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FORMATION OF MOLTEN SN AND SN-PB DROPLETS IN MAGNETOHYDRODYNAMIC PUMPS

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Abstract

In the present paper, an electromagnetic pump and nozzle are introduced and characterized, preparing an intermittent flow of molten Sn and Sn-Pb. In the designed nozzle, Eddy-currents inside the melt and the alternating electromagnetic forces combine and create a force to produce on-demand droplets. Pulse characteristics, including voltage, duty cycle, and frequency, are altered along with melt characteristics, including alloy composition and temperature. Droplets were produced at 48 conditions, and the shape, weight, and production rate were measured. Results indicate that owing to its higher surface tension; Sn produces larger and heavier droplets than Sn-Pb alloy at all identical test conditions. While the pulse parameters didn't significantly change the droplet weight, their increase resulted in an increasing droplet production rate. The effect of temperature was different at various conditions since it reduces the surface energy and increases electrical resistance and fluidity.

Keywords: Electromagnetic Pump, Drop-On-Demand, Metal Droplet

1. INTRODUCTION

On-demand droplets are formed by various stimuli technologies such as electromagnetic jets (Sukhotskiy et al. 2018) and piezoelectric (Luo et al. 2012). In magnetohydrodynamic technology, a time-varying magnetic field creates eddy currents inside conductive fluids; the coupling of this current and the external magnetic field creates a Lorentz force. As the Lorentz force increases, the pressure behind the fluid forces droplets to exit an orifice in the nozzle. By controlling the pulse entering the magnetic coil, various properties of the drop, including its size and shape, can be controlled. In most cases, when using molten metals as the conductive liquid, droplets lose temperature by exiting the nozzle and start to solidify. This process efficiently generates solidified droplets in micrometer dimensions (metal powders) or deposits them on a surface to build a 3D structure. As an industrial practice, this principle has been employed in 3D metal printers (Sukhotskiy et al. 2018).

The characteristics of the formed drop in the drop on demand (DOD) nozzles depend on many different physical characteristics, including (1) the electric pulse entering the magnetic coil, (2) the surface energies of the melt and the nozzle, and (3) the electrical characteristics of the melt. These parameters will be briefly introduced in the following:

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The Electric Pulse

Jang et al. (Jang and Seung S. 2000) studied and simulated the magnetic field applied to molten metal and calculated the governing equations, including the amount of pressure applied, the voltage, and the electric current in the mechanism. Ahmadi et al. (Ahmadi, McDermid, and Markley 2016) have developed a small-scale device to actuate droplets in planar fluids to investigate the parameters such as threshold voltage, the effective channel for the droplet movement, and the effect of surface tension and wettability to indicate the minimum volume of a movable droplet. They have reported that the resistive forces can be reduced by using a hydrophobic coating layer. Wang et al. (Wang et al. 2018) studied the effect of the coil current's frequency, pulse shape, and amplitude in a magnetohydrodynamic pump. They have shown that adjusting the pulse width makes it possible to prevent the formation of tail drops.

Surface Energies

White (White 1971) investigated the effect of temperature on surface tension on Sn and its alloys and reported that by increasing the temperature, the surface tension decreases. Surface tension reduction is also reported by Keene (Keene 1993), which has shown that the surface tension decreases by increasing the Pb content in Sn-Pb alloys. Zhu et al. (Zuo et al. 2014) investigated the influence of wettability and contact angle of aluminum melt with a graphite nozzle to produce Al droplets. They have reported that by increasing the contact angle of the melt with the surface of the nozzle, smaller droplets are formed. They have also changed the path of the drops on the substrate surface by using a variable wetting coefficient of the nozzle surface. The effect of the conical angle of the nozzle on the ejection of molten gallium metal was investigated by Lu et al. (Luo, Zheng, and Wang 2016). The experimental results show that the mass of the molten droplets, the jet distance, the initial velocity of the ejected droplets, and the kinetic energy of the ejected droplets first increase and then decrease by increasing the cone angle from 90 degrees.

Melt Characteristics

Drop-on-demand (DOD) technology has been used to produce droplets and print various materials, including wax, lead, tin, and aluminum alloys (Vader et al. 2016). Specifically, by increasing the melt temperature in metals, thermal and electrical conductivity and flow properties change. Such alteration affects the inducted eddy-current and the force balance in the nozzle. Ocak et al. (Ocak et al. 2010) measured the electrical conductivity of Sn and Sn-Pb alloys. Their results indicate that by increasing the Pb content, conductivity gradually reduces up to 50% (in pure Pb). Also, by increasing temperature, conductivity reduces almost at the same rate in Sn and Sn-Pb alloys. The same trend is observed in thermal conductivity. Kanda et al. (Kanda and Colburn 1968) plotted the absolute viscosity isotherms for Sn-Pb alloys and have shown that viscosity is reduced by increasing temperature and increased by increasing the Pb content.

