

INJECTION AND TRAJECTORIES OF PARTICLES IN DC PLASMA SPRAY PROCESSES

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ABSTRACT.

The injection and mixing of particles within a plasma jet was investigated using a laser 2-D imaging technique. As a preliminary, the pneumatic transport of particles in the injector was computed with a 3-D mathematical flow model.

INTRODUCTION.

In DC plasma spraying, as in most of thermal plasma processes involving the treatment of powdery materials, the injection and the distribution of particles in the plasma flow condition the quality of final products. In this paper, the injection and the trajectories of particles are investigated using a non-intrusive 2-D imaging technique. The measuring system consisted of a planar laser sheet, generated by an oscillating mirror, and a linear diode array detection system. This system made it possible to monitor the injection and the distribution of particles in the plasma flow, in real time mode [1]. The distribution and the velocity of particles at the injector exit were determined using a 3-D flow model.

Results on zirconia powder with different particle size ranges are presented for two configurations of the injector system. A close attention is turned on fine powders whose injection is often more critical.

EXPERIMENTAL CONDITIONS.

Plasma spraying was carried out using a Plasmatechnik PTF4 torch. The arc current was 600 A and the plasma-forming gas flow was 45 slm Argon and 25 slm Hydrogen. These spray conditions resulted in a potential of 60 V and a torch thermal efficiency of 60%.

Fused and crushed zirconia particles were sieved to particle size distribution of -80+63 μm , -45+5 μm , -45+22 μm and -15+5 μm . The powder was injected into the 7 mm diameter torch nozzle either through a single injector or through two diametrically opposed injectors, as shown in Fig. 1. In the former configuration, the injector had an internal diameter of 1.8 mm and the carrier gas flowrate (Argon) was 4 slm. In dual injection, the injectors had internal diameters of 1.8 and 1.5 mm and the carrier gas flowrates were 4 and 3 slm, respectively. The powder mass feed rate was fixed to 1 kg/h for both injection configurations.

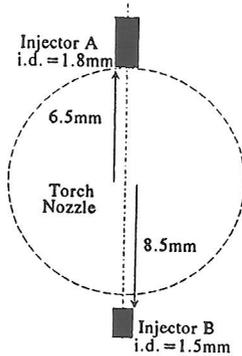


Figure 1 : Layout of dual injection system

MEASURING DEVICE.

Fig. 2 shows a schematic diagram of the experimental setup. The beam of a 2 W argon ion laser was focused through a lens (L1; $f = 500$ mm) onto a mirror oscillating at a frequency of 2400 Hz. This oscillating mirror made it possible to generate a plasma laser "sheet" orthogonal to the torch centerline. The laser sheet (50 mm high and 0.6 mm thick) was centered on the torch axis (Z) which also coincided with the starting position of the sweep. The light scattered by the particles passing through the laser sheet was collected at 10° by a lens (L2; $f = 210$ mm) and focused on the entrance slit, 25 mm high, of a monochromator with a magnification factor of 0.5. The monochromator was adjusted at the laser source wavelength (514.5 nm) and filtered the incoming optical signals with a band pass less than 0.1 nm, in order to limit background light from the strong plasma emission. At the exit of the monochromator, the light signals were recorded via a computer-controlled 1-D (1024) detector array, consisting of 1024 photo diodes.

Data acquisition and analysis were carried out by the "Spectraview - 1D" software by Jobin-Yvon. The software had the capability to monitor signals from the 1-D photo-diode array in real time on the computer screen. The time sequence for data acquisition varied between 0.013 and 0.5 s depending on the concentration of particles in the measuring volume.

The experimental procedure consisted of three sequential steps:

- recording of the light emitted by the plasma jet with no particle injection,
- recording of the light scattered by particles crossing the planar laser sheet as well as the light emitted by the plasma jet. By subtracting the light signal recorded in the first step from the latter, it was possible to monitor only the light scattered by particles,
- recording of the light emitted by particles at the 514.5 nm wavelength, with the laser turned off. Therefore by comparing the particle distribution profiles in the two last steps, it was possible to make an estimate of the distributions profiles of "hot" and "cold" particles within the plasma flow.

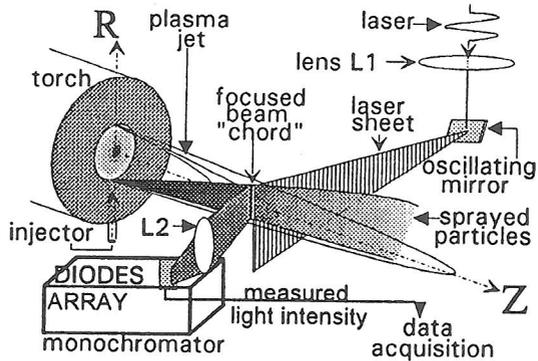


Figure 2 : Schematic view of the experimental set up

MATHEMATICAL MODEL.

