

MULTIFUNCTIONAL MATERIAL DIRECT PRINTING FOR LASER SINTERING SYSTEMS

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Abstract

The research reports the development of advanced techniques for the direct print of materials into parts made by laser sintering. The present invention provides for the production of three-dimensional objects with improved build and support materials. The direct printed material may be metals, elastomers, ceramic, or any other material, which is typically different than the laser sintering material. Aspects of the technique include direct printed materials within laser sintered parts to improve part strength, provide multi-materials, provide electrical conductivity, and provide other desirable benefits to the part.

Introduction

The ability to fabricate smart structures using multifunctional materials is an area of interest for the manufacturers of autonomous systems. Additive manufacturing (AM) provides the flexibility of fabricating complex shapes and monolithic structures that can reduce part count and increase mission readiness by reducing the lead times to fabricate these structures. An AM process that offers the robustness of functional parts and the flexibility of utilizing multifunctional materials would disrupt the way in which such systems are designed and the way in which they operate increasing and expanding the spectrum of mission capabilities (e.g. intelligence, reconnaissance, surveillance, sensing).

The need to achieve light weight multifunctional materials led to the development of carbon fiber composites and carbon nanocomposites. There is an on-going demand and need from costumers' applications to fabricate multifunctional parts with embedded electronics (e.g. antennas, sensors, wiring and circuitry). In the solar panel manufacture industry Direct-Write (DW) technologies are widely used to trace Silver (Ag) lines down to 10 μ m to collect solar energy. In a similar manner this technique has been used by several companies to trace conformal antennas, strain sensors, and conductive lines in helmets and aircraft wings. Systems such as Aerosol Jet (AJ), SmartPump, and MicroPen deposition among several others, are being used to print conductive material, and embedded circuitry onto the surface of parts.

Embedding electrical components to the body of structures has acquired the attention of the AM industry [1], where manufacturing costs and turn-around lead times are critical for the production scenario. Direct-Write of the electrical components not only allows for cost reduction and better turn-around time; it allows for payload reduction and concealed electrical components.

With the technological advances in material development for the rapid prototyping applications, the aerospace industry has adopted Selective Laser Sintering as the preferred manufacturing method for non-structural aerospace components. The advantage of the SLS

process is the turn-around lead time that is involved with manufacturing a part. Once a CAD model has been created, it is sent to an SLS machine for manufacturing.

The versatility provided by the SLS process to manufacture parts; and the practicality of Direct-Write to produce embedded electronics, make the combination of the technologies a novel method to incorporate multifunctional materials into autonomous systems structures. Some of the key advantages that embedded electronics offer to the manufacture of aerospace structures, and the Direct Part Manufacture industry in general, are:

- Payload reduction through electrical wiring reduction
- Concealed electrical components within the part
- Parts turn-around cost
- Start-to-finish part productions lead times.

Multifunctional Material Incorporation Into Additive Manufactured Structures

The most suitable AM technologies to integrate an in-situ hybrid direct write (DW) rapid manufacturing method use amorphous and semi crystalline polymers as extruded filaments or deposited powders. The most successful bonding mechanism for this application is typically laser consolidation/fusion. These AM processes of choice include Stereolithography (SLA), Fused Deposition Modeling (FDM), Selective Laser Sintering (SLS), and Selective Heat Sintering (SHS). The combination of technologies has focused on tracing conductive material on the surface of parts with DW methods; thus achieving multi-functionality within the material. The Direct-Write term covers a wide range of printing methods that follows the same principle of fabrication: deposition of material on two or three-dimensional structures through a stationary nozzle, with a motion-controlled substrate that determines the location of material deposition.

Paramount was able to demonstrate the proof of feasibility study of combining two additive manufacturing (AM) techniques to fabricate a part with embedded traces of conductive ink using thermoplastic materials. Compatibility of Nylon12 substrates to conductive inks was evaluated in collaboration with the Rochester Institute of Technology. Cabot CSD-32 was used with Optomec's Aerosol Jet, and 40-3920R HVA was used with nScript's SmartPump system. The adhesion and flexibility of the inks was demonstrated with a 3-point-bend test designed to print traces of conductive ink on SLS tensile bars.

The viability of performing in-situ printing traces of conductive Ag (4020R HVA dissolved in 15 - 25 wt% Xylene) was also proven at Paramount by retrofitting an open source 3D printer (Fab@Home) to a 2500-CI SLS platform. An ASTM D-638 test bar was produced with the laser scanner; a conductive trace was printed on top of the sintered Nylon surface, and a layer of powder was rolled over and sintered to finish the test bar. Conductivity was tested with a Fluke 28II TRMS multi-meter where a resistance of 0.3 Ω was shown along the XY-axis of the SLS process.

Embedded Sensors Fabrication Feasibility Using Additive Technologies

Feasibility of combining SLS with a direct-write technology was assessed in 3 phases. Each phase would study the feasibility of retrofitting a base technology in order to create a hybrid process.

- **Phase 1.1:** Presented and compared available AM technologies that are compatible with the physics of the SLS process.
- **Phase 1.2:** Studied the feasibility of incorporating the SLS process within a DW technology.
- **Phase 1.3:** Evaluated DW technologies inside the SLS process.

Phase 1.1 studied existing technologies that were considered practical for the deposition of conductive inks and compatible with the physics of the SLS process. There are several DW technologies in the market that are used to print electronics. The complexity and packaging of some of these prevents them from being easily adapted with an additional internal module to perform SLS of polymers inside them. Several technologies were evaluated and their characteristics are summarized in Table 1.

<i>System</i>	<i>Deposition</i>	<i>Viscosity</i>	<i>Interaction</i>	<i>Temperature</i>	<i>Setup</i>
AEROSOL JET <i>Optomec</i>	<i>Hydrodynamic</i>	<i>1 – 1E3cP</i>	<i>Contact-less</i>	<i>24 - 150°C</i>	<i>OEM</i>
MICROPEN <i>MicroPen Technologies</i>	<i>Micro-capillary</i>	<i>5 – 5E5 cP</i>	<i>Surface Contact</i>	<i>24 °C</i>	<i>Custom</i>
SMARTPUMP <i>nScript</i>	<i>Micro-dispense</i>	<i>1 – 1E6 cP</i>	<i>Surface Contact</i>	<i>24 - 150°C</i>	<i>OEM</i>
FAB@HOME <i>Seraph Robotics</i>	<i>Extrusion</i>	<i>1 – 3E9 cP</i>	<i>Substrate Contact</i>	<i>24°C</i>	<i>OEM</i>

Table 1. Summary of Systems Considered for Proof-of-Concept Study

Aerosol Jet®, by Optomec, is a mask-less, meso-scale, material deposition system that uses hydrodynamic deposition of atomized aerosol particles, and a motion-controlled system which allows for creation of complex patterns on the substrate without making contact with the surface. The Aerosol Jet process starts with the atomization of a liquid sample of the material to print, creating a dense aerosol of droplets with diameters between 1 and 5 microns that are transported to the deposition head using an inert carrier gas (Figure 1: A-C).