In the present research, a specific DOD nozzle has been employed to study the effects of various pulse parameters (voltage, frequency, and pulse on time) on the shape and size of Sn and Sn-Pb droplets. The results are presented, and the effects are discussed systematically.

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2. MATERIALS AND METHODS

Materials

Commercially pure Sn and Sn-Pb eutectic alloy (63/37 Sn-Pb) were selected as study materials. In both alloys, there is no freezing temperature range, i.e., the temperature is constant through solidification. Both materials were used as wires and were fed into the nozzle by the automatic feeding system.

The DOD pump

The DOD pump consists of two main parts: (1) the nozzle and (2) the electric circuit (pulse generating unit). A two-part nozzle (shell and core) has been designed and manufactured from non-magnetic 316 stainless steel (Figure 1a). The pressure required to eject the droplets out of the nozzle can be controlled by adjusting the channel width. The channel is shaped as a cone to effectively incline the Lorentz force radial direction towards the nozzle axis to push the fluid out from the orifice. The orifice is machined on the shell. The nozzle is heated by a cylindrical ceramic band heater and isolated by insulating fibers. The nozzle temperature is recorded from the plunger core (next to the melt pool) and the orifice. The melt volume inside the nozzle is kept at 50 grams to ensure constant weight force. The resulting droplet falls into the cooling medium (Figure 1b). A shielding Ar gas covers the orifice to prevent any oxidation at the opening of the orifice.

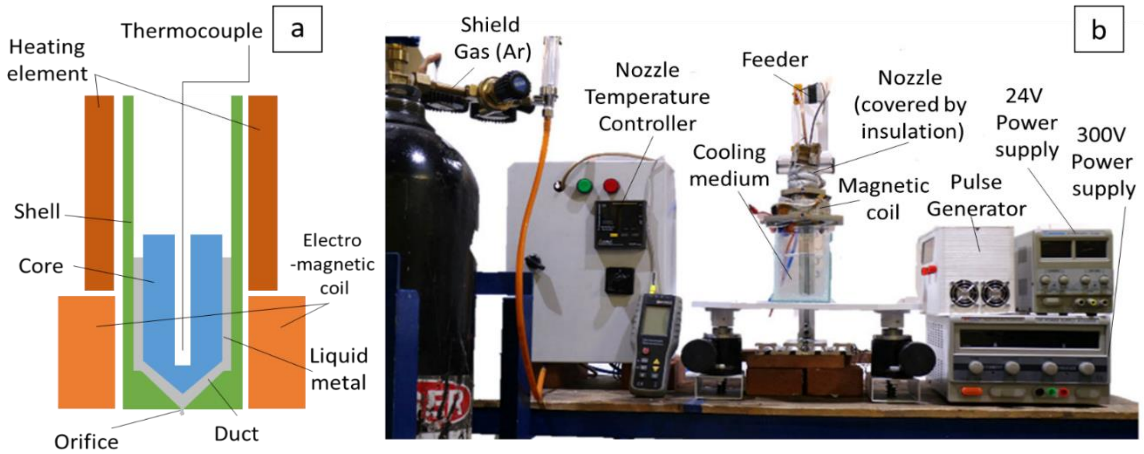

Figure 1: (a) Drawing of the nozzle and (b) the drop-on-demand droplet generator

A surrounding copper coil triggers the nozzle. The coil is water-cooled, connected to a 300V power supply, and controlled by a microcontroller that enables pulsed voltage (Atmega2560). The microcontroller can change the pulse characteristics. A schematic representation showing the voltage and current pulses is shown in Figure 2a. The positive domain of the pulse creates a radial Lorentz force towards the nozzle center, which pushes a droplet out of the nozzle. The direction of the Lorentz force and the subsequent pressure is reversed in the negative domain of the pulse, which pinches off the tail of the droplet. Figure 2b shows the nozzle, coil, and the initial drop formation stage.

