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Numerical Simulation and Experimental Investigation of Multi-function Micro-plasma Jet and Alumina Particle Behaviour

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Abstract. Turbulent flow in multi-function micro-plasma spray, as well as the trajectories and state-changing course of alumina particles in the plasma jet were simulated. The distribution of temperature and velocity of the plasma jet and in-flight alumina particles is discussed. Calculations show that particles are heated and accelerated sufficiently by the plasma flame due to a longer travel time than that of external injection system, therefore, possess higher temperature and velocity. Alumina particles temperature and velocity increase rapidly along the jet axis at the initial stage, but then decrease gradually. The velocity and surface temperature of in-flight alumina particles are measured by Spray Watch-2i system. The velocity and surface temperature of alumina particles measured agree well with the simulation results, confirming that the simulation model is suitable for the prediction of the turbulent flow and the particle characteristics, which also reveals the superiority of the plasma spray gun in this multi-function micro-plasma spraying system.

1. Introduction

Plasma spray process consists in injecting powder particles into a plasma jet where they are heated and simultaneously accelerated and after a given dwell-time, impact on the substrate to form lamellae, the stacking of which forming the deposit. A plasma sprayed coating is the result of the impact of melted and partially melted particles, their flattening and the corresponding splats layering on the substrate surface. Therefore, coating properties depend primarily on the particles behaviors prior to substrate, including mainly velocities, temperatures and sizes of particles in-flight [1].The higher is the velocity of the particles, the larger is the impulse force during deformation, hence the particles strike the substrate much more heavily, the deformation of particles is more sufficient, and with higher temperature, particles can be melted sufficiently, which is useful in increasing the area of contact region and contributes to improving the bonding strength of the coating. Therefore, a better understanding of the particle in-flight characteristics, such as velocity, temperature, and

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melting status, as well as the distribution of the plasma jet, will contribute to coating properties and optimizations of operation parameters [2].

In current work, multi-function micro-plasma spraying has been successfully developed [3]. Turbulent flow in this multi-function micro-plasma spraying, as well as the trajectories and state-changing course of alumina particles are simulated by combining standard *k-ε* turbulent model, particle heating and accelerating model and energy conservation. The distribution of temperature and velocity of the plasma jet and in-flight alumina particles is also discussed. The temperature and velocity of flying particles in the plasma flame are measured using on-line monitoring system the "Spray Watch-2i System", then the measured data are compared with simulation results verify the validity of the use of simulation.

2. Numerical Simulation of the Micro-plasma Jet

Basic Assumptions and Parameters at Nozzle Exit. In the plasma, rather complex physical and chemical reactions in the plasma jet will occur, however, conversation of energy still takes effect. So, a relationship of initial operation parameters and plasma jet velocity and temperature at nozzle exit can be established regardless of the complex reactions in the plasma torch. The present paper presents a 2D thermo-mechanical model based on the following assumptions: (1)The plasma is in local thermodynamic equilibrium, the temperature of the gas atoms, ions and electrons at a point are equal, and therefore can be characterized by a single temperature; (2)The plasma gas is ideal gas, which is composed of only one species: Ar; (3)Thermal physical characteristics of gas components are independent of practical states; (4) No energy is lost by radiation; (5)During a certain period, the plasma jet flow is a steady-state system.

As for plasma reactor, the input power is equal to the output power, which consists of mainly power taken by the cooling water, power heating the gas and power used for ionization. The temperature and velocity of the plasma jet on the torch axis can be theoretically derived from the basic processing parameters.

Governing Equations. Based on the determination of plasma jet velocity and temperature at nozzle exit and the gas components, boundary condition was decided, which is the key of the simulation result, a computational fluid dynamics (CFD) program FLUENT 6.0 was implemented investigate the distributions of plasma jet velocity and temperature. In this work, mass continuity equation, the momentum conservation equation and the energy conservation equation, as well as *k-ε* turbulence model are established. Finally, the velocity and temperature of the multi-function micro-plasma spray is simulated [4-6].