MicroPen® writing system, by MicroPen Technologies, is a micro-capillary technology where a pen tip “rides” on the surface of the material without touching the substrate surface (Figure 1: D-E). It uses a proprietary positive displacement pumping method to control ink volume of flowable materials onto a surface.

SmartPump™, by nScript, uses a micro-dispense pump to deposit material onto the substrate of contact. It uses positive pressure and a computer controlled needle valve that provides active valving and suck-back to control flow characteristics (Figure 1: F-H).

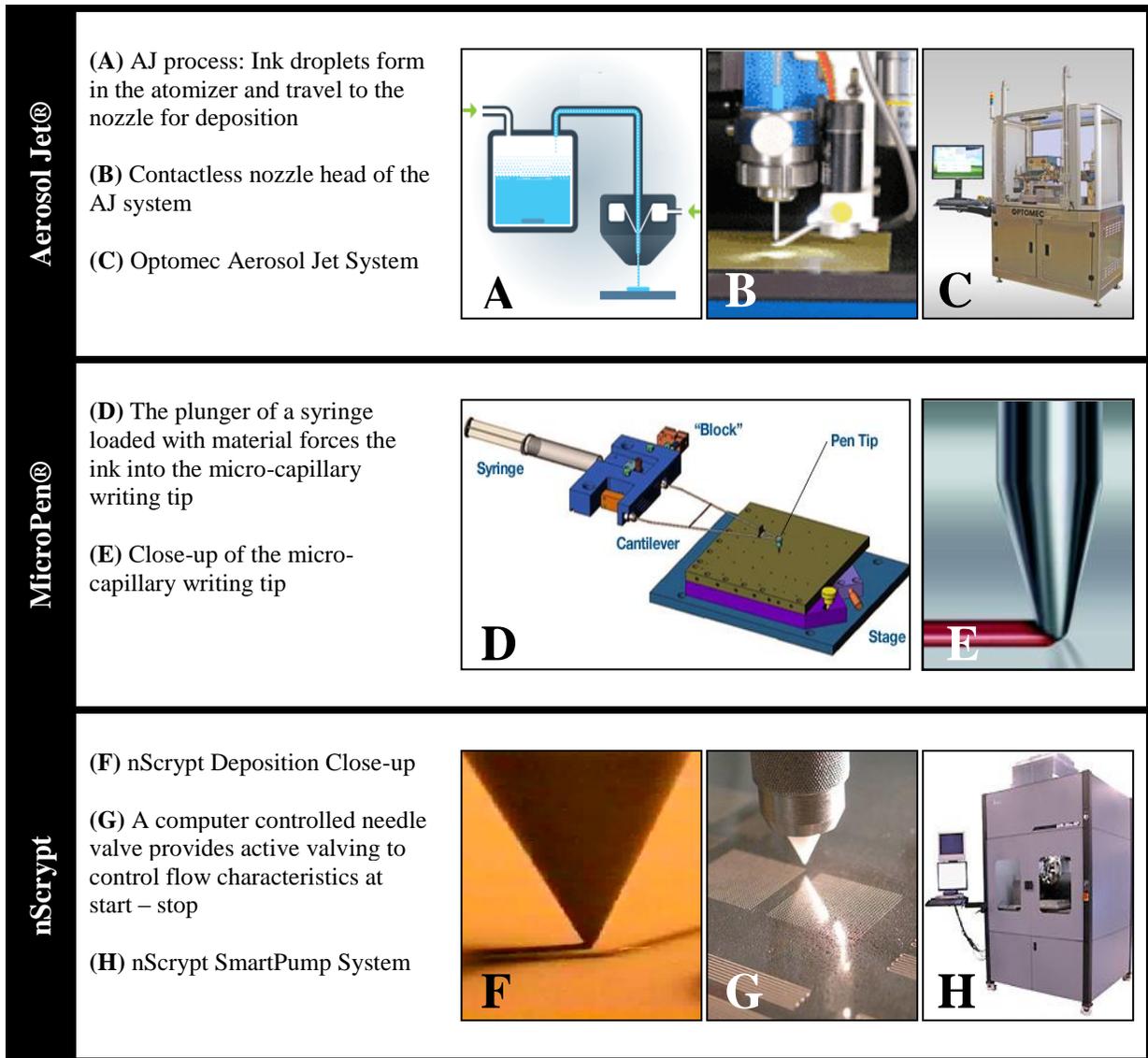


Figure 1: Direct Write systems evaluated in the feasibility study for application with Selective Laser Sintering: Aerosol Jet, MicroPen, and SmartPump.

Study Conductive Wire/3d Printing For Integrated Antennas/Sensors

Phase 1.2 studied the option of having the SLS process adapted within a DW technology. The DW technologies selected were Aerosol Jet and SmartPump systems, both available at RIT. Each technology uses a special Silver base ink and the resolution improves by using the manufacturer’s recommended ink. Cabot CSD-32 was used for the Optomec system and 40-3920R HVA for the nScript equipment; the viscosity of both inks was adjusted for printing the conductive material on Nylon 12 (PA12) substrate.

DW/SLS Experimental Setup

Aerosol Jet technology from Optomec was used as a base board to adapt an engineered fixture that would mimic the SLS environment. The flexibility of the system allowed enough room to implement a miniature powder bed where Nylon12-substrate conditions could be tested. Paramount designed a material delivery mechanism that mimics the deposition method in the laser sintering process. The goal was to document the technical challenges involved in the fabrication of parts with embedded sensors via a combination of selective laser sintering coupled with direct-write technologies. The main technical objective is to demonstrate the feasibility of embedding conductive paths in-situ during the laser sintering of polymers.

