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Properties of Aluminum Deposited by a High-Velocity Oxygen-Fueled Process

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ABSTRACT

Aluminum coatings deposited by a HVOF process have been demonstrated and relevant coating properties evaluated according to two deposition parameters, the spray distance and the oxygen-to-fuel flow ratio. The coating porosity, surface roughness, and micro-hardness are measured. The coating properties are fairly insensitive to spray distance, the distance between the nozzle and the workpiece, and fuel ratios, the oxygen-to-fuel flow. Increasing the fuel content does appear to improve the process productivity in terms of surface roughness. Minimization of nozzle loading is discussed.

INTRODUCTION

Aluminum coatings deposited by a high velocity oxygen-fueled (HVOF) process have been demonstrated. Flame-sprayed Al coatings onto steel is already known to serve as a passivating corrosion barrier. Another unique application of such Al coatings is as a surface treatment for high peak-power laser system enclosures. The laser system enclosures have surface requirements with very low cleanliness levels and high laser–resistances. These coatings are not functioning as reflective surfaces but as part of the walls where the laser beams and optic components are deployed. Laser optics are susceptible to laser-induced damage when contaminated with particulates or organic molecules. So the surfaces in proximity to the optics cannot be sources of particulates or organic contamination.

The enclsoure surfaces are exposed to stray light from the main, high-powered laser beam and intense flash-lamp irradiation. The flash-lamp irradiation comes from lamps pumping the laser amplifier crystals. The stray laser light comes from portions of the main beam which are scattered or back-reflected from the glass optics. The stray light still has damaging power densities because the forward propagating beam has such high power densities. Other Al surfaces, namely aluminum foil and conventional flame-sprayed Al coatings, are found to survive the fluences from the flash lamps and stray light. It is assumed that the Al deposited by an HVOF process retains this laser-resistant quality.

Another important requirement is that the precision-cleaned Al surfaces will not contaminate the optical components with organics and particulates. The characterization of Al deposited by an HVOF process is to obtain certain physical properties that lend themselves to surface cleanliness requirements, namely low porosity and surface roughness. A smooth surface does not trap particulates, is amendable to precision cleaning techniques using high pressure liquid sprays, and can be directly validated for surface cleanliness levels with a swipe method.

Two deposition parameters are varied to minimize the Al coating porosity: the spray distance and oxygen-to-fuel flow ratio. The porosity, surface roughness, and micro-hardness of the coatings are reported.

EXPERIMENTAL SET-UP

A Stellite Jet-Kote NOVA Lite IS system is used to deposit the Al coatings (Figure 1). The system consists of a JK 3000 torch, the NOVA II control console, water-to-water heat exchanger, and a powder feeder. Figure 2 is a cut-away view of the JK 3000 torch. Oxygen and fuel are fed through the inlet ports and into a combustion chamber. Combustion of the reactants generates the high temperature, high velocity gas which, after a right angle bend, passes though to the nozzle feed port. The nozzle feed port consists of four inclined holes, which converge together at the nozzle insert. The combustion products accelerate through the water-cooled constricting nozzle insert. The nozzle involves a converging section, which is conical and intersects the throat of a constant diameter bore. The nozzle and combustion chamber are temperature controlled through water cooled passages. The heat from the flame transfers to the walls of the nozzle and injected particles. As the particles traverses the length of the bore its temperatures steadily increases. When the powder reaches its melting point the temperature remains constant until the particle is completely molten.

