Thermal Spray: Practical Solutions for Engineering Problems, C. C. Berndt (Ed.), Published by ASM International, Materials Park, Ohio-USA, 1996

Voltage and Current Fluctuations in Wire Arc Spraying as Indications for Coating Properties

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Abstract

Electric arc spraying with dual wires is an economical coating process finding diverse applications. Turbulence and velocity of an atomizing gas exert strong effects on the droplet formation and therefore on the coating properties. Turbulence intensity of an atomizing gas flow can be estimated by analysis of the waveforms of arc voltage fluctuations, and the velocity can be estimated by the frequency and the amplitude of these waveforms. Higher gas velocities result in higher frequencies and smaller amplitudes of the voltage fluctuations, and in smaller molten droplets leading to coatings with lower porosity but higher oxidation levels. Lower turbulence levels at the electrode tips result in more periodic waveforms with less high frequency content, and in lower oxidation of the coatings. Nozzle configurations such as a converging-diverging nozzle provide higher gas velocities with less turbulence leading to coatings with lower oxidation and lower porosity.

ELECTRIC ARC SPRAYING with dual wires is an economical coating process finding diverse applications [1]. Arc spraying has been used widely to coat engineering structures to protect them against corrosion and wear. The material to be deposited is introduced into the arc in the form of two wires serving as consumable arc electrodes. A cold gas jet across the arc atomizes and drives the molten droplets from the electrode tips.

Arc fluctuations due to periodic narrowing and widening of the gap between the electrode tips have strong effects on the droplet formation, therefore on the coating properties such as porosity, microstructure and oxide content. We have investigated the existence of correlations between the electrical fluctuations, the droplet formation, and the coating properties. The purpose of this study is to correlate the process parameters and the coating properties with the measurements of the voltage and current fluctuations. Finding correlations between the coating properties and the voltage and current waveforms will raise the possibility of using the measurementsas a feedback diagnostics for coating quality control.

Experimental Procedures

Operating Conditions. The Miller arc spray system used consists of a power supply (Miller Thermal, Inc., Maxtron 450), a control unit (PF400R), and an arc spray gun (BP400). Aluminum has been sprayed with air used as the atomizing gas. Deposits have been obtained with atomizing gas pressures from 276 kPa to 414 kPa, with arc currents from 100 A to 200 A, and with the arc voltage set at 34 V. Before spraying, steel substrates are treated by grit blasting, acetone degreasing and ultrasonic cleaning. The stand-off distance between the gun and the substrate is 150 mm.

Three different nozzle configurations have been used for the atomizing gas as shown in Fig. 1: (1) a standard nozzle configuration, (2) a standard nozzle with a high velocity (HV) cap, and (3) a converging-diverging (c-d) nozzle. The conventional straight bore nozzle produces strong shocks at the exit of the nozzle resulting in a non-uniform, highly decelerated jet in the arc zone, while the c-d nozzle and the HV cap have been designed for providing higher gas velocities in the atomizing region. The c-d nozzle produces a properly expanded supersonic flow, therefore more consistently atomized particles can be obtained. The nozzle throat-to-exit area ratio is matched for a Mach number of 1.4. The HV cap provides a flow constriction around the wire tips which serves as a secondary nozzle and accelerates the atomizing gas flow at the electrode tips.

Process Diagnostics. The experimental set-up is shown in Fig. 2. Images of the luminous arc, the melting behavior of the wire electrodes and the droplet formation have been recorded with a laser strobe high speed video system with 100 ns shutter speed. The corresponding arc voltage and current between the consumable electrodes have been simultaneously recorded with an oscilloscope. These fluctuations have been analyzed using Fast Fourier