The miniature SLS fixture shown in Figures 2-3 consisted of a powder reservoir partition where powder was placed and then spread across a moving z-axis stage with 10 mm travel distance. The leveling of powder was done with a straight edge. The part bed lowering/rising mechanism used a micrometer screw to level the powder bed in 0.004-0.005" layer thickness increments.

Thin silicone heating pads were placed at the bottom and side walls of the SLS fixture to achieve melting of the PA12 powder at 175°C. A radiant heating strip was placed above the powder bed to maintain a variable current open-loop heating source to control the processing temperature of the polymer surface. An external 40W CO2 laser was used to melt the nylon. Layers of PA12 were sintered with the laser system and then quickly transferred the powder bed spreader fixture to the AJ system.

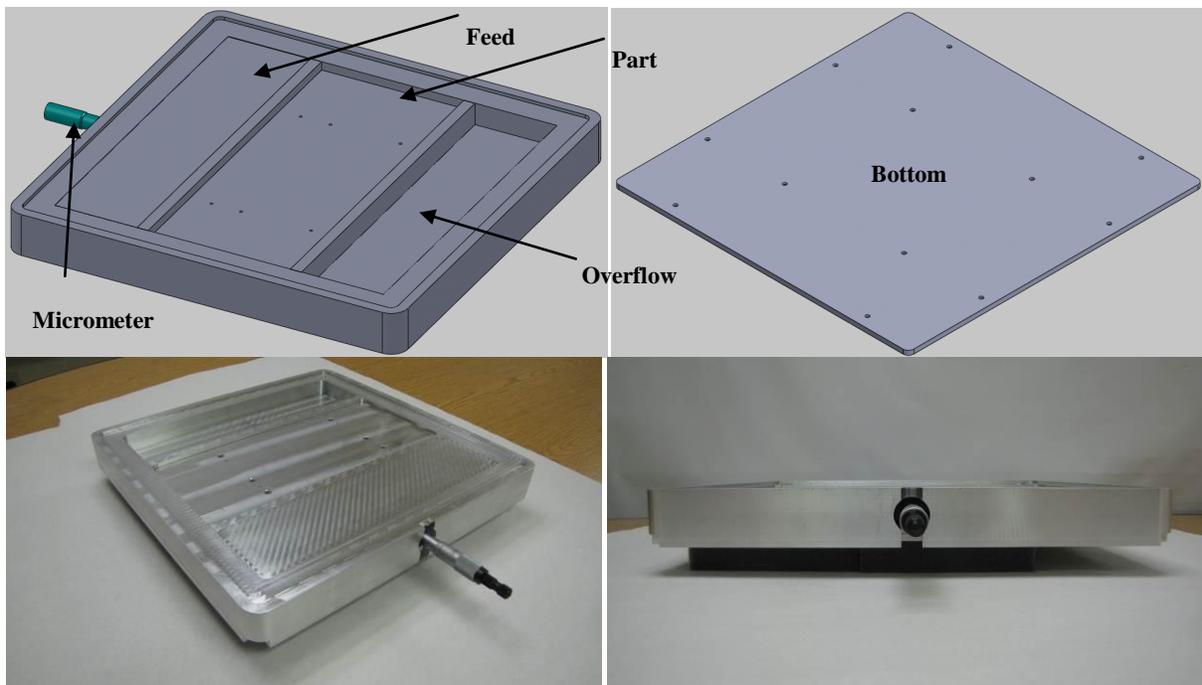


Figure 2: Powder Delivery Mechanism for the Feasibility Study of SLS/Direct-Write Hybrid AM Process

Figure 2 shows Paramount's designs and the fabricated parts for the material delivery mechanism. The system uses a micrometer to control the vertical travel of the part piston controlling the z-height (layer thickness) in 0.004-0.005" increments.

The mechanism was installed and tested as shown in Figure 3. This mechanism is heated from the bottom utilizing the heat from the platen of the Optomec Aerosol Jet Machine. A method to heat the top of the powder bed during sintering is necessary and proved to be very difficult to implement. The heat from the machine's bottom plate is keeping the sintered powder from curling up but this will become a challenge as more layers are consolidated in the z-direction.



Figure 3: Powder Delivery Mechanism Installed in the Aerosol Jet Machine at Rochester Institute of Technology for the Feasibility Study of SLS/Direct-Write Hybrid AM Process

Paramount provided several laser sintered Nylon-12 samples to RIT for the purpose of testing ink adhesion to the Nylon 12 substrate. These samples were carefully fabricated to show two different surface finishes that may be present during the laser sintering process. The first case is when a fresh layer of polymer powder is deposited on top of a previously sintered layer resulting in a rough surface formed by the partially bonded particles on top of the sintered polymer matrix. The second case shows the surface roughness present during an interim stage (fully molten layer) in between scans. In this later case the sintered layer was removed from the fabrication area immediately after the laser stopped scanning prior to the next recoat. The goal is to examine the microstructure of the conductive traces on both types of surfaces. This microstructure needs to be uniform to maintain good conductivity at the interlayer (in the Z-plane) after the new layer of powder is deposited (Figure 5).

Aerosol Jet and nScript technologies were used to print silver inks on the surfaces of these samples (Figure 4). The preliminary specimens are showing high electrical conductivity when measured with a regular ohm meter. Paramount will require more funding to perform more extensive studies to measure and baseline the volume and surface resistivity with the proper equipment. Table 2 summarizes the DOE for printing conductive inks in multiple material substrates. Table 3 shows a comparison of the multiple inks utilized for these experiments.

