CHARACTERIZATION OF IN-SITU CONDUCTIVE PASTE EXTRUSION ON POLYJET SUBSTRATES

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ABSTRACT

The integration of Direct Write technologies into Additive Manufacturing system enables the in-situ deposition of conductive traces during part printing, and thus the creation of parts with embedded electronics. In this paper, the authors detail their research of integrating an extrusion-based direct write system into a PolyJet material jetting system to create multi-material products with structurally integrated, functional electronics. An investigation of the dispensing (e.g. orifice diameter, dispense pressure, and toolhead speed), drying (e.g., time and temperature), and substrate parameters (e.g., VeroWhitePlus and TangoBlackPlus) on the geometry of the deposited trace is presented. Additionally, the adhesive compatibility of the conductive material on both rigid and elastomeric PolyJet substrate surfaces is investigated by measuring wet and dry contact angles.

1 INTEGRATION OF DIRECT WRITE AND ADDITIVE MANUFACTURING

The integration of Direct Write (DW) technologies, which can be used to selectively deposit conductive materials, with Additive Manufacturing (AM) processes can enable the realization of mechatronic products that feature embedded actuation, sensing, and power. Moreover, integration of DW and AM enables the embedding of the electronics within the component's structure, thus eliminating the need for external wiring and interconnects and providing a means for protecting the electronics from the environment.

As seen in Table 1, prior efforts in depositing conductive traces onto additively manufacturing parts has been focused in integrating DW with single-material stereolithography, ultrasonic consolidation, extrusion, and laser sintering AM technologies. However, none incorporate Material Jetting processes.

Table 1. Prior Combinations of Direct Write and Additive Manufacturing Technologies

Ref.	*Application*	*DW Technology*	*AM Technology*
[1]	Interconnects	Micropump	Stereolithography
[2]	Discreet Electronics	Pneumatic Extrusion	Stereolithography
[3]	Interconnects	Pneumatic Extrusion	Ultrasonic Consolidation
[4]	Batteries	Screw Extrusion	Screw Extrusion
[5]	Conformal Electronics	Manual	Stereolithography
[6]	Antenna & Interconnects	Aerosol Jet	Fused Filament Fabrication
[7]	Interconnects	Aerosol Jet & Micropump	Laser Sintering

A comprehensive review of combining direct write and additive manufacturing technologies can be found in [8]. In general, the major challenges in integrating DW + AM include:

- *Z-Direction Electrical Interconnects*: Depositing multiple and electrically continuous conductive structure in multiple layers.
- *Process Integration*: Combining different DW & AM technologies in a single process
- *Material Compatibility:* Ensuring that both DW & AM material are compatible in terms of adhesion, resolution, and thermal processing.

In this work, the authors explore the integration of extrusion-based DW technology with the Stratasys PolyJet material jetting AM technology. PolyJet is considered specifically because of its ability to simultaneously process both rigid and elastomeric photopolymers, which allows for the direct fabrication of mechanisms with actuated living-hinge joints [9]. The integration of PolyJet and DW could enable direct manufacture of complex, multi-material components that feature structurally integrated actuation and sensing in a single build. An overview of the embodied DW/PolyJet integration is provided in Section 2.

The goal of this work is to gain an understanding of the compatibility of the materials processed by the two material deposition technologies. Specifically, in this paper, the authors explore how process parameters of both the DW and the PolyJet processes affect the deposited materials. The research is guided by three questions:

1. How do tip size, dispense pressure, and tool head speed affect feature width and height?
2. How does drying time and temperature affect the geometry of conductive inks on PolyJet substrates?
3. What are the adhesion characteristics between the conductive ink and the PolyJet substrates?

Regarding Question 1, two experiments are performed to explore both the width and height of the deposited conductive geometries under various dispensing and drying parameters on both VeroWhitePlus (rigid) and TangoBlackPlus (elastomeric) PolyJet substrates (Section 3). Using the determined ideal dispense parameters (for thinnest depositable traces), a second experiment is performed to analyze the height of the dispensed traces and its relationship to drying parameters (Question 2, Section 4). To answer Question 3, the authors investigate contact angle between the PolyJet substrates and conductive ink as a means of determining adhesive compatibility between the two materials (Section 4). Finally, a discussion synthesizing lessons from all three experiments is provided for closure is presented in Section 6.

2 INTEGRATION OF DIRECT WRITE WITH POLYJET MATERIAL JETTING

As noted by the summary of literature presented in Table 1, no prior work has been demonstrated in combining DW and material jetting AM technologies. To enable the selective deposition of conductive materials during the PolyJet printing process, a separate deposition machine was realized. The system's embodiment was performed according to design consideration criteria for combining DW and AM technologies, as presented in [3]. The resultant DW setup is presented in Figure 6.