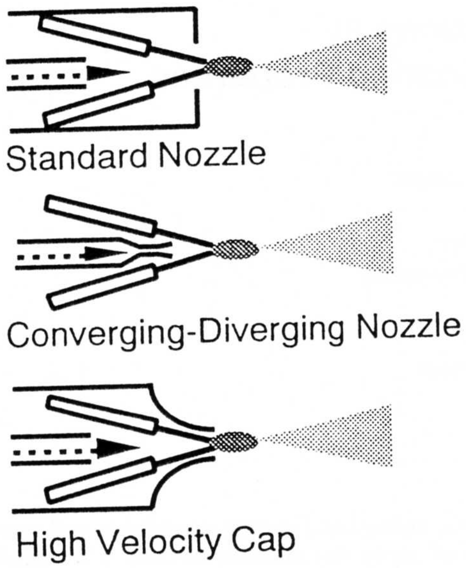


Fig. 1 - Schematic of atomizing gas nozzles

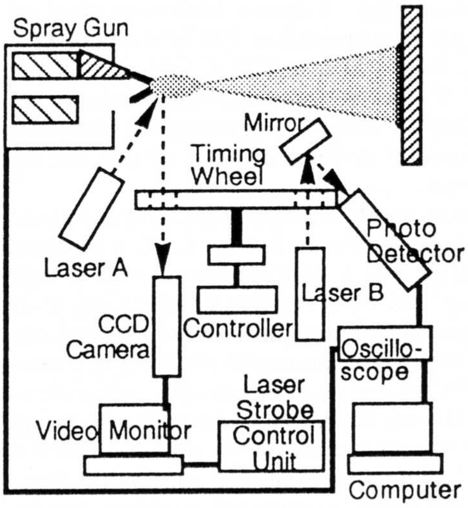


Fig. 2 - Experimental setup

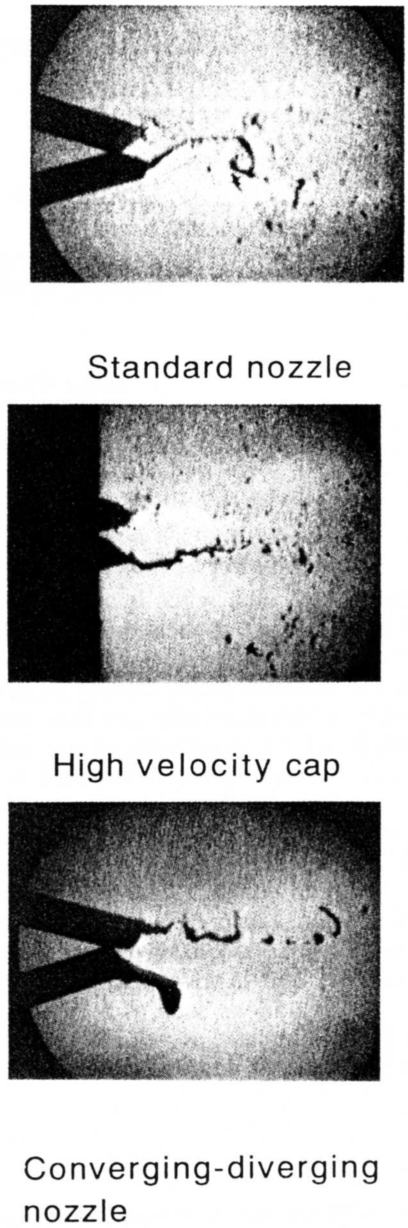


Fig. 3 - High speed images of droplet formation: (a) standard nozzle, (b) high velocity cap, (c) converging-diverging nozzle.

Transform for frequency content and amplitude analysis.

Sample Analysis. Porosity and microstructure of the resulting coating have been determined using scanning electron microscopy combined with image analysis, while oxide content of the coatings has been measured with wavelength dispersive spectroscopy.

Results and Discussion

Waveforms of arc fluctuations. Arc images of wire tips during spraying are shown in Fig. 3. The wire tips and the produced molten droplets were illuminated by a laser, and recorded with a CCD camera with an electronic shutter (ControlVision) with 100 ns shutter speed. Asymmetric melting behavior of the cathode (top wire) and the anode (bottom wire) is observed in the photographs. The cathode wire melting is more localized and the smaller molten droplets are immediately blown away by an atomizing gas. In contrast, the anode wire tip melts more slowly and unevenly, resulting in elongated larger droplets. The asymmetric melting is due to the more constricted arc attachment at the cathode tip compared to the more diffuse arc attachment at the anode tip. This uneven melting leads to an asymmetry of the arc and affects the spray pattern and the coating properties.

