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Properties of Aluminum Deposited by a HVOF Process

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Pure aluminum coatings deposited by a high velocity oxyfuel (HVOF) process have been produced and studied. A simple design-of-experiment (DOE) was used to assess the effect of two deposition parameters, the spray distance and oxygen-to-fuel ratio, on relevant coating properties. Porosity, surface roughness, and micro-hardness of the coatings were measured as responses to changes in the DOE parameters. The results indicated that these three properties of the aluminum coatings were normally insensitive to spray distance. Oxygen-to-fuel ratio, by flow, did appear to affect the porosity level of the coatings. Some post-coat processing of the aluminum coatings and minimization of nozzle loading are discussed.

Keywords aluminum, hardness, HVOF, porosity, roughness

1. Introduction

Flame-sprayed aluminum coatings on steel are known to serve as anodic sacrificial layers or passive corrosion barriers.[1] A unique application of aluminum coatings is as a surface treatment on structures situated in close proximity to the optics in laser system assemblies. High-energy laser systems must have surfaces that do not shed small particles nor outgas organic hydrocarbons. The laser optics are susceptible to laser-induced damage when contaminated by particulates or organic molecules. Therefore the surfaces in proximity to the optics should not be sources of particulates or organic contamination. In this application, the aluminum coatings do not function as reflective surfaces but as the surfaces of the walls and fixtures around which the laser optics are deployed. Other applications where this type of clean surface may be useful is in the fabrication of semiconductor or medical equipment.

The aluminum surfaces are exposed to stray light from the main high-energy laser beam and intense flash-lamp irradiation. The flash-lamp irradiation is produced by lamps that are used to pump the laser amplifier crystals. The stray laser light comes from portions of the main beam, which are scattered or reflected back from the glass optics. The stray light still has a sufficient power density to degrade metal surfaces because the forward-propagating beam has such high power densities. Other aluminum surfaces, namely aluminum foil and conventional flame-sprayed aluminum coatings, have been found to survive the fluences from the flash lamps and stray light.[2,3] Therefore it is expected that the aluminum deposited by high velocity oxyfuel (HVOF) will retain this laser-resistant quality.

Of equal importance to surviving repeated laser exposures is the requirement that the precision-cleaned aluminum surfaces do not contaminate the optical components with organic molecules and particulates. This paper describes an effort to obtain certain physical coating properties, namely low porosity and low surface roughness that would aid in achieving very clean surfaces. A smooth surface does not trap particulates, is amenable to precision cleaning techniques using high pressure liquid sprays, and can be directly validated for surface cleanliness levels with a swipe method.[4]

Aluminum coatings deposited by thermal spray[5,6,7,8] and a HVOF[7,8] process has been demonstrated. A Jet-Kote II NOVA-A system produced by Stellite Coatings (Goshen, IN) was used to deposit the aluminum coatings is shown in Fig. 1. The system consisted of a model JK3000 torch, the Jet-Kote II NOVA-A control console, water-to-water heat exchanger, and a powder feeder. Figure 2 shows a cut-away view of the torch. Oxygen and fuel are fed through the inlet ports and into a chamber where they are mixed and combustion occurs. The combustion generates the hot, high-velocity gas, which flows into four combustion ports. The volume of the ports is larger than that of the chamber. The volume expansion further increases the gas velocity and creates a stable flame into which the powder is introduced. The powder feeder introduces the aluminum from a fluidized mixture into the center of the flame, where the thermal energy is highest. The combustion gases and the powder pass into the nozzle bore where gas velocity increase further. The straight nozzle bore helps collimate the flame and is the section of the gun where the powder increases in temperature and velocity.

The exhaust of the combustion process generates visible shock diamonds after upon exit from the nozzle. The geometry of the exhaust plume is formed by the sudden reduction in the pressure. The pressure reduction adds to the gas and powder velocity. The powder is sprayed against a workpiece. A thick coating builds up in layers as the torch is rapidly moved across the work surface. The powder has either become molten or softened during its transport through the torch to the workpiece. The particle momentum from the deposition of overlayers compresses the particles into a well-bonded coating.

