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Numerical simulation of splat formation dynamics in plasma spray forming

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Abstract: Plasma spray forming shows overwhelming advantages in rapid fabricating parts and moulds. The coating microstructure is strongly dependent on the splat morphology and inter-splat contact nature. Therefore, it is necessary to investigate the splat formation mechanism in order to analyze the coating properties. A dynamical process of a single fully molten droplet impacting onto a smooth surface was investigated. At the same time, the interaction between the two molten droplets in the horizontal and vertical directions was also simulated. Finally, the simulations of impact of a molten droplet on an inclined plane and a sharp edge were presented. It is concluded that the relative distance of the two droplets strongly influences the dynamics of the two droplets interaction. The various surface conditions have direct effects on the dynamics of splat formation. When a droplet impacts onto an inclined surface and a sharp edge, the splat morphology changes obviously and the phenomenon of break up is observed.

Key words: numerical simulation; droplet impact; splat formation; plasma spray forming

1 Introduction

Plasma spray forming is a versatile technique to manufacture thin-wall parts and molds with a wide choice of materials, such high melting-point metal, alloy or ceramic materials[1−2]. Thereby, it has become an important research trend internationally[3]. Many studies have revealed that the coating performance depends strongly on the quality of the cohesion of the deposited layers[4], which is then determined by the interaction between the droplets and the previous deposited splats. Consequently, research on the splat formation has become one of the most important fundamental subjects involved in plasma spray forming.

During the process of plasma spray forming, the melted or self-melted droplets are accelerated and injected onto the spray mould or the deposited layer. At impact, due to the sudden deceleration, the droplets flatten and the high-pressure inside forces the melted material to flow laterally and then solidify to form the splats. The complex phenomena during impact occur very rapidly on a microscopic and microsecond scale, therefore it is difficult and insufficient to study only by experiments. Due to the high cost of spray materials and equipments, the numerical simulation has become the relative more feasible method to research the splat formation at present[5].

A large number of numerical simulations have been implemented to simulate a single droplet impact and flattening on the smooth substrate. Different techniques have been proposed up till now. For example, HARLOW and SHANNON[6] firstly used the Marker and Cell (MAC) method to simulate the droplet flattening on a flat substrate. And the Arbitrary Lagrangian Eulerian approach (ALE) and the volume of fluid method are also the current methods applied widely in the field of fluid simulation[7−10]. In general, the finite element method and finite difference method are both widely used internationally with some commercial codes, for example, Flow3D, RIPPLE, ANSYS. The volume tracking and surface tracking methods have been widely applied to solve the key problem of tracking the free surface.

Compared with dynamic behavior of a single droplet impact, interactions between multiple droplets are more complicated. PASANDIDEH-FARD[11]

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modeled the sequential impact of two molten droplets on a solid surface with the help of the numerical codes of RIPPLE. GHAFOURI-AZAR[12] described a joint experimental and numerical study to predict the shapes of splats formed by two-droplet interactions with a low impacting velocity of the droplets.

In this study the volume of fluid technique based on the volume tracking was used to simulate the flattening process of a single molten droplet during the plasma spray forming. And the dynamic behavior simulation of two-droplet impact and interaction was also conducted. Finally, splat formation on various surface conditions was investigated. The simulated results gave us quite useful information of the dynamics of splat formation and interaction, which would be very helpful on the optimizing control of the spray forming process.

2 Numerical methods

Numerical simulations of the droplet splat formation have been conducted by basically solving the full Navier-Stokes and energy equations coupled with the volume of fluid approach to track the surface of the deforming droplet.

The fluid dynamics of the splat formation is governed by the equations of mass and momentum conservation:

$$\nabla \cdot \boldsymbol{v} = 0 \tag{1}$$

$$\frac{\partial \boldsymbol{v}}{\partial t} + (\boldsymbol{v} \cdot \nabla)\boldsymbol{v} = \frac{-1}{\rho}\nabla p + \upsilon \nabla^2 \boldsymbol{v} + \frac{1}{\rho}\boldsymbol{F}_{\mathrm{b}} \tag{2}$$

where $\boldsymbol{v}$ is the velocity vector, p and ρ refer to the pressure and the density, and υ and $\boldsymbol{F}_{\mathrm{b}}$ represent the kinematic viscosity and body force acting on the fluid.