Numerical Simulation Results and Discussion. Figure 1 and figure 2 present distributions of the plasma jet velocity and temperature under typical operation condition， respectively. Arc current =250 A, argon flow rate = 25 l/min.

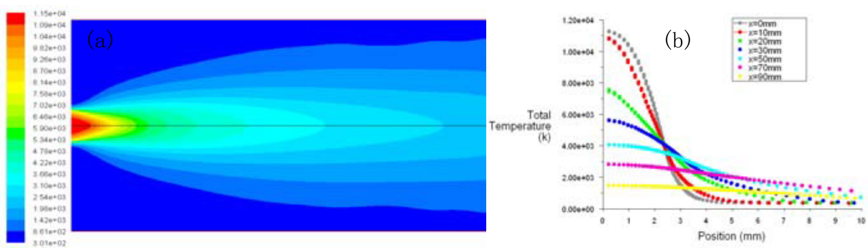

Fig.1 Spatial distribution of temperature of multi-function micro-plasma jet: (a) temperature contours (K); (b) temperature at different radial positions along the axis.

Figure 1(a) presents the spatial distribution of plasma jet distribution, it can be seen that the maximums plasma temperature exists at the nozzle exit about 11500K. As the plasma jet leaves far away from the nozzle, it is injected into the air and expands violently. There is no significant difference in the temperature near the torch exit within 10mm along the axis. At about 10 mm in the axial position, the ambient cold air begins to penetrate the jet, which causes the temperature decreasing rapidly. The temperature decreases with a rate of "slow, fast and slow again" both axially and radially.

Figure 1(b) shows plasma jet temperature at different radial positions along the axis. It is found that the temperature present the same distribution along both the axial and radial directions, however, even more obvious. At the outer boundaries, the temperature of the jet decreases and the temperature of the air increases. This means that, the plasma jet is cooled gradually by the ambient air. As the distribution of plasma jet temperature, maximums plasma velocity exists at the nozzle exit about 1560m/s and decreases slowly along the axis within 1～10mm shown in figure 2(a). After a steady decreases, the velocity reduce abruptly as the plasma jet injects into the air, the ambient air effect the plasma jet markedly after 10mm exiting the nozzle along the axis. As shown in figure 2(b) and figure 2(c), the plasma jet decreases first slowly affected little by the ambient air, and then reduce abruptly from a high velocity, finally reach a corresponding temperature with a full interaction with ambient air along the axis. Radial velocity behaves almost the same.

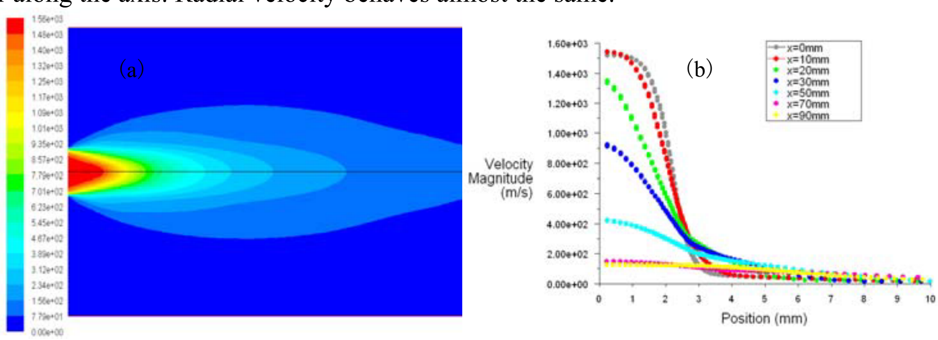

Fig.2 Distribution of velocity of multi-function micro-plasma jet: (a) velocity contours (m/s); (b) velocity at different radial positions along the axis.

3. Numerical Simulation of the Micro-plasma Sprayed Alumina Particles

Numerical Approach. Characteristics of alumina particles in plasma jet, such as velocity, temperature and the moving trajectory was calculated with the help of FLUENT 6.0 used in the anterior simulation of the plasma jet. alumina particles were discharge in the plasma jet which was calculated above. When flying in the plasma jet, several forces acted on the particles. The main force is drag force, gravity and the append force induced by the uneven distribution of gas dynamic parameters of the jet.