From previous coating trials and evaluations, two deposition parameters were selected as variables to minimize the aluminum

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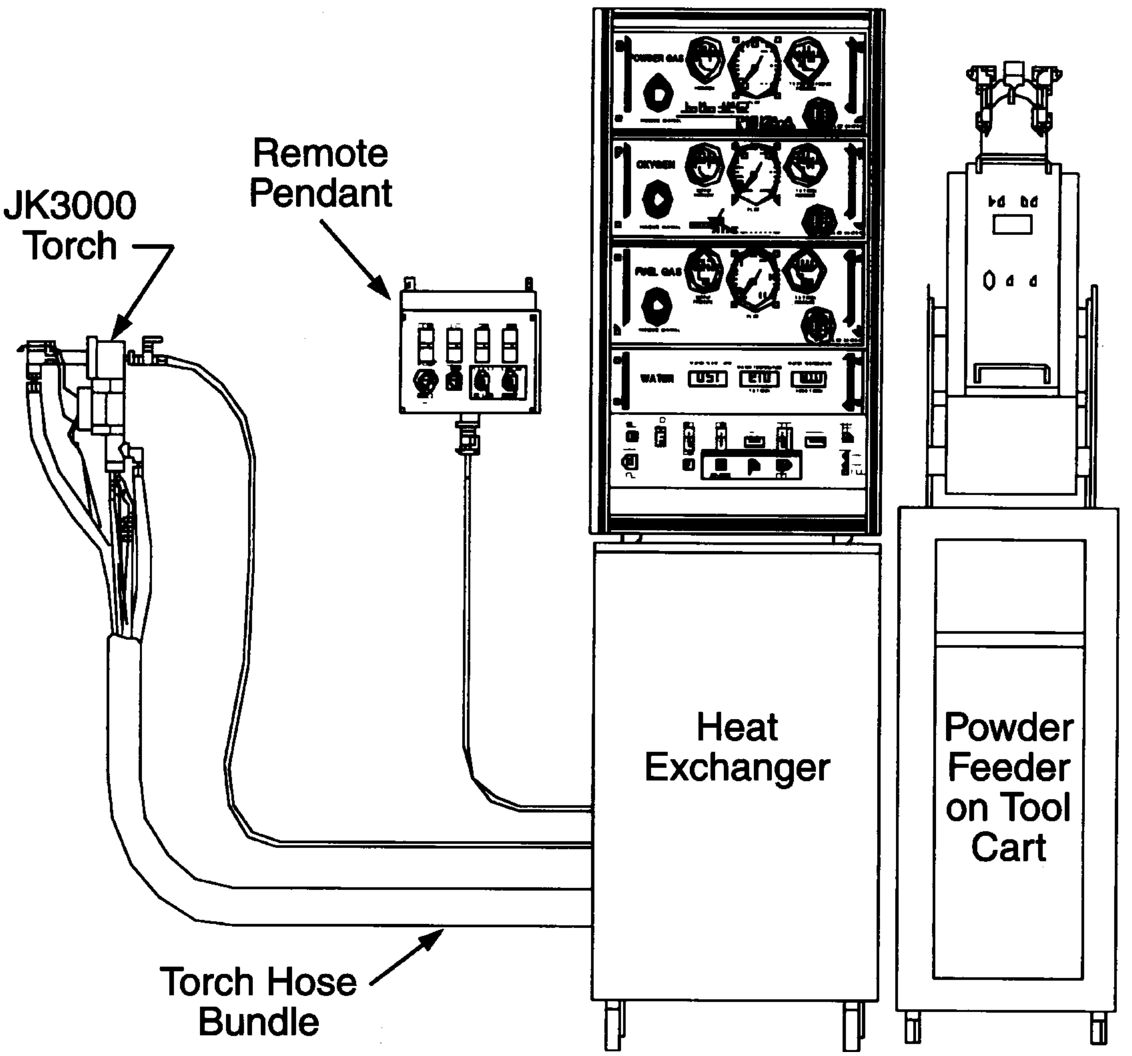

Fig. 1 JET KOTE II NOVA-A Surfacing System

coating porosity and surface roughness: the spray distance and oxygen-to-fuel flow ratio.[8] These two deposition parameters are easily controlled in practice. In addition, the equipment selected for the experimental set up was one that could be scaled up quickly for production in the field.

