Fabrication of Conductive Paths on a Fused Deposition Modeling Substrate using Inkjet Deposition

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Fabrication of Conductive Paths on a Fused Deposition Modeling Substrate using Inkjet Deposition

Abstract:
Inkjet deposition is one of the most attractive fabrication techniques for producing cost efficient and lightweight electronic devices on various substrates with low environmental impact. Fused Deposition Modeling (FDM) is one of the most used and reliable additive manufacturing processes by extrusion of wire-shaped thermoplastic materials, which provides an opportunity for embedding printed electronics into mechanical structures during the building process and enables the design of compact smart structures that can sense and adapt to their own state and the environment. This paper represents one of the first explorations of integrating inkjet deposition of silver nanoparticle inks with the FDM process for making compact electro-mechanical structures. Three challenges have been identified and investigated, including the discontinuity of the printed lines resulting from the irregular surface of the FDM substrate, the non-conductivity of the printed lines due to the particle segregation during the droplet drying process, and the slow drying process caused by the “skinning effect”. Two different techniques are developed in this paper to address the issue of continuity of the printed lines, including surface ironing and a novel “thermal plow” technique that plows a channel in the FDM substrate to seal off the pores in the substrate and contain the deposited inks. Two solutions are also found for obtaining conductivity from the continuous printed lines, including porous surface coating and using a more viscous ink with larger nanoparticle size. Then the effects of the printing and post-processing parameters on the conductivity are examined. It is found that post-processing is a dominant factor in determining the conductivity of the printed lines.

1. Introduction
Ever since its invention in 1936 [1], lithography technology has been widely adopted in the printed circuit board (PCB) industry for the fabrication of conductive lines. In recent years, the electronics industry has been searching for new methods for manufacturing conductive lines in order to meet the requirements of smaller feature size, less environmental impact, less weight and volume, flexible electronics, embedded electronics, etc. Many new techniques have been developed during the past decade, such as Curved Layer Fused Deposition Modeling (CLFDM) [2], Laser-based Direct Write (LDW) [3], Laser Micro-cladding Electronic Pastes (LMCEP) [4], screen printing [5], offset lithography [6], aerosol jet [7, 8], and inkjet deposition [9-14]. CLFDM is limited by the conductivity. The cost of laser-based technologies is often very high due to the operation and maintenance of the lasers. Screen printing and offset lithography requires a physical mask or printing plate, which significantly increases the design to production cycle. Although aerosol jet can provide good resolution and conductivity, the printing process is slow with a single nozzle and it is hard to scale due to the cost of the nozzles. Inkjet deposition stands out for its low cost, high resolution, scalability with multiple nozzles, wide choice of
conductive materials and substrates, no requirement of physical mask, and digital control of ejection and deposition. With different droplet hardening mechanisms, various conductive inks have been studied and successfully printed such as molten metal [15-17], conductive polymers [18, 19], organometallic compounds [20, 21], metal precursors [22], and metallic nanoparticle suspensions [11-13]. The operating temperature for molten metal is usually high and thus limits the choice of both inks and substrates and increases the cost of manufacturing while organometallic compounds or metal precursor need additional heat treatments for them to become metal, and the organic residues may reduce the conductivity. Also, heat treatments may involve chemical reactions that complicate the control of the manufacturing process. Metallic nanoparticle suspension, however, is really promising and has attracted lots of attention [23, 24] because it can avoid the extreme processing conditions required for standard lithographic fabrication and molten-metal-droplet deposition and the processing temperature (less than 300 °C) is compatible with various substrates. Suspensions of silver, gold, and copper nanoparticles are common choices and have all been successfully printed to form conductive lines [12, 24, 25]. With the cost of gold nanoparticles being prohibitive and the easy oxidization of copper nanoparticle, silver nanoparticle has been the most popular choice among all the relevant studies. Printed conductive lines with nanoparticle suspensions has been extensively studied by different research groups [9, 23, 26-29] with varying particle, particle size, solvent, weight concentration, hardening condition, etc. and different results on line width, line thickness and conductivity have been obtained. Compared to printed circuit boards that typically have a minimum trace width of ~25 µm and a trace thickness of 35 µm (thickness for 1 ounce of copper per square foot), inkjet can typically achieve smaller feature size with printed line width and thickness down to ~1 µm and ~100 nm respectively. With silver nanoparticle ink, the conductivity of the printed lines can often achieve over 30% of the bulk conductivity of silver with proper post processing [30]. Although the previously achieved conductivity of the printed lines is still not comparable to that of the copper used in PCB circuits, it is sufficient for many electronics applications. Considering the many benefits of printed electronics using inkjet, such as wider choice of substrates, reduced weight and volume, less environmental impact, and applications in flexible and stretchable electronics, inkjet shows a promising alternative to the traditional PCB technology.