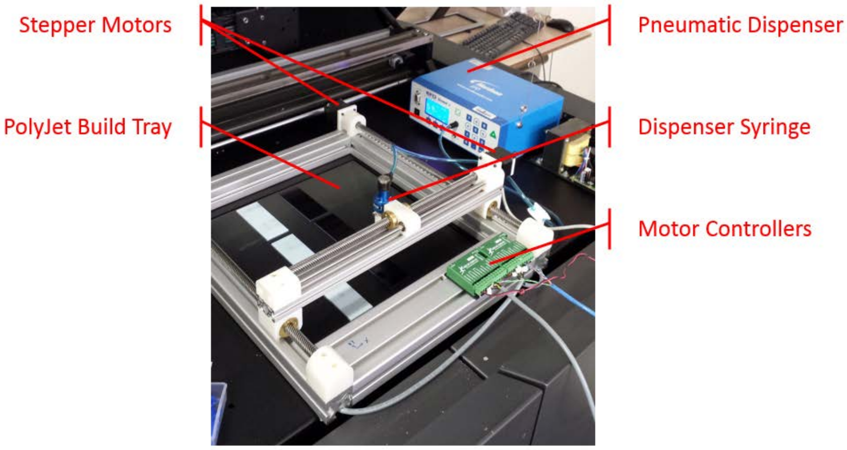


Figure 6. Direct Write setup for PolyJet process

The guiding design goal for the realization of the system was that it needed to be able to be placed onto the PolyJet build tray in order to deposit conductive material directly onto an in-situ part. As such, an extrusion-based DW technology was selected, as it is easily placed into the PolyJet system. Specifically, the infrastructure of extrusion processes is compatible with the PolyJet machine as it does not require a closed environment and can be incorporated in an appropriately-sized positioning system. In addition, extrusion DW systems have flexibility in processing conductive materials of varying viscosities. Specifically, extrusion-based DW is capable of dispensing heavily loaded inks; previous works have used inks with metal loadings in the 60-70% range [4]–[7]. Additionally, the 50 µm feature resolution is comparable to the PolyJet process (42 µm); although this resolution value may increase with the use of heavily loaded inks.

A Nordson EFD Ultimus V high precision dispenser was selected for the extrusion-based dispensing. The dispenser uses air pressure to dispense materials via a syringe. Positive pressure from 0-100 psi in increments of 0.1 psi can be applied to the syringe to extrude material, and a vacuum can be applied quickly to stop the material flow. Additionally, it has the ability to consistently meter materials from the syringe as the material level changes (nearly full versus nearly empty syringe). This removes the material metering control loop out of the larger control system, thus allowing for repeatable deposition control.

The syringe of the extrusion-system is mounted onto an X-Y frame, which is made from extruded aluminum framing, and is sized to fit on the Connex 350 build tray. Stepper motors are used to drive lead screws for X- and Y-direction translation. A one-inch lead screw pitch and 200 pole stepper motors result in a minimum system resolution of 125 µm per step. Translation is controlled by an Arduino programmed to interpret basic g-code. Dispense commands are also driven by the Arduino and interpreted from the g-code. An overhead camera (not shown in figure) was used with LabVIEW's vision and motion toolbox to provide image-based orientation alignment between the inserted extrusion platform and the PolyJet build tray.

In this work, the extrusion system is used to selectively deposit DuPont 5021 silver-loaded conductive ink. This ink was chosen as its post-processing temperatures were compatible with the low heat-deflection temperature of printed PolyJet substrates. Because the goal is to encapsulate the directly written traces after deposition with subsequently printed layers, the components cannot be removed from the build tray and treated in an oven. (Removing the components would require them to be replaced on the build tray with microscale precision.) As such, a heat gun is used to force warm air over the samples during the drying process on the build tray.

3 EXPERIMENT 1: DW PROCESS PARAMTERS' EFFECT ON TRACE THICKNESS

3.1 Context

During an assessment of the design considerations for hybridizing additive manufacturing and direct write technologies, depositable feature size was identified as a key metric for assessing the quality of the printed conductive traces. The following question guided the search of the DW process parameters that provided the smallest deposited feature: *How do tip size, dispense pressure, and tool head speed affect feature width?*

For the pneumatic extrusion-based dispenser selected, tip size, dispensing pressure, and tool head speeds are the main process parameters that influence the geometry of deposited beads of material [14]. While the review of direct write technology suggests that deposition resolutions from pneumatic solutions can match that of the PolyJet process [8] this assumption must be validated. Beyond the resolution qualification, this experiment aims to assess how different dispensing parameters affect feature width on different PolyJet substrates.

During the dispensing process, the material passes through the tip orifice and the extrudate assumes the cross-sectional geometry of the opening. As the material reaches the substrate, it is expected to slump, creating a trace wider than the tip orifice. Nonetheless, smaller tip diameters will yield smaller features relative to features from larger tip sizes. However, there is a practical limit to the minimum tip diameter used based on the material and clogging. Heavily loaded inks will clog smaller tip orifices. Because pressure is proportionally related to the volumetric flow rate, it is hypothesized that lower pressures will produce lower flow rates and thus smaller features, although insufficient pressure will not allow material extrusion.