2. Experimental Set Up

2.1 Design of Experiment

The constants used in the development of the coating are listed in Table 1. 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 energy the powder has at impact. The shorter the spray distance, the higher the particle velocity and particle impact force on the surface. The velocity term is squared in the energy equation (work = mv^2) and so has an effect on the kinetic energy. The other effect of spray distance 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 thermal energy it has to transfer to the workpiece. The spray distance in this study was either 203.2 or 304.8 mm. The crossover, or torch transverse, per pass is the distance the torch moves primarily in an incremental direction across a flat surface. The spray pattern of the deposit is close to 12 mm in

Table 1 Experimental Constants

Parameter	Unit	Value
Powder feed rate	gm/min	24-28
Nozzle length	mm	76.2
Nozzle bore	mm	7.94
Torch angle	Degrees	90
Carrier gas	…	N_2
Carrier gas flow rate	Liters/s	0.61
Fuel gas	…	C_3H_6
Oxygen gas flow rate	Liters/s	8.0
Water temperature difference	K	20
Water flow rate	Liters/s	0.536
Cross-over per pass	mm	2.54
Transverse torch speed	m/s	0.762
Coating thickness	mm	0.38

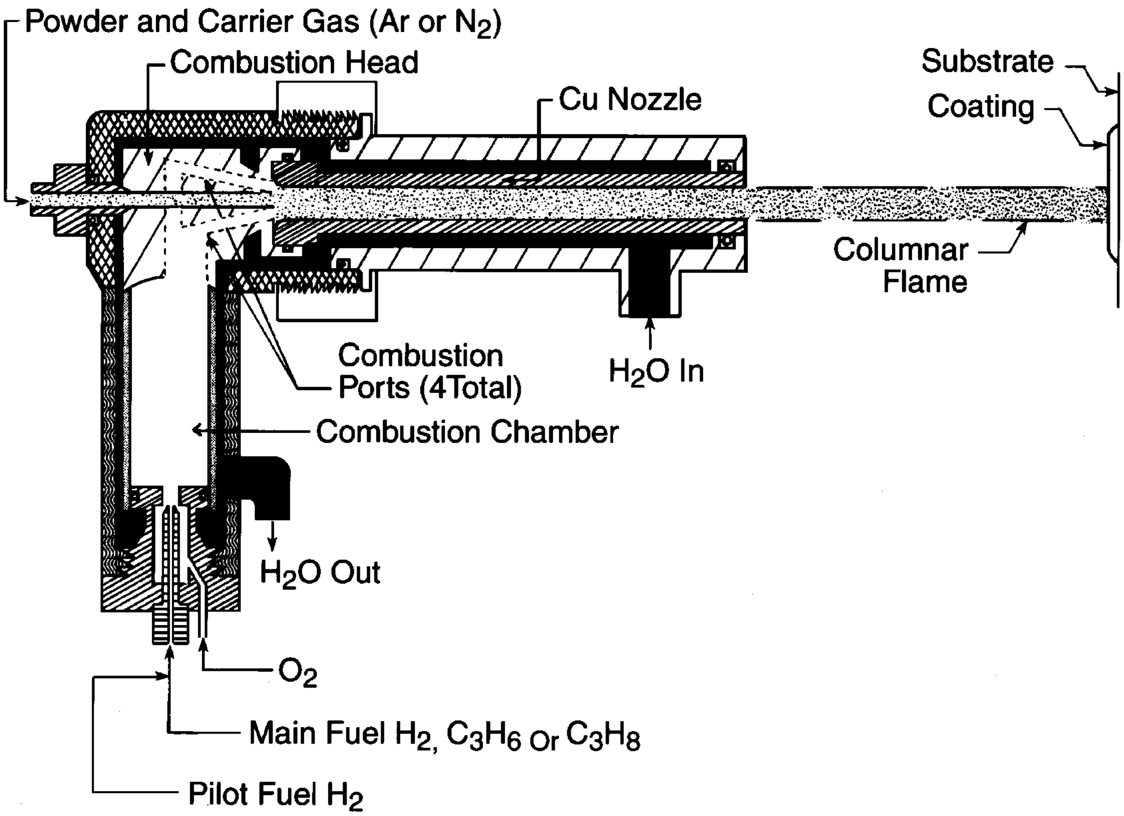

Fig. 2 HVOF torch

Table 2 Aluminum Powder Distributions

Powder Designation	Distribution Re-sizing	Sieve Analysis, wt.% by ASTM B-214					
		+100	+140	+170	+200	+325	−325
H30	None	…	…	…	Trace	Bal.	93.8
H60	None	…	0.3	1.8	17.3	Bal.	20.7
WMS103	None	…	Trace	11.7	31.5	Bal.	4
WMS103	Narrowed size dist: −170 to +325	…	…	0.2	13.8	Bal.	5
WMS103	Narrowed size dist: −170 to +325	…	…	Trace	14	Bal.	5
WMS103	Narrowed size dist: −200 to +325	…	…	…	4	Bal.	3

diameter. On the next horizontal pass, the torch is offset in the vertical direction by 2.42 mm, the crossover per pass.

It is known the amount of thermal energy (enthalpy heat content) transferred from the flame to the powder varies depending on the fuel flow rate and oxygen flows. In this study, the oxygen flow rate was more than sufficient (1.7-2.2× higher) for complete combustion of the fuel and was constant at 8.0 l/s. As a point of reference, the oxygen to propylene flow ratio for stoichiometry is 4.5. As the fuel-to-oxygen ratio is increased, by increasing the fuel flow rate; more thermal energy is transferred to the powder. Thus the temperature and velocity of the particles increases with the fuel-to-oxygen ratio. Preliminary work was also performed to evaluate the use of hydrogen. However, due to the very high heat transfer rate obtained using this fuel, the aluminum powder melted prior to injection into the flame, blocking the powder port into the nozzle. Because blockage of the carbide insert (powder port) was significantly reduced using propylene (C_3H_6) fuel, it was selected as the fuel for the rest of the study.

