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Influence of metal powder shape on drag coefficient in a spray jet

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ABSTRACT

In plasma spraying, particle shape, size, distribution and density are the important factors to be considered in order to ensure high spray efficiency and better coating properties. In the present work, nickel, iron and aluminium irregular powders in the size range from 50 to 63 μm were spheroidized using thermal plasma processing. The spheroidization experiments have been carried out at different gas flow rates and plasma torch power levels. The sphericity was analyzed using shape factor. Drag coefficients of the powders were estimated using Reynolds number and sphericity of the powders in plasma. For irregular particles, the drag coefficient is higher than that of the spherical because of its large area of contact with plasma. The temperature dependent on drag coefficient is also discussed. Increasing temperature increases the drag coefficient of the powder particles injected in to the plasma jet. Increasing plasma jet temperature changes the density and viscosity of the plasma which affects the particle's drag coefficient in the plasma. The results are reported and discussed.

1. Introduction

Thermal plasma is a highly viscous, electrically conducting fluid. A unique feature of thermal plasma jet that distinguishes it from other heat sources is its high power density. The energy density of thermal plasma devices is of the order of several GW/m^2, which is 10–100 times the power density of conventional oxy-fuel flames. The plasma torch generates a plasma jet which is characterized by a very high energy density (10^9 J/m^3) surpassing the conventional techniques of heat generation by at least 1000 times [1]. For thermal spray, the preferred particle shape is spherical in order to have high flowability of powders and optimal conditions of particle melting and spraying [2]. Micron-sized metal and ceramic particles can be melted by thermal plasmas that provide exceptional conditions for spheroidization due to its high temperature [3–12]. A particle injected into thermal plasma jet will experience a number of effects which are not present in an ordinary gas [13]. Study of drag coefficient of particles is important to understand their flowability in plasma jets. Spheres in particular are favored by the researcher due to their complete symmetry. Powder particles typically injected in plasma spray system may not be spherical. Hence, the effect on heat and momentum transfer due to non-spherical particle shape with large thermo-physical property variation in the flow field needs to be investigated [14]. Sphericity is a measure of the irregularity in the shape of the particles. For irregularly shaped particles, drag coefficient must be expressed in terms of Reynolds number as well as one or more shape factors [15]. The sphericity is generally recognized to be an appropriate single dimensionless number for characterizing the shape of irregular particles [15]. Different shape factors are used for characterization of shape of particles. In this paper, the Reynolds number and drag coefficient for aluminum, nickel and iron particles were calculated from the sphericity values. Correlation between the drag coefficient and the percentage of spheroidization was made for different plasma jet temperatures and gas flow rates and the results are reported and discussed.

2. Basic equations

The plasma jet velocity is determined by the nature and flow rate of the plasma gas, the diameter of the nozzle and the plasma

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arc power. The average velocity of the plasma jet can be calculated based on the pulse theorem [16]. The velocity of the plasma jet in relation to the mass flow rate of the gas and average density of the plasma gas (ρ_g) is given by

$$V_g = m/[(\pi/4)D^2\rho_g], \tag{1}$$

where m is the mass flow rate of plasma gas and D is the diameter of the nozzle. The average plasma gas velocity profile along the central line varies in a parabolic manner as given by the following relation [17]:

$$V_g = V_0[1 - (x/x_{ref})^2]. \tag{2}$$

In the above equation, V_0 is the plasma jet velocity determined at the nozzle exit and x_{ref} is the reference distance from the nozzle at which the gas velocity is assumed to be zero. For this study, plasma gas velocity is considered as the average value throughout the plasma jet and the variation along the central line is ignored. In flight residence time of the particle in the plasma, t_r may be calculated from the expression [18]

$$t_r = (2S/kV_g)^{1/2}, \tag{3}$$

where $k = 18\eta/d^2\rho_p$ and S, V_g, η, d and ρ_p are the particle path length, gas velocity, viscosity of the plasma, diameter of the particle and the density of powder material, respectively. The velocity and trajectory of a particle injected into the plasma are mainly affected by the viscous drag. The velocity of the powder particle at the end of the jet is equal to [19]

$$V_p = V_g[1 - \exp(-kt_r)]. \tag{4}$$

The particle Reynolds number can be expressed as:

$$Re = \rho_g d(V_g - V_p)\eta \tag{5}$$

The moment the powder particles are injected into the core of the plasma, they experience a drag force. Similarly, there is a transfer of heat flux from the hot plasma gas to the powder surface [20]. When a particle moves through plasma, there exists a resisting drag force which is dependent on the particle size, particle shape, relative velocity and density and viscosity of the plasma [21]. The shape of a particle and its drag coefficient can be correlated by the sphericity and the Reynolds number of the particle [13]. The drag coefficient depends on particle velocity relative to flame velocity [22]. For any particle of fixed shape, the drag coefficient must be a function of Reynolds. The particle Reynolds number is defined as the ratio of the inertial forces to the viscous forces. According to Haider and Levenspiel [23], the following equations can be used to predict quite accurately the drag coefficients of non-spherical particles. For non-spherical particles, the drag coefficient is written as,