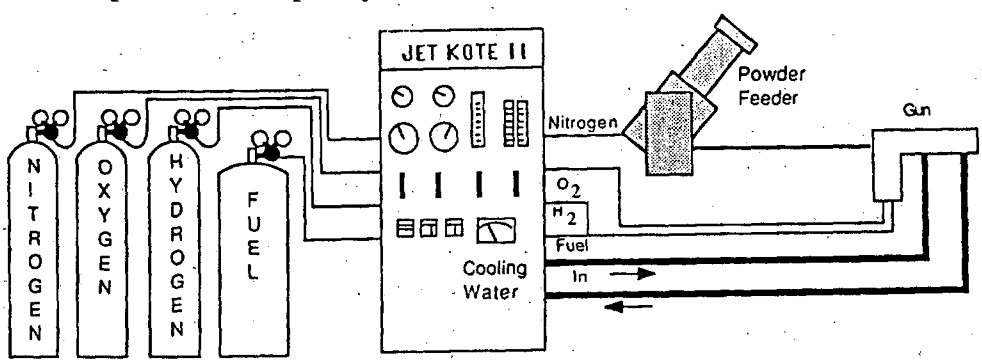

Figure 1 Sketch of the Stellite NOVA Lite system

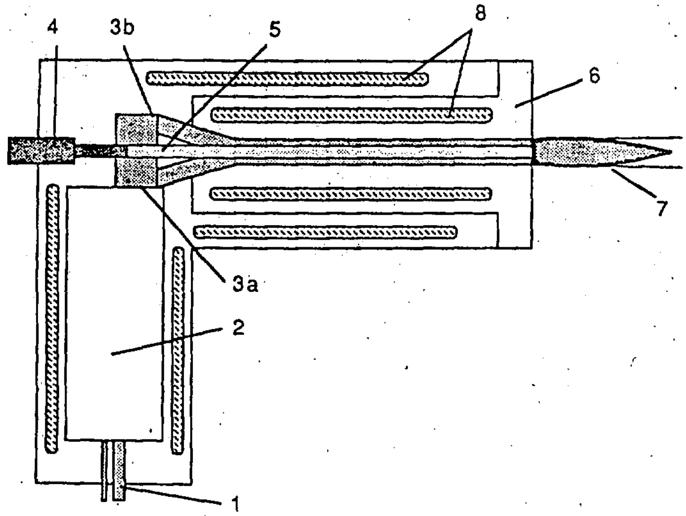

Figure 2 HVOF torch 1. Oxygen and Fuel inlets, 2. Combustion Chamber, 3a & b. Nozzle Feed Ports, 4. Powder Inlet & Carrier Gas, 5. Nozzle Feeder Port, Powder, 6. Nozzle, 7. Gas Jet, 8. Cooling Passage

The result of the combustion process generates a turbulent gas jet creating shock diamonds (mach waves) after exiting the nozzle bore. The plume of the exiting free jet is due to the sudden reduction in the pressure which the gas experiences as they leave the nozzle. With the occurrence of the pressure drop the gasses expand and accelerate. The source of these shock diamonds is the decreasing total pressure of the free gas stream.

Table 1 Experimental constants.

Parameter	Unit	Value
Powder Feed Rate	gm/min	26
Nozzle Length	inch	3
Torch angle	degrees	90
Carrier gas		N_2
Carrier gas pressure @ the console	psi	44
Carrier gas flow rate	SCFH	77
Fuel gas		C_3H_6
Fuel gas pressure @ the console	psi	60
Oxygen gas flow rate	SCFH	1020
Oxygen gas pressure @ the console	psi	85
Water Temperature difference	C	20
Water exchanger flow rate	gpm	8
Water exchanger pressure	psi	55
Cross-over	inch	0.120
Transverse torch speed	ft/min	150
Coating thickness per pass	inch	0.0035
Coating thickness (estimated)	inch	0.015

The spray distance variable is defined as the torch-to-work piece separation. The spray distance is a practical method of controlling the amount of mechanical energy given to the deposit. The shorter the spray distance, the higher the particle velocity upon impact on the surface. The velocity term is squared in the energy equation (work = mv^2) and so has a large effect on the mechanical energy. There is a secondary effect of spray distance which is the temperature of the deposit. The longer the particle takes to reach the work piece, the more heat it loses to the atmosphere, and the less energy it has to transfer to the workpiece. This effect is assumed small in this study because the spray distance is varied only by 2 inches.

The chemical energy (enthalpic heat content) supplied to the powder is varied by the fuel flow rate. The oxygen flow rate is always sufficient for complete combustion of the fuel. As the oxygen to fuel ratio decreases by increasing the fuel flow rate, more chemical energy is supplied to the powder, and the temperature of the powder increases. The exit velocity increases also.