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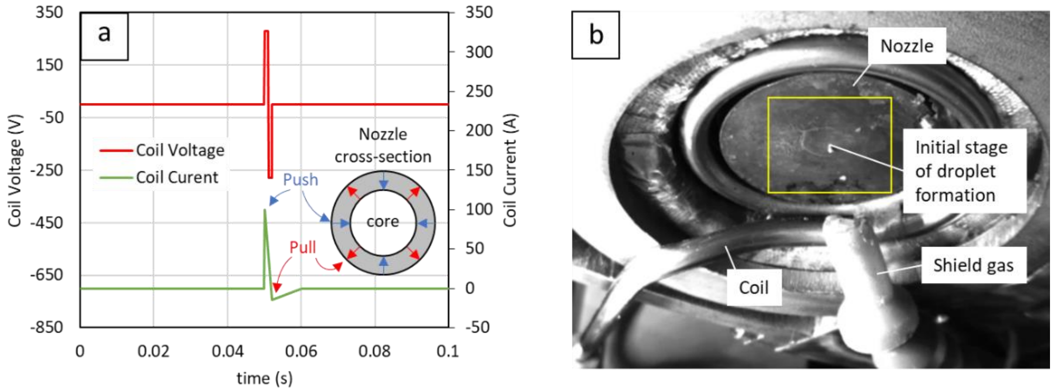

Figure 2: (a) An example of the voltage and current pulses and the Lorentz force directions at different pulse states. (b) The configuration of the nozzle, coil, and orifice from the bottom view. (The highlighted square represents the location of time laps presented in Figure 4)

Experimental Design

In this research, the effect of pulse-controlling parameters and melt characteristics are altered, and their effect on droplet shape, weight, and production rate are examined. The pulse parameters include (1) voltage 200V and 280V, (2) pulse on time (duty cycle) 1 and 1.5 milliseconds, and (3) pulse frequency at three levels 5, 12, and 20 Hz. Melt parameters include (1) temperature 250°C and 320°C and (2) alloy composition pure Sn and Sn-Pb alloy. Other effective factors, such as free fall distance (50mm) and cooling fluid temperature (25°C), are constant. In Figure 3, the change of parameters and planned measurements are shown.

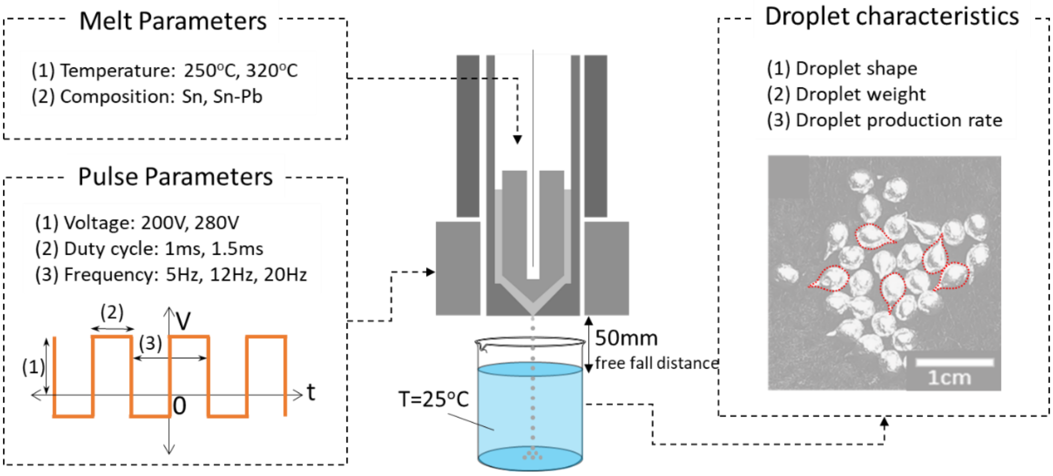

Figure 3: Schematic illustration showing the overall experiment design

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Time-lapse images were taken by a 750 frame per second Basler ac640 highspeed camera. An FEI Quanta FEG-SEM took secondary electron images. An electronic scale weighed ten produced droplets at the same test condition with 0.01g precision to report the weight. The average was calculated and reported. Micrographs were prepared by optical microscope. The best possible conditions will be the condition that produces the smallest droplets with the highest possible rate. The shape of the drops is important in the experiments, and this feature also determines the quality of the produced droplets.

3. RESULTS AND DISCUSSIONS

Size and Shape of Droplets

Figure 4 shows the time-lapse images of drop formation at the nozzle orifice. The Sn droplet is formed at 320°C melt temperature 280V, 1ms duty cycle, and 5Hz frequency and is an example of how all droplets at various nozzle and melt parameters form. At the initial stage, a small bulge of liquid metal is formed (Figure 4a) and starts to grow (Figure 4b-d). As the droplet grows larger, the weight force of the droplet elongates the drop and forms a tail (Figure 4e). The tail is elongated, then necking starts and proceeds (Figure 4f-g) to final separation (Figure 4h). In all the studied conditions, a tail is formed in the droplet, indicating insufficient pinch-off force when the drop is separated from the orifice (Aqeel et al. 2020). Videos show that the tear-shape drop rotates during free fall until it hits the cooling medium surface (25°C water).

