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Evaluation of Three Dual-Wire Electric Arc-Sprayed Coatings: Industrial Note

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Plasma-sprayed coatings of Ni-18.5Cr-6Al, molybdenum, and Al-12Si are used in selected applications for dimensional restoration of jet engine hardware. These coatings are usually limited, however, by the thickness to which they can be applied. In order to increase the coating thickness capability of these materials, the dual-wire electric arc process was investigated. This paper presents the results of a testing program to characterize the bond strengths, microstructure, hardness, and surface roughness of these three types of materials using a standard dual-wire electric arc spray system and a high-velocity (arc jet) spray gun. A comparison of bond strengths and microstructure to typical equivalent (in composition) plasma spray coatings was also made. The test program was designed to emulate, as closely as possible, substrate materials, spray application procedures, and coating thicknesses that would be used in service.

Keywords aerospace repair, dimensional overhaul, electric arc spraying, process efficiency

1. Introduction

PLASMA spray coatings have been used successfully since the 1960s for the dimensional restoration and repair of many different types of jet engine component surfaces. These coatings have been applied to parts that were undersized as a result of overmachining during the manufacturing process or that required material restoration at service overhaul. Several different types of coatings and compositions have been employed, depending on alloy base material and specific application.

Frequently, however, dimensional restoration requirements for components at overhaul have exceeded the maximum thickness guidelines allowable with plasma coatings. Consequently, the large buildup of coating required to salvage these parts has made plasma spray coatings impractical because of residual stresses resulting from the application process.

To overcome this problem, a Ni-5Al dual-wire electric arc spray coating was developed for some repair applications, where the coating thickness exceeded the thickness limits of available plasma-sprayed coatings (Ref 1). This nickel-aluminum coating is currently being used for dimensional restoration and repair of various commercial and military gas turbine engine components (e.g., bosses, lug faces, and flanges) made of various alloys.

Some properties of this spray-deposited Ni-5Al wire coating have been well documented and compared with plasma-sprayed Ni-5Al (Ref 2-4). To further investigate the capabilities and properties of other materials sprayed with the dual-wire electric arc spray system, Ni-18.5Cr-6Al, molybdenum, and Al-12Si wires were sprayed and the coatings evaluated.

These three material compositions were selected because of their current plasma spray use on various engine components. Nickel-chromium-aluminum has been applied for dimensional restoration of nickel and iron alloys to achieve a higher hardness and greater temperature capability than Ni-5Al can provide. Molybdenum is often used as a dimensional restorative material for titanium alloy components operating up to 427 °C (800 °F) in service. Aluminum-12Si applied over a bond coat of 0.076 to 0.127 mm (0.003 to 0.005 in) of Ni-5Al is typically used as a repair coating for aluminum and magnesium alloy applications. This Al-12Si alloy coating also produces a harder surface that is more resistant to galling than the aluminum alloy materials.

This study evaluated Ni-18.5Cr-6Al, molybdenum, and Al-12Si coatings produced by two arc spray methods. A standard dual-wire electric arc spray gun (TAFA Model 8835) and a high-velocity arc jet (TAFA Model 8835 AJ) were used to spray the three materials. The arc jet spray system contains a specially configured nozzle design incorporating a plenum arrangement that results in significantly higher particle velocities and a more constricted spray pattern than conventional arc spray. The arc jet configuration was evaluated along with the standard equipment because of this tighter "focused" spray pattern, which tends to result in higher deposit and target efficiencies as well as to generate less coating overspray than standard arc spray systems at similar conditions (Fig. 1). These characteristics also allow the arc jet to apply coatings at a lower cost than standard arc spray equipment and plasma spray (Ref 3, 5).

2. Methodology

The spray conditions to apply the three coatings of interest were developed in two phases. In phase one, the initial spray parameters were determined at TAFA Incorporated on the basis of previous experience with wires of similar composition, Taguchi-designed experiments, and correlation with resulting microstructures, bond strengths, hardness, and so forth. In phase two, these spray parameters were optimized at Pratt & Whitney (P&W) for coating application to jet engine components and their typical alloys. Since many of the parts to be coated are cylindrical in shape and of various diameters, the test samples in this study were sprayed with the gun traversing the specimens in a vertical plane.

