Integration & Process Planning for Combined Ultrasonic Consolidation and Direct Write

Authors: Ludwing A. Hernandez, Brent Stucker: Utah State University.

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Abstract

A research project is underway to integrate an nScrypt Smart Pump™ 100 direct write nozzle with a Solidica Formation™ ultrasonic consolidation machine to rapidly fabricate parts with novel multi-functional features. The process of integration of both machines has been addressed, and an appropriate process planning sequence to exploit the capabilities of the integrated technologies is developed. General processing guidelines are formulated, and form the basis for further fundamental research and for the production of proof of concept multi-functional parts to demonstrate the usefulness of this integration.

1 Introduction

In the modern world customers are everyday more demanding. They want cheaper products; with better quality, smaller lead times, and that are more compact, among other characteristics. More recently customers also desire some degree of customization. Additive manufacturing (AM) techniques might be the solution to help meet and exceed the requirements of the modern world customer. Using additive manufacturing we are able to create complex shapes that in the past were not possible to be fabricated by traditional manufacturing processes. Products can be made more compact and consolidation of parts is possible, thus reducing or eliminating assembly processes. As a result we are able to obtain reductions in cost, size, and mass on products manufactured by Additive Manufacturing. Ultrasonic Consolidation (UC) and Direct Write (DW) are two types of additive manufacturing technologies that when combined can be effectively used to fabricate integrated structures.

This paper explains how UC and DW technologies were physically integrated to work as a semi-automated single system for the first time and the current process planning sequence to follow for the safe and effective fabrication of structures using the integrated system. The fabrication possibilities that arise from this integration are useful in varied fields, such as electronics manufacturing, aerospace, automotive, and any industry that demands more compact and lighter parts.

Ultrasonic Consolidation (UC)

Ultrasonic consolidation (UC) is an additive manufacturing process that creates complex-shaped three dimensional metallic objects by combining the deposition of metal foils layer by layer, bonded by ultrasonic welding, with the operation of a CNC milling machine to create the desired cross-section [1].

UC is a process developed by Solidica Inc., using the basics of ultrasonic welding. For this project we are using the Solidica Formation™ machine at Utah State University (see figure 1).

Figure 1: Solidica Formation™ located at Utah State University [2].

The build process of the UC machine has the following sequence. First, the toolpaths file has to be loaded into the machine control PC. A metallic substrate (usually of the same material that is being deposited) is firmly bolted to the building chamber platform. When the build is triggered to start by means of the software, an automatic feeding system starts depositing the metallic foils on to the substrate and uses a sonotrode to induce normal force and vibration between the substrate or previously deposited layers and the new foil being deposited. The vibration induced modifies both surfaces by displacing surface oxides between the interfaces as a result of elastic-plastic deformation. Oxide-free regions are then in close-proximity, resulting in metallurgical bonding across the interface. After bonding one or several layers, the computer controlled milling head shapes the contour of the layer. This process is repeated until the finished part is obtained [1].

The UC process can weld with excellent bonding quality if the correct process parameters, oscillation amplitude, welding speed, temperature, and normal force, are used. The ability to build at a low temperature (150ºC or less) and ambient atmosphere are key process characteristics that make this technology ideal for electronics embedding [1]. Moreover, the system has the ability to be paused and restarted at any stage of the build without affecting the quality of the part. All the mentioned attributes of the UC process are very convenient for integration with DW in a single apparatus [2].

Direct write (DW)

Direct writing signifies a group of processes used to precisely deposit functional and/or structural materials on to a substrate in digitally preset locations, without the use of masks or geometry-specific tooling. Using DW technologies a wide range of materials can be deposited including metals, ceramics, polymers, electronically and optically functional materials, and biological materials including living cells. One of the characteristics that define DW is the small size of deposits, in terms of line width, ranging from sub-microns to millimeters. DW traces can be dispensed on virtually any substrate. Some systems can be equipped with a laser positioning feedback system, enabling it to dispense on flat, curvilinear, round, flexible, irregular or inflatable substrates [3].

According to Hon [3] the group of processes that constitutes DW can be classified into 4 categories: droplet, energy beam, flow and tip; depending on the method of material transfer on to a substrate. Droplet based can be obtained by thermal, piezoelectric, electrostatic, acoustic techniques or aerosol. Energy beam-based DW means that the deposition is accomplished by means of laser or ion beams. Flow-based DW use high precision pumps or extrusion to achieve micro-dispensing. Tip-based DW is a method for nano-manufacturing that employs dip-pen lithography to diffuse on to a substrate through micro-capillary action between the tip and the surface [3].