<i>System</i>	<i>Substrate</i>	<i>Ink</i>	<i>Result</i>
<i>Aerosol Jet</i>	<i>Fluff Powder</i>	<i>CSD-32</i>	<i>Fail</i>
	<i>Sintered Powder</i>	<i>CSD-32</i>	<i>Success</i>
	<i>Part Surface</i>	<i>CSD-32</i>	<i>Success</i>
<i>SmartPump</i>	<i>Fluff Powder</i>	<i>40-3920R HVA</i>	<i>Fail</i>
	<i>Sintered Powder</i>	<i>40-3920R HVA</i>	<i>N/A</i>
	<i>Part Surface</i>	<i>40-3920R HVA</i>	<i>Success</i>

Table 2. Design of Experiment Followed to Test System and Ink Compatibility to PA12

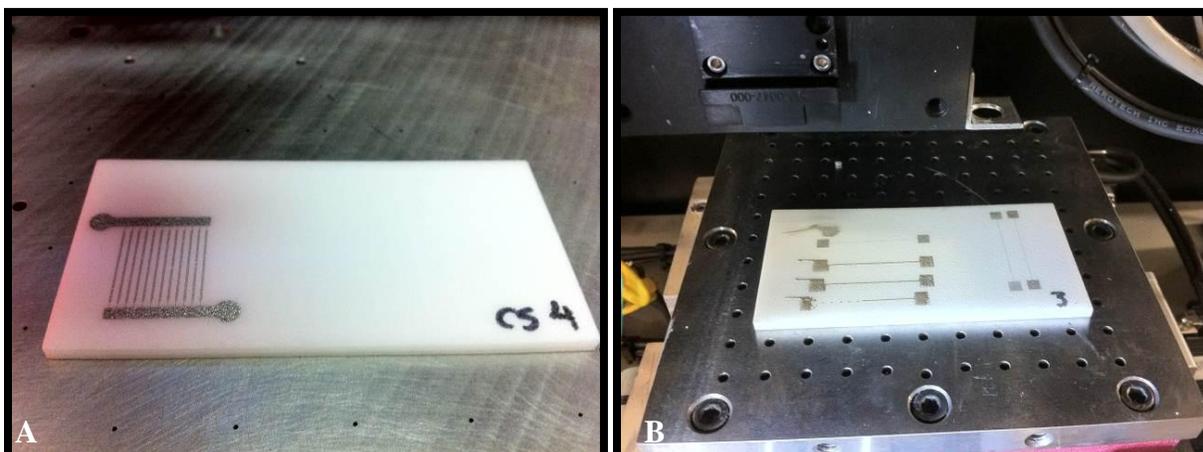


Figure 4: Traces of Silver Ink Printed on Laser Sintered Nylon-12 using A) Aerosol Jet® and B) nScript Direct-Write Technologies

	<i>CSD-32</i>	<i>40-3920R HVA</i>
<i>Deposition System</i>	<i>Aerosol Jet®</i>	<i>SmartPump™</i>
<i>Conductive Metal</i>	<i>Silver</i>	<i>Silver</i>
<i>Ink Form</i>	<i>Liquid</i>	<i>Paste</i>
<i>Metal Content</i>	<i>45 – 55 wt%</i>	<i>85 wt%</i>
<i>Viscosity</i>	<i>11 – 15 Cps @ 25°C</i>	<i>9,000 Cps @ 25°C</i>
<i>Cure Temperature</i>	<i>100°C – 300°C</i>	<i>100°C – 150°C</i>
<i>Volume Resistivity</i>	<i>0.004 – 0.080 Ω·cm</i>	<i>0.001Ω·cm</i>
<i>Compatible to</i>	<i>Ceramics, Metals, Plastics, Circuit Boards</i>	<i>Ceramics, Metals, Plastics, Circuit Boards</i>
<i>Applications</i>	<i>Membrane Switches, Flexible Circuits, Polymer Thick Film Circuits, and EMI/RFI shielding</i>	<i>Membrane Switches, Flexible Circuits, Polymer Thick Film Circuits, and EMI/RFI shielding</i>

Table 3. Comparison of Conductive Inks used in the Proof-of-Concept Experiments

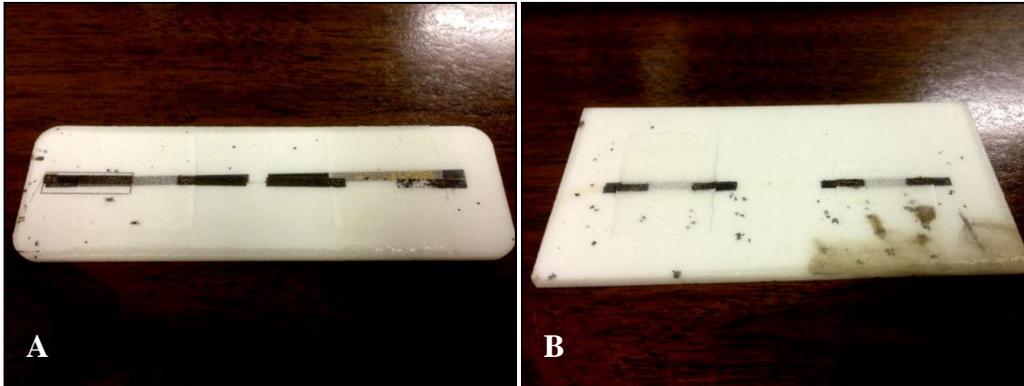


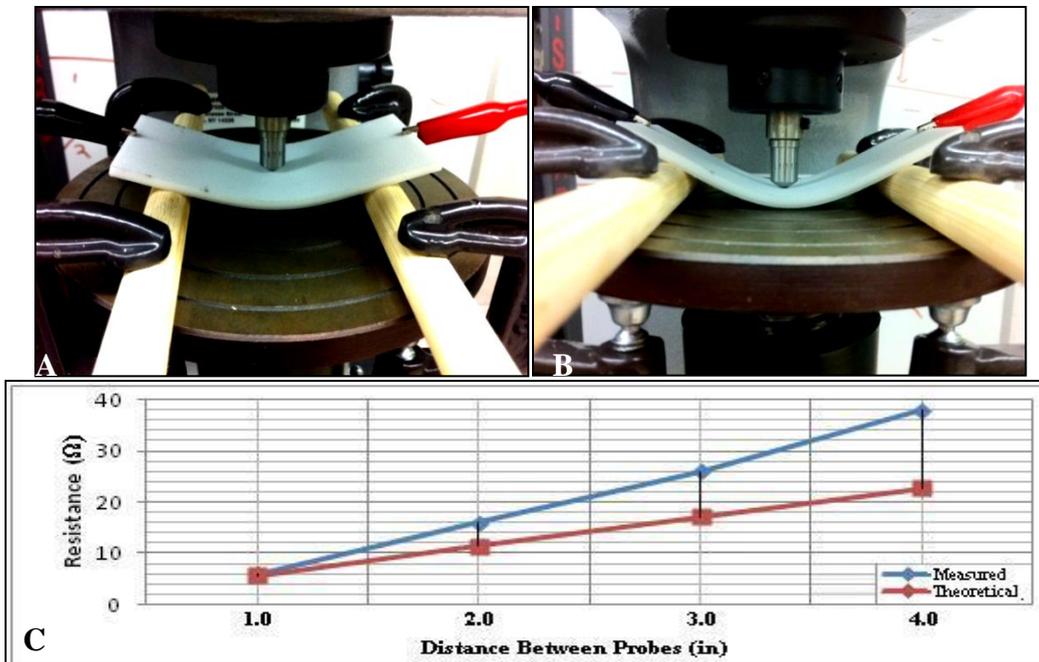
Figure 5: Conductive Ink Printed on PA12 Samples and then “Sandwiched” with a Second Layer of PA12 (A) Cabot CSD-32 Ag Ink Printed with AJ (B) 40-3920R HVA Ag Ink Printed with SmartPump™