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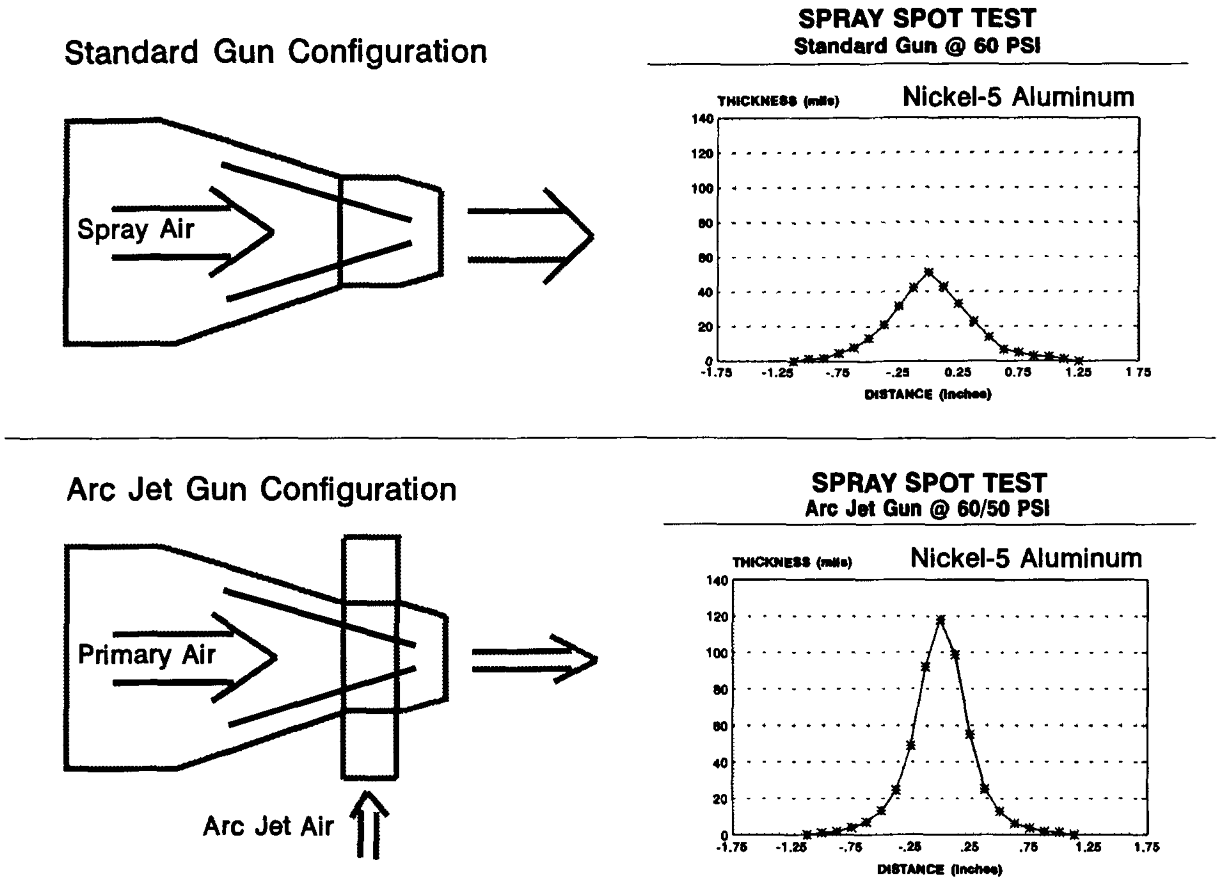

Fig. 1 Comparison of arc spray configurations

Table 1 Spray parameters for Ni-Cr-Al

Parameter	8835 standard process	8835 arc jet process
Volts	30	30
Amps	150	150
Standoff, cm (in.)	10.2 (4)	10.2 (4)
Spray pressure, bar (psi)		
Primary (air)	4.14 (60)	4.14 (60)
Secondary (air)	N/A	2.72 (40)
Air cap	Green	Arc jet
Positioner	Long cross	Arc jet cross