Moreover, faster tool head speeds should also produce smaller feature sizes. For a given pressure, the mass flow rate of conductive material exiting the nozzle is constant. Equation 1 relates the mass flow rate ($\dot{Q}$) to the cross-sectional area of the deposited conductive trace (A_{cs}) and the toolhead speed ($V_{toolhead}$).

$$\dot{Q} = A_{cs} \cdot V_{toolhead} \tag{1}$$

If velocity increases, the cross-sectional area will decrease. It is possible that this will cause the beads to become shorter, thinner, or both. The next section discusses the methods used to investigate this research question.

3.2 Method

In designing the experiment to assess the effects of the main factors (tip size, pressure, and tool head speed), it is assumed that there is no significant interaction between them; i.e., each factor should affect Equation 1 independently. However there is no specific proof when considering PolyJet substrates. Therefore, a full factorial analysis is performed with each main factor combination on both PolyJet substrates VeroWhite+ and TangoBlack+. The main experimental factors, and their variable ranges are outlined in Table 2.

Table 2: Selected main factor variable settings

Variable	Unit	Range	Rationale
Tip Size	[um]	[400]	Smaller tip sizes will produce finer features although there is a practical limitation where the conductive material will no longer extrude due to nozzle clogging. The selected range is also influenced by commercially available tip sizes for the pneumatic dispenser.
Dispensing Pressure	[kPa]	[31.03-41.81]	Equation 1 demonstrates that lower pressures will decrease the volumetric flow rate and thus lead to smaller features. Preliminary results show that pressures below 31.03 kPa are insufficient for extrusion. Pressure settings 37.92 and 41.81 kPa are also tested to observe potential interactions.
Substrate	[ ]	[VeroWhite+ TangoBlack+]	These are the two main materials for PolyJet printing. VeroWhite+ allows for rigid features, while TangoBlack+ is elastomeric and flexible.
Toolhead Speed	[mm/min]	[1000-3000]	Equation 1 demonstrates that faster toolhead speeds should also allow smaller features. 3000 mm/min is selected as an upper limit because the deposition machine is not capable of depositing reliably at faster speeds.

Preliminary screening eliminated tip size as a main factor when processing the DuPont 5021 material. It was observed that tips with a diameter smaller than 400 μm would clog repeatedly. At times, the metal particles clogged the nozzle to allow only the solvent portion of the ink to extrude. Therefore, experiments were only conducted with the combinations of the main factors using the 400 μm tip diameter.

For dispensing pressure, pressures less than 31.03 MPa were not sufficient to extrude material and those over 41.81 MPa caused material agglomeration on the substrate surface and resulted in many discontinuities. The range of toolhead speeds is determined by the maximum speed at which the X-Y motion system loses its positioning accuracy. While extrusion at faster speeds is possible, it is not done reliably with the current machine embodiment. Beyond this speed barrier, there is expected to also be a physical limitation to toolhead speed based on the rheology of the conductive ink.

There are 18 different combinations in total shown in Table 2, and each combination is tested four times. For each factor combination, a 40mm long line is deposited onto one of the two printed substrates. Width data of the resulting deposited line is measured using a HIROX KH-7700 3D digital video microscope.

3.3 Results

The average bead width data for each main factor combination is shown below in Table 3. The highest pressure setting (44.81 kPa) induced nozzle clogging and resulted in discontinuous lines. As a result, width data is not gathered for that particular setting. For varying pressure, lower pressures exhibited thinner lines. In addition, faster toolhead speeds resulted in thinner lines. When comparing both substrates, lines written on TangoBlack+ were on average 343 μm thinner than those on VeroWhite+.

An ANOVA analysis of the main factors did not demonstrate any significant interactions, as shown by the interaction plot in Figure 1. The lines in these plots are mostly parallel and represent the different setting for the parameter listed in that row. It is possible that there may be a slight interaction between speeds and dispense pressures as the green and blue lines show some convergence. Therefore, higher speeds may have more of a dependence on pressure as shown by the blue line (3000 mm/min) that has a larger slope than the green line (2000 mm/min) over different pressures.

The data for the explored parameter ranges fail to reject the hypothesis that there is no significant interaction between the varied parameters. This indicates that as speed increases and pressure decreases, the line feature width decreases. On VeroWhite+, the smallest achievable trace was 879 µm and 720 µm on TangoBlack+. These values are highlighted in green in Table 3.