Experimental Results

Nylon Tensile bars were produced on a 3DS S-Pro60 SLS machine to evaluate ink wear behavior under stress. A conductive print trace on a tensile bar measuring 10.16cm long and 0.3175cm wide and 10 layers thick (approximately 0.00562cm) was tested at different distances with a multi-meter to demonstrate connectivity along the trace. Results were compared to theoretical data calculated with equation

$$R = \frac{\rho L}{A} \quad (1)$$

Where ρ is the resistivity of the material measured in $[\Omega \cdot \text{cm}]$, L is the length of the conductive trace, and A is the cross-sectional area. Although the resistivity is higher than expected, the results are promising at the stage of the study. Electrical conductivity was not lost during strain test applied to the part is shown in Figure 6 below.



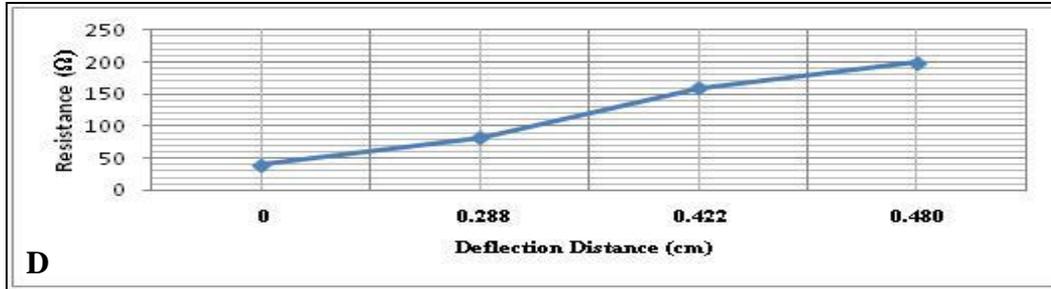


Figure 6: (A-B) Bending Test Setup used to Determine Conductive-Trace Wear and Durability under Flexural Load. Resistance Increases as Deflection Increases. (C-D) Resistance Readings vs. Deflection Distance and Distance between Proves

The resistance values from Figure 6 show how the electrical conductivity is recovered or goes nearly back to its original value after the load was removed. This particular experiment proved the feasibility of being able to print a strain gauge on the surface of an SLS part.

CSD-32 ink printed with AJ shows good deposition, flexibility and adhesion to the PA substrates. Aerosol Jet demonstrates to be a cleaner deposition method than nScript's SmartPump. Optomec's contactless deposition makes it a more suitable candidate for conformal deposition of conductive material to a produced part. Some of the advantages and disadvantages of Aerosol Jet system are:

- ✓ Contact-less deposition allows for clean prints.
- ✓ Ability to modify trace width and thickness without switching deposition head.
- ✓ Ink curing temperatures range between SLS processing temperatures.
- ✗ Droplet carrier/focusing sheath gas creates a cloud of powder in surrounding print area.
- ✗ Sheath gas creates a localized crystallization/solidification phase at the trace pattern.
- ✗ Localized layer bonding quality decrease due to localized solidification.

The 40-3920R HVA ink used with nScript's SmartPum was more difficult to apply and to manage its print resolution. In contrast to Aerosol Jet, the SmartPump prints thicker traces of material against the surface of contact. Some of the advantages and disadvantages of the SmartPum systems are:

- ✓ System deposits material without disturbing the surrounding print area.
- ✓ Ink curing temperatures range within SLS processing temperatures.
- ✗ Deposition requires indirect (substrate/ink/tip) contact with the substrate.
- ✗ Trace width and thickness are modified by changing the deposition head.

Demonstrate Fabrication Feasibility Using SLS and 3DP

Phase 3 evaluated the behavior of the Direct Write method within the SLS environment using a laser sintering machine. This effort required the design and modification of an apparatus that was adapted to the SLS machine to make possible the in-situ deposition of conductive ink within the SLS process. The feasibility of printing traces of conductive Silver ink (4020R HVA dissolved in 15 - 25 wt% Xylene) was proven by retrofitting an open source 3D printer (Fab@Home) to a 2500-CI SLS platform. ASTM D-638 test bars were produced with the SLS laser and conductive traces were printed in-situ on the molten nylon substrate. The layer wise process was repeated by adding a layer of powder over and sintering until the test bar was

completed. The conductivity of the embedded conductive traces was tested with a Fluke 28-II TRMS multi-meter and a resistance of 0.3Ω was reported along the XY-axis of the SLS process (Figure 90).

Experimental Setup

The Aerosol Jet and SmartPump systems previously studied were not considered as an option for this experimental phase due to the required cost, time, and the support from OEMs to develop custom-made components and software modifications. The integration of a DW to an existing SLS system was performed by retrofitting a Fab@Home 3D printer to fit the frame of a DTM 2500CI SLS system (Figure 7).

