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Integration of Ultrasonic Consolidation and Direct-Write to Fabricate an Embedded Electrical System Within a Metallic Enclosure

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INTEGRATION OF ULTRASONIC CONSOLIDATION AND DIRECT-WRITE TO FABRICATE AN EMBEDDED ELECTRICAL SYSTEM WITHIN A METALLIC ENCLOSURE

by

Ludwing A. Hernandez

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Mechanical Engineering

Approved:

Dr. Brent E. Stucker Major Professor	Dr. Stephen A. Whitmore Committee Member
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ABSTRACT

Integration of Ultrasonic Consolidation and Direct-Write to Fabricate an Embedded Electrical System Within a Metallic Enclosure

by

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Utah State University, 2010

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Department: Mechanical and Aerospace Engineering

A research project was undertaken to integrate Ultrasonic Consolitation (UC) and Direct-Write (DW) technologies into a single apparatus to fabricate embedded electrical systems within an ultrasonically consolidated metallic enclosure. Process and design guidelines were developed after performing fundamental research on the operational capabilities of the implemented system. In order to develop such guidelines, numerous tests were performed on both UC and DW. The results from those tests, as well as the design and process guidelines for the fabrication of an embedded touch switch, can be used as a base for future research and experimentation on the UC-DW apparatus. The successful fabrication of an embedded touch switch proves the validity of the described design and process parameters and demonstrates the usefulness of this integration.

(127 pages)

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Doing this research has given me a new perspective of life, making me a more mature professional in the world of engineering and leaving me what I consider a very important teaching for the rest of my life: how to do good research.

Ludwing A. Hernández Andino

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ACRONYMS

3DP	3-Dimensional Printing systems
AM	Additive Manufacturing
CAD	Computer Assisted Design
CNC	Computer Numeric Controlled
COTS	Commercial Off-the-Shelf
DW	Direct Write
ECLD	Electrochemical Liquid Deposition
FBG	Fiber Bragg Grating
FDM	Fused Deposition Modeling
FGM	Functional Graded Materials
FIB	Focused Ion Beam
IC	Integrated Circuits
LCVD	Laser Chemical Vapor Deposition
LED	Light Emitting Diodes
LENS	Laser Engineered Net Shaping
LM	Layered Manufacturing
LPG	Laser Particle Guidance
LS	Laser Sintering
M3D	Maskless Mesoscale Material Deposition
MAPLE	Matrix-Assisted Pulsed-Laser Evaporation
MEMS	Micro-Electronics Mechanical System
NSF	National Science Foundation
OD	Outer Diameter

PET	Polyethylene Terephthalate
PLC	Programmable Logic Controller
PLS	Plasma Spray
RM	Rapid Manufacturing
RP	Rapid Prototyping
SFF	Solid Free-Form Fabrication
SL	Stereo-Lithography
SLA	Stereolithograhy Aparatus
SLS	Selective Laser Sintering
SMD	Surface Mount Devices

CHAPTER 1

INTRODUCTION

Additive Manufacturing (AM) processes (also known as Rapid prototyping (RP) processes) have been widely investigated as a generic manufacturing approach for quickly building arbitrarily complex shapes. In general, AM processes in use today begin decomposing a 3D CAD model of an object into cross-sectional layers, followed by the use of additive manufacturing techniques to physically build up parts in a layer by layer fashion, using the sliced-object model.

Potential benefits of AM include the capability to build multi-material, functionally-graded, and embedded structures. In that sense, Embedded Structures are structures which contain any functional component enclosed within the part resulting in functional "smart" parts having other components/features (sensors, electronics, mechanisms, actuators, devices, etc.) embedded within its structure.

There are many situations in which the integration of embedded components in parts can be helpful. Indeed, sensors, actuators, and electronic devices are just some examples where embedded structures can be a feasible solution for specific applications. Through the use of additive manufacturing techniques enclosed structures can be assembled that would not be possible to build using traditional methods or would use a greater number of parts.

1.1 Background

1.1.1 Additive Manufacturing

Rapid prototyping (RP), rapid manufacturing (RM), layered manufacturing (LM), and solid free-form fabrication (SFF) are all names given to the evolution of the now mature

Additive manufacturing (AM) technologies. More recently, many of these technologies are used to produce parts for the final consumer, contrary to RP that had only design purposes.

In the late 1960s, Herbert Voelcker—then an engineering professor at the University of Rochester—asked himself how to do "interesting things" with the automatic, computer-controlled machine tools that were just beginning to appear on factory floors. With funding from the National Science Foundation (NSF), Voelcker first developed the basic mathematical tools needed to unambiguously describe three-dimensional parts. Thus, a computer-controlled machine tool would cut away at a hunk of metal until what remained was the required part.

In 1968 Charles Hull patented a process he coined “Stereolithograhy” (SLA) for automated manufacture of plastic 3D objects directly from CAD models by adding material layer-by-layer using an ultraviolet laser and photo-curable liquid polymers.

Similarly, in 1987, University of Texas researcher Carl Deckard came up with the idea of building up parts layer by layer using a laser and powders. Deckard took his idea to NSF, which gave him support to pursue what he called "selective laser sintering." Deckard's initial results were promising and in the late 1980s his team was awarded one of NSF's first Strategic Manufacturing (STRATMAN) awards [1]. The result of Voelcker's, Deckard's, and Hull’s efforts helped launch the additive manufacturing industry, which has revolutionized how products are designed and manufactured.

The similarity of a prototype to the “real product” is determined by its form, fit and function. Advantages of creating prototypes are that they (1) improve the ability to visualize the part geometry, due to its physical existence, (2) enables earlier detection and reduction of design errors, and (3) increases the capability to compute mass properties of components and assemblies. Preparing prototypes will help you describe your product more effectively with your team and customers contributing to the elimination of waste and costly late design changes [2].

In the last decades globalization has made the world a more competitive environment, especially in the industrial market. The bar has been raised for all companies that offer any product or service. Customers now require products with better quality, at lower prices and decreased lead times. Rapid prototyping, now known as additive manufacturing, arose as a tool for designers and developers to reduce their product design cycle; as a result, launching products faster and cheaper. Objects that have traditionally been impossible to build because of the complex shapes or variety in materials can now be built by additive manufacturing [3]. The general approach for additive manufacturing is presented in the following schematic (see Figure 1.1).

First a solid model is designed in a conventional CAD system; it is usually saved in the STL file format for it to be processed by the AM process planner, which inputs the data to the automated AM machine for it to build the physical object layer by layer.

Additive manufacturing technologies are often labeled as non-traditional processes because they use techniques not commonly used previously to fabricate parts. Some of the existing additive manufacturing processes and techniques are mentioned below (see Table 1.1).

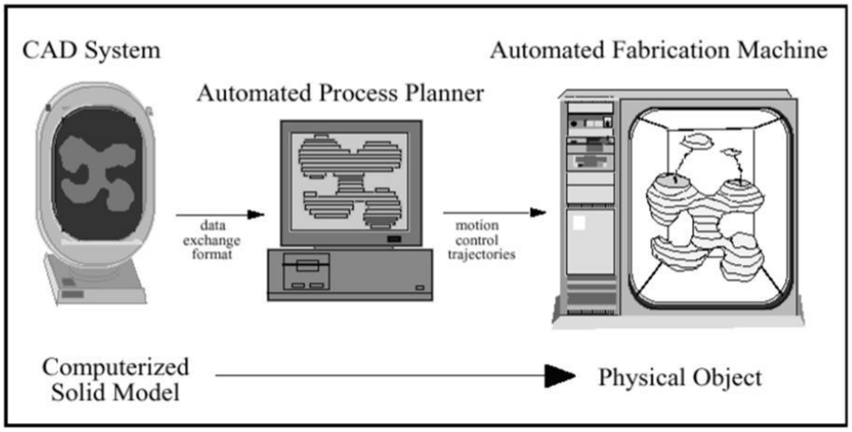

Figure 1.1: Additive manufacturing general approach [3].

Some of the most important technologies due to their market presence are: 3D printing systems (3DP), Selective Laser Sintering (SLS) of metals and plastics, Stereo-lithography (SL), and Fused Deposition Modeling (FDM) [4].

Currently additive manufacturing is being used widely in industry. The *2008 Wohlers Report* identifies three segments that make up the largest use of AM technology. The biggest is consumer products and electronics, including toys, cell phones, and televisions; followed by motor vehicles—cars, pickups, and motorcycles; and then by medical and dental devices.

The biggest is consumer products and electronics, including toys, cell phones, and televisions; followed by motor vehicles—cars, pickups, and motorcycles; and then by medical and dental devices. Examples of companies actively using additive manufacturing technologies include PET bottle consultant Plastic Technologies, Inc. in Holland, Ohio, which has been utilizing SLA for two and a half years to create a gripping chuck for its hand-held TorqTraQ torque-testing device (which measures the torque needed to twist off a bottle cap) [5].

Table 1.1: Additive Manufacturing Processes [3]

Category	Rapid Prototyping System	Manufacturer
Liquid-Based Systems	Strereo-lithography Aparatus (SLA)	3D System
	Solid Creation System (SCS)	D-MEC
	Solid Object UV laser plotter	CMET
	Stereos System	EOS
	Rapid Prototyping System	Meiko
Solid-Based Systems	Fused Depostion Modeling (FDM)	Stratasys
	Laminated Object Modeling (LOM)	Helisys
	ModelMaker-6B	Solidscape, Inc.
	Multijet Modeling (MJM)	3D System
	Selective Adhesive and hot pass (SAHP)	Kira
	Rapid Prototyping System	IBM
	Laser-engineered Net Shaping (LENS)	Optomec
	Ultrasonic Consolidation	Solidica
Powder-Based Systems	Selective Laser Sintering (SLS)	3D System
	Direct Shell Production Casting (DSPC)	Soligen
	Multiphase Jet Solidification (MJS)	Fraunhofer
	3D Printing (3DP)	MIT
	Laser Sintering	EOS

Other established companies that use additive manufacturing as their primary production process are Invisalign, which is a corrective technique used by dentists and orthodontists, which won the 2001 Stereolithography Excellence Award [6]. They use Stereolithography to build custom retainers for persons to correct tooth alignment problems. Another AM based company is Freedom of Creation, a design company founded by designer, Janne Kyttänen, in Helsinki, Finland. Freedom of Creation uses Selective Laser Sintering (SLS) and other AM technology to produce truly unique lighting shades and other products. This company is a model for localized manufacturing and distribution logistics, where no stock, no assembly, minimal transportation and just-in-time production are future goals [7].

1.1.2 Ultrasonic Consolidation

Ultrasonic welding is a solid-state joining process producing a bond by local high-frequency vibration, coupled with normal compression of the parts for a short time period [8]. Typically ultrasonic welding equipment converts 50/60 Hz current to 15, 20, 30, or 40 kHz electrical energy through a solid-state power supply. This high frequency electrical energy is supplied to the converter that transforms it to mechanical motion at ultrasonic frequencies. The mechanical motion is then transmitted through an amplitude-modifying booster to the horn. The horn, an acoustic tool, transfers this vibratory energy directly to the parts being assembled. The main components of an ultrasonic system are the power supply, converter/booster/horn stack, part fixture, and a means of providing horn contact with the parts; usually an actuator (see Figure 1.2) [9].

Ultrasonic consolidation (UC) is a novel additive manufacturing process developed for fabrication of metallic parts from foils.

The process uses a high frequency ultrasonic energy source to induce combined static and oscillating shear forces within metal foils to produce solid-state bonds and build up a near-net shape part, which is then machined to its final dimensions using an integrated, three-axis CNC milling machine (see Figure 1.3) [10]. UC combines the advantages of additive and subtractive fabrication approaches allowing complex parts to be formed with high-dimensional accuracy and surface finish, including objects with complex internal passageways, objects made up of multiple materials, and objects integrated with wiring, fiber optics, sensors, and instruments.

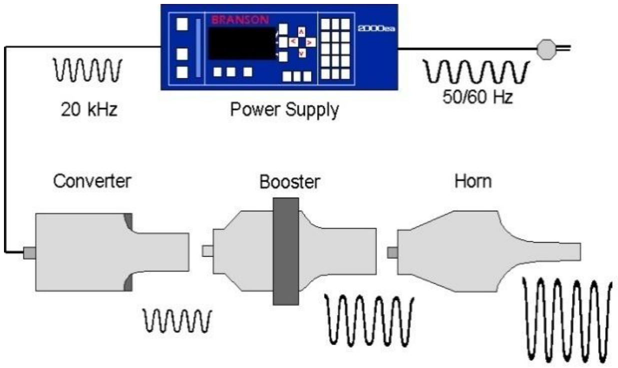

Figure 1.2: Schematic of the basic functional components in an ultrasonic welding apparatus [9].

Since, the process does not involve melting; one need not worry about dimensional errors due to shrinkage, residual stresses and distortion that are typically caused by high-temperature processing [11].

The main advantages of UC are that it does not need an enclosed inert atmosphere building chamber and/or very high temperatures in order to build when compared to other metal additive manufacturing processes [12]. The UC process can be performed at various temperatures ranging from room temperature (72^{O}F/22^{O}C) to 400^{O}F (204^{O}C). Generally a temperature of 300^{O}F (150^{O}C) is used to build, which is a relatively low temperature compared to other metal SFF processes. The ultrasonic welding produces localized heat at the welding spot but it usually does not rise higher than 50% of the melting temperature of the base metal [14]. Furthermore, since the UC bonding process takes place in the solid state; residual stresses, dimensional changes, and other metallurgical incompatibilities are not generated. This is different than other SFF processes that are phase transformation (solid-liquid-gas) based [15]. As a result, UC is one of the most suitable available technologies for structure embedding (see Figure 1.4).

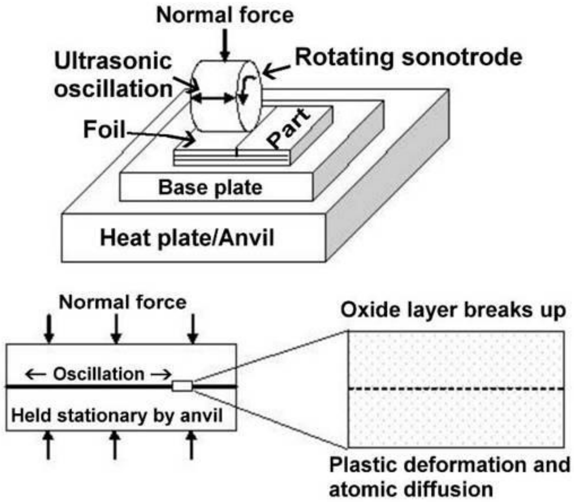

Figure 1.3: Schematic of UC process [13].

1.1.3 Direct Write Technologies

The term "Direct Write" (DW) refers to any kind of technology that dispenses or deposits different type of materials over various surfaces following a computer-generated pattern without any tooling or masks.

Figure 1.4: Solidica Formation™ located at Utah State University.

Several other additive manufacturing technologies, such as Laser Engineered Net Shaping (LENS) and Fused Deposition Modeling (FDM), might fit this definition but the difference is a matter of size. We can call a process Direct Write when the freeform deposition tool is intended to build structures of about 5mm or less with resolution ranging around 50µm on one or some of its features [13].

Different processes have been developed to attain DW; this includes ink-based processes, aerosol-based processes, laser-transfer processes, beam deposition processes and thermal spray processes [13]. Using the physics principals behind these processes different techniques have been developed to accomplish DW. Some of the most common are Nozzle Dispensing (Micropen and nScrypt), Plasma Spray (PLS), Laser Particle Guidance (LPG), Matrix-Assisted Pulsed-Laser Evaporation (MAPLE), Laser Chemical Vapor Deposition (LCVD), Micropen, Ink Jet, E-beam, Focused Ion Beam (FIB), and others (see Table 1.2) [16].

The most relevant DW techniques for this project are the ink-based processes, because we are using this type of technology for our experiments; more specifically the nScrypt direct write dispensing system utilizing a Smart Pump^{TM}. Ink-based systems typically use a nozzle attached to a pump or syringe mechanism to push the inks through an orifice to deposit it onto the substrate in a controlled fashion [13]. The deposited line width is directly dependent on the material. Generally, the minimum line width is a least 10 times bigger than the biggest particle size in the specific paste. nScrypt is able to print any line width between 25µm and 3mm with tolerances under ±5%.

Table 1.2: Available Direct-write Technologies [16]

Processes	Techniques
Ink-based	Micropen nScrypt Dip-Pen
Aerosol-based	M^3D
Laser-transfer	Laser Particle Guidance Matrix Assisted Pulsed laser Evaporation Direct Write (MAPLE DW)
Beam deposition	Laser Chemical Vapor Deposition (LCVD) Focused Ion Beam CVD Electron Beam CVD
Thermal & Electrochemical	Plasma Spray ThermoChemical Liquid Deposition (TCLD) Electrochemical Liquid Deposition (ECLD)

This high precision control is obtained through accurately controlled air pressure, timing, valve opening and dispensing height [17]. Moreover, the 3-axis movement of the DW head is controlled by a motion control system to which the equipment must be attached.

The materials that DW ink-based systems dispense are typically denominated inks or slurry pastes depending on their viscosities. These "inks" can have different properties according to the application for which they are being used. For example conductive, insulator and dielectric inks would be used for applications such as the fabrication of passive electronic components. Other application examples of DW include the printing of active electronic components (batteries, antennas, etc.), micro-electronics, MEMS, optics, pharmaceutics and biomedical materials; hence an ink suitable for each application must be available. The wide range of applications for DW is enhanced by the variety of materials processing capabilities, the simplicity of the DW processes and flexibility of "writing" in different substrate topologies (flat, round, inflatable, irregular and 3D) [17].

Direct Write techniques have been developed and used for embedding passive Surface Mount Devices (SMD's), such as resistors and capacitors, surface mount light emitting diodes (LED's), unpackaged semiconductor Integrated Circuits (ICs) in bare die form, and the required metal patterns to interconnect each of these components into a working circuit. They may be embedded in circuit boards, metallic or polymer parts.

