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Study of in-flight particle stream and particle behavior for understanding the instability phenomenon in plasma spraying process

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ABSTRACT

For understanding the effect of powder feeding fluctuation on coating structure, in-flight particles were investigated by means of image analyzing. Particle behavior was estimated through numerical calculation on the base of force equilibrium. High definition videos were captured focusing on the in-flight particle stream and transparent carrier tube. Yttria-stabilized Zirconia (YSZ) coating was prepared with vacuum plasma spraying for clarifying the effect of powder feeding instability on coating structure. Optic micro-morphology of coating was obtained for porosity ratio estimation. An imaginary ring of bent tube was proposed for understanding particle behavior when unavoidable bends exist. Results indicate that periodic fluctuations exist in in-flight particle trajectory and in powder feeding. A transition region was found for particles with different diameters in regions between 0° and 180° within which particles with large sizes are difficult to transport. As a consequence, accumulation of powder was thus found both on upslope and downslope. The effective cross-section of the carrier tube for powder carrying was found reduced. According to the calculation, reducing equivalent diameter and increasing carrier gas flowrate have the same effect on powder carrying. A threshold was proposed to understand the slug behavior as: growing, maturity and breaking. Due to the break of slug, 'powder flooding' happens and may cause mutation in in-flight particle stream. Obvious increase was found in injected particle quality to induce the three-layer structure of coating. An empirical equation was proposed to describe slug behavior as a synthesis of growth rate and loss rate.

1. Introduction

As an efficient method for surface modification, plasma spray is widely used for industrial solution. However, the development of plasma spray process is shortened by poor reproducibility which is mainly excited by the combination of fluctuations in operating condition and in the powder feeding [1–3]. The source of fluctuation is numerous, such as the arc root, plasma gas composition, and powder feeding. These fluctuations may cause an obvious deviation in in-flight particle characteristics even with the same operating parameters. Many works were reported concerning the instability of plasma jet and particle characteristic with various diagnostic methods, such as DPV-2000, and spray-watch. Bisson et al. [1] watched variation in particle temperature and velocity with a magnitude of 600 °C and 200 m/s respectively during one fluctuation period. Some works also show interest in the fluctuation of plasma jet. Kieschke et al. [2] observed a variation of 20% in plasma plume length (200 mm) with a high speed video for 1 ms. Meanwhile, both experimental and numerical works have been developed to clarify the influence of fluctuation on coating property [3–8]. The effect of powder feeding on in-flight particle characteristic was also investigated; that with different injector geometries the profile of particle temperature and velocity consequently varied before impacting [9].

The flow system involved in the plasma spraying process concerns the pneumatic conveyance of gas-powder. Due to the range of powder granularity, a visible difference may exist between fine particles and coarse particles in pneumatic conveying characteristics. Therefore, significant variations in pressure can exist along the tube that will cause unstable distribution of powder to form a dilute phase and dense phase [10,11]. With the introduction of the bending effect of the carrier tube, the core flow will shift toward the outer wall to form compressed flow while dilute flow is found in the inner wall region [12]. Meanwhile, solid particles following the cone flow can deposit on the inner wall with different patterns depending on the carrier velocity and powder mass flowrate, e.g. annular deposition with high velocity and gravitational deposition with high mass flowrate [13,14]. By employing motion equation of particle, e.g. drag force and gravity, particle behavior can be clearly predicted in horizontal pipe and in vertical pipe and in bent pipe [15–17].

Unfortunately, the influence of particle behavior inside the carrier tube on coating structure is still not clear. Thus, the aim of this work is to understand the behavior of particles inside the carrier tube and clarify the effect on coating structure. The diagnostic methods employed in

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these works only considered a small volume for data acquisition with a selected stand-off position or only focused on the plasma jet. There is no a contribution on dealing with the detail of in-flight particle trajectory considering the time fluctuation and position variation. Therefore, in this work, both of the plasma jet and in-flight particle stream were observed and recorded with a speed of 30 fps and resolution of 1280 × 720. Accordingly, a global view of the plasma jet and in-flight particles was obtained. With Matlab (R2009a, Mathworks, Natick, USA), video data was easily deconstructed and analyzed frame-by-frame.