2.2 Experimental Analysis

The coatings were analyzed for porosity, hardness, and roughness. The porosity was determined from the metallurgical cross-section of the samples. Photomicrographs were taken at 200× and the line-intercept method was used to calculate porosity. The micro-hardness measurements were performed with a diamond-pyramidal shaped indenter with a 300 g load. Five spots were tested on the same metallurgical samples used for the porosity determination. As reference, the average microhardness of the AISI 1020 mild steel substrate was 196 ± 5.6 DPH when using the same indenter tool. The surface roughness was measured on a stylus profilometer (Digital Instruments, Veeco Metrology Division, Santa Barbara, CA, Model: Detak

3ST). Scans of 2 mm lengths were taken and the instrument analyzed for R_a, the arithmetic average of the surface. Three scans were taken per sample.

3. Results and Discussion

3.1 Powder Distribution

Since one of the coating criteria for the laser application is a smooth surface, a fine particle cut was selected to obtain desirable coating characteristics. Large particles were thought to be undesirable as they typically create a rough surface and are more likely to produce porous coatings. Table 2 lists the powders used in the current study and the respective powder size distributions. Nozzle loading occurred within minutes with the original selection of powder designation H30. A coarser powder distribution, H60, was used next with better sprayability. A third powder, WMS103, with even more large particles was tested but resulted in decreased sprayability. At this point, the WMS103 type powders were narrowed in size distribution with a Stellite proprietary separation and blending method until a powder was produced that could be sprayed for a long period of time.

Powder size distribution was found to be a critical element regarding sprayability in early experimental trials. Nozzle loading was expected due to the low melting temperature of aluminum compared with the high melting point of materials normally deposited by the Jet Kote (JK) HVOF process. However, the particle build-up occurred at the nozzle entrance where temperatures were cooler, not at the nozzle exit, more typical of sprayability problems with HVOF processes. To improve particle throughput, the shortest nozzle was used that was available for the HVOF system used in this study. The powder was sieved to narrow the size distribution. Although there may be other solutions to nozzle loading, the sizing steps here permitted spraying times in excess of 60 min before the nozzle had to be cleaned. The powder size distribution of pure aluminum appears to be critical when it is deposited by the JK HVOF system.

