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Numerical studies of arc plasma generation in single cathode and three-cathode plasma torch and its impact on plasma spraying

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ABSTRACT

This paper is to study the characteristics of arc plasma torch generated by single cathode and three-cathode structure and their potential impact on plasma spraying. A comprehensive physical model is developed, which is capable of describing plasma generation, compressible reacting flow and its interaction with particles involving heat, momentum and mass transfer as well as particle melting and re-solidification. A computational scheme is also developed to solve the Navier–Stokes equations, Maxwell's equations and equations of particles' momentum, heat and mass transfer with plasma jet and particles' phase change. This scheme is applied to simulate thermal spraying processes using both single cathode and three-cathode plasma guns. Results show that plasma torch from the single cathode plasma gun shifts to one side, while that from the three-cathode plasma gun is axisymmetric along the jet axis with triangular structure on the jet cross sections. Temperature and velocity along the center axis are lower than those away from the jet axis in the three-cathode plasma torch. The regime with high temperature and velocity in the three-cathode plasma jet is larger than that in the single cathode plasma jet. By choosing a suitable injection position, the in-flight particles in the three-cathode plasma jet can be uniformly distributed within the high temperature and velocity region, and be heated and accelerated uniformly. The size of particles that can be fully melted is larger in the three-cathode plasma jet than in the single cathode plasma jet, therefore, beneficial to the coating quality.

1. Introduction

Plasma spraying technique has been widely used to produce various metallic and ceramic coatings. In plasma spraying processes, characteristics of plasma torch will have critical impact on in-flight particles' characteristics as well as coating quality. It was reported that three-cathode plasma spraying system may generate plasma jet with high stability since the anode arc root movement inside the plasma gun is largely avoided [1,2]. One of the three-cathode plasma torch systems – Triplex by Sulzer Metco might be a better tool for thermal spraying process, nevertheless, an optimal usage of this tool requires a good understanding of arc plasma generation, plasma jet formation and in-flight particles characteristics.

In practice, arc plasma generation is not accessible to direct measurement. Numerical study has thus been used to reveal the processes taking place inside the plasma torch. However, challenges in numerical simulations are at the proper handling of the strong interactions among electromagnetic, thermal and fluid fields especially in the cathodic and anodic arc attachment region whereas a variety of chemical and electrical phenomena occur. In the past, much work was carried out to simulate arc behaviors. Chen et al. [3] modeled free-burning arc based on local thermodynamic equilibrium (LTE) and chemical equilibrium approximation. Xia et al. [4,5] performed numerical study on atmospheric DC argon arc using a variable cathodic arc attachment model based on a simplified cathode sheath model developed by Lowke et al. [6], and compared with their previous results based on the fixed current density and temperature boundary conditions on cathode surface. Besides, models for anodic arc attachment have been developed and applied to single cathode plasma torch. For the steady state simulations, the location of the anode arc root is implemented by using the Steenbeck's principle of minimum power [7,8]. For the unsteady state simulations, Vardelle et al. [9–11] and Trelles et al. [12,13] predicted arc dynamic behaviors through specifying a hot gas column or artificially applying a high electrical conductivity channel near electrodes, respectively. Numerical investigation has also been extended to three-cathode

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Nomenclature

$\vec{A}$	magnetic vector potential, V s m^{-1}
$\vec{B}$	magnetic induction, T
C_D	drag coefficient
C_p	specific heat, J kg^{-1} K^{-1}
$\vec{E}$	electric field, V m^{-1}
e	the elementary charge, C
h	convective heat transfer coefficient, W m^{-2} K^{-1}
I	arc current, A
$\vec{j}$	current density, A m^{-2}
k	thermal conductivity, W m^{-1} K^{-1}
k_B	Boltzmann's constant, J K^{-1}
L_m	latent heat of fusion, J kg^{-1}
L_v	latent heat of evaporation, J kg^{-1}
M	molecular weight, kg mol^{-1}
$\vec{q}$	heat flux, J m^{-2} s^{-1}
p	pressure, Pa
r	radial coordinate, m
r_m	position of the melting interface, m
r_s	position of the re-solidification interface, m
T	temperature, K
T_f	film temperature, K
T_m	melting point, K
T_s	particle surface temperature, K
$\vec{u}$	velocity, m s^{-1}
$\vec{u}'$	velocity fluctuation, m s^{-1}
V_p	particle velocity, m s^{-1}
u, v, w	velocity components, m s^{-1}
x, y, z	coordinate, m