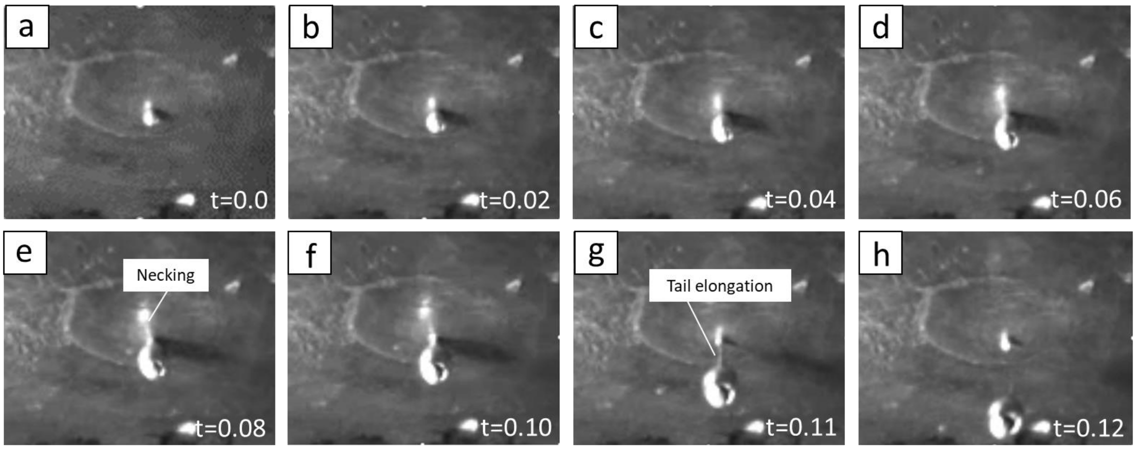

Figure 4: Time-lapse images showing consecutive stages (from a to h) of droplet formation at the DOD nozzle orifice

Figure 5a-c shows high-magnification SEM images of a single droplet formed under the same conditions as in Figure 4. The droplet cross section is oval and extended in the tail direction. The droplet shows moon-surface crater features formed as water evaporates in contact with the semi-solid droplet. Further experiments indicate that droplets falling in room temperature oil have a smooth surface without the craters.

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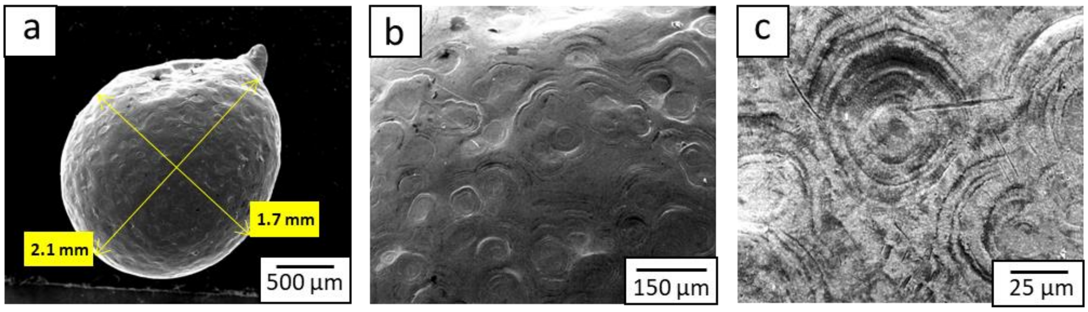

Figure 5: SEM micrographs showing (a) an individual droplet and (b,c) higher magnification images of the droplet surface features

To investigate the effects of frequency, voltage, and duty cycle on drop shape and size in the developed DOD magnetohydrodynamic pump, the temperature is fixed at 320ºC, and other pulse parameters are altered (Figure 6).