The most commonly used substrate material in the previous studies has been glass because of its hydrophilic property. The substrates with predefined patterns (patterned by different surface energy so that some part is hydrophilic and some part is hydrophobic) have also been investigated [31, 32]. Low surface energy substrate has also been used. Deposition of conductive tracks on untreated polymeric substrates has been reported by van Osch, et al. [13], however, the substrates used in most of the previous studies are flat and smooth, with the main objective of fabricating conductive circuits. Little has been reported on integrating existing mechanical structures, which may include textured or porous surfaces, with printed electronics. Based on a bottom-up manufacturing
philosophy, additive manufacturing provides an opportunity for embedding printed electronics into mechanical structures during the building process, which may potentially enable the design of compact smart structures that can sense and adapt to their own state and the environment. A.J. Lopes et al. explored the possibility of integrating stereolithography and direct print technologies for 3D structural electronics fabrication [33]. Aerosol jet has also been used to print conformal electronics on 3D structures [8]. C. Shemelya et al. recently reported their successful attempt on 3D printed capacitive sensors that have many potential sensing applications, such as biomedical and environmental sensing [34]. Fused deposition modeling (FDM) has become a prominent form of additive manufacturing and has been used to build mechanical structures for many commercial products. Although conductive polymers can be used in FDM to build conductive lines [2], the resistance is nonetheless too high for most of the applications. D. Espalin et al. demonstrated a multi3D system that can produce 3D, multi-material and multifunctional devices based on a combination of FDM process, direct printing technology, and a novel thermal embedding technology. To reduce the complexity of the multi3D system, this paper explores the possibility of direct integration of inkjet deposition with FDM process for making electro-mechanical structures.

Three challenges of printing on a FDM substrate have been identified and investigated separately in this paper. The first challenge is the discontinuity of the printed lines caused by the texture and the low surface energy of the FDM substrate surface. Two surface treatments have been developed to address this challenge--surface ironing that uses a weight with a flat surface to “iron” the surface of a FDM substrate at an elevated temperature and a novel “thermo-plow” technique that uses a heated needle to “plow” a predefined pattern of channels in the substrate to contain the deposited inks. The second challenge is the difficulty of obtaining conductivity from the printed lines due to both the particle segregation during the droplet drying process and the low post-processing temperature imposed by the FDM substrate. Two solutions are proposed, including using a porous surface coating to divert the evaporation flow in order to reduce the particle segregation, and using more viscous ink with larger nanoparticle size. Experiments have been performed to study the effects of the printing parameters and post-processing parameters on the conductivity. Post-processing parameters have been found to have a larger impact on the conductivity of the printed lines. The third challenge is that the time required to dry the deposited droplets is so long that it makes the fabrication inefficient due to crust formation on the top surface of the droplet known as the “skinning effect”.

The paper is organized as follows. In section 2, the issue of continuity of the printed lines is discussed and two surface treating techniques are developed to address this issue. Section 3 presents the challenges of obtaining conductivity from printed lines and the slow drying time and discusses the underlying reasons with proposed solutions. Conclusions are given in section 4.