Surface preparation

The surface preparation has two conflicting requirements. The conventional methodology is to generate an "anchor tooth" pattern on the substrate to assure coating adherence. The cleanliness need to produce a smooth coating and sustain low cleanliness levels argues for a smoother surface preparation. The compromise was to automate the surface preparation procedure for repeatability and uniformity. The as-blasted surface preparation consisted of using 60 grit aluminum oxide blasting grain at a pressure of 45 psi normal to the surface. Figures 3a and 3b are scanning electron micrographs of the as-blasted surface at two magnifications; a length scale is the dotted line in the foot of the picture.

DISCUSSION AND RESULTS

The early experimental trials are used to determine process parameters that prevent the Al powder from plugging up the nozzle. Nozzle loading was expected due to the low melting temperature of Al compared to high melting point materials normally deposited by HVOF process. However, the particle build-up occurred at the nozzle entrance, not at the exit where temperatures are cooler and condensation can occur. To improve particle throughput, the shortest possible nozzle was used (for a commercial unit) and the particle size of the powder sieved for size uniformity. There are probably other solutions to nozzle loading, but the steps taken here permitted deposition times as long as 60 minutes. The powder size uniformity appears to be critical to the HVOF deposition of Al.

A smaller particle size is selected in order to obtain desirable coating characteristics. Large particles may not be uniformly viscous and so create rough, porous surfaces. Smaller particle should create smoother surfaces. Smaller particles should also reduce the coating porosity because smaller crevices are produced than with large particles. The nozzle loading occurred within minutes with the Valimet H-30, H-60 and WMS-103 powder models. The nozzle loading situation improved as the sizing became more narrow.

Table 2 Powder uniformity needed to minimize nozzle loading. A Stellite proprietary separation and blending method is used to narrow the WMS-102 powder distribution.

Valimet Model	Variation performed on the powder	Sieve Analysis (wt/o) by ASTM B-214				
		(+)140	(+)170	(+)200	(+)325	(-)325
H-30	None			Trace	12.0	88.0
H-60	None	0.2	2.2	9.2	75	13.4
WMS-103	None	Trace	0.2	11.6	86	2.2
WMS-103	Narrow size dist: 140 to 325		0.2	13.8	86	
WMS-103	Narrow size dist: 170 to 325			14	86	
WMS-103	Narrow size dist: 200 to 325				100	

