Flexible and Printed Electronics

PAPER

Magnetohydrodynamic liquid metal droplet jetting of highly conductive electronic traces

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Abstract
Magnetohydrodynamic Jet Printing (MJP) is a novel additive manufacturing technique that offers tremendous promise for the fabrication of highly conductive electronic circuits with excellent adhesion on flexible substrates. MJP is an on-demand droplet jetting process in which the fluid is molten metal rather than a conductive nanoparticle ink. The work reported here examines the influence of drop spacing and jetting frequency on line morphology and electrical resistivity. Furthermore, the equivalent wire gauge of printed lines is estimated as a function of the drop volume and drop spacing. Under optimized jetting conditions, electrical resistivity as low as 3.2 MΩ cm (equivalent to bulk resistivity) has been achieved in aluminum 4043 alloy printed onto flexible polyimide. Little or no substrate cleaning is needed prior to printing, and post processing steps such as drying and curing are eliminated with this technique. The process uses metal wire as the feedstock material, making it significantly less expensive than conventional nanoparticle ink printing techniques.

1. Introduction

Digital printed electronics techniques have been widely used to pattern electrically conductive materials without the need for masks or other fixed tooling. These techniques reduce the iterative prototyping time and cost during product development, and they allow economical manufacture of circuit boards in small quantities. The additive nature of digital pattern-less printing processes results in significant reduction of material waste. This not only lowers the manufacturing cost, but also makes the process more environmentally friendly [1, 2].

With forecasted demand for connected and wearable devices in the ‘Internet of things’, fabrication of flexible electronics using digital pattern-less techniques is of particular interest [3, 4]. Digital printing techniques such as inkjet printing [5], aerosol based printing [6], and micro-dispensing [7] have been thoroughly investigated and subsequently commercialized for fabrication of flexible electronic devices. These processes typically involve deposition of conductive nanoparticle suspension inks onto polymer substrates such as polyethylene terephthalate (PET) or polyimide (PI) to fabricate electrically conductive features. Considerable research has been devoted to the formulation of silver and copper nanoparticle inks whose rheological properties are tuned for a given printing process and substrate [8–10]. Likewise, a great deal of research has been devoted to the topics of drying, curing, electrical conductivity, printability, substrate adhesion, and robustness of the conductive inks [11–13].

Several excellent review papers on these topics have appeared recently for the interested reader. For example, Abdolmaleki et al surveyed the application and working principles of various droplet-based printing technologies (inkjet, aerosol jet, and electrohydrodynamic jet), different functional inks (metal, carbon, polymer, and ceramic) and sintering methods commonly used in printed electronics [14]. Neumann and Dickey discuss recent progress in 3D printing of low melting point, gallium-based liquid metal alloys employed in soft circuitry for stretchable electronics and soft robotics [15]. Saleh et al report on a novel single step multifunctional additive manufacturing process which enables fabrication of 3D electronic circuitry within a polymeric structure.
using a combination of conductive and nonconductive materials within a single material jetting-based AM system [16].

On the materials side, much promising work involving alternatives to silver nanoparticle inks has been presented. LeFerrand et al introduce recent advances in fabrication of graphene-based devices for advanced electronics through controlling the microstructure of graphene nanomaterials [17]. Goh et al discusses the advancements in carbon nanotube (CNTs) alignment, either during the growth or post-growth processing. This paper also discusses various CNTs alignment mechanisms, process parameters, and challenges of each technique [18].

Although tremendous advances have been made in each of these areas, there is still considerable room for improvement in four areas. First, the electrical resistivity of the printed features is typically $>3\times$ the resistivity of the corresponding bulk metal. The ability to achieve bulk metal electrical resistivity would be highly desirable, as it would reduce resistive losses and could enable use in high current applications. Second, achieving good adhesion of printed nanoparticle traces to the substrate typically requires considerable tuning of ink chemistries and substrate pretreatments. This is particularly true for flexible electronics applications. Third, post-process steps such as drying and curing are required to remove the liquid ink vehicle and organic additives and to fuse (sinter) the nanoparticles together to create conductive electrical pathways. Tremendous care must be taken during drying and curing to avoid defects such as coffee ring, cracking, and/or delamination from the substrate. Elimination of the need for drying and curing could reduce capital costs, manufacturing cycle time, and/or defects that adversely affect conductivity of the printed traces. Lastly, the cost of raw materials for metal nanoparticles tends to be one to two orders of magnitude higher than the price of bulk metal [19–21]. Lower raw material costs would contribute to wider adoption of digital printing techniques for printed electronics. Addressing these issues with the current manufacturing approach may boost the adoption of pattern-less digital printing techniques for fabrication of flexible electronics.