$$CD = \frac{24}{Re}[1 + 8.1716\exp(-4.0655\Phi)]Re^{0.0964+0.5565\phi} + \frac{73.69Re\exp(-5.748\Phi)}{Re + 5.378\exp(6.2122\Phi)}, \tag{6}$$

where φ is sphericity of a powder particle. When particle drag is calculated, its drag coefficient depends on its orientation to the plasma jet. All the irregular particles tend to align themselves with their maximum cross section normal to the direction of the flow. Hence, for this study the orientation of the particle and the oxidation effects are omitted. Non-continuum effects, ionization, and evaporation effects have not been considered in the present study. Also the steep temperature difference in the boundary layer around the particle is ignored in this study. However, the sphericity is a theoretical concept which can be realized only imperfectly. There is no simple generally accepted method for measuring the sphericity of smaller irregular particles [21]. The roundness RN, of the powder particle which characterizes its shape is given by [24]

$$\mathrm{RN} = P^2/4\pi A \tag{7}$$

The shape factor SF = 1/RN is used to characterize the shape of the particle [24]. Where P and A are perimeter and area of the powder particle, respectively. Roundness of circle, hexagonal, square and equilateral triangle structures are 1.00, 1.10, 1.27 and 1.65, respectively. It shows that the deviation from unity leads to irregularity of the particle [24]. The corresponding shape factors (SF) are 1.00, 0.91, 0.78 and 0.61, respectively. Sphere, cube octagon, cube and tetragon are considered as the 3D shapes for circle, hexagon, square and triangle, respectively. Sphericity values for the above mentioned shapes are 1.00, 0.91, 0.80 and 0.67, respectively [21]. Hence, apparently shape factor (SF) has been taken as the sphericity of the shapes.

3. Experimental setup and methodology

The experimental setup consists of a 40 kW DC plasma spray torch. It has a thoriated tungsten cathode and a copper anode nozzle. It is mounted on a water-cooled reaction chamber which is made up of stainless steel. The reaction chamber is 8" in diameter and 24″ long. The chamber sits vertically on the powder collection chamber. The experimental setup includes a DC power supply, H.F.igniter, gas feed system, water cooling system and a powder feeder. A control console controls gas and water flow rates. The major diagnostic tool in this experiment is the monochromator (Thermo Oriel, ¼ M) and accessories to estimate the plasma jet temperature. It consists of an optical arrangement, monochromator, photomultiplier tube, power supplies, oscilloscope, X-T recorder and computer for running the monoutility program. Fig. 1 illustrates a schematic diagram of the diagnostics setup.

4. Experimental procedure

In the present work, aluminum, nickel and iron powders in the size range between 50 μm and 63 μm were spheroidized using a non transferred DC plasma spray torch. The plasma spray torch was ignited by striking a high current arc between the cathode and the anode and the desired power level was maintained by controlling the flow rate of plasma gas and arc current. The torch was operated at four different input power levels 8, 11, 16 and 18 kW and two different gas flow rates 15 lpm and 20 lpm. Argon was used as the both plasma forming and carrier powder gas in the experiment. The corresponding plasma jet temperatures at selected power levels and gas flow rates were measured by optical emission spectroscopic method. The optical emission spectroscopic methods are based on measuring the intensity of spectral lines. The argon spectrum was recorded between 400 nm and 451 nm. The excitation temperature was estimated using atomic Boltzmann method [25–31]. It is the average value along the line of sight. The radiation from the plasma jet is focused by optical fiber on the monochromator input slit. In this study, the radiation was collected for temperature measurement is at 5 mm down from the nozzle exit. The output signal from the PMT is fed into the X-T recorder and oscilloscope. The spectral lines are viewed in the oscilloscope. For better resolution of intensity peaks the input/output slit width and preamplifier gain are adjusted. The excitation temperature of the plasma jet was estimated from the intensity of atomic emission lines from the jet using atomic Boltzmann method, which gives the average temperature along the line of sight of measurement. The temperature is determined using the equation,

$$\mathrm{Log}(I\lambda/g_k A_k) = C - (625E_k/T), \tag{8}$$

where $C = \ln(lhcp_0/4\pi)$, A_k, g_k, E_k, λ, and I are line frequency, degeneracy of level, energy of the excited level, wavelength and intensity