Some of the reasons why the Smart Pump^{TM}, designed and developed by the company nScrypt, was the direct write system chosen for this project are the following: it extrudes virtually any material ranging from 1 to $1\text{x}10^6$ centipoises (it can process from water to tomato paste) as a continuous filament which enables it to maintain a fixed cross-sectional area and a wider range of ink rheologies. The capability of this equipment to maintain a constant and controllable cross-section is valuable (precisions down to 50µm lines and 75µm dots), as this is a major variable in the properties (conductivity, resistivity, etc.) of the dispensed materials. The dispensing tip has been designed to reduce the pressure drop inside the dispensing nozzle causing the material to be vacuumed back when the valve closes, resulting in no material sticking out of the dispensing tip which enables the ability to continue the next dispensing without any need of cleaning [18].

A Smart Pump^{TM} system consists of three basic parts a (1) pump, a (2) nozzle, and a (3) motion control system (see Figure 1.5). The pump design determines the volumetric control, the repeatability of dispensing and the speed at which the deposits can occur. The nozzle design will determine the smallest feature size and the shape of the deposit, influences the start and stop dispensing precision and also determine the size of the fillers which can be used on the inks to be dispensed. The motion controller to where the Smart

Pump™ is attached will determine the dimensional accuracy, repeatability and maximum size of the deposits, as well as the speed with which deposits can be laid down [13].

The Smart Pump™ preparation process is the following: First you load the ink to be dispensed into a 3cc syringe and screw the syringe to the flow inlet by means of a female lure.

A digitally controlled air pressure outlet that comes from the Smart Pump's control box is attached to the other end of the syringe; this enables the exact dispensing of the inks. The Smart Pump™ can be programmed through software to open or close the dispensing valve depending on the material's rheological properties. The dispensing tip will ultimately define the shape and size of the traces. For the actual printing process we need to define a trace path which the motion control system will follow while the DW head is dispensing material with a fixed z-height to maintain the same line width.

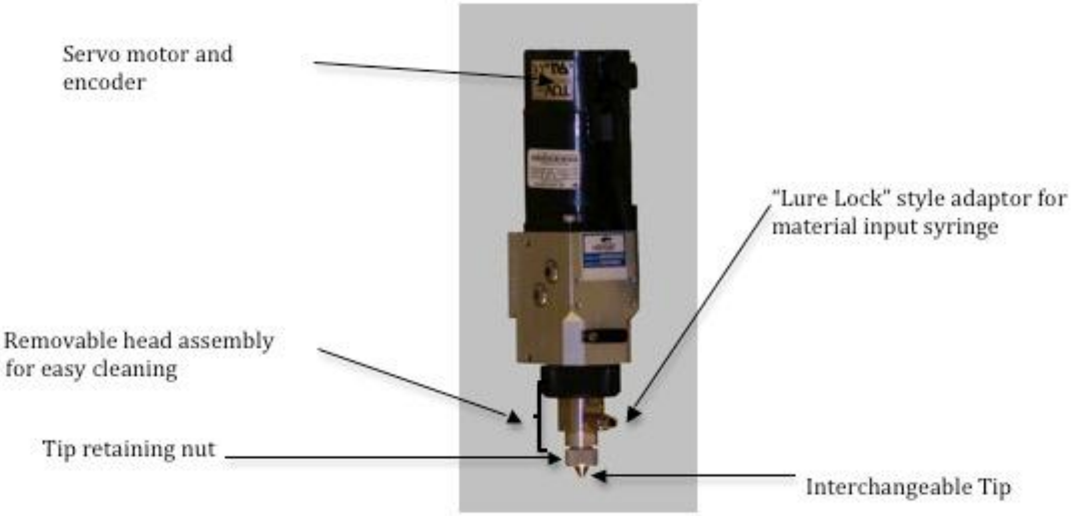

Figure 1.5: Schematic of the nScrypt Smart Pump™ direct-write system [19].

Some nozzle devices include a scanning system that first determines the topology of the substrate on which the deposit is to be made, and then deposits conformably over that substrate surface based on the scan data [13].

1.1.4 Embedded Structures

Embedded structures can be defined as functional parts with different components, features or devices (as sensors, integrated circuits, assemblies, actuators, and fiber optics) placed inside the part structure. In that sense, the term ‘embedded’ refers to the fact that there are elements firmly fixed in a surrounding mass [3].

Embedded structures have many advantages. Parts with embedded structures are fabricated with the components being added during construction, so post assembly is not needed. This characteristic is very attractive for automation, and indeed is used extensively in the fabrication of complex reliable and small electronics, which is a promising application area for embedding structures.

Sensors embedded within the structural materials add intelligence to structures and enable real-time monitoring. In general, sensors are useful means to gain data for validating or improving physical designs or to obtain information on the performance and conditions of functional components in service. This can have great benefits, for example, a tool die could have embedded thermocouples for process control purposes [20].

Embedded components offer great improvement opportunities for the products or parts that contain them by increasing their versatility. Embedded structures are designed to improve one or various aspects of the product and enhance their abilities. As a result of having embedded structures some designs can be optimized having strategic location of parts anywhere in the product, complex geometries or material gradients, size and weight reduction, and better protection of the embedded parts from the hazards of the environment, among other things [21]. The following paragraphs will expand on those ideas.

Embedded sensors may enable real-time monitoring at locations not accessible to ordinary sensors, which must be attached to the surface. For example, in a study sensors were embedded into the core and cavity of an injection molding process mold. Then, using the information from the sensors a quality control system was developed [3].

Embedded sensors have an extra protection layer from hazardous external environments as long as the component integrity stands. In many cases, outer environmental hazard effects are isolated or reduced by embedding; for example when the external part acts as a heat dissipating medium.

Using AM techniques embedded functional products with complex geometry or material gradients may be obtained. Optimizing the distribution of material properties (such as strength, hardness, thermal resistance, etc.) ensures desired responses to given mechanical, thermal, and electromagnetic or biochemical loading is achieved. Functional graded materials (FGMs) can be used to improve fracture toughness of machine tools, as thermal or flow gradient structures, or to provide wear and corrosion (oxidation) resistance of high temperature aerospace, automotive or chemical industry components [22].

Embedded structures are usually smaller and lighter than traditional structures or products. In fact, a wide range of applications really can be better served with lighter, smaller components. For example, embedding components is advantageous for creating small electromechanical systems, where the size and weight of the design are constrained by assembly factors, and aerospace/aeronautical devices where the weight is always a main design constrain [21].

Due to the mentioned advantages of component embedding numerous applications can be found on the field. For example, embedded structures are being widely used in the manufacturing industry to place sensors, such as thermocouples or strain gauges, into molds, dies, and drilling bits to analyze and improve their performance. In the same fashion the aerospace industry is embedding sensors on components of jet engines. Other industries that are taking advantage of the embedding technique are the automotive industry (components of motors), the oil industry (drilling equipment), the power industry (vessels and pipes) and the construction industry (structural components in buildings) [23].

In general, constraints for embedding are functionality and available processes to embed. The challenges actually faced result from the fact that tooling and components in the manufacturing, automotive, power, and oil industries, is frequently metallic. Most additive manufacturing techniques are designed to produce functional metallic parts in a high-temperature state in order to achieve high-quality interlayer bonding. Thus, embedded sensors will have to be protected during the high temperature deposition steps. It is important to maintain the integrity of the sensors to obtain functional metallic structures [23]. However, ultrasonic consolidation eliminates the need for thermal protection of sensors.

The principle of embedding structures is not complicated, but each kind of component presents different issues that must be taken into consideration. Some challenges are positioning, maintaining the functionality, and dealing with tolerances. The techniques used to solve these problems may add some extra steps to the process. Some tasks may include pre-treating the embedded component by adding material to preserve it or adding alignment features.

Furthermore, it must be assured that the building and support materials are thermally, chemically and mechanically compatible with the embedded components. Moreover, mechanical components that transmit forces such as motor shafts and springs need strong adhesion between the part and the embedded component. The design of parts with embedded components need integrated analysis to ensure manufacturability, functionality, mechanical behavior of the whole structure (deflections, stress gradients) and thermal behavior during operation.

Some real projects focused on structural embedding involve the following parts: sensors, integrated circuits, circuit boards, batteries, inductors, wires, complete functional assemblies, actuators, MEMS, thin film sensors, fiber optics, etc. Wireless sensor embedding and Fiber Bragg Grating (FBG) sensors are also popular [3]. FBG allows critical parameters of materials and structures to be sensed while offering lightweight immunity to electromagnetic interference, non-obtrusive embeddability, resistance to hostile environments, and extremely high-bandwidth capability. A network of embedded fiber-optic sensors can allow a structure to monitor its integrity or health during manufacturing and service. Moreover, these sensors could replace many of the functions traditionally performed by human visual inspection and could provide real-time feedback in the event of structure failure [23].

THESIS STATEMENT

The goals of this thesis are to integrate an nScrypt Smart Pump^{TM} direct write head into a Solidica Formation^{TM} ultrasonic consolidation machine and explore the capabilities to rapidly fabricate parts with novel features enabled by the combination of both technologies. The objectives of this project are:

1. Develop the process plan guidelines for operating the combined ultrasonic consolidation and direct write technologies.
2. Develop design guidelines for the effective fabrication of structures and use them to fabricate a proof of concept part using an ultrasonically consolidated metallic enclosure, as well as direct write (DW) to interconnect embedded components.

The research that is presented in and associated with this thesis is directed to obtain process and design guidelines to be used when fabricating structures using the integrated UC and DW apparatus. This research focuses primarily on the application of fabricating embedded passive electronic components (resistors and capacitors); hence the presented guidelines can be used for other applications as well. This is the first time UC and DW technologies have been merged into a single system and therefore necessitated fundamental testing of features that could be utilized in the fabrication of embedded passive components. The results of the tests performed to answer process and design questions are presented in the subsequent chapters of this thesis.

This is a multipaper thesis in which Chapters 2, 3, and 4 are individual papers that were published or submitted for publication. Chapter 2, published in the proceedings of the 20th Annual Solid Freeform Fabrication Symposium, addresses the process of integration of the nScrypt Smart Pump™ with the Solidica Formation™ ultrasonic consolidation machine, as well as an appropriate process planning sequence to exploit the capabilities of the integrated technologies. Testing and results of a study performed to assess the UC machine gantry system XY-axes accuracy and repeatability and the process to obtain the best possible post-cured electrical properties of several DW inks are discussed in Chapter 3. The information contained in Chapter 4 is related to embedding DW traces in UC structures. Chapter 4 describes how the results obtained in previous chapters are utilized to fabricate a functional embedded touch sensor circuit in an aluminum enclosure using direct write for passive components as well as commercial off-the-shelf (COTS) components enclosed in a UC bonded structures. Conclusions and future work are presented in Chapter 5. A summary of the process and design guidelines obtained throughout the various tests performed during the completion of this thesis is presented in the Appendix.

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CHAPTER 2

INTEGRATION AND PROCESS PLANNING FOR COMBINED ULTRASONIC CONSOLIDATION AND DIRECT WRITE[1]

This chapter is a paper published in the proceedings of the 20th Annual Solid Freeform Fabrication Symposium.

Abstract

A research project is underway to integrate an nScrypt Smart Pump™ 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.

2.1 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

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[1] Coathored by: Ludwing A. Hernandez, Brent Stucker: Utah State University.

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.

2.1.1 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^{TM} machine at Utah State University (see Figure 2.1).

Figure 2.1: Solidica Formation™ located at Utah State University [2].

The build process of the UC machine has the following sequence. First, the tool paths 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].

2.1.2 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^{TM} developed by nScrypt Inc. The Smart Pump^{TM} 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^{TM} system includes a positive pressure pump with a computer controlled needle valve (see Figure 2.2) 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].

2.2 Experimental Work

The plan is to physically and electronically integrate the Smart Pump^{TM} Direct write system 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.

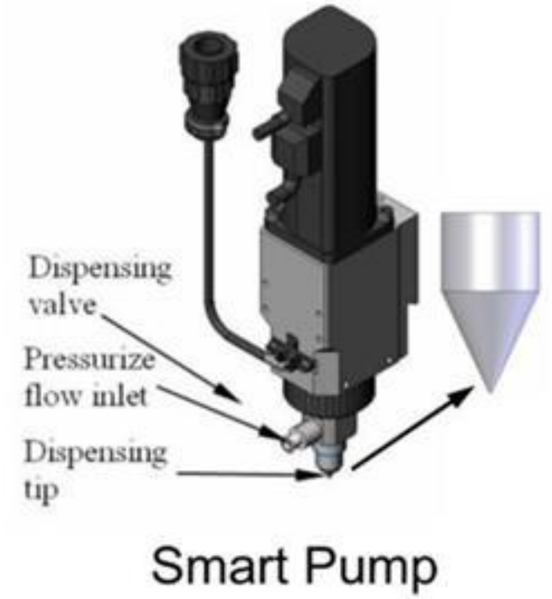


Figure 2.2: Schematic of the nScrypt Smart Pump^{TM} direct-write system [4].

2.3 Results

2.3.1 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} machine 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^{TM} 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^{TM} to the motion control system; taking into consideration user accessibility and jamming precautions for the 3-axes of motion (see Figure 2.3).

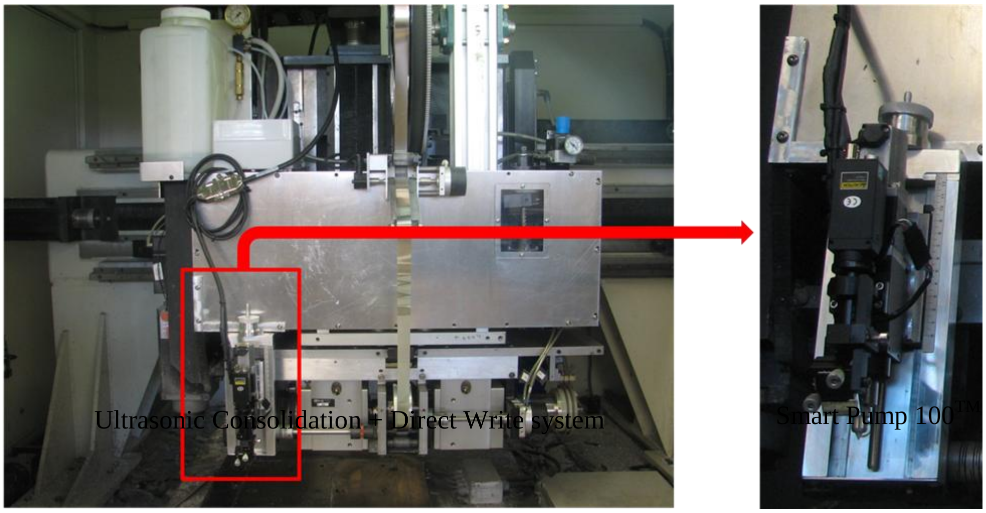


Figure 2.3: nScrypt Smart Pump^{TM} Direct-write and Solidica Formation^{TM} ultrasonic consolidation integration.

When the DW 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^{TM} 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 2.4) 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) (see Figure 2.5) [5].

For the physical integration some custom parts were fabricated from aluminum 3003. A custom aluminum bar was machined (see Figure 2.6) to firmly attach the slider and Smart Pump^{TM} to the UC motion control system. A small rectangular base (see Figure 2.7) was used between the Smart Pump^{TM} mounting bracket and the slider platform to avoid drilling additional holes in the slider's stainless steel platform.

Figure 2.4: Velmex A40 Series UniSlide assembly with graduated knob [5].

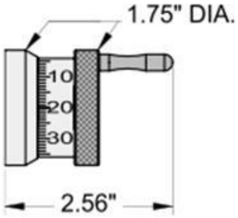


Figure 2.5: Velmex graduated knob [5].

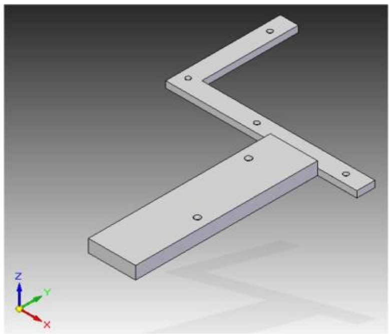


Figure 2.6: Custom base for Smart Pump^{TM} and slider attachment to motion control system.

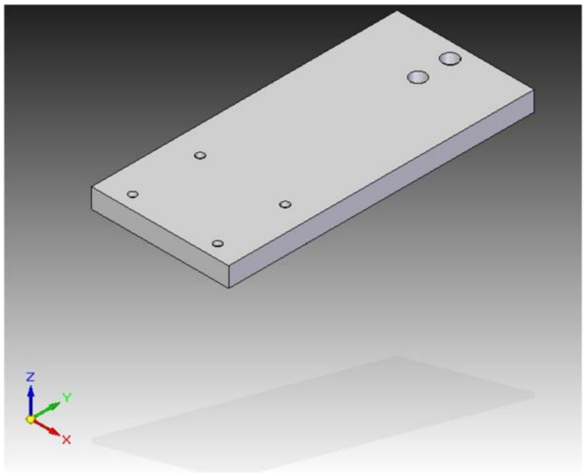


Figure 2.7: Rectangular base for Smart Pump ^{TM} attachment to slider.

To reduce vibration of the Smart Pump^{TM} during stage motion, a screw was used to maintain a fixed distance between the slider and one of the sonotrode's motor side walls (see Figures 2.8 and 2.9). This screw held the Smart Pump^{TM} perpendicular to the X,Y plane.

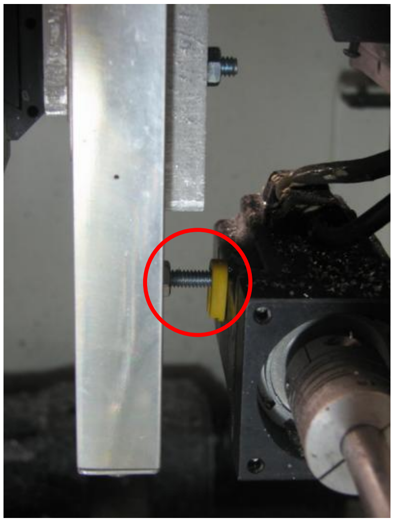


Figure 2.8: Side view of vibration reducer.