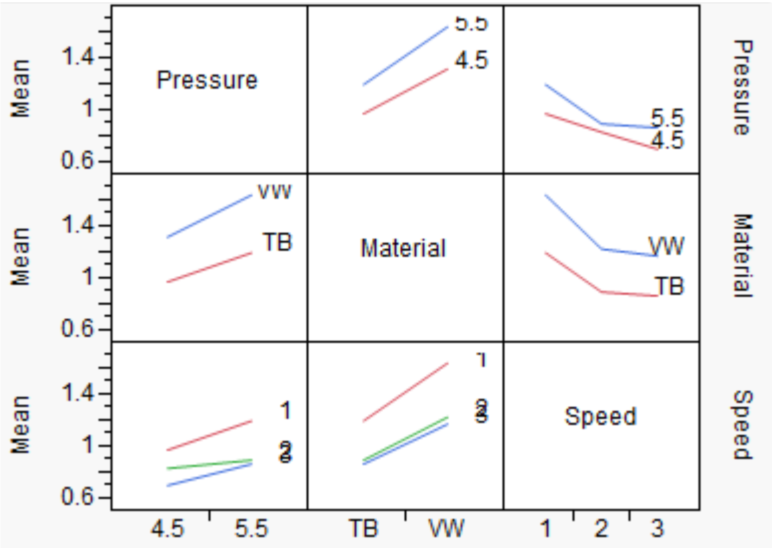


Figure 1: Interaction plots of average bead width between main factors

Table 3: Bead width data for main factor combinations

Trial Number	Dispensing Pressure [kPa]	PolyJet Substrate	Toolhead Speed [mm/min]	Average Width [mm]	Standard Deviation [mm]
1	31.03	VeroWhite+	1000	1.319	0.055
2	31.03	VeroWhite+	2000	1.070	0.045
3	31.03	VeroWhite+	3000	0.879	0.034
4	31.03	TangoBlack+	1000	0.957	0.062
5	31.03	TangoBlack+	2000	0.814	0.039
6	31.03	TangoBlack+	3000	0.720	0.069
7	37.92	VeroWhite+	1000	1.621	0.054
8	37.92	VeroWhite+	2000	1.206	0.131
9	37.92	VeroWhite+	3000	1.189	0.146
10	37.92	TangoBlack+	1000	1.200	0.049
11	37.92	TangoBlack+	2000	0.903	0.055
12	37.92	TangoBlack+	3000	0.837	0.112

3.4 Discussion

This experiment shows that all of the main factors have an effect on the average feature width. The relationships that exist are:

- Increased pressure yields wider features
- Increased toolhead speed yields narrower feature width
- Features on TangoBlack+ are narrower than those on VeroWhite+

If a consistent bead width is critical across the different substrates, the tool path could specify a change in toolhead speed to maintain consistency or adjust the dispense pressure. For example, it is shown that dispensing on TangoBlack+ at 37.92 kPa and 2000 mm/min, the feature width is comparable to dispensing on VeroWhite+ at 31.03 kPa and 3000 mm/min. The bead width differs by only 24 μm on average. Additionally, this feature width data can be used to assist with designing channels into the PolyJet parts for full encapsulation of the deposited conductive trace.

For all remaining experiments in this work, a dispense pressure of 31.03 kPa and a toolhead speed of 3000 are used since these settings yield the smallest feature sizes. While the bead height is not characterized in this experiment, it is measured in Section 3. The rationale is that these width measurements are taken before the ink is fully dry on the PolyJet substrate. Optical measurement indicated that the drying process does not affect the width, but the height changes considerably as the solvent evaporates. The next section discusses how different drying conditions affect the ink geometry. Once the drying process is better understood, height data is measured and discussed.

4 EFFECTS OF DRYING CONDITIONS ON DEPOSITED TRACE HEIGHT

4.1 Context

The drying conditions of conductive inks are understood to have a positive effect on the conductivity and adhesion of conductive materials [15]. Given the motivation of creating functional circuitry, high conductivity and strong adhesion is desirable. Commercially available conductive inks are prescribed a drying regimen of specific temperature and duration for ensuring quality conductivity and adhesion. It is recommended by the supplier to cure the DuPont 5021 ink at 120°C for at least 5 minutes [15]. However, these temperatures are in excess of the PolyJet material's glass transition temperatures (54°C) and, therefore, not compatible.

This experiment aims to explore how varying dry times and temperatures (compatible with PolyJet material) affect the final conductivity and adhesion of silver-loaded conductive ink on PolyJet substrates. More simply, how does drying time and temperature affect the geometry of conductive inks on PolyJet substrates? In addition, the height of dried lines is analyzed to determine if the narrower lines observed on TangoBlack+ versus VeroWhite+ substrates result in taller features.

Initially, it is hypothesized that drying the ink at temperatures near the published glass transition temperatures of the PolyJet materials will not significantly impact adhesion and profile geometry of the conductive traces. It is observed that as the deposited beads dry, the cross-section settles and shrinks in the Z-direction as the solvent evaporates. Rapid drying could potentially inhibit this settling effect and cause different cross-sectional profiles than specimens dried over a longer period of time at room temperature. If the geometry is not significantly affected, the heated drying regimen can be used as higher temperatures help the ink cure faster.