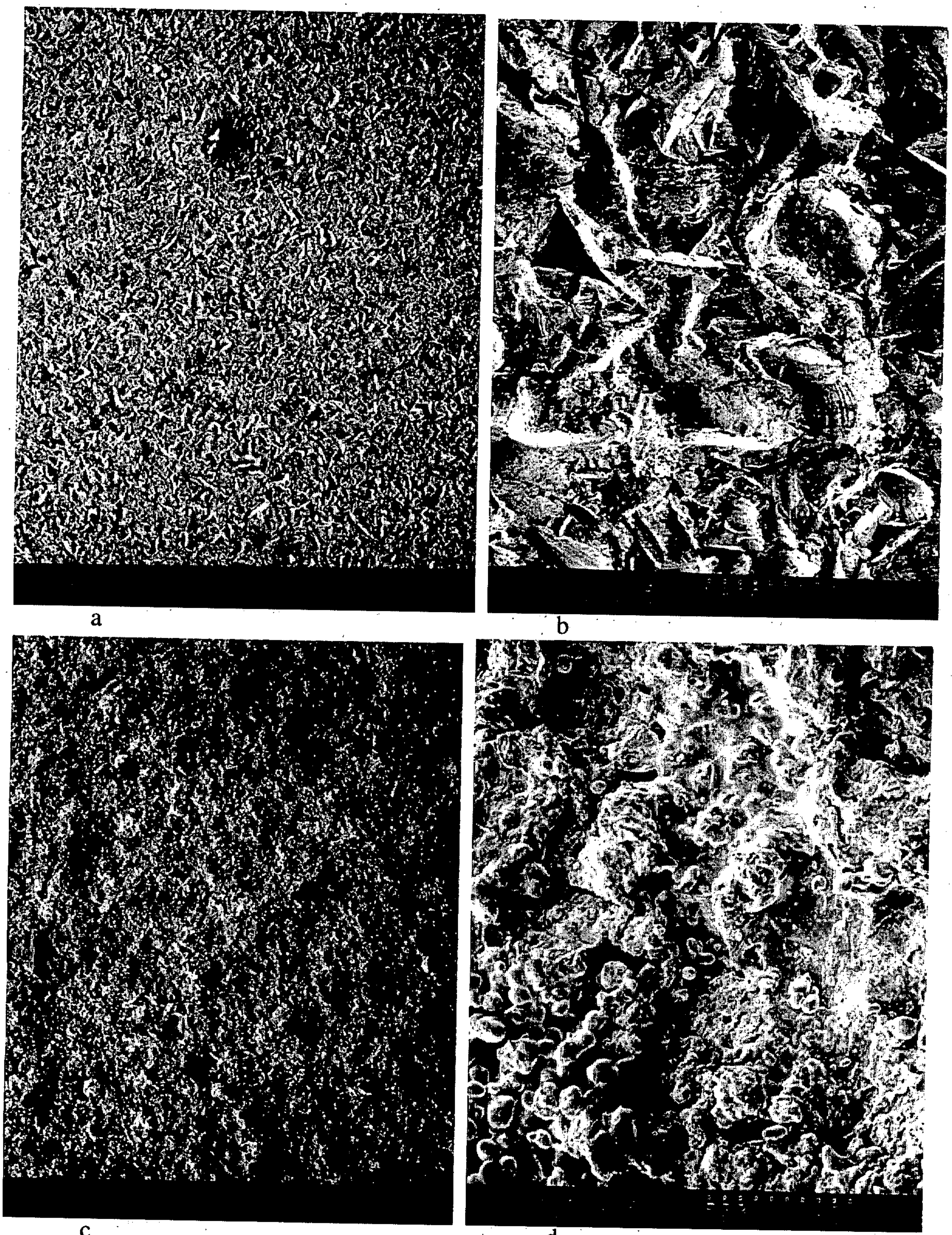

Figure 3 Surface morphologies prior to HVOF deposition. Scanning electron micrographs of surfaces for producing adherent but smooth coatings are in the upper panels. The lower panels are the as-spray HVOF Al coatings.

Porosity

The porosity as a function of spray distance and fuel ratio is shown in Figure 4. The porosity was determined from a metallography cross-section of the coating samples. Micro-photographs are taken at 200x and the line-intercept method use to calculate porosity. Table 3 lists the porosity of the sample as a function of deposition parameters.

The variations from 8% to 13% do not appear to be significant. However, Figure 4 may be indicating that low porosity deposition occurs at the lower and higher fuel ratios, and that porosity is not a strong function of spray distance between 10 to 12 inches.

