A STUDY OF THE INFLUENCE OF PLASMA JET CONFINEMENT ON PARTICLE PARAMETERS IN INDUCTION PLASMA PROCESSING

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Abstract

This study focuses on the influence of the injection of an external plasma confinement gas stream, on the in-flight particle parameters for fine alumina axially injected into the center of an induction plasma discharge. The external plasma confinement gas injector, was developed in order to limit the recirculation of cold particles close to the torch/reactor interface. The in-flight parameters investigated include the particle surface temperature and velocity, and the hot particles fraction in the overall particle stream. Measurements were carried out using laser Doppler anemometry, two-colour pyrometry and particle time-of-flight technique at different axial positions along the centerline of the jet. These reveal the presence of an important particle entrainment process by which cold, fine particles, from the reaction chamber environment are entrained into the plasma jet at the exit of the torch. The use of the external plasma confinement flow is shown to be very effective in reducing the number fraction of the entrained particles. As the flow rate of the external plasma confinement gas increases, the fraction of hot particles in the total particle stream increases, while the difference between the velocity of the hot particles and that of all the particles decreases without significantly affecting the mean particle surface temperature.

1. Introduction

The final properties of the products obtained by induction plasma processing are strongly dependent on the torch operating conditions, the properties of the processed material itself, and the interactions, in-flight, between the processed material and the surrounding gases. To better understand the influence of such parameters on the in-flight powder treatment and then to optimize plasma processes, in-situ particle diagnostic

techniques have been developed and used independently or combined [1-6]. Such techniques include laser anemometry [7] for the measurement of the particle velocity and particle-emission techniques [8,9], such as two-colour pyrometry [8,9,11,12] and particle time-of-flight technique [8,10], for the measurement of the particle surface temperature and velocity, respectively.

The simultaneous measurement of the particle surface temperature and velocity is generally realized by combining a laser Doppler anemometer (LDA) with a two-colour pyrometer [1-4]. This way to do requires the spatial coincidence of both measurement volumes and the correlation of both signals in order to simultaneously measure the particle surface temperature and velocity at the same spatial location, and on the same particles population. By combining the particle time-of-flight technique with two-colour pyrometry [8,9], one can obtain simultaneously the particle surface temperature and velocity with a single measurement volume and no needs for signals correlation.

In this study we used laser Doppler anemometry, particle time-of-flight technique and two-colour pyrometry to obtain statistical information of the particle parameters for fine alumina powders treated by an induction plasma processing installation. This special combination of measurement techniques allowed us to determine the velocity of the overall particles population, the surface temperature and velocity of the hot particles population, and the fraction of hot particles included in the stream of processed material. The use of a plasma jet confinement flow reducing the entrainment by the recirculation eddies of cold, fine particles, allowed us to vary the fraction of hot particles in the hot plasma stream [6].

2. Particle Diagnostics

The measurement setup [6,8] used is schematically represented in Fig. 1. A laser Doppler anemometer and the particle-emission spectrometer were mounted on an optical bench which could be translated along three orthogonal directions. A measurement volume of approximately 0.075 mm³, was defined by the spatial coincidence of both observational regions.
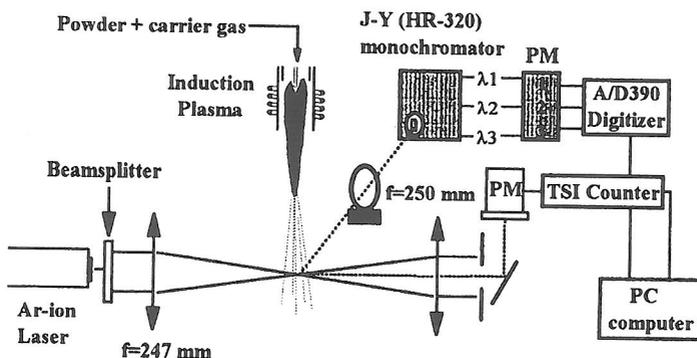

Fig. 1 Schematic of the particle diagnostic setup

The laser Doppler anemometer used was a TSI counter type model 1990 mounted in the forward scattering interferential mode with an Ar-ion laser (λ_3=514.5 nm) and a beam spacing of 50 mm. The emission spectrometer consisted of a 250 mm lens translating the image of the measurement volume on the entrance slit of a 1 m-focal length monochromator in such way that the image ratio was equal to 1.93. Three photomultipliers focused through optical fibers on the output plane of the monochromator allowed the simultaneous detection of light emitted at the measurement volume at three wavelengths. Respectively, λ_1=681.4 nm and λ_2=583.5 nm were used to measure the monochromatic thermal emission of the particle, while λ_3=514.5 nm (laser wavelength), was used as a triggering signal to start the acquisition. The number of acquisitions was N=1000 for all measurements, while the number of signals accepted after analysis by two-colour pyrometry and particle time-of-flight technique was N_p. The fraction of hot particles was estimated to be the ratio N_p/N since almost 90% of the signals rejected were due to too cold particles under these conditions [8].