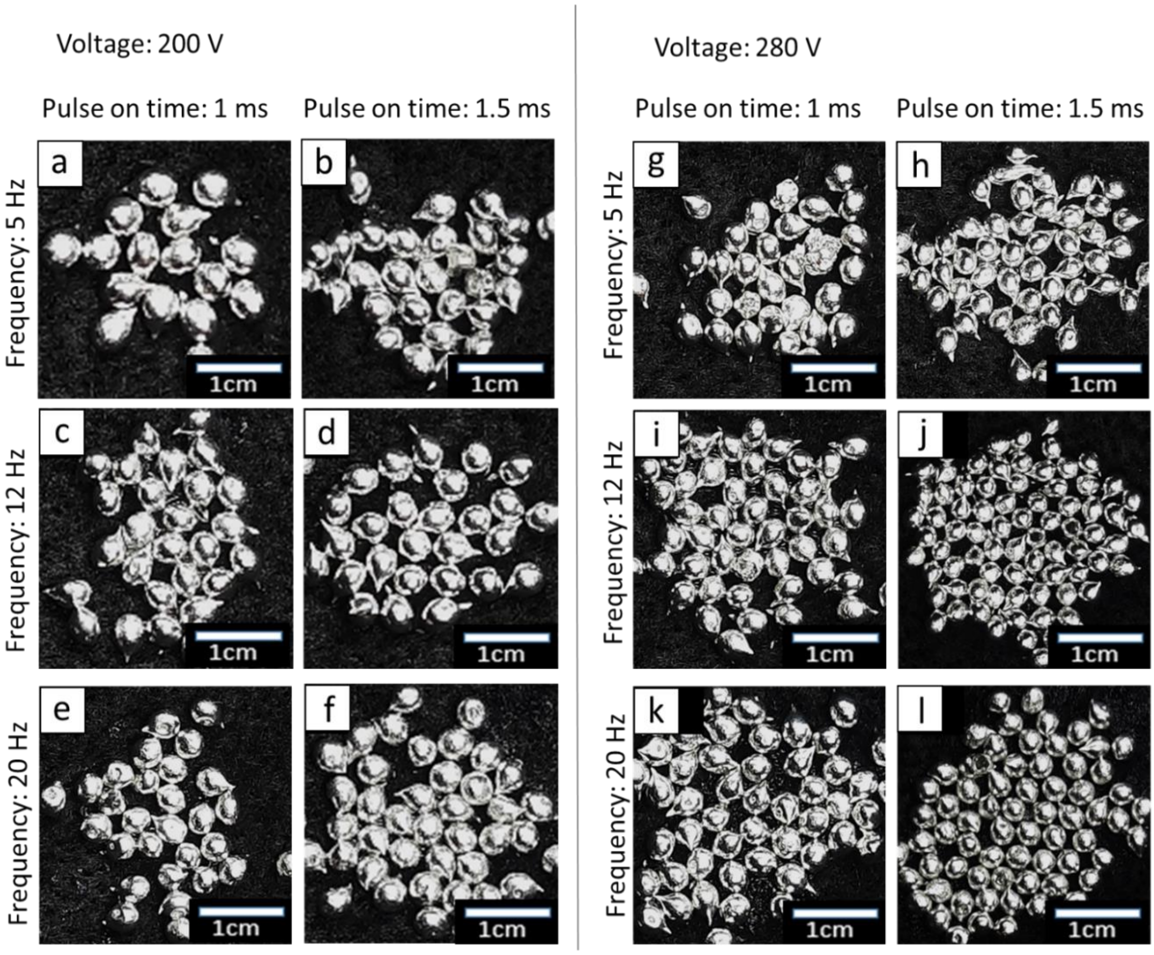

Figure 6: Sn droplets formed at various pulse conditions at 320ºC nozzle temperature

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Figure 7 presents the results of similar pulse conditions as Figure 6, but the temperature is set to 250°C. A detailed analysis has been performed on the weight of the droplets (results summarized in Table 1). Results indicate that the pulse parameters have an insignificant effect on droplet weight. However, the composition is causing a meaningful difference.