The critical coating characteristics for evaluation of each of these three materials were bond strength as a function of thickness and coating quality/microstructure. For completeness, hardness and as-sprayed surface roughness were also measured. The tensile bond strengths were measured at as-sprayed thicknesses ranging from 0.254 to 1.905 mm (0.010 to 0.075 in.) in accordance with P&W standards and ASTM C 633. At least three specimens were tested for each coating thickness/wire alloy combination. The coating microstructures and surface roughness were evaluated on panels coated to 0.889 to 1.016 mm (0.035 to 0.040 in.) thickness. All the test specimens were prepared by grit blasting with aluminum oxide at a pressure of 2.7 to 4 bar (40 to 60 psi) with a 10.2 to 15.2 cm (4 to 6 in.) nozzle standoff distance. Four sets of Vickers hardness readings (HV_{300}) and six surface roughness measurements were performed on each coating. The surface roughness was measured in microinches (R_a) across the surface of the coating using a digital readout instrument with a 0.762 mm (0.03 in.) cutoff and a range of 50.9 mm (2 in.).

Nickel-chromium-aluminum coatings were applied to AISI 410 stainless steel specimens. Molybdenum coatings were applied to titanium alloy specimens, and the aluminum-silicon coatings were sprayed on aluminum alloys over a bond coat of 0.076 to 0.127 mm (0.003 to 0.005 in.) nickel-aluminum. Analyses of the coatings and their respective properties were performed at both TAFA and P&W. Spray conditions and test data are presented in section 3.

3. Results

3.1 *Ni-18.5Cr-6Al*

Coatings sprayed with the standard and arc jet parameters (Table 1) produced the microstructures shown in Fig. 2 and similar bond strength results (Fig. 3). Coatings from both processes exceeded the 31 MPa (4.5 ksi) plasma spray minimum average bond strength standard to a coating thickness of 1.27 mm (0.050 in.). The microstructure of each coating displayed levels of oxides and porosity as shown in Fig. 2, comparable to oxide/porosity levels in corresponding plasma-sprayed coatings. Both arc coatings show a typical lamellar structure with interlamellar ox-