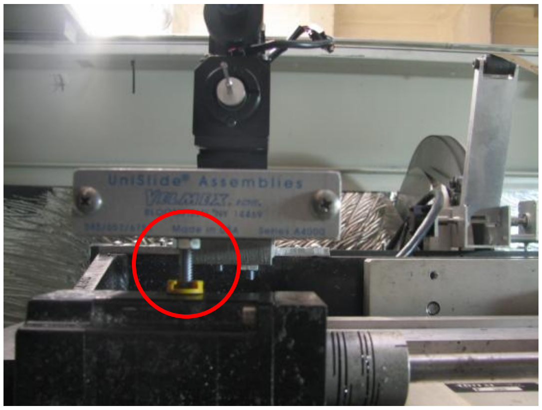


Figure 2.9: Bottom view of vibration reducer.

The Smart Pump ^{TM} control box was also bolted to the inner right side of the UC machine enclosure (see Figure 2.10).

In addition to the physical integration we were able to integrate the DW and UC system's 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 2.10) enables digital signal communication between the DW control box and the UC controller.

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 2.11) was connected to the J-box circuit to work as the trigger button for both systems.

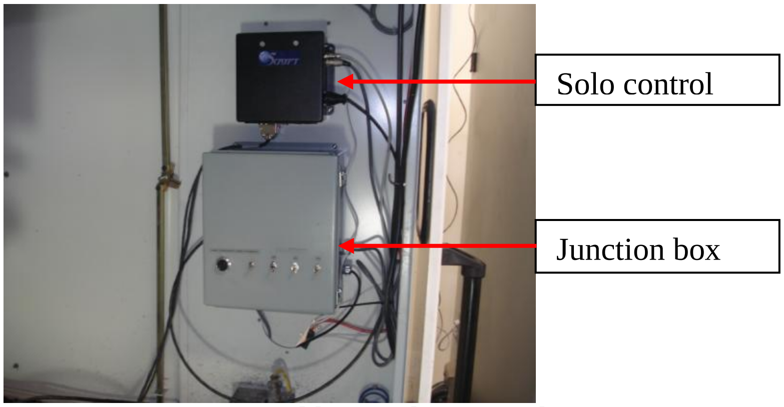


Figure 2.10: nScrypt control box and junction box.

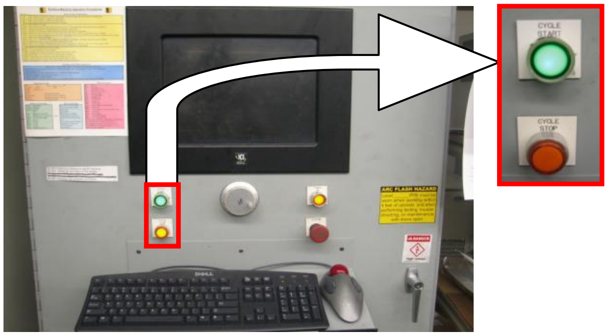


Figure 2.11: Solidica Formation^{TM} control box front panel.

2.4 Discussion

2.4.1 Process Planning Sequence

Figure 2.12 is a flow chart that describes the basic process planning sequence (see Figure 2.12). Each step is explained in detail. 1) The traces to be dispensed can be designed as sketches in any 2D CAD software, 2) converted to Gcode with a CAM application or Gcode converter. 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.

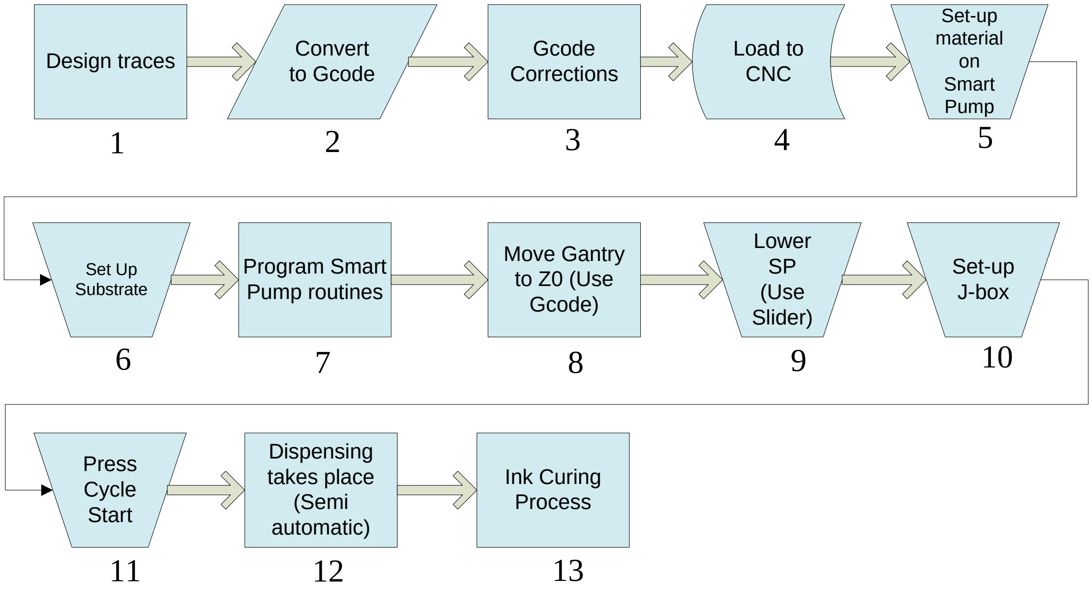
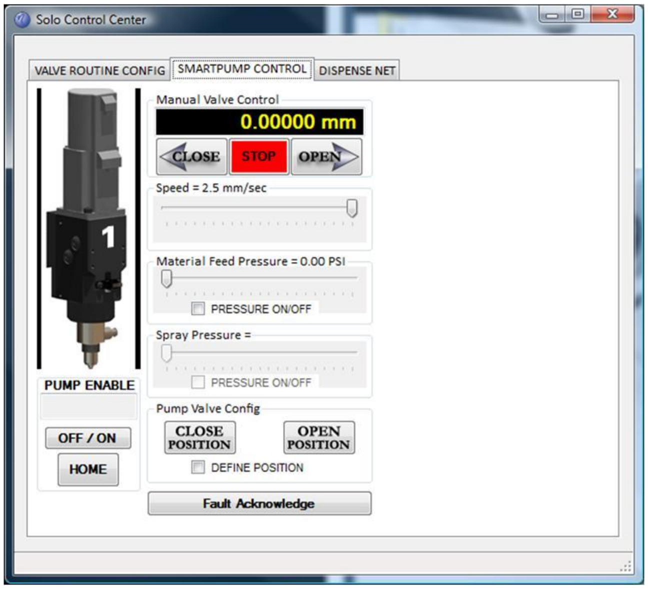


Figure 2.12: UC-DW process flow chart.

3) The Gcode must be modified to make it suitable for our purposes. 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. 4) 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; the motion control system is now ready start a build. The Smart Pump^{TM} is set up with material to dispense. 5) The Smart Pump^{TM} 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. 6) Set up of the substrate where the inks are to be dispensed occurs at the same time. 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. 7) Continuing with the Smart Pump^{TM} set up, the dispensing routines are programmed through the Smart Pump's "Solo Control Center" software. 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 2.13), 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. 8) The next step is to lower the stages to the lowest point programmed on the Gcode (ideally Z0). 9) Using the manual slider the Smart Pump^{TM} is lowered very close to the substrate (150µm). 10) After the Smart Pump^{TM} is ready, the J-box is set up. The J-box transmits the digital commands between the Smart Pump^{TM} and the motion control system (see Figure 2.14). The J-box triggers the Smart Pump^{TM} 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, and B0) that are used to manually select the bits to trigger each routine to the Smart Pump^{TM} with the parameters previously inputted in the Solo Control Center software, guided by the following routine select combinations. 11) Once the Gcode program is loaded into the Solidica system, the Smart Pump^{TM} is set up close to the substrate, and the J-box is prepared the cycle start button is pressed and dispensing is started (see Figure 2.15).



Manual Valve Control
0.00000 mm
Speed = 2.5 mm/sec
Material Feed Pressure = 0.00 PSI
☐ PRESSURE ON/OFF
Spray Pressure =
☐ PRESSURE ON/OFF
Pump Valve Config
☐ DEFINE POSITION

Figure 2.13: Solo control center: tab used to set up the dispensing flow rate.

12) As mentioned before, this process is semi-automatic, meaning that it needs some degree of human intervention to carry it out.

Figure 2.14: Junction box front panel.

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

While dispensing, this system needs an 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 B0, B1, B2 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^{TM} will only dispense were needed for the build to be completed. 13) The inks or pastes dispensed through the Smart Pump^{TM} usually need post-processing or curing. 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.

2.4.2 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.

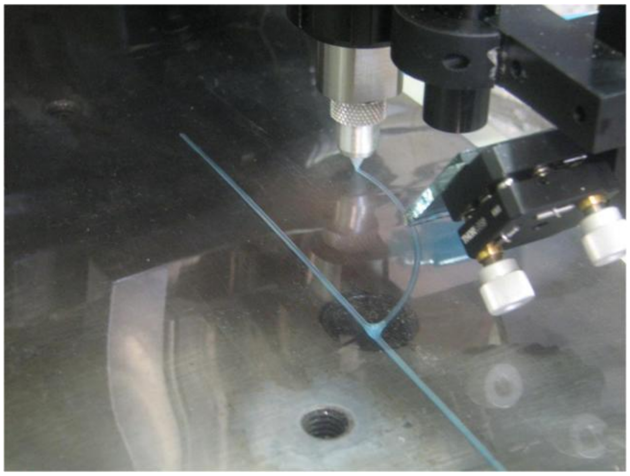


Figure 2.15: UC-DW integrated system dispensing onto a plastic substrate.

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.

See Table 2.1 for the posted design questions and tasks to be performed.

2.5 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: automating of the system by modifying the PLC of the UC machine to include new codes for the Smart Pump^{TM}; performing experiments to develop design guidelines for components made using the integrated system; and the fabricating proof of concept parts to demonstrate the capabilities of the system.

Table 2.1: Design Questions and Tasks for Future Experiments

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

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CHAPTER 3

DESIGN AND PROCESS GUIDELINES FOR EFFECTIVE FABRICATION OF STRUCTURES COMBINING DIRECT WRITE AND ULTRASONIC CONSOLIDATION[2]

Abstract

Design guidelines for the effective fabrication of structures using combinations of ultrasonically consolidated metallic enclosures and direct write (DW) to interconnect embedded components were developed. An uncertainty analysis was carried out on the Ultrasonic Consolidation (UC) machine to determine the accuracy and repeatability of its gantry system. A Taguchi experiment was designed to study the effects of thermal curing process and substrate materials on the electrical properties of conductive, resistor, and dielectric inks dispensed by direct write. DW traces were embedded in different orientations (0^o, 45^o, 90^o) with respect to the sonotrode's movement and using different methods (channel, no channel). The current UC system's dimensional accuracy of 0.008" and repeatability 0.002" were determined. The UC heat plate feature was shown to be effective for thermal curing of inks. Finally, embedding using channels proved to be more reliable than embedding without channels.

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3.1 Introduction

During the last few decades electronic products have followed a trend to become more compact, light weight and with integrated multiple functions in a single package. As a result the electronics industry had to find new alternatives to keep up with the demands of the market. Additive manufacturing processes have the capability to create compact parts in complex shapes, thus consolidating parts to reduce or eliminate assembly processes.

Additive manufacturing processes such as Ultrasonic Consolidation provide the ability to create three dimensional shapes with internal passages, multiple materials, and functionally-graded materials; and the ability to produce parts with embedded mechanical and electrical components. UC is particularly useful for embedding of electrical components into a metallic material because the process does not require high temperatures. UC possibilities include embedding passive components, sensors, and microprocessors to create “smart” structures. Embedding components is advantageous for creating small electromechanical systems, where the size and weight are constrained.

Direct write (DW) also presents numerous advantages dispensing electrical traces for embedding purposes. With DW it is possible to fabricate custom resistor networks, conductive traces, capacitors, and integrated Restistor-Capacitor (RC) filters on any kind of substrate; (polymer, ceramic, and metallic). Some systems include a laser positioning feedback to enable conformal printing over uneven surfaces, which makes them ideal for multilayer 3D dispensing.

This paper presents design and process guidelines for integrating DW ink dispensing, ultrasonic consolidation and thermal cure for embedding electronics in aluminum structures.

3.2 Background

3.2.1 Direct Write (DW)

Direct write refers to a group of processes intended to precisely deposit small functional and/or structural materials on to a substrate in digitally defined locations, without the use of masks. A variety of mechanisms and processes such as inkjet printing, laser transfer, mechanical pressure and extrusion tips are used to transfer material to a substrate to produce features from nm to mm scale. 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. The Direct write system available at Utah State University is the nScrypt Smart Pump^{TM}, 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 [1].

Direct write technologies are increasingly of interest due to trends for miniaturization of electrical systems. Direct write provides alternate methods to simplify printed circuit board manufacturing while reducing costs. Patterning of passive and active electrical components has been made by direct write techniques using a variety of materials. Suitable materials for DW technologies include “inks” and “pastes.”

Combinations of powders, nanopowders, flakes, surface coatings, organic precursors, binders, solvents, dispersants, and surfactants are typical components of DW inks. Their applications range from conductors to resistors and dielectrics, and are generally developed for low temperature deposition (less than 400^{o}C); intended for substrates such as plastics, paper, and fabrics. According to Chrisey [2] silver, gold, palladium, and copper conductors; polymer thick film and ruthenium oxide-based resistors; and metal titanate-based dielectrics are among the most used materials for electronic applications.

Metal filled inks consist of a colloidal suspension of nano-sized metal particles within a polymer matrix [3]. The electrical properties of composite materials of metallic filler particles embedded in polymer matrices strongly depend on the concentration and morphology of the particles. The electrical resistance shifts from dielectric to metallic behavior with increasing metal content [4]. The system can be considered as an average of the resistivity of the matrix and the filler. Hence, when the resistivity of the matrix is high compared with that of the particles, the resistance of the composite will be high [5].

The concentration of the filler in the composite can be augmented by a process called sintering or curing. The curing process can be performed using several methods such as heat-treatment, UV, microwave or laser [6]. Generally, after a nano-ink has been printed onto a substrate, it is cured and, upon solvent evaporation, forms a continuous conductive thin film. Curing is a necessary step to establish electrical contact in the feature, since the ink is essentially an insulator in its original state. The curing process initiates the polymer flow of the solvent allowing it to evaporate and leaving room for the metal particles to establish contact. This final process directly affects the electrical properties of dispensed features. In the case of conductive traces with metallic nano-particles, the post-cured resistivity measurements can approach close-to-bulk values [3].

3.2.2 Four-Point Probe Test

A method used to measure the resistance of thin film conductors is the 4-point probe test. The theory behind the four point probe test is a fixed current injected into the feature through the two outer probes, and the voltage is measured between the two inner probes (see Figure 3.1).

For a very thin layer (thickness t<<s) the expression for the area of the sample is defined as, A=2πxt. We can derive the resistivity as follows:

$$R = \int_{x_1}^{x_2} \rho \left(\frac{dx}{2\pi x t}\right) = \frac{\rho}{2\pi t}(lnx)_{x_1}^{x_2}$$

Since $x_1 = s$ and $x_2 = 2s$, the equation can be simplified to:

$$R = \frac{\rho}{2\pi t}\ln\left(\frac{2s}{s}\right) = \frac{\rho}{2\pi t}ln2$$

When R = V/2I, the sheet resistivity for a thin sheet is:

$$\rho = \frac{\pi t}{ln2}\left(\frac{V}{I}\right)$$

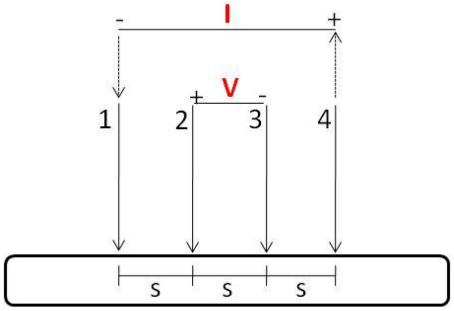

Figure 3.1: Four-point probe operation schematic.

This expression is independent of probe spacing s.

In case of a semi-infinite thin sheet (sample size 40 times larger than the spacing between the probes) sheet resistivity, $R_s \sim \rho/t$ can be expressed as:

$$R_s = k(\frac{V}{I})$$

where the factor k = 4.5324 is a geometric factor, which corresponds to the value of $\pi/\ln 2$.

Conductivity (c) can be obtained from the resistivity value as follows:

$$c = \frac{1}{\rho}$$ [7]

The units established by the International System of Units (SI) for resistivity and conductivity are Ωm and Sm^{-1} respectively [8].

3.2.3 Ultrasonic Consolidation (UC)

Ultrasonic Consolidation is an additive manufacturing process that uses the principles of ultrasonic welding to build up rough shape parts and 3-axis CNC milling to produce net shape parts. The UC machine available at Utah State University, the Solidica Formation^{TM}, is an integrated machine which incorporates an ultrasonic welding head, foil feeding mechanism, a 3-axis milling machine, a heat plate on top of which a base plate substrate is firmly bolted for part fabrication to take place, and software to automatically generate tool paths for material deposition and machining. The heat plate maintains the temperature of the base plate between ambient and 350^{o}F [9].

3.2.4 Uncertainty Analysis for Computer Numerical Controlled (CNC) Machines

To perform geometric error measurements on 3 or 5-axis CNC machines, direct or self-calibration methods can be used [10]. Direct methods, sometimes called parametric methods, generally use a measurement device, such as a probe ball, to measure the overall position error of all the axes of a machine tool. To perform the accuracy test, a three-degree-of-freedom measuring probe or extension bar is installed in the main spindle and attached to a turntable fixed in the CNC base plate (see Figure 2). The spindle is programmed to move in circles. The system continuously captures the spindles path. Data points are obtained and analyzed to explain the nature of the probe-ball error measurements [11].

A self-calibration method consists of measuring spatial coordinates of an artifact when it is placed in different positions in the machine working volume. The artifact has N defined points with invariant distances, measured in P positions [10]. By International accord, the evaluation is to be done in accordance with the ISO Guide to the Expression of Uncertainty in Measurement (GUM). The guidelines in ISO 230-2 International Standard are used to calibrate positional deviations of CNC machine tools [12]. In simple terms, the self calibration method requires to build a part and measure its offset compared to the CAD model dimensions. Standards like ISO 230-2 standardized to drill a certain number of holes in a flat plate depending on the machine's building area. It also specifies the displacement directions the spindle has to follow while in test. Finally measurements are taken and analyzed to draw conclusions about the accuracy and repeatability of the equipment.