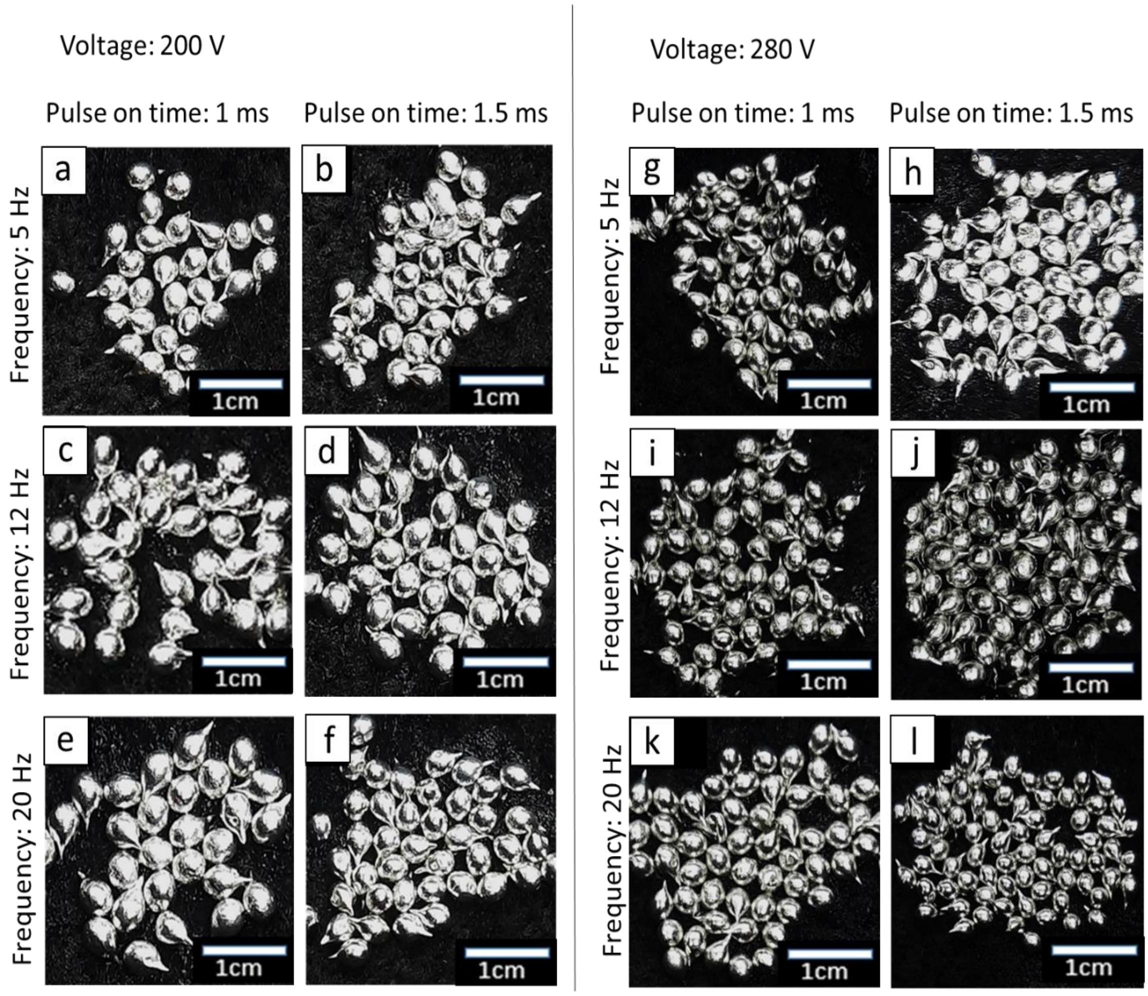

Figure 7: Sn droplets formed at various pulse conditions at 250°C nozzle temperature

Table 1: Droplets weight (mg) at all the studied pulse and nozzle temperature conditions

		Sn								**Sn-Pb**							
T		**250 C**				**320 C**				**250 C**				**320 C**			
V		**200 V**		**280 V**		**200 V**		**280 V**		**200 V**		**280 V**		**200 V**		**280 V**	
POT		**1 ms**	**1.5 ms**	**1 ms**	**1.5 ms**	**1 ms**	**1.5 ms**	**1 ms**	**1.5 ms**	**1 ms**	**1.5 ms**	**1 ms**	**1.5 ms**	**1 ms**	**1.5 ms**	**1 ms**	**1.5 ms**
Frequen	5	71	65	64	63	66	71	67	65	48	46	51	49	45	47	55	48
	12	64	72	66	68	70	71	72	67	50	52	52	47	48	46	49	52
	20	69	70	68	68	63	69	69	67	44	48	53	51	50	52	52	50

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Figure 8 presents the droplet weight in all the studied samples at constant pulse frequencies. It can be seen that the melt composition has a greater effect on droplet weight compared to all the pulse parameters combined. Even though Sn-Pb has a higher density, and it seems its droplets should be heavier, the results show the opposite. Figure 8a shows that Sn droplets are significantly heavier. It should be noted that Sn-Pb alloys have higher viscosity (Kanda and Colburn 1968) less thermal and electrical conductivity (Ocak et al. 2010), and less surface tension (Keene 1993). Less conductivity translates to less eddy current and less Lorentz force. Coupled with the higher viscosity of Sn-Pb alloy, its less electrical conductivity indicates the necessity of more force to push out Sn-Pb drops from the nozzle orifice (compared to Sn). In the meantime, the effect of lower surface tension of Sn-Pb is in the opposite direction and favors the easier separation of droplets. As previously mentioned, Sn has higher surface tension as its alloy with Pb (Keene 1993). Therefore, more mass is required to overcome surface tension when separating from the orifice. Consequently, Sn droplets need to be larger and heavier than Sn-Pb droplets to overcome surface tension (Figure 8b) when all the other nozzle parameters are constant.

