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ARTICLE

A Numerical Analysis on the Metal Droplets Impacting and Spreading out on the Substrate

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Abstract: The quality of 3D printing parts obtained by droplets deposition depends strongly on the mechanism of the interaction between the molten metal droplets and the substrate to be covered. The effects of various parameters such as impact velocity, substrate temperature, droplet diameters, specific heat, and thermal conductivity on the maximum spread factor during impacting and spreading with solidification of a molten droplet onto an aluminum surface under different parameters were studied. The free surface of the droplet was tracked by the volume-of-fluid (VOF) method. The simulation model was based on the N-S equations and the energy equations which included convection and phase change. These equations were coupled with the Level Set function to track the interface between molten particles and surrounding air. The maximum spread factors are obtained and agreement with the experimental data available in the literature.

Key words: impacting and spreading; metal droplets; impact velocity; substrate temperature

Rapid prototyping by deposition of metal droplets is an additive process in which components are produced from molten materials in a single operation without the use of any mold or other tooling. Near-net shaped parts are fabricated by sequentially depositing molten droplets layer by layer.

The motivation for this study came from research projects conducted by the molten metal deposition (MMD) research group at the University of the Texas at Arlington (UTA)[1]. Fig.1 provides a conceptual view of the overall process. It mainly consisted of a drop-on-demand generator, a droplet deposition system, a process monitor system and an inert environment control system. The pneumatic droplet generator was used to produce metal droplets on demand. It consisted of a droplet controller, a solenoid valve, a crucible, a heating furnace and a nitrogen gas resource. The droplet deposition system was used to form the parts by controlling the motion of a 3D platform according to data information. It consisted of a PMAC (program multiple axes controller), a 3D movement platform and the deposition substrate. The process monitor system which consisted of a CCD camera and an image acquisition card was used to observe the deposition process of droplets. The inert environment control system was made up of glove box and gas circulating device. It was used to protect molten metal from oxidizing. The whole process was coordinately controlled to complete the fabrication of prototype parts by industrial computer.

1 Literature Review

Despite of being studied over a century, a variety of parameters of metal droplets impacting and spreading onto a substrate have been the challenging problem for scientists due to their relevance to many engineering and industrial applications such as ink-jet printing, 3D painting and so on. So simulation of heat transfer and fluid flow during the impacting and spreading of molten metal droplets on a solid substrate are useful tools for better understanding and control of droplet deposition parameters[2]. Based on various impacting velocities and substrate temperatures, the

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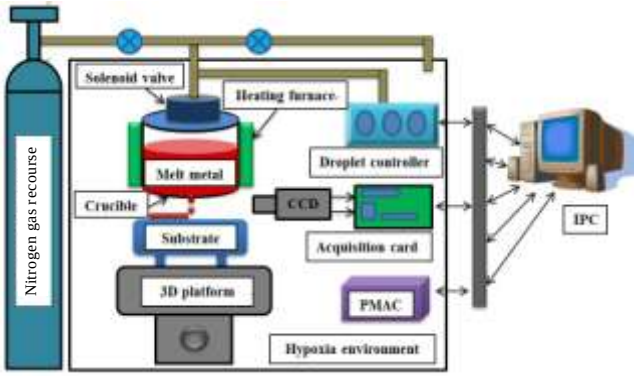