In this work, a two dimension model for the axis powder injection system was established. Injected axially, particles centralize along the axis of the plasma jet, thus receive more heating from the plasma jet and accelerate with a rather longer distance. Accordingly, particles possess higher velocity and temperature under the equal condition and the oxidation of particles is also reduced owing to enhanced protection from plasma jet, which results in higher coating properties. Figure 3 shows the alumina particles velocities and temperatures with axis powder injection, respectively. Particles temperature and velocity increase rapidly along the jet axis at the initial stage, but then decrease gradually; smaller particles possess higher temperature and velocity at the same axial position, but decrease much more rapidly with the increase of spraying distance.

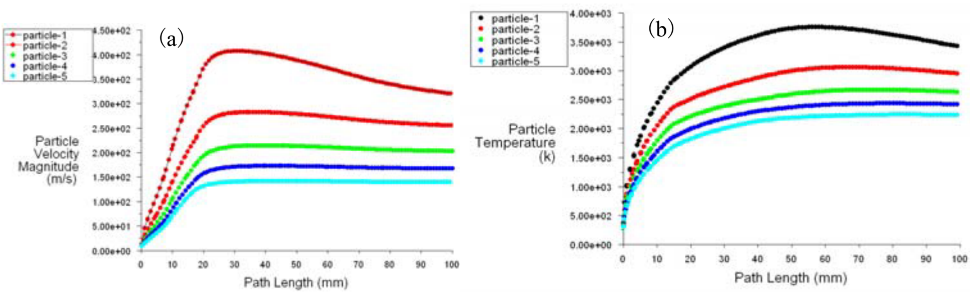

Fig.3 Velocity (a) and temperature (b) of alumina particles in the plasma jet.

In-flight Alumina Particle Measurement. The in-flight alumina particle temperature and velocity was measured using a spraywatch-2i system (made by Oser, Finland) at a distance of 40 mm. Alumina particles were deposited by multi-function micro-plasma spray with a mean size of 20 μm. The plasma spraying parameters include an arc current of 250 A, arc voltage 32 V, argon flow rate 25 l/min.

Table 1 shows the temperature and velocity of alumina particles during the multi-function micro-plasma spraying process. The velocities range from 399 m/s to 433 m/s, the temperatures are 3112 °C～3244 °C。According to simulation results, the velocity and temperature of a 20 μm alumina particle could reach 410 m/s and 3300 °C, respectively. In order to verify the availability of the simulation, practical measurement was carried out using spraywatch-2i system as above. The mean velocity of alumina particles is 418.4 m/s and the mean temperature reaches 3183.6 °C. Comparisons of the simulation results and measured ones reveal that the simulated temperature of the alumina particle is a little higher than that of measured one owing to neglecting the radiation losing of the plasma energy and energy losing of particles during flight in atmosphere, however, the velocity measured shows great agreement with the simulation, both of which indicate that the models for the plasma jet and the particles are effective.

Table 1 Test Results Of Temperature And Velocity Of Alumina Particles

Particles	Velocity (m/s)	Temperature (°C)
Particle1	399	3136
Particle2	418	3244
Particle3	420	3113
Particle4	433	3112
Particle5	421	3213
Mean vale	418.4	3183.6

4. Conclusion

With axis powder injection, particles centralize along the axis of the plasma jet, thus receive more heating from the plasma jet and accelerate with a rather longer distance. Accordingly, particles possess higher velocity and temperature and the oxidation of particles is also reduced, which results in higher coating properties. Simulation of multi-function micro-plasma sprayed alumina particles shows that temperature and velocity of alumina particles increase rapidly along the jet axis at the initial stage, but then decrease gradually, smaller particles possess higher temperature and velocity at the same axial position, but decrease much more rapidly with the increase of spraying distance. In-flight alumina particle measurement indicates that the practical values of alumina particles velocities and temperatures agree with simulation results, which in turn verify the availability of the simulation.

5. Acknowledgments

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