Modification of the Microcontact Printing Process for Conductive Ink Printing

A Major Qualifying Project Report

submitted to the faculty of

WORCESTER POLYTECHNIC INSTITUTE

in partial fulfillment of the requirements for the

Degree of Bachelor of Science

NTB: Interstaatliche Hochschule fur Technik Buchs

(The Interstate University of Applied Sciences of Technology Buchs)

Project Advisor: Prof. Sarah Wodin-Schwartz, WPI

Submitted By:

Adam Cyran & Michaela Dowling

November 3, 2017

Abstract

The goal of this project was to adhere miniature circuit chips to flex prints using conductive epoxy and microcontact printing techniques. To accomplish this goal, the printing process was first optimized. Tool properties were varied to determine their influence on final print quality. Optimized parameters included ideal ranges for inking force and acceptable alignment during inking. The prints created with the optimized parameters were used to bond substrates for shear resistance and electrical conductivity tests. Both tests showed that using microcontact printing to apply conductive epoxy for establishing continuity has potential to become an alternative solution for bonding electrical components.

Acknowledgements

Our team would like to thank every individual who provided assistance and guidance throughout the course of this project. Our WPI advisor, Professor Wodin-Schwartz, as well as our advisors at the Interstaatliche Hochschule fur Technik Buchs (NTB): Katrin Albrecht, Emine Cagin, and Mathias Mächler. Additionally, we'd like to thank the Switzerland project center director, Professor Nancy Burnham (WPI) and faculty members at the Interdisciplinary and Global Studies Division (WPI). We would like to give a special thank you to the entire staff of NTB for welcoming us and supporting our project in every way possible.

Authorship

All sections of this paper were written and edited equally by both authors, Adam Cyran and Michaela Dowling.

Table of Contents

Table of Figures

Table of Tables

Table of Equations

Executive Summary

Microcontact printing (μCP) is a form of soft lithography, originally discovered by Kumar and Whitesides in 1993 (B Michel et al., 2001). The process of microcontact printing involves using a patterned elastomeric stamp to transfer "ink" onto a substrate. The ink used can range from proteins to nanoparticles to polymers. The goal of this project was to adhere miniature circuit chips to flex prints using microcontact printing techniques. This could act as a replacement for current soldering techniques, as this can be done on a much smaller scale. To complete this goal, the current microcontact printing process had to be optimized for a conductive epoxy on a glass substrate.

The process of microcontact printing begins with the creation of an elastomeric stamp. For this project, Poly(dimethylsiloxane) (PDMS) was used for the stamp material. An ink pad was then created and used to apply ink to the stamp through conformal contact. The inked stamp was then brought in contact with the substrate to transfer the ink and create prints. Both inking and printing utilized the microcontact printing tool created at the Interstaatliche Hochschule fur Technik Buchs (NTB).

In order to optimize this process for a conductive epoxy on a glass substrate, different parameters were considered throughout the inking and printing process. The first parameter considered was the epoxy ink pad thickness. This was considered first because the appropriate ink pad thickness would be used for all subsequent prints. Four thicknesses were considered: 10 μm, 20 μm, 90 μm, and 150 μm. 90 μm and 150 μm were quickly ruled out as their thicknesses overpowered the heights of the structures on the stamps. Ink pads of 10 μm and 20 μm were then

created and characterized. The homogeneity of the ink pads and the prints created by each led to the decision to move forward with the 20 μm ink pad.

Printing trials were methodically planned out encompassing the remaining parameters: force, angle, and time during inking and printing.. Trials were ordered based on the anticipated level of impact each parameter would have. Inking force was the first parameter adjusted. A range of forces, as opposed to one exact force, created successful prints. The success of these prints, however, was reliant on the initial leveling of the stage. In order for a stamp to have success under varying forces, it had to first be made parallel to the tool stage when loaded onto the print head. Each stamp had to undergo this leveling before printing would be successful.

As stated in the goal of this project, parameters were optimized to be used to print conductive epoxy to adhere miniature circuit chips to flex prints. This adhesion method is preferable to soldering due to its higher production rate and its ability to produce smaller contacts. The inking force and inking angle were adjusted until windows of acceptable settings could be defined. Prints could have two levels of success. The first level of success was determined by visual analysis and was defined by the transfer of at least 90% of the patterned structures. Prints that exhibited success at this level were then examined under the White Light Interferometer (WLI). The length, width, and height of each print were measured and the length and width were compared to that of the structure on the stamp. A tolerance was set based the width of the aluminum pads on the miniature conductive chip. The second level of success of prints, therefore, was based on whether their dimensions fell within this tolerance. The success of prints at both levels showed that their inking forces and angles were within the acceptable window.

Once successful parameters were created, they were used to conduct shear strength and resistivity tests. These tests were successfully completed, showing that adhesion by conductive epoxy has the potential to match soldering, once fully optimized. Printing force, angle, and time were not tested during this project due to time constraints. Therefore, further optimization of this process could be attempted by running trials with the printing parameters and adding tools to the microcontact printing tool.

1.0 Introduction

As engineers continue to design new, more powerful electrical systems, a consistent caveat is the ability to condense the products into ever smaller footprints. For example, integrated circuit chip production has undergone several iterations of development over the past 60 years. Original prototypes were created by hand and were about the size of inventor Jack Kilby's thumb. Today, processes such as photolithography provide high precision to an extent where multiple components can fit within the cross section of single human hair (Nobel Media, 2014). However, even this methodology is limited by size constraints (Xia & Whitesides, 1998). In 1993, Kumar and Whitesides found that the "formation of a contact on the molecular scale between [an] elastomeric stamp and [a] substrate" was possible, leading to the discovery of soft lithography (B Michel et al., 2001). This project focuses specifically on the utilization of microcontact printing (μCP), a subset of soft lithography, to transfer conductive epoxy onto a glass substrate chip, pre-patterned with conductive circuitry.

This Major Qualifying Project (MQP) team partnered with the Interstate University of Applied Sciences of Technology Buchs (NTB) to optimize the current microcontact printing process. The focus of the project was placed on the optimization of the process by considering the various applicable parameters. **Figure 1** outlines the project steps and goal. The goal of this project was to adhere miniature pre-patterned circuit chips to flex prints using microcontact printing techniques. The first objective was to optimize the current microcontact printing process for a conductive epoxy on a glass substrate, specifically working to increase film homogeneity and the accuracy of the print relative to the desired pattern. The second objective was to use the

optimized process to print the conductive epoxy onto pre-patterned circuit chips, establishing contact between multiple metallic leads and therefore creating microscopic circuits.

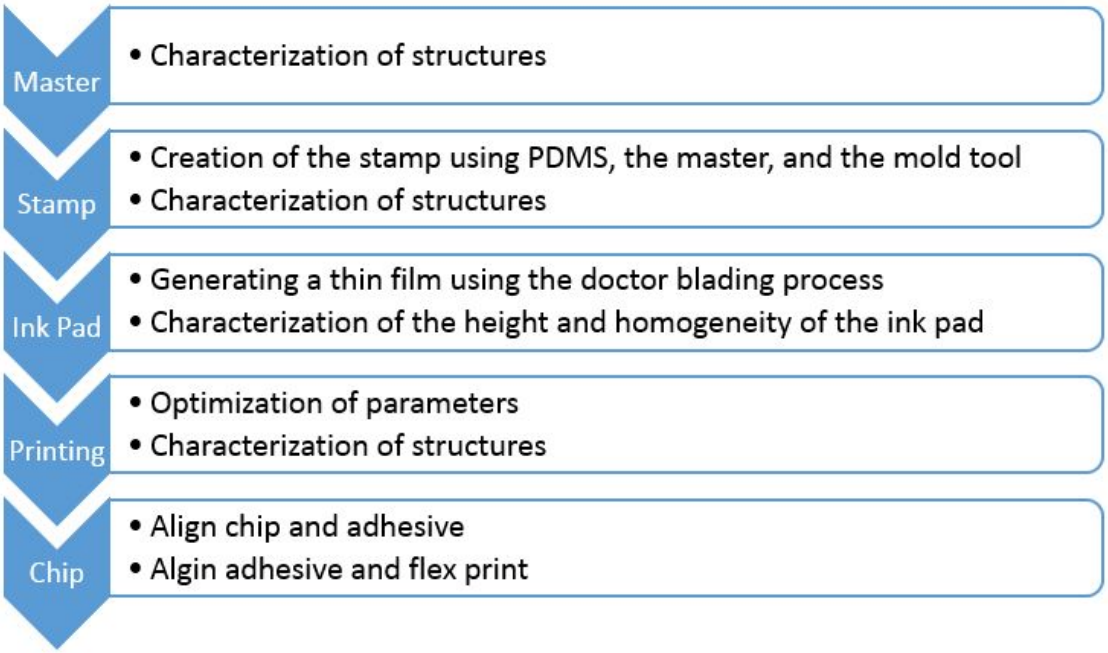


Figure 1: Project outline

2.0 Background

2.1 Soft Lithography

Soft lithography was developed in 1993, when Kumar and Whitesides found that alkanethiol and gold, when in close contact, developed a monolayer of molecules between them at the points of contact (B Michel et al., 2001). Soft lithography is the "formation of a contact on the molecular scale between [an] elastomeric stamp and [a] substrate" (B Michel et al., 2001). There are six different soft lithography techniques: microcontact printing, replica molding, microtransfer molding, micromolding in capillaries, solvent-assisted micromolding, and phase-shift photolithography (Xia & Whitesides, 2010). Each technique uses a different process and produces a different result. For this project, we will focus on microcontact printing.

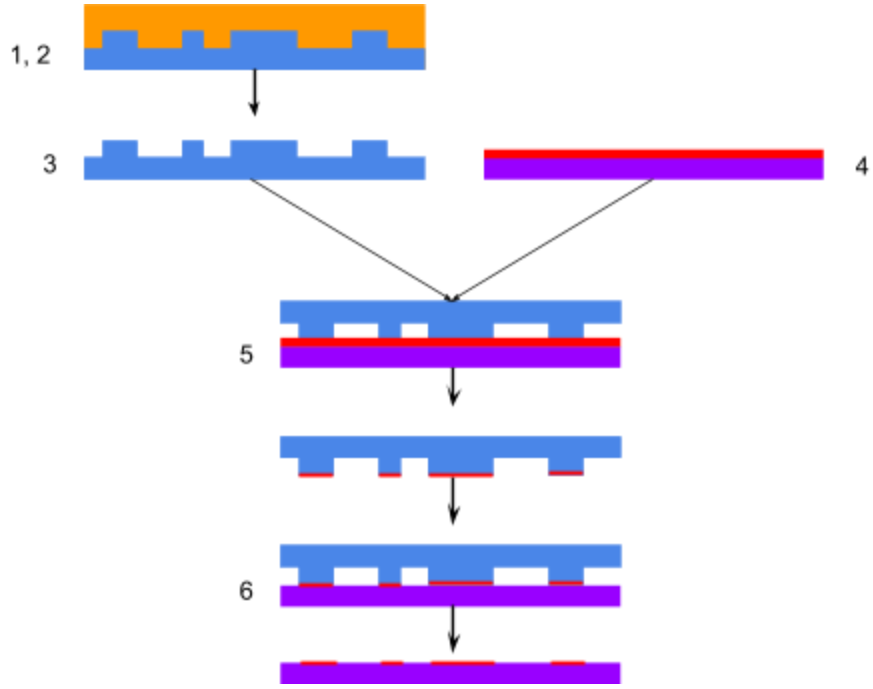
2.2 Microcontact Printing

Microcontact printing (μCP) can most easily be described as stamping on a microscopic scale and provides the accurate replication of patterns that are difficult to produce at such a small scale. It is a developing technology with many applications, including those in biology and electronics.

2.2.1 μCP Process for Adhesives

The μCP process for adhesives is a combination of six individual steps, shown in **Figure 2**, which produce a final print. The process begins with a master, "a structured silicon or resist surface with a vertical inverse of the desired pattern" (B Michel et al., 2001) (1). This acts as a mold for the stamp, which is fabricated through injection using a soft material, e.g. poly(dimethylsiloxane) (PDMS) (2). The stamp must then be cured for twelve hours at sixty degrees Celsius (3) (NTB, 2017). In order to apply ink to the stamp, an ink pad comprised of an

epoxy layer is generated (4). The epoxy is applied to the stamp by bringing the stamp into contact with the ink pad (5). The stamp can then be applied to the substrate under conformal, intimate contact (6).



Key: Master, PDMS Stamp, Conductive Epoxy, Glass Substrate

Figure 2: Microcontact printing process

2.3 Master

A master is required to produce a stamp that can be used in the microcontact printing process. The master contains a vertical inverse of the desired pattern. All features on the master that will be patterned possess a height of >1 micrometer and therefore can be developed on a silicon wafer. Any features at a submicron level must be produced using means other than soft lithography (B Michel et al., 2001). As shown in **Figure 3**, the standard photolithography process is followed to create the master from a silicon wafer and negative photoresist.

