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Effect of the surface morphology of solidified droplet on remelting between neighboring aluminum droplets

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ABSTRACT

Good metallurgical bonding between neighboring droplets is essential in droplet-based 3D printing. However, although the mechanism of remelting has clearly been mastered, cold laps are still common internal defects of formed parts in uniform aluminum droplets deposition manufacturing, which is due to the overlook of the surface morphologies of solidified droplets. Here, for the first time, the blocking effect of ripples and solidification angles on the fusion between droplets is revealed. To investigate the detailed process of remelting, a 3D numerical model was developed, basing on the volume of fluid (VOF) method. Experiments and simulations show that the remelting process between neighboring droplets can be divided into two stages according to the transient contact between the second droplet and the substrate. In the first stage, a non-intuitive result is observed that cold laps can also be formed even if the remelting conditions are satisfied in theory. Ripples on the surface of previously-deposited droplet block its direct contact with the new-coming droplet. In the second stage, cold laps on bottom surface are formed due to incomplete filling of liquid metal when the solidification angle is greater than 90°. Furthermore, these cold laps are difficult to be completely avoided by improving the temperature parameters. To address this problem, a novel strategy of decreasing the thermal conductivity coefficient of the substrate is proposed. This method effectively promotes remelting between droplets by eliminating ripples and decreasing solidification angles.

1. Introduction

Droplet-based 3D printing is a kind of novel direct-write techniques [1,2], and it is considered to be a promising method for numerous applications, such as printing of flexible circuits [3,4], advanced electronic components [5,6] and metal parts [7]. In the manufacturing processes, uniform metal micro-droplets as the basic building blocks are sequentially deposited onto a programmable substrate to fabricate complex 3D parts from their CAD models. However, due to the high temperature gradient and large surface tension of molten aluminum alloys, it is still a huge challenge to directly print high-quality structures from molten aluminum droplets.

Fusion behavior at the droplet/droplet interface is a fundamental issue in printing 3D metal structures. Poor remelting between neighboring droplets will lead to defects, such as cold lap pores, which result in the decrease of metallurgical bonding [8]. To determine the critical conditions of remelting, a calculated model of the interfacial temperature between neighboring droplets was developed [9]. The thermal behaviors of single droplet [10,11] and multi-droplets [12] sequentially impacting on substrates were investigated by experimental and numerical studies. The proper temperature parameters for achieving good metallurgical bonding between neighboring droplets were then ascertained [13]. Moreover, the scanning steps were optimized to decrease the inner porosities of the formed parts in droplet-based 3D printing [14]. However, the performance has not been significantly improved, cold lap pores are still common internal defects of the formed parts in aluminum droplets 3D printing. Therefore, other influencing factors in remelting have to be considered.

A number of theoretical and experimental studies [15–18] on molten metal droplets impact suggest that some ripples will be formed on the droplet surface after the complete solidification of the droplet. The reason of this phenomenon is that the solidification of metal droplets is always accompanied with underdamped oscillation, which is subsequently “frozen” by phase change to become ripples with different

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scales. Furthermore, because the surface tension of molten aluminum droplet is relatively large and the solidification process is rapid, the solidification angles of the deposition aluminum droplets are usually larger than 90° [16,19,20]. These facts bring us to the question that whether these surface morphologies influence the remelting behavior between neighboring droplets in 3D printing. However, this interesting case has yet to be well studied.

The present work aims to investigate the effect of surface morphologies of solidified droplets on the remelting behavior between neighboring droplets during the horizontal deposition process. To this end, some droplet deposition experiments were conducted, and a 3D numerical model was also developed, basing on the VOF method. By comparing the experimental and simulation results, the remelting process between two neighboring droplets is divided into two stages according to the transient contact between the second droplet and the substrate. The influencing mechanism of surface morphologies, including ripples and solidification angles, was then revealed by experiments and simulations. Finally, a method of using a substrate with relatively lower thermal conductivity was proposed. The corresponding experimental results verify that this proposed method can effectively promote the remelting between neighboring droplets by eliminating ripples and decreasing solidification angles.

