Combining Additive Manufacturing and Direct Write for Integrated Electronics – A Review

K. Blake Perez and Christopher B. Williams

Design, Research, and Education for Additive Manufacturing Systems Laboratory

Department of Mechanical Engineering, Virginia Tech, Blacksburg, VA 24061

Abstract

Direct write (DW) of conductive materials in the context of Additive Manufacturing (AM) enables embedded electronics within fabricated parts. Previous works use manual, hybrid, and native material patterning systems to deposit conductive materials in parts fabricated by different AM technologies. This capability could eliminate cabled interconnects and redundant electronics packaging, resulting in a significant reduction of mass and assembly complexity. In this paper, the authors explore applications of DW of conductive traces in the context of AM, review prior work in the integration, and analyze the technical roadblocks facing their hybridization. Barriers to integrating the two technology classes include material, process, and post-process compatibilities.

1 INTRODUCTION

1.1 Direct Write Overview

Direct Write (DW) technologies enable the selective deposition and patterning of material. DW is capable of single- and multi-layer, high-resolution, material deposition on both flat and conformal surfaces [1]. DW technologies have been comprehensively reviewed before [2]. Hon and coauthors' review included methods capable of depositing nonconductive materials. However this work considers only DW methods for conductive materials. In a review of DW applications, Church and coauthors asserted that DW enables rapid manufacturing of sensors and antennae because it eliminates the masking and etching steps of conventional electronics fabrication [3]. In general, DW processes have been researched and developed because of their potential to replace masked lithographic processes in electronics production.

All DW technologies serve the same function (i.e. selective deposition of conductive traces); however, the means of realizing this primary design goal varies dramatically. Extrusion technologies use positive pressure to extrude fluid materials through a small nozzle and onto a substrate. Droplet-based DW ejects small droplets of material onto a substrate. Aerosol Jetting systems aerosolize a material to create a gaseous stream that is aerodynamically focused and deposited on the substrate. Laser-based systems use a laser's energy to transfer material onto a substrate surface. Finally, tip-based deposition methods use capillary flow of an ink on microscale tip onto the substrate surface [2].

When combined with Additive Manufacturing (AM) processes (technologies that fabricate parts by the layer-by-layer joining of material), DW enables the creation of complex and conformal electronics that are structurally integrated into a manufactured part. When integrated into an AM process flow, DW can be leveraged to manufacture electronic signal routing, embedded sensors, and integrated power systems in additively manufactured structures.

1.2 Prior Research and Applications in the Hybridization of Additive Manufacturing and Direct Write

One of the first examples of a combination of AM and DW is by Palmer and coauthors who produced an electrical interconnects by combining DW and stereolithography(SL) [4]. Other works continued to hybridize AM and DW technologies to fabricate functional electronics on additively manufactures structures.

1.2.1 Structurally integrated signal routing

Because of the layer by layer process of AM, electrical interconnects can be structurally integrated into a build. Robinson and coauthors used Ultrasonic Consolidation (UC) and DW to fabricate a cellular aluminum panel with integrated circuitry [5]. The electronics are completely embedded in the robust and lightweight structure. Structural interconnects eliminate the need to design for cabling ducts and vias throughout a structure's interior. The circuit's encapsulation also protects interconnects from the outside environment.

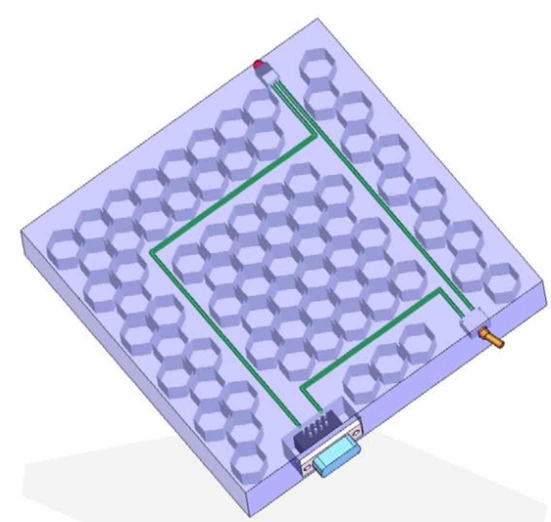


Figure 1 – Cross sectional view of embedded circuit in honeycomb structure fabricated with the hybridization of UC and DW [5]

1.2.2 Embedded 3-dimensional antennae

Fractal antennas are used to provide a multi or wideband response to different radio signals. Their design consists of fractal patterns to maximize the antennae perimeter while minimizing its footprint. Casanova et al. designed and produced a 3-dimensional fractal antenna using conventional manufacturing and found it to improve radiation efficiency and gain when compared to a 2-dimensional patch antenna [6]. Optomec has demonstrated its ability to use the Aerosol Jet DW process deposit on conformal substrates and create functional antennae on AM substrates [7]. One can see the potential of creating 3-dimensional antenna designs with a hybridized DW/AM process.