4.2 Method

The experiment outlined in this section is designed to investigate the effects of drying time and temperature on the geometry of the conductive traces on the PolyJet substrate. In order to understand the potential effects on adhesion on the cross-sectional geometry, contact angle and bead height are measured. Two sets of samples were evaluated: (i) samples that are allowed to dry in air for 24 hours and (ii) samples that are dried at 55 °C for 30 minutes (which is near the material's heat deflection temperature). As discussed in Section 2, the heated samples are exposed to heat mid-print on the PolyJet build tray using a heat gun.

3-dimensional profilometry (A HIROX Digital Video Microscope) is used to determine if there is any significant change in the cross-sectional profile between the two substrates' sample sets. The microscope uses a composite of multiple images with different focal planes to construct a 3D profile as shown in Figure 2. From the 3D profile, cross-sectional profile and height data is made available.

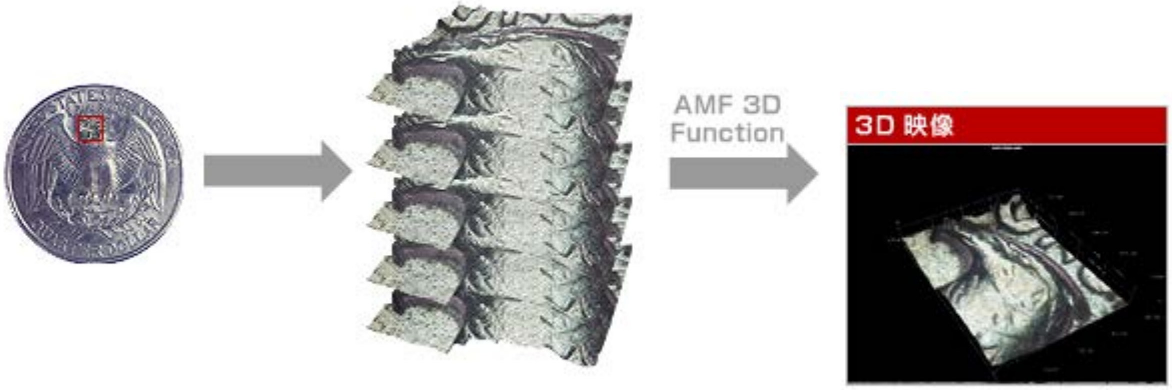
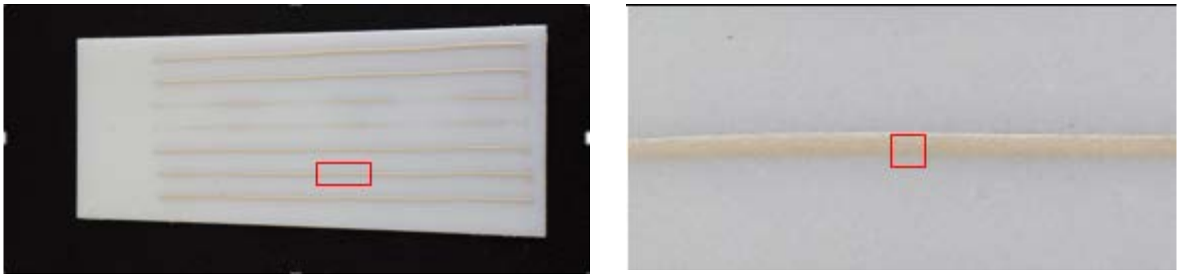


Figure 2: Demonstration of HIROX multi-focus 3D synthesis process (used under fair use, 2013[16]**)**

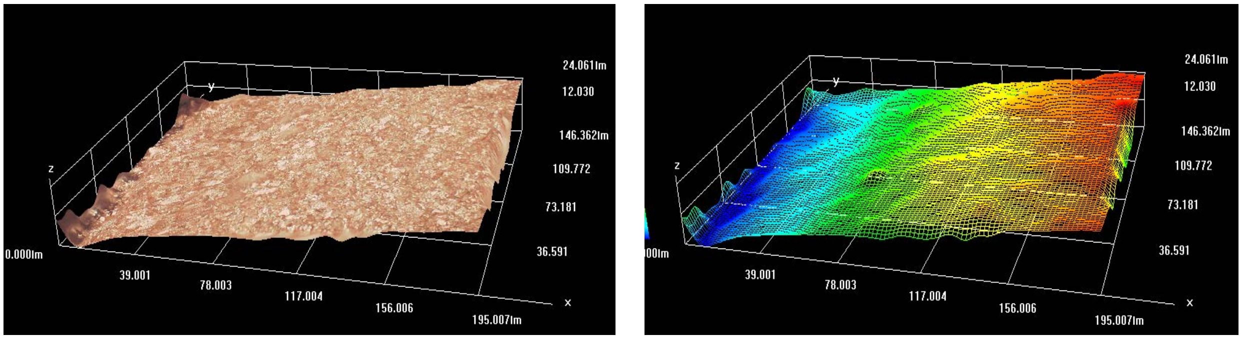
For this experiment, conductive traces were deposited on the surface of the PolyJet VeroWhite+ and TangoBlack+ substrates using the dispense parameters determined in Section 3.2: the dispense pressure was set to 31.03 kPa (4.5 psi) and the toolhead speed was 3000 mm/min using a 406 μm diameter dispensing tip. Once the traces were deposited, small sections were viewed under the microscope. A demonstration of where the microscope is focused is shown in Figure 3.