2. Continuity
The typical procedure of using inkjet deposition for fabricating a conductive path on a substrate with metallic nanoparticle suspension inks is as follows: the ink droplets are first deposited at the desired locations on the substrate and then dried to leave the metallic nanoparticles at the locations where the droplets are deposited. A post-sintering process is usually required to join the nanoparticles together in order to obtain high conductivity from the printed lines. Therefore the fabrication process can be broken down into three sub-processes: the printing process (i.e., the process of laying down droplets on the substrate), the drying process, and the sintering process. In the printing process, droplets with a typical diameter of 1 to 100 µm are ejected from the nozzles with a speed of 1 to 20 m/s at a typical frequency of 1 to 100 kHz [35]. The droplets impinge on the substrate and interact with each other and then achieve equilibrium after the kinetic energy is dissipated by viscosity [36, 37]. The typical timescale of the process for printing conditions of interest is on the order of micron seconds to milliseconds [36, 38]. The droplet drying process, however, typically takes seconds to hundreds of seconds or even longer for droplet of metallic nanoparticle ink with similar size to dry at temperatures ranging from room temperature to less than 200°C [39, 40], which covers the normal range of printing conditions. The sintering process typically starts around the time when the liquid is evaporated, and the time for this to occur is on the order of minutes to hours. We will next consider the three sub-processes independently and examine their influence on the final manufacturing results.

In order to fabricate a conductive path on a substrate, the deposited droplets must form a continuous well-defined line, which is often not a problem for a smooth hydrophilic substrate as long as the droplet spacing is small enough such that the deposited droplets can touch each other. However, conductor continuity is not a trivial problem for a substrate made with the FDM process. As shown in Figure 1(a), the substrate has a textured surface formed by the periodic extrusion of polymeric filaments with low surface energy.

![Figure 1](image)

Figure 1: (a) A typical substrate made with FDM under microscope; (b) discontinuous printed line on a FDM substrate.

An additional concern for printing on an FDM substrate is that the ink may infiltrate into the interconnected pores/gaps between the filaments in the substrate causing shorting of the printed circuit as reported in our previous work [41]. In our experiments, a Fuji Dimatix Materials Printer (DMP - 2831) is used to carry out the printing experiments on a FDM substrate made with ULTEM 9085 using aqueous ink loaded with silver nanoparticles from NovaCentrix (Metalon JS-B25HV). The viscosity and the surface tension of the ink are 8 cP and 0.03
N/m, respectively. The droplet size is 10 pL (~26 µm in diameter). The contact angle of water on a ULTEM surface is 75°. The irregular geometry of the textured surface tends to break the printed line as shown in Figure 1(b) due to the complicated droplet-surface interaction dynamics. There are many different thermodynamically stable contact angles (i.e., meta-stable states) on a non-ideal solid surface [42] due to surface inhomogeneity, surface roughness, and impurities on the surface [43], which is still far from being understood despite extensive study for over a century [44].

In order to avoid dealing with the complicated contact line dynamics on a textured surface to solve these problems, an attractive alternative is to prepare the surface before printing. Two different engineering techniques are proposed for surface preparation. The first approach is to “iron” the surface using a weight at an elevated temperature – similar to the ironing of clothes as illustrated in Figure 2 (a). In this process, the FDM part is put in an oven at a temperature of 175 to 250 °C with a weight on top that exerts a pressure of 5 psi (34474 Pa) for 1 to 60 minutes. A Teflon sheet is put in between of the FDM part and the weight to avoid sticking. The ironing condition of 200°C for 20 minutes at 5 psi pressure produces a visually smooth surface as shown in Figure 2 (b). The surface irregularities are eliminated, and the resulting printed line is continuous and well contained on the surface.

Figure 2. (a): Schematic of the surface ironing technique; (b): Printed line on a ULTEM surface of a FDM part “ironed” at 200°C for 20 minutes (the brightness in the center of the printed line is due to reflection).