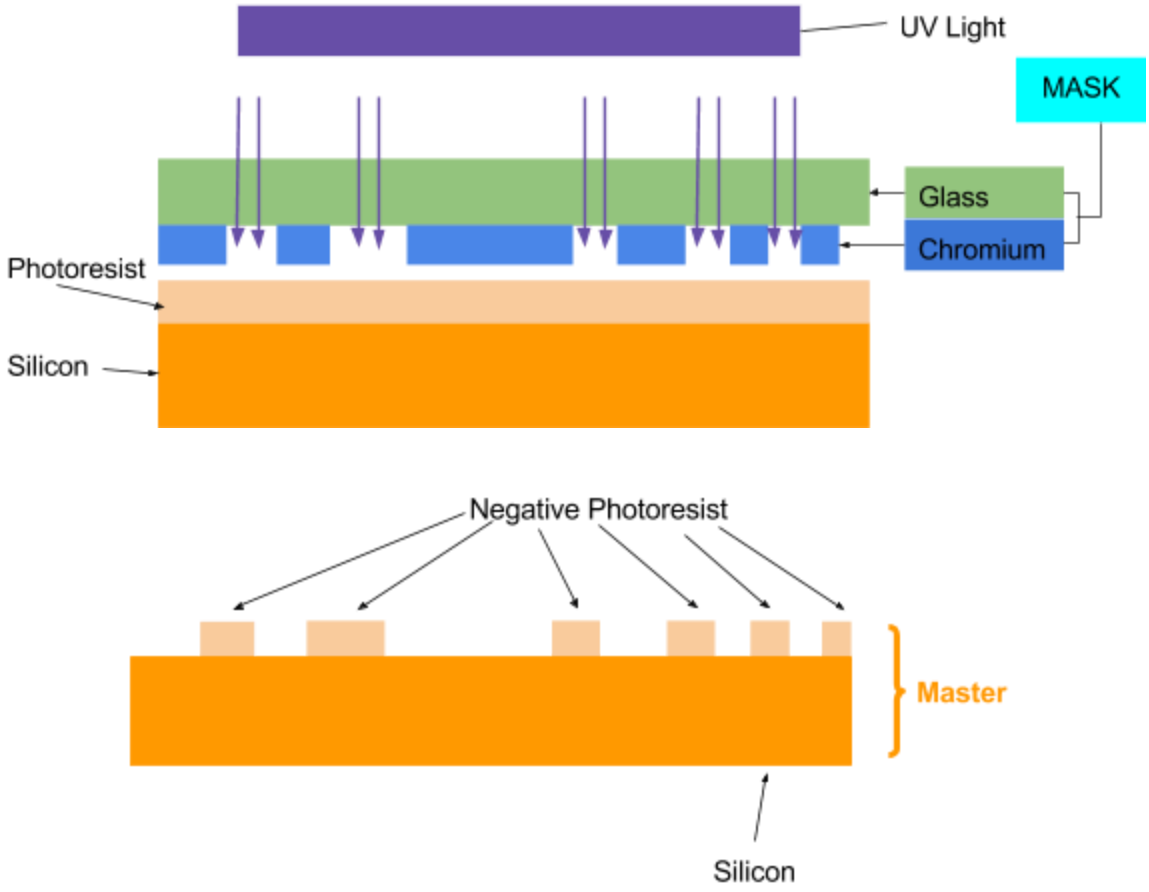


Figure 3: Master creation

2.4 Poly(dimethylsiloxane) Stamp

Once fabrication of the master is completed, it is then placed into a mold tool, as shown in **Figure 4**. By injecting poly(dimethylsiloxane) (PDMS) into the mold tool via syringe, a casting called a stamp is created, as shown in **Figure 5**.

Figure 4: Mold tool with master placed at center

Figure 5: Closed mold tool being filled with PDMS

The stamp is an essential part of the microcontact printing process, as it transfers the desired pattern onto the substrate, as seen in **Figure 6**. Therefore, the stamp must be a precision copy of the master and the desired pattern.

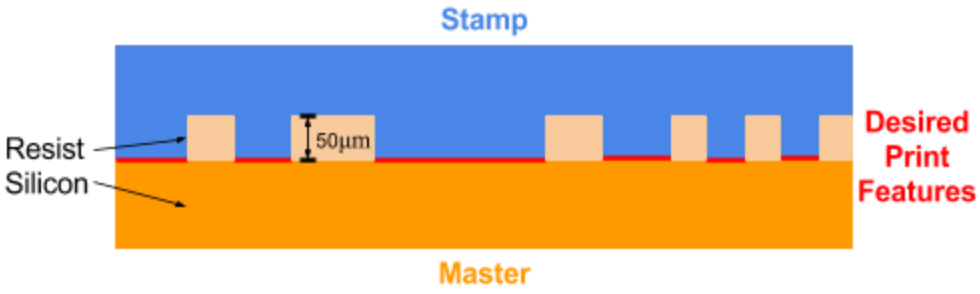


Figure 6: Stamp creation

The material PDMS is an integral part of producing a successful print. PDMS has many properties that make it ideal for microcontact printing. Before being cured, PDMS is a viscous fluid at room temperature, allowing it to be poured into the mold tool to make the stamp.

Additionally, PDMS possesses low interfacial energy and good chemical stability. PDMS is also a soft material, making conformal contact possible. However, PDMS creates many challenges when used for microcontact printing. While PDMS does not swell with humidity, it does shrink ~1% when cured, which must be accounted for when producing the stamp (Xia & Whitesides, 2001). PDMS is also a hydrophobic polymer when untreated. Hydrophobic polymers are not ideal for stamping because they have a low wettability characteristic, the tendency of a fluid to spread evenly over a surface, and therefore, large contact angles (Kim et al., 2004). A contact angle can be measured as the slope angle of a water droplet on a material, in this case PDMS, as seen in **Figure 7** (Kim et al., 2004). If the PDMS surface properties cause a large contact angle, the epoxy will not adhere properly. Instead of spreading out, it will bubble up, which will create an inaccurate print. Therefore, the PDMS must be treated as described below to facilitate a contact angle that is less than five degrees.

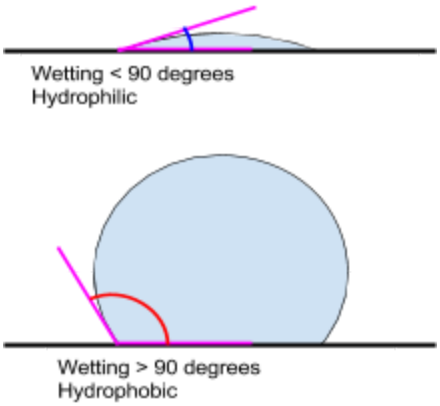


Figure 7: Contact angle

In order to increase the wettability at the surface of PDMS, the material is treated with oxygen-based plasma, in a process known as functionalization. This treatment increases the

hydrophilicity of the material as OH-groups are pushed to its surface. However, PDMS will only stay hydrophilic at the surface for a matter of hours, as the inner polymer chains of the material are still hydrophobic (Kim et al., 2004). The polymer chains of PDMS are very mobile, allowing hydrophobic groups to move to the surface of the material (Glasmästar et al., 2003). In order to retain wettability and hydrophilic properties for longer periods of time, the PDMS should be stored submerged in water (Kim et al., 2004).

2.5 Conductive Epoxy

The materials being printed via the PDMS stamp for this study are viscous conductive epoxies. The epoxies, EPO-TEK H2OE-PFC and EPO-TEK H2OS, each possess two parts (resin & hardener). Both the resin and hardener components of the epoxies possess a silver color and specific electrical, physical, and thermal properties as provided in **Appendix A** and **Appendix B**. These substances are most commonly used for joining electrical components in a solder-free method. Additionally, this type of epoxy is used in printed electronics and flip chip connectors due to its high conductivity.

2.5.1 Blade Coating Application Method

A layer of ink must be generated so the epoxy can be applied to the stamp. This ink pad consists of a thin, uniform layer of the desired epoxy. A method known as blade coating or doctor blading is used to achieve this repeatedly. Commonly used in the production of moldable solar panels, the traditional process is adapted to fit the application of this project. The general procedure begins with placing the ink (epoxy) on top of the substrate between two foil guides. The thickness of the foil guides utilized dictates the thickness of the ink pad created. A precision straight edge is lowered into contact with the top surface of the foil guides. The straight edge is

then wiped across the top surface at a constant velocity, ranging between one and two meters per minute, and with a constant surface pressure between two and three kilograms per square centimeter. This ensures a uniform layer of the epoxy is created. A diagram details process steps in **Figure 8**. The following equation describes the relationship between thickness of the final layer and material/application properties:

$$d = \frac{1}{2} g \frac{c}{\rho}$$

Equation 1: Blade coating layer thickness

In the equation, "d" represents the final dried film thickness, "g" is the gap distance between the blade and substrate, "c" is the solid material concentration in the epoxy, and "ρ" is the density of the epoxy (Burgués-Ceballos et al., 2014).

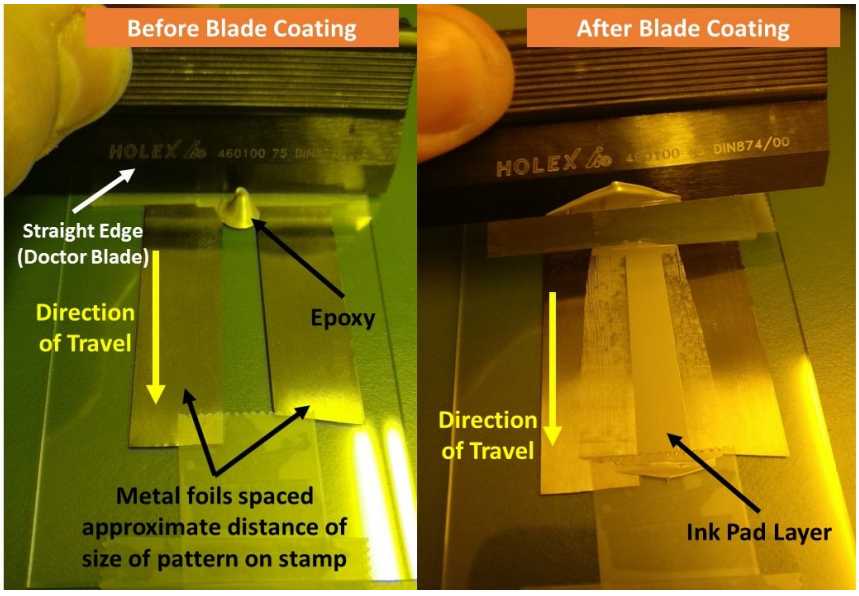


Figure 8: Blade coating method

2.5.2 Pot Life of the Epoxy

When the two parts of a certain epoxy or adhesive are combined, the material possesses specific properties at that initial mixing time. As time progresses, these specific characteristics

can change the behavior of the substance. In particular, pot life is a characteristic that quantifies the time required after mixing for a material to change in viscosity by a certain percentage. This is an important trait in our testing, as a change in viscosity of the material may affect print quality. The two epoxies used in experimentation, EPO-TEK H2OS and EPO-TEK H2OE-PFC, both possess a pot life of three days according to their respective data sheet provided in **Appendix A** and **Appendix B**. While this provides a large testing window, trials were executed within similar time intervals to ensure consistent inking, printing, and analysis conditions within a few hours of the initial mixing.

2.5.3 Curing

After application and when two materials are adhered together using epoxy, it is important to cure the adhesive to ensure the bond between the two materials is strong and possesses the proper material properties for application. The data sheets for both epoxies, EPO-TEK H2OE-PFC (**Appendix A**) and EPO-TEK H2OS (**Appendix B**), list multiple temperatures and times to cure the mixed and applied adhesive. The application of a sample determines which curing method will be utilized for testing. According to Epoxy Technology, using a quick, high temperature method to cure samples will "enable chemical crosslinks to form faster and more completely," therefore enhancing electrical conductivity properties of the sample. However, utilizing a slow, low temperature process will increase the strength of the sample (Epoxy Technology, 2015).

2.6 Substrate

The stamp applies the print to a substrate, which can be a variety of materials. For this project, the substrate used for process optimization was a standard microscope slide. When

printing with molecules, or using alternative substrates, the substrate must be processed through an advanced, multi-stage cleaning processes before, during and after the print. Because this project utilizes a glass substrate, as opposed to other materials commonly used for microcontact printing, the slide only requires cleaning prior to stamping. The standard cleaning process used by NTB involves two steps; sonication & alternative cleansing. Sonication is a process involving ultrasonic frequencies in the presence of water to effectively increase the surface flux of a material by cleaning the medium of most impurities. After exposure to this process, the substrate is then exposed to two cycles of a temperature controlled solution of Nitric Acid and rinsed with water. This method ensures that all particles, including dust, which may come attached to the glass during storage are removed before use. An expedited procedure is also available to clean the substrate. This method involves wiping down the glass with acetone and then isopropanol. While not the standard process, this method provides an adequately clean surface for the epoxy to properly adhere to and will therefore be utilized for testing purposes for convenience.