3.3 Experimental Plan

A previous paper included in the 2009 Solid Freeform Fabrication Symposium Proceedings, “Integration & Process planning for combined ultrasonic consolidation and direct write” explains in detail how a direct write head, nScrypt Smart Pump^{TM} and the Solidica Formation^{TM} UC machine were integrated to work in a semi-automatic fashion. This current paper contains results of studies performed on this system, in an effort to develop design guidelines to obtain good post-cured electrical properties on dispensed materials before and after embedding. In order to ascertain the capabilities of the combined machine, an uncertainty analysis was performed on the UC gantry. Additionally, the effectiveness of different thermal curing methods for DW inks dispensed on various substrates was evaluated. Finally, tests were performed to determine the most reliable embedding method. The experimental procedures for each of these are described below.

3.3.1 CNC Machine Uncertainty Analysis

In our integrated system, direct write dispensing accuracy is dependent on the accuracy of the 3-axis CNC machine to which it is physically attached. An uncertainty analysis was carried out on the UC machine to determine its accuracy and repeatability, using the ISO 230-2 International Standard. As the nScrypt direct write process used in this research is capable of fabrication of small features (nm to mm scale) [1]. the accuracy of the depositions will be a function of the UC machine rather than the DW head.

A pattern of 161 points distributed over a 14” x 14” plate was designed in AutoCAD (see Figure 3.2) and was fabricated using the CNC machine capabilities of the UC machine. Each point was drilled twice on the aluminum plate, first using a 0.125” end mill tool to a depth of 0.02” and then using a 0.03125” ball mill tool to a depth of 0.02” (see Figure 3.3).

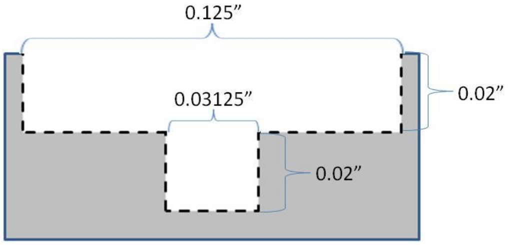

Figure 3.3: Sketch drilled holes from side view.

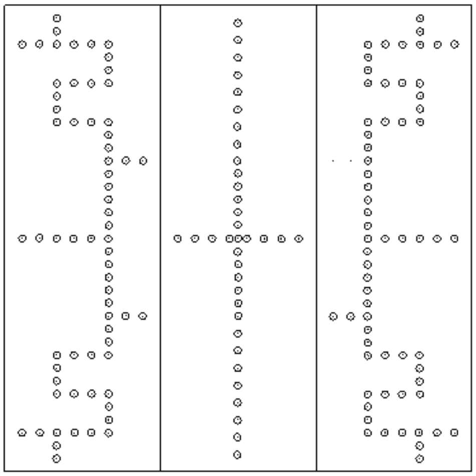

Figure 3.2: AutoCAD design for uncertainty analysis.

The following was measured:

- Accuracy: The actual positions p_{ij} of the points in the plate were measured and compared to the target positions P_{IJ} in the design file ($a_{ij} = P_{IJ} - p_{ij}$).
- Repeatability: The positions of the center points of the 0.125” diameter dots C_{ij} were measured and compared with the center points of the 0.03125” diameter dots c_{ij} ($r_{ij} = C_{ij} - c_{ij}$).

The measurements were carried out using an optical microscope with an embedded scale measurement system. The results were plotted and accuracy and repeatability ranges within a 95% confidence were determined.

3.3.2 Curing Method Evaluation

The effectiveness of the ultrasonic consolidation heat plate feature for use as a curing method for DW dispensed inks was evaluated. Each available DW ink was dispensed on four different substrates and post-cured electrical characterization was performed.

Table 3.1 lists the DW materials used for these experiments and their manufacturer recommended curing requirements. The substrate types are listed in Table 3.2 and show in Figure 3.4.

Table 3.1: Direct Write Materials

DW Materials	Curing Requirements
1. Polymer Thick Film Conductive Silver Coating (E1660)	121 C – 1 to 5 min
2. Electrical Resistor Ink (104-18)	175 C – 0.5 hour
3. High Dielectric Constant Ink (114-14A)	175 C – 1 hour

Table 3.2: Substrates

Substrates
1. Aluminum 3003 coated with Blue Insulator$^{\text{TM}}$
2. Aluminum 3003 coated with Aquaseal$^{\text{TM}}$
3. FR4
4. Glass

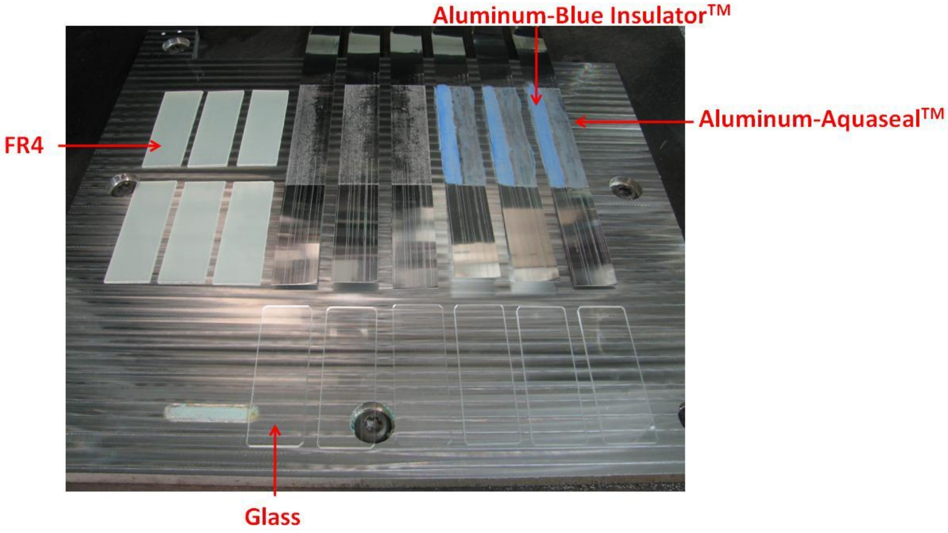

Figure 3.4: Substrates on Top of Aluminum 3003 Base Plate.

An L24 Taguchi experiment was designed to study the effects of thermal curing process and substrate materials on the electrical properties of conductive, resistor, and dielectric inks. In these tests, “Substrate temperature” refers to the temperature of the substrate before and at the moment dispensing takes place (85 F or 250 F). “Curing temperature” is the temperature the substrate is heated to for a period of time to cure the ink. “Curing method” is the source of thermal energy: UC heat plate, furnace, or a combination of UC and furnace. The supplier’s curing suggestions were taken as a guideline for the required curing temperatures and times for each material.

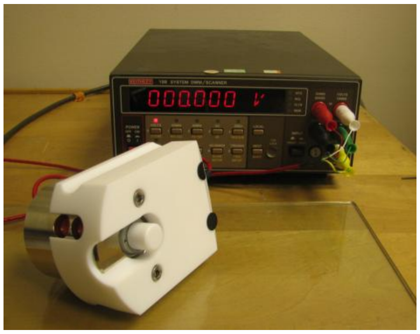

Figure 3.5: Keithley lab multimeter with hand applied four point probe.

Figure 3.6: LCR meter.

The response was taken as resistivity ρ for resistor and dielectric inks, and conductivity σ for the conductive ink. Resistor and conductive inks were measured with a four point probe (see Figure 3.5) and the resistance of the dielectric ink was measured with a Inductance-Capacitance-Resistance (LCR) meter (see Figure 3.6).

3.3.3 Embedding Method

Embedded components need to withstand the conditions inherent to the embedding process, such as temperature and pressure. The UC process welds metallic foils using ultrasonic vibration, resulting in applied shear and normal forces. Elements embedded using ultrasonic consolidation should be able to withstand the stresses induced during UC bonding. To find the best embedding method test specimens were built to determine the optimal positioning of the direct write traces with respect to the movement of the sonotrode. Specimens were built in 3 orientations: Vertical (0°), Horizontal (90°), and Diagonal (45°) (see Figure 3.7). Two different line widths were used for the dispensed lines, 50µm and 125µm. The use of channels to enclose ink traces was compared to direct welding over the traces using each of the orientations. The results were evaluated in terms of number of process steps and reliability.

3.4 Results

3.4.1 CNC Machine Uncertainty Analysis

The actual position p_{ij} of the points on the plate were compared to the nominal position P_{IJ} in the design file ($a_{ij} = P_{IJ} - p_{ij}$) (see Figure 3.8).

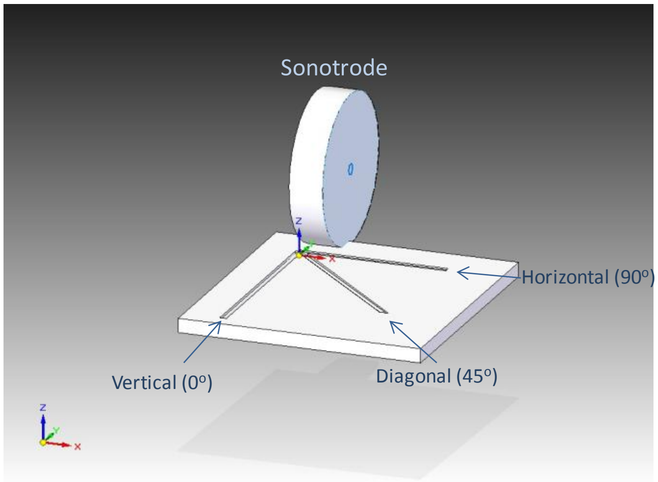

Figure 3.7: Build orientations (0°, 45°, 90°).

The distance between the points was designed to be 0.5”. If, for instance, the measurement from point to point gave 0.4985”, then the recorded value was a_{ij} = 0.5” – 0.4985” = 0.0015”. Fifty values were obtained for each (X and Y) axis. The results are shown in Figure 3.9 and Table 3.3.

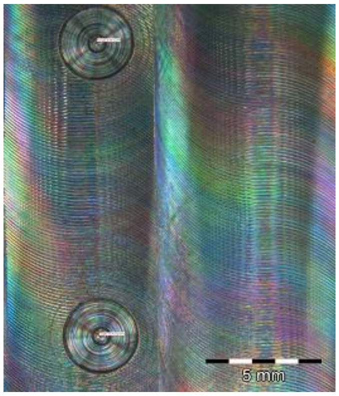

Figure 3.8: Point to point measurement for accuracy.

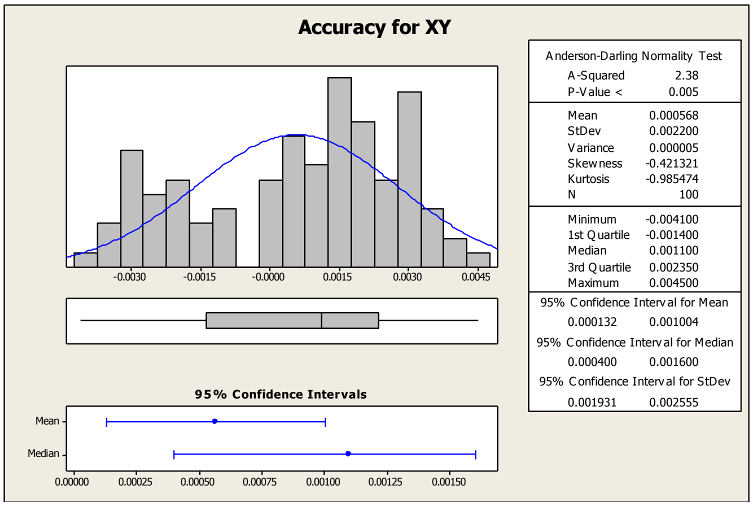

Figure 3.9: Graphical summary of accuracy measurements of XY-axes.

Table 3.3: Tolerance Results for Accuracy Measurements

```
Tolerance (Confidence) Level:  95%
Proportion of Population Covered:  90%

N    Mean      StDev      Tolerance Interval
100  0.000568  0.0021998  (-0.0035541,  0.0046901)~ ±100µm
```

Repeatability is the position of the center point of the 0.125” diameter dot C_{ij} compared with the center point of the 0.03125” diameter dot c_{ij} ($r_{ij} = C_{ij} - c_{ij}$) (see Figure 3.10). The results are the shown Figure 3.11 and Table 3.4.

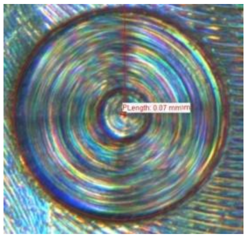

Figure 3.10: Center to center measurement for repeatability.

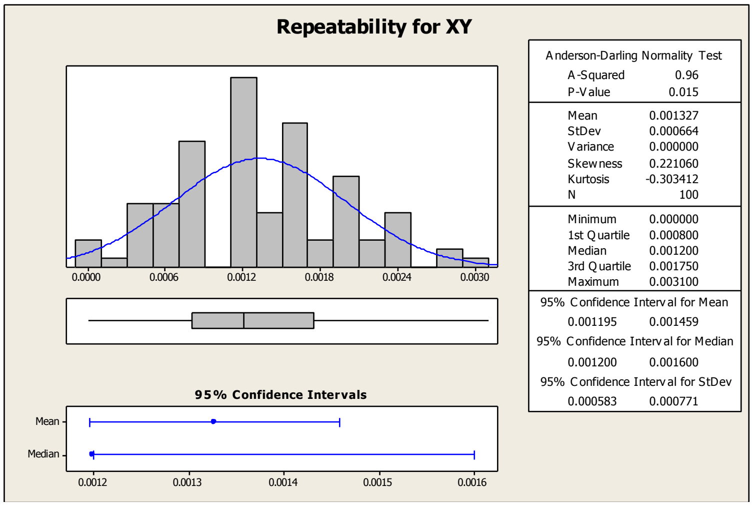

Figure 3.11: Graphical summary of repeatability measurements of XY-axes.

Table 3.4: Minitab Tolerance Results for Repeatability Measurement

```
Tolerance (Confidence) Level:  95%
Proportion of Population Covered:  90%

N    Mean      StDev      Tolerance Interval
100  0.001327  0.0006636  (0.0000835, 0.0025705) ~ ±30µm
```

The results indicate that we can expect from the CNC a positioning accuracy within 0.008” and position repeatability within 0.002” with a 95% confidence.

3.4.2 Curing Method Evaluation

The heat plate feature of the UC machine was evaluated to determine whether it is an effective curing method for the DW inks when dispensed on a metallic, polymer or ceramic substrate. For this study:

H_0 = Means are not statistically significantly different among levels of curing method, and

H_1 = Means are statistically significantly different among levels of curing method.

3.4.2.1 Statistical Analysis for Resistor Ink

The following are the results for the resistor ink. The response is resistivity, measured in Ωmm (see Table 3.5 and Figure 3.12):

Table 3.5: Response Table for Resistivity Means for Resistor Ink

```
          Response Table for Means

         Substrate                  Curing
Level         Temp  Substrate  Method
1            25.12      35.41   34.02
2            34.81      28.29   26.81
3                       19.03   29.06
4                       37.13
Delta         9.69      18.10    7.21
Rank             2          1       3
```

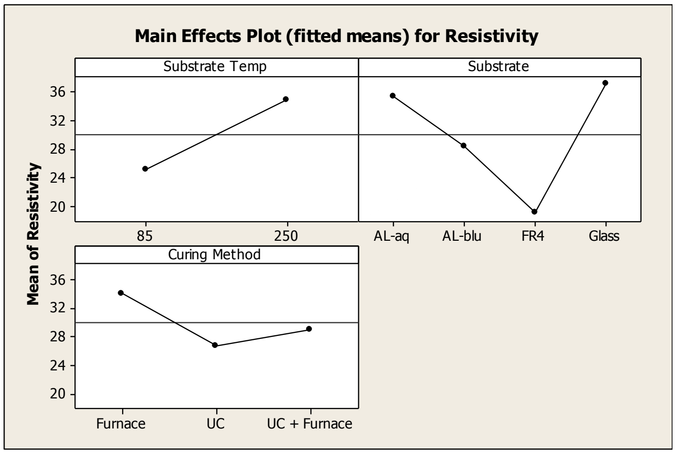

Figure 3.12: Main effect results of resistivity for resistor ink.

We can observe that the larger variation source among the evaluated variables is the substrate, followed by the substrate temperature, and the curing method constitutes the smallest variation source. To verify mean statistically significant difference between the variable levels One-way ANOVA is carried out for each variable (see Table 3.6)..

With a one-way ANOVA of Resistivity versus Substrate we can determine that there are no statistically significant differences between the mean values of the four substrates (AL-blue, AL-Aqua, FR4, and Glass) because $P > \alpha$ (0.071>0.05). “Substrate temperature” (P = 0.078) and “Curing Method”(P = 0.572) both have $P > \alpha$. Which means that the null hypothesis (H_0) could not be rejected; there is no statistically significant difference between curing using a furnace, the UC heat plate, or both combined.

Specific thermophysical properties must be known for electronic passive components for a circuit to perform as intended.

Table 3.6: One-way ANOVA of Resistivity vs. Substrate, Substrate Temperature, and Curing Method for Resistor Ink

One-way ANOVA: Resistivity versus Substrate

```
Source      DF    SS   MS     F      P
Substrate    3  1220  407  2.73  0.071
Error       20  2980  149
Total       23  4200

S = 12.21   R-Sq = 29.05%   R-Sq(adj) = 18.41%
```

One-way ANOVA: Resistivity versus Substrate Temp

```
Source           DF    SS   MS     F      P
Substrate Temp    1   564  564  3.41  0.078
Error            22  3637  165
Total            23  4200

S = 12.86   R-Sq = 13.42%   R-Sq(adj) = 9.48%
```

One-way ANOVA: Resistivity versus Curing Method

```
Source          DF    SS   MS     F      P
Curing Method    2   218  109  0.57  0.572
Error           21  3983  190
Total           23  4200

S = 13.77   R-Sq = 5.18%   R-Sq(adj) = 0.00%
```

Therefore, this study evaluates the response variability for each level, curing method, initial surface temperature, and curing temperature. A test for equal variances was performed (see Figures 3.13, 3.14, and 3.15).