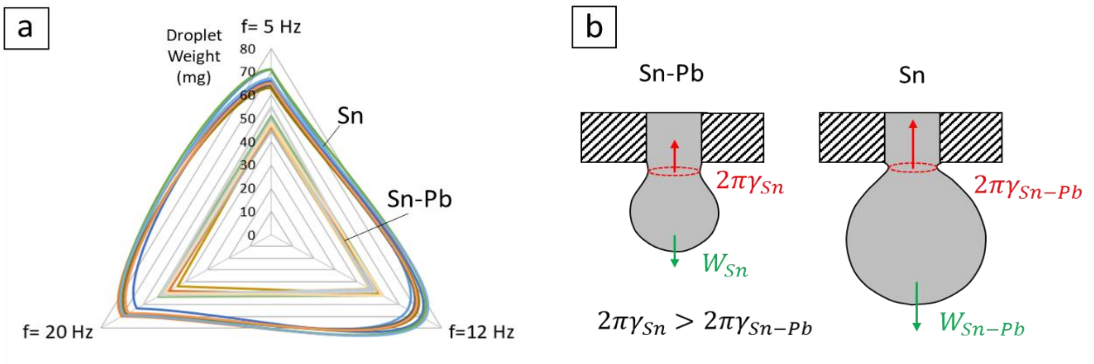

Figure 8: (a) Droplet weight in all the studied Sn and Sn-Pb samples at constant pulse frequencies (5, 12, and 20 Hz). (b) Schematic diagram illustrating the force balance in the smaller (Sn-Pb) and larger (Sn) droplets

Droplet Ejection Rate

Figure 9a-c shows the results of droplet ejection rate at different pulse, temperature, and composition conditions. By increasing the frequency, the drop ejection rate increases. Results indicate that the ejection rates are higher for Sn-Pb (Figures 9a and c) than for Sn (Figures 9b and d). This observation agrees with the previous findings that lower surface tension causes smaller droplets. Each small Sn-Pb droplet quickly reaches its critical weight and is separated from the nozzle. At the same time, it takes more time (more pulses) to accumulate more mass in the Sn droplet to reach its critical weight to overcome higher surface energies.

In the case of 200V (Figures 9a and b), by increasing the temperature, the ejection rate in Sn-Pb increases, while for Sn, the rate is reversed. This difference is repeated in the samples studied at 280V (Figures 9c and d).

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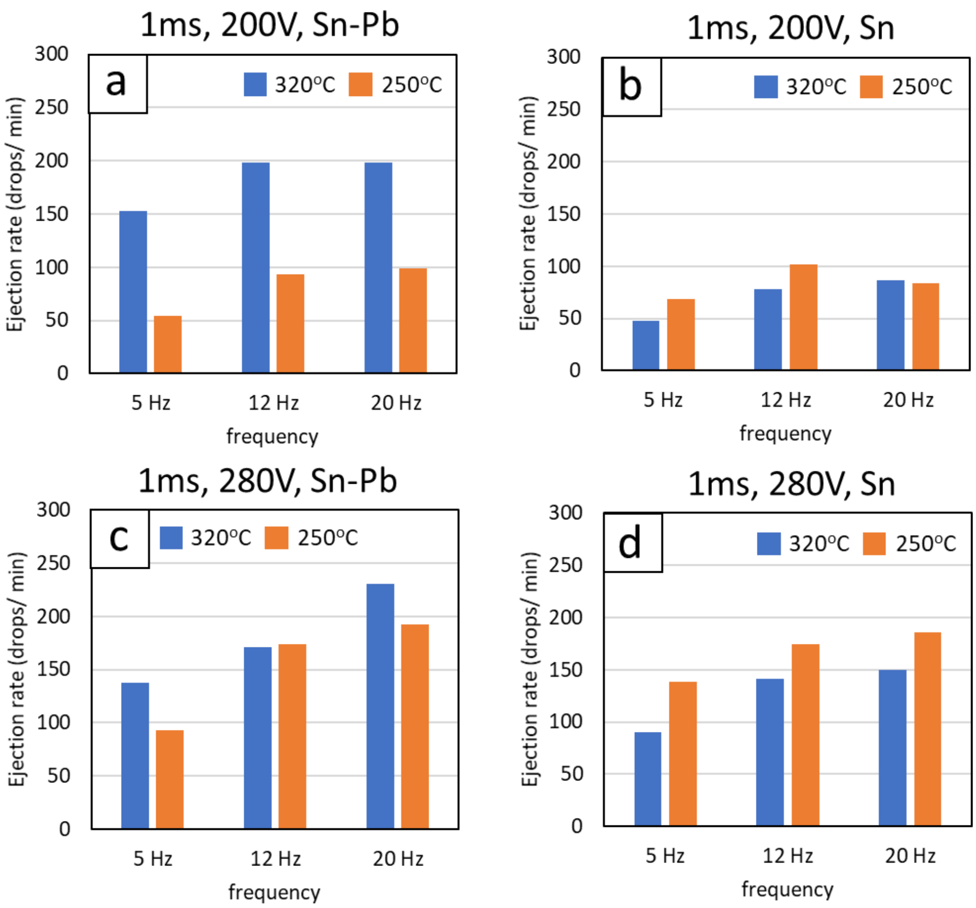

Figure 9: Ejection rate of droplets per minute at 1ms pulse on time, 200V for (a) Sn-Pb and (b) Sn, 280V for (c) Sn-Pb and (d) Sn

In Figure 10, the droplet ejection rate is presented at the same conditions as Figure 9 but at a higher duty cycle of 1.5ms (compared to 1ms in Figure 9. In all four diagrams, it can be seen that ejection rates are higher. A higher droplet production rate is a direct effect of more current in the coil, a stronger magnetic field, and a larger eddy current. Consequently, a larger force is applied to the fluid in the nozzle at every single pulse. The overall trends are quite similar to what has been presented when pulse on time is 1ms (Figure 9) except, here, at 280V, the Sn droplet rate increases by increasing temperature.