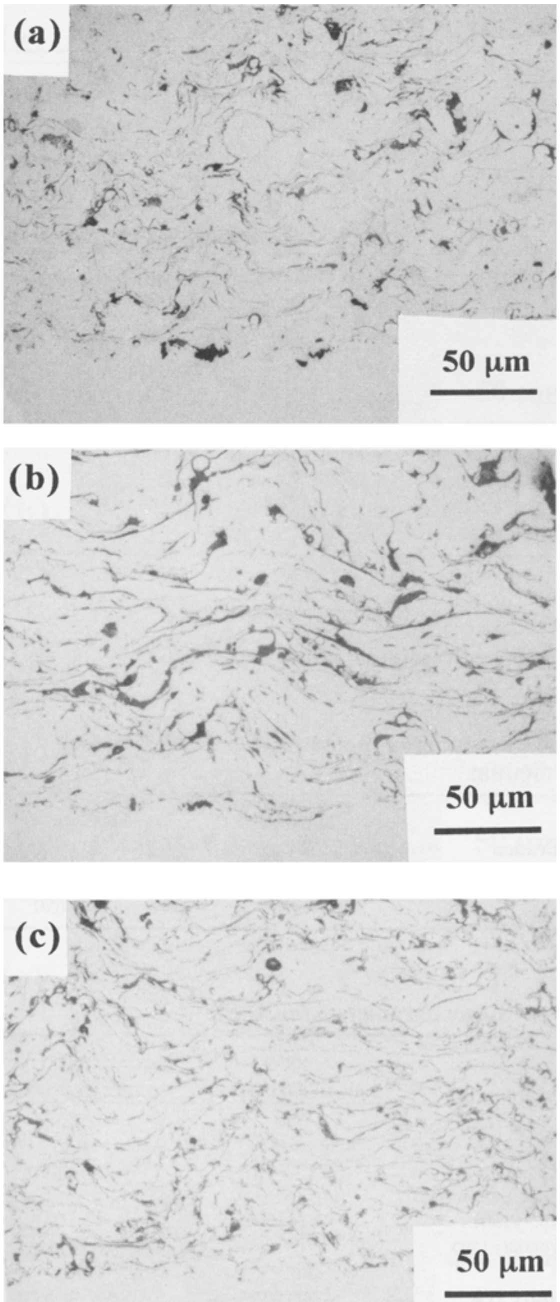

Fig. 2 Microstructures of Ni-Cr-Al coatings sprayed by three different processes. (a) Plasma spray process. (b) Standard gun configuration. (c) Arc jet gun configuration

ides and voids. The arc-jet-sprayed coatings had a finer-size microstructure with thinner oxide stringers than the standard coating. The nickel-chromium-aluminum dual-wire arc coating sprayed by the standard gun had an average hardness and surface roughness that were slightly higher than those produced by the arc jet (Table 2).

3.2 *Molybdenum*

With this material, sprayed as shown in Table 3, the standard gun produced coatings that exhibited a microstructure comparable to plasma coatings (Fig. 4), with bond strengths that exceeded the average bond strength of 41.3 MPa (6.0 ksi) for plasma spray coatings at thicknesses up to 0.762 mm (0.030 in.) (Fig. 5). Coatings produced with the arc jet configuration also exhibited microstructures comparable to plasma (Fig. 4) and bond strengths that exceeded the minimum requirement at thicknesses up to 1.016 mm (0.040 in.). The microstructures of each arc coating displayed levels of oxides and porosity comparable to the corresponding plasma coatings. All of the molybdenum coatings had low levels of interlamellar oxides. The arc jet coating, however, had a finer-size microstructure with thinner oxides and smaller voids than the standard coating. The higher bond strengths of the arc jet coatings may be a result of this finer structure. The average hardness of the standard coating was lower than the arc jet hardness (Table 4), and the standard coating surface was rougher than that of the arc jet (Table 4).

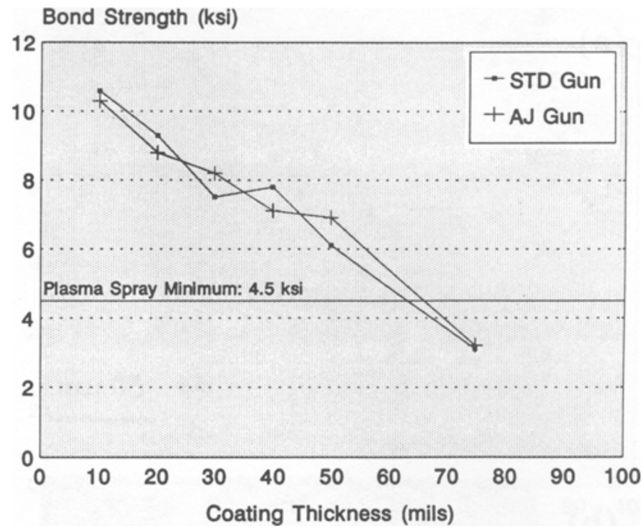

Fig. 3 Nickel-chromium-aluminum bond strength comparisons. STD, standard gun configuration; AJ, arc jet configuration (see Fig. 1)

Table 2 Surface roughness and hardness data for Ni-Cr-Al

Gun configuration	Hardness, HV_{300}	Roughness (R_a), µin.
Standard	299	750-1000
Arc jet	280	650-750

Table 3 Spray parameters for molybdenum

Parameter	8835 standard process	8835 arc jet process
Volts	35	35
Amps	150	150
Standoff, cm (in.)	11.4 (4.5)	11.4 (4.5)
Spray pressure, bar (psi)		
Primary (air)	4.14 (60)	4.14 (60)
Secondary (air)	N/A	2.75 (40)
Air cap	Blue	Arc jet
Positioner	Short cross	Arc jet cross

