface. Generally, the higher the molten droplet temperature is and the higher the particle velocity is, the lower the porosity of coating becomes. As seen from Fig. 8(b), the coating porosity increased with increasing both the powder particle size and the spray distance. The L1 coatings showed more porosity than that of S1 and M1 coatings. As will be shown later, the reduction of particle sizes can facilitate the exothermic reaction between Ni and Al elements during plasma spraying, which will increase molten particle temperature. The increased particle temperature will promote the formation of intermetallic compounds and then improve the compactness of the coating.

Effect of Plasma Arc Power on Ni-Al Intermetallic Formation and Coating Microstructure

To further reveal the effect of plasma arc power on coating microstructure, Ni-Al coatings were prepared by Ni-coated Al composite powders of three different size ranges at a spray distance of 120 mm and different plasma arc powers. The cross-sectional backscattered electron images of the coatings are shown in Fig. 9, 10 and 11, respectively. The S0 coating presents a typical lamellar structure. However, a small amount of unreacted Al was observed in the coating, as shown in Fig. 9(a) and (b). When the power was increased to 33 kW and 42 kW as shown in Fig. 2(a) and (b) and 9(c) and (d), no trace of unreacted Al was observed. This fact means that a complete exothermic reaction can be generated at a moderate plasma arc power to bring out the self-bonding effect by using S-powder. However, a large amount of unreacted Al can be seen in M0 and L0 coatings, as indicated by the arrows in Fig. 10(b) and 11(b). With the plasma arc power increased to 42 kW, there was still a fraction of unreacted Al in M5 and L5 coatings (Fig. 10(c), (d), 11(c), (d)). This fact was also confirmed by XRD patterns of the coatings deposited by M-powder and L-powder as shown in Fig. 12. This showed that exothermic reaction degree of Ni-clad Al powders during plasma spraying presents a significant particle size effect. When commercially available M-powder and L-powder are used, even using plasma flame at a plasma arc power up to 42 kW, the reaction of Ni with Al cannot be completed up to a spray distance of 150 mm. Such size effect on the

Fig. 9 Cross-sectional backscattered electron images of APS Ni-Al coatings prepared by S-powder at a spray distance of 120 mm and different plasma arc powers: (a, b) S0; (c, d) S5

reaction kinetics will limit the heating effect to spray particle by the exothermic reaction and thus subsequent self-bonding. On the other hand, the above-mentioned size effect also influences the coating compositional homogeneity and microstructure. As mentioned above, in the coatings deposited by M-powder and L-powder there was certain amount of retained pure Al. Thus, the coatings consisted of Ni-Al intermetallic phases and pure Al.

As revealed by the XRD patterns of the coatings shown in Fig. 12, the plasma-sprayed Ni-Al coating consisted mainly of Ni_3Al , NiAl and Al. The peaks located at about 38.5° (2θ) and 65.1° (2θ) corresponding to Al were observed in all coatings prepared by M-powder and L-powder. The peaks of NiO were observed with increasing the plasma arc power. For the S-powder, the peaks located at about 30.9° (2θ) and 64.5° (2θ) corresponding to NiAl were observed with increasing the plasma arc power. It is well known that the structure of the coating is closely related to particle temperature (Ref 24). When the plasma arc power was low (e.g., 25 kW), some particles are partially melted and the temperature of the particles is low, which caused a deficiency of reaction between Ni and Al

elements. This result is in an agreement with Fig. 9, 10 and 11.

Figure 13 shows the porosity and oxide content of the coatings. The porosity of the coatings deposited by three powders was $4.4 \pm 0.2\%$, $5.7 \pm 0.5\%$ and $6.4 \pm 0.4\%$, respectively, at a plasma arc power of 25 kW. The porosity of the coating decreased significantly when the plasma arc power was increased to 42 kW. This result is attributed to increased droplet temperature at a high plasma arc power. When the coating is deposited at a low plasma arc power such as 25 kW, the heating of spray particles by plasma flame and intermetallic compound formation by exothermic reaction are limited, and particle temperature is low. Up on molten droplet impact, spreading molten melt with a poor fluidity cannot sufficiently wet and fill inter-splat clearance, resulting in higher porosity of the coating. Although the high plasma arc power can provide enough energy to raise particle temperature, the coating has a high oxide content due to the high temperature of the particles at 42 kW. For S5 coating, the oxide in molten particle and on pre-deposited Ni-Al particles decreases the wettability of inter-lamellar interfaces within the coating, which makes porosity of S5 coating increase.