3. Experimental Setup

A schematic of the induction plasma processing setup with a gas-sheathed nozzle [6] is shown in Fig. 2. The r.f. plasma torch consisted of a water-cooled plasma confinement tube of 50 mm i.d., surrounded by a four turns induction coil. The operating frequency and the power of the r.f. power supply were 3.0 MHz and 20 kW, respectively. The plasma gas was argon (Q_2=43.0 l/min [Ar]) while a mixture of argon and hydrogen was used as the sheath gas (Q_3=71.5 l/min [Ar] + 5.6 l/min [H$_2$]). The alumina +45-53 μm particles were carried out of the powder feeder by a carrier gas (Q_1=3.0 l/min [Ar]) and injected into the center of the plasma discharge by a water-cooled stainless probe at a mass feed rate of 1.6 g/min. An external sheath gas (Q_4=0.0-42.0 l/min [Ar]) was injected axially in an annular slot surrounding the exit of the confinement tube. The latter acted as a barrier to prevent the entrainment by the plasma jet of cold, fine particles, suspended in the gaseous recirculation eddies in the vacuum chamber. The plasma torch was mounted on the top of a 200 i.d., water-cooled stainless steel chamber connected to a vacuum system. Three quartz windows located in the chamber side walls allowed the necessary optical access. The chamber pressure was 250 torr. The measurements were carried out at a distance of 188 mm from the tip of the injection probe.
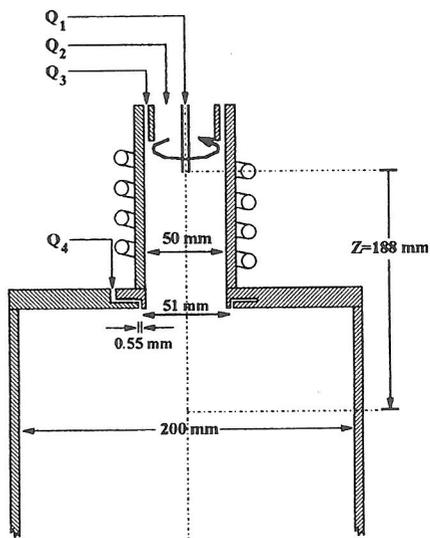

Fig. 2 Schematic of the induction plasma processing setup

4. Results and Discussion

Fig. 3 shows the mean particle surface temperature (T_p) and the fraction of hot particles included in the stream of processed material (N_p/N) as a function of the plasma jet confinement flow rate (Q_4). This figure shows that the addition of a high plasma jet confinement flow caused a small decrease of the mean particles surface temperature. This mean surface temperature was approximately 3450 K for Q_4=0.0 and approximately 3000 K for Q_4=42.0 l/min. This cooling of the particles surface was associated with the decrease of their mean velocity (Fig. 4). The lower was their velocity, the longer was their travel time in the cooling part of their trajectory and then, the larger was the radiative cooling effect. Fig. 3 also shows that the plasma jet confinement flow was efficient in controlling the fraction of hot particles. This fraction increased from approximately 60% to almost 80% as Q_4 increased from 0 to 42.0 l/min.
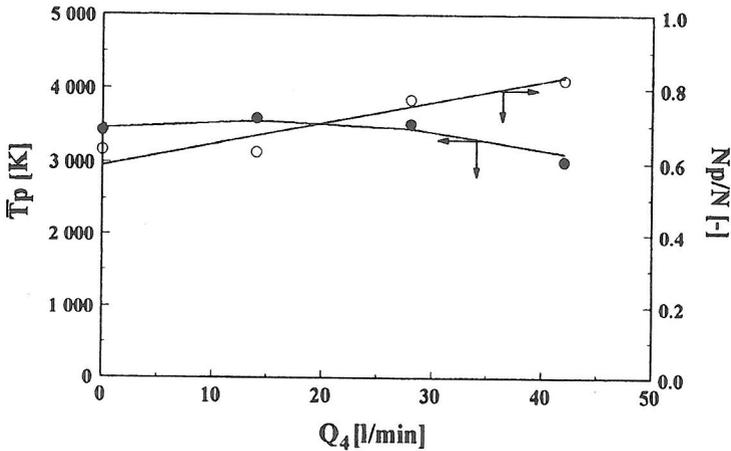

Fig. 3 Mean particle surface temperature and fraction of hot particles as a function of Q_4

Fig. 4 shows the velocity distributions obtained by laser Doppler anemometry (LDA) and by particle time-of-flight technique (TOF) as a function of the plasma jet confinement flow rate (Q_4). The velocity distributions were essentially Gaussian with a difference between the mean particle velocities proportional to the plasma jet confinement flow rate (Q_4). The higher was Q_4, the lower was the difference between the two velocities. This difference was approximately 9 m/s for Q_4=0.0 while it vanished for Q_4=42.0 l/min. This figure also clearly shows that the hot particles (TOF distributions) had the highest velocities of the overall particles population and that, the two distributions became almost identical when the fraction of hot particles approached 100%.

