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Modeling the impact, flattening and solidification of a molten droplet on a solid substrate during plasma spraying

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ABSTRACT

It is quite important to clearly understand the dynamic process of single splat formation for optimizing the plasma spraying process. In present study, a three-dimensional model including heat transfer and phase change was developed on Ansys Fluent 14 platform to simulate the impact, flattening and solidification of a molten droplet on a solid substrate during plasma spraying. The phase, contact pressure, temperature and velocity fields at different spreading times were presented to gain an insight into splat formation mechanism. The predicted splat morphology was in good agreement with the experimental photos. The effect of mushy zone constant, a parameter dominating the solidification behavior of fluid in Fluent, on the flattening of droplet was further investigated. Through comparing the calculated spread factor from present model with the experimental value, a mushy zone constant of 10^8 or 10^9 was found to be more appropriate for simulation on the solidification problem occurring in high-speed impact and flattening process, instead of the range of 10^4–10^7 recommended in Fluent.

1. Introduction

Plasma spraying is an advanced surface treatment technology used to fabricate a variety of coatings to protect engineering materials against wear, corrosion, erosion and thermal shock [1]. In plasma spraying process, fine metallic or non-metallic particles are fed into a plasma jet, where they are melted and propelled to impact on the prepared substrate and form a thin splat. Coatings are built up by successive deposition of the droplets, thus the coating quality depends strongly on the adhesion between splat and substrate. In order to improve the coating quality or optimize process parameters, it is important to understand the formation mechanism of splat [1–3].

Considerable works have been devoted to understanding the splat formation process through numerical and experimental methods as reviewed by Chandra and Fauchais in Ref. [4]. Since the splat flattening and solidification in plasma spraying occur in a few microseconds, together with the device limitation, it is extremely difficult to thoroughly understand the underlying physics of splat formation by experiment [5,6]. In the last two decades, many efforts have been made to numerically investigate the droplet impact, deformation and solidification [4,7–10]. Bussmann et al. [11] developed a three-dimensional model by employing volume tracking algorithm to track the free surface of water droplet impinging on a solid surface. Pasandideh-Fard et al. [12] extended the work of Bussmann et al. [11] by adding heat transfer and solidification to the 3D model. The effect of thermal contact resistance on the spreading and solidification was investigated in his further work [13]. Later, there have been a growing number of techniques for simulation of droplet impingement, spreading and solidification [14–16]. Li et al. [17] calculated the transient contact pressure during the droplet impact process by using “Marker-And-Cell” technique. Abdellah El-Hadj et al. [18] investigated the splat formation under different surrounding gas temperatures using Ansys/Flotran code. Zhang et al. [19] applied a smoothed particle hydrodynamics (SPH) model, a meshfree method using a set of particle to represent the fluid, to study the droplet impacting and spreading problem. Kang et al. [20] performed a numerical investigation of splat geometric characteristics during oblique impact of plasma spraying using Flow-3D software. Kamnis and Gu [21] used famous commercial software Fluent to simulate the impingement of tin droplet on a plate. The same software was used by Alavi and Pasandideh-Fard [22] to study the thermal shrinkage phenomenon caused by the variation of density during the cooling and solidification process.

In Fluent, the solidification and melting is modeled by defining a mushy zone constant to measure the amplitude of the damping. The higher this value, the steeper the transition of the velocity of the material to zero as it solidifies. However, selection of the constant

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for plasma spraying received less attention in previous works. In this paper, the influence of the mushy zone constant on the flattening of droplet was investigated using Ansys Fluent 14. Meanwhile, the whole dynamic process of droplet impact, flattening and solidification were completely simulated by solving the fluid flow and energy equations on a 3-D Eulerian structured grid.

2. Numerical methods

Fig. 1 is a schematic sketch of the droplet impingement model. A molten droplet, which is initially assumed to be spherical and completely molten, impacts vertically on the stationary substrate and flattens and solidifies into a splat. The following assumptions were made while developing the model:

(1) The flow of molten droplet and surrounding gas was incompressible and laminar.
(2) Thermal contact resistance and surface tension were kept constant.
(3) The physical properties of the droplet, surrounding gas and substrate were constant.
(4) The heat transfer is dominated by convection and conduction modes, ignoring radiation from the droplet surface to the surroundings.

