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Finite element modeling of coating formation and transient heat transfer in the electric arc spray process

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ABSTRACT

The electric arc sprayed coating can be described as a superposition of Gaussian profile particles whose overlapping depends on the movement of spray gun. The heat transfer behavior during the deposition has a significant influence on the performance of the process. In this paper, simulation of the coating formation and analysis of the transient heat transfer were performed based on a newly developed finite element model, in which the dynamic stochastic multiple particles deposition characteristic of the process was taken into account. In order to investigate the effects of the kinematics and dimensional aspects on the coating/substrate temperature distribution, a traditional layer-by-layer finite element model without consideration of gun movement and particles Gaussian profile was also performed as a comparison. The stochastic deposition model provided a more objective result of the transient heat transfer of the coating/substrate than that of the layer-by-layer model, especially the severely inhomogeneous temperature distribution characteristics in different locations and spraying conditions. Finally, the molding results were experimentally compared with the temperature measurements on the coating surface and substrate back face using an infrared thermal imaging video camera, which shows that most of the modeling findings are consistent with that of the experiment.

1. Introduction

The twin-wire electric arc thermal spray process has been widely used as a cost-effective method in industry, especially in the fields such as components corrosion protection, wear resistance, and tools spray forming [1]. In the spraying process, two metal wires are connected the anode and cathode of a direct current power supply, and guided to the core of a high velocity gas jet where an electric arc is formed. Subsequently, the feedstock wires are melted, atomized and propelled out of the jet to impinge upon the substrate, resulting in solidification. Heat of the newly deposited particles is transferred to the ambient and lower splat layers or substrate by means of convection, radiation and conduction. In addition, phase change and variation of latent heat may take place during the solidification. The thermal transfer characteristic of the spraying process is therefore very complicated and highly transient with large amplitude excursions. Numerous studies have shown that, the temperature of coating/substrate during the deposition has a significant influence on the properties of the coating, such as residual stress, microstructure, oxidation, and adhesion/cohesion strength [2–6].

Thermal analysis and measurements of the electric arc sprayed coatings and other thermal spraying processes by using the instruments such as thermocouple, pyrometer and infrared thermal imager were much concerned in pervious literatures [7–11]. However, precisely measuring the transient temperature variation of the coating/substrate is a real challenge, because the hot particles are added on the substrate or previously formed coating surface dynamically and randomly with a simultaneous movement of the spray gun [12–14]. Numerical simulation provides another way to understand the details of temperature for the thermal sprayed coatings [15]. For example, Finite element and finite difference simulations of temperature field during the thermal spraying processes [16,17], where coating buildup was simplified as a layer-by-layer deposition model and the layer thickness was derived from the cross-section profile of an actual coating. Literatures [18,19] also reported a layer-by-layer finite element model (FEM) used to simulate the transient temperature distribution of plasma thermal sprayed coatings, and calculate the associated residual stresses of the coatings. However, most of them mainly concerned the high velocity oxygen flame (HVOF) or plasma spray process, instead of electric arc spray process.

Generally, the thermal sprayed coating can be described as a superposition of Gaussian profile splats whose overlapping depends on the process kinematics [20,21]. These kinematics and dimensional aspects ought to be considered when modeling the process [22,23], because the thermal histories of the individual particles may relate with the coating stress status, deformation

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Nomenclature

C	specific heat (J kg^{-1} K^{-1})
f	fraction solid or liquid of the deposit
h	heat transfer coefficient (W m^{-2} K^{-1})
ΔH_f	latent heat of fusion (J kg^{-1})
i, j	mesh integers
K	thermal conductivity (W m^{-1} K^{-1})
P	temperature load array (K)
$\dot{q}$	heat flux (W m^{-2})
r	radial distance (m)
R	outer radius of the specimen (m)
T	temperature (K)
t	time (s)
x, y	displacement in the x, y direction (m)

Greek symbols

Δ	finite change
δ	Stefan–Boltzmann constant (J m^{-2} s^{-1} K^{-1})
ε	emissivity
θ	difference time discrete factor
ρ	density (kg m^{-3})

Subscripts

a	ambient
dep	deposit
e	element
eq	equal
H	convection
$inter$	interface between deposit and substrate
l	liquid
n	step number
q	heat flow
Q	internal heat flow
rad	radiation
s	solid
sub	substrate

and phase transformation. Zhu et al. [24,25] developed a finite difference model (FDM) to analyze the temperature/time history of the electric arc sprayed particles deposition process, where the individual particles adding process was modeled by assuming a Gaussian distribution of particles around the axis of the spraying jet and the movement of the spray gun was taken into account. This study may represent the latest development of the applications of numerical modeling to the electric arc spray process.