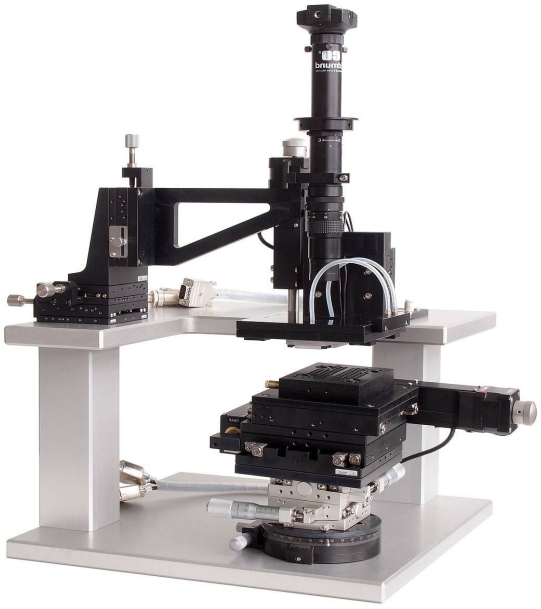
2.7 Stamping

Once the stamp has been made and coated in epoxy, the print can be applied to the glass substrate. This is done using the microcontact printing tool, discussed below. There are many variables that can be considered and adjusted using the settings on the microcontact printing tool. For the purpose of this project, the three specific parameters to be isolated include the approach distance, approach angle of the stamp, and application pressure. These variables are important as they directly influence the quality of the final print. Previous MQP research gives baseline values for two of the three parameters. The baseline for the approach distance for a glass plate is 23

mm, while the printing force is between 0.45 and 0.65 N (Han et al., 2016). The baseline for the approach angle is zero degrees, i.e. the stamp and the glass substrate are parallel.

2.7.1 The Microcontact Printing Tool

The microcontact printing tool, shown in **Figure 9**, used for this project was designed by the Institute for Micro and Nanotechnology (MNT) at the Interstate University of Applied Sciences of Technology Buchs (NTB). Once the PDMS stamp is created, the microcontact printing tool is used to produce the print on the glass substrate. The tool is designed with versatile specifications for different needs, including inking and printing for the purpose of this project.



Microcontact Printing Tool Specifications	
Stamp Size	1 mm^2 - 10 mm^2
Structure Size	1 micrometer - mm
Force Control	50 mN - 10 N
Translation in x and y	50 mm
Translation in z	25 mm
Minimum Step size in x, y, and z	<1 micrometer
Rotation around z-xis	+/- 180 degrees
Rotation Resolution	<5 arc seconds
Tilt around x- and y-axis	+/- 5 degrees
Tilt Resolution	<0.5 arc seconds
Optical Zoom	0.7x to 4.5x

Figure 9: Microcontact printing tool & specifications (NTB, 2017)

2.8 Materials for Application

2.8.1 Flex Print

Flexible printed electronic circuits (FPCs) have been developed for electrical connection applications to meet demands for higher-density packaging of electronic equipment. (Tyco Electronics Corporation, 2013). This type of connector is commonly made out of polymer materials to allow the connective lines embedded within the ribbon to preserve a static "flexed" position. The particular flex print utilized within the scope of this project is created from a 50 µm thick strip of material called polyimide. Polyimide is a heat and chemical resistant organic material commonly used in electronics implemented at high temperatures (Underwriters Laboratories, 2017). Copper pads at either of end of the print provide the contacts for electrical connectivity. The flex print to be utilized in the project is pictured in **Figure 10**.

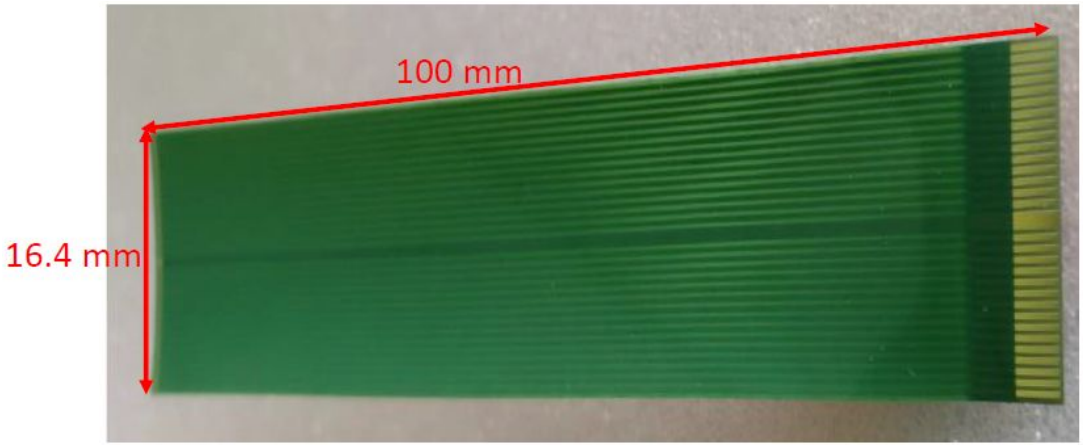


Figure 10: Flex print dimensions

On the current flex print copper contact pads, there exists a layer of "solder-stop" referred to by the technical name of SD 2463 FLEX-HF. During traditional electrical adhesion processes, this 20 µm thick material acts as an insulator to prevent solder from shorting nearby connections (Peters Group, 2017).

2.8.2 Miniature Circuit Chips

Miniature circuit chips were designed by the MNT at NTB specifically for use in this project. These chips vary in size, ranging from 8mm x 8mm to 18mm x 18mm. All have pre-patterned aluminum contacts etched onto the top surface which progressively become smaller as the chip size decreases as shown in **Figure 11**.

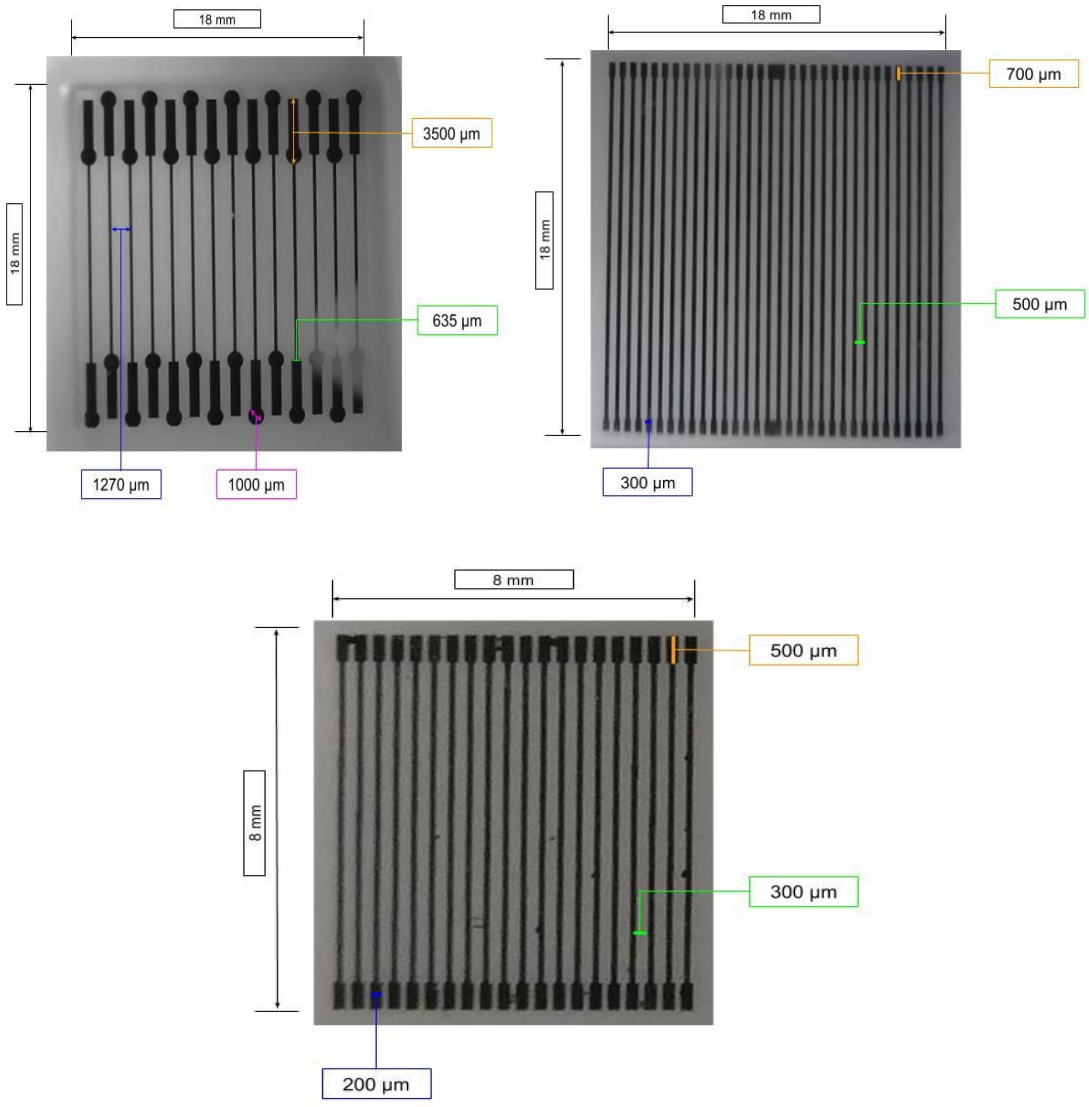


Figure 11: Miniature chip examples

3.0 Methodology

In this section, the methods and procedures for implementing and characterizing stamp creation, inking and printing conductive epoxy, operating the μCP tool, and compiling analyses are discussed.

3.1 Overview of Optimization Process

While basic print properties (e.g. inking force) will change depending on the master, based on the work conducted in the following chapter, the flowchart in **Figure 12** was created to provide a guide on how to methodically work through optimizing the μCP Process.

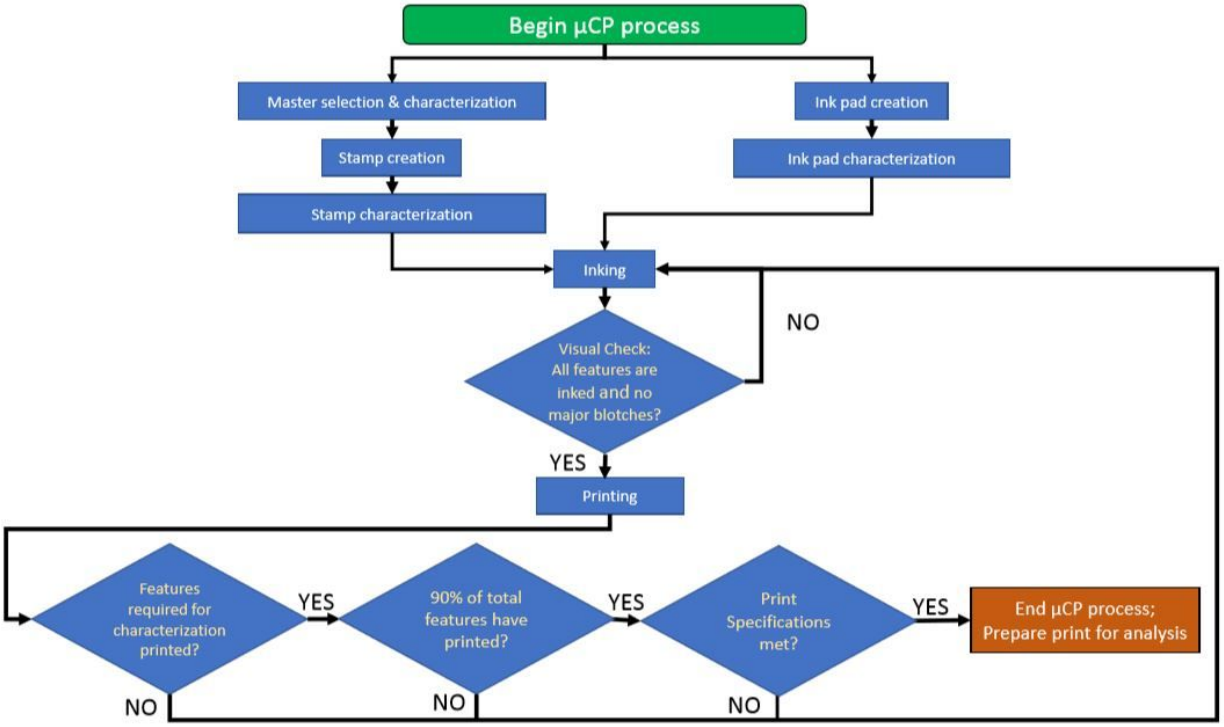


Figure 12: μCP process flow chart

3.2 Master

3.2.1 Master Selection

Different masters were utilized throughout the project to observe the effects of adjustable independent variables and to ensure that an optimized procedure was created to be used in the adhesion of a flex print to a miniature circuit. Each of the masters used in the process are listed in **Table 1**.

Master #	Stamp Layout	Structure Size (µm)	Picture
1	2 rows of 20 rectangular structures surrounded by a thick, raised box	290 x 85	Picture Not Available
2	2 rows of 20 rectangular structures surrounded by a thick, raised box	290 x 85	Picture Not Available
3	2 columns of circular structures	Diameter = 315	
4	2 rows of 20 rectangular structures	270 x 124	
5	2 rows of 20 rectangular structures surrounded by a thin, raised box	280 x 124	
6	1 diagonal line of 32 rectangular structures with thick, raised trapezoids on either side	500 x 195	

Table 1: Master specification

Masters 1, 2, 4, & 5 were utilized to aid in the calibration and development of methodology. Master 6 was specifically used for the chip and flex print adhesion application.

Master 3 was made to explore how circular structure geometry impacted print quality. However, due to time constraints, the single stamp created from master 3 was never tested.

3.2.2 Master Characterization

The stamp investigation began with the master, which houses the inverses of the desired structures for the stamp. Each master was characterized, noting the topography of individual structures. The topographical measurements included height, width, and depth of the structures. Continued measurements showed that measuring the accuracy of the transfer of selected structures from master to stamp to print was more important than the number of structures measured. Because of this, measurements were carried out on feature numbers 1, 10, 11, and 20. The stamp structure layout can be found in **Figure 13**.