UC heat curing method presents the smallest variance. Dispensing at room temperature (85F) contributes less variation to the process. Using FR4 substrates brings less variation into the process. When dispensing over aluminum there is no statistically significant difference between Blue Insulator^{TM} (thermoplastic) and Aquaseal^{TM} insulator (thermoset).

Tests for equal variances for resistive ink

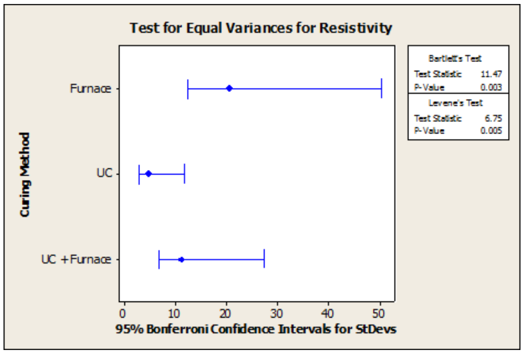

Figure 3.13: Curing method levels.

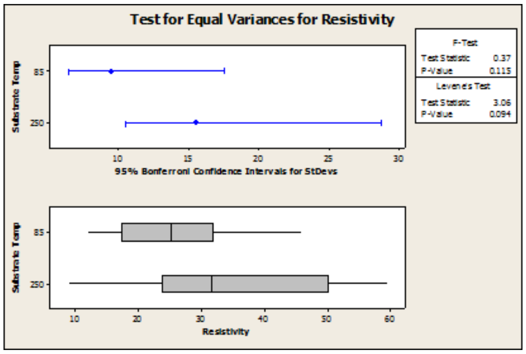

Figure 3.14: Initial substrate temperature levels.

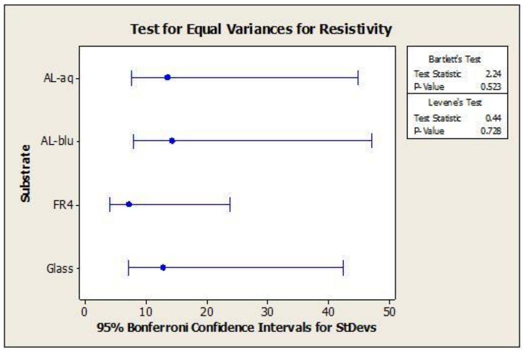

Figure 3.15: Substrate levels.

3.4.2.2 Statistical Analysis for Silver-Filled Conductive Ink

The same set of experiments was performed for the conductive silver ink. H_0 and H_1 remain the same as for the resistor ink analysis. The response is conductivity, in Smm^{-1} units. The results are shown in Table 3.7 and Figure 3.16.

The larger variation source is the substrate, followed by the substrate temperature, while curing method constitutes the smallest variation source.

One-way ANOVA is used to statistically compare the means between levels (see Table 3.8).

Table 3.7: Response Table for Conductivity Means for Conductive Ink

```
        Response Table for Means

          Substrate                 Curing
Level          Temp  Substrate  Method
1             2.011      1.572   2.183
2             2.472      2.007   1.962
3                        2.014   2.579
4                        3.372
Delta         0.461      1.800   0.618
Rank              3          1       2
```

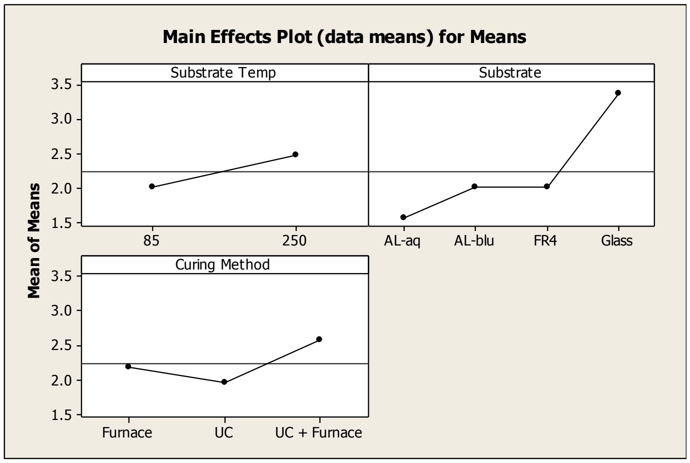

Figure 3.16: Main effect results for conductivity for conductive Ink.

Using a 95% confidence interval ($\alpha = 0.05$), none of the variables have statistically significant differences among their levels.

The null hypothesis H_0 could not be rejected. There is no statistical difference between the three curing methods used.

Design guidelines will be addressed based on the test for equal variances, which are shown in Figures 3.17, 3.18, and 3.19.

Variables levels with less variation contribution when using silver filled conductive ink are the following: aluminum coated with Aquaseal^{TM} insulator, low temperature (85°F), and UC heating feature as heat source to cure the ink.

Table 3.8: One-way ANOVA of Conductivity vs. Substrate, Substrate Temperature, and Curing Method for Conductive Ink

```
One-way ANOVA: Conductivity versus Substrate

Source     DF     SS    MS     F      P
Substrate   3  11.00  3.67  1.93  0.157
Error      20  37.98  1.90
Total      23  48.97

S = 1.378   R-Sq = 22.45%   R-Sq(adj) = 10.82%

One-way ANOVA: Conductivity versus Substrate Temp

Source          DF     SS    MS     F      P
Substrate Temp   1   1.28  1.28  0.59  0.451
Error           22  47.70  2.17
Total           23  48.97

S = 1.472   R-Sq = 2.60%   R-Sq(adj) = 0.00%

One-way ANOVA: Conductivity versus Curing Method

Source         DF     SS    MS     F      P
Curing Method   2   1.57  0.78  0.35  0.711
Error          21  47.41  2.26
Total          23  48.97

S = 1.502   R-Sq = 3.20%   R-Sq(adj) = 0.00%
```

Test for equal variances for conductive ink

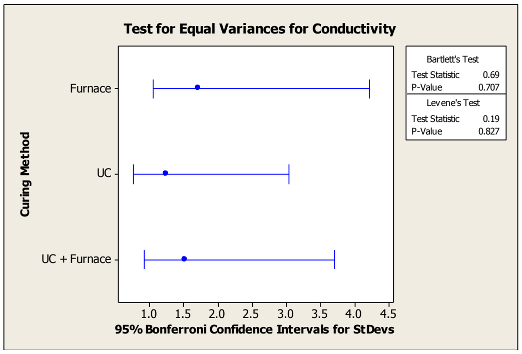

Figure 3.17: Curing method levels.

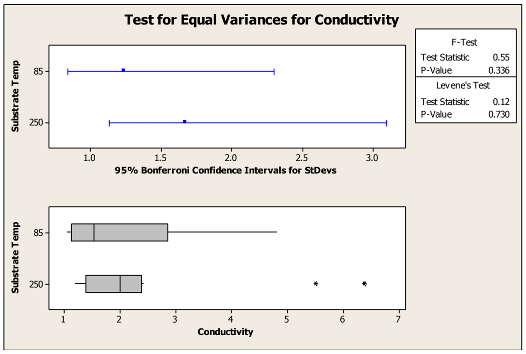

Figure 3.18: Initial substrate temperature.

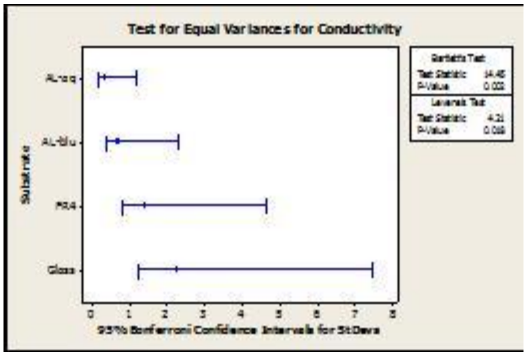

Figure 3.19: Substrate levels.

3.4.2.3 Statistical Analysis for Dielectric Ink

The experiments were repeated for the dielectric ink. The hypotheses remained the same as the above results. The response is resistivity expressed in MΩmm. The results are shown in Table 3.9 and Figure 3.20.

Table 3.9: Response Table for Resistivity Means for Dielectric Ink

```
          Response Table for Means
          Substrate                Curing
Level          Temp  Substrate   Method
1             48.39      48.11    49.39
2             50.97      43.44    46.60
3                        49.50    53.06
4                        57.68
Delta          2.58      13.24     6.46
Rank              3          1        2
```

Substrates represent the largest variation, followed by curing method and then the substrate dispensing temperature. One-way ANOVA is carried out to verify statistically significant difference among the levels (see Table 3.10). The F value from the ANOVA is F = 7.02, which falls very far from the F = 1 value expected if there are no differences between the means.

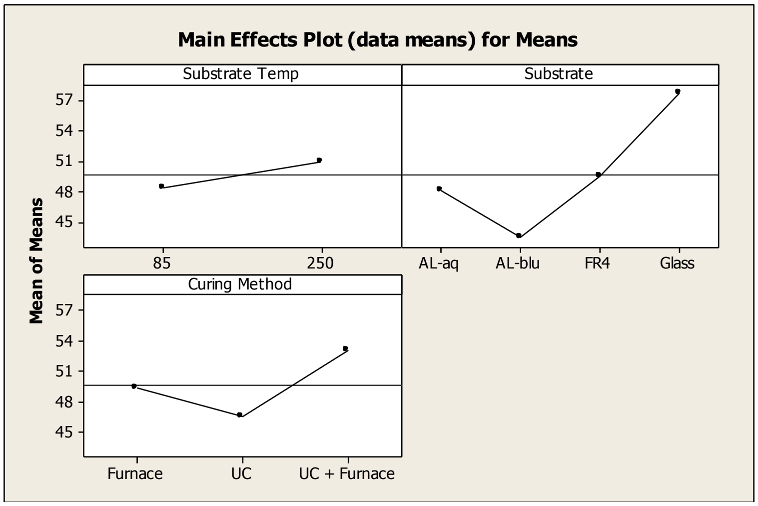

Figure 3.20: Response table for resistivity means for dielectric ink.

The p-value p = 0.002 provides evidence that the average resistivity is different for at least one of the substrates from the others when α = 0.05. Thus, the multiple comparison results need to be interpreted to evaluate where the differences exist among the substrates.

Table 3.10: One-way ANOVA of Resistivity Versus Substrate for Dielectric Ink

One-way ANOVA: Resistivity versus Substrate

```
          Source      DF       SS      MS      F       P
          Substrate    3    632.7   210.9   7.02   0.002
          Error       20    600.6    30.0
          Total       23   1233.3

          S = 5.480   R-Sq = 51.30%   R-Sq(adj) = 44.00%


Individual 95% CIs For Mean Based on
                           Pooled StDev
Level    N    Mean  StDev  -----+---------+---------+---------+----
AL-aq    6  48.106  5.154         (-------*-------)
AL-blu   6  43.437  5.752  (------*-------)
FR4      6  49.503  6.715            (-------*------)
Glass    6  57.678  3.921                          (-------*-------)
                           -----+---------+---------+---------+----
                             42.0      48.0      54.0    60.0
```

Tukey’s honest significant difference (HSD) test was used to provide multiple comparison intervals (see Table 3.11). When statistically comparing means using Tukey’s test method every possible pair of treatment is considered; their means are substracted and compared to the critical value w_{α}.

$$w_{\alpha} = \frac{S_{\varepsilon} Q_{\alpha,k,df_{\varepsilon}}}{\sqrt{n}}$$

where $Q_{\alpha,k,df_{\varepsilon}}$ is the critical value of the Studentized range distribution. $Q_{\alpha,k,df_{\varepsilon}}$ is a function of the significance level α, the number of treatments k, and the number of errors degrees of freedom for the ANOVA df_{ε}. If the difference between the means $\Delta X > w_{\alpha}$, we can conclude that those means are significantly different from each other [13].

Table 3.11: Tukey’s Test of Multiple Comparison Intervals for Dielectric Ink

Means with the same letter are not significantly different				
Tukey's Grouping		Mean	N	Substrate
	A	57.678	6	Glass
B	A	49.503	6	FR4
B		48.106	6	AL-aq
B		43.437	6	AL-blue

w_{α} = 8.855

With a 95% confidence interval, our experiment has k = 4 treatments, and df_{ε}. = 20, S_{ε} = 5.48, and n = 6, as shown in the ANOVA Table 3.10. In reference 13 of this paper, Appendix A, Table A.7, we can find that $Q_{0.05,4,20}$ = 3.958. Performing the calculations for this simple formula: w_{α} = 8.85.

When the dielectric ink is dispensed over glass it results in the highest mean resistivity value, thus it is not statistically significantly different from when dispensed on FR4, which has the second largest mean resistivity value. Nonetheless, FR4 is not statistically significantly different from AL-aq or AL-blue which have the two lowest mean resistivity values respectively, but the last two are statistically significantly different from glass.

In order to formulate design guidelines for the use of dielectric inks, tests for equal variance were performed (see Figure 3.21, 3.22, and 3.23).

The test for equal variances graphs indicate which level of each variable contributes with less variation to the process while fabricating an electrical component. Glass substrate, UC and furnace curing method, and 250F substrate temperature are the optimum parameters in order to reduce resistivity variation.

Test for equal variances for dielectric ink

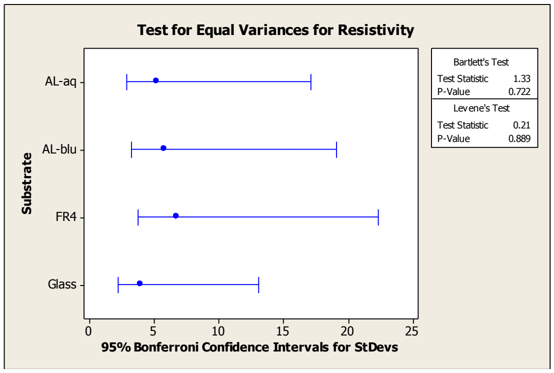

Figure 3.21: Substrate levels.

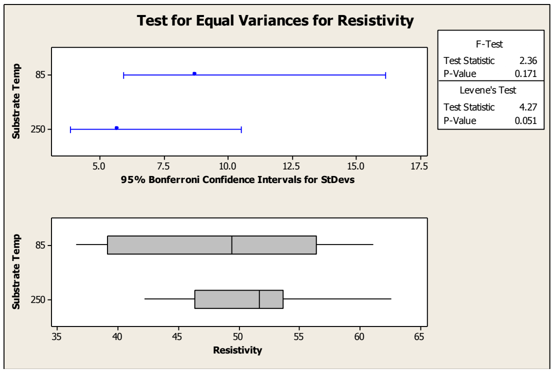

Figure 3.22: Initial substrate temperature levels.

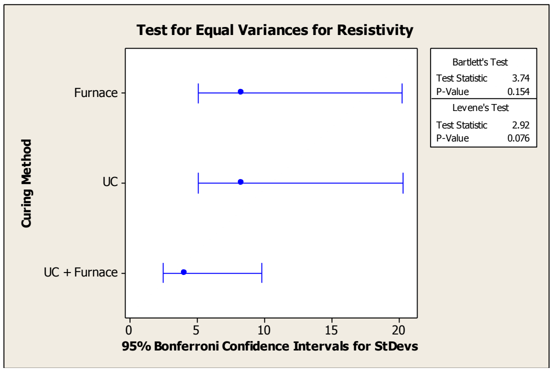

Figure 3.23: Curing method levels.

3.4.3 Embedding Method

Theoretically the preferred embedding method is direct welding over the DW traces because it would involve less process steps. Therefore, the first attempt was to weld directly on top of the DW traces, 0^o, 45^o, and 90^o taking as reference the sonotrode's movement. The procedure was to apply an insulator coating with a small brush on top of a layer of ultrasonic consolidated aluminum 3003; with approximate dimensions of 4" x 0.3" x 0.005" in order to leave some uncoated aluminum on both sides of the insulator, for welding (see Figure 3.24); After it dried, a conductive ink line of 50µm or 125µm was dispensed on top and then covered with an insulator coating with the same dimensions.

Welding was attempted on top of the traces using the following parameters: force = 1750N, feedrate = 40in/min, amplitude = 160, tension = 45. The result for 0^o was that the aluminum foil did not weld (see Figure 3.26), for 45^o it welded very poorly, and for 90^o aluminum welded on both sides but not on to the trace (see Figure 3.25). Nonetheless, the sonotrode partially destroyed the traces (see Figure 3.27), therefore the continuity test presented short-circuit failure.

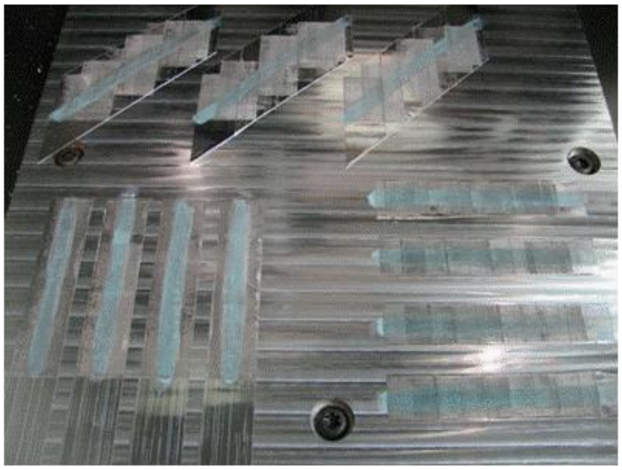

Figure 3.24: Experiment setup for direct embedding.

The test was repeated in an effort to achieve successful results by doubling the top and bottom insulator coating thicknesses to protect the conductive line. The results in terms of welding were the same for all angles, but the continuity test this time presented non-continuity electrical failure because of fatigue failure along the trace.

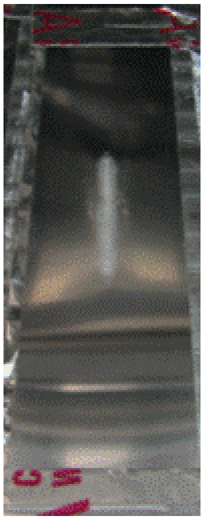

Figure 3.26: 0^{o} Direct embedding.

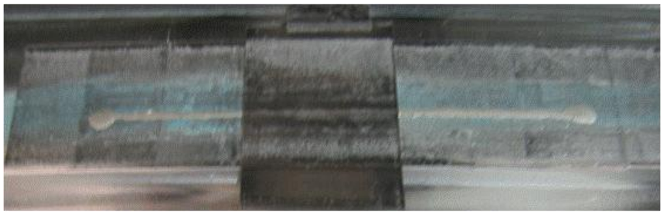

Figure 3.25: 90^{o} direct embedding.

