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Producing solder droplets using piezoelectric membrane-piston-based jetting technology

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ABSTRACT

This paper proposes piezoelectric membrane-piston-based jetting technology, an improved drop-on-demand (DOD) jetting technology for generating micro-droplets. The main components of the experimental apparatus are a nozzle head, a cooling chamber, a vibration bar, a computer system, a temperature controller and a three-dimensional (3D) platform. Based on the proposed working principle, a physical model was constructed and used to conduct a theoretical analysis of the jetting process. This theoretical analysis clearly separated the critical experimental parameters from the other parameters. The critical parameters were found to be the pulse length (t) and voltage value (U) of the electrical pulse signal and the temperature (T) of the chamber. With the commercial tin-lead alloy Sn63Pb37 as the raw material, the experimental apparatus was used to produce micro-droplets. Fifty micro-droplets were randomly selected, their diameters were measured, and the average value and corresponding standard deviations were calculated. The results showed that the micro-droplets fabricated under the same experimental conditions displayed only a small standard deviation in diameter. The diameter of the micro-droplets increased with the pulse length (t) and voltage value (U) of the electrical pulse signal and with the temperature (T) of the chamber. The results also indicated that the values of these three critical experimental parameters should be within an appropriate range. Larger values resulted in the production of satellite droplets, and smaller values did not permit the steady micro-droplets. As a demonstration, a micro-droplet array was fabricated. The diameters of all micro-droplets in the array were approximately 85 μm. The results indicate that the proposed membrane-piston-based jetting technology can produce micro-droplets on demand, and serve as an alternative method for the generation of uniform micro-droplets.

1. Introduction

Uniform micro-droplet deposition (UMDD) is a noncontact direct manufacturing technology that was developed by Duthaler (1995); Orme (1993) and Yim (1996) in the1990s. In micro-droplet deposition, a driving force is employed to squeeze a functional material out of a nozzle and deposit it onto a substrate as either a continuous stream of micro-droplets or a single droplet, thereby forming two-dimensional patterns, dot arrays or 3D objects. UMDD has a number of advantages, such as its data driven, its high rate of deposition, its low cost, its ability to use a broad range of materials, and its reliance on environmentally friendly processes, as described by Liu and Orme (2001b). UMDD has wide potential application in fields such as biomedicine, metal additive manufacturing and the electronics industry. Tse et al. (2016) used a piezoelectric inkjet printer to print porcine Schwann cells and neuronal cells, and proved that the printed cells showed no significant difference in cell viability compared with cells cultured via standard seeding. Vaithilingam et al. (2018) realized the fabrication of macroscopic metal parts from silver nanoparticle ink by using inkjet printing technology, and examined the samples using X-ray computed tomography and scanning electron microscopy. The results showed that a higher printing resolution resulted in fewer inner voids and improved mechanical properties. Luo et al. (2012) used a pneumatic DOD system to produce solder droplets (also called solder bumps) for electronics packages. They considered a flexible circuit with dense gold fingers on the substrate, in which copper cables needed to be soldered to the pins of the flexible circuit to provide power or transfer signals. Solder bumps were accurately deposited on the joints between copper cables and pins

Abbreviations: DOD, drop-on-demand; PMPJT, piezoelectric membrane-piston-based jetting technology; 3D, three-dimensional; UMDD, uniform micro-droplet deposition; LMJP, liquid metal jet printing; CIJ, continuous inkjet; CNC, computer numerical control

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by synchronizing the droplet generation with the substrate motion. A re-melting process was then applied in which the gold fingers were heated to realize good interconnects between the copper cables and the flexible circuit. Tomaszewski and Potencki (2017) printed a circuit using a piezoelectric print head with 128 nozzles, and analyzed the influence of the drop parameters on the defects characteristics and quality of the printed patterns.

There are two types of UMDD: continuous inkjet (CIJ) deposition, as demonstrated by Liu and Orme (2001a), and DOD deposition, as demonstrated by Fan et al. (2008). In the CIJ process, as described by Hon et al. (2008), pressure applied to the liquid forces the liquid to form a stream that emerges from a nozzle; a periodic disturbance generated by an actuator is then applied to the liquid stream, and under the combined action of this disturbance and the surface tension, the liquid stream is broken into micro-droplets. The primary drawback of CIJ deposition is that the jetting cannot be rapidly stopped when it is no longer needed. Lee et al. (2008a) developed a solder DOD generator that employs an actuator to generate pressure pulses only as needed, with those pressure pulses inducing a volumetric change in the fluid. Such a volumetric change produces pressure and velocity transients in the fluid, causing the formation of a single micro-droplet. DOD deposition offers better controllability than CIJ deposition with regard to production of uniform metal micro-droplets.