“Surface ironing” is an interesting engineering technique to prepare the textured surface of the FDM parts for printing such that a continuous line can be printed on top of it. During the “ironing” process, the material is heated to a temperature such that the material flows under pressure to achieve a flat surface. The process is similar to the injection molding process except with an open boundary and a much slower “flow rate” to avoid damaging the mechanical structure of the FDM part. The “ironing condition” needs to be optimized in order to achieve a balance between the quality of the surface, the speed of the process, and the damage of the existing structure.

In contrast to the “surface ironing” technique that modifies the surface globally, we have also developed a surface preparation technique, referred to here as “thermo-plow”, which only modifies the surface locally where the
conductive line is printed using a heated metal tip to “plow” a channel in the substrate. An automated system has been developed to perform the “thermo-plow” as shown in Figure 3 (a). An Antex G-3U soldering iron is used to heat the tip, and a variable autotransformer is used to control the power (and therefore the temperature) of the tip, which can range from room temperature to 400 °C. A copper tip with a diameter of 350 µm is used to “plow” the substrate as shown in Figure 3 (b). The travel speed of the tip can be varied from 0 to 5 mm/s and the plowing depth (i.e., the depth that the tip is going into the surface) can be varied with a precision of 25 µm. The tip size, temperature, travel speed, and plowing depth are important parameters that affect the plowing results. The heated tip first “melts” the materials and then plows them out to form a channel. The combination of the parameters determines the size and the smoothness of the channel. For example, fast travel speed of the tip typically leads to a small channel size because less material is melted and plowed away. If the tip moves too fast such that the material is not heated up enough and fractures mechanically, a rough surfaced channel may be formed. At a tip travel speed of 0.2 mm/s, tip temperature of 400 °C, and plowing depth of 150 µm, we can obtain a smooth channel as shown Figure 3 (c). Figure 3 (d) shows the microstructure features on the bottom surface of the produced channel at 400X magnification. This microstructure is likely the result of a phase/glass transition of the material (i.e., from solid to liquid-like and back to solid again). The features have a “bullet-like” geometry pointed to the travel direction of the tip and the size and geometry of the features depend on the “plowing” parameters.

Figure 3. (a): automated thermo-plow system; (b): copper tip for plowing; (c): a thermo-plowed channel in a FDM ULTEM substrate at a tip travel speed of 0.2 mm/s and plowing depth of 150 µm; (d): microstructures on the bottom surface of a thermo-plowed channel under 400X microscope.

Although the surface of the channel is not perfectly smooth, it serves well for the purpose of containing the ink to form a continuous printed line as long as we deposit enough ink into the channel. We can align the Dimatix printer with the thermo-plowed channel and deposit ink into the channel. Discontinuities of the
printed line in the channel may still result due to the roughness of the surface of the channel as shown in Figure 4 (a). However, if we deposit enough ink into the channel with smaller droplet spacing and multiple passes, we can almost guarantee a continuous line as the channel serves as a good container of the deposited ink as shown in Figure 4 (b) although the deposited ink is still in liquid state due to the slow drying process. Nonetheless, the thermo-plow technique can effectively modify the surface with defined patterns locally without damaging the structure of the entire part and prepare the surface for printing conductive lines.

3. Conductivity and drying process

Physical continuity of a printed line using conductive ink is required for it to be conductive. However, it does not guarantee conductivity. With a continuous printed line, the intention was to enable the silver nanoparticles to form a conductive line by drying the liquid component of the ink. However, the nanoparticles do not always stay together as intended during and after the drying process. Figure 5 shows a dried printed line using the NovaCentrix ink on a smooth ULTEM substrate. As we can see, there are many cracks in the printed line due to particle segregation, and no conductivity is measured. One of the reasons is the well-known “coffee ring” effect [45], which has been extensively studied since its discovery around two decades ago. The evaporation rate difference between the center of the droplet and the edge of the droplet causes a replenish flow from the center to the edge, which brings the nanoparticles to the edge of the droplet and forms a ring. Contact line pinning has been identified as an essential condition for the coffee ring effect, which often occurs due to surface contamination or self-pinning by the accumulation of the nanoparticles on the contact line. Marangoni flow has been used to suppress the “coffee ring” effect by introducing surfactants [46]. Electro-wetting has been employed to de-pin the contact line to eliminate the coffee ring effect [47]. The timescale of the evaporation flow and the nanoparticle motion has also been studied to reduce the coffee ring effect by increasing the timescale of the particle movement [48].