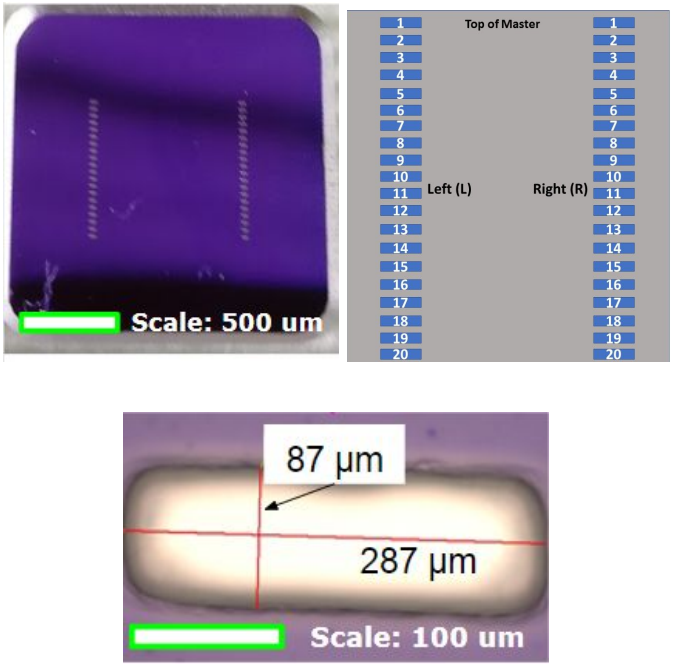


Figure 13: Master layout (top pictures) and structure characterization (bottom picture)

3.3 Ink Pad

3.3.1 Ink Pad Creation

The ink pad creation method used for this project was developed within the past year at NTB, as described in section **2.5.1 Blade Coating Application Method**. Two epoxies were utilized during this project: EPO-TEK H2OE-PFC and EPO-TEK H2OS. **Table 2** lists the material differences between the two epoxies.

Epoxy Technical Name	Mix Ratio	Part A Specific Gravity	Part B Specific Gravity	Ion Content
EPO-TEK H20E-PFC	1:1	2.88	3.31	Cl : 199ppm; NA+ : 12ppm; NH4+ : 349 ppm; K+ : 12ppm
EPO-TEK H20S	1:1	1.74	3.07	Cl : 162ppm; NA+ : 0ppm; NH4+ : 282 ppm; K+ : 4ppm

Table 2: Epoxy comparison table

3.3.2 Ink Pad Characterization

Characterization of surface topography from the epoxy layer was required in order to determine if the doctor blade ink pad creation procedure could create a usable, homogenous film for the μCP process. The ink pad was put under a White Light Interferometer (WLI) to measure height and assess homogeneity. The entirety of the ink pad profile must be within 10% of the average height of the ink pad to be acceptable.

3.4 Stamp

3.4.1 Stamp Creation

Once the master was characterized, it could be used to create stamps. Each master was put into a mold tool and the procedure outlined in section **2.4 Poly(dimethylsiloxane) Stamp**

was used to create the stamps. **Table 3** shows a compilation of all stamps created for use during the project trials.

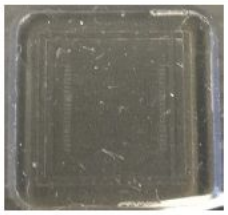
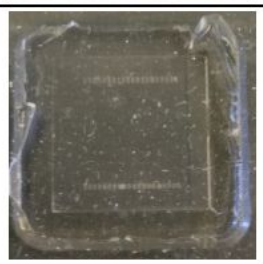
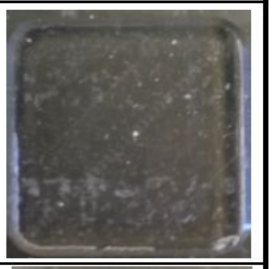
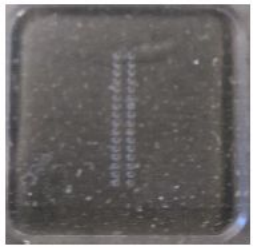
Stamp #	Picture	Stamp #	Picture
1.1		4.1	
1.2		4.2	
2.1		5.1	
2.2		6.1	
3.1		6.2	

Table 3: Stamp inventory

3.4.2 Stamp Characterization

Individual stamps were characterized following the same method used for their respective master. Topography was studied to determine if the individual structures were the correct height as well as if the stamp was level, as shown in **Figure 14**.

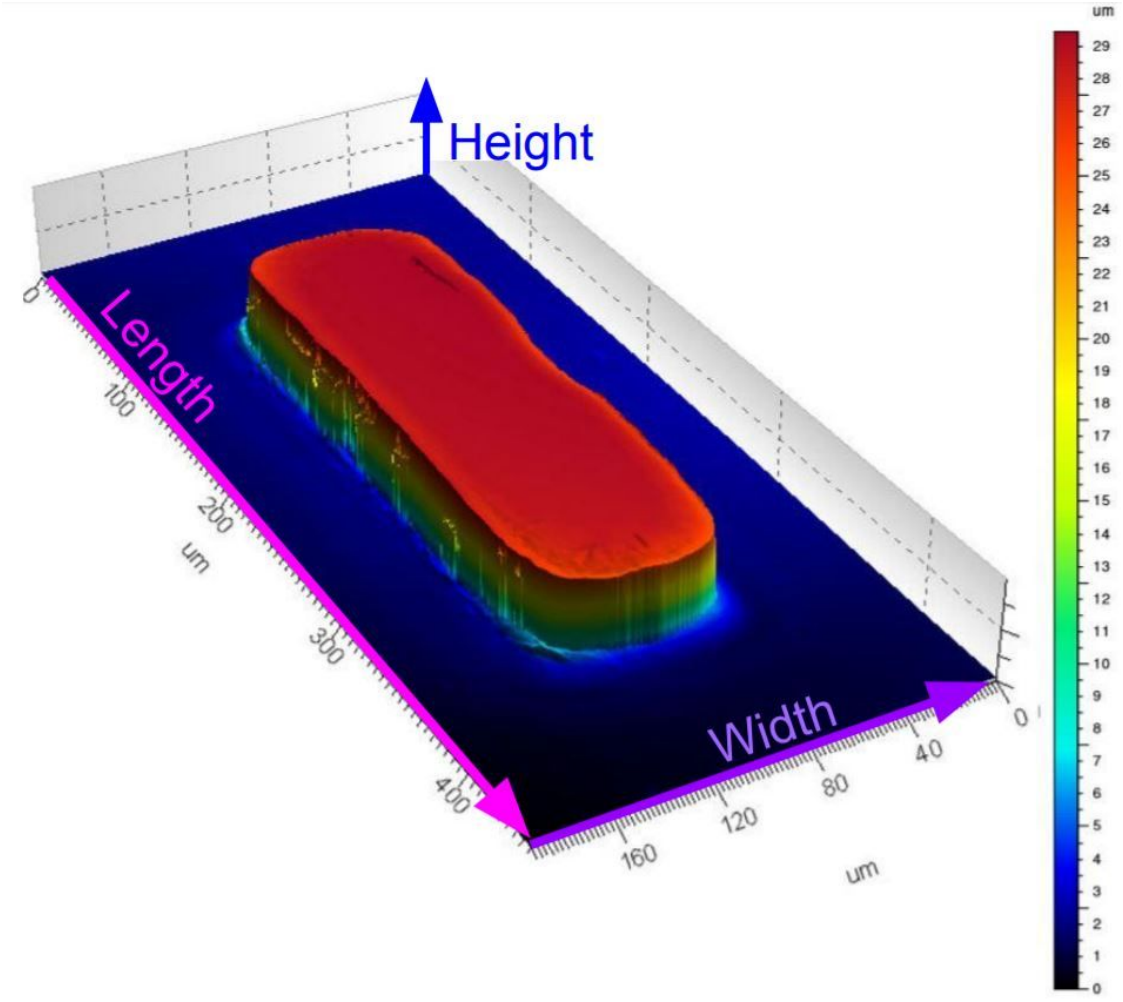


Figure 14: Stamp characterization, stamp 1.1 structure 1 right

The width and length of individual structures were also measured. Comparing the stamp's structures to those of the master showed that the current process created stamps that correctly represented the desired patterns. For reference, when analyzing data from individual structures, the dimensions recorded are displayed in **Figure 15**.

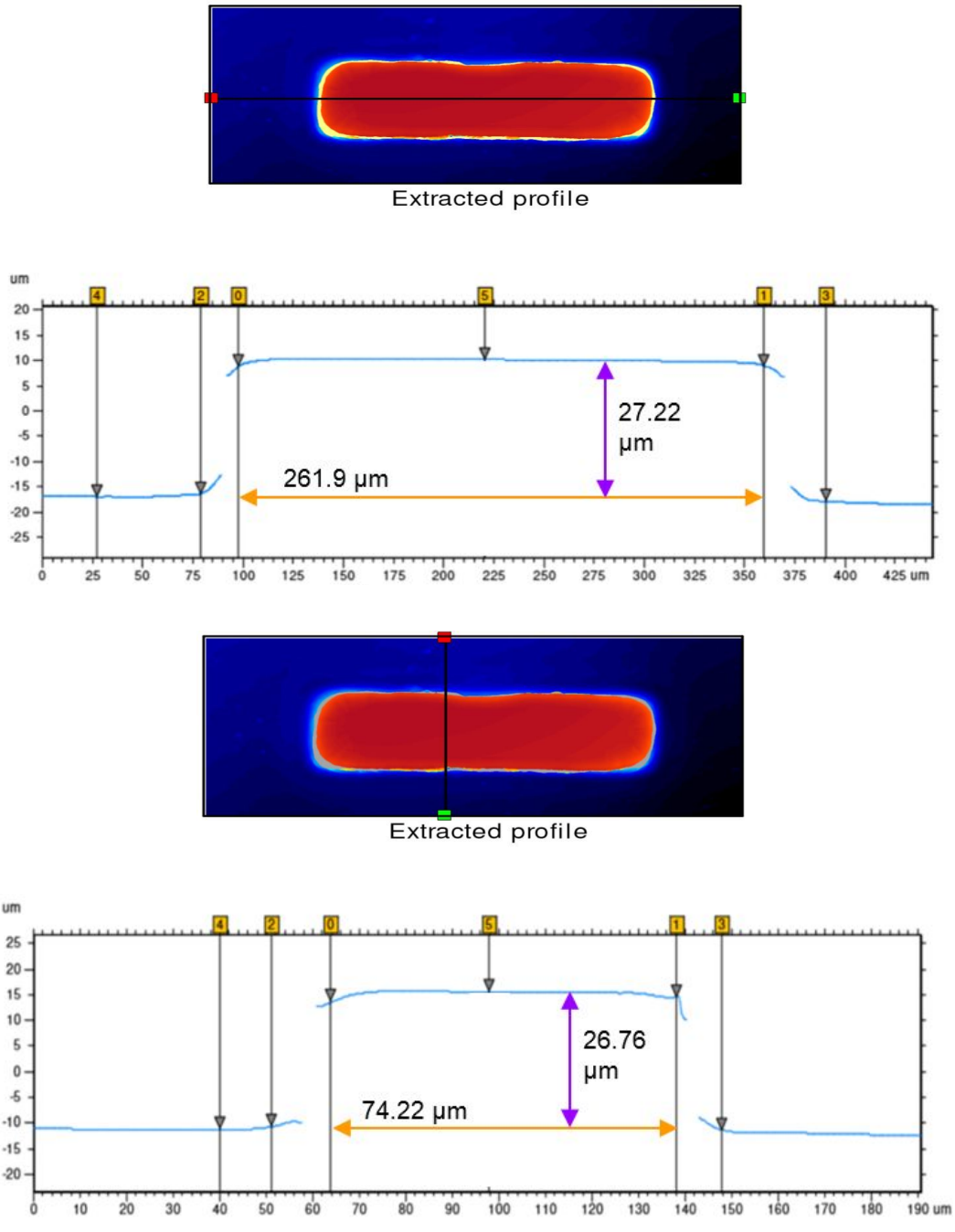


Figure 15: Stamp characterization, stamp 1.1 structure 1 right. Length measurement (top two pictures) and width measurement (bottom two pictures)

3.5 Optimizing the µCP Process

3.5.1 µCP Process Optimization Test Matrix

A test matrix was created to outline all variables that could potentially be adjusted during the printing process. Emphasis was placed on monitoring which parameters were adjusted and listing the other factors that influenced the specific trials. The test matrix is displayed in **Table 4**.

Trial	Parameter Adjusted	Tested Value	Surface Topography	Notes
Baseline (Inking)	Ink Pad Thickness		Definition: The homogeneity of the ink layer on the pre-characterized stamp. % of features covered based on topographical observations	
	Force			
	Time			
	Time after mixing epoxy			
	Angle of Print Application			

	Parameter Adjusted	Step 1	Step 2	Surface Topography	Accuracy Of Print (um*um/um*um)	Shear Resistance	Resistivity (Ohms-cm)
Baseline (Printing)	Force			Definition: The homogeneity of the thickness of the print on the substrate. Observing the ink layer thickness and the uniformity. Quantified by average and standard deviation	Definition: Average % of ink transferred over to substrate compared to features on stamp	Definition: Stress required to disconnect flex print from adhered chips. Voltage readings on testing rig will be converted to shear stress in grams.	Definition: Indicator of electrical conductivity by applying print to contact across the leads of a minaiturized chip. May be initially neglected while fine tuning print process.
	Time						
	Time after inking epoxy						
	Angle of Print Application						

Table 4: µCP blank test matrix and measurement definitions

Initial variables to be adjusted for each trial were determined based on a discussion involving which parameters were most influential for print quality. Hand-printing trials were used for initial testing in order to gain insight into the appropriate parameter ranges. The list shown in **Table 5** was compiled with background information and previous experience from hand printing trials.