(a) (b)

Figure 3: Demonstration of sample profilometry location

In Figure 4, topographical data of only half the bead is visible because at the magnification necessary to gather 3-dimensional data from different focal planes the field of view is limited. However, it is assumed that the bead's profile is symmetric. Using the HIROX multifocal synthesis, a 3D model is constructed as shown in Figure 4.



(a) (b)

Figure 4: 3-dimensional model using HIROX multi focal synthesis with (a) actual image data overlaid and (b) a colored surface for indicating relative height.

4.3 Results

With five deposited traces for each material (TangoBlack+ and VeroWhite+), and sampling 5 maximum heights from each trace, a total of 50 height measurements are recorded. The maximum height of each deposited trace was analyzed for the different samples that underwent room temperature drying and heated drying on both TangoBlack+ and VeroWhite+ substrates. The recorded data is tabulated in Table 4. The data shows only a small difference in the observed average heights between those dried at room temperature and those accelerated with heat. On the samples without any sort of heat treatment, the heights averaged to be 27 and 36 μm on VeroWhite+ and TangoBlack+, respectively. With heat treatment, there was very little change. The average heights were 28 μm on VeroWhite+ and 38 μm on TangoBlack+.

Using a simple t-test, assuming a two-tailed distribution and an alpha of 0.05, a p-value of 0.583 was calculated; we therefore cannot conclude a significant difference in geometry between the drying methods on either TangoBlack+ or VeroWhite+. The accelerated drying conditions do not significantly affect the profile geometry of the conductive materials to the PolyJet substrate.

Table 4: Tabulated height data for samples (i) heated at 55 °C for 30 minutes and (ii) air-dried for 24 hours

Sample	Heat Treatment	Height [μm]		Average [μm]	Standard Dev. [μm]
		VeroWhite+	TangoBlack+		
1	Y	26.06	38.55	**VeroWhite+**	
2	Y	27.66	37.48	**27.513**	**0.919**
3	Y	28.39	37.86		
4	Y	26.94	37.32	**TangoBlack+**	
5	Y	28.51	37.36	**37.714**	**0.459**
6	N	26.17	35.45	**VeroWhite+**	
7	N	31.41	36.17	**26.758**	**2.548**
8	N	24.06	36.22		
9	N	27.14	35.93	**TangoBlack+**	
10	N	25.01	37.14	**36.182**	**0.551**

4.4 Discussion

This experiment shows that the heating process, which helps the ink dry faster, does not significantly impact the final geometry of the deposited features. There is no information from the supplier that indicates temperatures below the recommended curing temperature will have any positive impact on the final conductivity [3]. The heat applied is to reduce the drying time before printing can be resumed. The height of the traces after heating is also of interest because it can influence the decision to design channels for embedding the material into the printed part. Traces on VeroWhite+ are shorter than 32 μm, which is the layer height of the PolyJet process. Traces on TangoBlack+ are only 5 μm taller than the PolyJet layer height on average. Because of this, channels should be designed to be 32 μm deep as the PolyJet process would not be able to accommodate shallower features.

Reflecting on results shown in Section 3 regarding profile geometry, we also notice a difference in heights between the VeroWhite+ and TangoBlack+ features. Recalling the results from Experiment 1, we know that the features on TangoBlack+ are narrower. Therefore, from Equation 1, the height should also be taller. This relationship is confirmed by these results. Conductive features on TangoBlack+ are taller and narrower than those on VeroWhite+. This effect is possibly related to adhesion or surface interaction of the conductive materials to the PolyJet substrates and is explored in Section 5.

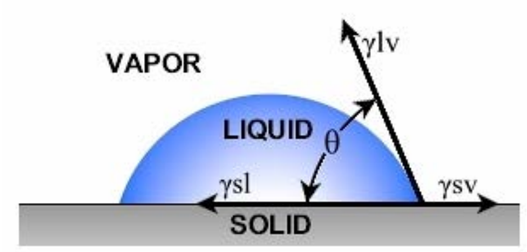
5 EFFECT OF POLYJET SUBSTRATE ON CONDUCTIVE INK ADHESION

As mentioned in Section 1, the embedding process prevents the servicing of integrated conductive traces after manufacture. An internal connection failure or physical break in the conductive trace could render the component nonfunctional. In order to ensure reliable connections, it is important to understand the adhesion characteristics between the conductive materials and the PolyJet substrates. When not bonded to a surface, the thin conductive traces are prone to breaks from movement or vibrations. However, when the conductive material is able to bond to a surface, the traces are constrained and less susceptible to breaks. Good bonding between the conductive material and PolyJet substrate creates stable traces and thus reliable connections. Poor bonding, results in suspended traces that are more susceptible to cracking and failure.