In this work, a molten metal droplet jetting approach to printed electronics is considered to address the four areas for improvement described above. Work done by Wallace et al has shown the feasibility of depositing low temperature molten solder droplets (melting point < 250 °C) onto polymer substrates using a piezoelectric drop-on-demand deposition process [22, 23]. However, virtually no studies involving droplet jetting of high temperature highly conductive molten metals (melting point > 250 °C) such as copper or aluminum onto polymer substrates have been published.

In this work, Magnetohydrodynamic Jet Printing (MJP) is used to print circuit patterns of 4043 aluminum alloy onto polyimide substrates. This enables fabrication of highly conductive features without the need for post processing. The raw material used in this technique is coiled wire whose cost is several orders of magnitude lower than the equivalent weight of nanoparticles [20, 21]. The MJP fabricated features have considerably higher electrical conductivity than those typically achieved via nanoparticle digital printing approaches. Furthermore, the research reported here demonstrates excellent substrate adhesion under appropriate jetting conditions without any need for special substrate cleaning or surface modification prior to printing. This is believed to be the first report on the use of MJP to print circuit board patterns.

2. Experimental section

2.1. Printing method

The printing system used in this study was an MK1 magnetohydrodynamic liquid metal jetting system manufactured by Vader Systems (now part of Xerox Corp, Rochester, NY, USA). A conceptual illustration of the MJP system elements is shown in figure 1. 4043 aluminum alloy wire having a diameter of 0.9 mm was fed into a small heated crucible where it was resistively heated to the target melt temperature of 900 °C for all experiments in this study. For reference, the maximum temperature of the machine used in this research is 1100 °C. Future generations of the machine are intended for higher melting point metals. The molten metal is gravity fed into a lower pump chamber that is capped with a nozzle having the selected orifice diameter (e.g. 150 μm, 250 μm, 500 μm, etc). The ejection chamber is surrounded by an electromagnetic coil through which pulsed direct current flows.

The generation of electrical pulses in the coil produces a transient magnetic field that permeates the molten metal and induces a corresponding transient electric field. This, in turn, causes circulating eddy currents within the liquid metal. The interaction of magnetic and electric fields results in magnetohydrodynamic Lorentz forces within the chamber. At sufficiently high magnitude, these forces act to eject liquid metal droplets from the orifice. Droplets are ejected with a velocity of $1–10$ m s$^{-1}$ depending on the droplet ejection parameters [24, 25]. The droplets can be jetted on demand at the desired ejection frequency, typically 10–1000 Hz depending on the application, using the current control system [24]. Ejected droplets are deposited onto the substrate which has been placed on a heated platen. An X–Y motion stage moves the platen according to the programmed toolpath. The jetting fixture moves up and down along the Z-axis. As jetted droplets land upon the moving substrate, they spread, coalesce, and solidify to form the intended circuit pattern.
In this process, the pulse length (µs), pulse voltage (V), and jetting frequency (Hz) can be independently controlled in order to optimize the dynamics of droplet ejection. The pulse length and voltage primarily affect consistency and stability of the droplet stream. The exact values are considered proprietary to the machine manufacturer, however, they are typically kept constant to ensure jetting stability. They have minimal impact on printed line quality provided the jet stream is stable. Several other aspects of the jetting process can also be changed, such as orifice diameter (µm), standoff distance between the orifice and substrate (mm), reservoir temperature (°C), heated platen temperature (°C), and center-to-center drop spacing (µm). For all experiments in this study, a nozzle having an orifice diameter of 250 µm was used, as this was the smallest diameter nozzle available from the manufacturer during this proof of concept study. Magnetohydrodynamic jetting of 3D printed structures with smaller diameter nozzles has been demonstrated though. For example, Simonelli et al reported silver droplet diameters as small as ~80 µm in a 3D printing setup [26]. The minimum achievable feature size depends on the degree of droplet wetting upon impact, however, the droplet diameter gives a reasonable estimate of the minimum achievable feature size. Larger nozzles (e.g. 500 µm) have been used to deposit traces having extremely large cross-sectional area for high power printed electronics applications, however, lower jetting frequencies are needed to avoid melting through the substrate in this case. The substrate temperature was set at 200 °C to reduce the thermal gradient between the substrate and the impinging droplet. The standoff distance between the nozzle and substrate was fixed at the default distance of 15 mm because it was experimentally found to work well. At smaller standoff distances, heat from the nozzle sometimes caused substrate distortion. Larger standoff distances were not used to minimize in-flight cooling of the droplet.