Test Parameter	Ranking: Impact on Final Print Quality	Notes contributing to rank	Ranking: Order of Focus
Approach distance of stamp	4	Studied in previous MQP ; Baseline readings provided How far can the stamp w/ epoxy travel before the epoxy starts to deform? Film Homogeneity Shape Deformation - specific deformation	4
Approach angle of stamp	3	Recommended investigation by sponsor Not studied previously in MQP Film Homogeneity Shape Deformation - Shifting may cause unequal dispersion	2
Force applied to stamp	1	Studied in Previous MQP; Baseline provided Pressure directly impacts print quality Shape Deformation - Too much much pressure will ruin prints Stamp Life is not affected Easily adjusted via tool settings	3
Thickness of Epoxy Ink Pad	2	Current method not studied in previous MQP Print Quality may be directly affected based on thickness Film Homogeneity	1

Table 5: Parameter rankings

3.5.2 Leveling Calibration of the µCP Tool

Before any operation of the µCP tool, it was imperative to ensure that the stage and print head were completely parallel to each other, such that the baseline parameters could be tested. A single-axis spirit level was utilized to fully align the stage and the print head. In order to adjust the roll and pitch angles of the µCP stage, alignment dials were rotated to finely adjust the profile of the stage. **Figure 16** labels and showcases the major components of the µCP tool.

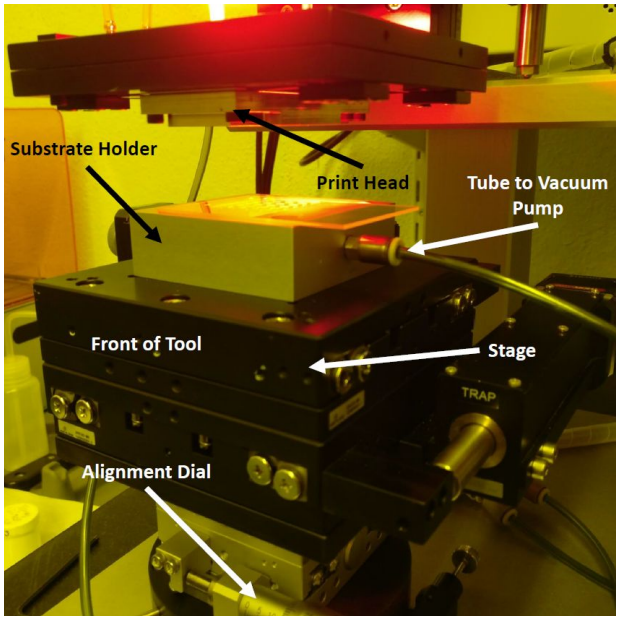


Figure 16: Major components of the µCP tool

In conjunction with the level, a stamp with large open features was attached to the print head. The motor to lower the print head to contact the stage was then placed in an idle mode through the Labview Graphical User Interface (GUI). A dial attached to the top of the print head motor assembly, as shown in **Figure 17**, was manually turned to slowly lower the print head onto the μCP stage.

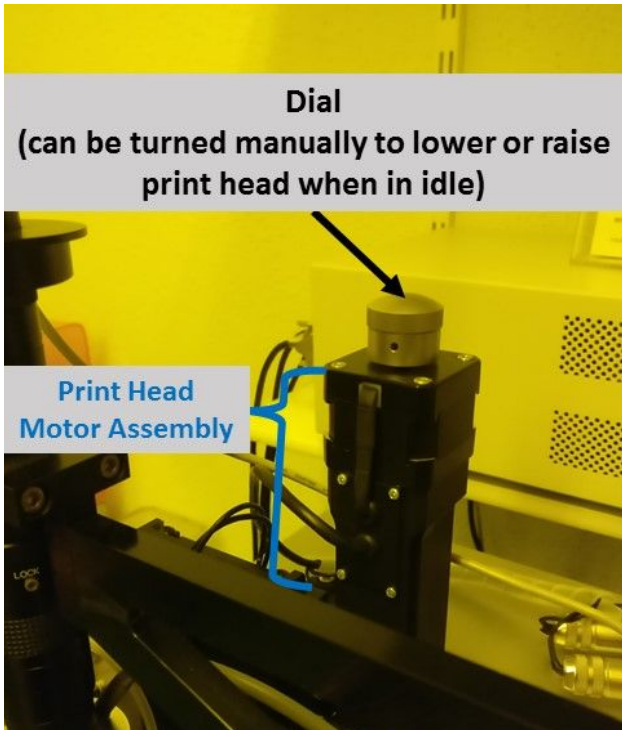


Figure 17: Top view of uCP tool, isolating print head motor assembly

As the print head was applied and removed, the adhesive dispersion could be viewed through the clear PDMS. These visual observations were used to adjust the parallel nature of the stage with the print head with alignment dials shown in **Figure 18**.

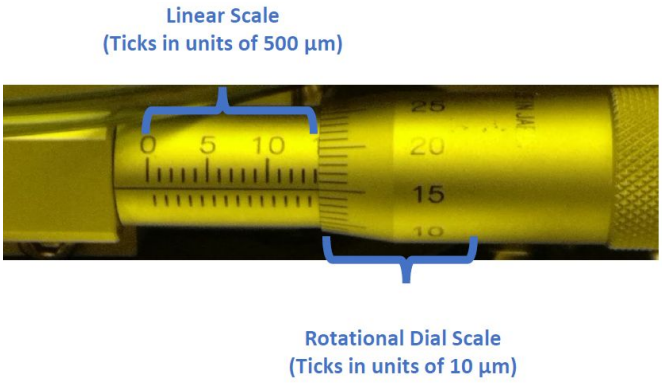


Figure 18: Enlarged view of an adjustment dial

Each tick on the rotational dial represents a unit of 10 µm. The linear scale is comprised of ticks divided into units of 500 µm. Dial adjustments made to prints throughout trials with a particular stamp were noted in the test matrix and taken into account when analyzing prints. Axes of adjustment are defined as the roll axis and pitch axis of the µCP stage as described in **Figure 19**.

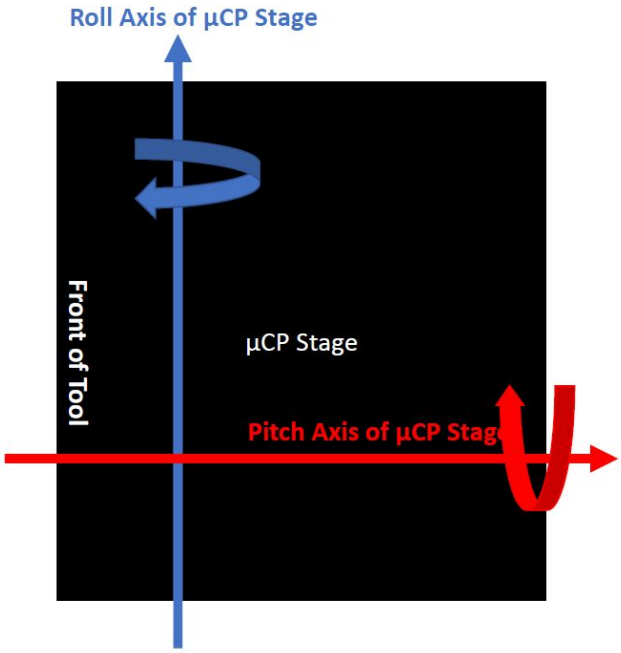


Figure 19: Top view diagram of µCP stage

3.5.3 Inking the Stamp using the µCP Tool

The µCP tool was utilized to accurately apply and measure the force and time for inking compared to the desired output. The Labview GUI allowed a single force or sequence of forces to be altered during a specific duration as shown in **Figure 20**. Using the tool for this process ensured parallel contact with the ink pad, reliable variable isolation, and consistent results.

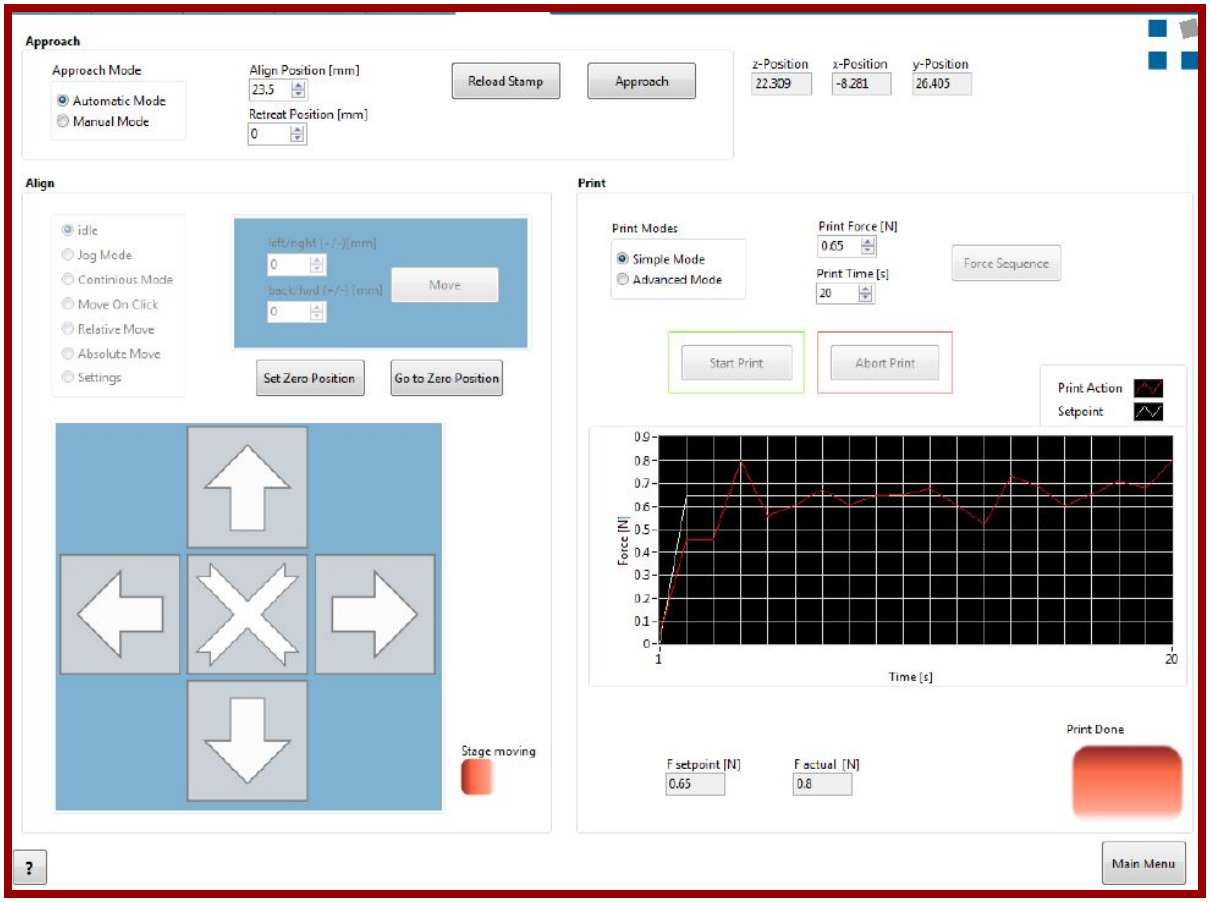


Figure 20: µCP tool Labview front panel

3.5.3a Characterization of Ink on the Stamp

The stamp was characterized again under the WLI after the ink was transferred from the ink pad to the stamp. Length, width, and total height were measured on an inked stamp to determine the homogeneity of the ink layer on the stamp. A homogenous ink layer is required on

the stamp to produce an accurate print. The amount of ink adhered to the stamp must also be considered, as too much ink could create too large a print.

3.5.4 Printing using the μCP Tool

Similar to execution of the inking process, a glass slide was placed onto the μCP tool stage under the inked stamp. In order to accurately apply and measure the force and time for printing, the Labview GUI once again allowed for either a single force or sequence of forces to be altered for specific duration during printing. Using the tool for this process improved parallelism between the stamp and substrate, reliable variable isolation, and consistent results.

3.5.4a Visual Print Analysis

In order to improve timeliness for analyzing and compiling data, and because features were large enough to observe without instrumentation, printed ink transferred from the stamp to a substrate was visually assessed without assistance from the WLI. The following criteria were created to determine whether a print was usable for further data collection:

1. Pre-characterized features visually observed to be printed on the substrate
2. 90% of all features are visible on the substrate

An example can be seen in **Figure 21** where an unacceptable print is compared to an acceptable print.