The pneumatic transport of the powder in the injector has been investigated using a numerical model which estimated the distribution of particles at the injector exit and their velocities. The model was based on the following assumptions:

- the 3-D flow in the converging tube was steady and turbulent; turbulence was modeled by the $k-\epsilon$ model,
- the motion of particles was followed using a Lagrangian scheme,
- particle turbulent dispersion was taken into account,
- interactions of particles with the injector wall were considered, particles were represented as complete spheres; the rotational velocity of particles after collision was computed.
- interactions between particles were neglected; for the powder mass flow rate of 1 kg/h used in the present study, the mean distance between two particles following the same trajectory ranged from 6 to 10 times the particle diameter.

The flow simulation program ESTET [2] was used for the solution of flow conservation equations and particle motion equations.

RESULTS AND DISCUSSION.

1. Particle distribution at the injection exit.

The distribution of particles at the injection exit was computed with the mathematical model. The computation domain consisted of a 70-mm long cylinder, with an internal diameter of 1.8 mm. The rectangular mesh was composed of 27, 27 and 48 planes along the x, y and z directions respectively (the z-axis corresponded to the axial direction), so that 34992 nodes were generated. An irregular grid spacing was chosen along the x and y axis, narrowing from the center to the injector wall. Similarly, the grid spacing along the z-axis expanded from the entrance to the plane located 50 mm further, then shrank to the exit. In the entrance plane, a turbulent velocity profile was assumed. Particles were uniformly injected at the nodes of the grid, at the first plane in the axial direction, for each powder size distribution.

Fig. 3 shows the distribution of particles as a function of injector radius. The initial powder size distribution was divided into three classes: small particles (less than 20 μm), medium (20 - 50 μm) large particles (more than 50 μm). The results show that the small particles had a tendency to tilt towards the injection wall, due to turbulent dispersion. This results in a low velocity as shown in Fig. 4. These small particles which have a low momentum and may have difficulty to penetrate into the plasma jet at the injection point.

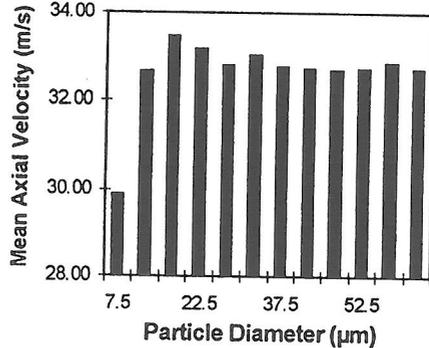
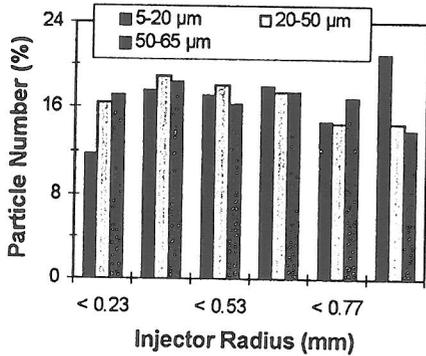


Figure 3 : Particle distribution at the injection exit as a function of particle size

Figure 4 : particle mean injection velocity as a function of particle diameter and injector radius.

2. Single-point injection.

The observed light signals, emitted and scattered by particles as they crossed the laser sheet, had a large fluctuating component, in the order of 30% of the mean value. Fig. 5 shows an example of two signals taken over 13-ms intervals at a distance of 45 mm from the injection point and with the laser light turned off. The fluctuation is mostly due to the irregularity of the powder feed rate and the natural fluctuations of the plasma jet both in the spatial and time nodes.

For the type of plasma torch and operating conditions used in this study, the frequency of the restrike mode of the arc root was typically about 20 kHz; this resulted in variation of the rate of electric power dissipation in the plasma jet of about 30%. Since the carrier gas flow rate is set on the basis of the plasma gas flow and the average level of power dissipation, the particle trajectories are continuously fluctuating. Therefore, the velocity and residence time of particles in the hot zone of the jet are also fluctuating. This contributes to the rather large distributions of particle velocities and temperatures observed upon impact on the substrate [3].

Comparison of the emitted light signal of Fig. 5 and the scattered plus emitted light of Fig. 6 shows that two smaller peaks occur at a radius of about 12 mm from the jet centerline. These peaks were also observed further away from the nozzle exit and are due to scattering of laser light by particles which at the injection point did not have enough momentum to penetrate the plasma jet and are therefore carried around the jet envelope. As shown in Fig. 7, the height of these secondary peaks decreased with increasing particle size.