Fig. 10 Cross-sectional backscattered electron images of APS Ni-Al coatings prepared by M-powder at a spray distance of 120 mm and different plasma arc powers: (a, b) M0; (c, d) M5

Particle Temperature

For Ni-coated Al powder particles, when they are injected into high temperature flame, it will be heated up rapidly by intensive convection heat transfer effect. At the same time, the exothermic reaction may be ignited to provide additional heat to raise droplet temperature. It can be estimated theoretically that the exothermic reaction between Ni and Al can contribute an adiabatic temperature increment from 1400 to 2000 K based on the type of resultant intermetallic compound. Therefore, this additional heat may increase droplet temperature significantly, which leads to local metallurgical bonding by substrate melting upon impact of high temperature droplet. Therefore, the Ni-clad Al powder is well known as the self-bonding spray material which is expected for use of bond coat for long since the exothermic reaction was recognized (Ref 25). Whether it can be used to enhance adhesive or cohesive strength depends on the temperature that can be heated to. The higher its droplet temperature is raised, the higher the possibility to cause metallurgical bonding upon impact. Thus, the temperature evolution of spray particles during in-flight within plasma jet becomes critical. Figure 14 shows the temperature

evolution of in-flight Ni-Al powder particles in three different size ranges against spray distance at the plasma arc power of 33 kW. Among the three powders, the particle surface temperature of S-powder is higher than M-powder and L-powder. It was observed that S-powder reached a mean temperature of 2436 ± 81 °C at the spray distance of 60 mm. Such NiAl droplets achieved almost the highest temperature since the boiling point of aluminum is 2470 °C. Taking account of the phase structure of the resultant NiAl coating, it can be inferred that the exothermic reaction for S-powder is completed at plasma arc power of 33 kW up to the spray distance of 60 mm. Then, particle temperature tends to decrease with the increase in the spray distance as observed in Fig. 14 than those with the other two particle sizes. When spray distance becomes larger than 90 mm, the temperature of all spray particles tended to decrease with the increase in the spray distance. The high temperature of S-powder can be attributed to high degree of the exothermic reaction. Thus, the interface temperature upon high temperature droplet impact will increase significantly, and consequently, localized substrate melting occurs, resulting in the metallurgical bonding formation. On the other hand, when the spray distance was

Fig. 11 Cross-sectional backscattered electron images of APS Ni-Al coatings prepared by L-powder at a spray distance of 120 mm and different plasma arc powers: (a, b) L0; (c, d) L5

Fig. 12 XRD patterns of Ni-Al coatings prepared by the three different powders at a spray distance of 120 mm and different plasma arc powers

increased from 60 mm to 150 mm, the oxidation of in-flight particles became more severe, because higher oxide content was observed. It was argued that oxidation of Ni-Al system may also contribute to enhanced bonding (Ref 26). However, the high oxide content leads to the inclusion of

oxide scale along the lamellar interfaces. This is adverse to the formation of metallurgical bonding at the splat interface for cohesion and the substrate/coating interface for adhesion.

It was generally observed that the particle temperature will decrease with the increase in the spray distance during plasma spraying (Ref 27). In this study, for M-powder and L-powder, it was observed that the particle temperature first increased up to a spray distance of 90 mm from 60 mm and then tended to decrease when the spray distance was increased further from 90 mm to 150 mm. Therefore, the increase in particle temperature up to 90 mm can be attributed to the exothermic reaction between Ni and Al for M-powder and L-powder. Larger powder particles may experience a low heating rate and thus low exothermic reaction. As a result, the larger the powder particles are, the lower the overall temperature is. At a spray distance of 90 mm, M-powder and L-powder reached their maximum mean temperatures of 2349 ± 52 °C and 2322 ± 45 °C, respectively, and then, the mean temperature tends to decrease with the increase in the spray distance. It can be considered that the exothermic reaction takes place over the whole in-flight process up to a

Fig. 13 Porosity (a) and oxide content (b) of the coatings prepared by three powders at a spray distance of 120 mm and different plasma arc powers