(a) **(b)** **(c)**

Figure 1 – (a) 3-dimensional fractal antenna [6]**; (b) Aerosol Jet of conductive traces on conformal substrate; (c) Aerosol Jet of antenna on AM substrate** [7]

1.2.3 Conformal Electronics

Conventional fabrication of high density circuitry relies on flat substrates because of process steps such as lithography which require a planar surface. However, products that benefit from complex geometries, such as wearable technology, rely on conformal geometries to better fit the user. Castillo et al. applied conductive materials to additively manufactured conformal substrates to showcase wearable technology [8]. The helmet insert contains an accelerometer for detecting mechanical shock to the head and can transmit communication of such an event. Figure 2 shows the helmet fabricated using stereolithography, IC components, and manually deposited traces of silver ink [9].

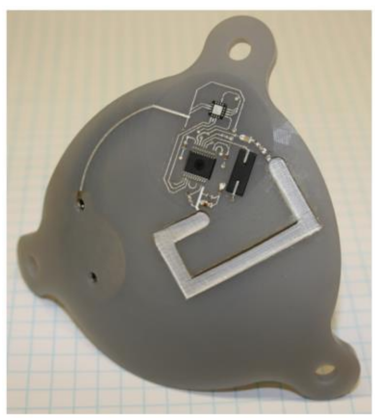


Figure 2 – Helmet insert for detecting traumatic head injury [8]

1.2.4 Batteries

In 2008, Malone et al. developed and characterized a Zinc-air battery created with AM technology. The battery was fabricated with a multi-material capable AM extrusion based system [10]. The zinc-air battery is capable of an energy density up to 1.07 mW/cm^2. Lewis et al. developed a lithium-ion battery design using extrusion processing with a power density of 2.7mW/cm^2 [11]. The lithium battery is very small (6.6mm^3), however it relies on a separate substrate with a gold on glass current collector and packaging. Future work could involve the integration with additively manufactured encapsulation.

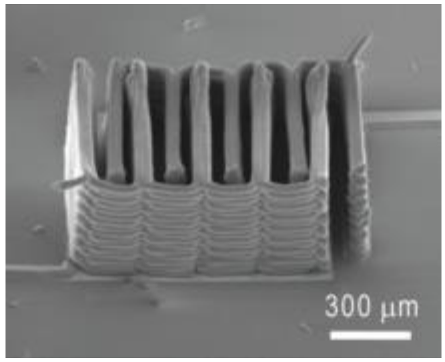
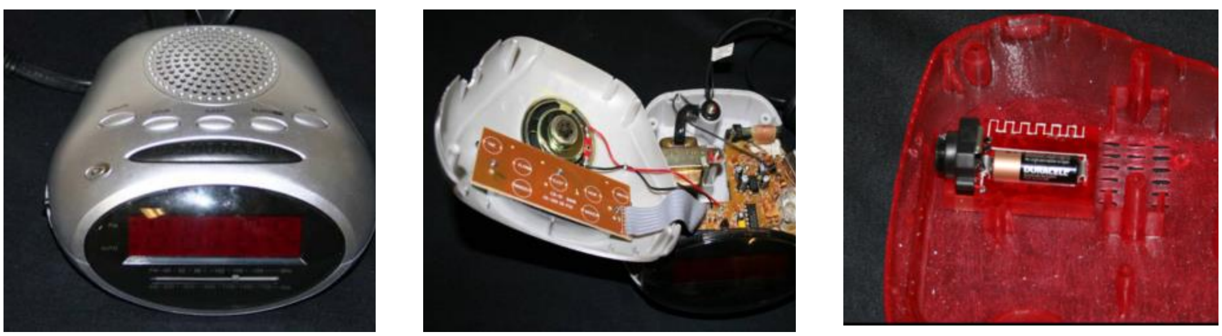


Figure 3 – SEM images of additively manufactured battery electrode [11]

1.2.5 Discreet Electronics

AM and conductive materials can also be utilized to discreetly implement electronics into common or unsuspecting items. This application enables discreet and unobtrusive data collection. Medina et al. used stereolithography and DW to place a small camera and video transmitter within the internal structure of a printed alarm clock [12]. The camera embedded in the alarm clock showcases the ability to leverage AM's geometric reproduction abilities and the utility of conductive traces to create discreetly embedded electronics.



(a) **(b)** **(c)**

Figure 4 – (a) original alarm clock; (b) alarm clock internals; (c) printed base to incorporate wireless camera module

1.3 Context

While technologies and applications of both AM [13] and DW [14] have been independently reviewed before, the literature analysis presented in this paper is specifically focused at the intersection of AM and DW. Previously, Lopes and coauthors identified the opportunity for expanding AM to include electronics systems [15]. Their implementation is narrow in the context of utilizing only Stereolithography and extrusion-based deposition. In this work, the authors analyze different combinations of DW and AM processes to evaluate the tradeoffs considered in selecting the technologies and materials as well as their resulting performance characteristics (e.g., feature size, conductivities, and material-substrate compatibilities). Section 2 details the DW processes most applicable to hybridization with AM technologies. Section 3 addresses roadblocks and challenges that are present in integrating AM and DW processes. Closure is offered in Section 4.

2 DW PROCESSES FOR AM

In order for DW technologies to integrate with AM processes, it is paramount that the material deposition system is maneuverable and reliably positioned. Additionally, for manufacturing relevance, the write speeds should be comparable to the corresponding AM process. Of these technologies reviewed by Hon et al., Aerosol Jet, inkjet, and extrusion methods are considered immediately relevant for hybridization with AM because they afford freeform control of both the deposition tool and the material delivery system. Basic performance capabilities of these DW technologies are summarized in Table 1 and summarized in the following sub-sections.