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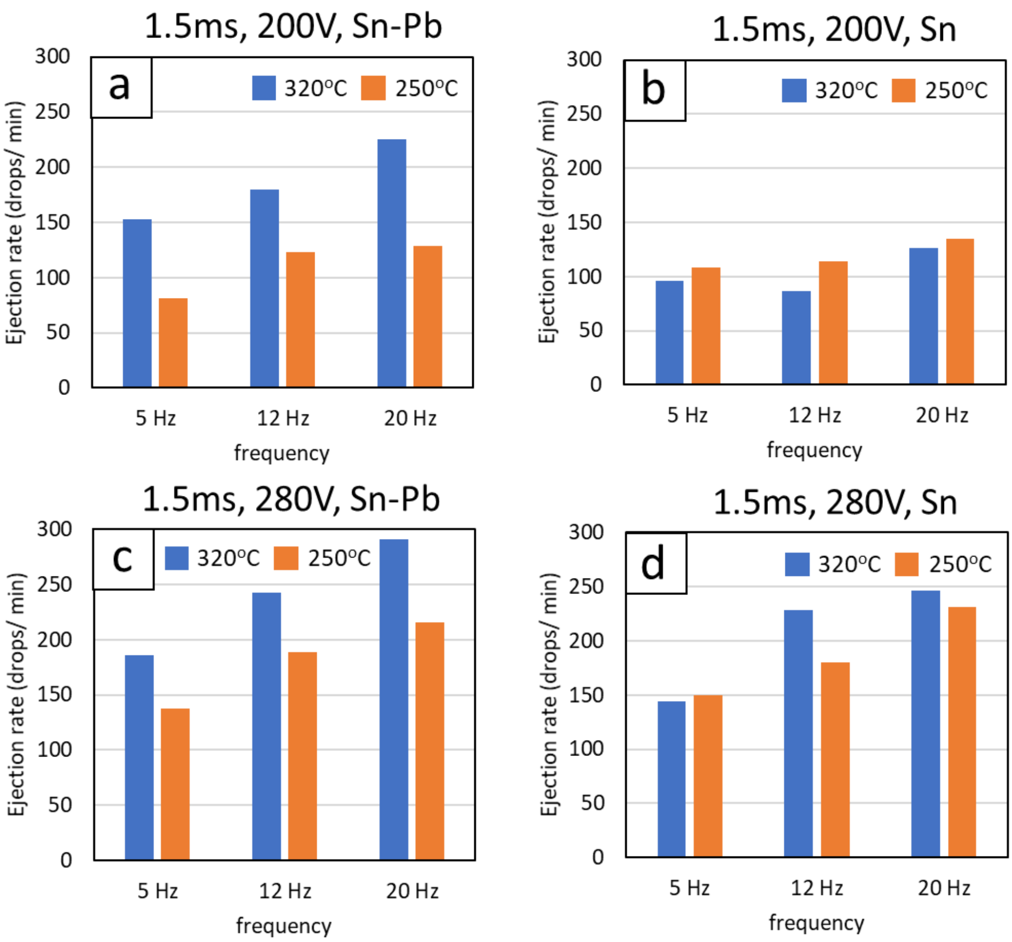

Figure 10: Ejection rate of droplets per minute at 1.5ms pulse on time, 200V for (a) Sn-Pb and (b) Sn, 280V for (c) Sn-Pb and (d) Sn

4. CONCLUSIONS

Effects of various pulse and melt parameters of a designed drop-on-demand magnetohydrodynamic pump on droplet weight shape and production rate is studied, and the following main conclusions are drawn:

- Pulse parameters, including voltage, duty cycle, and frequency, have notable direct effects on droplet production rate but are not that significant on droplet weight.
- Sn-Pb droplets are smaller than pure Sn at identical nozzle conditions. The difference is attributed to the lower surface energy of Sn-Pb alloy.
- Temperature changes melt characteristics in different directions, some increasing the droplet production rate (lower viscosity and lower surface tension) while some are in the opposite direction (lower conductivity). Therefore a general trend was not observed.

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