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Research On HVOF Thermal Sprays
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Abstract

Independent control of particle velocity and temperature in the HVOF process has been achieved in this research, allowing the variables to change by 170 m/s and 200 °C, respectively. The independence was achieved using a specially designed nozzle with multiple axial injection ports, and with an inert diluent added to the oxygen used for combustion. With these changes, notable changes in splat morphology, porosity, and coating oxidation are readily apparent. Increased particle velocity correlates with improved splat deformation, but appears to have little effect on porosity or oxidation. Particle temperature, however, correlates strongly with splat deformation, porosity, and oxidation. In fact, highly dense coatings that have little oxidation can be formed with relatively low velocity particles that have average temperatures in the vicinity of the melting point of the material. This surprising result suggests particle temperature control is the key to creating dense, low-oxide HVOF-sprayed coatings.

1. Introduction

Above all other variables, particle velocity and temperature play the most significant roles in determining the properties of a thermally sprayed coating. For some time, attempts have been made to determine the separate effects of particle temperature

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and velocity on HVOF-sprayed coating properties. While a number of methods have been demonstrated to provide independence at least over a limited range, a parametric study of the effects of such control has not previously been performed over a wide range of velocities and temperatures.

2. Experimental Equipment and Methods

2.1 HVOF Spray Equipment

The equipment used in these experiments has been described in detail previously in JTST and therefore only the features most pertinent to this research will be discussed here. The spray torch is a modified Praxair-Tafa JP-5000 unit (Praxair-Tafa, Concord, NH) in which the original nozzle has been replaced with a conical converging-diverging nozzle incorporating several axial locations for spray particle injection. A schematic of this nozzle is seen in Figure 1. This nozzle has an 8-mm diameter throat and an 11-mm diameter exit, and it produces approximately Mach 2 flow at the exit. Two of the injection locations are located downstream of the nozzle throat where the flow is supersonic; the furthest downstream and the next port upstream are referred to as locations 0 and 1, respectively. Location 2 is effectively at the nozzle throat, and location 3, though not used in this study, is located well upstream of the nozzle throat in the subsonic region of the nozzle. These ports provide a key means to control particle temperature and will be discussed in detail later.

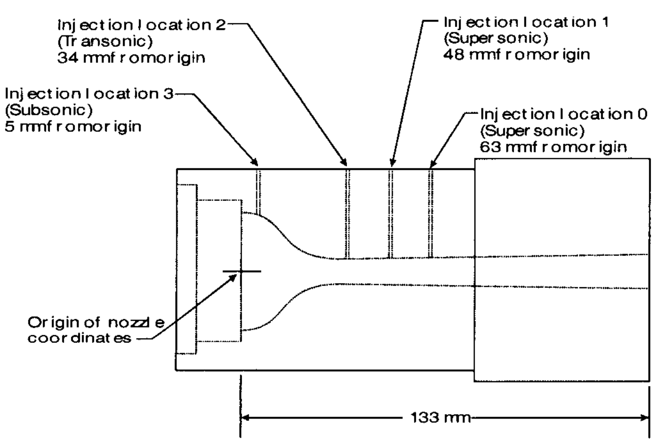

Figure 1. Schematic of the conical converging-diverging nozzle used in this study.

2.2 Fuel and Oxidizer

The JP-5000 torch is designed to operate on kerosene and pure oxygen. Early in this current research, it was recognized that diluted combustion gas mixtures would provide an element of additional control over combustion temperature, and hence, particle temperature. To ensure that the separate effects of particle velocity and temperature would not be obscured by this possible loose variable, stoichiometric fuel-air mixtures were used throughout these experiments.

2.3 Choice of Spray Particles

The powder sprayed in these experiments was gas-atomized 316L stainless steel powder (Tafa 1236F). The particle size distribution analysis showed an average particle diameter of 39 microns and a standard deviation of 9 microns. The powder was chosen because of its common use in applications for corrosion resistance, and for purposes of comparison with previous work.

3. Results

In this study, the independent effects of particle velocity and particle temperature on splat morphology, coating porosity, and coating oxidation were assessed. Prior to beginning these experiments, it was expected that high-velocity, low-temperature particles would produce coatings with both low oxidation and low porosity. This behavior was expected from previous measurements in which the separation of velocity and temperature was restricted to a small range. Furthermore, the advantages of the cold-spray process are largely based on this assumption.

A range of particle velocities and temperatures clearly exists within which process efficiency and coating characteristics may be optimized for a given material. It appears that a certain amount of particle oxidation is unavoidable in the spray process, and that it is relatively unaffected by particle temperature until some particles become molten upon impact. It is interesting to note that this baseline level of oxygen found in the coatings, approximately 0.25% by mass, was also unaffected by the widely varying combustion gas mixtures which were as much as 30% nitrogen by mass. Previous experiments by Hackett (1) that used a nitrogen gas shroud showed that oxidation can be kept constant across a wide range of spraying conditions, whereas unshrouded molten particles become highly oxidized. This suggests that the oxygen contained in coatings formed of unmelted particles is an artifact of the time the particles were within the torch.

