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The analysis of melting and refining process for in-flight particles in supersonic plasma spraying

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ABSTRACT

To understand the effect of in-flight particle behavior so as to improve the coating quality, an accurate description of transport phenomena of particles is essential. For supersonic plasma spraying (SAPS), a three-dimensional computational model is developed to describe the plasma jet coupled with the injection of carrier gas and particles. The heating and melting processes of single particle were also studied by a numerical method. The model treats the particles in the flow as discrete Lagrangian entities that exchange mass, momentum, and energy with the gas. The governing equations for the Reynolds averaged flow parameters were solved using FVM method and the continuity and momentum equations are coupled using the PISO algorithm. The velocity and temperature of the in-flight particles were measured by SprayWatch-2i, and the morphology of particles was observed by Scanning Electron Microscope (SEM). Numerical and experimental results showed that, the velocity and temperature of the in-flight particles were reached maximum at the spraying distance of 80–100 mm. Particles were melted and broken into small child particles by plasma jet. The small child particles were accelerated to higher in-flight velocity by gas flow. Particles were completely melted when the spraying distance about of 95 mm at the time of 0.35 ms. Numerical results were compared with the experimental measurements and a good agreement has been achieved.

1. Introduction

Plasma spraying involves three separated but interrelated processes, such as plasma generation, plasma-particle interactions, and coating formation [1]. The above three processes can be exercised some controls by operator to maintain a better particle's melting and motion and finally get better coatings. The characterization of plasma jet mainly concerns the experimental determination and numerical prediction of the spatial distribution of velocity and temperature. These parameters determine, in turn, the density, thermal conductivity and viscosity of gas streams, which influence the momentum and heat transfer between gas and particles [2]. The axial and radial temperature and velocity distribution (temperature and velocity fields) in the plasma jet significantly affect the temperature and flying behavior of particles, and then affect the quality of the coatings. So, it is desirable to study the heat and mass transfer between the particles and plasma jet.

The behaviors of in-flight particles in plasma jet directly affected the quality of coatings [3]. It was difficult to observe the flying trajectory of particles during heating and accelerating process by the experimental methods [4]. In order to research the flow and temperature field of particles, it is necessary to analyze the flight behavior of particles during spraying using numerical method [5]. With the rapid development of CFD methods, more and more researchers started to study the flight characteristics of particles by numerical methods [6–9]. Ahmed and Bergman [10] simulated the flight conditions of nanostructured zirconia particles. In their study, the melting and solidification of sprayed material was correlated to a spray processing parameter that has been introduced in the literature by some of the spray processing practitioners. Transition regions for the phase change response of the sprayed material to the thermal processing conditions were identified. The retained nanostructure content and liquid fraction of the sprayed material were correlated to particle diameters, injection velocities, as well as this thermal spraying processing parameter. They suggested that by using the powder which size distribution present bimodal size distribution as the coating material to obtain the desired coating structure. Li et al. [11] and Zhang et al. [12]

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defined a melting index to characterize the molten state of particles, which is related to the temperature, speed and diameter of particles. Feng Lajun [13] analyzed the velocity and temperature distributions of in-flight particles in the plasma jet using Runge–Kutta method. Li et al. [14] tracked the flight trajectory of particles by using Lagrangian method based on newton's second law. The model considered the influence of thermophoretic force, drag force, pressure gradient, etc.

Particles of powders injected into plasma jet are subjected to rapid acceleration and intense heating prior to becoming in contact with the substrate. The velocity of particles in supersonic plasma spraying is far larger than that in atmosphere plasma spraying. The liquid particles can evaporate and reduce their sizes. Knowledge of the properties of plasma jet and its interaction with sprayed particles covers the area of fluid mechanics and chemical engineering which are not well-mastered by materials or mechanical engineers and technicians, who are frequently involved in thermal spraying. Recently, numerical simulation for the supersonic spraying mainly concentrated in the study of physics and chemistry of plasma spraying, coating-build-up and properties of coatings. But the numerical simulation for the refined behavior of particles was rarely reported. Zhao et al. [15] simply analyzed the melting process of particles in supersonic plasma spraying, and studied the phenomenon of particle refinement by experimental methods. This project has studied the inside and outside flow characteristics of the spraying gun for the supersonic plasma spraying [16]. In this paper, a 3D computational model of spraying gun was built to study the features of plasma jet and its interactions with the sprayed particles. The heating and melting processes of single zirconia particle in the supersonic plasma spraying were also analyzed using CFD methods. The velocity and temperature of the flying particles were measured by SprayWatch-2i, and the morphology of particles was observed by Scanning Electron Microscope (SEM). The numerical results agreed well with the experimental data.