For this project the DW dispensing method utilized is the precision pump flow-based DW rendered by the Smart Pump 100™ developed by nScrypt Inc. The Smart Pump 100™ is a high precision micro-dispensing pump with accurately controlled air pressure timing, valve opening and dispensing with an integral suction function to remove all residual materials sticking on the tip; preparing it to continue the next dispensing without the need for cleaning [3].

The Smart Pump 100™ system includes a positive pressure pump with a computer controlled needle valve (see figure 2) attached to a control box that receives the digital signals from a computer and sends it to the pump to execute the preprogrammed routines [4].

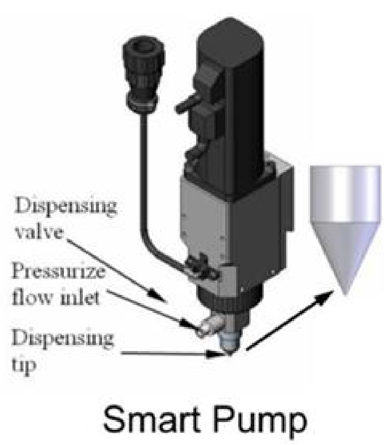


Figure 2 : Schematic of the nScrypt Smart Pump™ Direct-write system [4].

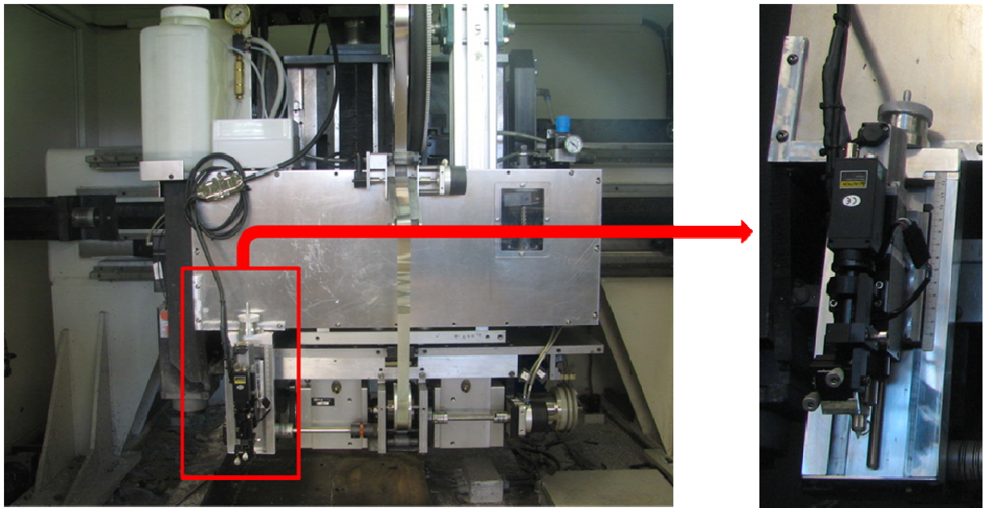
2 Experimental Work

The plan is to physically and electronically integrate the Smart Pump^{TM} Direct write system developed by nScrypt Inc. to the Solidica Formation^{TM} Ultrasonic Consolidation machine to make them work in a semi-automatic fashion. In this paper we address how the physical-electronic integration was done and the process plan to work with both machines simultaneously. Furthermore, details for the near future experimentation to develop design guidelines and proof of concept are exposed.

3 Results

3.1 Integration Process Description

To operate the Smart Pump^{TM} the system needs three basic parts: a pump, a nozzle, and a motion control system. On the other hand the Solidica Formation^{TM} machines consist of a sonotrode, a milling head and a foil feeding system mounted on a computer controlled 3-axis motion control system. The compact design and low weight (2.5lb) of the smart pump permitted it to be attached to the motion control system of the UC machine. Available locations for the DW head were evaluated to determine the best place to install the Smart Pump to the motion control system; taking into consideration user accessibility and jamming precautions for the 3-axes of motion. (see figure 3)



Ultrasonic Consolidation + Direct Write system   Smart Pump 100™

Figure 3: nScrypt Smart Pump™ Direct-write and Solidica Formation™ Ultrasonic Consolidation integration.

