ABSTRACT

The formation of highly uniform charged molten metal droplets from capillary stream break-up has recently attracted significant industrial and academic interest for applications requiring high-speed and high-precision deposition of molten metal droplets such as direct write technologies. Exploitation of the high droplet production rates intrinsic to the phenomenon of capillary stream break-up and the unparalleled uniformity of droplet sizes and speeds attained with proper applied forcing to the capillary stream make many new applications related to the manufacture of electronic packages, circuit board printing and rapid prototyping of structural components feasible. Recent research results have increased the stream stability with novel acoustic excitation methods and enable ultra-precise charged droplet deflection. Unlike other modes of droplet generation such as Drop-on-Demand, droplets can be generated at rates typically on the order of 10,000 to 20,000 droplets per second (depending on droplet diameter and stream speed) and can be electrostatically charged and deflected onto a substrate with a measured accuracy of ±12.5 μm. Droplets are charged on a drop-to-drop basis, enabling the direct writing of fine details at high speed. New results are presented in which fine detailed patterns are “printed” with individual molten metal solder balls, and issues relevant to the attainment of high quality printed artifacts are investigated.

INTRODUCTION

The photograph in Figure 1 illustrates a pattern that was printed with charged and deflected solder balls onto a black card-stock substrate. The molten solder balls were generated from capillary stream break-up from a 100μm diameter orifice. Individual splat diameters are measured in the range of 375 – 400μm, and the scale shown with each image indicates 1.0mm lines. These particular realizations, which resemble “Moorish Arches”, are included as a demonstration of the intricate detail possible with molten metal printing. The charge waveforms employed while making the prints were sine waves in which the time base of the charge waveform was not synchronized with that of the droplet generation waveform. Hence, the position of the droplets relative to the charge waveform was not fixed, allowing the droplets to essentially “walk” up and down the crests and valleys of the sine wave. When the droplets impinge upon the translating substrate, they sweep out the pattern shown.

Figure 2 illustrates a conceptual schematic of the charging and deflection technique for a simple sinusoidal pattern. In this case, the time base of the droplet generation waveform is synchronized with that of the charging waveform, and the frequency of the charging waveform is much lower than the droplet generation frequency allowing a dense sinusoidal

Figure 1: “Moorish Arches” printed with electrostatically charged and deflected solder balls. Individual splats are approximately 375 μm and divisions shown are 1 mm.
pattern to be printed. The substrate moves along one axis, and deflection occurs along the perpendicular axis. The time-varying charge signal is applied to the charge electrode, and a potential of ±3000V is applied to the deflection plates.

**Droplet Generation**

The generation of highly stable droplet streams is a requirement for Direct Write applications. Any variations in droplet formation time will lead to significant errors in droplet placement via electrostatic charging and deflection is discussed in detail elsewhere [1]. Under carefully controlled conditions, droplet formation from capillary stream break-up provides droplet streams with speed dispersions as low as $1 \times 10^{-6}$ times the average speed, and angular deviations as small as one micro-radian [2]. The molten metal capillary stream is excited with a periodic disturbance by means of a vibrating piezoelectric crystal whose frequency is chosen to be in the Rayleigh regime [3] for uniform droplet generation. The science of droplet generation from capillary stream break-up is well understood, and the interested reader is urged peruse the review articles by Bogy [4] and McCarthy & Molloy [5] for a more in-depth discussion. In brevity, Lord Rayleigh showed that if the applied disturbance is chosen such that it’s wavelength is greater than the stream’s circumference, the surface waves will become unstable and grow exponentially in time as $e^{\beta t}$, ultimately resulting in droplet formation, where $\beta$ is the growth rate of the disturbance. Later, Orme [2] showed that the most uniform droplet stream is one that is perturbed with a disturbance whose frequency associated with the maximum $\beta$.

**Droplet Charging and Deflection**

Molten metal droplets are charged by electrostatic induction. The molten metal jet passes through the charge electrode that surrounds the jet at the point of droplet formation. The conductive molten liquid is grounded and a positive periodic potential, $V_c$, is applied to the charge electrode. As drops are formed from the continuous column of molten metal, a negative charge is induced on the drop that is proportional to the charge potential. In order to print the droplets to different locations, a distinct potential is applied to the charge electrode for every drop to be formed, and therefore, synchronization between the charge waveform frequency and the droplet production frequency must be maintained.

This method of droplet charging is similar to that employed in the technology of ink-jet printing. A few of the more important experimental works on ink-jet printing are given by Sweet [6, 7], Schneider *et al.* [8], Kamphoefner [9], and Fillmore *et al.* [10]. Analogous to the applications described in this work, an ink-jet jet printer produces characters on paper by deflecting charged droplets on one axis while the print head moves along the perpendicular axis. The droplet charge and the strength of the electric field through which the droplet moves...
determine the amount of deflection achieved by a droplet. The net charge on the droplet is acquired at the time of droplet formation.