Based on the popular theory that the splat solidification starts only after flattening is completed, it is assumed that the splat formation is an isothermal process. Consider the vertical impingement of a spherical droplet on a smooth flat substrate, the fluid flow is assumed to be laminar, viscous and incompressible. Based on the above assumptions, a two-dimensional, axis-symmetric model is developed. The governing equations are described using the finite element technique.

The volume of fluid algorithm is used to determine the shape and location of free surface based on the concept of a fractional volume of fluid. Consider the function f is defined as the fraction of a cell fluid volume.

$$f = \begin{cases} 1, & \text{with the liquid phase} \\ 0, & \text{without} \end{cases} \tag{3}$$

For a cell (i, j, k) of volume $V_{i,j,k}$, a volume fraction $f_{i j,k}$ is defined as[13]

$$f_{i,j,k} = \frac{1}{V_{i,j,k}} \int_{V_{i,j,k}} f \,\mathrm{d}V \tag{4}$$

The cell density of $\rho_{i,j,k}$ is defined as

$$\rho_{i,j,k} = \rho_f f_{i,j,k} \tag{5}$$

where ρ_f is the liquid density. It is clear that $f=1$ is deemed to a cell filled with liquid and $f=0$ represents for an empty cell. When $0<f<1$, the cell is considered to be occupied by a portion of fluid, termed an "interface cell". The volume of fluid advection equation of f is as follows:

$$\frac{\partial f}{\partial t} + (\boldsymbol{v} \cdot \nabla) f = 0 \tag{6}$$

In a volume of fluid analysis, a continuum-surface force (CSF) method is introduced to evaluate the fluid surface tension[14]. The CSF model reformulates the surface tension into an equivalent volume force $\boldsymbol{F}_{\mathrm{s}}$ as follows:

$$\boldsymbol{F}_{\mathrm{s}} = \boldsymbol{f}_{\mathrm{s}} \delta_{\mathrm{s}} \frac{\boldsymbol{F}}{\langle F \rangle} \tag{7}$$

where $\boldsymbol{f}_{\mathrm{s}}$ is the surface force, $\langle F \rangle$ represents the averaged volume fraction across the interface, and δ_{s} is the surface delta function:

$$\delta_{\mathrm{s}} = |\boldsymbol{n}| = |\nabla \boldsymbol{F}| \tag{8}$$

The surface tension is then incorporated into the flow equations to be a component of the body force acting on the free surface of the molten droplet.

3 Results and discussion

3.1 Dynamics of splat formation

In this study, the numerical simulation of a fully molten pure aluminum droplet flattening was conducted. The initial conditions and physical properties of spray material used in the numerical computation are listed in Table 1.

Table 1 Initial conditions and physical properties

Parameter	Value
Impinging droplet	Aluminum
Impinging velocity, v	50−100 m/s
Droplet diameter, D	30−50 μm
Droplet density, ρ	2.38×10^3 kg/m^3
Droplet kinematic viscous, υ	1.3×10^{-3} Pa·s
Droplet surface tension coefficient, σ	0.914 N/m

Fig.1 shows the 2D images of the flattening process of a 50 μm diameter molten aluminum droplet on the smooth substrate. The droplet with a velocity of 100 m/s falls onto the substrate. Due to the sudden deceleration, the droplet flattens and the high-pressure inside forces the melted droplet to spread out laterally into a disk-like shape, and the splat height decreases with the increase of

