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Dominant factors to produce single droplet per cycle using drop-on-demand technology driven by pulse electromagnetic force

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ABSTRACT

A nontoxic liquid metal droplets, such as gallium based eutectic alloys, has been used to develop the microelectromechanical systems (MEMS). Therefore, a droplet generator on demand has been proposed to study the formation process of droplet by using pulse electromagnetic force technology. It allows the production of uniform droplet in a controlled way, which entails important technological advantages over existing techniques. The results indicates that, compared with triangular wave and sine wave, the pulse wave can produce single droplet per cycle at a constant amplitude current and higher droplet formation frequency; the process parameters, such as the amplitude, frequency of input current, and electronic pulse width have a significant effect on the droplet formation. This work provides a useful parameter-selection approach for droplets production.

1. Introduction

Compared with mercury, the gallium based eutectic alloys (75% gallium, 25% indium) has many remarkable properties, including excellent electrical and thermal conductivity, melting points below room temperature, and most importantly low toxicity [1]. Table 1 lists the physical properties of the gallium-based liquid metal [2,3]. Tunable radio frequency (RF) components are essential enabling mechanism for microelectromechanical systems that is used in wireless communication and instrumentation [4,5]. At present, the droplet of gallium based eutectic alloys as a flexible RF device has been used to develop the components of MEMS, such as antennas, inductors, and capacitors et al. [6]. In addition, the droplet as a element of a system will be applicable to a wide range of microfluidics actuators [7] and 3D printing in flexible electronic material [8,9]. Therefore, the droplets of gallium based eutectic alloys as basic building elements will have wide applications in many fields.

At present, the methods of production uniform droplets can be categorized into either continuous-ink-jet printing (CIJ) or droplet-on-demand (DOD) technology [10], both dependent upon periodic pulses that propagate through liquid and eject droplets from the nozzle. In CIJ technology, the jet material is kept in the liquid phase inside a tank, and a constant pressure is applied onto the free surface of liquid for producing stable jet. The jet eventually breaks it up into a series of uniform droplets based on the Rayleigh capillary instability when an certain disturbance is imposed onto capillary jet. This technique can generate droplets with great uniformity and high generation rate [11,12]. Although this method is easy to conduct, it cannot product single droplets on demand. Therefore, it is hard to produce one droplet per cycle.

In DOD technology, the droplets are squeezed out by the pulse pressure as it is demand. The DOD technology has gradually replaced the CIJ technology because that it is easy to control the droplet formation. The DOD technology can be generally divided into three modes: piezoelectric pulse, pneumatic pulse, and pulse electromagnetic force, as summarized in Table 2. The main feature of the mode of piezoelectric pulse is that the jet liquid is driven by a piezo driver, which amplifies an appropriate voltage signal synthesized by an arbitrary waveform generator. An experiment of piezoelectric pulse mode was designed and accomplished by Alvin U [13]et al. to produce droplet of significantly reducing radius without change of the nozzle radius. The droplets were formed using mixtures of glycerol and water ranging from pure water to 61 wt% glycerol. The fabrication of a bending type piezoelectric droplet was presented by Hesam Sadeghian [14] et al. to investigate the relationship between the diaphragm performance and the droplet generation, and a procedure for evaluation of the diaphragm was presented. It usually requires a solid rod to transfer the displacement from the piezoelectric generator, and the whole apparatus is complicated.

The mode of pneumatic pulse is to drive the liquid with a pneumatic pulse, which is produced by switching solenoid valve on and off. S. Cheng [15] et al. designed a pneumatic droplets generator for producing water droplets on demand, and investigated the effect of the

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Table 1
Physical properties of Ga-In eutectic alloy [2,3].

Mass ratio of Ga-In (ratio)	Conductivity/S·cm^{-1}	Density/Kg·m^{-3}	Surface tension/(N·m^{-1})	Viscosity/mPa·s	Melting point/°C
75%Ga, 25%In	3.4×10^4	6280	0.624	1.70	15.5

Table 2
List of typically methods for formation uniform droplets by drop-on-demand.

Formation mode	The frequency	Eject materials	Reference
Piezoelectric pulse	< 3500 Hz	glycerol	[13]
	< 3000 Hz	water	[14]
Pneumatic pulse	3 Hz	water	[15]
	< 10 Hz	Tin and zinc alloy	[16]
	< 4 Hz	Tin and zinc sphere	[17]
Pulse electromagnetic force	< 150 Hz	Solder ball	[18]

negative pressure on the generation of single droplet. A. Amirzadeh [16] et al. showed that the ejection frequency, pulse width and secondary gas flow had a significant effect on the droplet formation, and this method made it possible to produce droplets as small as 60% the nozzle diameter. The usage of this mode for producing uniform tin and zinc sphere was studied by Stewart Xu Cheng [17] et al. and the results showed that uniformly droplets with diameters ranging from 0.17 to 0.60 mm were formed using nozzles 0.076–0.254 mm. However, the frequency of switching solenoid valve on and off is usually lower than dozens of Hertz, so it is difficult to produce droplets at a high frequency.