Material wetting is a fair indicator of inter-material adhesion [17]. Material wetting is defined as how well a liquid phase material contacts a solid surface on a molecular level and is a result of interaction of cohesive and adhesive forces. Young's equation (Equation 2) effectively models the scenario of a fluid droplet on a solid surface by relating solid-liquid free energy (γ_{sv}), solid-surface free energy (γ_{sl}), and liquid-surface free energy (γ_{lv}) to the droplet's contact angle.

Materials with contact angles below 90° are considered hydrophilic and exhibit a strong solid-liquid interaction. This interaction provides ample contact between the liquid and solid for adhesion. The experiments designed to measure the contact angle to determine if the conductive inks adhere well to the PolyJet substrates.

$$\gamma_{sv} = \gamma_{sl} + \gamma_{lv} \cos\theta \tag{2}$$



θ = Contact Angle

γ_{lv} = liquid-surface free energy

γ_{sl} = solid-surface free energy

γ_{sv} = solid-liquid free energy

Figure 5: Diagram of Young's equation variables

5.1 Method

Sample pieces of VeroWhite+ and TangoBlack+ substrates were printed and droplets of the conductive material were applied. The droplets were semi-manually applied to the substrate using a discrete 0.25-second extrusion dosage from the Nordson EFD pneumatic dispenser, as shown in Figure 6. In order to measure the contact angle, a digital microscope was positioned parallel to the adhesion surface and the sample was backlit in order to create a silhouetted droplet as shown in Figure 7F. Using the images captured by the microscope, the contact angle was digitally measured via ImageJ measuring software. A sample image is shown in Figure 8. Finally, transparent pressure-sensitive tape is applied and removed to the dried sample to see if any material is removed to test adhesion strength.

Figure 6: Droplets produced by 0.25 second dispensing pulses on VeroWhitePlus substrate

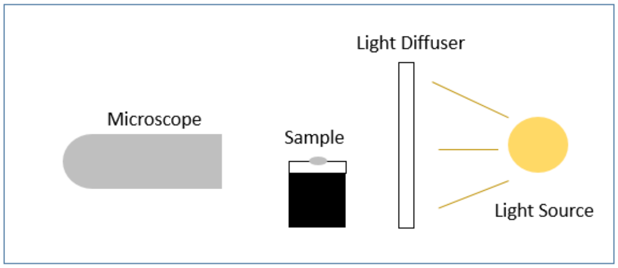


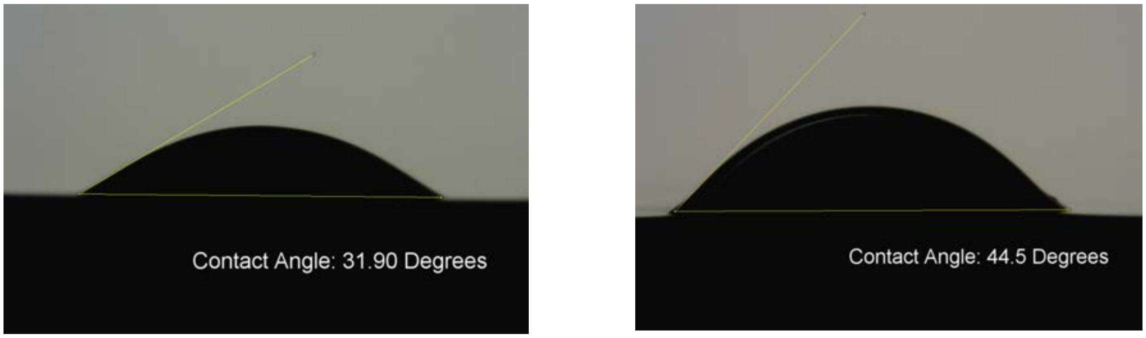
Figure 7: Contact angle measurement setup schematic

Figure 8: Example of ImageJ digital measuring process

5.2 Results

The resultant contact angle measurements are presented in Table 5. Droplets on the VeroWhite+ substrates had an average contact angle of 31.6 degrees with a standard deviation of 2.7 degrees. The TangoBlack+ samples had an average of 37.7 degrees with a standard deviation of 3.2 degrees. Both of these averages are well within the hydrophilic range and demonstrate good wettability and adhesion. Moreover, no material was removed from either substrate using the scotch tape test. When adhered and removed, no material was visibly resent on the surface of the tape.