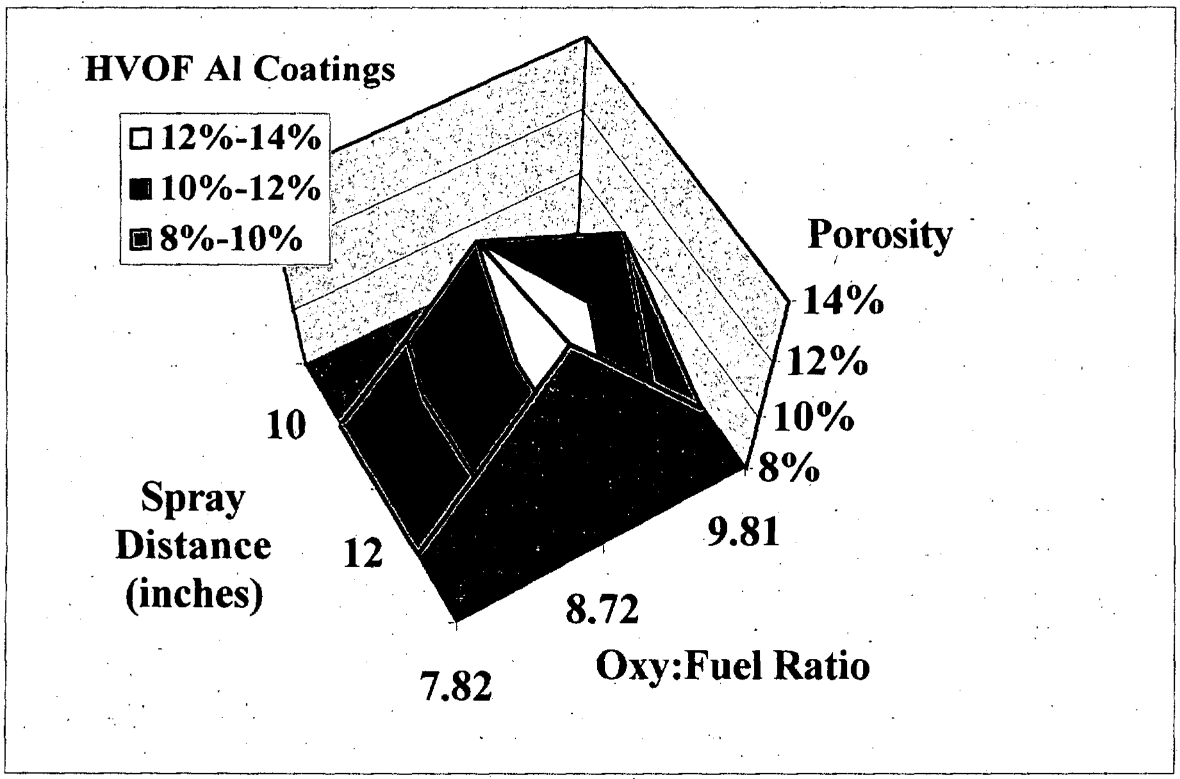

Figure 4 Porosity as a function of deposition parameters.

Surface roughness

The surface roughness as a function of spray distance and fuel ratio is shown in Figure 5. The surface roughnesses are measured on a stylus profilometer (Detak 3ST). Scans of 2 mm lengths are taken and the instrument analyzes for R_a, the arithmetic average of the surface. Three scans are taken per coating sample. The average and standard deviation of the surface roughnesses are listed in Table 3.

The most significant change in surface roughness occurs at the 10" spray distance, going from a fuel ratio of 7.82 to 8.72. The roughnesses at constant fuel ratio but changing spray distances are within a standard deviation of each other. The figure may indicate that the roughness is lower when depositing at low fuel ratios.