Greek symbols

ε	Emissivity
Φ	electrical potential, V
μ	viscocity, kg s^{-1} m^{-1}
μ_0	vacuum permeability, H m^{-1}
θ	circular coordinate, m
ρ	density, kg m^{-3}
σ_e	electrical conductivity in local thermodynamic equilibrium state, Ω^{-1} m^{-1}
$\vec{\tau}$	stress tensor

Subscript

cath	cathode
in	inlet
p	particle
t	turbulence
w	wall

Superscript

c	chemical reaction

plasma torch [14–18]. Simulation results show that the presence of the Lorentz force leads to the unification of three arcs at the downstream of the cathodes and more homogeneous velocity field at the torch exit. Subsequently, an intensive fluid can swirl into the convergent part of the torch chamber so as to form a threefold symmetrical distribution of temperature at the torch exit.

To understand the influence of plasma torch on thermal spraying, attention has also been drawn to the interactions between particles and thermal plasma jet. A large number of papers on numerical simulations are related to single cathode plasma spraying system with the extensive investigation on in-flight particles characteristics, such as particles acceleration, heating up, melting and re-solidification processes [19–29]. Most simulation models only consider the plasma jet exited from the plasma torch, and the conditions at the torch exit are given based on the measurement and theoretical estimation. In terms of three-cathode plasma spraying system, the limited investigation has been conducted for arc plasma generation inside the plasma torch, and interactions between the particles and plasma jet [14,15,30,31]. For example, Muggli et al. studied heat transfer between plasma jet and particles using a friction-heating model and neglected non-uniform temperature distribution within particles in-flight. This might be acceptable for metal particles. For ceramic particles with the size over 100 μm, the Biot number related to particle is higher than 0.01 and temperature gradient within the particle can be large. Heat transfer in the particle should be considered. For better prediction of particles in-flight characteristics, it is necessary to conduct a coupled simulation of plasma arc, plasma jet and its interaction with particles such as momentum, heat and mass transfer, as well as phase change.

This paper will present comparative studies on single cathode and three-cathode plasma spraying process. Firstly, a comprehensive physical model is presented to include arc plasma generation, plasma jet formation and particles' acceleration, heating up, melting and re-solidification processes. Secondly, an integrated computational scheme is discussed for the integral solutions of governing equations for the full process of thermal spraying including the transport for multi-species multiphase reacting flow, Maxwell's equations and equations of particles' momentum, heat and mass transfer with plasma jet and particle phase change process. Finally, numerical simulations are presented for thermal spraying processes based on single cathode and three-cathode plasma guns. Results will be analyzed including structure characteristics of the plasma arc, plasma jet and their impact on particles characteristics upon impacting on substrate.

2. Physical and mathematical model

DC plasma spraying process includes plasma generation, plasma jet formation, plasma jet – particle interaction, and coating formation on the substrate, as shown in Fig. 1. The plasma is initiated by a high-voltage pulse that creates a conductive path for an electric arc formed between cathode and anode. The electric arc then heats the working gas to a high temperature so that the gas is dissociated and ionized to form thermal plasma inside the plasma gun. Finally thermal plasma flows out from the nozzle exit of the gun to form plasma jet.

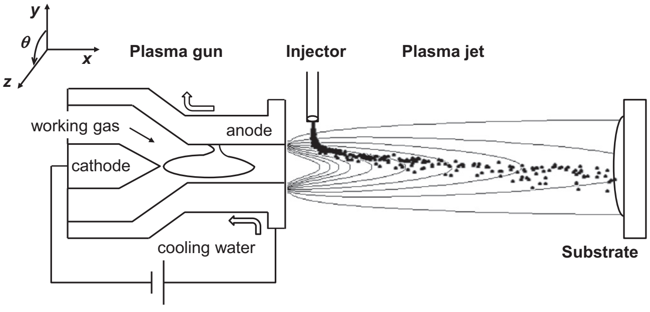

Fig. 1. Schematic of DC plasma spraying process.