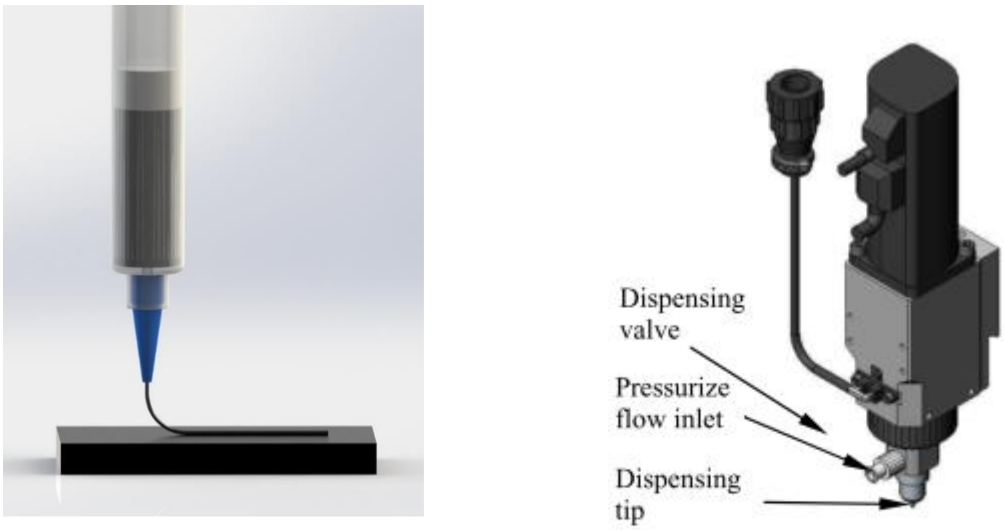
The remaining DW technologies were excluded from this review due to their slow write speeds, incompatible reaction environments, and large deposition tool heads or material precursors that are difficult to integrate with the AM environment. As both DW and AM technologies evolve, excluded DW processes may become relevant in the context of hybridization. These other technologies are sufficiently explained and analyzed in previous reviews of DW technologies [2], [14].

Table 1 – Comparison of direct write technology capabilities. Adapted from [2]

Technology	Minimum Resolution	Viscosity Range	Max Write Speed
Inkjet	≥20 μm	≤0.1 Pa·s	0.30 mm^3/s
Aerosol Jet	≥10 μm	Not Applicable	0.25 mm^3/s
Extrusion	≥25 μm	≤5000 Pa·s	300 mm/s

2.1 Extrusion-based Deposition

Extrusion-based DW deposition uses positive pressure to dispense conductive materials in fluid form through a small nozzle. Both syringe (Figure 5a) and micro-dispensing pump (Figure 5b) systems fall in this category. The pneumatic control of these systems allows for dynamic operation and pressure regulation. Maintaining precise control over pressure is important as pressure directly affects feature width, even if ink type and nozzle diameter are held constant. These systems can also apply a vacuum to draw fluid into the dispense tip and mitigate dripping or over dispensing. The distance from which material can be deposited from the substrate can vary; however, it is understood that for different machine parameters (i.e. tool speed, material type, pressure), there is an optimal offset for the dispense tip [16], [17].



(a) **(b)**

Figure 5 – (a) schematic of basic syringe system (b) micro-dispensing pump [16]

Extrusions systems can dispense fluidized materials with viscosities up to 5000 Pa·s with feature widths as low as 25 μm. Linear writing speeds can reach 300 mm/s, although 50 mm/s is typically observed [2]. Volumetric rates depend on nozzle size, which is limited by the material selection.

These systems are most typically used to dispense metal-based inks. Metal-based inks consist of metal particles or flakes dispersed in a volatile solvent that evaporates after being dispensed. The metals most commonly used are silver and gold because of their resistance to oxidation; however, this can be cost prohibitive (e.g. 70% silver by weight inks can cost about $2 USD per gram). Other formulations use metal particle suspended in a semi-conductive matrix as used in [18].

Carbon based inks can also be dispensed with these systems although they are less conductive than metal inks. Leigh et al. showed a measured a conductivity of 10^3 S/m, two orders of magnitude less conductive than unsintered metals [19]. Carbon based conductors could find an application in an education context where cost is more critical than electrical performance. Carbon based conductive inks cost less than $0.50 USD per gram.

For DW purposes, the metal content of the ink is a critical factor. Higher loading results in higher particle density as deposited and thus better conductivity. However, inks with high metal loadings are more viscous and difficult to dispense. Viscous inks require more pressure to dispense and their high particle content leads to clogging issues in the dispensing orifice. Clogging is alleviated by using larger nozzle tip diameters, although this negatively impacts the minimum achievable feature size of the system. Most importantly, high metal loadings improve conductivity but limit the minimum achievable feature size. As deposited, these metal-based inks can achieve a conductivity in the range of 10^5 S/m [17]. If these materials can be exposed to higher temperatures to undergo sintering, the conductivity approaches 10^7 S/m, the conductivity of bulk metals. This temperature processing is discussed in depth in section 3.1. Ideal inks balance loading for clog-free dispensing and desired feature resolution while maximizing conductivity.