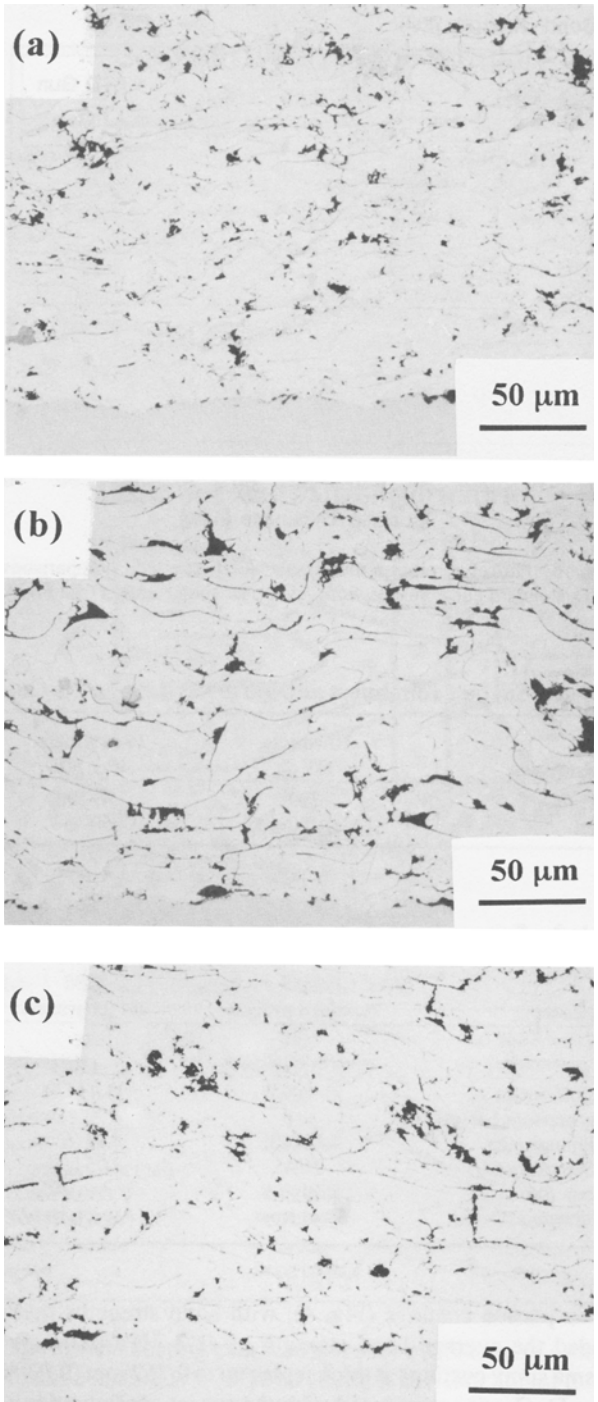

Fig. 4 Microstructures of molybdenum coatings sprayed by three different processes. (a) Plasma spray process. (b) Standard gun configuration. (c) Arc jet gun configuration

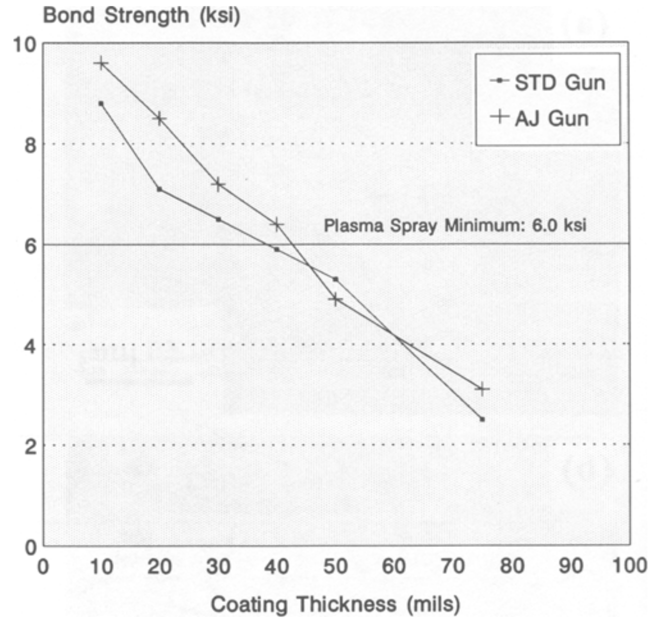

Fig. 5 Molybdenum bond strength comparisons

Table 4 Surface roughness and hardness data for molybdenum

Gun configuration	Hardness, HV_{300}	Roughness (R_a), μin.
Standard	351	650-800
Arc jet	394	550-650

