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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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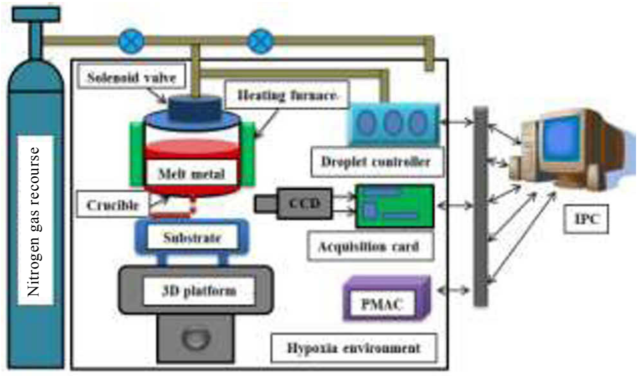


Fig.1 Schematic diagram

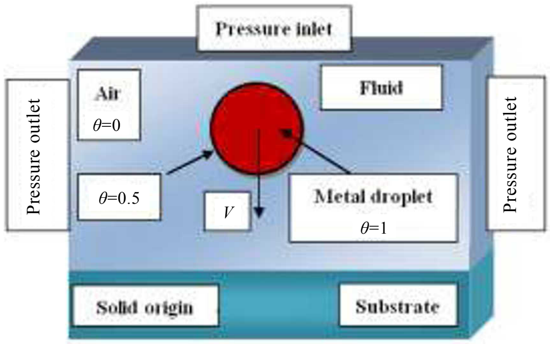


Fig.2 Initial configuration of the droplet

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 $\sigma$ =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)):

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

$$\nabla\cdot V=0 \tag{2}$$

where, $V$ is the velocity, $P$ is the pressure, $\rho$ is the density, $\mu$ 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):

$$F_{TS}=\sigma m\delta k \tag{3}$$

where $\sigma$, $\delta$ 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 $\theta$. This function $\theta$ is a smoothed step function that equals 0 in a domain and 1 in its complementary