This paper is mainly aimed to develop a stochastic multiple particle deposition model (in the following text, as called "stochastic deposition model") to simulate the transient heat transfer and coating formation of electric arc spray process using the finite element method. The finite element method has many advantages in the applications such as thermal and theomechanical coupled analyses [26,27]. In order to investigate the effects of the kinematics and dimensional aspects on the coating/substrate temperature distribution, a traditional layer-by-layer finite element model without consideration of gun movement and particles Gaussian profile was also developed. Comparisons between the stochastic deposition model and the layer-by-layer model were subsequently carried out under different electric arc spraying conditions, such as different gun traverse speeds and interruption spraying modes. Furthermore, an infrared thermal imaging video camera was used to monitor the sample surface temperature during the spraying, and the temperature histories at some specified positions were recorded and compared with the modeling results.

2. Finite element model

2.1. Governing equation and boundary conditions

During the electric arc spraying, as schematically shown in Fig. 1, metal droplets with high initial temperature are flattened and deposited on the substrate surface to form coating, the heat of the deposit is therefore transferred to the substrate and surrounding gas. The governing heat transfer equation for the coating structure in two dimensional Cartesian coordinates (x, y) can be written as

$$\rho C \frac{\partial T}{\partial t} = K\left[\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right] + \rho \Delta H_f \left(\frac{\partial f_s}{\partial t}\right), \tag{1}$$

where T is the material temperature, t is time, x and y are the displacements in x and y directions, respectively, ρ is the material density, C is the specific heat, K is the heat conductivity, ΔH_f is the latent heat, and f_s is the solid fraction.

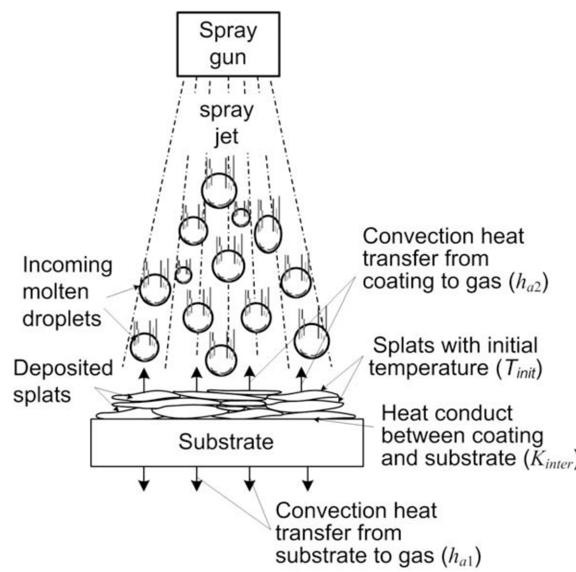

Fig. 1. Schematic physical and thermomechanical description of the electric arc spray process.

Eq. (1) can be transformed to

$$\rho\left(C - \Delta H_f \frac{\partial f_s}{\partial t}\right)\frac{\partial T}{\partial t} = K\left[\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right]. \tag{2}$$

Defining a term "equivalent specific heat" C_{eq} as

$$C_{eq} = C - \Delta H_f \frac{\partial f_s}{\partial t}, \tag{3}$$

a standard heat transfer equation without the last term of latent heat releasing in Eq. (1) is therefore obtained

$$\rho C_{eq} \frac{\partial T}{\partial t} = K\left[\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right]. \tag{4}$$

For the substrate, since the temperature variation is very low, the latent heat change can be ignored. Therefore, the equivalent specific