Upon initial startup of the machine, a warm-up and nozzle priming procedure is performed to obtain a stable jet stream. After the machine has been warmed up to produce a stable jet stream, there will typically not be any stray satellite drops (or over-spray). In rare cases where the jet does not stabilize after warm-up, the nozzle can be swapped out for a new one. In order to get an accurate estimate of the jetted drop diameter, a calibration routine is then run prior to each print job in which 10,000 drops are jetted into a weigh pan on a digital scale. The calibration mass (m_c) in grams per 10,000 drops is then recorded. Using m_c together with the density (ρ) of the metal alloy being jetted in g cm⁻³, the volume (V_d) per drop in cm³ is given as:

\[ V_d = \frac{m_c}{10000 \rho}. \]  

Equating the volume of a spherical droplet to the empirically measured V_d and solving for the diameter of the drop (D_d) in cm, we have

\[ D_d = \left(\frac{6V_d}{\pi}\right)^{1/3}. \]

The center to center distance between adjacent droplets deposited onto a substrate is referred to as drop spacing (d_s). An illustration of the top view of partially overlapping droplets deposited onto a surface is provided in figure 2. Prior studies on droplet based deposition processes such as inkjet printing have shown that drop spacing has a major impact on the morphology of the printed lines [27, 28]. With MJM, the nozzle diameter, and hence nominal drop size, can be changed by swapping out nozzles. In order to normalize drop spacing for any given nozzle diameter, a droplet overlap fraction (O_d) relative to the droplet size is used rather than an absolute drop spacing distance. The numerical relationship between O_d, D_d, and d_s is shown in equation (3). An overlap fraction of 0.0 would indicate that adjacent droplets tangentially touch each other but do not overlap prior to liquid spreading. An overlap fraction of 1.0 would indicate that droplets land directly on top of each other. A negative overlap fraction would indicate that the drop spacing is larger than the droplet diameter, thus resulting in discrete isolated drops rather than a continuous line. It is important to emphasize that the drop spacing is relative to the drop diameter and does not account for droplet spreading, coalescence, or surface tension effects after the drops land

\[ d_s = D_d (1 - O_d). \]
2.2. Materials
The feedstock material used was 0.9 mm diameter 4043 aluminum alloy wire. The flexible polymer substrate was 125 µm thick polyimide (Kapton, DuPont). Polyimide was selected because it is widely used in the electronics industry as a flexible nonconductive substrate. Polyimide can withstand high temperature and is known for its structural integrity. All printing experiments were done with Kapton film in the as received condition other than a quick wipe with a dry lint free cloth to remove any dust that might have accumulated on the surface. No surface treatments were performed.

2.3. Characterization
Following printing of straight lines under different jetting conditions, metallurgical samples were prepared for microscopy via cold mounting. Struers Tegramin-20 grinding and polishing were used to reveal the morphology and microstructure of printed lines both parallel and perpendicular to the print direction. A Hirox KH-7700 optical microscope was used to capture micrographs of the printed features. ImageJ image processing software was employed to measure the cross-sectional area of printed tracks. 4-point electrical resistivity measurements were taken by passing a current of 6 Amps through printed traces using a DC power supply. The voltage drop across a known length was measured, and the resistivity of the printed tracks was then calculated.

3. Results and discussion
3.1. Printed line behavior
The demand for feature quality from the electronic industry necessitates the ability to produce uniform, smooth lines of fine resolution for printed electronic devices. Soltman and Subramanian have demonstrated the importance of process conditions such as drop spacing and frequency on uniformity of lines printed using inkjet printing with an electrically conductive polymer-based ink [27]. In the present work, a similar approach is taken to characterize the morphologies of lines printed with molten metal droplets as a function of printing process conditions. This is intended to classify and understand the process conditions that lead to uniform printed lines.