Figure 21: Visual print comparison [unacceptable (left) vs. acceptable (right)]

3.5.4b Print Characterization

The number of printed structures was counted and structures 1, 10, 11, and 20 in both rows were measured, as done with their respective stamp and master. The length, width, and height of the printed epoxy, defined in **Figure 22**, were measured as shown in **Figure 23**. The length and width were then compared to those of the structures on the stamp to determine how accurate the print was compared to the desired pattern. The difference was calculated to help direct future adjustments of the parameters of the microcontact printing tool, such as the force and the angle of application. The peak height of the printed epoxy was also measured using the WLI to determine the homogeneity of the printed layer.

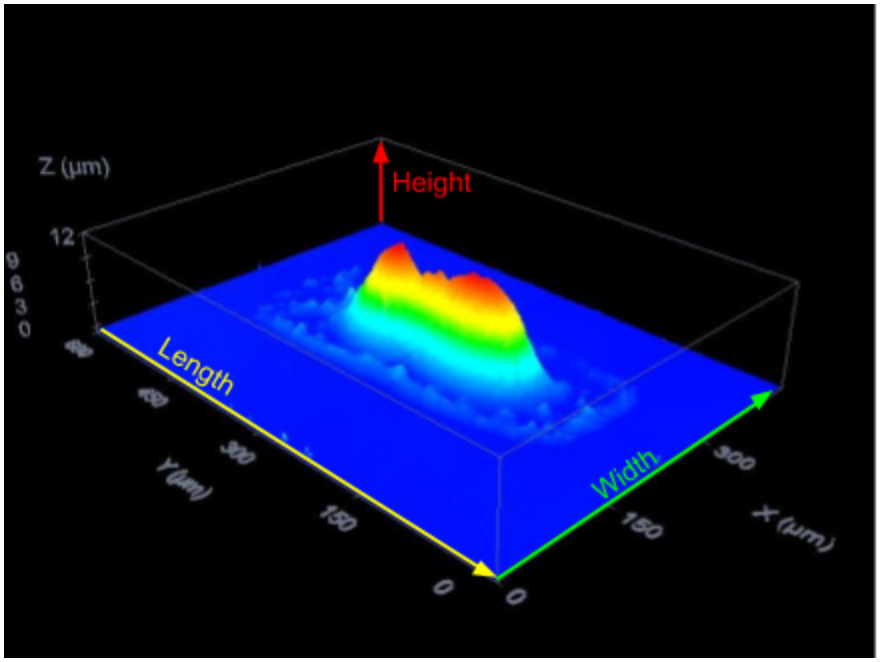


Figure 22: Printed structure

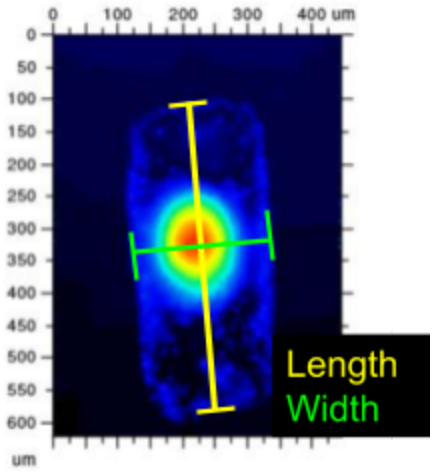


Figure 23: Definition of length and width measurements

3.6 Printing Large Structures for Flex Print Application

The optimization processes and results developed in the previous sections were then used for printing larger structures. These structures are sized to be utilized to connect the flex print ribbon and miniature conductive chip as shown in **Figure 24**.

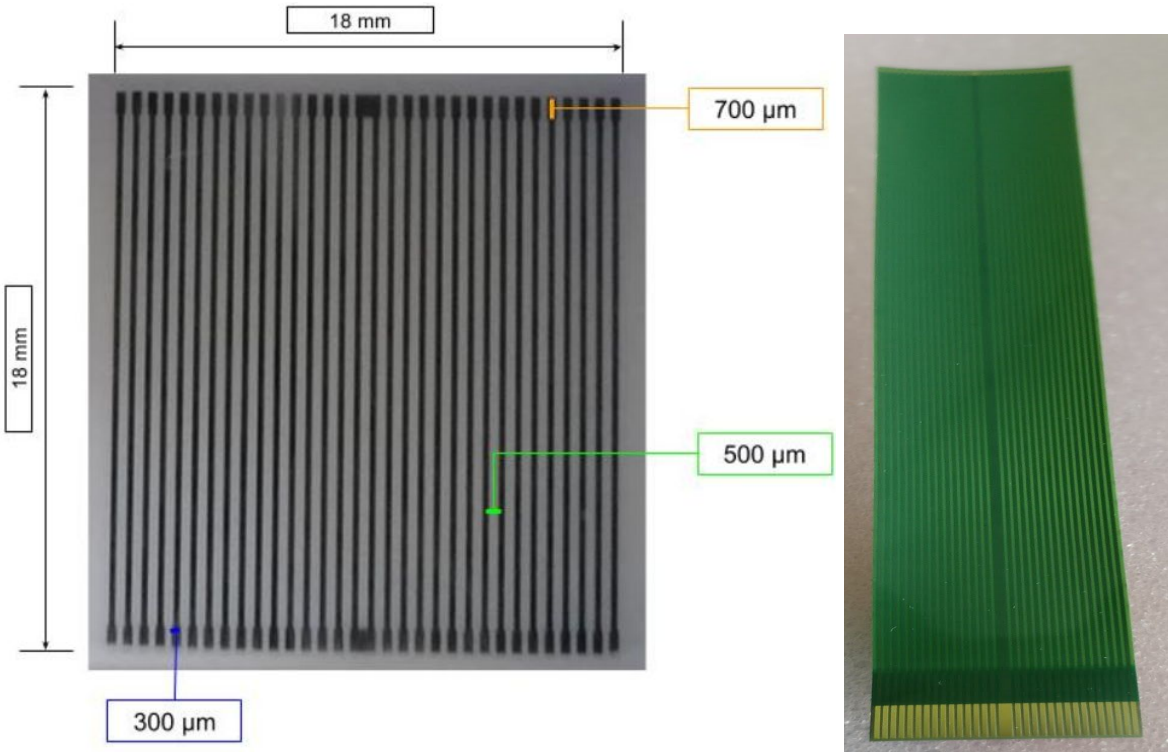


Figure 24: Enlarged view of miniature circuit chip (left) and flex print ribbon (right)

This application based printing required focus to be shifted to master 6 and stamps 6.1 and 6.2 as the structure sizes of masters 1-5 were too small and not fit for use.

3.6.1 Defining Tolerance for Acceptable Prints

In order to understand how adjusting parameters, as outlined in section **3.5.1 µCP Process Optimization Test Matrix**, can affect printing in an electrical connection application, a tolerance was defined for the print width. The tolerance was defined to ensure that there would not be any electrical shorting between individual connections. This could easily happen if the epoxy was not applied accurately or spread past the contact when pressure was applied to both the chip and flex print during the bonding process. Therefore, the tolerance was determined by considering the width of the contact, the gap between any two contacts and the factor of safety using the equation:

Tolerance = Width of Contact + (Gap Between Contacts/Factor of Safety)

Equation 2: Tolerance of printed structures on a flex print (μm)

Based on the design requirements and for initial testing purposes, a factor of safety of two (2) was selected to allow for error in application. Therefore, for prints to be acceptable, they must be under 400 μm wide after force is applied to bond the flex print and conductive chip. The sizing and tolerance is displayed in **Figure 25**.

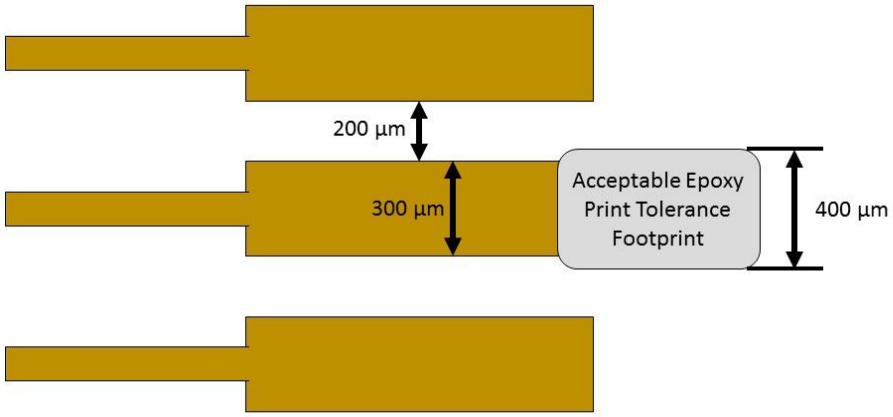


Figure 25: Enlarged diagram of chip and flex print contact spacing

3.6.2 Epoxy Spread Testing

To quantify epoxy spreading when force was applied to bond the flex print and conducive chip together, multiple prints were created with varying parameters and then characterized as described in section **3.5.4b Print Characterization**. Once printed, the epoxy on a glass substrate was then brought into contact with another glass substrate. A predetermined amount of weight was then applied above the epoxy on each sample for five minutes, as displayed in **Figure 26**.

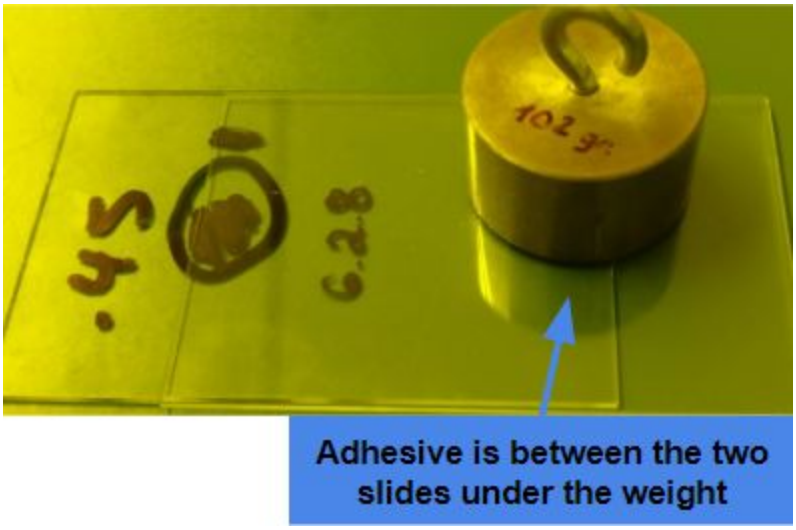


Figure 26: Weighted bonding of substrates

Once the weight was removed, the samples were once again characterized and changes in dimensions were recorded.

3.6.3 Shear Resistance Testing

Shear testing of the newly bonded samples was the next step in the process. To prepare each bonded sample for testing, the samples were cured in accordance with the epoxy data sheet listed in **Appendix B**. The shear testing machine shown in **Figure 27** was used to determine the shear force required to break the test samples' bonds. Parameters were adjusted and data was acquired through the Labview GUI in **Figure 28**.

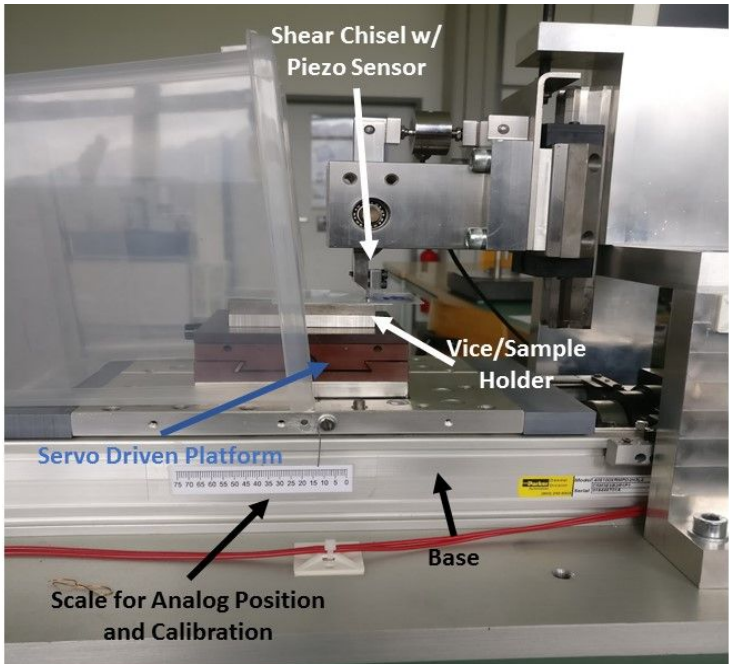


Figure 27: Shear testing machine

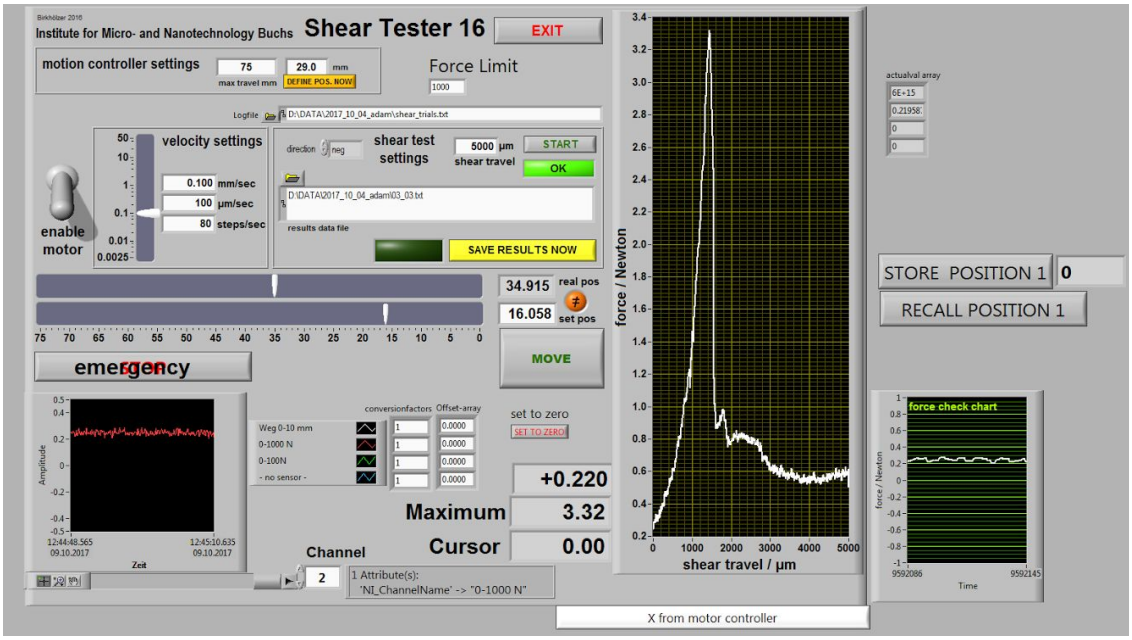


Figure 28: Shear Tester Labview GUI

A matrix was created to list both sets of parameters including inking/printing parameters and the force applied to bond the two materials together.