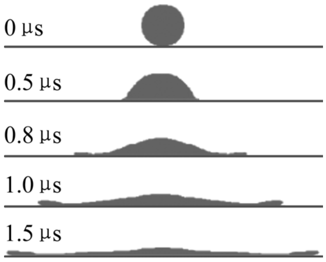

Fig.1 Dynamics of molten aluminum droplet impacting onto flat surface

spreading time. It is obvious that the liquid splat is symmetric around the droplet axis. Spreading and recoiling are the basic features of any droplet impact[15]. The kinetic energy provides the driving force of spreading, while the viscosity dissipation and surface tension of the flow are the resisting force, which may result in the phenomena of recoiling. With the diminishing of the droplet inertia, the surface tension pulls back the liquid to the center of the droplet and hence the splat rim recoils. Thereby, it can be clearly observed that the splat periphery is not the thinnest part, especially at the end of the flattening. In addition, it is noticed that there is an obvious warp between the spat rim and the substrate when the fluid is flowing. This is because the rim of flowing liquid spreads the most rapidly and the atmosphere around is then forced to push out, which results in the pressure forming between the front and the substrate. It can be deduced that when the liquid flows so fast that the gas does not escape absolutely from the gap between the liquid and substrate, the pore is formed, which would have a strong effect on the coating microstructure and properties.

3.2 Interaction between molten droplets

The interaction between molten droplets impacting onto the substrate has been proved so complex that only a little literature is related till now. In this study, a set of simulations on the two aluminum droplets collision were implemented in the horizontal and vertical directions. The dynamic process and final splat shape are quite sensitive to the droplet diameter, velocity and the offset distance between the centers of the two droplets. Great attention is focused on finding the effect of offset distance on the splat formation in this study. The results give us much insight into the dynamics of the molten droplets collision.

Fig.2 shows the collision between the two identical aluminum droplets of 50 μm in diameter with a velocity of 50 m/s in the horizontal direction. The offset distance between the two droplet centers is only 55 μm. It can be observed that the two droplets distort on the substrate simultaneously at impact. Each droplet spreads out radially and collides, and then joins with each other to form an uprising sheet, whose thickness and velocity were calculated by ROISMAN et al[16]. The effect of the relative location of the impact point on the interaction between the two droplets was studied. When the distance between the centers of the two droplets is elongated to 160 μm as shown in Fig.3, they do not touch with each other until almost the end of spreading, and then they join together only over a small uprising sheet. It can be seen that the splash occurs at 1.0 μs. This is because that the radial velocity of the splat rim is the fastest and when the two droplets collide, the liquid is then forced to divert to other directions, which may induce the phenomenon of splashing.

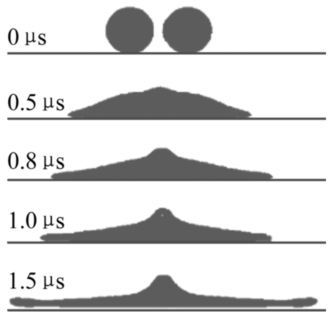

Fig.2 Interaction between molten droplets in horizontal direction with offset distance of 55 μm

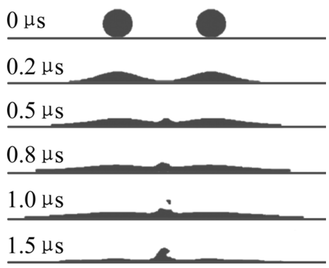

Fig.3 Interaction between molten droplets in horizontal direction with offset distance of 160 μm

Fig.4 shows the interaction between the two aluminum droplets with a diameter of 30 μm in the vertical direction. The upper droplet with the velocity of 50 m/s impacts on the lower one with the velocity of 100 m/s. It can be seen that the upper droplet lands on the flattening lower one, and then they join together and spread out radically into a disk-like shape. The final shape is quite alike with the single droplet impact.

Fig.5 shows a similar set of simulations with almost identical conditions to Fig.4. The difference is the offset distance of the upper droplet, which is 10 μm. It can be seen that the change in the impact position affects the splat morphology in the dynamics of droplet spreading. The final shape predicted is more elongated than that of Fig.4.