Observations of a large number of such images indicate that there are distinct differences of the droplet formation among the different nozzle configurations. The nozzle with the HV cap produces widely scattered small droplets indicating strongly turbulent flow. The c-d nozzle produces consistently larger droplets from the anode tips which are subsequently atomized. The smaller droplet sizes in the region of highest gas temperatures may be a reason for higher degrees of oxide formation. No distinct predominant pattern of droplet formation has been found with the conventional nozzle.

The difference in atomizing gas velocity at the electrode tips among the different nozzle configurations are shown in Fig. 4. The velocities have been measured with a Pitot tube, and these measurements have been carried out without the arc. The c-d nozzle produces the highest velocity, because the c-d nozzle prevents choked flow formation and creates a fully expanded atomizing gas flow. The HV cap was also designed for producing a high velocity atomizing gas, however, the velocity with the HV cap as measured with the Pitot tube is lower than that with the standard nozzle. The low velocity values are attributed to strong turbulence caused by the forced convergence by the HV cap.

The influence of the atomizing gas flow on the droplet formation can be seen in the arc voltage and current fluctuations. The voltage and current fluctuations with the standard nozzle, the c-d nozzle, and the HV cap recorded with an oscilloscope are presented in Figs. 5 to 7, respectively. The voltage waveforms with the c-d nozzle indicate a clear periodicity at a dominant frequency, while the voltage fluctuations with the standard nozzle and with the HV cap occur over a broader frequency range. The periodic waveforms with the c-d nozzle are attributed to the most uniform flow field and to less turbulence as indicated in Fig. 3. The more varying waveforms with the HV cap indicate that the HV cap creates strong turbulence which is also shown in Fig. 3. It appears that the waveforms of the arc voltage fluctuations can serve as an indication of turbulence at the electrodes.

Frequency and amplitude of arc fluctuations. The frequency and the amplitude as well as the waveform of the arc fluctuations are regarded as important parameters for the indication of the droplet formation. Accordingly, the voltage and current fluctuations have been analyzed by Fast Fourier Transform, and by amplitude analysis. Standard deviations of the voltage and current fluctuations are adopted as the indication for the amplitude of the fluctuations. The example results of power spectrum by Fast Fourier Transform for the c-d nozzle are shown in Fig. 8. The

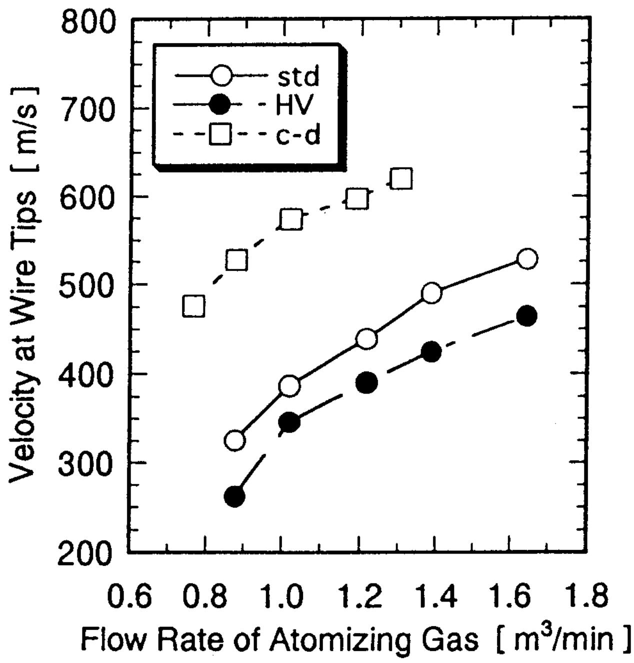


Fig. 4 - Atomizing gas velocity at the electrode tips with different nozzle configurations.

voltage fluctuations have the peak frequency at 890 Hz, and the current fluctuations at 1870 Hz. The characteristic frequency of the voltage fluctuation corresponds to a periodic shortening of the arcing gap. On the other hand, the current fluctuations are little related to the arc characteristics, because the arc current is being controlled by a system control unit through the arc voltage.