The best way to produce low melting point of metal droplets is to drive the liquid by a pulse electromagnetic force. An external electromagnetic field and an internal pulsed current pass through the metal liquid, subsequently, the pulse electromagnetic force is introduced to make the liquid eject from the nozzle. The droplet formation process is easy to control and operate due to a higher controllable precision of input current signal. Zhiwei Luo et al. [18] succeeded in designing and accomplishing a droplet generator using pulse electromagnetic force, and this method provided a fast and cost-effective method for the printing of conductive 3D-traces. In addition, this work also investigated the effect of pulse width, magnetic field intensity and nozzle diameter on droplet diameter. However, the detailed researches on the effect of waveform and amplitude of the input current, and the electronic pulse width on the droplet formation process are not well investigated.

In this work, a new DOD system based on the mode of pulse electromagnetic force for producing droplets of gallium based eutectic alloys is developed. The objectives of the present paper are: (1) to develop a DOD generator for the generation of controllable droplet; (2) to understand the influence of input current parameters, including waveform and amplitude of the input current, and the electronic pulse width, on the droplet formation.

2. Experiment principles and apparatus

2.1. Experiment principles

Fig. 1 schematically illustrates the principle by the mode of pulse electromagnetic force on demand. The driven cavity is filled with liquid metal by the throttle hole, which is built to connect the driven cavity and the feedstock tank. This cycle electromagnetic force, being perpendicular to the direction of both magnetic field and variable electric current, is produced by the moving charges in magnetic field experiencing the Lorentz force and together forming electromagnetic force. Droplet formation is initiated when electromagnetic force is applied in the liquid metal, making the liquid metal flow out of the nozzle to generate a liquid column. When the variable electric current disappeared in the liquid metal, subsequently the micro-column broke up into droplets.

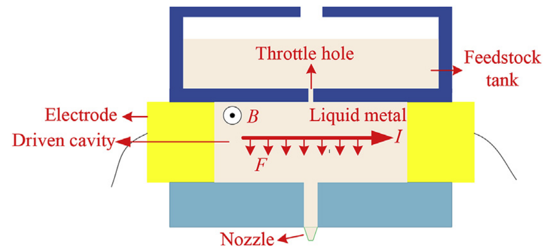

Fig. 1. Schematic diagram showing the principle of the electromagnetic force actuator.

2.2. Experimental apparatus

The experiments for droplet formation were performed with a laboratory scale droplets generator, which was mainly consisted of a generator, high-speed camera, and optical source, as shown in Fig. 2. The main body of droplet generator was designed to produce single droplet on demand, which consisted of a feedstock tank, an actuator, and a plate with a small nozzle set into its bottom. Two pieces of permanent magnets were placed in parallel in the driven chamber to generate a constant magnetic field between liquid metal. The electrodes were embedded in the ceramic structure to make the current flow uniformly through the liquid metal. During the droplet generation, the current of various forms was produced by the connection of power amplifier and signal source.

The pulse-current signal was generated using the function generator (Model: DG1022U, Rigol, China). A power amplifier (Model: HEA-500G, Nanjing foneng technology industrial co. LTD., China) was used to amplify the signals of the pulse-current. The images of the jetting and dropping processes were recorded using a high-speed CCD camera (Model: CR5000X2, Optron, Germany) assisted by a stroboscopic light source (Model: AKLED150W SUN LJGHT, Beiyang, China). In this research, the maximum output current of 40 A and the magnetic field intensity of 0.63 T crossing the chamber were used.

3. Results and discussion

3.1. Effect of the input current waveform on droplet formation process

One of the important and critical tasks was the selection of the input current waveform for the formation of droplet by pulse electromagnetic force actuator. The sine wave, triangular wave, and pulse wave were used as driven waveform to study the frequency consistency of the droplets formation and waveform.

The droplet was formed through four stages: ejection, stretching of liquid column from the nozzle, necking phenomenon of the liquid column, and breaking up into droplets. Fig. 3 showed the generation of one droplet from 0.448 mm diameter nozzle using the sine wave model. The liquid column was elongated in the axial direction gradually during the time from 0 to 0.01 s, as shown in Fig. 3(a and b). When the current in sine curve passes through zero at the first cycle, the direction of current was changed, and the effect of electromagnetic force was transformed from the driven force to the restoring force. No droplets were ejected out during the time from 0.01 to 0.02 s because that the kinetic energy of stretching liquid generated by the driven force was not