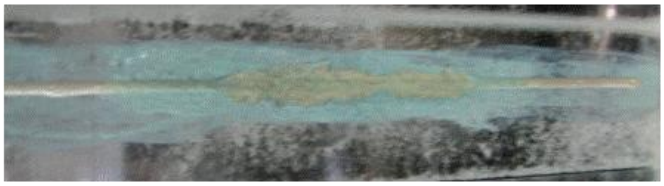

Figure 3.27: DW conductive trace after welding attempt.

The next step was to place one, two, or three strips of aluminum 1100 on top of each other on each side of the DW trace to reduce the pressure of the sonotrode on the trace (see Figure 3.28). We observed poor welding at 0^{o} and 45^{o} (see Figure 3.29) and fairly good welding at 90^{o} (see Figure 3.30). 0^{o} and 45^{o} failed continuity after the first welded layer. For 90^{o} the failure happened after subsequent layers of aluminum welded on top of the trace. The samples with one and two Al1100 strips failed continuity on the second layer and the ones with three strips failed on the third layer. None of the direct embedding trials were successful.

Channels were implemented at 0^{o}, 45^{o}, and 90^{o}. The channels' dimensions were 4" x 0.3125" x 0.02" (see Figure 3.31). An insulator coating of approximately 0.01" in thickness was manually dispensed into the channel with a small flat spatula. The traces were dispensed and cured, and then the channel was filled up with insulator. Welding was successful on all samples, although the 45^{o} samples presented some difficulties due to foils warping during the sonotrode pass.

Figure 3.28: AL1100 strips used to embed traces.

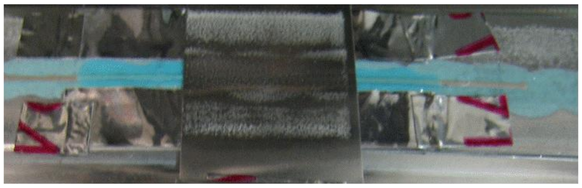

Figure 3.29: 0^{o} embedding with Al 1100.

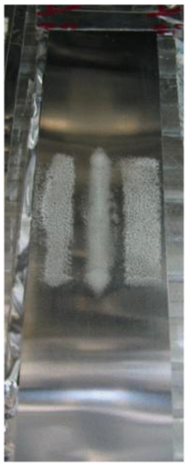

Figure 3.30: 90^{o} Embedding with Al 1100.

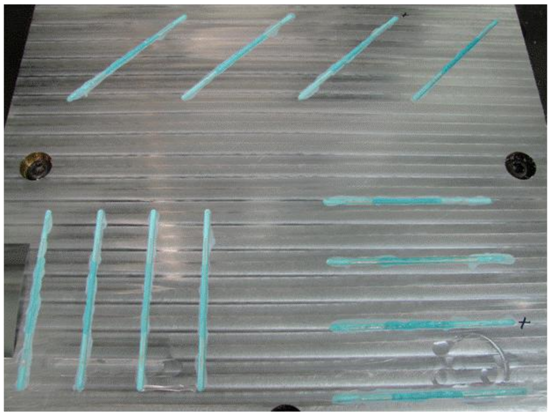

Figure 3.31: Experiment setup for embedding using channels.

Thus, all samples passed the continuity test. Hence a dramatic increase in the resistance values of the traces were appreciated; from approximately 1.5 ohms to about 30 ohms. For future studies, the effects of this increase will be evaluated on a circuit.

3.5 Discussion

3.5.1 CNC machine Uncertainty Analysis

After analyzing the obtained data using a 95% confidence interval, we can conclude that the accuracy of the XY-axis of the CNC machine is 0.000568” ± 0.002” (14.43µm ±100µm) and its repeatability is 0.001327” ± 0.002” (33.70µm ±100 µm). This accuracy and repeatability are acceptable for our initial applications; fabricating conductive traces and passive electronic components. Therefore, the DW dispensing unit can be effectively utilized without further modifications to the integrated UC-DW system.

3.5.2 Curing Method evaluation

The heat plate feature of the UC machine was evaluated to test its curing capabilities for the resistive, conductive, and dielectric inks. After conducting experiments for three inks with different properties, on different substrates, dispensing them at different temperatures, and curing them using various methods several design guidelines are apparent. The optimum parameters are summarized in the following table (see Table 3.12)

Table 3.12: Optimum Parameters for Each Ink

Inks	**Substrate**	**Initial Substrate Temperature**	**Curing Method**
Conductive	Aluminum w/aquaseal	30C ~ 85F	UC
Resistor	FR4	30C ~ 85F	UC
Dielectric	Glass	120C ~ 250F	UC + Furnace

These parameters can be used as a baseline for the fabrication of electronic components. Nonetheless, other factors have to be considered in order to establish design standards for embedding in UC. When inks are dispensed on a substrate at temperatures near or above the suggested curing temperature, generally the binder in the fluid begins evaporating immediately when it comes in contact with the substrate; reducing the adherence properties of the material and increasing the surface roughness of the trace. Experimental observations include:

- Resistive ink resistance value is a function of the trace length, and has an inverse relationship with the curing temperature and time.
- Conductive ink and dielectric ink resistance value is independent of the trace length and is only determined by the curing temperature and time.

FR4 can be used as an alternate substrate, but aluminum is preferred in order to reduce process complexity. Glass was used as a substrate for comparison purposes, although it cannot be used for embedding due to its brittle properties. Aluminum with Aquaseal^{TM} coating proved to be a better option than Blue Insulator^{TM} in terms of variation reduction and temperature resistance. Among the evaluated substrates, aluminum with Aquaseal^{TM} insulator has the best combined effects, and will be recommended as the substrate to be used for all dispensed electrical traces.

3.5.3 Embedding Method

From the experimental results we conclude that the use of channels is more reliable than direct embedding; nevertheless direct embedding remains a challenge for future research. 45^o angle channels should be avoided to prevent poor welding quality issues. Advantages of using channels include the ability to embed components with larger dimensions than the tape width. It also enables the use of any set of welding parameters with less risk of damaging the traces. It was found, however, that care must be taken to make sure that the DW traces do not come in contact with the side walls of the channels to prevent short circuiting.

3.5.4 Design Guidelines

The following design guidelines were are recommended:

- The initial substrate temperatures for each ink will be standardized as per the experimental results; room temperature (85F) for conductive and resistor inks and 250F for the dielectric ink will be used.

- The UC heating feature proved to be effective to cure the inks; it will be used as a standard method to cure. The following are the process parameters to be used for dispensing and ink curing (see Table 3.13).

Table 3.13: Suggested Process Parameters

Inks	**Substrate**	**Initial Substrate Temperature**	**Curing Method**	**Curing Temperature**	**Curing Time**
Conductive	Aluminum w/aquaseal	30C ~ 85F	UC	120C~250F	10 min
Resistive	Aluminum w/aquaseal	30C ~ 85F	UC	120C~250F	30 min
Dielectric	Aluminum w/aquaseal	120C ~ 250F	UC	175C~350F	60 min

Circuits often need electronic components with specific values to achieve good performance. Tests were run using the previously suggested process parameters to cure the inks. The approximate resistance values obtained for each ink, which can be used as design guidelines for the fabrication of passive components and conductive traces, are shown in Table 3.14. As can be seen from this table, there is still significant variability in the resistance values achieved (a factor between 1.5 and 2) and thus care must be taken to design circuits that can work robustly over a large resistance range.

Table 3.14: Electrical Characterization Results

Inks	**Resistance**	**Length**
Conductive	0.7-1.4Ω	independent
Resistive	9-17Ω	Per mm
Dielectric	36-51MΩ	Per mm

Note that bulk resistivity of silver is 1.6×10^{-5} Ω mm [3]

3.6 Conclusions

The positional uncertainty of the CNC gantry system with the Smart Pump^{TM} installed is acceptable for simple circuit applications. Experimental results with combined UC/DW have enabled the development of design guidelines for the fabrication of conductive traces and passive components, such as capacitors and resistors. The effectiveness of the UC heat plate for curing was demonstrated for the standard aluminum substrate with Aquaseal coating as an insulator. Curing temperatures depend upon the ink being used. Embedding using channels proved to be more effective in terms of reliability of the embedded components. Future work includes designing and fabricating a circuit that will be encapsulated in aluminum – as a proof of concept to demonstrate the integrated UC/DW system capabilities.

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CHAPTER 4

USE OF DIRECT WRITE TO FABRICATE EMBEDDED ELECTRONIC ELEMENTS AS PROOF OF CONCEPT FOR COMBINED ULTRASONIC CONSOLIDATION AND DIRECT WRITE TECHNOLOGIES[3]

Abstract

General design and process guidelines were developed for the fabrication of embedded circuits using direct write to dispense passive electronic components and interconnects combined with Commercial Off-the-Shelf (COTS) electronic components, embedded into an ultrasonically consolidated metallic enclosure. Passive components such as resistors were fabricated in different shapes in an effort to tailor their electrical values. The performance of fabricated passive components was evaluated. Finally, an embedded touch sensor circuit with a Light Emitting Diode (LED) was fabricated as a proof-of-concept.

4.1 Introduction

Additive Manufacturing (AM) technology has emerged from modern world needs for faster product development, customized end-user products, and more compact designs. AM technologies produce 3-dimensional objects from digital data by adding layers of material together in a controlled fashion.

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[3] Coauthored by: Ludwing A. Hernandez, Brent Stucker, Miguel Leonardo, Utah State University.

Direct write (DW) technology, a subset of AM, have gained increasing interest from the electronics industry. DW is a collection of AM techniques which deposit small-scale traces of material, primarily to build up electronic circuitry. These technologies offer the potential for low cost, customized low volume manufacturing and component integration, which is important for Micro-electronic mechanical systems (MEMS) industry development. Highly compact and light-weight assemblies are generally the target applications for DW. The ability of DW to print onto virtually any substrate, including uneven surfaces, makes it very attractive for the fabrication of components for embedding in polymer or metal based additive manufactured parts [1].

One of the most promising metal based additive manufacturing technologies for electronics embedding is ultrasonic consolidation (UC) due to its capability to weld metal in a layer by layer fashion at or near room temperature. This opens up a possibility for the creation of “smart” structures intended for shape, size and weight constrained applications [2].

The capabilities of an integrated UC-DW system to fabricate structures with embedded circuits were explored and design and process guidelines for their successful fabrication have been outlined.

4.2 Background

4.2.1 Ultrasonic Consolidation for Embedding Electronic Components

The Solidica Ultrasonic Consolidation (UC) additive manufacturing process utilizes solid state ultrasonic welding to manufacture components from metal foil feedstock directly from CAD models at or near room temperature (< 400 F). The additive welding is enhanced by the subtractive capability of an integrated CNC machine, allowing 3-dimensional objects to be formed, including objects with complex internal channels, multiple material objects and structures with integrated wiring, sensors and electronic components. The result is a monolithic part with enclosed components, without any bolts [3].

UC's additive manufactured layers are approximately 150 microns thick, permitting small cavities to be built into the structure for inserting components at the right time during the build. Since the UC process can be stopped and re-engaged without any harm to the part it is ideal for integration with Direct write technologies to produce metallic parts with embedded DW fabricated electronic components [3].

4.2.2 Direct Write (DW) for Electronic Applications

Traditional deposition techniques used in the microelectronics industry are thin film and thick film processes. Thin film refers to the use of chemical or physical deposition such as chemical vapor deposition, evaporation, spin coating, sputtering or plating to deposit a layer of material. Patterns are formed using photolithography or etching. Thick film process use screen printing to deposit ink or paste of electronic materials and then need to be cured at temperatures ranging from 300 ^{o}C to 900^{o}C. Both methods require masks, can be expensive, time consuming and limited in feature capability. DW can be used to produce these same patterns, but are controlled directly by a computer-driven deposition tool, and can thus be used in the microelectronics industry in place of traditional thin and thick film processes. The same or better results can be achieved by

DW without the need of masks (pholithography, etching, etc.) at much lower costs and using lower curing temperatures [4].

The need for high-density microelectronics requires integration of diverse materials, use of nontraditional substrates, and rapid prototyping. Traditional methods such as screen printing and lithography become very complex processes for the requirements of today. CAD/CAM controlled DW is intended to precisely deposit small size functional and/or structural materials on to a substrate, without the use of masks [1]. One good example of such a method is the nScrypt Smart Pump^{TM} (see Figure 4.1), a high precision micro-dispensing pump currently capable of 50µm resolution printing, 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 [5]. With a wide range of fluid viscosity (1 – 1,000,000 cp) the Smart Pump^{TM} is able to print almost any slurry such as conductors, resistors, dielectrics, magnetic materials, and chemically sensitive material structures. Some systems can be equipped with a laser positioning feedback system, enabling it to dispense on flat, curvilinear, round, flexible, irregular or inflatable substrates [6].

According to Chrisey [1], the most used materials for electronic applications are silver, gold, palladium, and copper for conductive lines; polymer thick film and ruthenium oxide-based pastes or inks for resistors; and metal titanate-based pastes or inks for dielectrics.

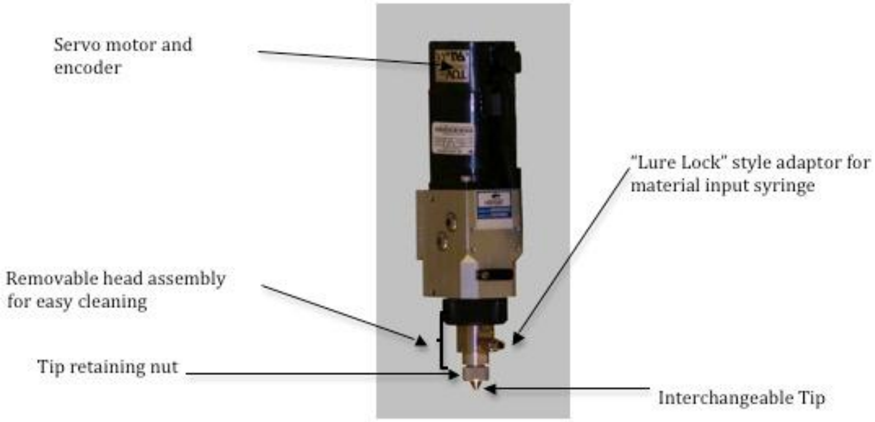

Figure 4.1: Schematic of the nScrypt Smart Pump^{TM} Direct-write system [7].

The main drawback of DW based systems is that the inks must typically be post-processed, using methods such as thermal, laser or UV curing, to achieve the desired properties for most end-use applications.

The curing process initiates the polymer flow of the solvent allowing it to evaporate and leaving room for the metal particles to establish contact. This final process directly affects the electrical properties of dispensed features. In the case of conductive traces with metallic nano-particles, the post-cured resistivity measurements can approach close-to-bulk values [6].

4.2.3 Passive Electronic Components

A common accepted category heading for types of electronic components are active and passive electronic components. Active components provide gain to current or direct current; for example transistors and diodes. On the other hand, passive components do not provide gain or direction, thus they can slow current or store electrical energy;

examples include resistors, capacitors, inductors and transformers. Using active and passive electronic components, complex electronic systems can be created [9].

Resistance of an electric circuit is considered a scalar property which describes the rate at which electrical energy is converted to thermal energy. Measured in ohms, resistors can limit the amount of current and the potential difference in certain parts of a circuit. One ohm is defined as the potential difference between two points of 1 volt, associated to the current of one ampere (one coulomb per second) and a thermal dissipation on one watt (one joule per second). Changes in resistance value are associated with physical, mechanical, and chemical changes in the structure and materials of a resistor [10].

Direct write technologies are developing to be an enabling tool to produce well-controlled resistance values. Most resistors for integrated electronic applications are required to display good tolerance from their predetermined value, and to have small temperature coefficients of resistance (TCR). The key to achieving a resistor with specific resistivity and low TCR lies in tailoring composition of the material. Two approaches can enable desired resistance values. Conductivity can be lowered by mixing a conductive ink with an insulative paste. Another method is to dispense very thin and/or elongated paths to achieve reproducible results. Typically, material formulations for direct write have to be designed for processing at temperatures below 400^{o}C. The challenge is the achievement of proper conductive, insulative, or semiconductive phases without relying on high temperature sintering [1].

Capacitance is a physical property enabled by two electrically conductive surfaces separated by a dielectric material, such as air, vacuum, or any material of very high resistivity. When an electrical potential is applied across the conductive plates the charge is drained from one conductive surface and accumulates in the opposite; the extent to which this phenomenon occurs depends on the time and amount of voltage applied. The farad, unit of capacitance, is defined as the amount of capacitance that will produce a current of one ampere during a voltage change of one volt per second (1 farad = 1 coulomb per volt). Because the farad is a large measurement typically picofarads (10^{-12}), nanofarads (10^{-9}), and microfarads (10^{-6}) are used [10].

4.2.4 Embedded Electronics

The development of embedded passive electronics, active component interconnects and power source elements opens opportunities for new levels of miniaturization. By embedding circuits inside a part a significant weight and size reduction can be achieved. Moreover, embedded circuits typically show enhanced electrical performance and enables function integrations to create “smart” structures [11].

Patent application number US20070040702A1 “Method for Creating Highly Integrated Satellite Systems,” describes a process for fabricating integrated satellite systems and electronic systems using advanced additive manufacturing techniques, such as ultrasonic consolidation and direct write. Integrating ultrasonic consolidation with direct write capabilities provides the ability to create features such as encapsulated devices, directly from a computer aided design (CAD) rendering, with the ability to automatically write networks of conductive, resistive, and insulator material traces on conformal surfaces directly onto one or more internal or the external surfaces of the structure to perform a predetermined function. Employing the mentioned technologies provides the ability to fabricate structures with encapsulated electronics and computational and processing components, as well as wiring, sensors and antennas within a dense metal matrix, such as aluminum. This process can be carried out in a single operation flow at relatively low cost and high flexibility for design changes; having as a result high performance products. The main advantage of this process is the complete elimination of tooling as well as enhanced geometric complexity, novel material combinations, and reduction of human-related errors in manufacturing. As a result, production times can be significantly reduced from months to days by automating traditionally labor-intensive operations [12].