Fig.1 Schematic diagram

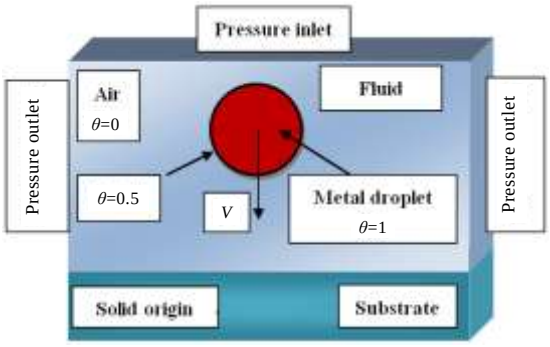

Fig.2 Initial configuration of the droplet

droplets can perform different behaviors[3,4]. Since then there has been much effort devoted to the studies of droplet impacting, motivated by the development of several technologies involving deposition of molten metal droplets on solid surfaces[5]. From a researcher's viewpoint, analysis of droplet impacting and spreading offers very interesting challenges[6-9]. But many of the physical phenomena involved were poorly understood, including flow of free molten metal surfaces. The problem becomes even more complex if droplets freeze while solidifying[10-12]. Thermal contact resistance between a surface and an impinging molten droplet has been estimated by measuring either the substrate temperature variation[13], or the cooling rate of a molten droplet after it spread on a metallic substrate[14,15]. However, in all these investigations the response time of the temperature sensors was much longer than the time taken for a droplet to spread during impact, so that their measurements are not applicable to the instant of initial impact on the surface.

2 Numerical Formulations

2.1 Boundary conditions

Fig.2 shows the geometry of the problem and the initial configuration at t =0 s; a spherical metal droplet of a diameter D_0 =200 μm impacts at a velocity V_0 =2 m/s onto a substrate at a normal incidence. The equilibrium contact angle chosen is 90°. The droplet has a density of 8474.4 kg/m^3. For the surrounding gas (air), the density and the latent heat have values of 1.3 kg/m^3 and 47560 J/kg, respectively. The liquid-gas surface tension has a value of σ =0.6 N/m. The coordinate system is represented by the axial coordinates (x, y) and we assumed that both fluids are incompressible and Newtonian. It is assumed that the surrounding gas has no effect on the deposition process.

The present paper mainly discusses collision of molten droplets of different diameters and impact velocities, considering the effect of air around the molten droplet and the heat-affected zone of heat that molten droplets send to the substrate. A two-dimensional model was used to simulate the impingement of a molten droplet onto a rigid substrate. The geometry of the problem and the initial configuration are shown in Fig.2. The geometry contains two domains: the fluid origin contains the metal droplet and the surrounding air while the solid origin contains the substrate only.

2.2 Flow dynamics

The fluid flow during the droplet spreading onto the substrate is modeled by the Navier-Stokes equations for incompressible flows as shown in (Eq.(1) and Eq.(2)):

$$\rho\frac{\partial V}{\partial t}+\rho(V\cdot\nabla)V=-\nabla P+\nabla\cdot\mu(\nabla V+(\nabla V)^T)+\rho g+F_{TS}+F \quad (1)$$

$$\nabla\cdot V=0 \quad (2)$$

where, V is the velocity, P is the pressure, ρ is the density, μ is the kinematic viscosity and g is the gravitational acceleration. F is the term source corresponding to the occurrence of the droplet solidification and F_{TS} represents the capillary forces given by Eq.(3):

$$F_{TS}=\sigma m\delta k \quad (3)$$

where σ, δ and m are the surface tension coefficient, the Dirac function and the average local slop of the curve at the liquid-gas interface, respectively. k is the normal at the liquid-gas interface. Both fluids are assumed incompressible and Newtonian, and the surrounding air has no effect on the deposition process. Other assumptions are that the liquid is incompressible and the fluid flow is laminar.

2.3 Advection on the interface

To track and follow the evolution of the interface between the two fluids (metal droplet and air), we have used the level set method[16,17] which has been proven popular in recent years for tracking, modeling and simulating the motion of moving interfaces or boundaries. In this method, the interface is represented by a certain level set or iso-contour of a globally defined function: i.e. the level set function θ. This function θ is a smoothed step function that equals 0 in a domain and 1 in its complementary

part. Across the interface, there is a smooth transition from 0 to 1 and the interface is represented implicitly by the 0.5 iso-contour (Fig.2). The interface moves with the fluid velocity *v*. This is described by following Eq.(4):

$$\frac{\partial\theta}{\partial t}+v\nabla\theta=\eta\nabla\left(\varepsilon\nabla\theta-\theta(1-\theta)\frac{\nabla\theta}{|\nabla\theta|}\right) \quad (4)$$

The terms of Eq.(4) give the correct motion of the interface, while those on the right-hand side are necessary for numerical stability. The parameters ε and η determine the thickness of the region and the amount of re-initialization or stabilization of the level set function, respectively. Any property α of the two fluids at the interface such as density, viscosity or thermal conductivity may be expressed as:

$$\alpha=\alpha_{\text{gas}}+\theta(\alpha_{\text{liquid}}-\alpha_{\text{gas}}) \quad (5)$$

The process of spreading and solidification of a molten droplet impinging onto a solid surface involves fluid flow, heat transfer and phase change. Complex phenomena involved are not thoroughly understood yet. For example, the interface between the droplet and the surrounding gas and between the liquid and solid phases remains a challenging problem to deal with for scientists and engineers.