3.2 Surface Preparation

In preparation for producing a smooth coating, two conflicting requirements became apparent for the surface condition. The

Table 3 Mechanical Properties of the Coatings as a Function of Spray Distance and Fuel Flow Ratio. The Standard Deviations of the Measurements Are Listed Along With the Average Values

Spray Distance, mm	Oxygen: C_3H_6 Flow Ratio	Porosity, %	Surface Roughness, μm	Micro-hardness, DPH
254	9.81	9-11	16.4 ± 3.6	90 ± 15
304.8	9.81	8	13.3 ± 1.6	90 ± 10
254	8.72	12	16.2 ± 0.5	102 ± 17
304.8	8.72	13	12.3 ± 0.6	107 ± 11
254	7.82	8	11.2 ± 2.9	106 ± 11
304.8	7.82	8	11.0 ± 1.8	100 ± 12

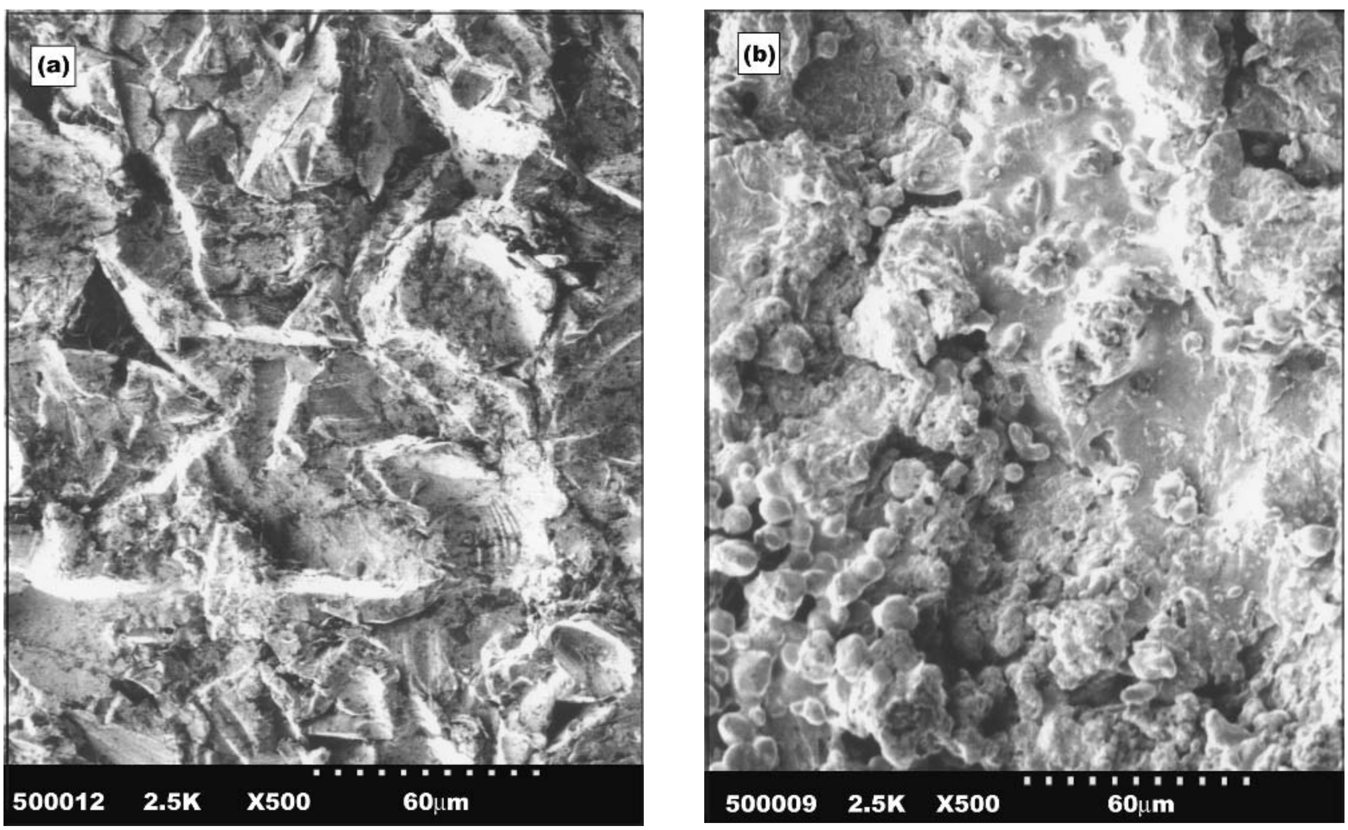

Fig. 3 Surface roughness morphologies of **(a)** uncoated and **(b)** coated HVOF aluminum coatings