Inking Force Parameter	Trial 1: Bonding Force 1	Trial 2: Bonding Force 2	Trial 3: Bonding Force 3
Force 1	Measured Shear Resistance		
Force 2			
Force 3			

Table 6: Shear force test matrix

3.6.4 Resistivity Testing

Resistivity testing needed to be completed to determine whether adhesion by conductive epoxy had electrical properties comparable to soldering. To do so, two miniature circuit chips were adhered to each other. Two glass chips with aluminum pads were used, rather than a chip and a flex print. These chips had larger contacts than those designed for adhesion to the flex prints, easing the alignment process. The chips were adhered using the same process as described in section **3.6.2 Epoxy Spread Testing**. The inking force use was 0.65 N and the bonding mass used was 228.68 g. The chips were then cured at 120^{o} C for 15 minutes. After the chip pair was cured, a multimeter was used to test the resistivity across each pad set.

4.0 Results and Discussion

This section contains detailed analyses and discussions of all trials executed during this project. The following processes and parameters were explored and yielded results:

- Ink Pad Creation
- Stage - Print Head Parallel Alignment
- Inking Force
- Epoxy Spread
- Shear Resistance
- Resistivity

4.1 Generating an Ink Pad

As outlined in section **2.5.1 Blade Coating Application Method**, foil guides determined the thickness of the generated ink pad. Four different foil guide thicknesses were available for this project: 150 μm, 90 μm, 20 μm, and 10 μm. Early experiments proved that ink pads created utilizing foil guides with thicknesses of 90 μm or 150 μm created an ink pad layer that was too thick. In order to print successfully, epoxy should only be applied to the raised structures on the stamp. When using an ink pad of 90 μm or 150 μm, epoxy covered all portions of the stamp as shown in **Figure 29**.

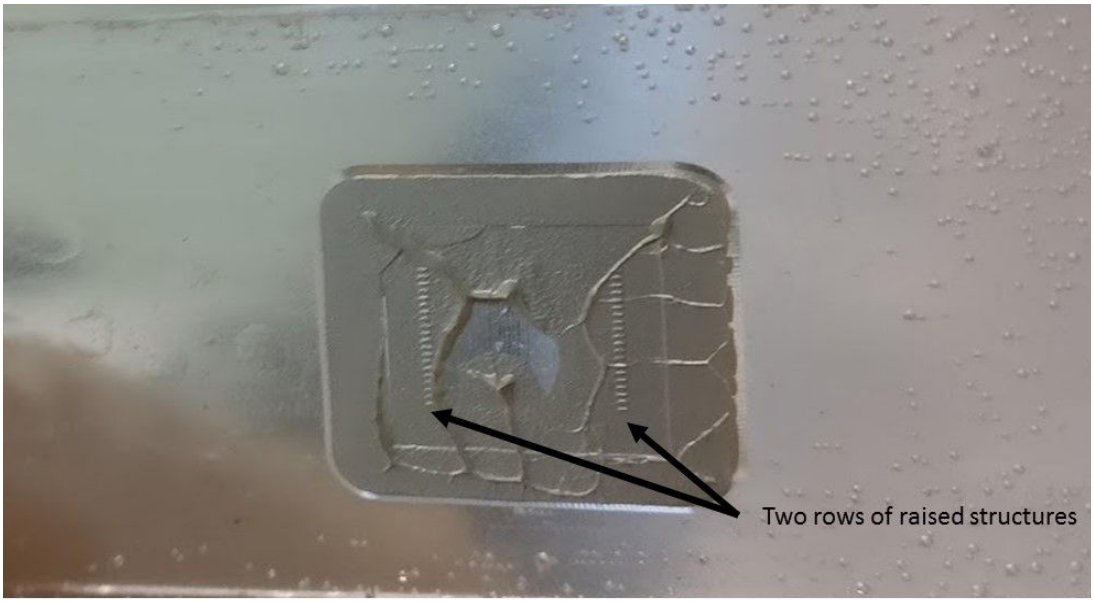


Figure 29: Resultant inking profile of 90+ µm ink pad

These early inking setbacks shifted focus toward the two remaining foil thicknesses: 20 µm and 10 µm. Stamp structure height was measured as 25 µm. Therefore, an ink pad could be generated with either of the remaining foil guides, as they were both less than 25 µm thick. Ink pads created using the 20 µm foil guides were compared to those created using the 10 µm foil guides, as shown in **Figure 30**. Ink pads created using the 20 µm foil guides were found to have an average height of 15 µm, while ink pads created using the 10 µm foil guides had an average height of 5 µm. The 10 µm ink pad experienced peaks and valleys of +/- 4 µm, while the 20 µm ink pad has +/- 2 µm. Because of these findings, all testing utilized ink pads created using the 20 µm foil.

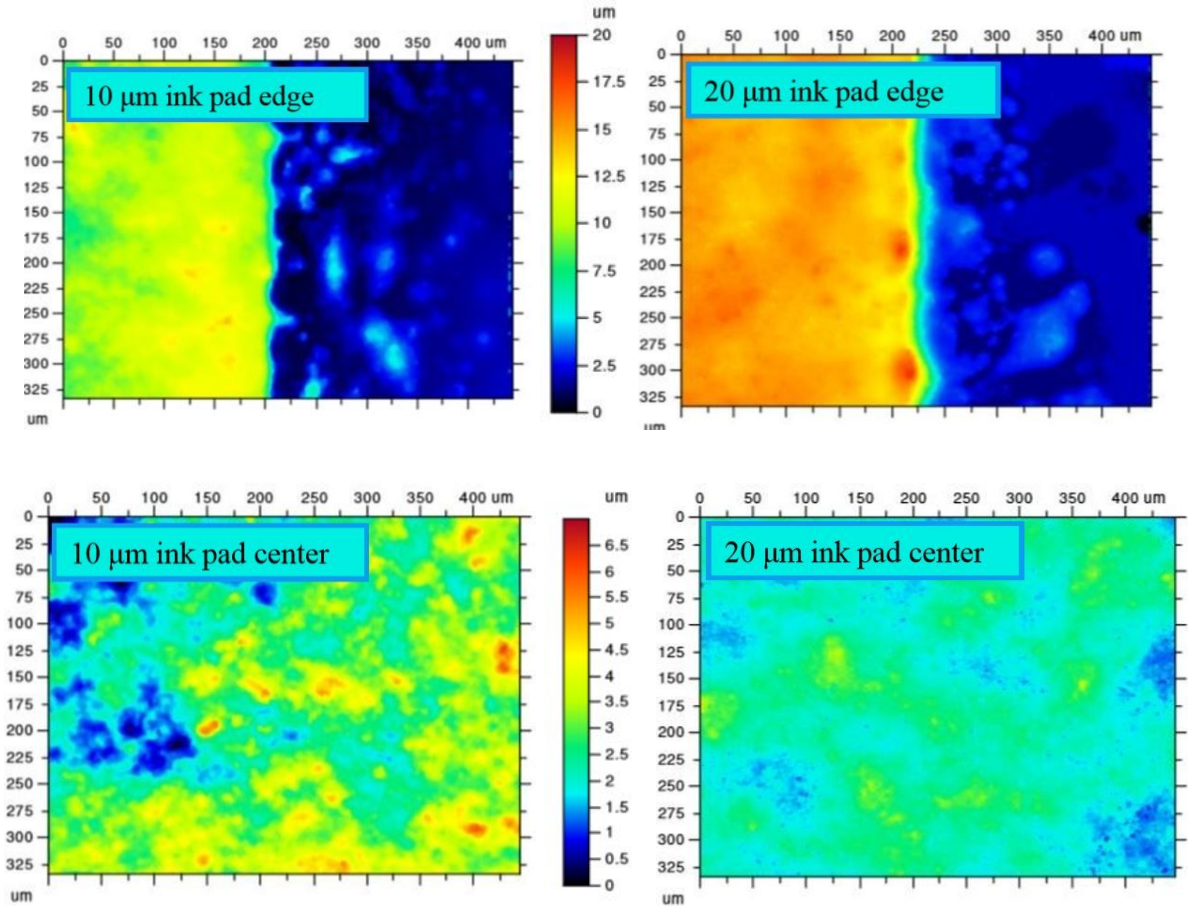


Figure 30: EPO-TEK H2OS, 10 µm ink pad edge (top left) and center (bottom left), EPO-TEK H2OS 20 µm ink pad edge (top right) center (bottom right)

In an attempt to improve the homogeneity of the thin film and overall print quality, ink pads were created with both EPO-TEK H2OS and EPO-TEK H2OE-PFC. This trial was performed to see how the differences in epoxy material properties, listed in section **3.3.1 Ink Pad Creation**, would affect overall film generation. Analyses proved the lower viscosity to be a positive change in regards to ink pad creation. EPO-TEK H2OS spread over the foil guides with much less resistance when compared to EPO-TEK H2OE-PFC. When measured under the WLI, both ink pads averaged a thickness of 15 µm, as seen in **Figure 31**.

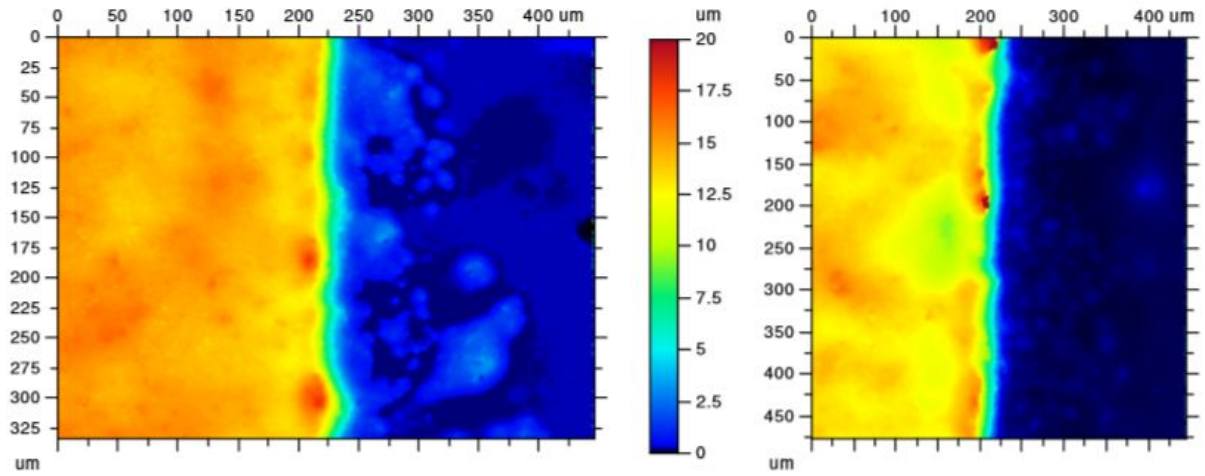


Figure 31: EPO-TEK H2OS, 20 µm ink pad edge (left), EPO-TEK H2OE-PFC, 20 µm ink pad edge (right)

However, when at the entire ink pad and assessing the average homogeneity, peaks and valleys of the ink pad created with EPO-TEK H2OS only differed by +/- 2 um as compared to EPO-TEK H2OE-PFC ink pads that possessed variance of +/- 4 um as observed in **Figure 32**. Therefore, EPO-TEK H2OS was used for printing.