Extrusion processes are favored for dispensing heavily loaded inks as they are capable of extruding such viscous material. Previous works have used inks with metal loadings in the 60-70% range. From a control perspective, extrusion systems are favorable for integration with AM technologies because the tool tip is maneuverable, can dispense in different orientations, and can process high volumes of material. Additionally, the 50 μm feature resolution is comparable to contemporary AM technologies, although this value increases with the use of particle loaded inks.

2.2 Ink Jetting

Similar to technology in inkjet printers, Inkjet DW is a droplet-based technology that places material where it is needed. Some Inkjet DW systems use a piezoelectric diaphragm and a small orifice to dispense material in liquid form. As the diaphragm expands, it places positive pressure on the fluid, which is expelled through the orifice as shown in Figure 6. Alternatively, some systems use a heat source to heat the ink and generate a bubble. This bubble provides the pressure to expel the droplet through the orifice. Thermal systems however can cause solvents in an ink to volatize rapidly, leaving behind a high concentration of particles which can clog the printing orifice.

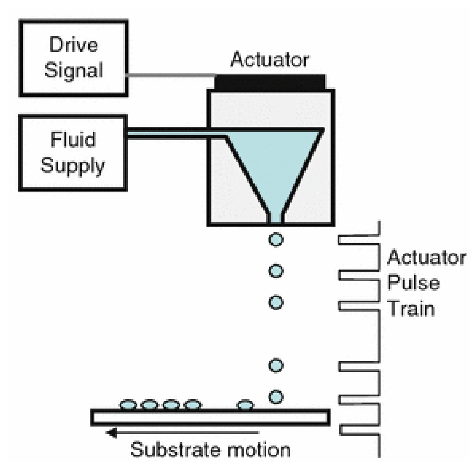


Figure 6 – Schematic of ink jet deposition [13], [20]

Inkjet systems can dispense fluid materials up to 100 mPa and can create features as small as 20 μm. The volumetric dispense rate of a single nozzle is only 0.3 mm^3/s, however this can be increased by using an array of nozzles. The formation of droplets and their corresponding size is heavily influenced by the distance of a print head from the substrate [14]. Deviations from an optimal distance can result in poor resolution control. Unlike extrusion systems, inkjet technology has drop by drop control allowing for more discrete placement of material.

Like extrusion technologies, inkjet systems use metal or carbon particles suspended in a volatile solvent; however, the inks must be less viscous to be compatible (i.e. lower solids loading) [14]. As with the extrusion-based systems, the particle loading plays a significant role in the dispense characteristics as well as conductivity. Higher concentrations imply higher conductivities; however, high concentrations make the ink more viscous and therefore difficult to jet. When compared to extrusion-based systems, for the same orifice diameter, inkjet systems are more sensitive to particle loading and clog at lower concentrations. A thorough review of droplet formation and viscosity limitations for ink jetting is found in [21]. Typical formulations contain 30-40% metal by weight although up to 50% loadings can be found. These higher percent loadings implement very small particle sizes which faces the challenge of agglomeration and reduces jetting reliability[22].

Inkjet systems are also well suited for dispensing metallo-organic decomposition (MOD) inks. MOD inks contain no particles. Instead the metals are dissolved in solvent such as toluene or xylene [23]. When exposed to air, the solution decomposes leaving the metal precipitate. This reaction time can be longer than the dry times of solvent based inks. MOD inks' viscosities can be tailored specifically for ink jetting—favorable for high resolution capabilities [24]. The metal content of these inks is typically only 20-25% by weight. Previous works have used multiple printing passes order to deposit more metal and improve conductivity. As with any metal ink, post-process sintering can dramatically improve conductivity. Both metal-loaded and MOD inks are compatible with ink jet technology. Choosing a solution depends on the importance of metal content (higher with metal-loaded inks) versus the rheological customization (and thus resolution) of MOD inks.

Ink jet deposition heads are maneuverable and can also print in different orientations making it a good candidate for AM hybridization. Ink jetting can be tailored to produce traces with high resolution in arrays that are comparable to AM processes in terms of throughput. Compared to extrusion systems, ink jetting is capable of higher resolution. However, lower achievable metal loadings negatively impact conductivity. Additionally, ink jetting is currently used to deposit inks for pulsed photonic sintering which may be a sintering solution that is compatible with low temperature substrates. This technology is discussed further in section 3.1.

2.3 Aerosol Jetting

Aerosol Jet DW systems aerosolize solutions into a vapor stream to deposit material. For the DW of conductive materials, the same metal-solvent inks can be used. This mixture is dispensed through a high velocity nozzle as shown in Figure 7. The vapor accelerates through the nozzle and impacts the substrate surface. The aersolization process can help to dry out the solvent constituents of the solution and decrease dry times. The size distribution of the particles can be controlled independently of the feedstock's distribution using virtual impactors. A virtual impactor uses a secondary gas flow with a different flow rate. Smaller particles are diverted by the secondary flow. Larger particles' momentum prevents them from being diverted and continue on the main path. This allows for a homogenous mixture of uniformly sized particles, which enables high resolution and consistent post-processing outcomes (discussed further in Section 3.1).