When the direct write system is actively dispensing it needs to be very close to the substrate (about 100µm), thus it has to be positioned at the lowest point with respect to all the other parts on the Sonotrode head. Nonetheless, to attach the Smart Pump in one fixed position the tip of the pump has to be lower than the sonotrode head but higher than the smallest tool used on the milling machine. Although it was possible to use a fixed point, the clearance was so small it constituted a hazard for the equipment. The solution was to incorporate a manual precision slider (see figure 4) to make it possible for the DW head to be in different positions (while at rest or in use). The slider has a high precision lead screw with an accuracy of 0.0015”/10” or 0.033mm/20cm or better. In addition the slider features a graduated knob with 100 divisions. One complete turn of the knob moves the slider platform 1mm, meaning that each visual division represents 0.01mm (10µm) [5] (see figure 5)

Figure 4: Velmex A40 Series UniSlide Assembly with Graduated Knob [5].

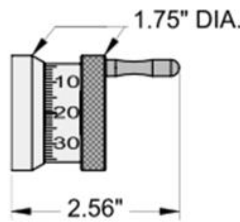


Figure 5: Velmex Graduated Knob [5].

For the physical integration some custom parts were fabricated from aluminum 3003. A custom aluminum bar was machined (see figure 6) to firmly attach the slider and Smart Pump to the UC motion control system. A small rectangular base (see figure 7) was used between the Smart Pump mounting bracket and the slider platform to avoid drilling additional holes in the slider's stainless steel platform.

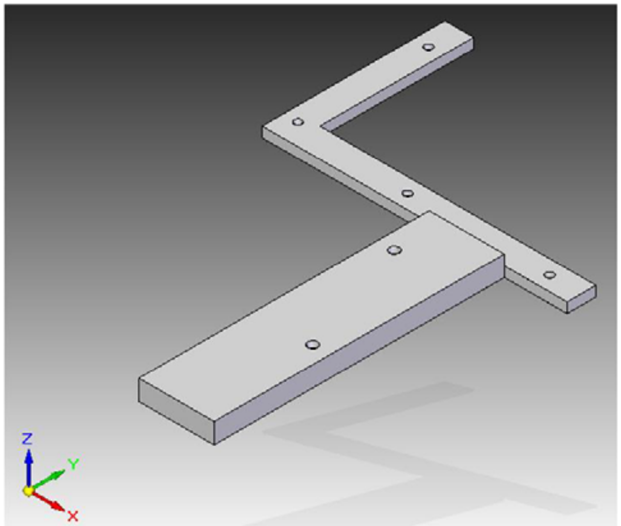


Figure 6: Custom base for Smart Pump and slider attachment to motion control system.

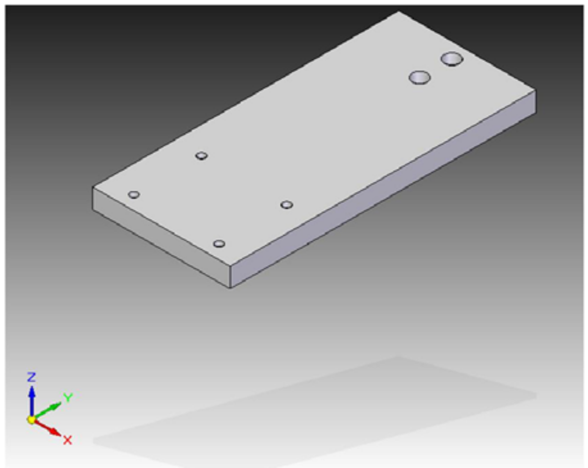


Figure 7: Rectangular base for Smart Pump attachment to slider.

To reduce vibration of the Smart Pump during stage motion, a screw was used to maintain a fixed distance between the slider and one of the sonotrode motor side walls (see figures 8 and 9). This screw held the Smart Pump at 90 degree from the X,Y plane.