2.4 Heat transfer and solidification

The heat exchange between the droplet, air and substrate is modeled by the energy equation Eq.(6):

$$\rho C_{\text{p}}\frac{\partial T}{\partial t}+\nabla.(-\lambda\nabla T)=-\rho C_{\text{p}}u.\nabla T \quad (6)$$

where T, ρ and C_{p} denote the droplet temperature, density and specific heat, respectively. The thermal contact resistance is introduced to take into account the discontinuity of temperature at the interface due to the non-perfect contact between the droplet and the substrate. The thermal contact resistance (T_{CR}) is modeled by defining a thin layer of arbitrary thickness L_0. The effective thermal conductivity K_{L} for the splat is related to the T_{CR} by Eq.(7):

$$K_{\text{L}}=\frac{L_0}{T_{\text{CR}}} \quad (7)$$

As the hot droplet spreads on the cold substrate, it cools down and solidifies. Many approaches have been used for modeling solid/liquid transitions. The enthalpy porosity method shows a good ability for modeling some complex problems involving phase change as crystal grows from the melt [18-20]. The specific heat C_{p} in the energy equation Eq.(6) is replaced by:

$$C_{\text{p}}=C_{\text{Psolide}}+\frac{\Delta H}{T_{\text{m}}}+\Delta H.\delta \quad (8)$$

where, f is a smooth Dirac delta function with nonzero values in a range of temperature equal to ΔT and its integration over temperature is equal to unity, ΔH is the latent heat of the transition, T_{m} is the melting temperature. ΔT is the temperature gap between liquidus temperature ($T_{\text{m}}+\Delta T$) and solidus one ($T_{\text{m}}-\Delta T$) and δ is a Gaussian curve given by Eq.(9):

$$\delta=\frac{\exp\left(-(T-T_{\text{m}})^2\Big/(\Delta T)^2\right)}{\Delta T\sqrt{\Pi}} \quad (9)$$

3 Results and Discussion

3.1 Impact and spread

Fig.3 shows the different stages of a 200 μm droplet impacting a substrate surface with a velocity of V=2 m/s in 2D model (Fig.3a). The results agreed well with those obtained experimentally by CCD (Fig. 3b).

The ultimate goal of this research is to predict the dynamics and the phase change of the impacting and spreading process. Fig.3 presents a history of the standard case where results are shown at selected time instants. The droplet starts its usual normal impact; then, as the heat leaves the droplet, its temperature falls. Once the temperature (actually, the enthalpy) falls below the solidification temperature, the liquid metal begins solidifying, forming a liquid/solid boundary. This liquid/solid boundary can be seen between 10 and 20 μs, after which the droplet is almost completely solidified. This liquid/solid boundary starts from the substrate and propagates upwards through the droplet. At about 30 μs the droplet has achieved its maximum spread. No rebounding is observed because the liquid metal solidifies along the substrate, which stops the outward flow and prevents it from rebounding [21].

3.2 Effects of several parameters

The ability to produce uniform droplets is only one aspect of the overall process. The impacting and spreading of these droplets onto a substrate also plays an important role. The focus of the present study is on these impacting and spreading phenomena, especially the solidification of liquid metal droplets impacting onto a rigid substrate.

The impacting and spreading of a molten metal droplet on a substrate surface has been extensively evaluated, using the maximum spreading factor $\varepsilon_{\text{Max}}=D/d$. The flattening degree is usually used to describe the droplet evolution in this study. A VOF model using finite volume analysis has been proposed to simulate the impacting and spreading of a droplet onto a substrate, taking into account the effect of the diameters of droplet, the impact velocity and the substrate temperature which are the most important parameters necessary to understand, clarify to control the impacting and spreading of droplets.