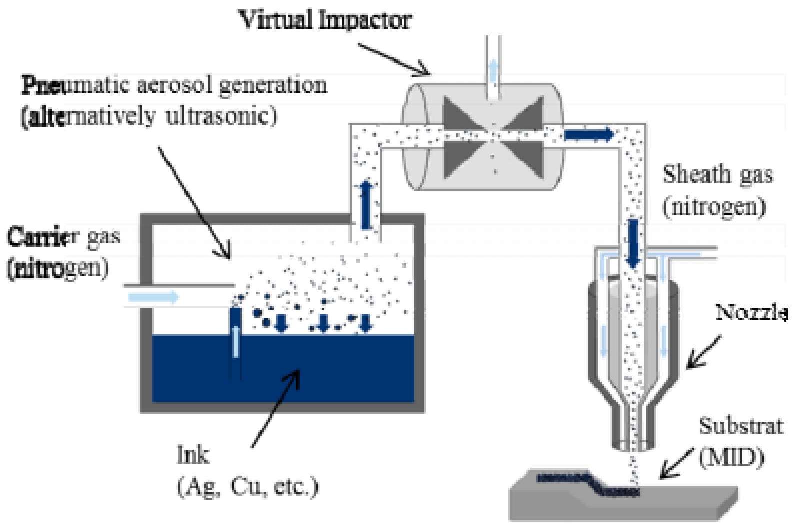


Figure 7 – Optomec Aerosol Jet process [25]

Aerosol Jet DW is capable of producing features as small as 10 µm with linear write speeds of 300 mm/s although 50 mm/s is typically observed. Single passes can be as thick at 2 µm depending on the ink [7]. Therefore at a resolution comparable to extrusion system (50 µm), the volumetric deposition rate is limited to 0.03mm^3/s. Because of the aersolization process, viscosity is not so much an issue as long as the material can be aerosolized (includes metal and carbon). The deposition head can also deposit material at a range of distances from the substrate surface. Deposition is possible with a standoff distance within the range of 1mm to 5mm [14]. This makes motion control for deposition on conformal surfaces simpler.

Again the maneuverability of the deposition head and the systems control make Aerosol Jetting a good candidate for integration with AM systems. The tolerance of the dispensing nozzle's standoff distance makes the system flexible and ideal for deposition on conformal surfaces. Flat surfaces or high volume production requirements however are better suited by the other technologies given the Aerosol Jet deposition rate is relatively low.

3 ROADBLOCKS AND SOLUTIONS THROUGH ANALYSIS OF PREVIOUS WORKS

The hybridization of DW and AM is non-trivial because of (i) material post-processing temperature compatibilities, (ii) adhesion between conductive and substrate, (iii) adhesion between conductive layers, and (iv) adhesion to external circuitry. Potential solutions are presented in the context of an analysis of previous works encountering these roadblocks.

3.1 Temperature Processing

Most of the work done in the past decade in combining AM and DW has been confined to selecting AM materials that can withstand high-temperatures and DW materials that require relatively low post-processing temperatures. For example, most metal DW inks require post processing at a minimum of 100°C to become conductive. Only a few polymeric AM materials can withstand these temperatures. Some of these materials include Duraform HST (SLS), Prototherm (Stereolithography), and ULTEM (FFF). Other AM processes like PolyJet have materials that can only withstand a maximum of 80°C.

High temperatures allow individual particles to form necks and eventually grain boundaries between particles. This neck and subsequent grain boundary formation increases contact area and, consequently, conductivity. The temperature at which diffusion and sintering occur is different for different metals. This is typically at least 70% of the material's melting temperature which is near 1000°C for metals. The melting temperatures of metals in particle decreases when the particles are sufficiently small [26]. Figure 8 demonstrates how melting temperature decreases as particle diameter also decreases. One conclusion is that sufficiently small particles on the nanoscale could sinter at low temperatures compatible with AM substrates.

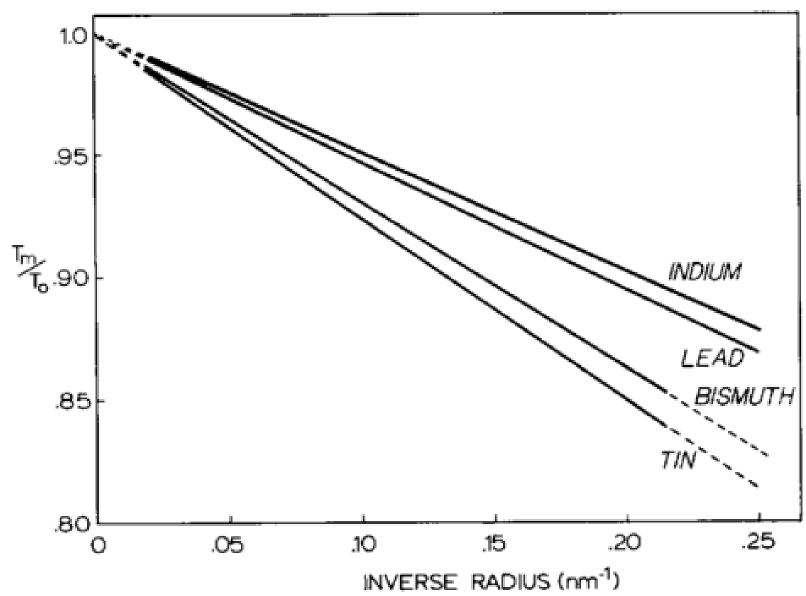


Figure 8 – Melting temperatures as a function of particle radius demonstrating lowered melting temperatures as size decreases [26]