2. Experimental and numerical approach

2.1. Experimental approach

As shown in Fig. 1(a), the uniform aluminum droplet deposition manufacturing system mainly consists of a uniform metal droplet generator, a droplet deposition subsystem and a hypoxic condition control subsystem. In short, this system works as follows. First, the metal blank was grinded to remove its oxide skin and then melted in a graphite crucible. A vibration bar was driven by a specified waveform which was created by a pulse generator. Under the periodical vibration of the ceramic bar, the liquid metal was forced out of a nozzle to generate uniform molten metal droplets. During the ejection process, the piezoelectric actuator was placed in a cooling case, and the liquid metal could maintain filling the cavity in the crucible under the back pressure. The droplet deposition subsystem consisted of a programmable multi-axes controller (PMAC), a substrate and a 3D programmable platform. The motion of the platform was controlled according to the computer numerical control (CNC) file generated by model design and slice software process. As shown in Fig. 1(b), under the cooperative control of droplet ejection and platform movement, the metal droplets were sequentially deposited and fused together to fabricate 3D structures. The temperatures of molten metal droplets and substrate were measured and controlled by heater controllers. During the uniform droplet deposition process, the metal droplet generator and the 3D platform were both enclosed in an argon gas environment. The oxygen and water vapor content of the argon gas environment was kept below 1 PPM (parts per million) to prevent the molten aluminum droplets from being oxidized. The above subsystems were coordinately manipulated by an industrial personal computer (IPC) to complete the fabrication of complex shapes.

In the deposition experiments, two 99.999% aluminum rods with the dimension of 35 mm × Φ20 mm were put into the graphite crucible and heated to a preset temperature. Uniform droplets were ejected out at a rate of 1–10 Hz through a nozzle of ~450 μm in diameter. The perpendicular distance between the substrate and the nozzle was ~10 mm. H59 brass and one kind of silver-plated ceramic (which are commonly used in advanced electronics) were chosen as the materials of the substrate. 99.998% Argon gas was supplied to maintain an inert atmosphere to eliminate the oxidation of the molten aluminum droplets during the deposition process. The micro-morphologies of the deposition samples were obtained by using a scanning electron microscope (VEGA3-TESCAN).

2.2. Numerical approach

To analyze the detailed fluid flow and thermal behavior during the aluminum droplets horizontal deposition process, a 3D simulation model was developed, basing on the VOF method. The mathematical

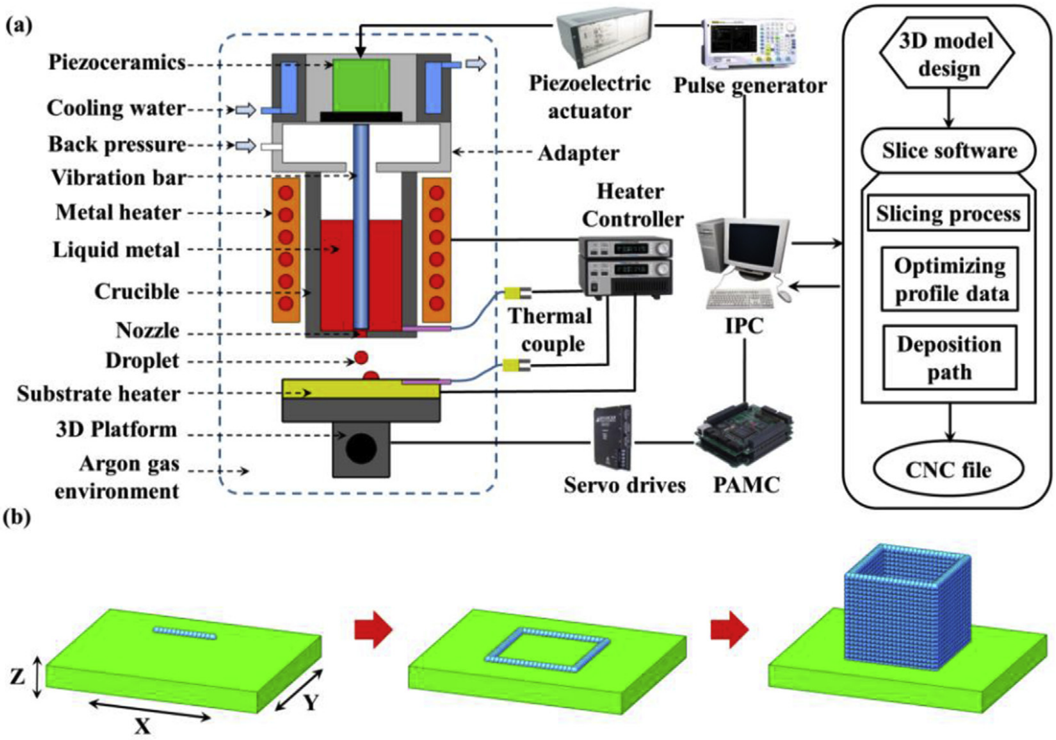

Fig. 1. Schematic diagram of (a) experimental setup and (b) process principle of uniform aluminum droplet deposition manufacturing.