The independent variables used in this experimental study were the overlap fraction and drop ejection frequency. Overlap fraction was adjusted between 0.0 and 0.7 in increments of 0.1. The droplet deposition frequency was varied from 25 Hz to 125 Hz in increments of 25 Hz. Jetting frequency directly determines the time that one droplet has to cool down and begin solidifying before the next droplet arrives. Likewise, drop overlap fraction affects the volume of molten metal deposited per unit length of a conductive trace. At one extreme, printing with low overlap percentage and low jetting frequency will result in drops that are spaced apart and which have time to cool and solidify prior to arrival of the next drop. At the opposite extreme, printing with a large droplet overlap percentage at high frequency will result in drops that overlap a great deal and which do not have time to solidify prior to arrival of the next drop.

The droplet overlap fraction and jetting frequency values used in this study were chosen such that complete melting through the 125 µm thick Kapton film was avoided. Damage to polyimide in the form of charring and substrate distortion was noted at overlap fractions >0.8 and frequency conditions >150 Hz. The combination of large droplet overlap with modest or high droplet jetting frequency results in sufficiently high thermal flux to damage the substrate. Other parameters, such as the drop size, droplet temperature, substrate material, and substrate thickness, can also affect the presence or absence of substrate damage. For example, the thermal energy within each droplet varies as a function of drop volume. The droplet volume, in turn, varies as a function of the cube of the diameter. Therefore, as drop diameter decreases, the risk of thermal damage to a given substrate rapidly decreases. Substrates with low glass transition temperatures, such as PET, are more susceptible to thermal damage. For example, 125 µm thick PET completely melted at the jetting conditions used for the polyimide substrate. Future work using progressively smaller diameter nozzles is planned to assess the potential for printing onto low cost thermally sensitive PET substrates. Substrate thickness can also affect the results. At the conditions where no substrate damage was noted for a 125 µm thick polyimide, significant warping was observed in 75 µm thick polyimide.

Lastly, substrate temperature can have a significant effect on print quality. It was noted that large entrapped gas pores were observed within metallic traces printed on room temperature (unheated) polyimide substrates. In some cases, the pores extended through the top edges of printed traces in the form of pinholes. This would obviously be undesirable for flexible electronic applications where the pores would likely lead to cracking and failure during flex cycles. When the polyimide was sufficiently heated (200 °C in this study), the printed traces were essentially free of these pores. Polyimide is known to be highly hygroscopic, and the hypothesis is that the molten metal causes release of water vapor upon impact with the polyimide substrate. The 200 °C substrate temperature was experimentally found to be sufficiently high to eliminate trapped gas pores without causing any visually apparent damage to the polyimide. This is the subject of ongoing study.

In order to keep the experimental matrix at a reasonable size for purposes of this exploratory study, the drop size, substrate material, and substrate thickness were fixed. Not surprisingly, the morphology of printed traces changes as the combination of overlap...
fraction and jetting frequency traverses from one extreme (low overlap at low frequency) to the other (high overlap at high frequency). Five distinctly different regimes were observed and are described as follows.

3.1.1. Scalloped lines
At very low jetting frequency (i.e. 25 Hz) each drop has time to cool and solidify prior to arrival of the next drop. When the drop overlap fraction is also very low (i.e. 0–0.3), the result is distinct semi-spherical drop volumes connected by small necks. An example of a scalloped trace printed with an overlap fraction of 0 and a frequency of 25 Hz is shown in figure 3.

3.1.2. Lift-off lines
At very low jetting frequency (i.e. 25 Hz) and medium to high overlap fractions (i.e. 0.5–0.7), the printed traces begin to vertically lift up off of the substrate. When there is a fair amount of overlap between successive drops jetted at low frequency, drops landing on a fully solidified drop themselves begin to solidify before the drop rolls over and touches the substrate. Consequently, there is a vertical lifting of the printed trace away from the substrate until the mass of material is sufficiently large to cause the trace to droop back down towards the substrate. Top and side views illustrating this behavior produced at a droplet overlap fraction of 0.6 and a jetting frequency of 25 Hz are shown in figure 4.

3.1.3. Discontinuous lines
At intermediate frequencies (i.e. 125 Hz), drops arrive before the previous drop(s) have had sufficient time to cool down and at least partially solidify. At low droplet overlap fractions (i.e. 0–0.2) with high jetting frequency, liquid surface tension effects dominate, resulting in discontinuous beads. Similar behavior is seen in inkjet printing at larger line widths with slow-drying inks. Figure 5 shows discontinuous lines which resulted from a droplet overlap fraction of 0.1 and a jetting frequency of 125 Hz.