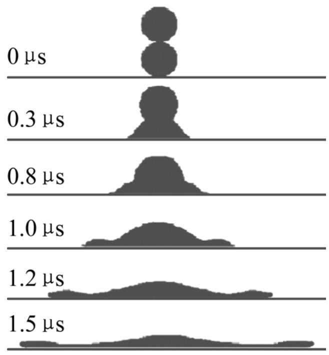

Fig.4 Interaction between molten droplets in vertical direction

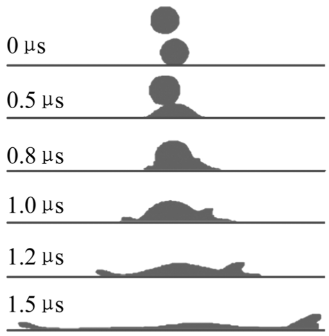

Fig.5 Interaction between molten droplets in vertical direction with offset distance of 10 μm

The simulations of impacting aluminum droplets, and their interactions, have shown the fluid mechanics taking place during the splat formation process. A conclusion is drawn that the dynamic behaviors and final shape are very sensitive to the offset distance between the two droplets centers.

3.3 Splat formation

During the process of plasma spray forming, the substrate surface may be various configurations. Thereby, it is necessary to study the splat formation under different substrate surface conditions. We focus most attention on the droplet impacting onto the sharp edge and declined substrate surface.

Fig.6 illustrates the images of a aluminum droplet with diameter of 50 μm impacting onto a sharp edge. The elapsed time, measured from the transient moment of impact, is given in the figures. The droplet with a velocity of 50 m/s lands on the sharp edge, and it is divided into two parts, with one part on the edge and the other down to the lower substrate. The kinetic energy of the droplet is gradually lost due to the viscosity dissipation and surface tension resistance when flattening. There is no significant fluid flow after 1.0 μs. But it is noticed that the phenomenon of break up occurs at 1.5 μs and the fluid recoils due to surface tension.

Fig.7 shows the simulated images of a 50 μm aluminum droplet impacting with a velocity of 50 m/s on

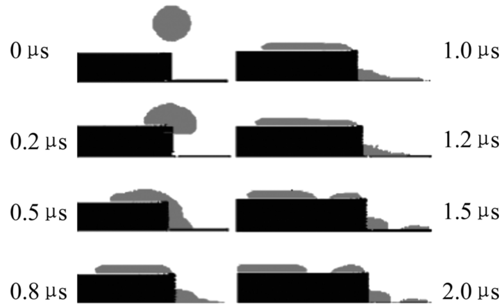

Fig.6 Dynamics of molten droplet impacting onto sharp edge

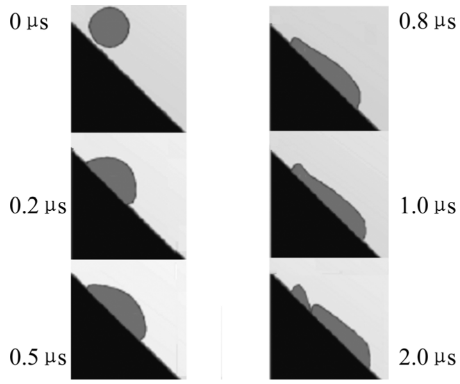

Fig.7 Dynamics of molten droplet impacting onto inclined surface

a surface inclined at 60° to the horizontal. The dynamics of the droplet early during impacting is similar to that during the normal impacting (as shown in Fig.1), and then the droplet begins slide down the inclined surface after 0.5 μs. By 1.0 μs, most of the droplet inertia has been consumed, and there is not very obvious further movement. It can be observed that the splat is elongated and divided into two parts at 2.0 μs. The final configuration of the splat is the thinnest at the topside and the splat thickness is increased with the distance from the top edge.

4 Conclusions

1) The fundamental dynamics of flattening droplet in plasma spray forming was investigated. Specifically, the interaction between molten droplets was studied. It is clear that the relative distance of the two droplets strongly influences the dynamics of the two droplets interaction.

2) Simulations of a molten droplet impacting onto an inclined surface and a sharp edge were presented. When a droplet impacts onto an inclined surface and a sharp edge, the splat morphology changes obviously and various surface conditions have direct effects on the dynamics of splat formation.

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