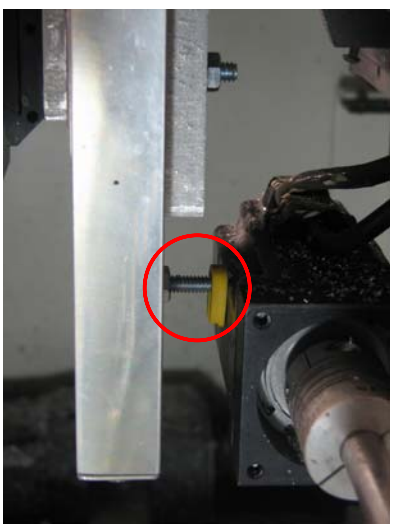


Figure 8: Side view of vibration reducer.

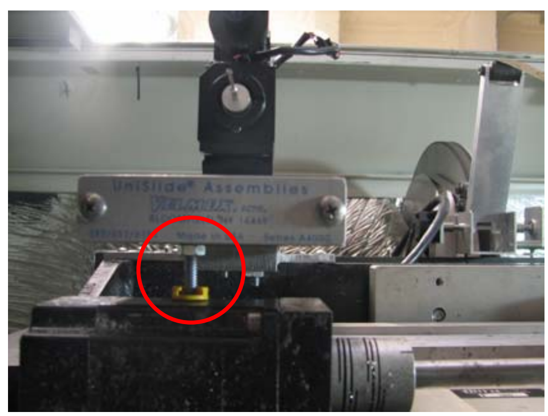


Figure 9: Bottom view of vibration reducer.

The Smart Pump control box (called the Solo control box by nScrypt) was also bolted to the inner right side of the UC machine enclosure (see figure 10).

In addition to the physical integration we were able to integrate the DW and UC systems electronically, enabling both technologies to work in a semi-automatic fashion for the first time. A junction box (J-box) containing a smart relay (see figure 10) enables digital signal communication between the DW control box and the UC controller.

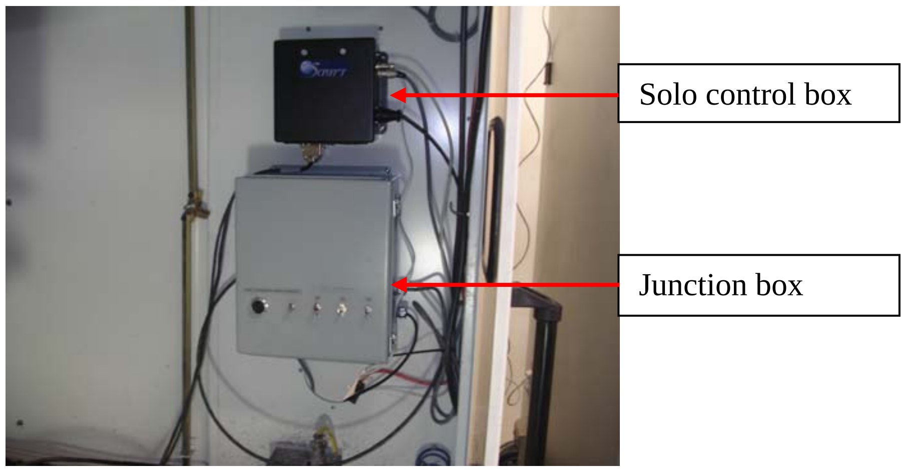


Figure 10: nScrypt "Solo control box" and Junction box.

The main purpose of the J-box is to trigger the dispenser and the motion control system movement simultaneously by the push of a button. The Cycle Start button on the front panel of the Solidica control box (see figure 11) was connected to the J-box circuit to work as the trigger button for both systems.

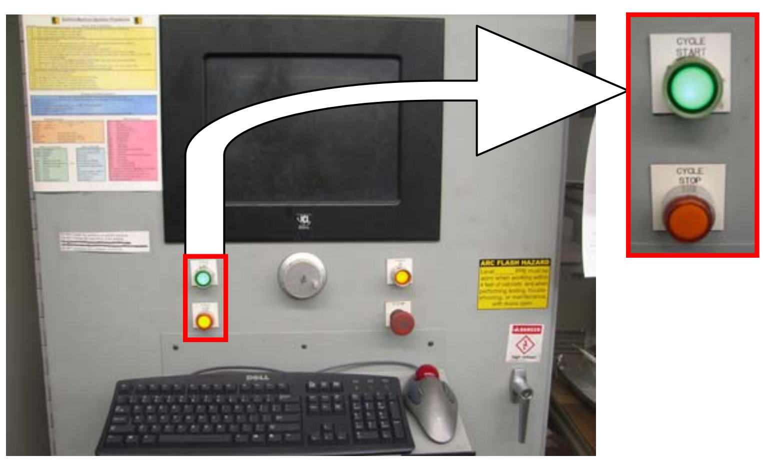


Figure 11: Solidica Formation™ control box front panel.