The effects of several parameters on the maximum spread factor ε_{Max} have been determined and the simulation and experimental results are shown in Fig.4~8.

The impact velocity of the droplet has been determined to have the most important influence on the maximum spreading factor ε_{Max}. Fig.4 presents ε_{Max} as a function of

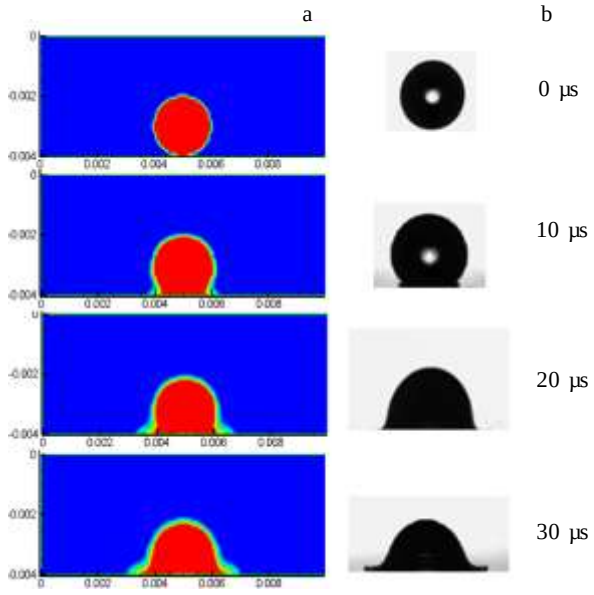

Fig.3 Impact and spreading of a 200 μm droplets: (a) 2D simulation and (b) experimental results

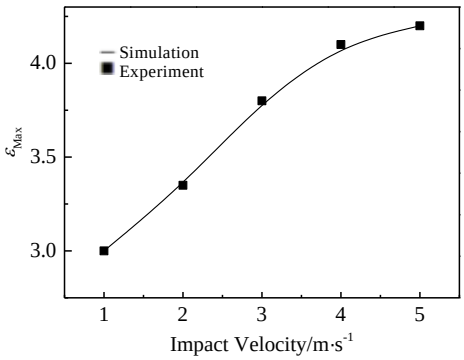

Fig.4 Results of impact simulations maximum spread factor ε_{Max} vs impact velocity

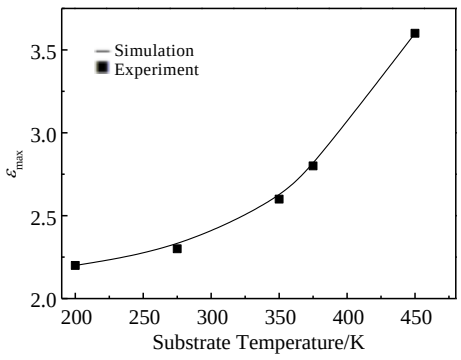

Fig.5 Results of impact simulations maximum spread factor ε_{Max} vs substrate temperature

the impact velocity. When the droplet impacts and spreads without solidification, the faster the impact velocity, the larger the spread factor and the faster the droplet spreads. The main difference is that the maximum spread factor ε_{Max} is smaller during the solidification because when the droplet starts solidifying, the outward flow of the fluid is inhibited.

The substrate temperature, T_s, is the second parameter studied. The influence of this variable on the spread factor has been found to be substantial. As shown in Fig.5, the higher the substrate temperature, T_s the farther the droplet spreads. This is because the higher the substrate temperature (which yields a smaller temperature difference between droplet and substrate), the lower the heat transfer rate, which, in turn, allows the droplet to dissipate the energy at a slower rate. The droplet thus spreads farther before it is arrested by solidification.

The influence of droplet diameter on the impacting is shown in Fig.6, where maximum spread factor ε_{Max} versus droplet diameter is plotted. As droplet diameter decreases, the surface tension effect increases, exerting larger resistance against the droplet spreading. For the diameter range studied, the maximum spread factor appears to vary linearly with the droplet diameter.