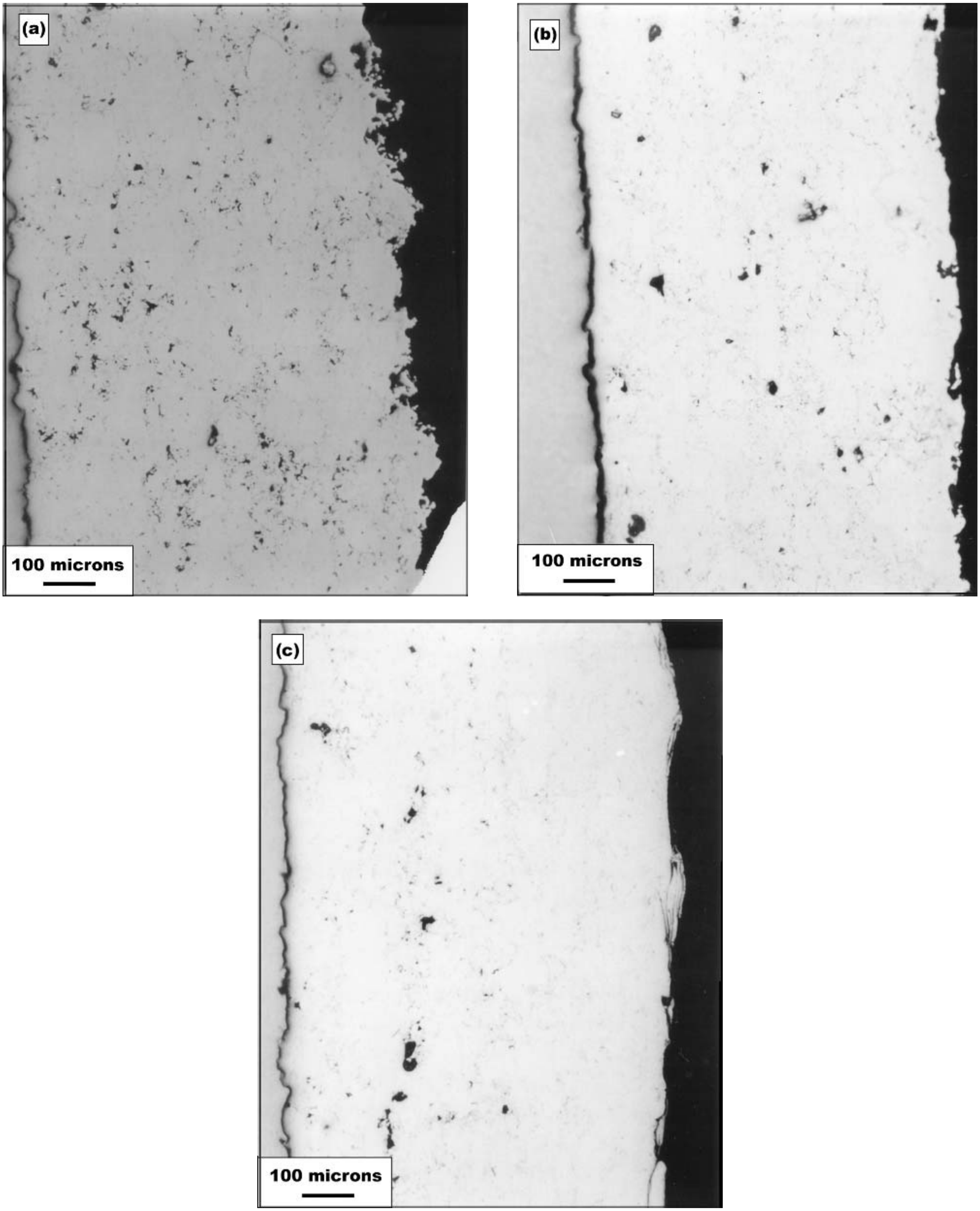

Fig. 4 Cross sections of HVOF deposited aluminum coatings. The surfaces face the right side and are **(a)** as-deposited, **(b)** sanded, and **(c)** bead-blasted.

conventional methodology is to generate an "anchor tooth" pattern on the substrate for increased coating adherence. The other requirement is that the surface preparation minimizes its contribution to the film roughness. The chosen surface preparation procedure consisted of using #60 grit aluminum oxide blasting media at a pressure of 0.28 MPa from a suction blaster. The blaster nozzle was nominally held normal to the surface. Figures 3(a) and (b) are scanning electron micrographs of the as-blasted and coated surface. The HVOF coating appeared to smooth out the sharp angular protrusions of the grit-blasted surface. However, the coating retains the longer spatial features such as 20-60 μm wide valleys. These surfaces will be too rough to achieve the required cleanliness levels.

3.3 Coating Properties

Table 3 summarizes the mechanical properties of the aluminum coatings deposited by the JK HVOF process as a function of the two parameters: spray distance and oxygen-to-fuel flow ratio. Low porosity coatings were obtained at the lowest oxygen-to-fuel flow ratio. Otherwise the spray distance did not measurably affect porosity of the sample at any given oxygen-to-fuel ratio.

There were no statistically significant variations of microhardness within the range of the test conditions. There were also very little differences in the surface roughness with in the range of the test conditions.

Given the test parameters, the porosity, roughness and hardness properties of the aluminum coatings appeared to be relatively insensitive. No optimization for the desired properties was observed. This indicates that the JK HVOF process may not require stringent controls on the spray distance and the oxygen-to-fuel ratio. For example, spray distances from 254-304.8 mm are well within the robotic control of a torch for linear traverses and corner swings

3.4 Post-Coat Treatments