Fig. 14 Effect of particle size and spray distance on the molten droplet surface temperature of Ni-coated Al composite powders

spray distance of 150 mm. Since even at a spray distance of 150 mm, the unreacted Al phase was still observed in M4 and L4 coatings (Fig. 5(e), (f), 6(e), (f)). This fact showed that heating effect by exothermic reaction at the later stage over spray distance of 90 mm is limited. As mentioned previously, heating to spray particles by exothermic reaction may be contributed by oxidation since the oxidation becomes intensive with the increase in the

Fig. 15 Effect of particle size and spray distance on adhesive strength of the coatings (a) and the relationship between the molten droplet surface temperature and adhesive strength of the coatings prepared by three powders at a plasma arc power of 33 kW and different spray distance (b)

spray distance. However, taking into account of dependency of the droplet temperature on in-flight distance (Fig. 14), the contribution from oxidation exothermic reaction to particle heating and subsequently to improved adhesion or cohesion may not be expected.

Adhesive Strength of the Coatings

The tensile adhesion test is often used to evaluate the adhesion and cohesion of the coating and mechanical properties of Ni-based coatings as well (Ref 28). The adhesive strength test result of the coatings depends on the inter-lamellar interactions and lamellar-substrate interactions (Ref 29). In this paper, the effects of spray distance and powder particle size on the adhesive strength of the Ni-Al coatings were investigated to clarify the contribution of exothermic reaction. Figure 15(a) shows the test results of typical coatings. Among these specimens, the S1 coating

exhibited the highest adhesive strength of 51.3 MPa. The adhesive strength of S1 coating is higher than that of S2, S3, S4, M4 and L4. The high adhesive strength of S1 coating can be related to high molten droplet surface temperature, which could result in dense microstructure and local metallurgical bonding at the interface of the coating/substrate during plasma spraying. The average adhesive strength of the coating decreased with increasing spray distance and powder size. Moreover, the adhesive strength of the coatings decreased to 41.1 MPa and 40.2 MPa for M4 and L4 coatings, respectively. This decrease in adhesive strength can be attributed to high degree of porosity and oxide phases, which decreases the bonded regions between the coating and substrate.

Figure 15(b) shows the relationship between the molten droplet temperature and adhesive strength of the coatings prepared by three powders at a plasma arc power of 33 kW. It could be seen that high adhesive strength is positively related to high molten droplet surface temperature. With the increase in the molten droplet temperature, the adhesive strength of the coatings tends to increase. Although the coating deposited by small sized powder particles contained high amount of oxides, it presented the highest adhesive strength since its mean temperature is the highest among the coatings deposited at different conditions. Regarding the particle size effect on the overall heat of spraying particles and limited contribution of the exothermic reaction to heating up for M-powder and L-powder, it is clear that the potential self-bonding effect can only be realized with the selection of the powders with the proper size range.

Conclusions

In this paper, the effects of powder size and APS spray distance on the microstructure of plasma-sprayed Ni-Al coatings using conventional self-bonding Ni-coated Al composite powders were investigated. The results showed that the exothermic reaction between molten Al and Ni during in-flight significantly depends on the spray particle size. It was revealed that when M-powder and L-powder were used, the exothermic reaction between molten Ni and Al during in-flight progresses so slow that at the plasma arc power of 42 kW, the reaction is hardly completed up to a spray distance of 150 mm. As a result, the unreacted Al was present in the coatings prepared by M-powder and L-powder. On the other hand, when S-powder was used, the exothermic reactions were significantly promoted and the droplets can be heated to their highest temperature of about 2470 °C for self-bonding. The positive relationship between molten droplet temperature and tensile adhesive strength was recognized. Therefore, the development of

self-bonding effect by exothermic reaction using Ni-Al composite powders should take the size effect on the reaction into account, and otherwise, the self-bonding effect to improve the coating-substrate adhesion could not be effectively developed during spraying. However, it was also found that using S-powder leads to high degree inclusion of oxides in the coating. The results showed that the coating deposited at a short spray distance (60 mm) presented the lowest oxide content with the highest density, adhesive strength and the lowest porosity. Therefore, how to limit or prevent the in-flight oxidation of Ni-Al spray particles during plasma spraying at normal long spray distance in an ambient atmosphere would be a great challenge.

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