In contrast to the ink-jet droplets, the molten metal droplets in this work attain significantly higher charges so that large lateral areas can be printed. The high charges cause significant inter-droplet mutual electrostatic interactions to occur which are not evident in the ink-jet printing technology. The importance of these interactions has been reported in the recent paper by Orme et al. [1]. The charge to mass ratio, \( Q/m \), can be predicted by the relation given by Schneider et al. [8]:

\[
\frac{Q}{m} = \frac{2\pi e V_c}{\rho_o^2 \ln(b/r_o)}
\]  

Here, \( m \) is the droplet mass, \( \varepsilon_o \) is the permittivity of free space, \( V_c \) is the charge potential, \( b \) is the radius of the charge tube, \( \rho \) is the molten metal density, and \( r_o \) is the radius of the unperturbed capillary stream. We have shown excellent agreement between measured droplet charge and the above equation in reference [1].

**EXPERIMENT**

The experimental setup consists of a droplet generator that is situated in a fume-hood, and injects droplets into a chamber that experiences a slow purge of an inert gas. We have found that it is necessary to eliminate traces of oxygen from the chamber in order to avoid the disruptive effects of oxidation, which act to impede molten metal droplet formation. Immediately below the droplet generator is the charging electrode and the parallel deflection plates as sketched in Figure 2. The separation between the orifice, which is contained at the lower end of the droplet generator, and the substrate, is 325 mm. The orifice diameter is 100 \( \mu \)m, and the mean droplet diameter is 189 \( \mu \)m. The substrate is mounted on an x-y table that moved at a speed of 5.2 cm/s. A microscope with long working distance optics and equipped with a camera is mounted outside the chamber. Properties used in the experiment are listed in Table 1 unless otherwise indicated in the text.

In previous work [11] we have found it necessary to actively control the position of the orifice in order to obtain a printing accuracy of \( \pm 12.5 \mu \)m. To this end, the orifice is situated in a hemispherical seat assembly with the orifice at the center of curvature. Active feedback and control of the stream’s position with information from two perpendicularly positioned CCD array cameras allows the adjustment of the hemisphere to compensate for any small deviations in the stream’s trajectory. However, in this work the aforementioned feedback and control system was not utilized (though plans for it’s implementation for future studies are underway), and therefore, the results presented here will possess dispersions in placement.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>droplet fluid</td>
<td>63% Sn, 37% Pb</td>
</tr>
<tr>
<td>specific gravity</td>
<td>8.420</td>
</tr>
<tr>
<td>surface tension</td>
<td>0.49 kg/s²</td>
</tr>
<tr>
<td>viscosity</td>
<td>1.58x10⁻⁷ m²²/s</td>
</tr>
<tr>
<td>orifice diameter</td>
<td>100 microns</td>
</tr>
<tr>
<td>ambient &amp; stagnation gas</td>
<td>Nitrogen</td>
</tr>
<tr>
<td>driving pressure</td>
<td>20 psi</td>
</tr>
<tr>
<td>solder reservoir temp.</td>
<td>200°C</td>
</tr>
<tr>
<td>disturbance frequency</td>
<td>12,000 Hz</td>
</tr>
<tr>
<td>charge electrode diameter</td>
<td>0.318 cm</td>
</tr>
<tr>
<td>deflection plate separation</td>
<td>1.27 cm</td>
</tr>
<tr>
<td>deflection plate length</td>
<td>5.08 cm</td>
</tr>
</tbody>
</table>

Table 1: Properties used in experiment
that are not representative of the “comprehensive” system. Nonetheless, the raw results below show excellent potential for the application of direct writing.

RESULTS

Figure 3 illustrates a double sine wave that was printed with electrostatically charged and deflected solder droplets onto a copper substrate. In this case, the droplets were generated at a frequency of 20,000 Hz and the charge waveform was a sinusoid with charged with a frequency of 10,010 Hz. Had the charging frequency been exactly half of the droplet generation frequency (i.e., 10,000 Hz), the original stream would have been split in two angularly stable streams and the resulting printed pattern on the translating substrate would be two parallel lines. However, since the charging waveform was 10,010 Hz, it was intentionally slightly out of phase with the droplet generation frequency, causing the charge to drift between maximum and minimum values. Hence, the original droplet stream was split into two streams that were simultaneously scanning on the horizontal axis (i.e., perpendicularly to the translation axis) in mirror images. This example illustrates the stability of the droplet break-up and charge mechanism.