Table 5 Spray parameters for Al-Si

Parameter	8835 standard process	8835 arc jet process
Volts	30	30
Amps	125	125
Standoff, cm (in.)	11.4 (4.5)	11.4 (4.5)
Spray pressure, bar (psi)		
Primary (air)	4.14 (60)	4.14 (60)
Secondary (air)	N/A	3.10 (45)
Air cap	Green	Arc jet
Positioner	Long cross	Arc jet cross

Table 6 Surface roughness and hardness data for Al-Si

Gun configuration	Hardness, HV_{300}	Roughness (R_a), μin.
Standard	122	775-925
Arc jet	125	600-850

3.3 *Al-12Si*

This material was sprayed over a 0.076 to 0.127 mm (0.003 to 0.005 in.) thick bond coat of Ni-5Al (Ref 6) (Table 5). The standard gun produced coatings with a microstructure comparable to that produced by the plasma process (Fig. 6), with bond strengths that exceeded the 20.7 MPa (3.0 ksi) plasma spray coating average bond strength minimum at thicknesses up to 1.905 mm (0.075 in.) (Fig. 7). Coatings produced with the arc jet configuration also exhibited microstructures comparable to plasma and bond strengths that exceeded the minimum requirements at thicknesses up to 1.016 mm (0.040 in.). The micro-

