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Numerical and experimental investigations of splat geometric characteristics during oblique impact of plasma spraying

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ABSTRACT

Splats are obtained on the substrates inclined at different angles (0°, 20°, 40° and 60°) by plasma spraying process and characterized by SEM and WYKO® optical surface profiler. Numerical model is developed using CFD software FLOW-3D® to simulate the process of droplet impact, spreading and solidification onto the substrates. Splat characteristics such as spread factor, aspect ratio and fractional factor are defined and compared between simulation and experiment. Fair agreements are obtained. In addition, the impacting behavior including spreading and solidification are analyzed in details from the simulation results. The rates of reduction in droplet kinetic energy during impact, spreading and solidification are also compared between different inclination angles.

1. Introduction

Plasma spray coating – in which millions of molten droplets are propelled at high speed onto the substrate – is a well-established manufacturing process. This process allows manufacture of near net-shaped components, making it material and energy efficient, enhance manufacturing flexibility and cost saving. Although the process is promising, there are numerous parameters that could influence the properties of coating. Among which, dynamics of spreading, degree of solidification and conditions of the prepared substrate play an important role. Thus, considerable efforts have been devoted via theoretical, numerical and experimental investigations to improve the understanding of the process.

Assuming that solidification occurred subsequent to deformation, Madejski [1] proposed a model, considering only the effects of inertia and viscosity.

$$\xi = 1.2941Re^{0.2} \quad (1)$$

where ξ is the spread factor which defined as the ratio of splat diameter, d to droplet diameter, D_d: $\xi = (d/D_d)$, the Reynolds number, Re is $Re = (\rho u D_d/\mu)$; where ρ, u, D_d and μ are density, velocity, diameter and viscosity, respectively of an impinging droplet. Despite this simplification, the experimental investigations conducted by Vardelle et al. [2] largely supported the model. In addition, the spread factor model, experimentally derived by Kang and Ng [3], was a slight modified version of Eq. (1); i.e. $\xi = Re^{0.22}$.

However, only final splat dimensions can be determined by using Madejski's model. In order to impove coating quality, it is important to understand the underlying physics governing the spreading, solidification and adhesion of splat on the substrate. To achieve this, predictions of time history of droplet evolution have been carried out via computational studies. Trapaga and Szekely [4] examined the isothermal impact of a lead droplet using a three-dimensional code, FLOW-3D®. Their study focused on the relationship between the final splat diameter and operating parameters. By using modified SOLA-VOF method, Liu et al. [5] investigated the deformation and interaction behavior of multiple droplets, and Pasandideh-Fard et al. [6] simulated the spreading and solidification of a tin droplet on a flat stainless steel plate. A deformable finite element method was adopted by Fukai et al. [7] and Zhao et al. [8] to examine the effects of impacting droplet characteristics on coating properties. In order to predict efficiently the rate of solidification, spread factor and splat morphology, Zhang et al. [9] combined the VOF scheme with rapid solidification model. The simulation results revealed that the droplet and substrate temperature had significant influences on the melting depth of the substrate and adhesion of the splat. Abdellah El-Hadj et al. [10] adopted numerical approach to investigate the significance of surrounding gas temperature on splat morphology and the adhesion of splat on the substrate. A higher gas temperature was found to provide better adhesion. By integrating finite element method with volume of fluid and specific heat method, Zirari et al. [11] found that melting state of the particle had significant effects on the

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Nomenclature

Roman symbols

A	splat area (m^2)
A_d	area of the splat located downstream of the impact point (m^2)
A_x	fractional area opening to flow in the *x*-direction
A_y	fractional area opening to flow in the *y*-direction
A_z	fractional area opening to flow in the *z*-direction
$CLHT$	latent heat of fusion (J/kg)
C_l	fluid specific heat (J/kg K)
C_w	substrate specific heat (J/kg K)
d	splat diameter (m)
d_x	major diameter of an elliptical splat (m)
d_y	minor diameter of an elliptical splat (m)
D_d	droplet diameter (m)
f_x	viscous acceleration in the *x*-direction (m/s^2)
f_y	viscous acceleration in the *y*-direction (m/s^2)
f_z	viscous acceleration in the *z*-direction (m/s^2)
f_S	solid fraction
fr	fractional factor of the splat
F	volume of fluid value
h	fluid–substrate heat transfer coefficient (W/m^2 K)
I	macroscopic internal energy (J/kg)
k	fluid thermal conductivity (W/m K)
k_w	substrate thermal conductivity (W/m K)
K	kinetic energy (J)
$m_{i,j,k}$	mass of fluid in grid (*i,j,k*) (kg)
p	pressure (Pa)
q	heat transfer through a specific surface in a cell (W)
Ra	arithmetic surface roughness (μm)
Re	Reynolds number
t	time (s)
T	fluid temperature (K)
T_{DIF}	heat conduction diffusion (W/m^3)
T_{SOR}	fluid–substrate heat transfer (W/m^3)
T_w	substrate temperature (K)
u	velocity component in the *x*-direction (m/s)
$U_{i,j,k}$	velocity of the fluid in grid (*i,j,k*) (m/s)
v	velocity component in the *y*-direction (m/s)
V_F	fractional volume opening to flow
V_S	volume of splat (m^3)
w	velocity component in the *z*-direction (m/s)
wsx	wall shear stress in the *x*-direction (N/m^3)
wsy	wall shear stress in the *y*-direction (N/m^3)
wsz	wall shear stress in the *z*-direction (N/m^3)
W_A	interface area within the cell (m^2)