The measurements of coating porosity showed that even high velocity particles have insufficient kinetic energy to become deformed to an extent where porosity is below 0.2% if those particles are much below the melting temperature. Since increased temperature softens the particles, however, relatively low velocity particles can make highly dense coatings when the particle temperature is sufficiently high. Since particle deformation and coating density increase with temperature, particularly when the average temperature nears the material melting point, it appears that the ideal spray particle temperatures are in the vicinity of the liquidus of the material. This result was previously found by Voggenreiter, et al., though the methods used in those experiments were different from those presented in this study. By contrast, particle velocity appears to play a less significant role in HVOF sprayed coatings than had previously been thought. While particles deform more as their kinetic energy prior to impact increases, low temperature particles still do not deform sufficiently to produce coatings with porosity below 0.1%. Still, all the evidence seen in these experiments indicates that higher particle velocity, when particle temperature can be independently controlled, is desirable.

When oxidation comes into consideration, it is clear that particle temperature should not far exceed the melting temperature. The advantages of having relatively cool particles, with respect to oxidation, however, are few since the oxidation diminishes slowly with temperature when particle temperature is below the melting point. For corrosion-resistant coatings, there is evidence that some oxidation in the coating improves the resistance. From this, then, one can conclude that ideal spray particles for creating dense, low-oxide coatings have high velocities and temperatures near or slightly above the melting point of the material.

4. Resulting Publications

Interested parties should refer to the latest publication in the Journal of Thermal Spray Technology which will be published in the upcoming months.

Hackett, C. M., Settles, G. S., and Miller, J. D., "On the Gas Dynamics of HVOF Thermal Sprays," Proceedings of the National Thermal Spray Conference, Anaheim, CA, June 7-11, 1993.

Hackett, C. M. and Settles, G. S., "Turbulent Mixing of the HVOF Thermal Spray and Coating Oxidation," Proceedings of the National Thermal Spray Conference, Boston, June 20-24, 1994.

Hackett, C. M., Settles, G. S., and Miller, J. D., "On the Gas Dynamics of HVOF Thermal Sprays," *Journal of Thermal Spray Technology*, Vol. 3, No. 3, September 1994, pp. 299-304.

Hackett, C. M. and Settles, G. S., "Research on HVOF Gas Shrouding for Coating Oxidation Control," Proceedings of the 8th National Thermal Spray Conference, ASM International, Houston, September 11-15, 1995, pp. 21-29.

Hackett, C. M. and Settles, G. S., "The Influence of Nozzle Design on HVOF Spray Particle Velocity and Temperature," Proceedings of the 8th National Thermal Spray Conference, ASM International, Houston, September 11-15, 1995, pp. 135-140.

Hackett, C. M. and Settles, G. S., "The HVOF Thermal Spray: Materials Processing from a Gas Dynamics Perspective," AIAA Paper 95-2207, AIAA 26th Fluid Dynamics Conference, San Diego, June 1995.

Hackett, Charles M. *The Gas Dynamics of High-Velocity Oxy-Fuel Thermal Sprays.* Ph.D. Thesis, Penn State University, 1996.

Hackett, C. M. and Settles, G. S., "Independent Control of HVOF Particle Velocity and Temperature," Proceedings of the 9th National Thermal Spray Conference, ed. C. Berndt, ASM International, Materials Park, OH, Oct. 1996, pp. 665-673.

Bekofske, Sarah R. "Control of HVOF Thermal Spray Particle Temperature and Velocity" M.S. Thesis. The Pennsylvania State University, 1997

Settles, G. S., "HVOF Thermal Spray Velocity, Temperature, and Stainless Steel Coating Properties," presented at the 16th Symposium on Energy Engineering Sciences, Argonne National Labs, IL, May 13-15, 1998.

Hanson, Thomas C. "Independent Control Of Particle Velocity and Temperature In the High Velocity Oxy-Fuel Spray Process" M.S. Thesis, Penn State University, 2001.

Hanson, T. C., Hackett, C. M., and Settles, G. S., "Independent Control of HVOF Thermal Spray Temperature and Velocity," *Journal of Thermal Spray Technology*, Vol. 11, No. 1, March 2002, pp. 75-85.

Hanson, T. C. and Settles, G. S., "Particle Temperature and Velocity Effects on the Porosity and Oxidation of an HVOF Corrosion-Control Coating," accepted by *Journal of Thermal Spray Technology,* July 2002.