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Impact-driven ejection of micro metal droplets on-demand

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ABSTRACT

On-demand metal droplet deposition will be a cornerstone technology in 3D metal printing. However, suitable small nozzles are hardly available, limiting the resolution and surface finish of final products. Here, the ejection of record-small metal droplets with a diameter of only 0.55 ± 0.07 times the nozzle diameter was demonstrated. To this end, a novel metal drop-on-demand (DoD) generator for high-temperature metal processing was designed and manufactured. A metal rod was utilized to transfer a vibration pulse, which was required to eject a liquid droplet, from a low-temperature region to the high-temperature liquid metal close to the nozzle. The influence of the pulse characteristics on the droplet ejection regime was studied experimentally and numerically. A 2D axisymmetric numerical model revealed that the shorter pulses allow reducing the droplet size, with the pulse duration of 13 μs resulting in the smallest feasible droplets. A novel method to create such short pulses, by impacting the metal-ring connected rod with a solid impactor was manufactured and tested, and the benefits of this method over more the spring-type pulse transfer was experimentally confirmed. This research provides a feasible way to achieve ejection of the small metal droplet on-demand.

1. Introduction

Drop-on-Demand (DoD) printing is a versatile method that has been widely used in digital manufacturing areas such as inkjet printing [1], rapid prototyping [2,3], MEMS [4], cell printing [5], organic transistors manufacturing [6]. In DoD, an individual droplet is ejected and deposited by one pulse. It shows a great advantage in low-cost, contact-free, and environment-friendly manufacturing. However, most commercialized DoD generators only work at temperatures below 673 K, since almost all piezoelectric materials lose their function above the Curie temperature. Therefore, ejection of metal droplets, which has enormous potential for 3D-printing, remains challenging [7].

The key problem is to transfer the pressure pulse, which is required for droplet ejection, into the molten metal. This process requires a medium with high-temperature resistance and strong corrosion resistance. To this end, the use of lasers, gases, and solid objects were all considered. For example, laser-induced forward transfer (LIFT) [8,9] now enables droplet-based deposition of various metals [10,11]. However, in LIFT, the transferred volume is relatively low since only droplet diameters below 10 μm can be transferred. A pneumatic pulse is another promising way to eject a metal droplet. So far, aluminum [12], solder [13], and tin [14,15] have already been processed by using a single pneumatic pulse. However, usually, a single pneumatic pulse produces a droplet that is much larger (around 2.5 times) than the nozzle diameter. Since small nozzles of heat-resistant materials are challenging to fabricate, this problem severely limits the resolution and accuracy of current pneumatic systems. To achieve droplets with a diameter smaller than the nozzle diameter, an oscillated pressure pulse has been used [15]. However, when the reported system operates at a frequency exceeding 10 Hz, a metal jet is ejected instead of the single droplet.

Alternatively, a solid rod can transfer a displacement from an actuator into the liquid metal at a high repeat frequency, to eject droplets on-demand. Already, solder [16,17], gold [18], iron [19,20], copper [21], and fusible alloy [22] droplets were ejected. Droplets with average diameters close to the nozzle diameter were obtained in this manner. By using an assistance gas pressure, droplets smaller than the nozzle in diameter can even be obtained [21]. Based on a comparison of the mentioned rod driven ejection [21] to the single pneumatic pulse ejection [12], a high-pressure pulse with the short duration is expected to be very important for producing small metal droplets. Therefore, to create the shortest possible pulse and thereby decrease the droplet size, the top of the

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rod could be impacted with a second rod, in contrast to previous studies in which a piezoelectric element was used to move the metal rod.

The present paper aims to improve the ejection of micro metal droplets by using an impacting rod system. A novel impacting rod driven droplet generator is designed and manufactured, and a numerical model is developed to describe the droplet generation as a function of the pulse width and pulse duration applied to the nozzle. The model for impact-actuated metal rods is validated. The principles of the droplet formation by using the impacting system are discussed. Finally, the ejection experiment shows that droplets as small as 55% of the nozzle diameter can be obtained by using the proposed impacting generator.

2. Design of experimental setup and experimental approach

Fig. 1(a) shows the schematic diagram of the proposed metal DoD setup. In short, this system works as follows. The metal droplet generator mainly consists of a cooling case, a solenoid derived impacting system, an adaptor, a crucible, and a nozzle plate assembled to the crucible bottom. To generate a droplet, first an electrical pulse is created by the pulse generator, which is transferred to the solenoid by the solenoid driver. The solenoid moves the impacting rod, which hits the heat-resistant vibration transferring rod on the head. The bottom end of this rod, which is located directly above the nozzle and submerged in the liquid metal bath, results in a liquid flow that pushes out a single droplet through the nozzle. In the experiments, this setup was operated at 673 K. The individual components and their working principle are described as follows:

(1) *Impacting system*: The impacting system consists of a solenoid, an impacting rod, a vibration transferring rod, and a piston. This solenoid generates a pulsed electromagnetic force when a pulsed voltage is input. This electromagnetic force drives the impacting rod (detailed in item 2) to move forward and impacts the top of the vibration transferring rod. A longitudinal elastic wave is generated under this sudden impact and is transferred into the metal liquid close to the nozzle through the vibration transferring rod. The liquid metal inside the nozzle is forced by this pulse and forms metal droplets. The maximum ejection repetition rate is limited by the repeat rate of the impacting system, which is 25 Hz. A 100 μm diameter nozzle was used. The complete impacting system is placed in a cooling case. The impacting system isolates the heat by using a long vibration transferring bar, to enable metal processing at high temperatures. A preliminary heating test showed that the device functioned well at temperature up to 1500 K, indicating that ejecting metals such as aluminum, copper, and silver may be feasible.

(2) *Pulse transfer to nozzle*: The vibration transferring rod is connected to the adaptor through a spring (shown in Fig. 1(b)) or a metal ring (and Fig. 1(c)) to realize two working modes of the impacting system. When using the spring, the vibration transferring rod, and a piston make up a spring-mass system. This spring-mass system responds as a simple damped harmonic vibration when it is impacted. If the vibration transferring rod is fixed through a metal ring, the rod hardly moves during the impact. However, the collision between the impact rod and the vibration transferring rod generates a compressional stress wave inside the rod. This wave is transferred to liquid metal at another free end of the vibration transferring rod.

(3) *Piston*: The piston is connected to another end of the vibration transferring rod. The piston has three axial flow channels on its cylinder surface. A cavity is formed between this piston bottom and the nozzle inner surface. The vertical position of the rod can be changed in the crucible to adjust the distance of

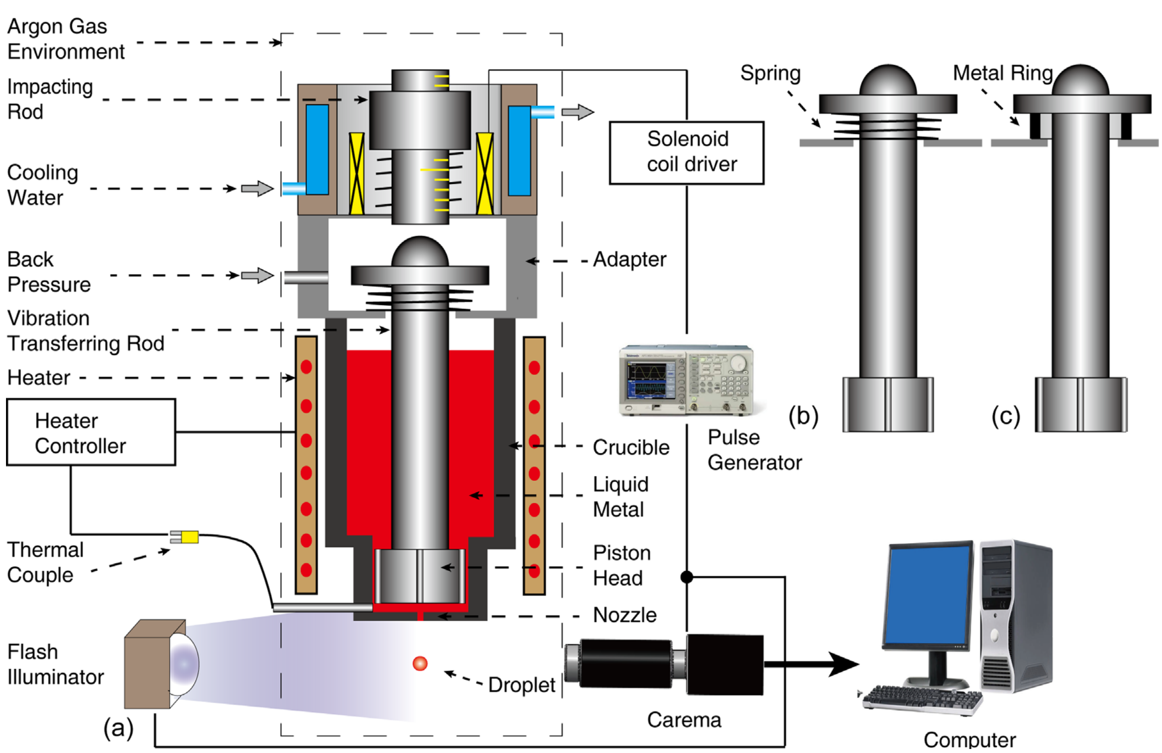

Fig. 1. The metal DoD system and two working modes of the impacting system: (a) Schematic diagram of the experimental system. The vibration transferring rod is connected to the adaptor in two different ways: in figure (b) the rod is connected to adaptor by a spring; in (c) the rod is connected by a metal ring and is essentially fixed to the adaptor.