![Figure 4](image)

Figure 4. (a): A printed line in a thermo-plowed channel using Dimatix printer; (b): Deposited ink into a thermo-plowed channel using Dimatix printer for multiple times.
Another challenge is that the drying of the ink droplets can be a very slow process, which increases manufacturing time and cost. Figure 6 shows the comparison of the drying process of a water droplet and that of a NovaCentrix ink droplet on a ULTEM substrate at 60°C in an environment of standard temperature and pressure and 50% relative humidity. The starting droplet volume is 1 µL in both cases, and the recorded time span is 1440 seconds with equal time intervals between frames. What we observed is that the water droplet dries at a nearly constant rate all the way to nothing while the ink droplet dries to a certain extent and then stops drying. It is because the evaporation flow brings the nanoparticles to the top surface of the droplet and forms a crust that significantly reduces the drying rate [49]. The fluid transport through the porous crust formed by the nanoparticles can build up stress in the crust and lead to the collapse of the crust at high evaporation rate [50].

Given the challenges of the coffee ring effect and crust formation, we have proposed two solutions to reduce the particle segregation and speed up the drying process simultaneously in order to print conductive lines. Considering that both of these effects are caused by evaporation flow, one solution is to divert the...
evaporation flow using a porous substrate as shown in Figure 7(a). We have chosen a commercial porous substrate, Novele™, produced by NovaCentrix, which is a PET substrate coated on one side with a porous oxide film. The porous substrate provides channels for the fluid to flow through the substrate, which brings the nanoparticles to the substrate and breaks the replenish flow to the edge. Figure 7(b) shows a printed line on the porous substrate using the NovaCentrix ink. The nanoparticles stick together after drying and form a conductive line, the resistivity of which was measured to be $4.75 \times 10^{-7} \, \Omega \cdot m$ (~ 30 times of the bulk silver and copper resistivity) after post-sintering in a 125°C oven for 20 minutes.

![Figure 7. (a): illustration of an ink droplet sitting on a porous substrate; (b): printed line using the NovaCentrix ink on a porous substrate dried at room temperature; (c): printed line after sintered in 125°C oven for 20 minutes.](image)

Since both the coffee ring effect and crust formation are due to the motion of the nanoparticles caused by the flow in the droplet, a second solution is to reduce the particle motion caused by the flow to a minimum such that the nanoparticles can stay together. We have chosen an alcohol based commercial ink CCI-300 from Cabot Corp with viscosity of 15 cP compared to the viscosity of 8 cP for the NovaCentrix ink. The liquid component of the Cabot ink consists of ethanol and ethylene glycol [51], which have a surface tension of 21.97 mN/m and 47.3 mN/m, and a boiling point of 78.37°C and 197.3°C, respectively. The increase of the viscosity plays an important role in reducing the motion of the nanoparticles to the edge of the droplet for the Cabot ink. It should be noted that the NovaCentrix ink is aqueous based while the Cabot ink is alcohol based and the solution becomes much more viscous as the alcohol evaporates first. Figure 8 shows a printed line using the Cabot ink. Although there are still some visible pores (the scattered black dots) in the printed line, the pore size is much smaller than that of the printed line using the NovaCentrix ink as shown in Figure 5 and a non-zero conductivity is measured after it is dried and post-sintered in a 125°C oven for 20 minutes.