4.3 Experimental Plan

A previous paper titled “Design and Process Guidelines for Effective Fabrication of Structures Combining Direct Write and Ultrasonic Consolidation” describes dispensing, curing, and embedding methods. These guidelines were implemented to design and fabricate a proof of concept part involving an aluminum enclosure with insulator coating, DW passive components, commercial off-the-shelf (COTS) surface mount actives and passives, all interconnected by DW conductive traces and embedded using UC.

To show DW-UC integrated system capabilities, an embedded touch sensor circuit was fabricated using DW passive components and surface mount COTS components. The circuit was fabricated in the order described in the process flow chart. As per the previously developed design guidelines the touch switch was printed onto a continuous surface of aluminum 3003 to prevent from short circuiting; previews coating of the surface with thermo set insulator was done by hand with a pallet to insulate the dispensing area. It was applied and dried at room temperature to obtain an acceptable surface flatness. Because the width of the channel is greater than a tape width the part was build at 45^o angle to completely cover it. The conductive traces were dispensed onto the insulator preventing them to touch any un-insulated aluminum surface or corner. The resistors where obtained with the required values using lessons learned from the resistor tailoring experiments.

4.3.1 Touch Sensor Design

The objective of the part is to light a light emitting diode (LED) when a certain interconnecting line is touched, which stays on until touched again. A circuit was designed to perform the touch sensor function [13, 14] (see Figure 4.2).

A combination of embedded DW printed components and COTS was implemented for the fabrication of a human touch sensor.

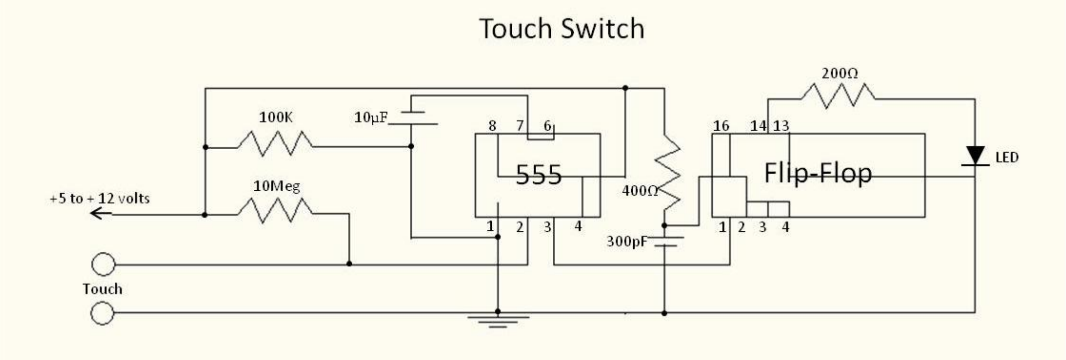

Figure 4.2: Touch switch circuit.

This circuit was designed with a “555 timer” integrated circuit (IC) that senses human capacitance, when touched it triggers a logic pulse (0 or 1) to a SN74F112D “J-K negative-edge-triggered flip-flop” IC, which upon the received signal opens or closes the current flow to the output. In addition to the mentioned IC’s the circuit required four resistors (200ohm, 400ohm, 100Kohm, 10Mohm), four capacitors (300pF, 10uF), and a light emitting diode (LED). Three resistors and a capacitor were fabricated using DW technology as well as the interconnecting conductive traces, the rest of the parts are COTS components.

When touched in a specified trace the electronic circuit lids a Light Emitting Diode (LED) that stays on until it is touched a second time to turn it off. In this particular case our final product did not have any size constraints or requirements, thus the metallic structure was designed so it can hold the interconnected electronic components.

4.3.2 Direct Write Embedded Structure Process Guidelines

The process plan to fabricate the embedded component will be explained in this section. Considering the aforementioned design guidelines, the process to fabricate an embedded circuit including resistors, capacitors, COTS components and conductive traces embedded in a UC enclosure is in Figure 4.3.

In general, to fabricate DW circuitry including external components embedded in a metallic substrate, first weld the base of the part; make sure it is completely flat. Drill the channels needed with the minimum possible width and enough clearance so that the sonotrode does not apply force directly onto the parts.

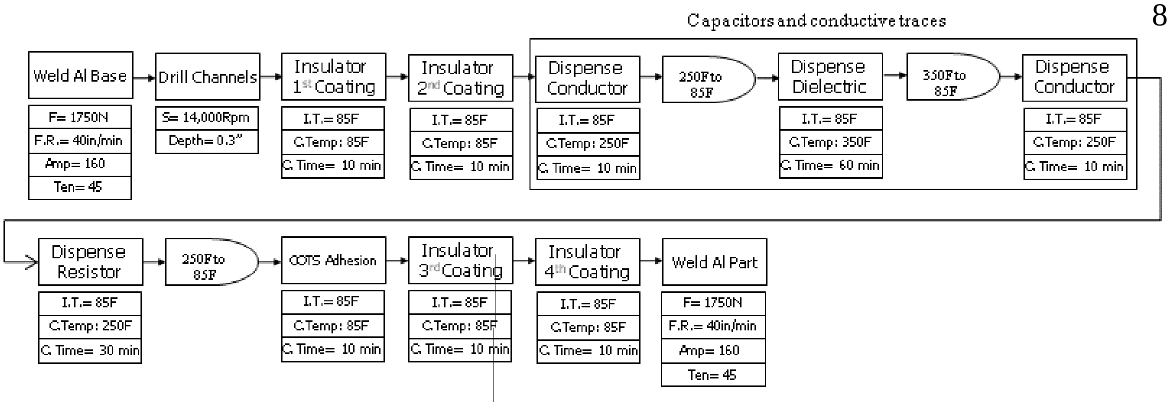

Figure 4.3: Flow chart to fabricate embedded circuitry in a metallic enclosure.

Dispense or manually apply two layers of thermo set insulator onto the metallic substrate to prevent circuit shorting. Start by dispensing the conductive ink interconnecting traces and the bottom capacitor layer; then cure. After cooling, dispense a shape with dielectric ink on top of the previously deposited conductive layer and cure. Cool the substrate again and finalize the capacitors by dispensing the top conductive layer and cure. Make sure the top and bottom conductive layers never come in contact, thus leave out a trace connected to each conductive plate to interconnect the capacitor with the rest of the system. Next, resistors need to be dispensed. Proceed to glue the COTS components in their places using conductive epoxy. Test that the circuit is operating correctly and cover it with thermo set insulator. Finally, weld on top of the channels until the part is finished. Remember to design appropriately the connections for the voltage source and the output signal.

4.3.3 Resistor Tailoring Study

There are two ways of tailoring resistor values when printing: by controlling the length and width or by mixing resistive and dielectric material. A study was performed to create guidelines for the fabrication of resistors with specific ohmic values based on 104-

18 Electrical Resistor Ink. The used substrate was Aluminum 3003 with Aquaseal thermoset polymer coating. The samples were cured with the UC machine heat source at 250F for 30 minutes. A tip size of 150μm was used to dispense the resistive ink. The purpose of the study was to determine which shows a higher resistance value in order to reduce space requirements for resistors in any given circuit. The printed shapes were 0.7in x 0.8in rectangles, 2in straight lines, 1in long step function shape, and 1 in long 45^{o} and 60^{o} angles triangular function shape (see Figure 4). A second study was performed in an effort to achieve high ohmic value resistors. Resistive and dielectric ink was mixed by volume in the following percentages: (resistor-dielectric) 70%-30%, 50%-50%, and 30%-70%. A 0.25 inch long, 0.02in line width was used.

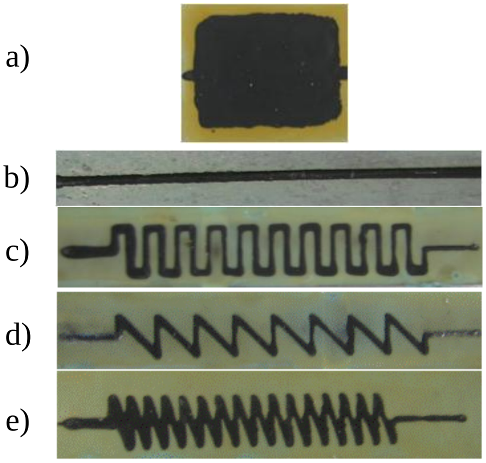

Figure 4.4: Resistors: a) rectangle, b) straight line, c) step function, d) 45^{o} triangular function, e) 60^{o} triangular function.

4.4 Results and Discussion

4.4.1 Building Process for an Embedded Touch Sensor Circuit

The touch sensor circuit was sketched in AutoCAD, then was converted to Gcode to DW fabricate resistors, capacitor, and interconnecting conductive lines (see Figure 4.5).

The enclosure was modeled in Solid Edge with the appropriate dimensions to hold the previously designed circuit (see Figure 4.6). The general process flow explained before was used as guideline for the fabrication of an embedded touch sensor.

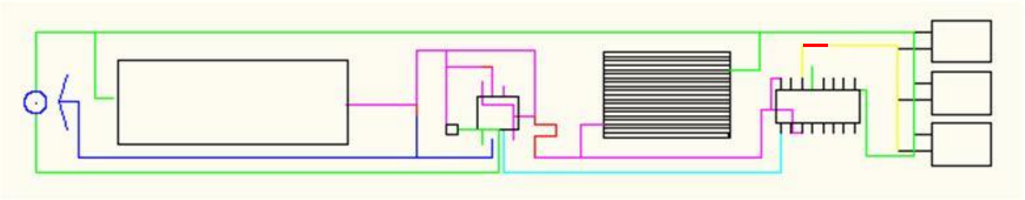

Figure 4.5: Drawing of the touch sensor circuit including COTS components.

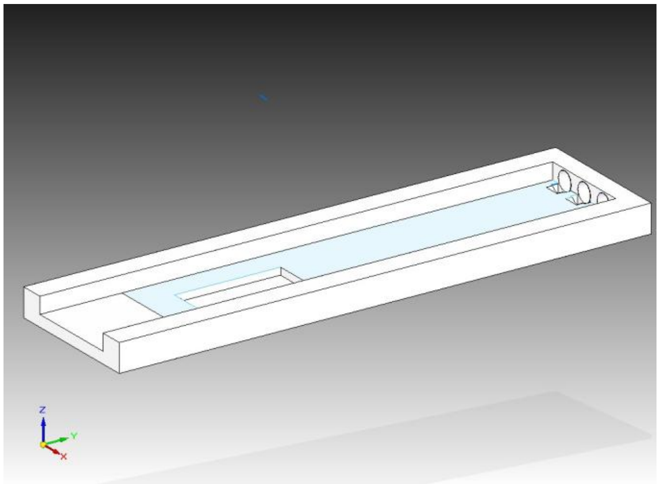

Figure 4.6: CAD model of touch sensor metallic enclosure.

4.4.1.1 Base part formation

Welding is a crucial step since it is the housing to the embedded electronics and must be able to completely hold the components on an internal or external surface. It is important to consider that the traces should be printed onto a continuous surface to prevent short circuiting. Since our machine is designed to automatically feed 0.9 inches wide aluminum tapes, when traces are printed onto a typical UC surface, short circuits can occur at periodic small gaps between foils (see Figure 4.7).

This fault can be prevented in two ways: by welding metallic sheets which cover the entire area of the circuit (which eliminates gaps between foils) or by using the aluminum base plate as the substrate on which to print the circuit and then continue building over it until the part is finished. Our part was able to be fabricated by machining a channel into the aluminum base plate, onto which the traces were printed and then embedded.

4.4.1.2 Machine channels and features

The channel was designed deeper than the highest embedded component to prevent the sonotrode from smashing it while embedding.

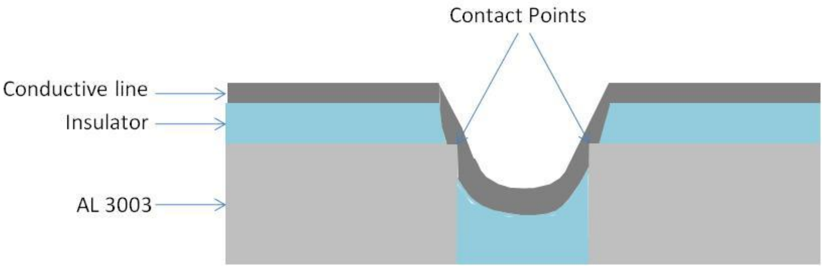

Figure 4.7: Sketch of gaps between aluminum tapes.

It may have different levels, but no trace should come in contact with an edge of the channel because the insulator is not capable of protecting the corners and the circuit will short when coming in contact with the metal (see Figure 4.8).

4.4.1.3 Apply substrate insulator coating

The insulator coating used was Aquaseal™, which is electrically nonconductive. It was manually applied with a plastic pallet at room temperature to obtain a flat and smooth surface for the direct write tip; to maintain a constant height in order to print constant thickness traces (see Figure 4.9).

4.4.1.4 Dispense inks (Conductive, dielectric, resistive)

Inks were printed in a continuous manner to enable current flow (see Figure 4.10). The width of the traces affects the conductivity of resistor inks; however for conductive inks the difference is negligible. The touch sensor includes two direct write manufactured resistors with 200Ω and 400Ω values, which were tailored to those values by varying length while maintaining constant line width (see Figure 4.10).

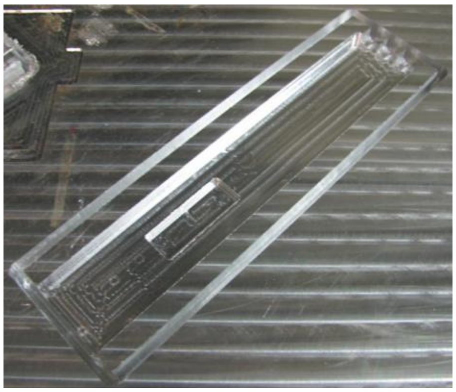

Figure 4.8: Machined aluminum 3003 part base.

Figure 4.9: Aquaseal themoset insulator coating.

4.4.1.4.1 Resistor tailoring study results

The average resistance results for the printed shapes (2in straight lines, 0.7in x 0.8in rectangles, 1in long step functions shape, 1 in long 45^o and 60^o angles triangular functions shape) were 280Ω, 59Ω, 4.62KΩ, 3.18KΩ, and 2.25KΩ respectively. This illustrates that thin elongated lines give higher resistance values. The step function kind of a shape was used to obtain 400Ω and a straight line, 200Ω resistance. 10MΩ and 100KΩ resistors were also required for the touch circuit. An ink mixing study was performed in an attempt to DW fabricate high value resistors. The results for the resistor and dielectric ink mixing (70%-30%, 50%-50%, 30%-70%) were approximately 400Ω, 1KΩ, and 15MΩ, respectively, though the used Inductance-Capacitance-Resitance (LCR) meter showed up to 35% variability in the measurements for the 15MΩ resistor.

For this experiment surface mount COTS resistors were used, as the repeatability of high resistance traces using ink mixtures was low. Future studies will include variation reduction studies for high value resistor tailoring.

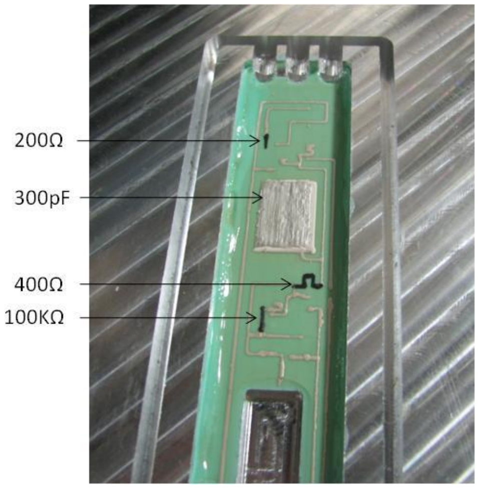

Figure 4.10: DW fabricated passive components interconnected with silver-filled conductive traces.

4.4.1.5 COTS components mounting

Surface mount COTS components were adhered to their correct locations after all DW traces were printed. Silver-filled epoxy was used to paste the surface mount components by their pads to the conductive traces (see Figure 4.11). The use of silver-filled epoxy enhances the contact between the already cured traces and the COTS components to improve conductivity as opposed to just making surface contact onto the conductive traces.

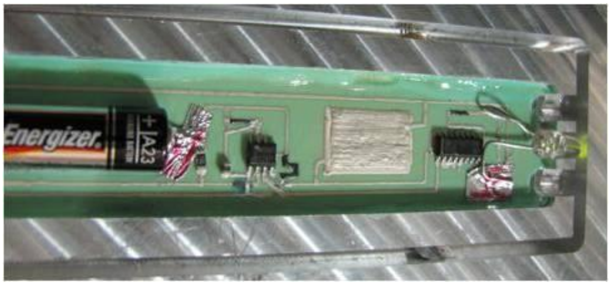

Figure 4.11: Touch sensor circuit with lid LED.

4.4.1.6 Apply top insulator coating

A study was carried out to compare the resistance values of the conductive and resistive traces before and after an insulator layer was applied onto them as well as after embedding in a channel. The samples used were 3 inches long and 150 µm wide embedded in channels 4 inches long by 0.325 in wide. The following are the results (see Table 4.1):

Table 4.1: Average Resistance for Conductive and Resistive Inks

	Average resistance		
Ink	**Before top insulator coating**	**After top insulator coating**	**After embedding**
E1660 Polymer Thick Film Conductive Silver Coating	1.4 Ω	2.2 Ω	1.8 Ω
104-18 Electrical Resistor Ink	360 Ω	372 Ω	365 Ω

The observed resistance fluctuation phenomena after the top insulator coating dries is attributed to particle interchange between the interfaces. Since the insulator is non-conductive the particles that come in contact with the conductive trace surface causes its resistance value to rise. The substrate was heated up to 250°F for better welding while embedding, simultaneously further curing the inks, which causes the resistance value to decrease. Optical microscope pictures were taken to learn about embedded trace interfaces with the insulator and the metallic structure (see Figure 4.12).

The observed cracks in the traces that were embedded without channels resulted in discontinuities along the matrix, which disabled the current flow through the conductive line. The channel method was used to embed the touch sensor circuit.