As hypothesized from observations in Experiment 1, the conductive material on the TangoBlack+ surfaces averaged a larger contact angle, which would imply that the lines are thinner for a constant cross-sectional area. An example of the VeroWhite+ and TangoBlack+ profiles that demonstrate these differences are shown in Figure 9.



(a) VeroWhite+ (b) TangoBlack+

Figure 9: Comparison of contact angles on (a) VeroWhite and (b) TangoBlack substrates

Table 5: Contact angle measurements

	Contact Angle [°]	
	VeroWhite	**TangoBlack**
1	31.9	33.74
2	33.2	36.99
3	34.7	40.02
4	35.15	39.47
5	32.82	36.3
6	31.12	35.4
7	31.59	44.5
8	30.54	39.75
9	30.22	36.18
10	25.33	35.04
Average	**31.66**	**37.74**
Std. Dev.	**2.77**	**3.2**

5.3 Discussion

The contact angle results provide further insight into the results from Section 3 that demonstrated that features on TangoBlack+ are thinner than on VeroWhite+. Given that both average contact angles are well within the hydrophilic range, good adhesion is expected on both substrates, although adhesion to VeroWhite+ is relatively better (as per the smaller contact angle). Additionally, ink on both substrates passed the “scotch tape test.”

While using the HIROX digital video microscope during experiments conducted in Section 4, it was observed that the PolyJet material surfaces (both VeroWhite+ and TangoBlack+) had many small imperfections or divots on the surface, as shown in Figure 10. It is unclear what causes the small holes; it may be attributed to inkjet head misfires, imperfections in the roller, or adhesion to the roller. However, these holes may also play an important role in the conductive materials’ adhesion to the PolyJet surface on the macro scale by allowing the material to penetrate and gain more surface area for adhesion.

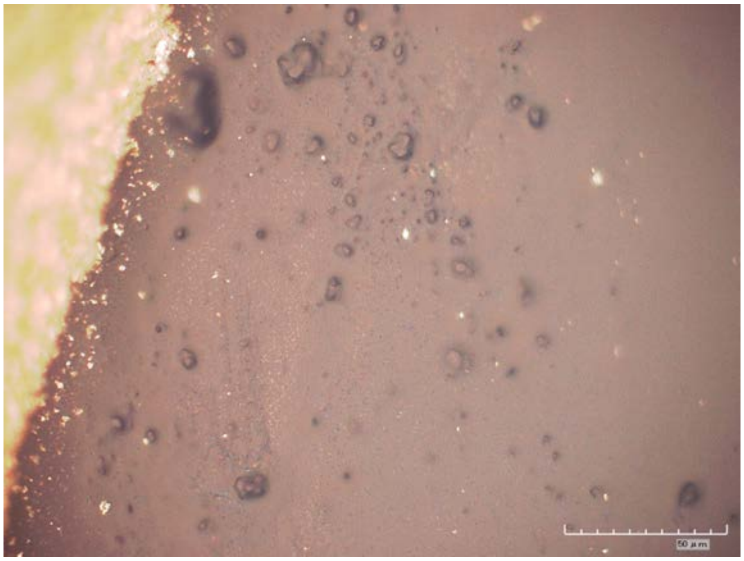


Figure 10: Microscope image of surface imperfections on TangoBlack+ substrates.

6 CLOSURE

With a goal of directly fabricating mechatronic products with integrated actuation and sensing, the authors are exploring the integration of extrusion-based DW with PolyJet material jetting AM. As discussed in Section 2, this goal has been achieved via the development of an extrusion-based DW system that can be placed directly into the PolyJet build tray to enable the deposition of conductive materials (DuPont 5021 silver-loaded conductive ink) directly onto in-situ 3D printed parts.

The goal of this paper is to gain an understanding of how process parameters affect material compatibility of the DW and PolyJet systems. Specifically, experiments were conducted to determine (i) how DW extrusion parameters (tool tip diameter, toolhead speed, and extrusion pressure) affect the deposited bead width on two PolyJet materials, (ii) how post-processing drying parameters affect the deposited bead height, and (iii) how the adhesion characteristics of the deposited material differ on two different PolyJet substrates. Regarding (i), it was found that increased pressure yields wider traces, increased toolhead speeds yield narrower traces, and deposited traces on TangoBlack+ are narrower than those by VeroWhite+ (Section 3). Regarding (ii), it was observed that the use of a heat gun does improve material drying times and does not affect the geometry of the trace profile (Section 4). Regarding (iii), it was discovered that the conductive material deposited onto the TangoBlack+ material had a larger contact angle than that deposited on the VeroWhite+ material, which explains the thinner traces. Furthermore, contact angles of deposits on both substrates were well within the hydrophilic range, which suggests good adhesion (Section 5). These results provide detailed characterization of the profiles of the deposited conductive ink, which can to design channels into the PolyJet part for full encapsulation of a deposited conductive trace. Future work will focus on exploring (i) how conductivity changes as a function of temperature in the drying process and, (ii) how conductivity is affected by full encapsulation.

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