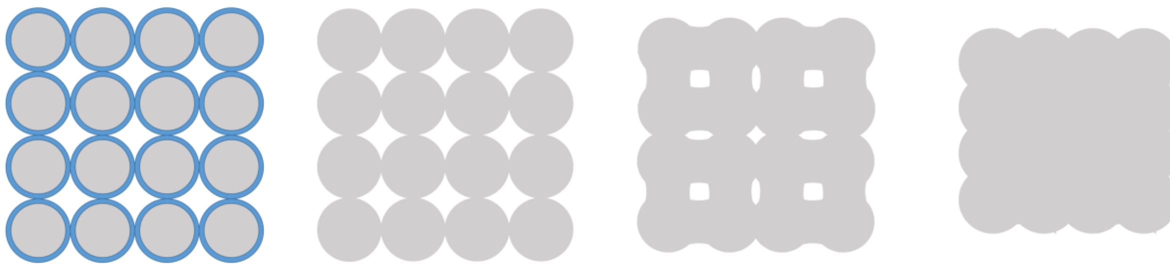
As the diameters decrease into the nanoscale, inter-particle forces begin dominate the suspension of the particle-solvent mixture. Maintaining a homogenously dispersed mixture becomes a challenge. Resulting agglomerates of the particles are larger than their singular, dispersible, counterparts. Agglomerates are difficult to dispense without clogging. It is possible to coat the metal particles with capping agents to prevent agglomeration; however, the capping agents themselves require high temperature processing for removal. The capping agents then become the limiting factor for post-processing temperature.

Figure 9a shows particles still encapsulated by the capping agent that prevents agglomerations while in solution form. At this stage, the materials is only slightly conductive, if at all.

b exhibits the interfacing of the particles after the capping agent is removed. Temperatures of at least 100°C are typically required for this.

c demonstrates low temperature sintering. Based on Ostwald ripening, surface particles have migrated to more stable sites, lowering the overall surface energy [27]. This results in densification and more contact area between particles, however at its limit the resulting structure is still porous and thus not as conductive as the bulk material.

d shows a fully sintered and dense formation. This formation reaches the conductivity of the bulk metal however it requires temperatures of 70-90% of the materials melting temperature. Perelaer et al. provide a more extensive review of conductive inks and the factors governing their post-process requirements [28].

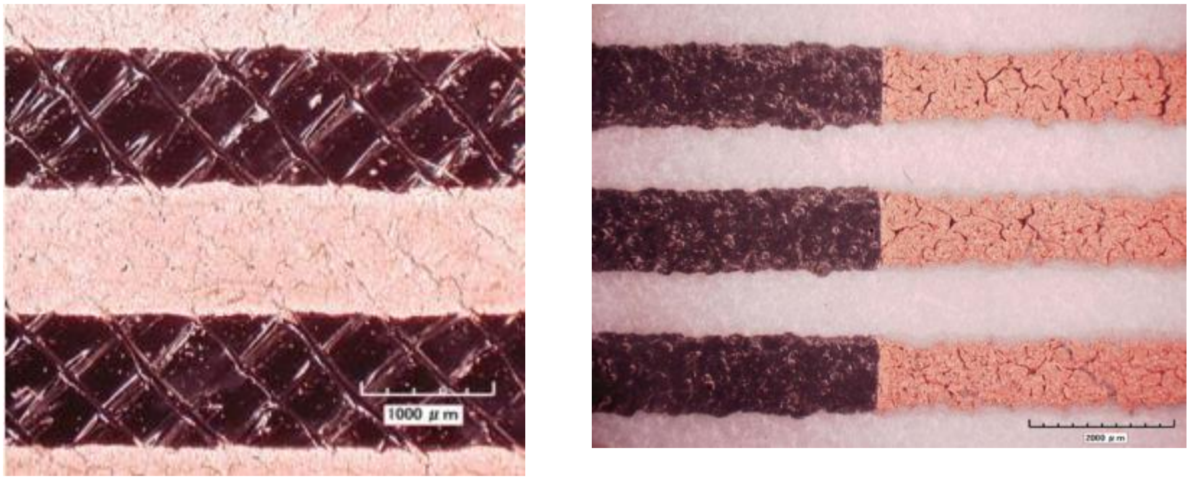


(a) **(b)** **(c)** **(d)**

Figure 9 – Different stages of post-processing to improve conductivity of particle-based metal inks

Multiple works by Medina, Wicker, & Lopes have integrated Stereolithography and DW technologies to create an array of functional electronics printed onto additively manufactured structures. All of these examples take advantage of high-temperature SLA resins that can withstand the 110°C post-processing temperatures required by their inks [5], [8], [9], [15], [17], [29].

While not focused on AM, there has been interest in evolving sintering techniques to be compatible with low temperature substrates, specifically polymers. Perelaer and Schubert have investigated multiple localized methods for sintering directly written conductive traces [28]. They found that material can be locally sintered using laser or microwave radiation. Laser based sintering still poses the risk of damaging a polymer substrate. This damage on an SLA substrate is characterized by Medina et al [17]. Microwave radiation based sintering exhibited promising results; however, microwave conductors or antenna were required to absorb useful amounts of radiation which is unpractical for volume processing. Another method for polymer compatible sintering is pulsed photonic curing. Pulsed photonic curing is interesting in the context of AM because it can heat metal traces to high temperatures without damaging the surrounding substrate. It is also a broadcast energy source so alignment to the traces is not necessary [30]. Preliminary work by Cormier suggests that the technology is safe for low temperature AM substrates [31].