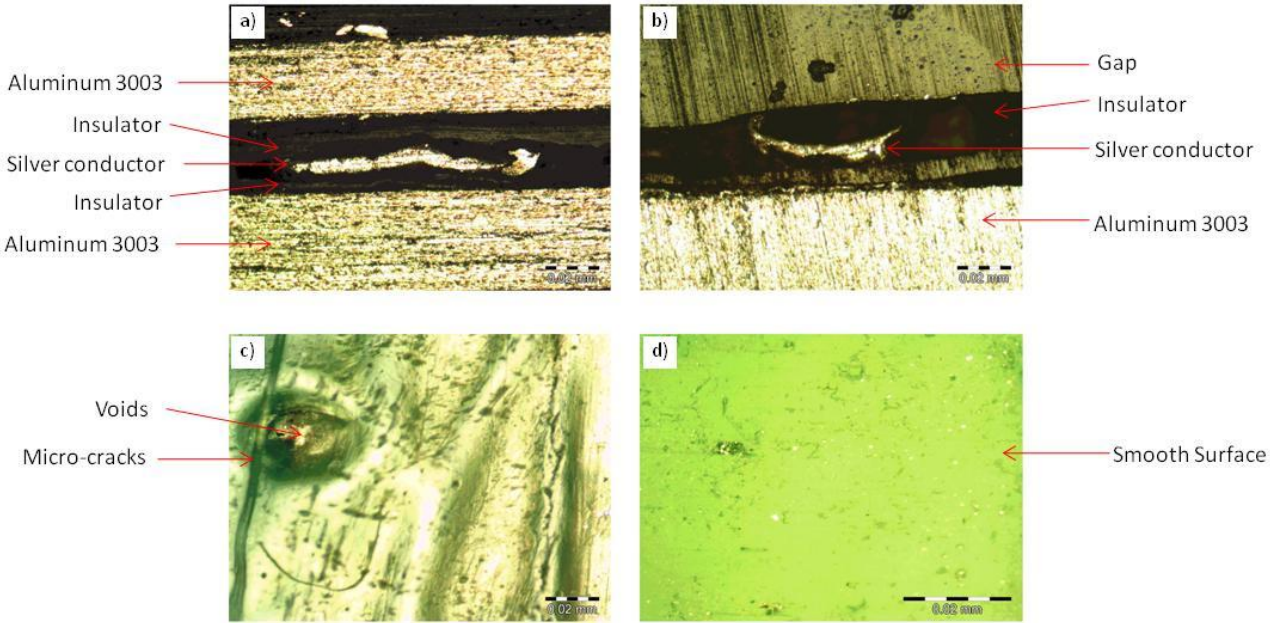

Figure 4.12: Embedded traces: a)front view of embedded trace with no channel, b) front view of embedded trace with channel, c) top view of trace surface that was embedded without channel, d) top view of trace that was embedded using a channel.

The channel height after insulator coating application was 0.16 in, leaving a clearance of 0.08 in from the tallest embedded components, which are the integrated circuits (IC) with a height of 0.08in max. This proof of concept part was not completely encapsulated in order to leave exposed the traces that actuate the system when touched, as well as the battery that powers the circuit, which eventually will have to be replaced. For future demonstrations, similar circuits can be completely embedded, but for initial demonstration purposes a gap was left on a side of the structure to connect the battery.

The resulting circuit is powered from a 12 volt battery connected to the traces using regular flexible wire (0.016 outer diameter (OD)) adhered from the battery poles to the conductive traces with silver filled conductive epoxy. Three LEDs were connected to the traces with conductive epoxy. A touch lit the LEDs, staying on until touched again, indicating that the circuit is working properly.

4.4.1.7 Embedding Process

The part was built at a 45 degree angle with respect to the sonotrode welding direction to help the embedding process. The channel that contains the circuit has the width of 0.09 inches, which is close to the default aluminum 3003 tape on the machine, thus the part would not be possible to embed at a 0 degree angle. It was possible to embed at a 90 degree angle but 45 degree results in a more robust welding for encapsulating relatively wide channels without the use of support material.

4.4.1.8 Testing of the DW circuitry

In each stage of the process the DW dispensed traces were tested to check their proper function, continuity, and resistance value. Two resistors were tailored to a resistance value of 200Ω and 400Ω and their values were re-measured after each subsequent step and their values remained within a 10% range. Also non-continuity was tested for traces that are very close to each other. Capacitance was measured for the fabricated capacitor of 300pF. The COTS components were adhered to the conductive traces; continuity was assessed to check for proper positioning. Finally, the LED responded to touch, as a proof that everything in the circuit was properly installed.

4.4.2 Benefits of the Integrated System

The integration of the Solidica Formation^{TM} ultrasonic consolidation machine and the Smart Pump^{TM} 100 direct write nozzle into a single apparatus enables the fabrication of novel structures with embedded circuitry impossible to achieve by traditional manufacturing methods. The UC machine can manufacture metallic parts in a layer-by-layer fashion by ultrasonically welding metal foils (i.e., aluminum, stainless steel, copper, and titanium) at near-room temperature. On the other hand, the direct write nozzle can print traces of inks, pastes or slurries, directly from a digitally predefined sketch, onto any flat surface to create complex shaped electrical paths.

The UC-DW apparatus at Utah State University main benefit is its ability to rapidly fabricate custom “smart” metallic structures with complex shaped embedded electrical traces without the use of tooling or masks. These kinds of structures are very useful for applications such as data acquisition through sensors or antennas located within the structure, as well as computational and processing components.

The direct write Smart Pump^{TM} 100 attached to the UC gantry system has the capability of printing active and passive electronic components such as transistors, diodes, batteries, resistors, capacitors, inductors, transformers, and antennas with high accuracy. It was tested with the successful fabrication of resistors, capacitors and conductive traces with a printing accuracy of line widths down to 0.003in and distances between two lines down to 0.01in.

The UC-DW system in the Additive Manufacturing Laboratory at Utah State University will be used in the future to fabricate custom metallic parts with embedded electronics for naval and other applications.

4.4.3 Limitations of the Integrated System

Although the UC-DW system at Utah State University is ready to fabricate custom embedded structures some limitations may be considered during the planning and fabrication stages of embedded parts.

The integrated system faces some software limitations. Before dispensing any given set of traces these have to be sketched and converted to Gcode. Commercial software is utilized for these purposes; hence Gcode optimization is done manually in a text editor. Manually revising a couple of Gcode pages can take several hours and can also generate new errors in the Gcode that then need to be manually fixed.

Since the software used by the Solidica UC machine was not modified to include functions of the nScrypt DW system, the nozzle is manually activated by a push button. For this reason accuracy limitations are faced during the fabrication stages. It is possible to obtain feature sizes down to 0.01 in ("Feature" in this context is referred as the distance between two traces that cannot touch each other.) Features smaller than 0.02 in are only obtained using pen tips with OD of 0.002 in or smaller while also tightly controlling parameters such as air pressure, valve opening position, valve opening speed, and gantry moving speed. Ink dispensing starts and stops are key process steps that should be controlled by achieving the correct combination among the mentioned parameters for each specific ink rheology. "Dispensing height" is a variable that is limited by the operator’s intervention limiting the traces width repeatability. All these limitations result in less overall printing accuracy and can be improved by adding automation to the system, such as a PLC for automated starts and stops and a laser feedback positioning system for controlled dispensing height as well as enabling printing over 3D surfaces. Although these limitations exist the system was successfully used to fabricate electronic circuits including conductive wires, resistors, and capacitors with features down to 0.015 in.

4.5 Conclusions

The fabricated embedded touch sensor has demonstrated that the DW-UC integrated system is capable of producing complex shape aluminum parts with embedded circuitry. “Smart” structures can be fabricated for applications that need electronics protected from harsh environments or where size and weight of multi-functional parts are a constraint.

Some improvements to the UC-DW system would be beneficial for future studies. Further automation of the machines’ intercommunication by including in the ultrasonic consolidation Gcode program a function for the activation and deactivation of the DW valve’s routines would be highly beneficial for the quality and reliability improvement of the traces and passive components. Installing the conformal printing feature to this system would constitute a solid step towards a wide range of fabrication possibilities, including 3-dimensional circuitry. Finally, it would be interesting to add the video recording option to the camera that the system already holds for presentations and teaching purposes.

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CHAPTER 5

CONCLUSIONS AND FUTURE WORK

5.1 Conclusions

This thesis constitutes one of the first steps towards the combination of two promising technologies, Direct Write and Ultrasonic Consolidation, that will likely have an important impact in the future of Direct Digital Manufacturing. It was demonstrated that “smart” integrated structures can be fabricated using the Ultrasonic Consolidation and Direct Write. A touch switch was fabricated as a proof of concept to demonstrate the capabilities of the integrated system.

5.1.1 Direct Write and Ultrasonic Consolidation Integration

A Direct write dispensing nozzle system was integrated to an Ultrasonic Consolidation apparatus for the first time. The Smart Pump^{TM} was chosen as the ideal equipment for the integration with the Solidica Formation^{TM} ultrasonic consolidation machine due to its small size, reduced weight and dispensing capabilities. A safe, yet accessible place to install the nozzle and the control box to the ultrasonic consolidation machine was determined. A manual slider with graduated knob was used to attach the pump to the UC gantry system enabling the pump to have multiple positions. The systems where electronically integrated using a smart relay, enabling to work in a semi-automatic fashion. A process plan for the use of the UC-DW integrated system was standardized and used as reference for all the subsequent experiments.

5.1.2 Uncertainty Analysis

The accuracy and repeatability of the CNC gantry system in the Ultrasonic Consolidation machine was evaluated using an indirect method, which consists on building a certain part and then measuring key points. This study demonstrated that the CNC positioning accuracy of ± 0.004” and a repeatability of ± 0.001” with a 95% confidence interval. This uncertainty was considered acceptable for our applications in embedded electronics.

5.1.3 Curing Method

Design guidelines for each direct write ink (resistive, conductive, and dielectric) use in combination with the UC machine was evaluated through statistical analysis. The variables included were three curing methods (UC heat, furnace, and a combination of UC and furnace), four substrates (Aluminum with thermo set polymer coating, aluminum with thermo plastic polymer coating, Fire Retardant (FR4) polymer and glass) and two initial dispensing temperatures (85^{o}F and 250^{o}F). The optimum parameters where determined maximizing conductivity for the conductive ink, while minimizing it for the resistive and dielectric inks. For the conductive and dielectric inks the best initial substrate temperature to dispense is 85^{o}F, thus the dielectric ink conductivity is lower when dispensed over a substrate heated to 250^{o}F. The conductive ink best conductivity occurs when dispensed onto aluminum with thermo set coating using the UC heat plate feature. The conductivity is lowered for the resistive ink when dispensed onto FR4 and is cured using the UC heat plate. Finally, the dielectric ink has lower conductivity when dispensed onto glass and cure combining UC and furnace. When using E1660 silver filled conductive ink, dispensed in traces of 150µm or less and cured at 250^{o}F for at least 10 minutes, resistance values between 0.7Ω and 1.4Ω can be expected, the length of the trace is negligible. Many variables influence the value of the resistors, nonetheless in these initial experiments traces of approximately 150µm width where dispensed and cured for 30 minutes in the UC heat plate; values between 9Ω and 17Ω were obtained. Finally, the dielectric ink was also dispensed in 150µm line width and cured for 60 minutes on the heat plate; getting results in the ranges of 36MΩ to 51MΩ. These values were taken as a guideline for the upcoming experimentation.

5.1.4 Embedding Method

It was demonstrated that using a channel of slightly higher depth than the thicker component to be embedded is a more reliable method than direct embedding and gives more flexibility for COTS component embedding combined with direct write fabricated components. When embedding at 45^{o} from the sonotrode movement some unbonded areas where observed. The same did not happen for 0^{o} and 90o embeddings. For channels of less than 0.3" wide 0^{o} and 90^{o} orientation are recommender and 45^{o} for wider channels. While setting up the build remember to arrange the foils positioning so the edges are decoupled resulting in a brick-wall kind of orientation.

Using a conductive material such as aluminum to encapsulate electronics requires placing an insulator coating onto the substrate and on top of the traces prior to embedding. Sheet foils of material are required for the substrate where the traces are printed; conductive lines can easily short circuit in the small gaps between inherent to the tape deposition ultrasonic welding process.

5.1.5 Resistor Tailoring

Experiments to tailor resistors where done by varying the shapes of the lines and mixing the resistor ink with dielectric ink, which has a much higher resistive value. The step function shape resulted in greater resistance values than the triangular wave shape, the straight line and the filled rectangle. By mixing inks in different percentages a wide range of resistors values where obtained, from 400Ω to 15MΩ in 0.25” length samples. Nonetheless, the values were not easily repeatable,thus three different resistors where fabricated as concept proof for the touch switch, with 200Ω, 400Ω, and 100KΩ. Future studies can include the fabrication of resistors with specific values.

5.1.6 Touch Switch Design

Based on the results from the performed experiments integration of DW and UC, uncertainty analysis, curing method, embedding method, resistor tailoring, a circuit was designed for the fabrication of an embedded touch switch. The enclosure was done by the UC machine and the circuitry by direct write plus several COTS components. The developed design and process guidelines were used and a “smart” part with an embedded touch switch was successfully fabricated as a proof of concept.

5.2 Future Work

Taking as a base line the work presented in this thesis, further work can be done to improve the UC-DW system and its performance.

5.2.1 Direct Write and Ultrasonic Consolidation Integration

It is suggested for future studies to do an upgrade of the UC-DW system to work automatically. The PLC can be modified to include commands for the direct write pump directly from the programs Gcodes. A laser feedback system can also be added to the current system to enable printing over conformal substrates.

5.2.2 Curing Method

Other curing methods can be studied to increase the repeatability of the DW dispensed components, for example a laser can be suggested as curing method and it will reduce the waiting time for the plate to chill to room temperature and might give more stable resistance results. Other insulator coating, as well as other inks can be explored.

5.2.3 Embedding Method

Studies can be performed to embed 3D circuitry by printing onto several levels within the structure or different external faces. The laser feedback positioning system would be of great utility for this application.

5.2.4 Resistor Tailoring

There is great potential with the passive components that can be fabricated using the Smart Pump^{TM}. A variation reduction study can be done for the direct write fabrication of resistors, as well as capacitors, and the fabrication of inductors can be implemented for future studies.

5.2.5 Proof of Concept Part

The UC-DW integrated system has a big potential and additional work needs to be done to answers many questions that remain unanswered. Different DW materials can be explored for a wide range of applications. This work has laid a foundation for future work to be done in any of the aspects already studied or new ones such the integration UC and DW with integrated FDM apparatus, for the fabrication of a proof of concept part with a specific applications for an industry or government institution.

APPENDIXES

APPENDIX A

UC – DW SYSTEM GUIDEBOOK

Gcode programming: The Gcode should be arranged in a way to minimize the dispensing starts and stops or maximize line length in order to achieve better quality.

Direct write material set up: Usually materials need to be thoroughly mixed to a uniform consistency using a plastic or stainless steel spatula. Mix slowly to avoid the creation of bubbles. After intake to the syringe put the syringe in an upright position and wait for several minutes (if more viscous wait more minutes) for the bubbles to go away.

Pre-dispensing check: After setting up the Smart PumpTM with material in the syringe, but before using the system, it is recommended to check for any misalignment that the Smart Pump might have suffered. Place a level on top of the slider knob and manually correct any possible misalignment in the X direction and in the Y direction; also check the slider back for correct positioning of the vibration damper.

Dispensing height: A good dispensing height is 0.006”. An aluminum 3003 foil with that thickness can be used for the first time dispensing height set up and the graduated knob of the slider can be used for subsequent repetitions of the same dispensing height.

Substrate temperature: It is usually better to dispense with the substrate at room temperature. Heating up the plate causes more clogs in the pen tip as well as a fast drying effect in the ink that changes the surface texture of the trace and degrades its adhesive properties.

Pen tip size: Pen tips sizes offered by nScrypt Inc. go from 25µm to 175 µm (0.00098” to 0.0069”) outer diameter (OD). If the diameter of the pen tip is smaller the trace width will be less. A general rule researched by nScrypt is that the solid particles in the ink must be 10 times smaller than the inner diameter of the pen tip for flow to occur.

Dispensing parameters: To print good quality traces a good combination of parameters should be obtained for each material rheology. The following are the parameters that must be controlled:

Material feed pressure: The applied air pressure depends upon the ink rheology and will determine the flow speed. Establish air pressure as low as possible to avoid excess of material flow.

Valve opening position: This parameter opens a gap that enables the flow of material. It is good to fairly open the valve to prevent clogging.

Valve closing position: Is used to stop the flow. It should be as close as possible to the valve opening distance to reduce material that stays in the chamber and is expelled when dispensing reinitiates.

Valve opening speed: It is recommended to set it up at slow speed to prevent the fast expel of material in the chamber when dispensing starts.

Valve closing speed: Fast valve closing speed is helpful for precise stops.

Substrate: The electro conductive traces must never come in contact with conductive substrates; an insulator must be applied before printing the traces. The flat substrate must always be firmly attached to prevent unwanted movement.

Side clearance: A minimum clearance of 0.02” should be left from any channel side wall if the depth of the channel is .2” or less. For deeper channels the clearance must be evaluated.

Capacitors: To build a capacitor three layers are need in a sandwich form. Conductive layers on top and bottom and dielectric in the middle. Capacitor’s value is dependent upon the material properties, nonetheless it increases with contact area between the conductive plates and dielectric plates; hence the top and bottom conductive plates cannot make contact with each other.

Resistors: The resistor’s values are dependent upon the utilized ink; nevertheless there are two ways in which resistor values can be tailored: By printing thin traces in non straight shapes that prevent current flow and/or by mixing resistive inks with other resistive inks, thinner or dielectric inks to significantly increase the resistive value of the ink. High resistor values are unrepeatable.

COTS Components Mounting: Conductive traces must be printed to match the off-the-shelf components contact fingers. Using silver filled adhesive COTS can be glued to the conductive traces.

Potting: The ideal potting epoxy should be a heat dissipater, electrically non conductive, and ideally it should serve as support material for the top layers.

Embedding: The contact area where the foils are welded need to be clean and clear of any obstruction for good ultrasonic welding results.

APPENDIX B

PERMISSIONS

This appendix includes the required permissions for publication of the papers presented as Chapters 2-4 and Appendix A of this thesis.

Date 08/31/2010

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