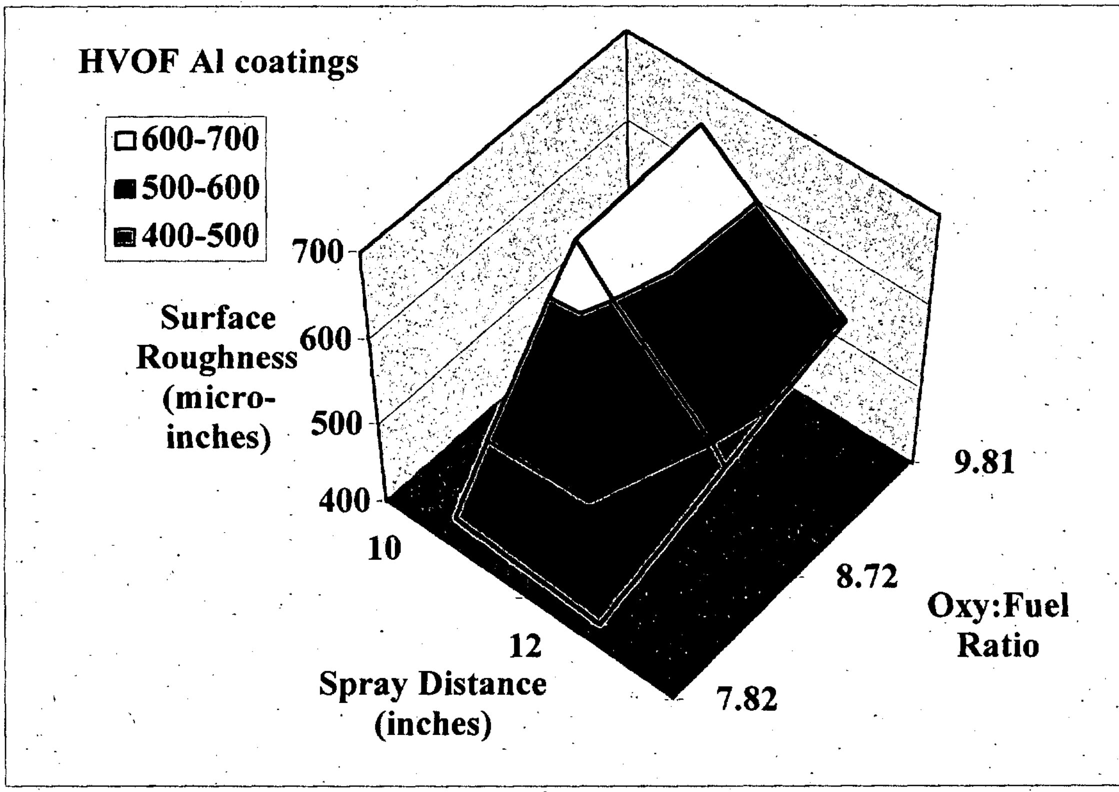

Figure 5 Surface roughness as a function of deposition parameters.

Micro-hardness

The micro-hardness as a function of spray distance and fuel ratio is shown in Figure 6. The micro-hardness measurements are performed with a diamond-pyramidal shaped indenter. Five spots are tested on each sample. The average and standard deviations are listed in Table 3. For reference, the average micro-hardness of the 1020 mild steel substrate is 196±5.6 DPH. The micro-hardness is evaluated in order to minimize post-coat processing to create smoother surfaces. There is no significant variations of micro-hardness given the test conditions. This is in agreement with the small variations of porosity observed.

The as-deposited surface roughness are too rough to satisfy the cleanliness requirements even at around 400 micro-inches. A post-coat treatment of sanding and bead-blasting produce smoother surfaces. Figure 7 are metallographs of as-deposited HVOF Al. Sanded, and bead-blasted HVOF Al surfaces. Bead-blasting appears to have the added benefit of compressing the top surface, so as to reduce porosity and shot-peening the surface for more durability. The bead-blasting was done with 2 mil diameter alumina balls at a carrier gas pressure of about 80 psi.