![Figure 8. A printed line using the Cabot ink with larger nanoparticle size and viscosity after dried.](image)
The reduction of nanoparticle motion can also alleviate the crust formation and speed up the drying process. Experiments were conducted to study the effects of the drying temperature and droplet size on the drying speed for the Cabot ink. The drying time required for a 1 µL droplet of Cabot ink is recorded at different temperatures from 150°C to 200°C as shown in Figure 9 (a). The required drying time decreases exponentially with the increase of the temperature. Putting the same data on an Arrhenius plot, as shown in Figure 9 (b), suggests that the evaporation of the liquid is a thermally activated process when the temperature is below the boiling point of ethylene glycol. The required drying time does not decrease further when the drying temperature goes beyond the boiling point of ethylene glycol. These results suggest that the crust formation plays very little role in preventing the droplet from drying for the Cabot ink. We have also tested the effects of the droplet size on the drying time of the Cabot droplet at 200°C as shown in Figure 10. Since the volume of the evaporation is cubic of the droplet radius while the droplet surface area is square of the droplet radius, the required evaporation time is expected to be linearly proportional to the droplet radius for pure water droplet. Figure 10 shows a linear relationship between the droplet radius and the drying time for the Cabot ink as well, which suggests the presence of the nanoparticles did not affect the drying process very much. Both Figure 9 and Figure 10 suggests that the effects of the crust formation for the Cabot ink are negligible and the reduction of the nanoparticle motion can effectively reduce the crust formation as well.

Figure 9. (a): Required drying time for different drying temperature for Cabot ink droplet with a droplet size of 1 µL; (b): Analyses of the data in the form of Arrhenius plot.
Figure 10. Required drying time for different droplet size for Cabot ink at drying temperature of 200 °C.

A further test is conducted with a different kind of ink from NovaCentrix (Metalon HPS-021LV) that has a particle size of 2 µm (compared to 60nm for the NovaCentrix Metalon JS-B25HV ink) and a viscosity of more than 1000 cP. This ink is too viscose to be printed with current commercial inkjet print heads and is typically used for screen-printing. In this study, a syringe needle was used for delivery of the ink. Figure 11 shows several manually printed lines into thermoplowed channels using the NovaCentrix ink. As shown in the figure, the ink forms a dense, shiny surface. The measured resistivity is 6.94e-8 Ω-m after it is dried and post-sintered in a 125°C oven for 20 minutes, which is much lower than previously used ink. Many factors may contribute to the better conductivity, such as less particle segregation due to the larger particle size and viscosity, and much higher loading of the silver nanoparticles (75% versus ~20%). In addition, the shape of the particles may also play an important role in keeping the particles together as recently discussed in [52]. The nanoparticle of the NovaCentrix screen print ink is similar to a snowflake while the shape of the nanoparticles in the Cabot ink is more spherical. All these factors can reduce the motion of the nanoparticles such the nanoparticles can stay closely together, which is believed to be an important cause for the better conductivity.
Given a couple of possible solutions for obtaining conductivity from the continuous printed lines, the next step involves investigating the influence of the printing, drying, and sintering conditions on the conductivity. As previously analyzed, the drying and sintering process occurs on a much longer timescale than the droplet interaction dynamics (i.e., drying only becomes significant after the droplets have achieved equilibrium). We can therefore consider the influence of the printing conditions separately from the drying and sintering conditions. Theoretically, if different printing conditions lead to the same equilibrium state of droplets interaction, the printing conditions should have a negligible impact on the final conductivity of the printed line. For pure fluids without nanoparticles, the equilibrium state of droplet dynamics typically only depends on the contact angle of the fluid on the substrate surface under ideal conditions. For suspension fluids, however, the final nanoparticle distribution (i.e., the morphology of the nanoparticles) in the fluid before drying is dependent on the droplet interaction dynamics. The nanoparticle distribution after the droplets achieve equilibrium can be considered as the initial nanoparticle distribution for the droplet drying process. If the droplet drying process strongly modifies the nanoparticle distribution towards a different equilibrium state (e.g., the ring pattern for the coffee ring effect), the impact of the printing conditions may become insignificant. In other words, the drying and sintering processes play a more important role in determining the final conductivity of the printed line because they have the opportunity to modify whatever nanoparticle distribution is left from the printing process as they occur on a longer timescale.