(a) **(b)**

Figure 10 – Photonic curing of copper on (a) FFF and (b) SLS substrates. (b) Also shows an intentionally uncured region in black [31]

Figure 10 shows examples of copper cured by photonic curing on both FFF and SLS manufactured substrates. The conductive materials for photonic curing can easily be deposited using inkjet technology and the cured material and results have shown conductivities of 10^9 S/m which is greater than bulk conductivity of copper. The disadvantages of photonic curing are that the distance from the energy source is critical, therefore curing conductive inks is restricted to planar surfaces. Additionally, the thickness of the deposited ink is critical for curing and is restricted to relatively thin layer heights. Successful curing has not been demonstrated with thicknesses larger than 1-3 microns [30].

3.2 Adhesion of DW materials to AM substrates

For any deposition process, adhesion between the deposited material and substrate is important. Poor adhesion between the materials can result in delamination of the conductive materials from the substrate and failure. This is especially important for traces that are embedded within a print and not on the surface. After a circuit is embedded, access and repair is not possible. It is difficult to discern without testing if the adhesion between particular inks and AM substrates is possible. Factors influencing adhesions include:

- Surface energy of both DW material and AM substrate
- AM substrate surface roughness
- AM substrate surface treatment
- Chemical interaction between DW & AM materials

The surface energy of the DW material and AM substrate can determine the contact angle between the materials or surface wetting. Better wetting implies more contact area, more surface energy and thus better adhesion. The surface roughness of the AM substrate also can affect the adhesions characteristics. Cheng et al. determined that the surface roughness could be especially important to the adhesion of microparticles on a substrate, A more detailed explanation of this interaction can be found in [32]. Surface treatments such as etching, plasma treatment, and priming can change the surface tension of substrates to enhance adhesion characteristics [33], [34]. Finally, a chemical interaction between the DW material and AM substrate can also contribute to the adhesions characteristics of the parts. Understanding these parameters is important to achieve good adhesion.

Some AM technologies pose unique challenges with respect to surface adhesion because of the surfaces that they produce. Technologies like fused filament fabrication (FFF) have a very non-uniform surface on the macro scale which poses a unique problem for DW. FFF produces a ridged surface because its material patterning process.

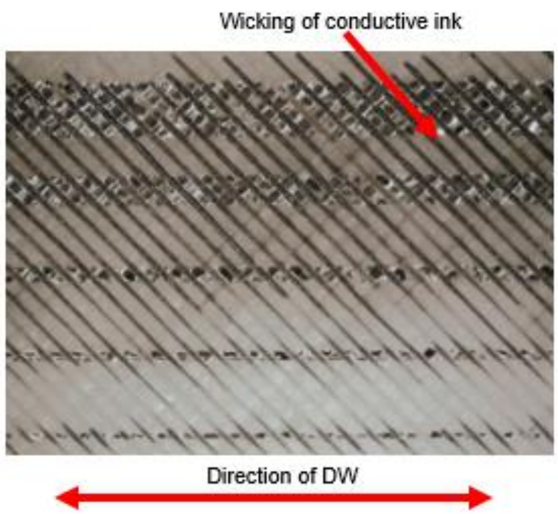


Figure 11 – Close up image of silver inks deposited on FFF ULETM 9085 printed substrate [35]

Figure 11 is a magnified image of silver ink deposited on an FFF surface. Since the surface is not flat, conductive inks tend to fill into the valleys between the AM traces resulting in short circuits or discontinuities. Optomec and Stratasys utilized a UV curable dielectric material as an intermediate bonding layer between the FFF part surface and the conductive ink [35]. The dielectric material fills the voids and dries with a planar surface as shown in Figure 12.

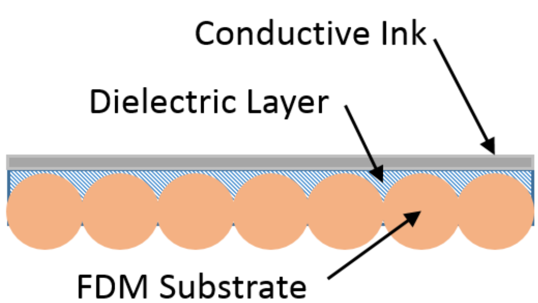


Figure 12 – Conductive ink deposited on FFF substrate using dielectric intermediate bonding layer

The dielectric material creates a flat surface for depositing conductive material. The dielectric can also be chosen with good adhesion characteristics to both the substrate and conductive materials. For this reason, an intermediate layer can also be used with other AM processes such as Stereolithography to benefit adhesion even if the surface is much smoother than that of the FFF process. Because of the flexibility of DW systems it is possible to use the same systems for depositing the dielectric material.

Moreover, an intermediate bonding layer can help to alleviate stresses induced by a mismatch in the CTEs of the AM and conductive materials which is common between a metal and a plastic. Sintering elevates the temperature of the conductive material and cracking may occur if the difference in CTEs is sufficiently high as discussed in section 3.1.