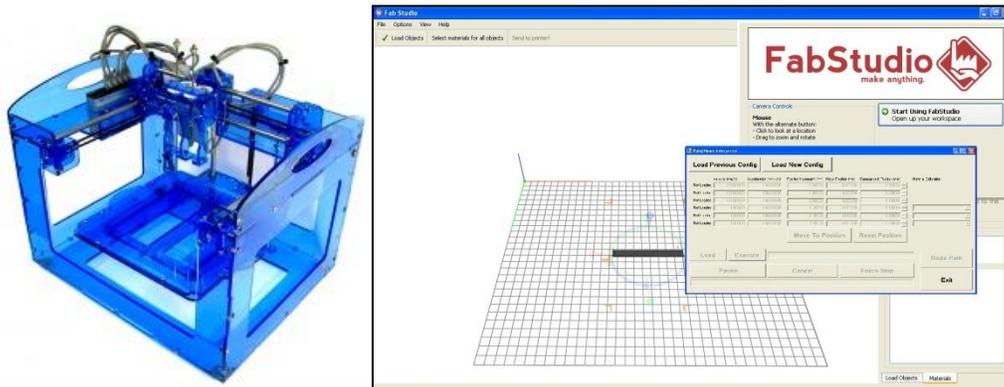


Figure 7: Fab@Home Uses Open Source Software to Create Files that are Sent to the Equipment for Printing

The Fab@Home printer is fabricated with acrylic sheets that are laser-cut in a “puzzle” like configuration. It uses 2D parts to build a 3D structural part. Some of the modifications that needed to take into account to be able to use the machine in the SLS equipment are:

- Reduce frame size from 16.15in high to 6.29in to fit in the SLS machine.
- Use a heat resistant material to withstand 175°C without deformation.
- Design a rail mechanism to insert and remove the printer fixture.

The Fab@Home printer was redesigned to meet the requirements that would allow the fixture to slide in and out of the SLS machine without difficulty (Figure 8 - 9). The Fixture was modified in SolidWorks and re-designed to be built in as fewer parts.

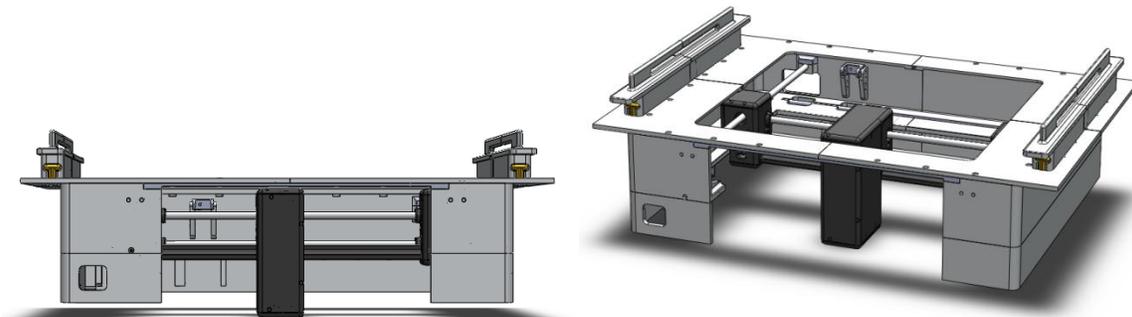


Figure 8: CAD Modeling of the Retrofitted Prototype 3D Printer

The prototype was fabricated in a EOS P-730 machine, with a 38% glass-filled PA 12 build the entire fixture in one part. The retrofitted printer frame was made with Aluminum to address the PA12 processing temperature at 175°C, required to melt the powder. For experimental purposes the printer fixture needed to withstand the SLS environment for at least 2 minutes without deforming structural parts.



Figure 9: Aluminum 3D Printer Inside the SLS Machine During Testing

Experimental Results

Traces of conductive ink (4020R HVA dissolved in 15 - 25 wt% Xylene) were printed inside a 2500-CI SLS platform. ASTM D-638 test bars were produced with the laser scanner; a conductive trace was printed on top of the sintered Nylon surface, and a layer of powder was rolled over and sintered to finish the test bar. The deposition methods were varied in order to determine the optimum deposition sequence to produce parts with embedded conductive traces. The experimental sequences are illustrated in Figure 10 and 11 below.

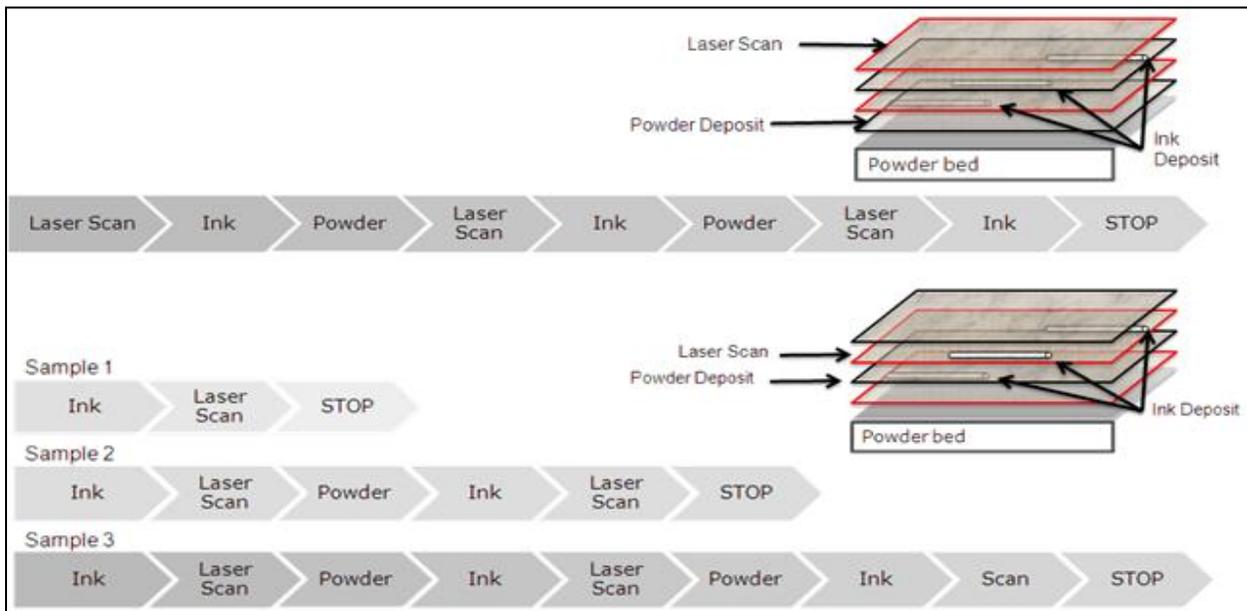


Figure 10. Sintering and Printing Configurations used to Produce SLS Parts with Embedded Conductive Paths. Configurations that Required Deposition of Ink before Laser Sintering Failed to Produce a Complete Part