Unfortunately the as-deposited surface roughness was too rough to satisfy the cleanliness requirements. Post-coat treatments such as sanding and bead-blasting were used to produce smoother surfaces. The sanding of the HVOF-deposited aluminum surfaces was performed manually. Sandpaper with 240 grit alumina was rubbed against the surface in a circular fashion for a period of 2 min over an area of 930 cm^2. The bead-blasting step was carried out on another section of the aluminum coating. Bead-blasting was carried out using alumina beads of 51 μm diameter. An induction feeder was used to draw the beads into an airstream and direct the beads towards the surface. A pressure of 0.414 MPa was supplied at the input side of the feeder. Figures 4(a-c) show the metallurgical cross-sections of the as-coated, sanded, and bead-blasted aluminum coatings, respectively. The bead-blasting process appeared to smooth the surface of the aluminum coatings better than the sanding process. Also, the bead-blasting appeared to reduce the porosity of these coatings. The latter is an added benefit because dense coatings minimize the entrapment of organic contaminants.

4. Summary

Aluminum coatings were deposited by the JK HVOF process. The two deposition variables were the spray distance and oxygen-to-fuel flow ratios. The aluminum coating samples were deposited with the variables set at combinations of the minimum and maximum values in a pre-determined range. The coating properties of hardness, roughness and porosity were evaluated at each of these deposition conditions. The coating properties were fairly insensitive to spray distance and the oxygen-to-fuel flow ratio. The process appears to produce coatings with uniform hardness, roughness, and porosity within the given deposition parameters.

Even though the as-deposited surfaces were too rough to high to satisfy the cleanliness requirements, the coatings are soft enough for simple post-coat treatment(s). Bead-blasting the aluminum coatings appears to increase the density and smooth the surfaces better than the sanding treatment.

Acknowledgments

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