We have investigated the effects of droplet spacing and line width on different substrates using the Cabot ink. Standard 2-cm long lines with input widths of 100 µm and 500 µm are printed using the Dimatix printer with the Cabot ink on both Polycarbonate (PC) and ULTEM substrates. Figure 12 shows a typical double-hump cross-section shape of a printed line with an input line width of 100 µm measured with a profilometer. Two observations should be noted. One is that the actual line width of the printed line is much larger than the input line width. This is because only the droplet spacing is accounted for in the input width and the droplet size is neglected. In addition, droplets are often deposited in an overlapped fashion (i.e., droplet spacing is smaller than droplet size) and the diameter of the wetted area is typically larger than the droplet diameter. The second
observation is the common double-hump profile of the cross section, which suggests that the nanoparticles are still trying to move to the edge during the drying process due to the coffee ring effect.

Figure 12. A typical double-hump cross-section of a printed line with input line width of 100 µm.

The resistance of the printed lines on different substrates with different droplet spacing and line width is plotted in Figure 13. The general trend is that the resistance increases with larger droplet spacing and narrower line width due to less deposited silver nanoparticles. In order to investigate the conductivity, the area of the cross section of the printed lines is required. Because the printed lines are typically not perfectly uniform, the cross section area varies along the length of the line. In order to calculate the resistivity of the printed lines, we take the average area of three cross-sections along the printed line at points that are visually widest, narrowest, and medium. Then we can calculate the resistivity of the printed lines as plotted in Figure 14. As we can see, there is no clear trend of the relationship between the droplet spacing and the resistivity when the droplet spacing is small enough such that the printed line is still continuous. When the droplet spacing is around the droplet diameter (~26 µm), the resistivity starts to increase as the droplet spacing increases and some of the lines become non-conductive. The line width does not have a clear impact on the conductivity either, as indicated in the graph. This result agrees with our previous analysis that the printing conditions may not have a big impact on the final conductivity.
The sintering kinetics of the silver nanoparticles are investigated separately in our previous work [41] to understand the influence of the sintering process on the conductivity. It is found that the conductivity improves with the increase of the sintering temperature for low temperature sintering and the conductivity improvement stops at a critical temperature that is associated with the boiling point of the liquid component of the ink because it is a liquid phase assisted sintering process. The results suggest the drying and sintering processes do play a more important role on determining the conductivity than the printing process. Future efforts should be devoted to improving the drying and sintering processes for better conductivity of the printed lines.

4. Conclusions
This paper explores the possibility of integrating the FDM process with inkjet deposition for making embedded electronics and smart structures. Two challenges have been identified for printing on an FDM substrate: producing a printed line that is (1) continuous and (2) conductive. At a minimum, a printed line must be physically continuous on a FDM substrate to achieve functionality. Two different surface treatment techniques were developed to address the texture and the irregular geometry found on an FDM substrate, including a global modification approach (“surface ironing”) and a local modification approach (“thermo-plow”). Both techniques proved effective for obtaining continuous lines using inkjet deposition on a FDM substrate. The poor conductivity of printed lines and the issue of slow drying were also presented. It was found that both are caused by nanoparticle motion driven by evaporation flow, which leads to nanoparticle segregation (the “coffee ring” effect) and a crust formation on the top surface of the droplet that prevents the droplet from further drying. Two different solutions were proposed. One involves using a porous substrate to divert the evaporation flow through the substrate such that the nanoparticles stay together and do not form crust. The other approach was to increase the viscosity of the fluid and/or the nanoparticle size to minimize the nanoparticle motion caused by the evaporation flow. Both of these approaches have successfully demonstrated conductive printed lines. The influence of the printing conditions and the drying and sintering conditions on the conductivity of the printed lines were also discussed and experimentally investigated. Results showed that the printing conditions do not have a clear influence on the conductivity of the printed lines and the drying and sintering processes dominate conductivity. Further efforts will focus on improving the drying and sintering process.

References