In an attempt to explain the increase of the fraction of hot particles, and the decrease of the difference between the velocities of the hot (TOF) and overall particles population (LDA) with the injection of a plasma jet confinement flow, the concept of cold particles suspension must be introduced. Cold, fine particles, suspended in the vacuum chamber due to the low velocity recirculation eddies, were entrained by the plasma jet. These low velocity

particles were detected by LDA but not accepted after analysis by particle-emission spectrometry due to their low temperature, reducing then the fraction of hot particles in the main stream. The external argon flow introduced as plasma jet confinement gas, acted as a barrier against the cold particles entrainment.
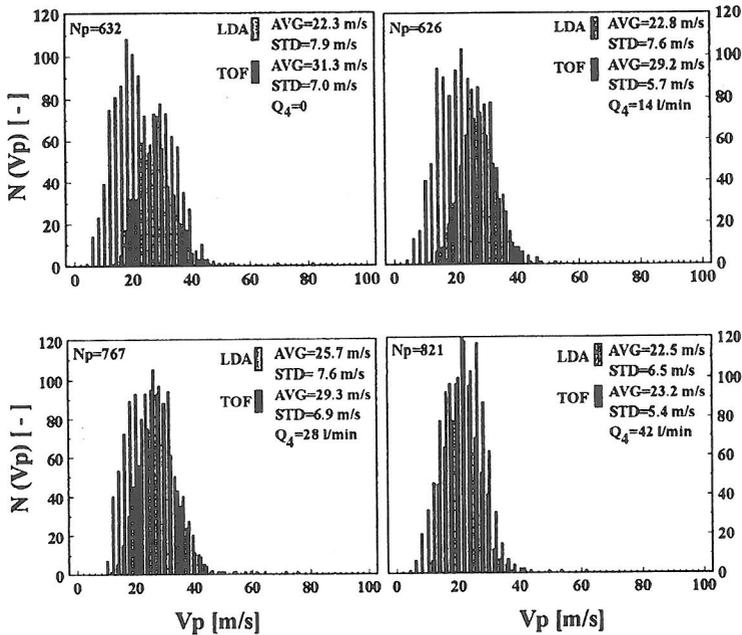

Fig. 4 Particle velocity distribution obtained by LDA and TOF as a function of Q_4

The phenomenon of cold particles entrainment by the plasma jet in the vacuum chamber becomes particularly important when the mean individual particle mass decreases as it can be seen with Fig. 5. This figure reports the relative difference between the hot (TOF) and the overall particles population (LDA) for four types of powder treated under the same plasma conditions. These powders were alumina +45-53 µm, alumina +63-75 µm, tungsten +45-53 µm and nickel +60-96 µm, respectively. The diminution in importance of the cold particles entrainment process with the increase of the mean individual particle mass can be directly related to the substantial drop in number of particles that can remain suspended by the recirculation eddies in the ambient atmosphere in the vacuum chamber.

5. Conclusion

Using a combination of a laser Doppler anemometer with a particle-emission spectrometer, it has been shown that the entrainment by the plasma jet of cold particles suspended by the recirculation eddies close to the torch/reactor interface can be controlled by the introduction of a plasma jet confinement flow. This phenomenon of cold particles entrainment is shown to be particularly important when the mean particle individual mass is

low. The introduction of the plasma jet confinement flow had a beneficial effect on the fraction of hot particles included in the stream of processed material without strongly affecting the mean particles surface temperature.
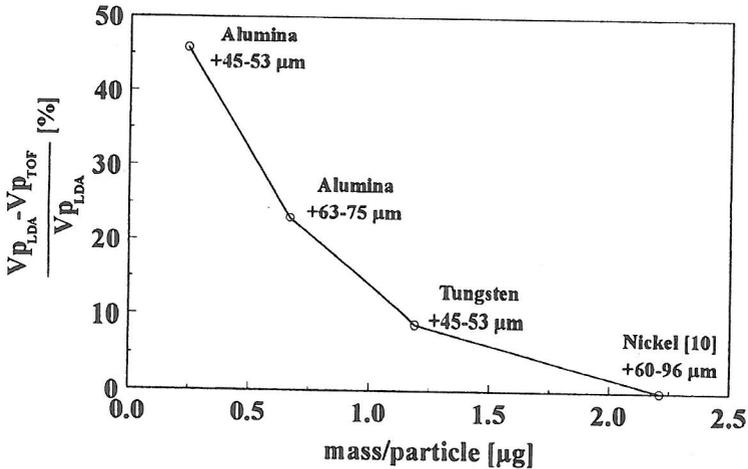

Fig. 5 Influence of the particle mass on the relative difference between the velocities obtained by LDA and TOF techniques

Acknowledgment

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