**Effects of Droplet Stream Frequency**

Figure 4 illustrates the effect of droplet generation frequency on the thickness and uniformity of the printed line. A “full” stream corresponds to a droplet stream generated at a frequency of 12,000 Hz as shown in the second trace in the figure. The fractions indicate the reduction in frequency accomplished by electrostatic charging and deflection. For example, the top line pictured was generated with a droplet production frequency of 1/24th that of the full stream, i.e., every 500 Hz (12,000/24). Hence, in this case, every 24th droplet was deflected out of the stream by the same magnitude, thereby creating two angularly stable streams of different droplet densities, where in practice, either line may be collected in order to avoid impingment. The line width, the ball density, and the flow rate for each of the pictured cases are provided in Table 2 below. The droplet impingement temperature is constant for each line shown. The line width generally decreases with the droplet frequency. As the line becomes more dense, such as in the case with 1/4th full or full frequency, the solidification time increases due to a larger accumulation of molten metal at one location, thereby providing the ability for the fluid to “roll” off the top of the printed line, leading to deviations in straightness. Alternatively, as the droplet

![Figure 3: A double sine wave of solder onto a copper substrate. Grid lines are 1.0 mm apart.](image)

![Figure 4: Examples of solder lines printed with different droplet frequencies. Droplets are deflected out of the stream in order to vary the frequency. Grid lines are 1.0 mm apart.](image)
frequency is reduced, the splats rapidly solidify, eliminating the possibility of relaxation into a smooth cord by the action of surface tension. Hence, for the production of straight and smooth lines, it is desired to simultaneously decrease the droplet frequency and increase the droplet temperature.

**Line Separation and Thickness**

Figures 5-7 illustrate magnified lines printed by three different means. In each case the substrate translation speed was 5.2 cm/s. The grid marks on each figure are 1.0 mm lines. In Figure 5, the lines were printed by electrostatically charging the solder stream generated at a frequency of 12,000 Hz with a 3,000 Hz sine wave. Synchronization between the charging waveform and the droplet generation waveform insured that each charge waveform cycle contained four droplets whose positions relative to the charge waveform did not shift in time. Hence the effective droplet frequency of the each droplet stream impacting the substrate is 1/4th that of the original uncharged droplet stream, i.e., 3,000 drops/second. Since the substrate speed was 5.2 cm/s, four 5.2 cm long lines were printed in 1.0 second. The separation between the inner-most printed lines is consistently of the order of 250 µm.

Figure 6 illustrates the printing of four lines by traversing the substrate four times under an angularly stable droplet stream generated with a frequency of 1/4th that of the full stream, so that the line densities are the same as those shown in Figure 5. The printing speed of four lines 5.2 cm in length is 4.0 seconds in addition for the time required to re-position the substrate after each pass.

Figure 7 illustrates four lines printed by traversing the substrate under a stationary stream that was generated with a frequency of 1/24th that of a full stream. Hence, the lines are narrower, but less smooth due to the rapid solidification. Nonetheless, it can be seen that four distinct lines can be printed within a 2.0 mm space. In order to obtain smoother lines, the droplets must impinge at a higher temperature in order to compensate for the reduction in mass delivery rate.

<table>
<thead>
<tr>
<th>Stream frequency</th>
<th>Full</th>
<th>1/4</th>
<th>1/6</th>
<th>1/12</th>
<th>1/24</th>
</tr>
</thead>
<tbody>
<tr>
<td>mean line diam. (mm)</td>
<td>1.75 ± 0.2</td>
<td>.550 ± 0.05</td>
<td>.525 ± 0.05</td>
<td>.450 ± 0.05</td>
<td>.450 ± 0.05</td>
</tr>
<tr>
<td>number of balls/mm</td>
<td>230</td>
<td>47.6</td>
<td>38.4</td>
<td>19.2</td>
<td>9.6</td>
</tr>
<tr>
<td>flow rate (g/cm)</td>
<td>0.535</td>
<td>0.0134</td>
<td>0.00892</td>
<td>0.00446</td>
<td>0.00223</td>
</tr>
</tbody>
</table>

Table 2: properties of printed lines of varying frequency
which reduces the heat flux to the specific location. Experiments to demonstrate this assertion are currently underway.

CONCLUSIONS

The “printing” of solder lines from discrete solder balls generated from capillary stream break-up was presented. It has been shown that fine detailed pictures (e.g., “Moorish Arches”) can be printed at high speed with electrostatic charging and deflection of the molten metal balls. Studies showed that droplet streams generated at lower frequencies (by deflecting a desired fraction of droplets out of the main stream) result in finer pitch lines, though the use of such streams requires that additional heat must be supplied to the droplets if smooth lines are required. Our results show that four distinct parallel lines can be printed in a 2.0 mm space, providing excellent potential for fine-pitch printing.

ACKNOWLEDGMENTS

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REFERENCES

3. Lord Rayleigh, Phil Mag. 14, 184 (1882)