Effects of the operational parameters such as the flow rate of an atomizing gas with three different nozzle configurations on the peak frequency and on the amplitude of the voltage fluctuations are shown in Figs. 9 and 10, respectively. Increasing the flow rate of an atomizing gas leads to increasing frequency and to decreasing amplitude of the voltage fluctuations. The c-d nozzle produces higher frequency fluctuations with a smaller amplitude, because the c-d nozzle producing high velocities and less turbulence results in relatively stable arcs with the only variation due to the periodic gap lengthening. The nozzle with the HV cap produces lower frequency and larger amplitude fluctuations, because the HV cap producing lower velocity and stronger turbulent flow resulting in a more unsteady arcing behavior. These results suggest that higher velocities of the atomizing gas can be correlated with higher frequencies and smaller amplitudes of the voltage fluctuations.

The photographs of the solidified droplets with different flow rates of an atomizing gas are shown in Fig. 11. These particles have been produced with the standard nozzle by spraying into a sheet of ice. Smaller droplets are produced at higher flow rate of the atomizing gas, because increasing the atomizing gas flow rate breaks the molten droplets more finely during the flight.

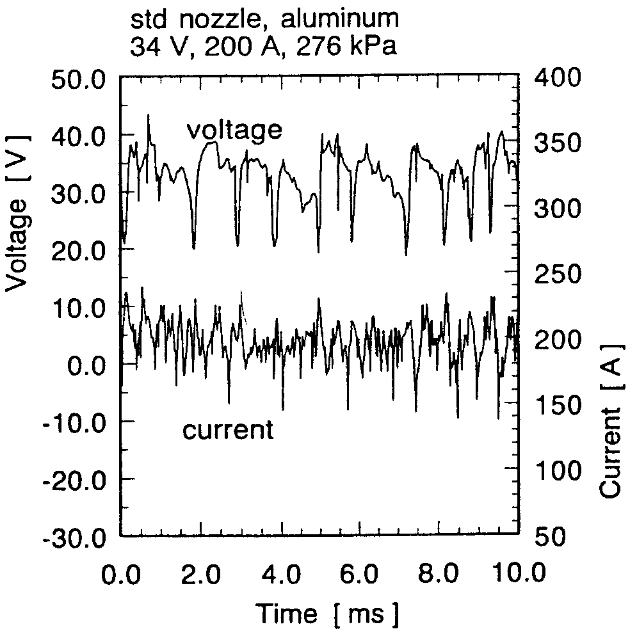


Fig. 5 - Voltage and current fluctuations with a standard nozzle.

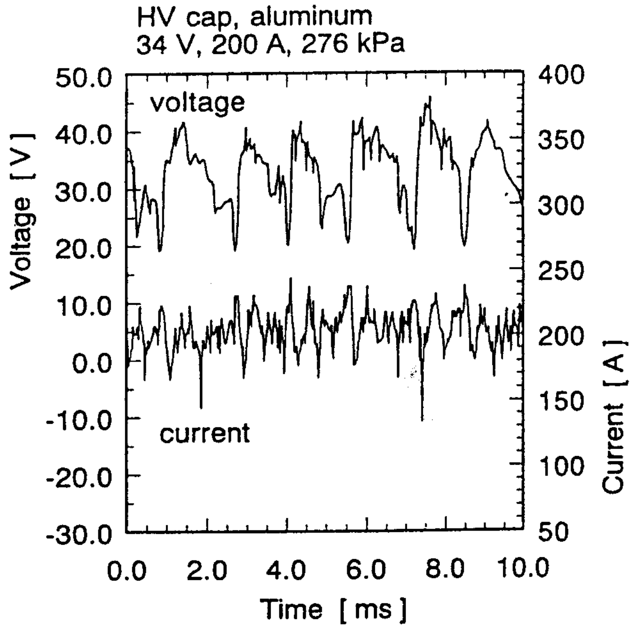


Fig. 7 - Voltage and current fluctuations with a high velocity cap.