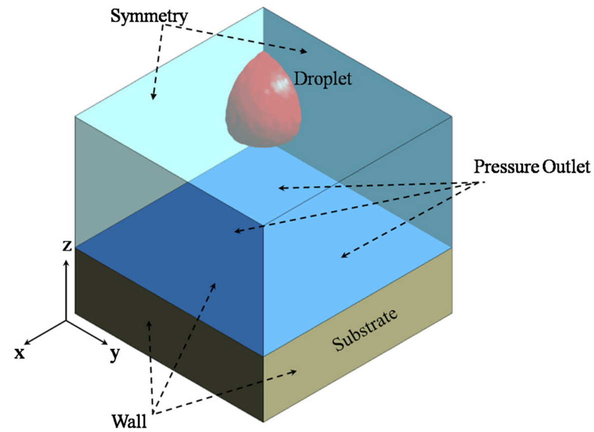

Fig. 1. Schematic of the droplet impingement model.

2.1. Governing equations

2.1.1. Fluid flow

The fluid flow and heat transfer in the molten droplet impact model are modeled by solving mass, momentum and energy equations discretized using a control volume based technique on a 3D Eulerian structured grid. The governing equations of mass and momentum conservations are presented as below:

$$\nabla \cdot u = 0 \tag{1}$$

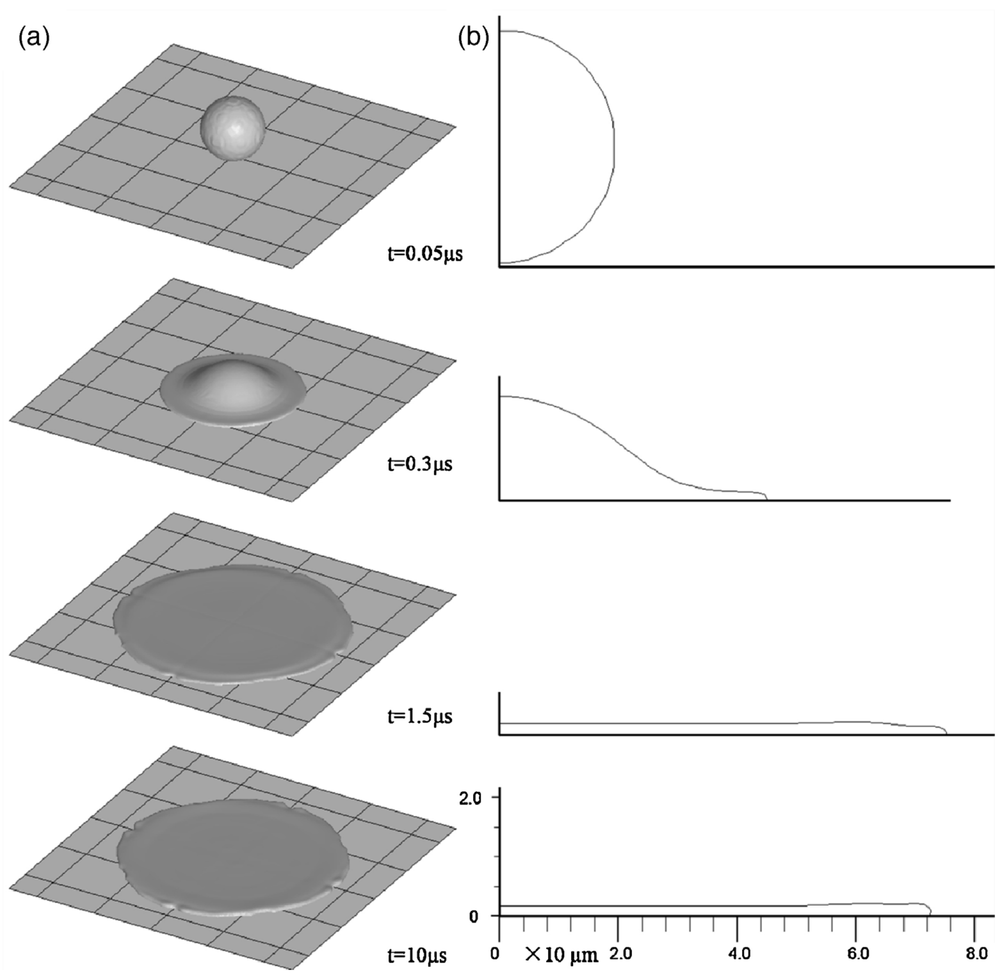

Fig. 2. (a) Flattening sequence of a 40 μm diameter zirconia droplet at 3250 K impact with a velocity of 100 m/s on the stainless steel substrate at 300 °C. The thermal contact resistance at the splat/substrate interface was 10^{-7} m^2 K/W. (b) Cross section of the splat at the corresponding times.