3.1.4. Straight lines
As jetting transitions to intermediate overlap fractions (i.e. 0.3–0.5) and low frequency (i.e. ~75 Hz), the line quality substantially improves. Figure 6 shows a trace printed with a drop overlap fraction of 0.4 and a jetting frequency of 75 Hz. This trace exhibits a straight and uniform line width, however, ridges corresponding to partially overlapping droplets are evident. Figure 7 shows a trace printed with a slightly higher drop overlap fraction of 0.7 and a jetting frequency of 75 Hz.

3.1.5. Bulging lines
When intermediate jetting frequency (125 Hz) is combined with intermediate to high droplet overlap fractions (i.e. 0.5–0.7), there is sufficient heat and material deposition to allow puddling and bulging of lines due to surface tension effects prior to solidification. Figure 8 shows a trace that resulted from printing with a drop overlap fraction of 0.5 and a jetting frequency of 125 Hz. Figure 9 conceptually illustrates a process map for each of these morphologies when considering jetting frequency and overlap fraction. It must be emphasized that these results are specific to 4043 aluminum alloy at 900 °C jetted through a 250 μm diameter nozzle onto a 200 °C heated Kapton film. With different process parameter values and/or materials (e.g. molten copper), similar process parameter mapping experiments must be performed. For instance, the volume of each drop decreases as a function of the cubed root of the nozzle diameter when smaller diameter nozzles are used. It is to be expected that higher jetting frequencies will be used with smaller drop volumes in order to obtain the desired melt fusion between drops needed to produce high quality conductive traces. This is a focus of current research efforts.

3.2. Equivalent wire gauge of uniform lines
In contrast to printed electronics that are fabricated with nanoparticle inks, traces printed via jetting of liquid metal droplets produce very high aspect ratio conductive traces capable of carrying high currents. These printed traces behave similarly to solid core wires. For high current carrying applications in which the designer provides a wire gauge specification, it is useful to map the cross-sectional area of printed traces to the cross sectional area associated with standard wire gauges.

In printing regimes that result in uniform traces, the volume of material deposited per unit length can be used to estimate the average cross-sectional area \( A_t \) of a printed trace in cm\(^2\). This holds true regardless of the cross-sectional shape of the printed trace. Using \( V_d \) (equation (1)) and \( d_t \) (equation (3)), \( A_t \) is determined as

\[
A_t = \frac{V_d}{d_t} \quad (4)
\]

To estimate axial cross sectional area in printed traces, selected samples were mounted, ground and polished to reveal their horizontal cross-section. Figure 10 shows that the straight line cross-sections resemble a truncated cylinder on the substrate. As expected, the
cross-sectional area of printed traces increases as the overlap fraction increases.

The calibration mass of 10,000 droplets \( m_c \) jetted through a 250 \( \mu \)m diameter nozzle onto a weighing pan was measured before conducting the experiments. The density of 4043 aluminum alloy is 2.69 g cm\(^{-3}\). Using equation (1), the volume per drop \( V_d \) was calculated to be 6.5741 \( \times \) 10\(^6\) \( \mu \)m\(^3\). This corresponds to a drop diameter of 232 \( \mu \)m. Using equation (4) with \( V_d \) and the different drop spacing values used to print straight lines, the expected cross sectional areas of printed traces produced using different drop spacing \( d_s \) values were computed. The actual cross-sectional areas of printed traces was measured using the area function in ImageJ software with cross-sectional images obtained for each drop spacing value. Figure 11 shows predicted and measured cross-sectional areas of the straight traces printed at different overlap fractions. The estimated and measured cross sectional areas are rounded down to the nearest American Wire Gauge cross sectional area for purposes of being conservative when estimating current carrying capability. From figure 11, the predicted cross-sectional areas from equation (4) are in reasonably good agreement with measured cross-sectional areas, thus equation (4) can be used as an indicator of the expected wire gauge for maximum current calculation purposes in high power electronics. It is noteworthy that the height-to-width aspect ratio of the printed traces is massively greater than one would normally see with printed nanoparticle traces that are typically a few microns tall. The large aspect ratio underscores the potential to carry high currents in these printed traces.