The goal of the preliminary tests was to prove functionality, flow-ability and conductivity of the ink on the XY plane as show in Figure 12. The steps followed to produce hybrid parts were:

1. Inert process chamber and warm-up Nylon 12 powder
2. 30 min. SLS build warm-up stage
3. Test bars begin to sinter layers
 - Process pause
 - 3D printer slide in and setup (Figure 11 A)
 - Conductive ink deposition (Figure 11 B)
 - 3D printer slide out (Figure 11 C)
 - Process resume
4. Roller puts down powder
5. Sintering of a layer
 - Process pause
 - 3D printer slide in and setup
 - Conductive ink deposition
 - 3D printer slide out
 - Process resume
6. Sintering continues to finish

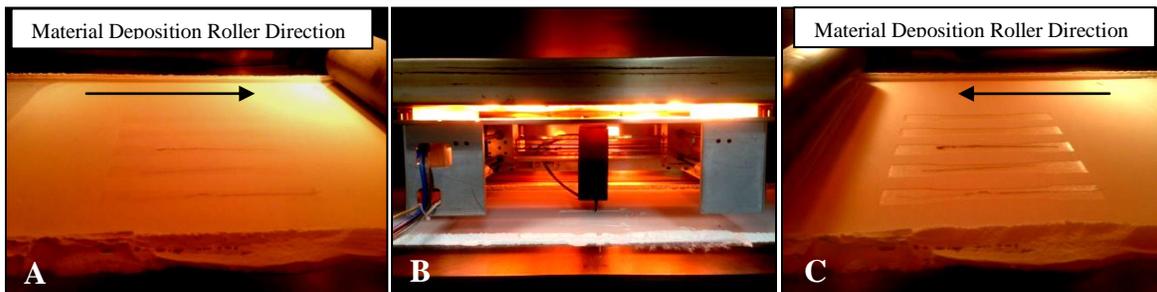


Figure 11. In-situ DW/SLS Stages during Printing and Deposition

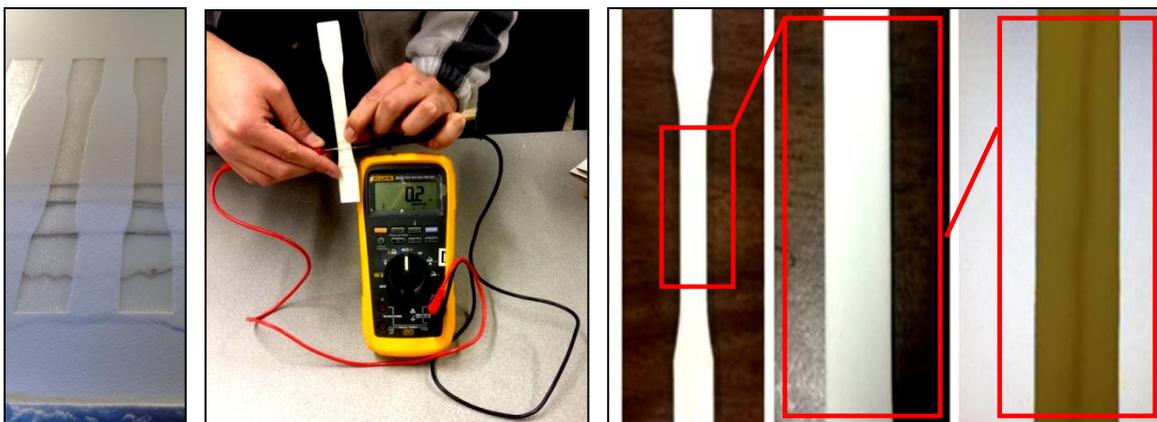


Figure 12: Fabricated Parts with Embedded Ag-ink Traces Embedded in PA12 SLS Bars Demonstrate a Novel Technique for Embedded Sensor Printing

Electrical conductivity in the Z direction will be a challenge for any AM process with polymers. The layers deposited act as insulating barriers that prevent the electrical conductivity through them in the Z direction. Any hybrid process must consider a way to mitigate this technical challenge. This study, however, demonstrated signs of feasibility by showing conductivity through multiple traces of Silver ink printed between alternating layers (different z-heights). The DOE was limited to DW through only 5 layers sandwiched in the mid-section of a standard tensile bar fabricated via SLS. The results presented in Figure 13 show electrical conductivity readings ranging between 0.3Ω (1-2), to 6.4Ω (4-5).

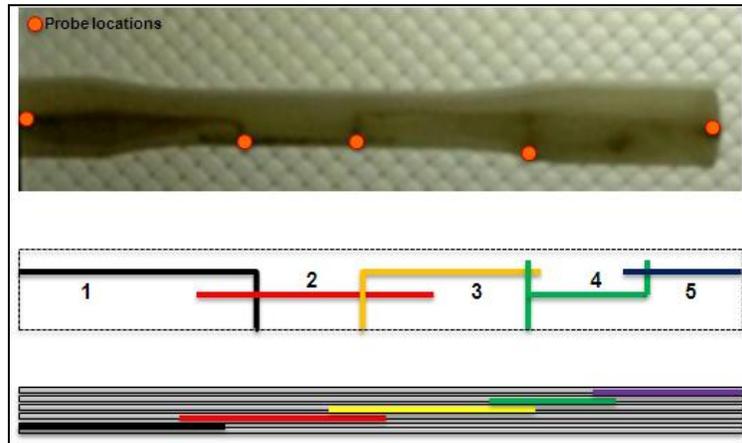


Figure 13: Electrical Conductivity Demonstrated in the Z-Direction for Multilayer Experiments, for a 5-Layer DW/SLS Printed Section of an SLS Tensile Bar

An SEM analysis was conducted to study and document the microstructure of the silver deposited on the nylon 12 as a polymer substrate. The results are presented in Figures 14-15 showing a single trace of Ag printed in-situ on top of a previously melted [by the CO₂ laser] layer of nylon 12. The polymer matrix shown in Figure 14 appears to be very porous showing regions only partially melted.