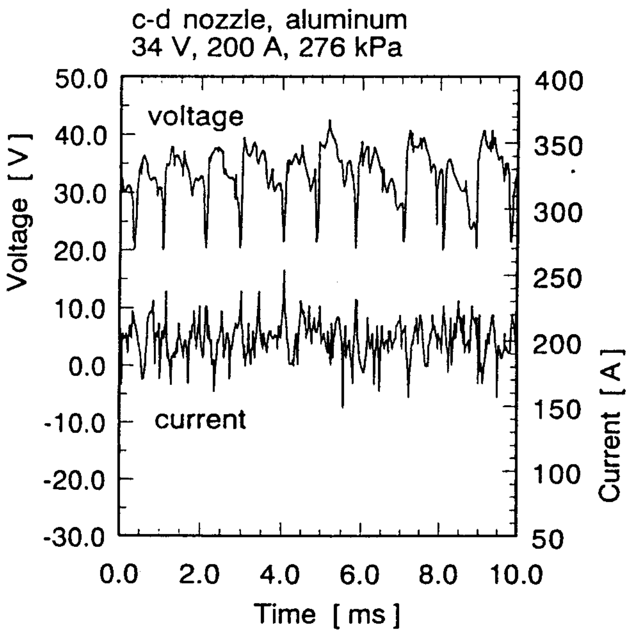


Fig. 6 - Voltage and current fluctuations with a converging - diverging nozzle.

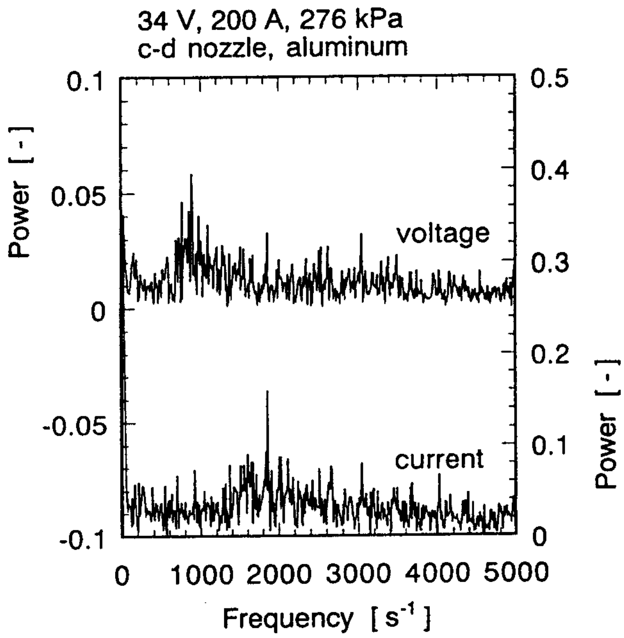


Fig. 8 - Power spectrum of voltage and current fluctuations with a converging - diverging nozzle.

Effects of arc fluctuations on coating properties. Effects of the flow rate of an atomizing gas with three different nozzle configurations on the oxide content of the coatings are shown in Fig. 12. In three configurations, higher gas flow rate leads to coatings with higher oxide content, because smaller droplets produced at higher gas flow rates cause stronger in-flight oxidation. The nozzle with the HV cap produces the coatings with the highest oxide content, because strong turbulence at the electrode tips with the HV cap enhances the oxidation in the electrode region.