3.3. Electrical conductivity and adhesion characterization

Straight lines were also ground and polished parallel to their longitudinal axes in order to assess the presence or absence of pores or other defects that might affect electrical conductivity. Figure 12(a) shows a representative longitudinal cross-section of a trace printed at 100 Hz frequency with a 0.60 overlap fraction. A radiograph shown in figure 12(b) indicates continuous material that is free of pores or other discontinuities.

Electrical characterization of the printed lines was performed using a 4-point conductivity measurement over a path length of 10 mm. A current of 6A was passed through the printed traces, and the voltage was measured using a multimeter. The resistivity of the tracks was calculated using equation (5),

\[
\rho = \frac{RA}{L} \tag{5}
\]
Figure 9. Process map for printed line behavior as a function of overlap fraction and frequency.

Figure 10. Axial cross-sections of uniform lines printed using (a) 0.40 overlap fraction 75 Hz frequency; (b) 0.60 overlap fraction and 100 Hz frequency.

Figure 11. Wire gauge predicted and measured through the volume of droplet over drop spacing formulation.
Figure 12. (a) Longitudinal cross-section of a uniform printed line printed at 0.60 overlap fraction and 100 Hz frequency; (b) radiograph of printed trace showing dense material.

where $\rho$ is the resistivity, $R$ is the resistance, $A$ is the cross-sectional area and $L$ is the length of measured conductive line. As the longitudinal cross-section of the lines revealed no significant porosity, the cross-sectional areas of the printed traces were determined from the micrographs (figure 11). The resistivity of the aluminum wire feedstock material used for printing was measured to be 4.178 $\mu\Omega \cdot \text{cm}$. This value was used as the bulk metal baseline for comparison with resistivities of the printed traces. Table 1 shows the resistivity values of traces printed using eight different combinations of overlap fraction and jetting frequency that resulted in straight high quality lines. The final column in table 1 shows the resistivity values of the printed traces relative to the resistivity of the bulk metal. These values ranged from $1.07 \times$ to $1.23 \times$ the resistivity of the bulk metal. These results indicate that the process achieves near bulk conductivity over a reasonably wide range of processing conditions. It is also worth noting that the large cross-sectional area and high conductivity of the printed traces enables much higher current to be carried than would normally be the case with nanoparticle printed traces. This makes these features very well suited for high power electronics.

The adhesion of the aluminum 4043 alloy printed onto PI substrates was measured by a standard tape test commonly used for nanoparticle printed electronics. Pressure sensitive tape was firmly attached to the printed area and quickly removed. The dashed rectangle in figure 13 shows the tape. The completeness of the printed feature after the removal of the tape indicates the good adhesion to PI substrate.

Additional characterization of substrate adhesion was performed in flexure. A uniform trace printed using an overlap fraction of 0.6 and a jetting frequency of 100 Hz was bent on a mandrel having a radius of 20 mm. Electrical resistance of the trace was measured using a 2-point probe approach before the sample was bent and when the sample was in the bent state (figure 14). There was no observable change in resistance as the sample was flexed over the mandrel.

Visual inspection of samples flexed over the 20 mm radius mandrel indicated that no delamination of the printed trace took place anywhere along the length of the printed trace. As mentioned in section 3.2, the printed traces behave very much like ductile solid core wire. Longitudinal cross-sections of an as-printed unflexed trace and a trace that was flexed over the 20 mm radius mandrel were prepared to assess whether or not any micro cracks or local delamination could be detected (figure 15). No macroscopic cracks were noted in the trace after bending, and no delamination of the trace from the substrate was detected. Future work is planned to assess the effect of repeated flex cycles (i.e. 100's to 1000's of flex cycles) on resistivity and adhesion of the printed traces.