This microstructure is an artifact of unstable and inconsistent processing temperatures inside the SLS processing chamber during this experiment. The processing-temperature set points fluctuated as much as $20\text{-}30^{\circ}\text{C}$ due to the alterations made to the latching and seal mechanisms of the front door of the SLS machine. These engineering modifications were required to allow for the insertion and extraction of the fixture holding the DW extruding print head. Figure 15 shows the microstructure of the cross section of an SLS tensile bar with embedded traces of silver ink printed in-situ at different z-heights. The microstructure of Figure 15 also shows a variation in density from left to right going from fully dense to porous. The variable density is shown not only within the polymer matrix, but also in the deposited silver ink with the adverse density effect worsening in the same direction (left to right). This phenomenon was caused by the same thermal gradients (hot and cold regions) introduced by the opening and closing of the door.

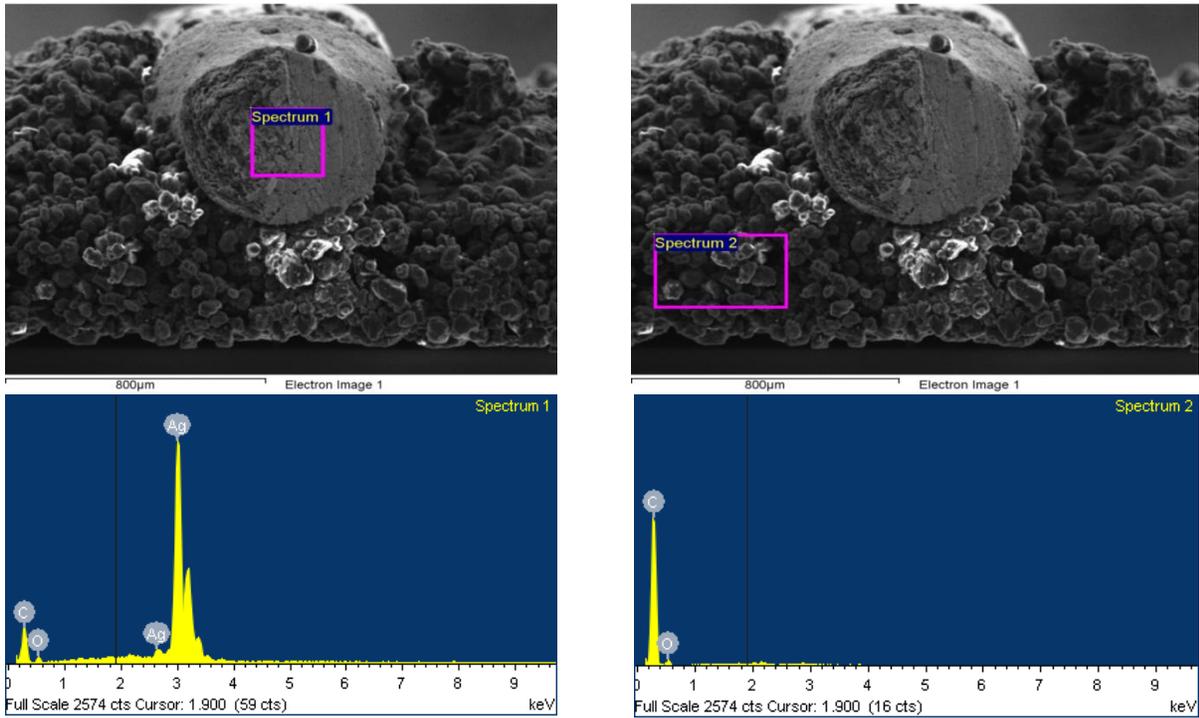


Figure 14: SEM Analysis Validating the Presence of Silver Ink Printed In-situ on the Nylon-12 Substrate via DW/SLS Hybrid Process

The orientation of the tensile bar shown in Figure 15 coincides with the fabrication orientation inside the SLS machine. The left side of the tensile bar was positioned at the back of the machine and the right side of the bar was closer to the front. The thermal regions were hotter in the back and colder towards the front of the fabrication area.

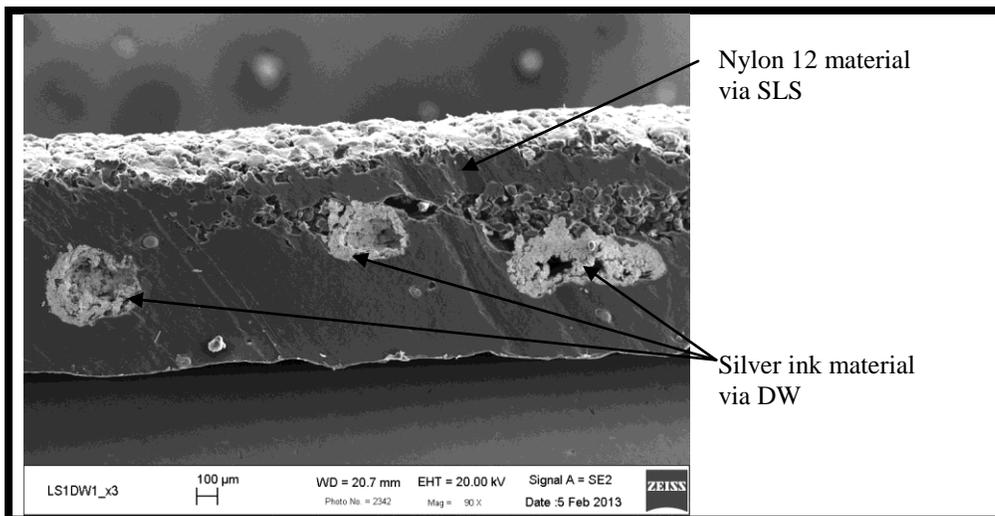


Figure 15: SEM Analysis Showing Variable Microstructure for the Polymer Matrix and the Silver Ink Printed In-situ on the Nylon-12 Substrate via DW/SLS Hybrid Process

Conclusion

3D Systems has proven the ability to use multiple additive manufacturing technologies for the fabrication of complex parts with embedded sensors using direct-write/direct-print technologies combined with the laser sintering (LS) process and laser sintering materials. The versatility provided by the SLS process to manufacture parts; and the practicality of Direct-Write to produce embedded electronics, make the combination of the technologies a novel method to incorporate multifunctional materials into autonomous systems structures. This novel additive manufacturing technique provides for the ability to improve part strength, provide multi-materials, provide electrical conductivity, and provide other desirable benefits to the part.

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SLS is a registered trademark of 3D Systems Corp. Aerosol Jet is a registered trademark of Optomec. MicroPen is a registered trademark of MicroPen Technologies. SmartPump is a registered trademark of nScrypt, Inc.

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