2. Experimental methods

2.1. Operating condition

This work was based on the experiment carried out in a VPS chamber (Fig. 1a). A F4-VB type torch (Sulzer, Metco, Wohlen, Switzerland) was employed with a XY movement motor (Fig. 1b). The internal diameter of the anode used is 6 mm. The torch was automatically controlled at 35 °C with a water cooling system. The internal diameter of the injector was 1.8 mm which was installed 3 mm downstream of the nozzle exit, and the out-port of the injector was aligned to the anode internal wall. The powder feeder was horizontally separated from the spray chamber with a distance of about 3 m. The powder was transported to the injector through a carrier pipe with a length of 5 m along which four bends exist. The feedstock used is Yttria-stabilized-Zirconia (YSZ, 8 mol%, $(ZrO_2)_{92}(Y_2O_3)_8$, Metco 6613) with a size of $d_{50} = 14$ μm and $d_{10}/d_{90} = 7$ μm/23 μm. 304L stainless steel with a composition of 18 wt.% Cr + 2 wt.% Mg + 8 wt.% Ni + 72 wt.% Fe was used as the substrate material. The substrate was prepared as a disk with a dimension of Φ 40 mm × 5 mm. The vacuum pump automatically pumps out the excess gas in order to keep the chamber pressure at 70 mbar. Sample was sprayed by focusing the plasma torch on the substrate center with a stand-off of 350 mm for 5 s. During spraying, current intensity was always fixed at 500 A. Flowrates of argon and hydrogen were constant with values of 45 L/min and 3 L/min respectively. Argon was also used as the carrier gas with a flowrate of 3 L/min (in order to let fluctuation happen). The powder feeding rate was 10 g/min. Optic micromorphology of coating structure was captured through an OM (optic microscope). Powder behavior inside the carrier tube was watched and recorded by a video camera through a connected-in transparent PVC tube.

2.2. Video analyzing

All videos were analyzed frame-by-frame to detect variation in light intensity and position. As indicated in Fig. 2, a RGB (Red–Green–Blue) image can be converted into a gray value map with several algorithms, such as average method (average over three colors), red channel (only red included), green channel (only green included) and blue channel (only blue included). With the blue channel, it is able to focus on plasma jet while minimizing influence from the particle stream. With both the red channel and green channel, particle stream is enhanced, but a difference exists at the end of plasma jet. With the green channel, the in-flight particle stream can be clearly distinguished from the plasma jet.

Illustration of the selected region is presented in Fig. 3. Length of plasma jet is about 300 mm, and the length of selected particle stream is 233 mm. The selected view B (Fig. 3) covers the whole in-flight particle stream starting from the end of the plasma jet. And view A is selected with a range from 30 mm above the particle stream's upper edge to 10 mm below the lower edge. The gray values vary from 0 to 255 means a variation of color from dark to white. The gray degree indicates particle temperature: high temperature results in white color, low temperature conducts a gray color or even darker if the particle cannot be seen. However, a decrease of particle amount also leads to a gray color. Thus, for distinguishing these two differences, the distribution of gray value along view A is dedicated to the variation of particle number and the decrease of gray value along view B is assigned to temperature loss. But with a normal video camera, it is impossible to measure particle temperature precisely. In addition, the variance in injected particle quantity is more interesting in this work. Thus, variation of the gray value mentioned in the current work only denotes the change of particle quality. The significance of which temperature the gray value denoted is not provided.

2.3. Force equilibrium of particles in the boundary region

The characteristic of in-flight particles is significantly dominated by powder entering state (from the exit of injector to plasma jet) which is decided by powder behavior during transport inside the carrier tube. Therefore, clarifying powder behavior during transport can help to understand the fluctuation of in-flight particle stream. As the most reasonable method, force analysis can easily predict particle behavior in the carrier tube. The force equilibrium on a single particle can be described with Eq. (1). Considering the immense difference of specific density between carrier gas and feedstock (Table 1), the unsteady forces (basset force, the added mass force and the pressure gradient force) are negligible [15,18].

$$d\boldsymbol{u}_p/dt = \boldsymbol{F_D} + \boldsymbol{g}\left(\rho_p - \rho_g\right)/\rho_p + \boldsymbol{F_x}. \tag{1}$$

[19–21].

With $\boldsymbol{u_p}$, the particle velocity; ρ_g, the carrier gas density; ρ_p, the particle density; $\boldsymbol{F_D}$, the drag force term; $\boldsymbol{g}$, the gravitational acceleration; and $\boldsymbol{F_x}$, other force sources, can be the centrifugal forces in the bent tube in this work.

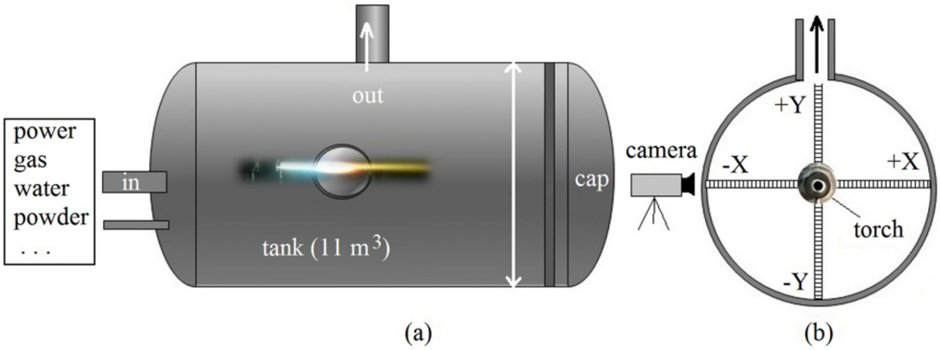

Fig. 1. Experimental installation for plasma spraying process: (a) VPS chamber; and (b) cross section of chamber.