3.4. Pattern fabrication

Based on the evaluations performed in the previous section, several 2D patterns were printed using aluminum 4043 alloy on the polyimide substrate. Various directly printed electronic circuits on polyimide (a) serpentine circuit containing regular bends (b) serpentine structure being subjected to bending (c) inductance coil (d) microcontroller circuit are provided in figure 16. The circuit shown in figure 16(b) illustrates the excellent adhesion
Table 1. Relative resistivities of traces printed for different combinations of overlap fraction and droplet jetting frequency.

| Overlap fraction | Jetting frequency (Hz) | Applied current (A) | Measured voltage (mV) | Measured resistance (mΩ) | Computed resistivity (µΩ cm) | Resistivity relative to bulk metal |
|------------------|------------------------|---------------------|-----------------------|--------------------------|------------------------------|----------------------------------|
| 0.30             | 50                     | 6                   | 78                    | 13.0                     | 3.655                        | 4.753                            | 1.13×                            |
| 0.30             | 75                     | 6                   | 61                    | 10.1                     | 4.416                        | 4.490                            | 1.07×                            |
| 0.40             | 75                     | 6                   | 67                    | 11.2                     | 5.457                        | 5.078                            | 1.22×                            |
| 0.50             | 75                     | 6                   | 50                    | 8.3                      | 5.438                        | 4.532                            | 1.08×                            |
| 0.50             | 100                    | 6                   | 54                    | 9.0                      | 5.717                        | 5.145                            | 1.23×                            |
| 0.60             | 75                     | 6                   | 45                    | 7.5                      | 6.273                        | 4.704                            | 1.12×                            |
| 0.60             | 100                    | 6                   | 41                    | 6.8                      | 6.524                        | 4.458                            | 1.07×                            |
| 0.70             | 100                    | 6                   | 28                    | 4.7                      | 10.206                       | 4.763                            | 1.14×                            |

Figure 13. Typical tape test for testing the line adhesion on PI substrate (a) with the tape attached and (b) tape removed.

Figure 14. (a) 2-point probe conductivity measurement on an as-printed flat sample; (b) conductivity of sample bent over a mandrel with a 20 mm radius.

Figure 15. Longitudinal cross section of (a) a trace that has not been flexed, and (b) a trace that has been flexed on a mandrel with a 20 mm radius. Both traces were printed with an overlap fraction of 0.6 and a jetting frequency of 100 Hz.

and flexibility between the deposited lines and the polyimide substrate. The printed features demonstrate the feasibility of employing MJP processes in fabricating complex patterns.

Given the large cross sectional area and high conductivity of the printed traces, this process is ideally suited for high power electronics applications in which large currents must be carried. Examples could
Figure 16. Magnetohydrodynamic jet printed electronic circuits (a) serpentine circuit containing regular bends (b) serpentine structure being subjected to bending (c) inductor (d) microcontroller circuit.

Figure 17. 4-point probe conductivity test in which a constant current of 10 amps is passed through a printed trace.

4. Conclusions

This study shows the feasibility of fabricating highly conductive features on polymer substrates using molten metal droplet deposition. The process conditions of overlap percentage and deposition frequency were shown to have a significant impact on the morphology of the printed features. At low deposition frequencies, the printed features transitioned from a scalloped line to a wave-like line with the increase in overlap. At high deposition frequencies, the isolated droplets transition into pairs and then into bulging lines as the overlap increases. Intermediate deposition frequency and overlap conditions were suitable for printing uniform lines.

A simple formulation that considers the volume of individual deposited droplets and drop spacing is provided and validated to predict the equivalent wire gauge of the uniform printed lines. This could be useful for knowing the current carrying capabilities of the printed features in high power electronics applications. The electrical conductivity of the printed features was characterized and found to be close, if not
equal, to the bulk metal resistivity of the aluminum alloy used as the raw material. This is highly significant, as resistivity values achieved with cured nanoparticle inks is typically several times higher than the bulk material conductivity. The raw material used in this technique is in the form of a wire and is therefore several orders of magnitude less expensive than the equivalent weight of metal nanoparticles. This makes the process significantly more economical than the conventional approach for printing electronics using solvent based metal nanoparticle inks. The current approach does not require any post processing steps such as drying, curing, or sintering in order to make the fabricated circuitry electrically conductive. This is highly desirable. The features fabricated with the MJP process also show excellent substrate adhesion and flexibility.

In summary this study provides a novel and cost-effective approach for fabricating highly conductive electronic circuit patterns. Work is currently under way to adapt the printing technique to enable jetting of copper. The present work could be further extended by studying the feasibility of jetting molten metal patterns on other low-cost polymer substrates such as PET, poly carbonate, polyethylene naphthalate etc. Fabrication of higher resolution (<100 µm) features is also highly desirable. The flexibility performance of the printed features will be quantitatively studied in the future to evaluate the performance of the printed features in flexible electronic circuitry.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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