4 Discussion

4.1 Process Planning Sequence

The following flow chart describes the basic process planning sequence. (see figure 12).

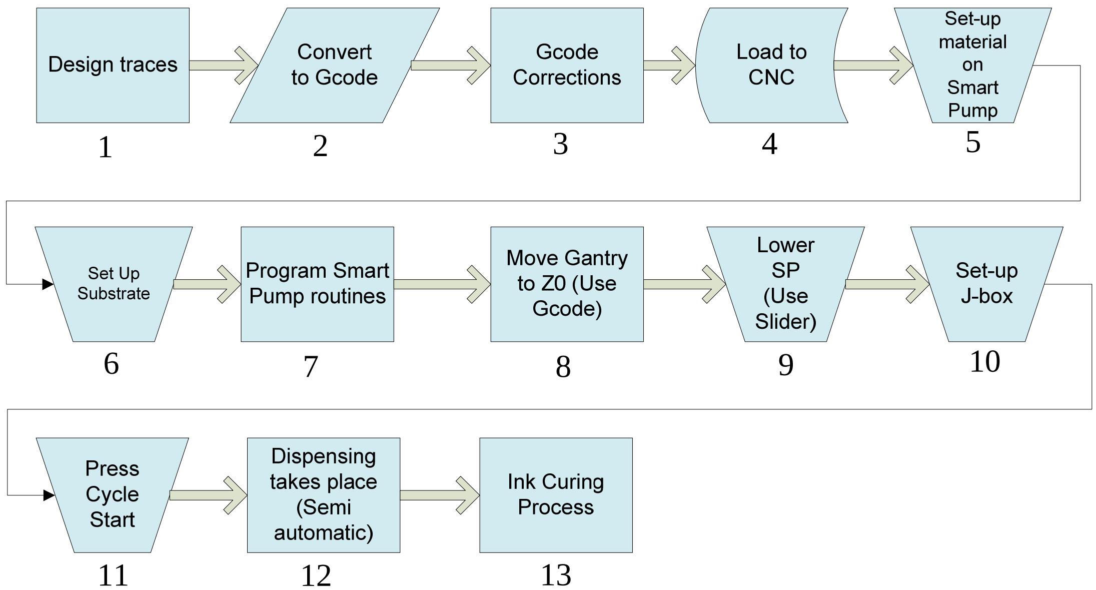


Figure 12: UC-DW process flow chart.

Each step is explained in detail below.

The traces to be dispensed can be designed as sketches in any 2D CAD software (1) and then converted to Gcode with a CAM application or Gcode converter (2). For our purposes we have found good results using AutoCAD 2010 to design the 2D traces and a software called "Image to Gcode" to convert ".dxf" files to Gcode. The Gcode must be modified to make it suitable for our purposes (3). Some possible modifications needed are the following: delete the tool spindle on and off commands (M3, M5), establish the coordinate system to work with (i.e. G54), and add program stops (M0) right before and after each trace movement. The M0's are later used during the building process to start and stop dispensing by manually pressing the Cycle Start (CS) button. The next step is to load and activate the modified Gcode as a ".ppg" file in Solidica's programs data base and activate it on the software (4); the motion control system is now ready start a build.

The Smart Pump is now set up with material for dispensing (5). The Smart Pump set up process starts with the ink to be dispensed being loaded into a 3cc syringe. A digitally controlled air pressure outlet from the smart pump's control box is attached to the syringe. Set up of the substrate where the inks are to be dispensed occurs at the same time (6). This system can dispense on virtually any substrate the only requirement is flatness. The substrate is firmly secured to the building platform to prevent movements that would affect the quality of the build.

Continuing with the Smart Pump set up, the dispensing routines are programmed through the Smart Pump's "Solo Control Center" software (7). The parameters are defined according to the material's rheological properties. The DW system has an integrated camera zoomed into the pen tip for better set-up purposes. In the software (see figure 13), the routines are configured to precisely open and close the dispensing valve by setting up the pressure and position of the valve according to the viscosity of the material.