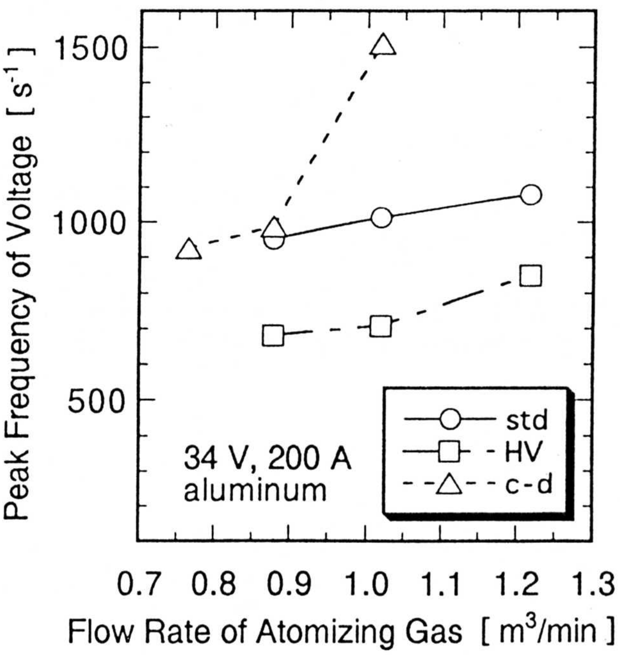


Fig. 9 - Effect of flow rate of atomizing gas on peak frequency of voltage fluctuations with different nozzle configurations.

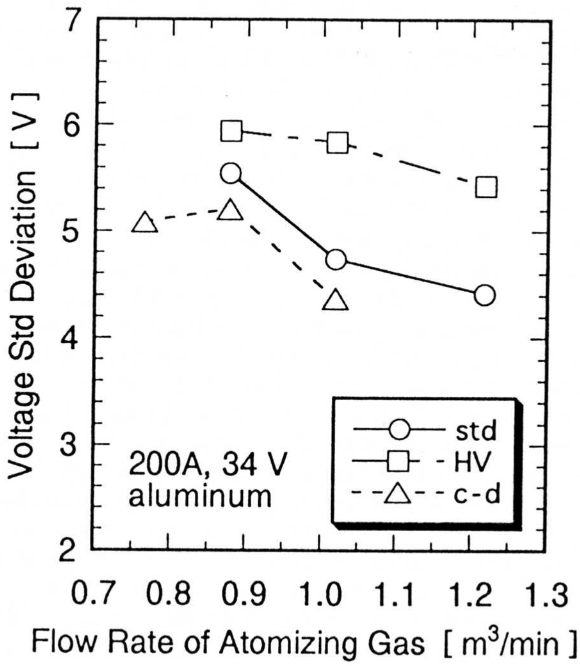
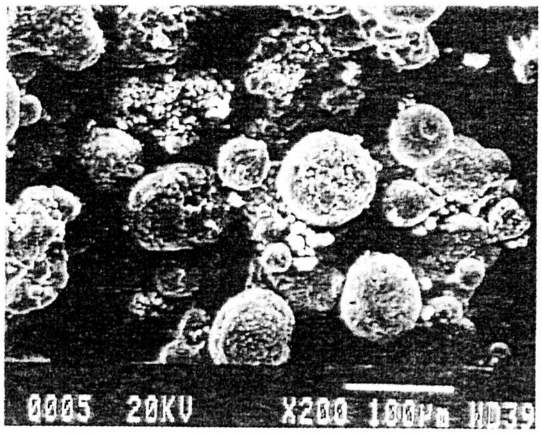
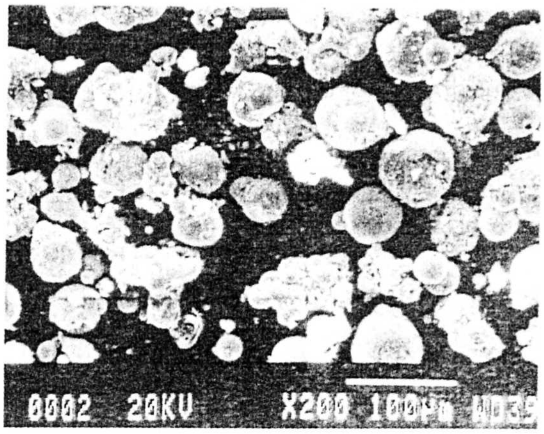