Cheng and Chandra (2003) developed a pneumatic DOD technique in which a pressure pulse is generated through the rapid opening and closing of solenoid valves; this pressure pulse is then applied to the liquid to produce a single micro-droplet emerging from the nozzle. The compressed gas used to apply the driving force in this technique is nitrogen, so there is no thermosensitive limit and no need for expensive driving devices. However, some time is required to form a steady pressure pulse after the compressed gas is released, and then, the pneumatic DOD technique has a low working frequency. Moreover, because of the absence of an inner pressure controller, the driving accuracy is also low. Shu (2009) proposed another pneumatic DOD technique that employs a pneumatic pressure pulse actuator and an elastic metal membrane. The pressure pulse distorts the metal membrane in contact with the molten metal, and the squeezing action induced by the distortion of the membrane forces a droplet of the molten metal to emerge from the nozzle and form a single micro-droplet. In the pneumatic DOD system proposed by Shu (2009), a solenoid valve is installed between the pneumatic supply and the metal membrane. The opening and closing of the solenoid valve is controlled by an electrical pulse signal coming from a computer system, and a pneumatic pressure pulse is generated via the rapid opening and closing of the solenoid valve. According to the experimental results reported by Shu (2009), the maximum jetting frequency is 99 Hz, and the diameter variation of the obtained micro-droplets is less than 3%. Lee et al. (2008b) developed a DOD apparatus that employs a piezoelectric actuator to produce a pressure pulse, enabling the realization of a high working frequency. To prevent the high-temperature inactivation of the piezoelectric actuator, an insulation block was installed in the apparatus. However, Wang et al. (2016) have note that the dominant lead zirconate titanate (PZT) type ceramics used in piezoelectric actuators have a Curie temperature (T_c) of approximately 300–360 °C, which limits their application temperature to 180 °C (half of T_c). Because of the low T_c of the piezoelectric actuator, the applicable working temperature of a DOD apparatus equipped with a piezoelectric actuator is limited.

Vader Systems (2017) developed a molten metal printing technology called liquid metal jet printing (LMJP) that offers new possibilities for metal additive manufacturing. The LMJP system propels molten metal from a 1200 °C chamber encased in an electromagnetic field through print nozzles to produce micro-droplets with diameter in the range of 150–500 μm. The electromagnetic field is generated by a coil around the chamber; a real-time varying magnetic field is created by changing the current in the coil. When the molten metal enters into this real-time-varying magnetic field, eddy currents are induced and produce a repulsive magnetic field that pushes the molten metal out of the nozzle. When enough molten metal has accumulated at the exit of the nozzle, a droplet forms and is ejected. The LMJP system developed by Vader Systems (2017) can currently use aluminum and its alloys as well as bronze as raw materials, and it can fabricate 3D parts at least two times faster than can be achieved with current powder bed fusion technology in which a high-energy beam is used to melt or sinter metallic powders to form metal parts. Furthermore, the part cost of LMJP is reduced by up to 90% compared with that of powder bed fusion technology. Despite these advantages of LMJP, Wang et al. (2017) have noted that LMJP still faces multiple challenges; for example, the materials must be conductive or pre-charged, which limit the possible choices of raw materials. Moreover, it is difficult to control the wetting properties and coalescence behavior of the micro-droplets during the LMJP process. So far, the application of LMJP for the generation of uniform micro-droplets has seldom been reported.

With the goal of developing a DOD system equipped with a piezoelectric actuator that can operate at a working temperature higher than 180 °C (the application temperature of piezoelectric ceramics, which is half of the corresponding T_c value), a piezoelectric membrane-piston-based jetting technology (PMPJT) is proposed in this paper. This technology takes advantage of the use of a piezoelectric actuator while employing a cooling unit to prevent high temperatures from inactivating the actuator. A physical model of the jetting head was constructed and the critical processing parameters were analyzed theoretically. Using a laboratory-built PMPJT apparatus, the effects of the processing parameters on the fabrication of metal micro-droplets were investigated experimentally.

2. Experimental method

Fig. 1 shows a schematic diagram of the PMPJT system, in which a vibration bar is rigidly connected to two elastic metal membranes and a piezoelectric ceramic. Based on the embedded control program, a computer numerical control (CNC) system produces an electrical pulse signal that excites the piezoelectric ceramic to generate a mechanical deformation that forces the vibration bar to move downward, simultaneously stretching the elastic metal membranes downward. Under the combined action of the backpressure from the compressed nitrogen gas, the oscillating motion of the vibration bar and the hydrostatic pressure, a droplet of molten metal emerges from the nozzle and forms a single metal micro-droplet, which is dropped into a glycerin-filled beaker. Driven by a pump, water continuously flows though the cooling chamber. The moving water cools the vibration bar, thereby impeding the transfer of heat to the piezoelectric ceramic. The two elastic metal membranes play the following roles. First, the membranes form the upper and lower walls of the cooling chamber; second, they hold the vibration bar in a precise location; third, they ensure that the motion of the vibration bar is solely in the vertical direction.

Fig. 2 shows a simple illustration of the working principle of PMPJT. The downward movement of the vibration bar induces the molten metal to move in the opposite direction. Some of the molten metal flows upward through the side gap between the wall and the head of the vibration bar, and another part of the molten metal flows though the orifice of the nozzle to form a stream. When the electrical pulse signal applied to the piezoelectric ceramic is turned off, the stretched elastic metal membranes begin to retract, inducing necking of the stream at the orifice. Because of gravity and inertia, the end of the stream moves downward and finally separates from the main body. Because of the surface tension, the separated molten metal forms a spherical micro-droplet. The rest of the stream flows back, returning to its initial state.

3. Analysis

Since micro-droplet generation is achieved essentially through the flow of the molten metal, it is very important to analyze this flow. The