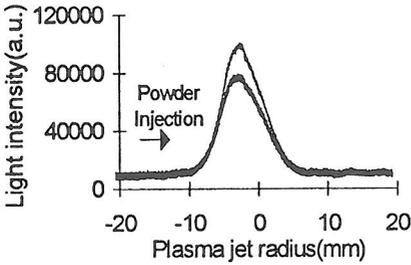


Figure 5 : Fluctuation of light signal with time at 45 mm from injection point.

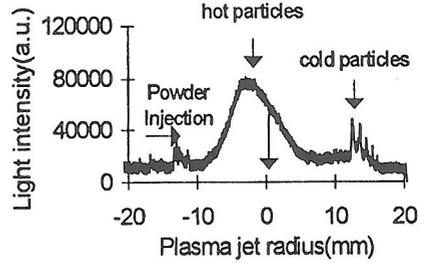


Figure 6 : Radial profile of observed light signal at 45 mm from the injection point.

The above experimental observations are in line with the projections of the mathematical model, as was discussed in the previous section.

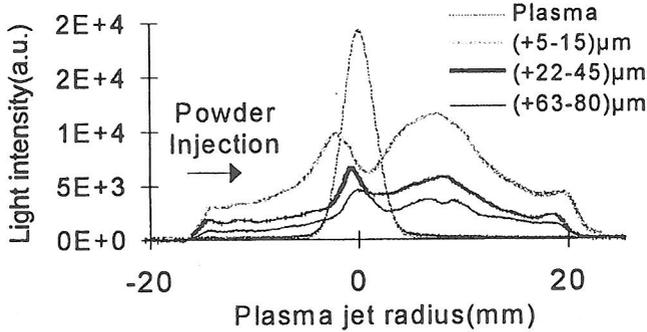


Figure 7 : Radial profiles of observed light signals at 45 mm from the injection point, for various particle size ranges.

3. Dual injection system.

The first experiment with the dual-injection system investigated the influence of carrier gas on the plasma jet. The light emitted by the plasma jet was recorded at a distance of 40 mm from the injection point and at a wavelength of 514.5 nm, first without carrier gas, then with the carrier gas issuing from injector B (3 slm) and finally with carrier gas issuing from injectors A (4 slm) and B. As it can be seen on Fig. 8, the maximum light intensity decreased by about 40 % when injector B was used and about 60 % when both injectors were used. It could be estimated that the difference between the last two peaks corresponded to a fluctuation of the temperature T_e of the order of 1000 K, assuming that the electron density n_e varied by 20 % ($\epsilon_v \sim n_e/\sqrt{T_e}$ where ϵ_v is the volumetric emission coefficient of the plasma gas). A mean trajectory of particles was estimated from the position of the maximum of light intensity collected in different sections orthogonal to the jet centerline. It should be noted that when both injectors were used at the same time, the mean trajectories of

the mean trajectories with the jet centerline was equal to 3.5° , as compared to 4.8° when each injector was used alone [4]. Fig. 9 shows the two mean trajectories crossed at about 20 mm from the injection point. The trajectory determined from the light scattered by particles as they crossed the laser sheet was slightly different from that determined from the radiation emitted by hot particles. This is due to the contribution of cold particles which did not penetrate into the plasma flow at the injection point. The deposition efficiencies determined when using injector B alone or injectors A and B together were about the same, in the order of 50 %. However the deposition rate was doubled in the latter case.

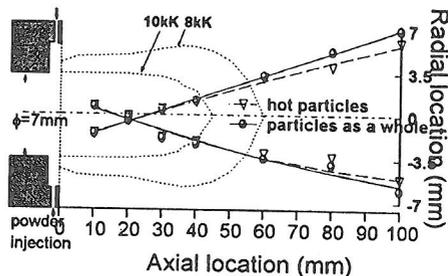
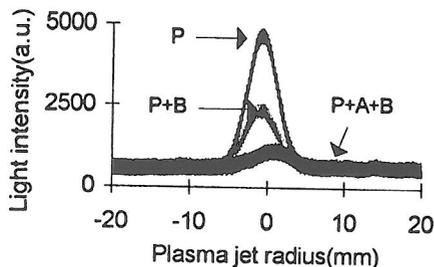


Figure 8 : Perturbation of carrier gas injection to the plasma jet. "P" stands for the original plasma, "A" and "B" for the injectors.

Figure 9 : Average trajectories of particles in the plasma flow for dual injection system.

CONCLUSION.

The laser 2-D imaging technique has been proved to be a successful non-intrusive technique for monitoring the particle distribution within the plasma jet, in real time mode. The measuring system consisted of medium-priced optics a commercial data acquisition software. This system can be used in industrial applications.

The present study emphasized the difficulty of injecting fine particles into a plasma jet due to their relatively low momentum. However, it should be noted that when the particles are entrained into the plasma jet, they are generally evaporated within the jet flow and they do not contribute to the formation of the coating.

The dual injection configuration system increases the rate of coating formation by a factor of two without changing the deposition efficiency.

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