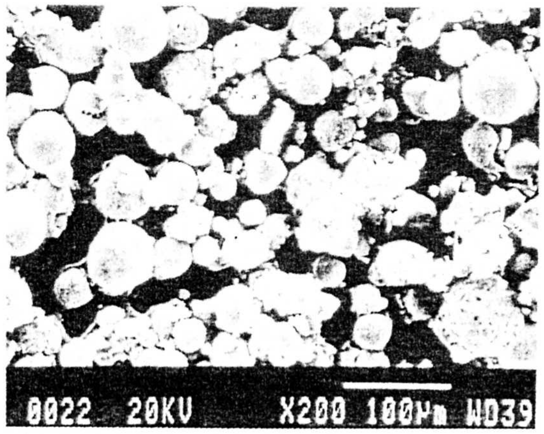
Fig. 10 - Effect of flow rate of atomizing gas on amplitude of voltage fluctuations for different nozzle geometries.



276 kPa



345 kPa



414 kPa

Fig. 11 - SEM photos of particles obtained at different pressures (34 V, 200 A, aluminum, standard nozzle).

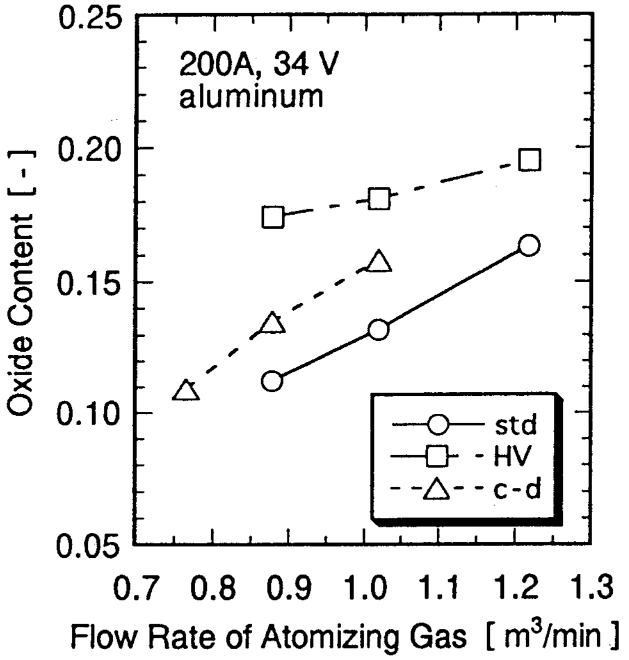


Fig. 12 - Effect of flow rate of atomizing gas on oxide content of the coating with different nozzle configurations.

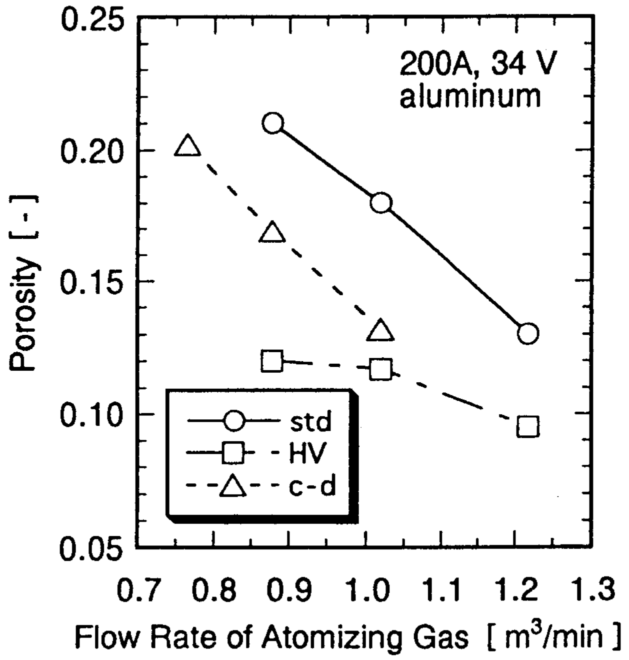


Fig. 13 - Effect of flow rate of atomizing gas on porosity of the coating for different nozzle configurations.