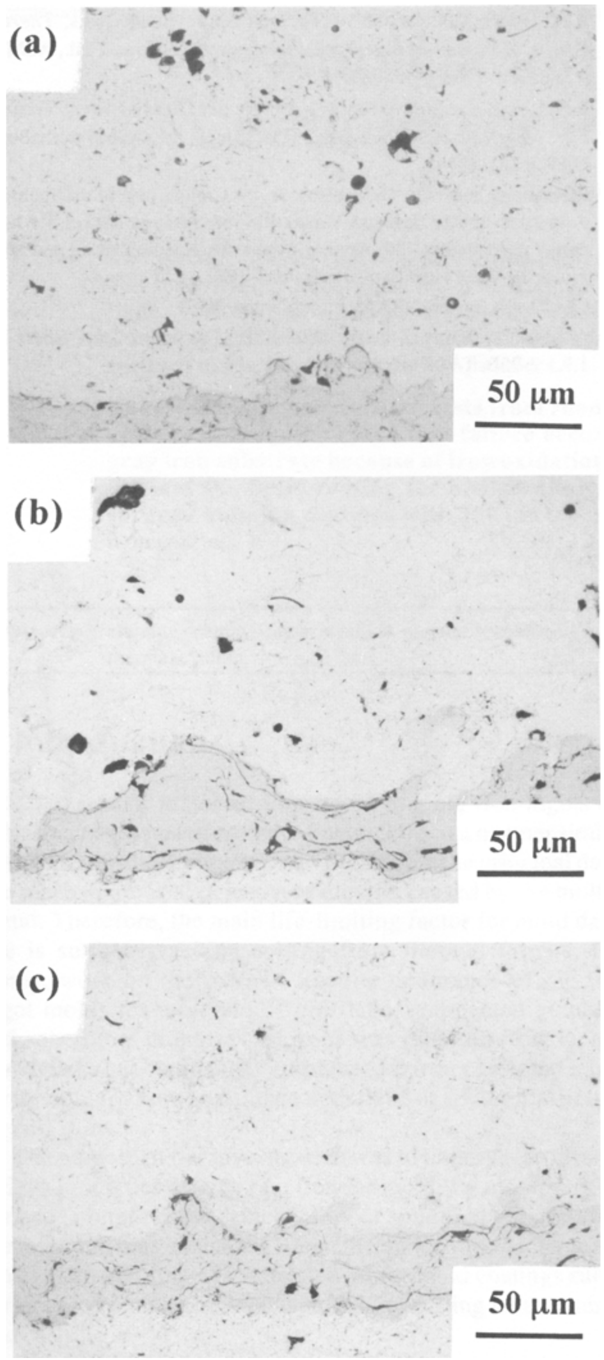

Fig. 6 Microstructures of Al-Si coatings sprayed by three different processes. (a) Plasma spray process. (b) Standard gun configuration. (c) Arc jet gun configuration

structures of each coating displayed levels of oxides and porosity comparable to the plasma coatings. Porosity and oxide levels were low for both coatings, with good adherence to the bond coat. The average hardness for the standard coating was essentially the same as the hardness for the arc jet version (Table 6), and the surface roughness of the standard gun coating was slightly greater than that of the arc jet coating.

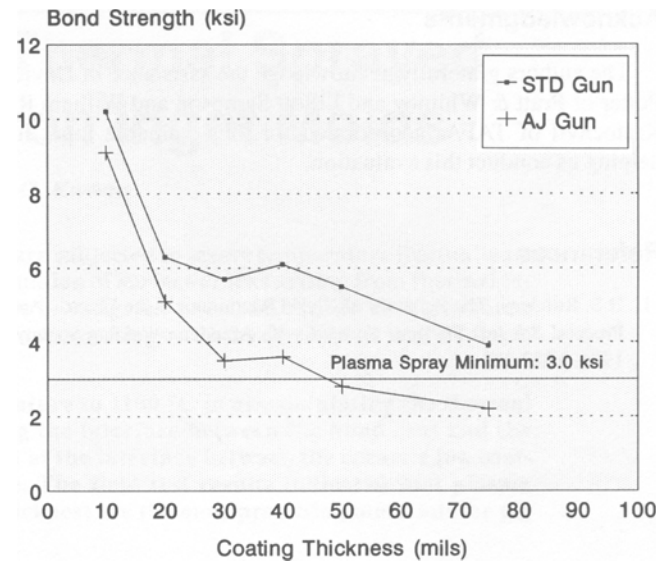

Fig. 7 Aluminum-12Si bond strength comparison

4. Summary

The microstructures of each of the coatings evaluated are comparable to their respective equivalent-composition plasma spray coatings in terms of overall coating integrity and quality. Although there are no apparent significant microstructural differences between the standard gun and arc jet configurations with aluminum-silicon, the arc jet generally produced coatings that exhibited a more refined microstructure with fewer voids and thinner oxides than did the standard configuration. This effect is a result of the arc jet technology (Fig. 1). The finer microstructure also tends to result in smoother as-sprayed coating surfaces than those applied with the standard process.

Comparable nickel-chromium-aluminum and molybdenum coating bond strengths are produced with the standard gun and arc jet configurations. Both dual-wire spray coating materials, however, can be sprayed with either configuration to thicknesses that exceed the corresponding plasma minimum average bond strength. The aluminum-silicon material can also be sprayed with both spray systems, but is limited in thickness to 1.016 mm (0.040 in.) when sprayed with the arc jet. The standard gun, however, displayed no thickness limitations in bond strengths up to 1.905 mm (0.075 in.).

Based on the ability of the dual-wire arc coatings to achieve the equivalent plasma spray coating minimum bond strength with both arc spray systems, the dual-wire arc thickness capabilities are 1.27 mm (0.050 in.) for Ni-18.5Cr-6Al, 0.889 mm (0.035 in.) for molybdenum, and 1.016 mm (0.040 in.) for Al-12Si.

In conclusion, the results demonstrate some of the characteristics of these coatings, including acceptable microstructures and high coating thickness capability of nickel-chromium-aluminum, molybdenum, and aluminum-silicon materials when applied with the dual-wire electric arc spray process.

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