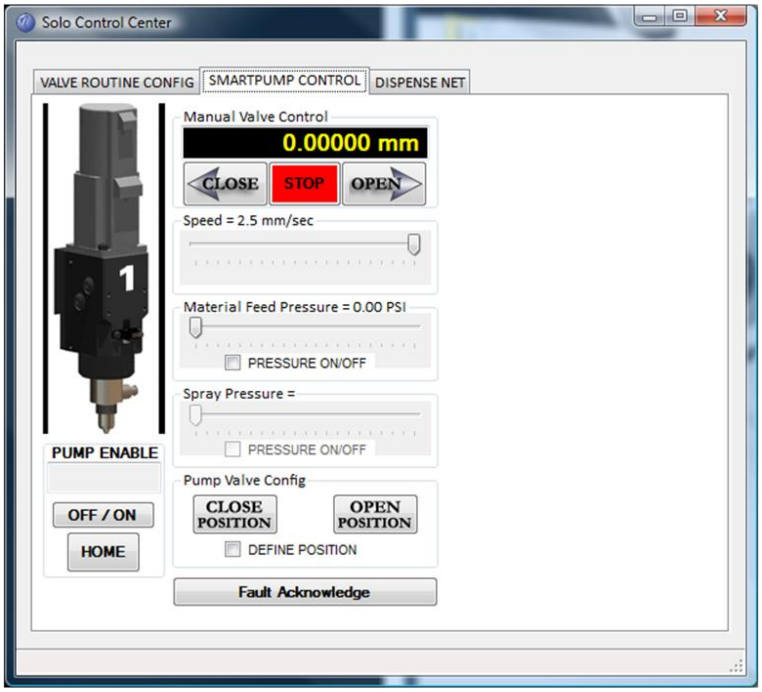


Figure 13: Solo Control Center: Tab used to set up the dispensing flow rate.

The next step is to lower the stages to the lowest point programmed on the Gcode (ideally Z0) (8). Using the manual slider the Smart Pump is lowered very close to the substrate (100 to 150µm) (9).

After the Smart Pump is ready, the J-box is set up (10). The J-box transmits the digital commands between the Smart Pump and the motion control system. (see figure 14)

Figure 14: Junction Box front panel.

The J-box triggers the Smart Pump commands by pushing the black button on the J-box or by pushing the Cycle Start green button on the front panel of the Solidica control box. Furthermore, the J-box has an on/off switch to power up the circuitry and three other switches (B2, B2, B0) that are used to manually select the bits to trigger each routine to the Smart Pump with the parameters previously inputted in the Solo Control Center software.

ROUTINE SELECT			
B2	**B1**	**B0**	
0	0	0	Routine 1
0	0	1	Routine 2
0	1	0	Routine 3
0	1	1	Routine 4
1	0	0	Routine 5
1	0	1	Routine 6
1	1	0	Routine 7

Once the Gcode program is loaded into the Solidica system, the Smart Pump is set up close to the substrate, and the J-box is prepared the cycle start button is pressed (11) and dispensing is started. (see figure 15)

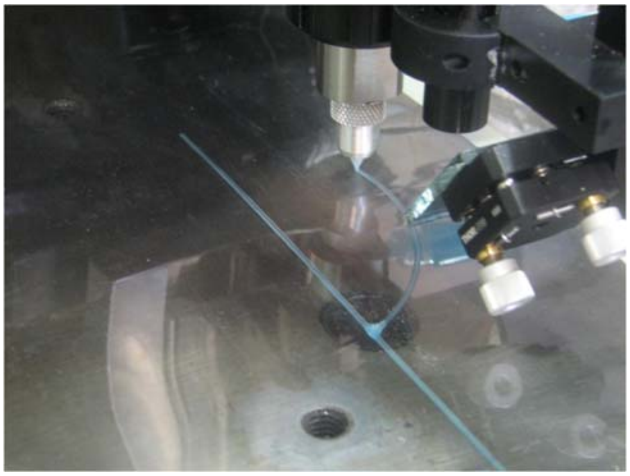


Figure 15: UC-DW integrated system dispensing onto a plastic substrate.

As mentioned before this process is semi-automatic (12), meaning that it needs some degree of human intervention to carry it out. While dispensing, this system needs a operator present, whose job is to select the correct routine (i.e; routine 1 (valve close) and routine 2 (valve open)) on the J-box considering whether the stages are doing a trace movement or just moving between traces. The B2, B1, B0 switches on the J-box must be manually moved to the desired position for dispensing to start or stop before the motion control system reaches a pre-established program stop (M0). When an M0 is reached the operator must push the cycle start and the build will continue. In this way the Smart Pump will only dispense were needed for the build to be completed.