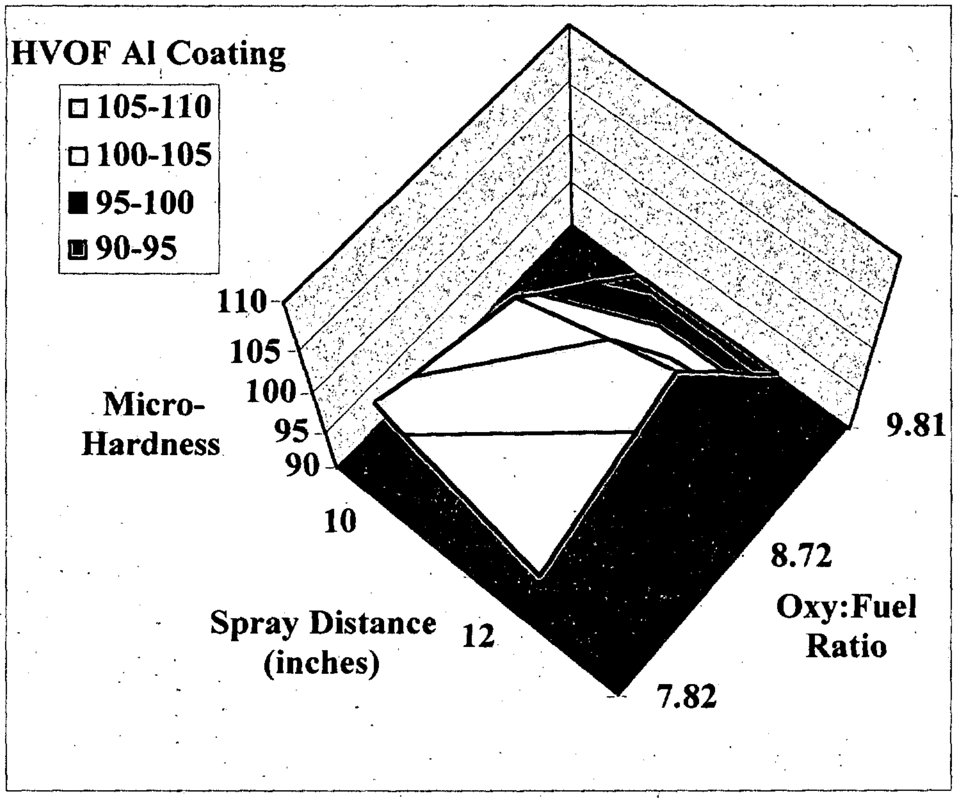

Figure 6 Micro-hardness as a function of deposition parameters.

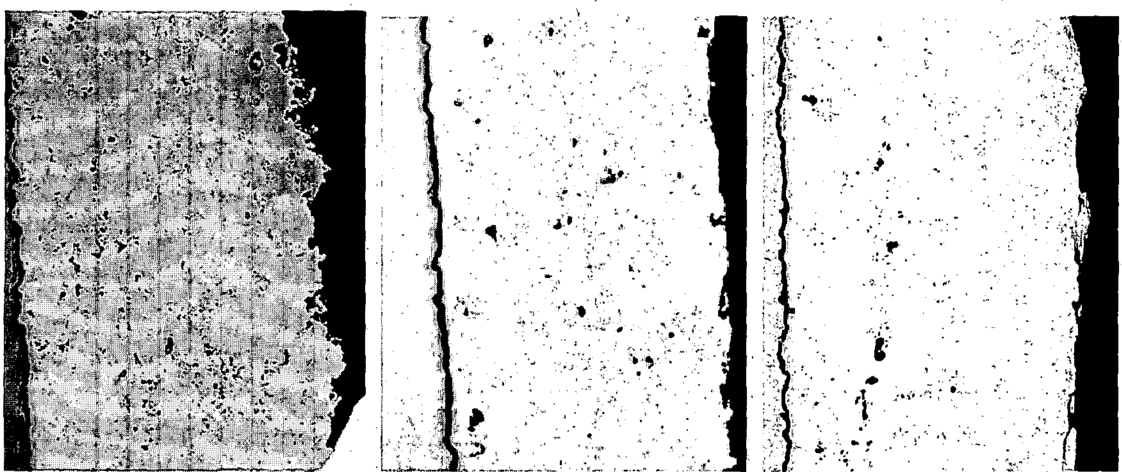

Figure 7 (a) As-coated HVOF Al, (b) Sanded surface, and (c) Bead blasted surface

SUMMARY

Table 3 summarizes the Al coating properties as a function of the HVOF deposition parameters. Hardness and porosity are relatively constant in the parameter space used in these depositions. Spray distance from 10 to 12 inches is well within the robotic control of a torch for linear traverses and corner swings. At a high fuel ratio (low enthalpic content), the surface roughness is affected by the spray distance. The surface roughens as the spray distance decreases. The relative constant surface properties of the HVOF Al coating shows the robustness of the process to deposition parameters.

Table 3 Mechanical properties of the coatings as a function of spray distance and fuel ratio. Averages and standard deviations (STD) of the measurements are given. Surface roughness is R_a.

Spray Distance (inch)	Oxygen:C_3H_6 Flow Ratio	Porosity	Average R_a (µinches)	STD (µinches)	Average Micro-hardness (DPH)	STD (DPH)
10	9.81	9%-11%	648	143	90	15
12	9.81	8%	524	63	90	10
10	8.72	12%	640	19	102	17
12	8.72	13%	484	24	107	11
10	7.82	8%	442	114	106	11
12	7.82	8%	433	69	100	12

Aluminum coatings deposited by a HVOF process have been demonstrated and the coating properties evaluated according to two deposition parameters that are easily controlled in practice. The coating properties are fairly insensitive to spray distance and fuel flow ratios. Increasing the fuel content appears to improve the coating in terms of surface roughness. Even though the as-deposited roughnesses are too rough to satisfy low cleanliness requirements, the coatings are soft enough and have low porosity that simple post-coat treatment(s) may be applied. Examples of sanded and bead-blasted HVOF Al surfaces are shown.

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