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ARTICLE

Experimental Investigation of the Overlap Process in Metal Droplet Successive Deposition and Solidification

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Abstract: This paper presents a systematic numerical and experimental investigation of the transient transport phenomenon during the overlap of successive aluminum droplets impinging onto a substrate surface. The 3D models based on a volume of fluid (VOF) method were developed to investigate the successive deposition of molten metal droplets on a horizontally fixed aluminum substrate surface. The numerical models are validated with experiments. The comparisons between numerical simulations and experimental findings show a good agreement. The effects of various parameters such as impact velocities, substrate temperatures and droplet diameters on the maximum spread factor during impacting and spreading with solidification of a molten droplet onto an aluminum substrate surface under different parameters were studied. Based on the above research, the relationships between external morphology and internal microstructure were proposed, which was further certified by investigating the overlap of successive droplets.

Key words: metal aluminum droplets; successive deposition; morphology; internal microstructure

3D printing by deposition of metal droplets is an additive process in which parts 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, which was described by Li et al[1]. Compared to other metal additive manufacturing technologies, it possesses the obvious advantage of the lower cost of equipment.

Up to now, the two main modes of molten metal droplets deposition technology are continuous jetting (CIJ) and drop-on-demand jetting (DOD). In the DOD mode, the metal is firstly melted in a crucible, and then the liquid metal droplets are ejected from a nozzle under the combined actions of pulse pressure, surface tension and gravity. Finally, the molten droplets are deposited on a moving substrate to form 3D metal components, described by Chao et al[2]. The molten metal in crucible deposits onto a moving substrate with drop-on-demand (DOD). Cao and Miyamoto[3] believed that this technique should be an effective and low-cost method for building metal parts directly.

Metal droplet deposition process was proposed by MIT in early 1990 s[4]. Thereafter, the process was studied in Northeastern University[5], Oak Ridge National Laboratory[6], University of Toronto[7] and so on. However, the research was forced on low-melting point alloys in American Microfab Company[8].

When this technique was applied to aluminum alloy which had more practical value in industrial areas, there were more difficulties because of its higher melting point and larger surface tension than low-melting-point alloys. Currently, the simulation works[9] related to droplets deposition and overlap processes were mainly based on 2D models, which focused on the single droplet impinging onto a fixed substrate surface. However, 2D models could not provide comprehensive details of the deposition process. Thus, a 3D model has been developed to study complex flows in the successive deposition process of droplets.

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Ghafouri-Azar et al[10] investigated the impinging of two tin droplets with the diameter of millimeter scale, and simulated the overlap behaviors of droplets. Cheng et al[8] investigated the overlap process of droplets by assuming that the impinging droplets were pre-deformed into cylindrical discs with a given thickness. The droplet morphology was considered as a disc after impacting onto a substrate and the fluid dynamics of spreading and overlaps of droplets were neglected.

Li et al[11,12] investigated the process of 3D parts by DOD technique; droplets were deposited onto a horizontally moving aluminum substrate surface and overlap each other to form a column. However, successive deposition and solidification of molten metal droplets on the horizontally fixed substrate have not been studied. In the present paper, the successive deposition and solidification of molten aluminum droplets on a horizontally aluminum substrate were numerically simulated by the 3D model based on the volume of fluid (VOF) method, and the 3D images of morphology evolution of droplets were also discussed.

1 Modeling and Analysis

Fig.1 shows the schematic diagram of experimental system, and the experimental system mainly consists of pneumatic droplet generator, droplet deposition system, process monitor system and inert environment control system. The pneumatic droplet generator is used to produce metal droplets on demand. It consists of a droplet controller, a solenoid valve, a crucible, a heating furnace, an electromagnetic device and a nitrogen gas resource. The droplet deposition system is used to form parts by controlling the motion of 3D platform according to data information. It consists of PMAC (program multiple axes controller), 3D movement platform and deposition substrate. The process monitor system which consists of a CCD camera and an image acquisition card is used to observe the spraying and deposition process of droplets. The inert environment control system is made up of glovebox and gas circulating device. It is used to protect molten metal from oxidizing. The above four parts are coordinately controlled to complete the fabrication of sample by industrial computer.

2 Experimental Model

This paper aims at developing a 3D model of successive deposition of uniform molten metal droplets on a stationary substrate. So, the model consisted of the droplets and a substrate, the schematic of the initial free surface and the boundary conditions for the overlap process is shown in Fig.2. A rigid free-slip condition was applied to the substrate surface, and pressure outlet conditions were prescribed for the upper and outer boundaries. In addition to these conditions, an adiabatic boundary condition is applied on all free surfaces.

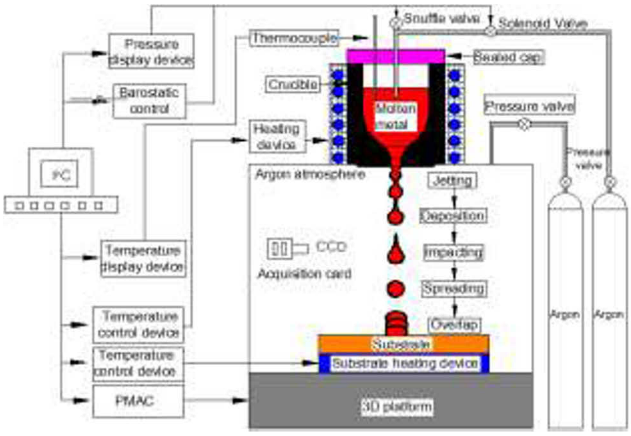

Fig.1 Schematic diagram of experimental system

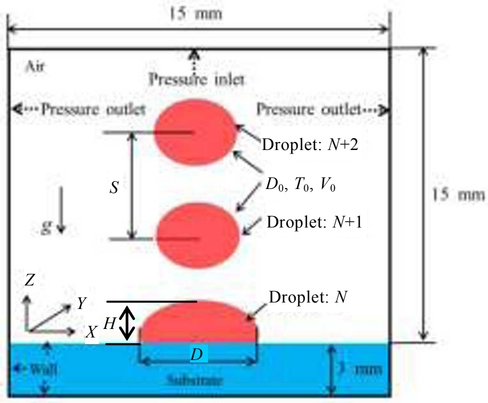

Fig.2 Schematic of the successive droplets deposition

Several assumptions have been made as follows:

(1) The droplets with spherical morphology are generated.

(2) The initial temperature distribution within droplets is uniform.

(3) The surrounding gas is considered as a void region, and thus the heat loss of droplets by convection and radiation are ignored[13,14].

To validate the numerical model, experimental observation of the end-shapes of successive droplets was performed to compare and validate the numerical results. Aluminum droplets with a diameter of 1 mm and an initial temperature of 935 K were generated and successively deposited onto an aluminum substrate; the relevant thermo-physical parameters of the molten droplet and the substrate material are listed in Table 1. During deposition, the metal material was firstly melted in a crucible, and then the liquid metal droplets were ejected from a nozzle under the combined actions of pulse pressure, surface tension, and gravity. A nozzle with 0.5 mm diameter was located at the bottom of the crucible, which was built in a resistance furnace.