Greek symbols

μ	liquid droplet viscosity (kg/ms)
ξ	splat spread factor
ρ	liquid droplet density (kg/m^3)
ρ_w	substrate density (kg/m^3)
τ	viscous stress (N/m^2)
ψ	splat aspect ratio

morphologies of the splat. For the ease of tracking moving interfaces of droplet during impact, Xiong and Zhu [12] employed one of the mesh free methods, i.e. smoothed particle hydrodynamics model to investigate splat morphology due to the effects of substrate roughness and solidification.

The theoretical, experimental and numerical studies presented earlier have shed much insight on how a droplet spreads and solidifies after impinging at normal angle. However, for engineering component, spraying at other angles is usually required, in particular when there is no automation during the spraying process to sustain the spray torch at normal angles to three-dimensional complex-shaped substrates. Compared to vast studies on perpendicular impact, explorations on oblique impact are rather limited. Montavon et al. [13] statistically analyzed the geometric characteristics of experimentally captured splats due to the effect of oblique impact. Leigh and Berndt [14] reported an increase in porosity and reduction in adhesion strength with the increase in oblique angles. In order to quantify the spreading behavior of splats obtained at different inclined substrates, Kang and Ng [3] measured two geometric characteristics; i.e. spread factor and aspect ratio using surface profiler. Fitted quadratic equations were obtained. Bussmann et al. [15] developed a three-dimensional model based on the VOF-based RIPPLE code. Their results revealed that greater than 90% of material accumulated "downstream" of the point of impact. Smoothed particle hydrodynamics was applied by Zhang et al. [16] and the spread factor was found to increase with impact angle. This was different from the theoretical prediction by Madejski [1] and numerical calculation by Bussmann et al. [17].

In this study, both numerical simulation and experiments are conducted to obtain more insights on the impact, spreading and solidification of molten droplets due to oblique impacts. In the numerical simulation, complete solutions of the Navier-Stokes and energy equations, based on FLOW-3D® are used to model the process of droplet spreading and solidification during different angles of impact. Two experiments are conducted, with the first being the droplet in-flight velocity and temperature measurements using SprayWatch® and the other is splat capture and analysis testing. The first experiment provides input parameters required in the numerical simulation and the latter is to obtain splat geometric characteristics for comparison with simulated results. Brief description of experimental process, numerical procedure, discussions on the numerical results and comparison between simulation and experiments are presented in this paper.

2. Experimental methodology

Fig. 1 shows the experimental setup. The investigation is carried out using SG-100® plasma torch. The torch is operated at current of 900A and voltage of 35 V. Argon gas is used as primary and secondary gases. A roto-feed powder hopper (model 1264®) is used to introduce yttria-partially stabilized (8%) zirconia (YSZ) at the rate of 9.6 g/min and sprayed atmospherically onto the substrate. The standoff distance is 80 mm. Four cases with substrate inclination angles ranging from 0° to 60°, at intervals of 20° are conducted. The substrate inclination angle is defined as the angle between vertical plane (*Y*-axis) and substrate surface, as shown in Fig. 2. The substrate is inclined by means of the tilting mechanism behind the backing plate with the aid of spirit level and protractor. In order to provide reliable measurement of splat volume, the substrates are polished to a mean arithmetic surface roughness $Ra = 0.5$ μm. This is important as they provide consistent surface conditions for spraying experiment.

2.1. Splat capture experiment

At the beginning of the experiment, the substrate is preheated to an estimated temperature of 823 K by traversing it for 20 passes in front of the torch without powder supply (from previous experimental study by Gan [18]). This is because a preheated substrate is a necessity for obtaining well-formed splats (with regular shapes). After preheating, the backing plate, onto which the substrate is attached, is fast traversed in front of the