The effect of the specific heat, C_p, on the impact process is given in Fig.7 which shows a monotonic increase of maximum spread factor with specific heat. This is because higher C_p, which represents a higher energy storage capacity, has more energy to transfer to the substrate. Such as, for a given temperature difference, the process of energy transfer takes longer for larger C_p. The effects of C_p on the maximum spread factor appear to be relatively small.

Fig.8 shows that the higher the thermal conductivity, the lower the spread factor. This reduction in spread is caused by the increased rate of heat conduction throughout the droplet. The faster the heat is transferred throughout the droplet, the faster the spread is arrested by solidification on the substrate surface.

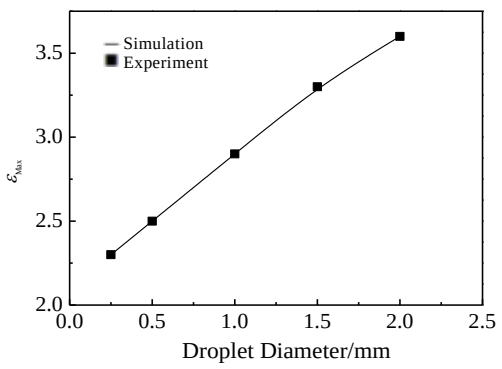

Fig.6 Results of impact simulations maximum spread factor ε_{Max} vs droplet diameter

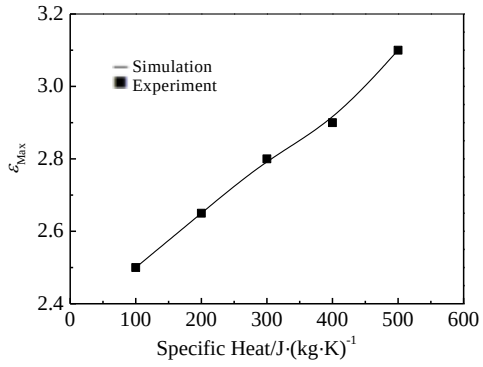

Fig.7 Results of impact simulations maximum spread factor ε_{Max} vs specific heat

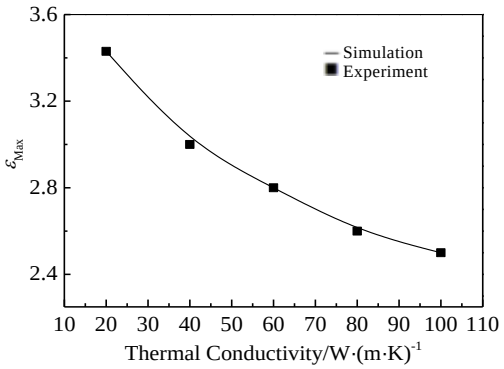

Fig.8 Results of impact simulations maximum spread factor ε_{Max} vs thermal conductivity

4 Conclusions

1) The dimensional analysis is used to yield a group of dimensionless parameters. A correlation that predicts the ε_{Max} as a function of some dimensionless numbers is obtained.

2) The correlation agrees with the experimental data available in the present study, suggesting that the basic impacting and spreading mechanism has been revealed in the numerical model. These include the metallurgical or chemical changes at the interface between substrate and droplet and the effect of oxidation on the substrate. Some of these interactions, although known, are very difficult to quantify to such an extent that they can be incorporated into a computer program. The authors believe, however, that even though the computer simulation presented here does not include all interactions, it does provide a good approximation of an actual impacting metal droplet within the confines of the above stated assumptions.

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金属熔滴碰撞、铺张数值分析

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摘 要：基于金属熔滴沉积成形的 3D 打印技术，金属熔滴沉积成形质量与金属熔滴及基板参数有很大关系。对金属铝熔滴在不同参数下(比如：熔滴直径、滴落速度、比热、导热系数、潜热以及基板温度等)凝固过程中的最大铺展因子关系进行了研究。采用 VOF 对自由表面进行追踪的方法，建立包括对流和相变的计算方程和能量方程的仿真模型，耦合水平集函数，跟踪熔融粒子与周围空气之间的接口，获得的最大传播因子之间的关系，与在文献中出现的实验数据吻合。

关键词：碰撞与铺展；金属熔滴；碰撞速度；基板温度

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