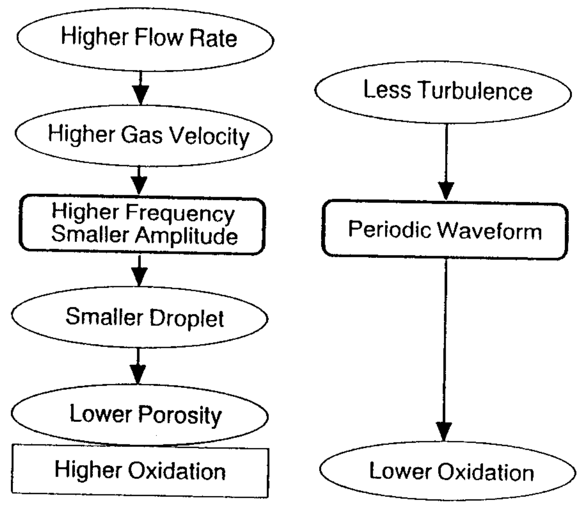


Fig. 14 - Relationship between the electrical fluctuations, the coating properties, and the velocity and the degree of turbulence of the atomizing gas.

Effects of the flow rate of an atomizing gas with three different nozzle configurations on the porosity of the coatings are shown in Fig. 13. Higher gas flow rate leads to coatings with lower porosity, because higher impact velocity of the droplets on a substrate results in larger deformation of the droplets, then to higher coating strength. The porosity of the coating is related to the impact velocity of the droplets as well as the droplet size. The c-d nozzle produces coatings with lower porosity when compared to the standard nozzle, because of the high velocity of the atomizing gas. The coatings produced with the HV cap show low porosity in spite of the lower gas velocities with this configuration because the turbulence effects on atomization result in smaller size particles which are accelerated more easily to higher velocities.

A hypothesis is developed for a relationship between the electrical fluctuations, the coating properties, and the velocity and the degree of turbulence of an atomizing gas as shown in Fig. 14. Higher velocity resulting in higher frequency and smaller amplitude of the voltage fluctuations leads to the smaller molten droplets. The coatings with lower porosity and with higher oxidation are produced by the smaller droplets. Meanwhile, less turbulence at the electrode tips resulting in periodic waveforms of the voltage fluctuations leads to lower oxidation of the coatings. Velocity and turbulence are important functions for the coating properties; turbulence can be estimated by the waveforms of the arc voltage fluctuations, and velocity of the molten droplets can be estimated by the frequency and amplitude spectrum. Therefore the arc voltage fluctuations can be used as an indication for the coating properties.

For coatings with minimal porosity and minimal oxidation e.g. for protection of engineering structures against corrosion and wear, a nozzle configuration with higher velocity as well as less turbulence would be desirable. The c-d nozzle configuration is one of the solutions for this purpose. On the other hand, the HV cap will provide with lower velocities comparable low porosity coatings, however with higher oxide content.

Conclusions

Aluminum wire has been sprayed with air using a standard nozzle, a HV cap, and a c-d nozzle. The existence of correlations between the arc voltage and current fluctuations and the coating properties has been investigated. Arc voltage fluctuations can be used as an indication for the coating properties which have strong relationships with turbulence and velocity of an atomizing gas. Turbulence can be estimated from waveforms of arc voltage fluctuations, while the velocity can be estimated from the frequency and the amplitude. The c-d nozzle produces high frequency fluctuations with a small amplitude, and coatings with low porosity and low oxidation. The nozzle with the HV cap produces low frequency and high amplitude fluctuations, and coatings with low porosity and high oxidation. Higher velocity resulting in higher frequency and smaller amplitude fluctuations lead to higher oxidation and lower porosity of the coatings. The nozzle configuration such as a c-d nozzle producing higher velocity with less turbulence is required for good coatings with low oxidation and low porosity. Quantifying the effects of turbulence on the atomization of the molten metal droplets could be an area of further investigation.

Acknowledgment

Partial support for this work by NSF through the ERC for Plasma-Aided Manufacturing, grant no. EEC 87-21645 is gratefully acknowledged.

Reference

[1] E. R. Sampson, Proc. 5th National Thermal Spray Conference, p.257 (1993).