The inks or pastes dispensed through the Smart Pump usually need post-processing or curing (13). Curing process experiments have not yet been carried out, but the plans are to test the post-cured materials properties after using the substrate heating feature of the UC machine versus curing them in a furnace.

4.2 Future experiments to formulate general design guidelines

The first set of experiments to be performed with the UC-DW integrated system are basic research experimentation to develop general knowledge about the system's capabilities for the effective fabrication of structures.

A project is underway to formulate design guidelines, focusing on electronics fabrication. Conductive, insulator, dielectric, and resistor inks properties are going to be tested when dispensed onto aluminum 3003 and the post-cured adhesion will be evaluated as well.

The substrate heating feature of the UC machine is going to be tested as curing method for the DW materials and compared to the regular furnace curing process. Traces resistance to ultrasonic welding will be evaluated and the best orientation with respect to the sonotrode's movement will be determined. Parallel experimentation will be performed using small channels on the substrate to deposit the DW materials.

A second set of experiments will be performed to fabricate discrete electronic elements (resistors and capacitors) using the DW system; thus embedding them into an aluminum enclosure. The final objective of this project is to fabricate a proof of concept using the design guidelines previously learned.

The following are the posted design questions and tasks to be performed. (See table 1)

Objective	Design Questions	Tasks
Develop design guidelines for the effective fabrication of structures.	a) Can DW traces be dispensed directly on aluminum and maintain the same material properties? b) Is an insulator always needed between DW traces and the aluminum enclosure?	a) Dispense a trace of each material to be used in a non-conductive substrate and dispense it on the aluminum substrate and perform different tests according to the material; electrical conductivity for conductive inks, resistance for resistor inks, and dielectric constant for dielectric inks. Then evaluate and compare. b) Different substrates will be tested for conductive DW traces (Insulators, Dielectric)
	Do the DW traces adhere to aluminum 3003?	Dispense the available inks in an aluminum substrate, go through the curing process and then do pilling tests to evaluate the adhesion of the cured inks to the aluminum substrate.
	Can the DW ink traces cure by heating the aluminum substrate?	Compare the properties of each ink when cured in an oven versus when cured using the substrate heating system available on the UC machine.
	a) Can aluminum foils be ultrasonic welded directly on top of DW traces? b) Are channels or pockets needed on the aluminum substrate to protect the DW traces?	a) Build test specimens to determine the optimal positioning of direct write traces with respect to the movement of the sonotrode. - Specimens will be build in 3 orientations (Horizontal, vertical, and diagonal) - Specimens will be build in 3 different sizes b) The inks are going to be deposited in small channels. Seep test are going to be performed.
	Can passive components such as resistors and capacitors fabricated by DW be embedded within a UC structure?	Fabricate *discrete electronic elements* by dispensing conductive and dielectric inks through the Smart Pump to demonstrate the possibility of embedding those elements into the structure. (Embedded resistors and capacitors)
	Can DW write traces be used as support material for UC?	Build test specimens using the DW system as a support material dispenser for small overhanging features.
	Can a UC structure with embedded DW circuitry be fabricated in an effective manner?	Design a proof of concept part using a UC metallic enclosure, FDM material as dielectric substrate and support material, as well as DW to interconnect embedded components and support material for small features - Test ABS dielectric properties - Tensile testing with cured DW ink - Seep testing of DW ink - Fabricate the enclosure to demonstrate the proof of concept

Table 1: Design questions and tasks for future experiments.

5 Conclusions

An integrated Ultrasonic Consolidation–Direct write (UC-DW) apparatus has been put in place for the first time. It works in a semi-automatic fashion to dispense a 2D trace with virtually any ink or paste onto any flat substrate at room temperature and normal ambient conditions. This integration constitutes a step towards fully automated additive manufacturing of functional products with metallic enclosures and embedded electronic circuitry. Future work includes: the automation of the system by modifying the PLC of the UC machine to include new codes for the Smart Pump; performing experiments to develop design guidelines for components made using the integrated system and the fabrication of proof of concept parts to demonstrate the capabilities of the system.

6 Acknowledgements

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7 References

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