3.3 Interlayer bonding and conductivity

Interlayer bonding is an important aspect of DW to consider in the context of AM because a multilayered process is inherently more compatible with AM process. Moreover, it enables more complex circuit geometries and configurations within a part. Previous research regarding DW of circuits has largely focused on planar, single layer, deposition because of its applications in PCB fabrication. Many of the hybridizations of DW and AM so far have only incorporated these single layer DW methods. While DW has been shown feasible on 3-dimensional conformal surfaces, the deposition is still done in a single layer [9].

Lopes and coauthors have shown DW compatibility in three-dimensions with deposited vias [15]. This process combines SLA and extrusion-based DW. Figure **13** diagrams the process. First, IC components are embedded in a partially completed build. A second build process creates vertical interconnects for connecting the embedded components. The stereolithography build finishes with traces to connect all the embedded components. The extrusion-based DW process finally dispenses conductive ink in the traces and into the vias. The vertical interconnects are explicitly cited as a potential manufacturing and design issue. They require direct access from the surface and complex channels can be difficult to fill with ink. In situ multilayer deposition would allow for conductive materials to be deposited layer by layer in conjunction with the corresponding AM process and alleviate the design complications of the vias with designs that do not require access from the surface. However bonding between the layers of conductive inks is a critical issue.

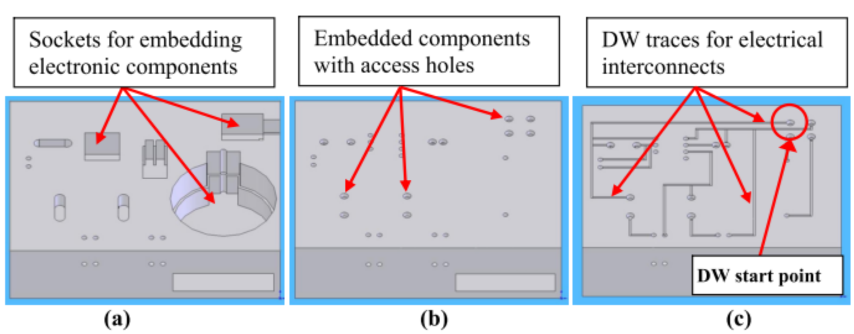


Figure 13 **– Build stages for DW and SLA incorporating vertical interconnects. (a) sockets for embedded components; (b) vias to access embedded components (c) planar interconnects** [15]

Multilayer DW is desired in the hybridization of DW and AM to leverage the full capabilities of the AM process. Layered DW allows for multiple layers of circuitry in a single build as well as conductive features orthogonal to the build plane. However, it has been shown that in layer based deposition of conductive materials, the Conductivity along the plane of depositions is higher than conductivity between layers, perpendicular to the plane of deposition. [19]. This is due to lower contact density between layers versus along layers. Good interlayer bonding minimizes this.

A potential solution to promoting interlayer bonding and hence conductivity is a graded volatility solvent. Sun et al. have shown this type of solvent to promote adhesion between layers so that printed structures can withstand sintering without delamination and distortion [11]. Water is used to enable the deposited layer to dry enough to solidify and maintain shape. Ethylene glycol and glycerol are also part of the solvent to maintain moisture after the water has evaporated and promote interlayer bonding. Once the structure is finished, the other solvent constituents can be removed with temperature processing. This is one potential solution to creating solvent based inks that are compatible with AM processes yet maintain conductivity.

4 CONCLUSIONS

This paper evaluates different DW technologies specifically well-suited for hybridization with AM technologies. The hybridization of DW for conductive materials and AM creates a new class of manufacturable technology that integrates electronic signals and sensing within the structure of a manufactured part and leverages the design freedoms enabled by AM. The applications and benefits of this have only partially been exposed but are plenty and promising. As both technologies are additive processes, there is a significant reduction in waste when compare to traditional machining and electronics fabrication processes. Moreover, the versatility of both classes of technologies allow for a significant reduction in process chain complexity through a reduction in processing steps. These hybridizations have application in both prototyping and high-volume production spaces. Understanding the metrics that make certain AM and DW processes compatible is paramount in developing successful pairings of the two technologies.

The previous works discussed in this paper have provided a foundation to understanding the capabilities and limitations of combining DW and AM systems. While the functional aspects are well demonstrated, relevant metrics for the electrical performance of these devices are not fully evident. More process modeling and optimization remain to be done in order to understand the adhesion between DW and AM materials as well as analysis of achievable conductivities of different materials on various substrates.

While this paper focuses on the hybridization of two distinct technologies, it is prudent to understand how these technologies could come together as a unified solution. An example of this is the carbon-filled FFF material developed by Leigh and coauthors [19]. Although not as conductive as the metal materials used in other works, the carbon material is processed through the AM technology's native material patterning system allowing the deposited conductive material to match the parameters of the structural components. An AM process that is capable of depositing both structural and conductive materials is ideal. But by matching the parameters of both DW and AM systems, it is feasible to create a hybridized system that behaves more as a unified technology. Compatible process resolution, throughput, and temperature capabilities in conjunction with conductive and substrate materials matched for quality adhesion defines the most desirable case of hybridization.

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