2. Numerical model

In order to simplify the computational model, it is need to make some assumptions, as following:

(1) Particle is assumed to be spherical with a constant size, without considering the phase change and particle deformation in the whole heating process.
(2) It is assumed that the particle's density, thermal conductivity, and latent heat of fusion are constants in simulation.
(3) The average intensity of plasma fluctuation is assumed to be constant during the interaction between particles and vortex.
(4) Without broke-up and evaporation occurs during the melting process in the study of heating and melting process for single particle.

2.1. Plasma governing equations

The governing equations for the SAPS plasma jet consist of the following several parts: continuity, momentum and thermal energy equations for the multi-component fluid mixture, species equations for each component of the mixture. Heat transfer from plasma is characterized by several distinct features, such as transport of dissociation and ionization energy and of electrical charges in addition to mass transport. All the model of the plasma therefore must contain not only the conservation of mass, momentum and energy, but also Maxwell's equation and current conservation [17]. The continuity equation can be represented as $\partial\rho_g/\partial t + \nabla(\rho_g\vec{V}_g) = 0$, where ρ_g is heavy particles density, $\vec{V}_g$ is heavy particles velocity vector. Plasma gas is a dense cloud of electrons, ions, atoms and molecules. The plasma-forming gas is $Ar + H_2$ in this paper. So the following species were considered: e, Ar, Ar^+, ArH^+, H, H^+, and H_2^+, and for including the effect of electronic excitation, hydrogen atom and argon species are taken in various possible excited states depending upon temperature. The species continuity equation can be represented as

$$\frac{\partial n_i}{\partial t} + \nabla\cdot(n_i\vec{V}_i) = \frac{d\omega_i}{dt} \tag{1}$$

The subscript i represents different species, n_i is the ith species particles number per unit volume/m^{-3}, $\vec{V}_i$ is the ith species particles velocity, $\frac{d\omega_i}{dt}$ is the ith species particles net change rate due to chemical reaction.

The Momentum conservation equation links the flow velocity of a fluid element with the external forces acting on it. The following equation is a general one, as the gravity force can be ignored, the last term can be omitted.

$$\rho\frac{d\vec{V}_g}{dt} = Fv_c - \nabla P_g - \frac{2}{3}\nabla\cdot(\mu\nabla\vec{V}_g) + \nabla 2\mu[\dot{\varepsilon}] \tag{2}$$

where the left term $\rho\frac{d\vec{V}_g}{dt}$ is the inertia force term, the right term Fv_c is volume force term which equal to the total force of mass force, electric field force and Lorentz force. ∇P_g is the gas pressure gradient. $\frac{2}{3}\nabla\cdot(\mu\nabla\vec{V}_g)$ is viscous stress causing the gas volume expansion, μ is the gas Dynamic viscosity. $\nabla 2\mu[\dot{\varepsilon}]$ is the viscous stress caused by fluid deformation when fluid move, $[\dot{\varepsilon}]$ is strain rate tensor. Due to charged particles movement in plasma, the energy equation should contain joule heat generation rate term caused by electromagnetic field $\vec{E}\cdot\vec{J}$:

$$\rho_g\frac{d}{dt}\left(\varepsilon + \frac{\vec{V}_g^2}{2}\right) = \nabla\cdot(\vec{P}\cdot\vec{V}_g) + \rho\vec{g}\cdot\vec{V}_g + \vec{E}\cdot\vec{J} - \nabla\vec{q} \tag{3}$$

where ε internal energy, is the heavy particles density, $\vec{q}$ is the heat through unit area in unit time.

The standard $k-\varepsilon$ model has been adopted in the numerical simulations of turbulent jet under plasma conditions [21,22]. Although the results predicted by the $k-\varepsilon$ model are not satisfactory, it still provided semi-quantitative information on the plasma jet.

The current density in the arc column of a typical high-intensity arc may reach values in excess of 10^6–10^{10} A/m^2. Arcs may attach to the electrodes, and in particular to the cathode, the current continuity equation is governed by:

$$\frac{\partial\rho_e}{\partial t} + \nabla\cdot\vec{J} = 0 \tag{4}$$

where ρ_e is the charge density, and $\vec{J}$ is the electric current density.

The control equation of DC plasma jet in steady condition can be expressed as:

$$\frac{1}{\mu}\nabla^2\vec{A} = \sigma_e\nabla\phi - \vec{J}_s \tag{5}$$

where $\vec{A}$ is the magnetic vector potential, σ_e is the electrical conductivity, ϕ is the electric potential, $\vec{J}_s$ is the other source term. The Lorentz force exists in the plasma jet produced by electromagnetic field. The Lorentz force $\vec{J}\times\vec{B}$ can add to the MagnetoHydroDynamic equation as a source term. In the equation current density can be express as:

$$\vec{J} = \sigma_e(\vec{E} + \vec{u}_e\times\vec{B}) \tag{6}$$