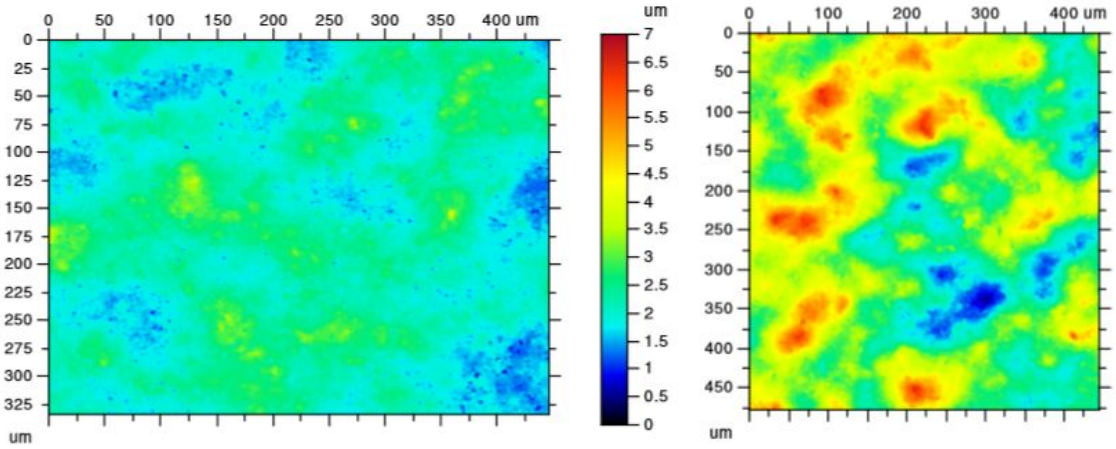


Figure 32: EPO-TEK H2OS, 20 µm ink pad center (left), EPO-TEK H2OE-PFC, 20 µm ink pad center (right)

Neither of these epoxies produced ink layers that had a homogeneity within +/- 10%, however printing trials were attempted. Prints were successfully created with the 20 μm EPO-TEK H2OS ink pad.

4.2 Optimizing the μCP Process

The overall findings discussed in this section reveal that print specifications (e.g. structure sizes, master geometry, tolerance of print, and application) will influence the ways in which tool parameters may be adjusted to influence print quality.

4.2.1 Inking the Stamp using the μCP Tool

4.2.1a Force

The force applied while inking the stamp using the μCP tool proved to be an important parameter in the success of a print. The force used during early trials was 0.65 N. These trials used Masters 1 and 2, which had structures that were 290 μm long, 85 μm wide, and 25 μm tall and a supporting structure surrounding the print structures, as described in **Table 1**. However, this force became too high when Masters 4 and 5 were used, as these masters lacked the support provided by the thick surrounding structure in Masters 1 and 2. The force was cut approximately in half and varied about that point to determine the allowable forces. The window of acceptable force for these small structures was 0.15 N to 0.25 N, as shown in **Figure 33**. These prints were deemed acceptable because they reflected the rectangular shape of the structure on the stamp and had changes in length and thickness within 100 μm. Surpassing 0.25 N created prints as shown in **Figure 34**, which were deemed unacceptable due to their large sizes and irregular shapes.

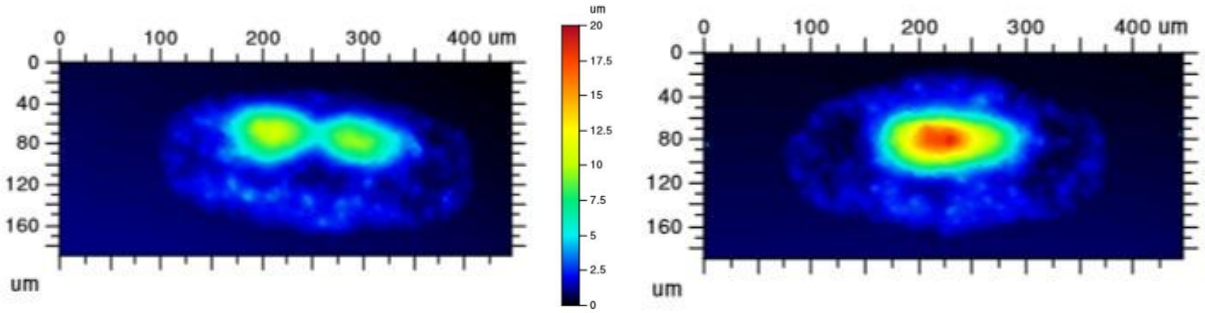


Figure 33: Print created with inking force of 0.15 N (left) and print created with inking force of 0.25 N (right)

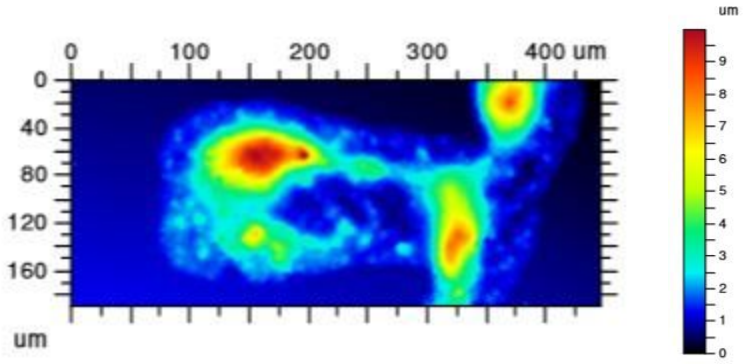


Figure 34: Print made with inking force of 0.35 N

When the size of the structure was increased, the force required to print acceptable structures for analysis increased. The first trial was done with an inking force of 0.2 N, however this resulted in an incomplete print. The inking force was then raised to 0.45 N and subsequent trials were done at 0.45 N (**Figure 35**), 0.65 N (**Figure 36**), and 0.85 (**Figure 37**).

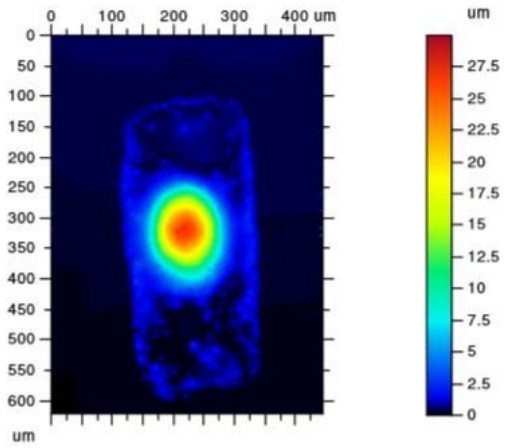


Figure 35: Print created with inking force of 0.45 N

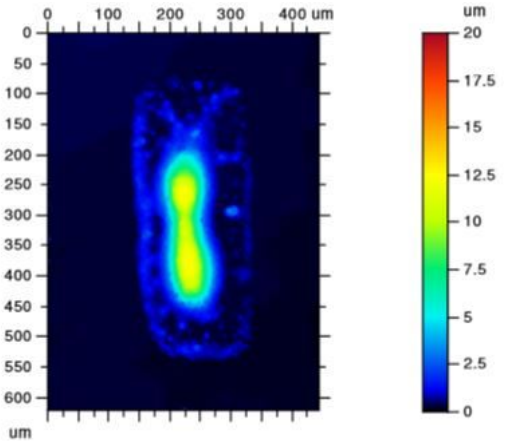


Figure 36: Print created with inking force of 0.65 N

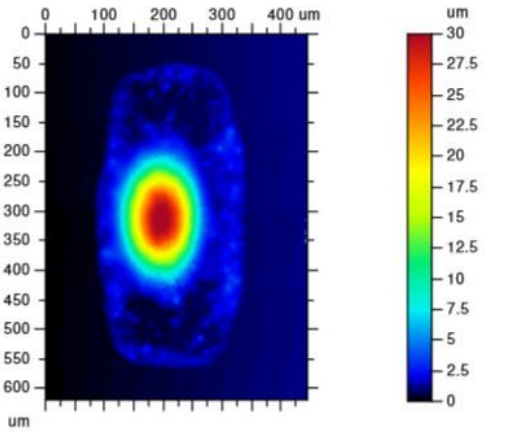


Figure 37: Print created with inking force of 0.85 N

The prints created using these three inking forces were characterized and their lengths and widths were compared to those of the structures on the stamp. This data was compiled and graphed onto a scatter plot, as shown in **Figure 38**. An acceptable change in width was defined based on the tolerance of the aluminum pads on the miniature circuit chips and is shown on **Figure 38** as the purple line at y = 200 µm. This graph shows that all prints, with the exception of one structure, created using inking forces between 0.45 N and 0.85 N were acceptable for use adhering miniature circuit chips to flex prints. This graph also highlights the most successful print created during this project, represented by the yellow and green data points. This print, also shown in **Figure 36**, accurately represented both the shape and the dimensions of the desired print.

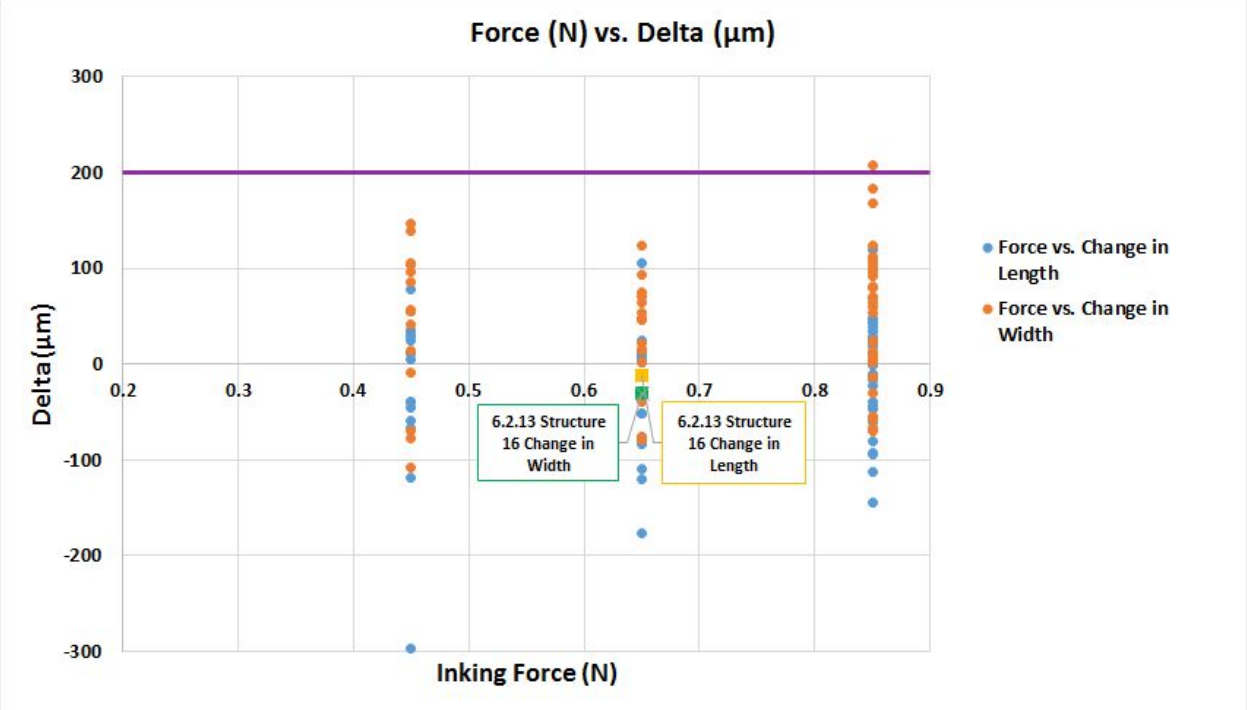


Figure 38: Force (N) vs. Delta (µm)

4.2.1b Roll and Pitch Adjustment for Stage - Print Head Parallel Alignment

Once a set parallel alignment between the print head and stage of the μCP tool was reached for a particular stamp, as outlined in section **3.5.2 Leveling Calibration of the μCP tool**, major changes (e.g. adjustments of 1000 + microns through the roll and pitch alignment dials) were not required. However, this alignment process had to be repeated for each different stamps. These adjustments were necessary in order for prints to fulfill basic specifications as described in section **3.5.4a Visual Print Analysis**. This effect can be seen in **Figure 39** where two different stamps created from the same master print epoxy differently under the same alignment, inking, and printing parameters.

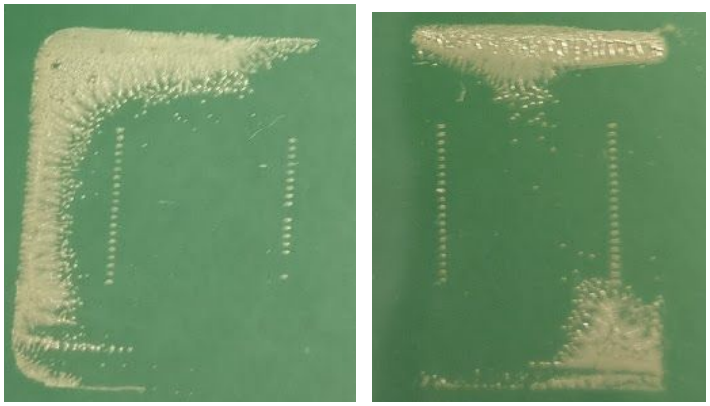


Figure 39: Print 4.1.1 (left) and 4.2.1 (right) (identical alignment and force parameters)

Upon further investigation of each stamp's profile using the WLI, topography measurements revealed that stamp 4.1 was not level. **Figure 40** shows a top view of stamps 4.1 (left) and 4.2 (right), which both begin with structure 1 at the top and finish with structure 20. The height difference between structure one and structure 20 was 30 microns for stamp 4.1. The difference in height between the same two structures in stamp 4.2 was only three microns. This difference in the levelness of the stamps justifies the need to adjust the stage and print head

alignment with every new stamp used. Surface topographies from a top view and side profiles of the cross section of stamps are compared in **Figure 40** and **Figure 41**, respectively.

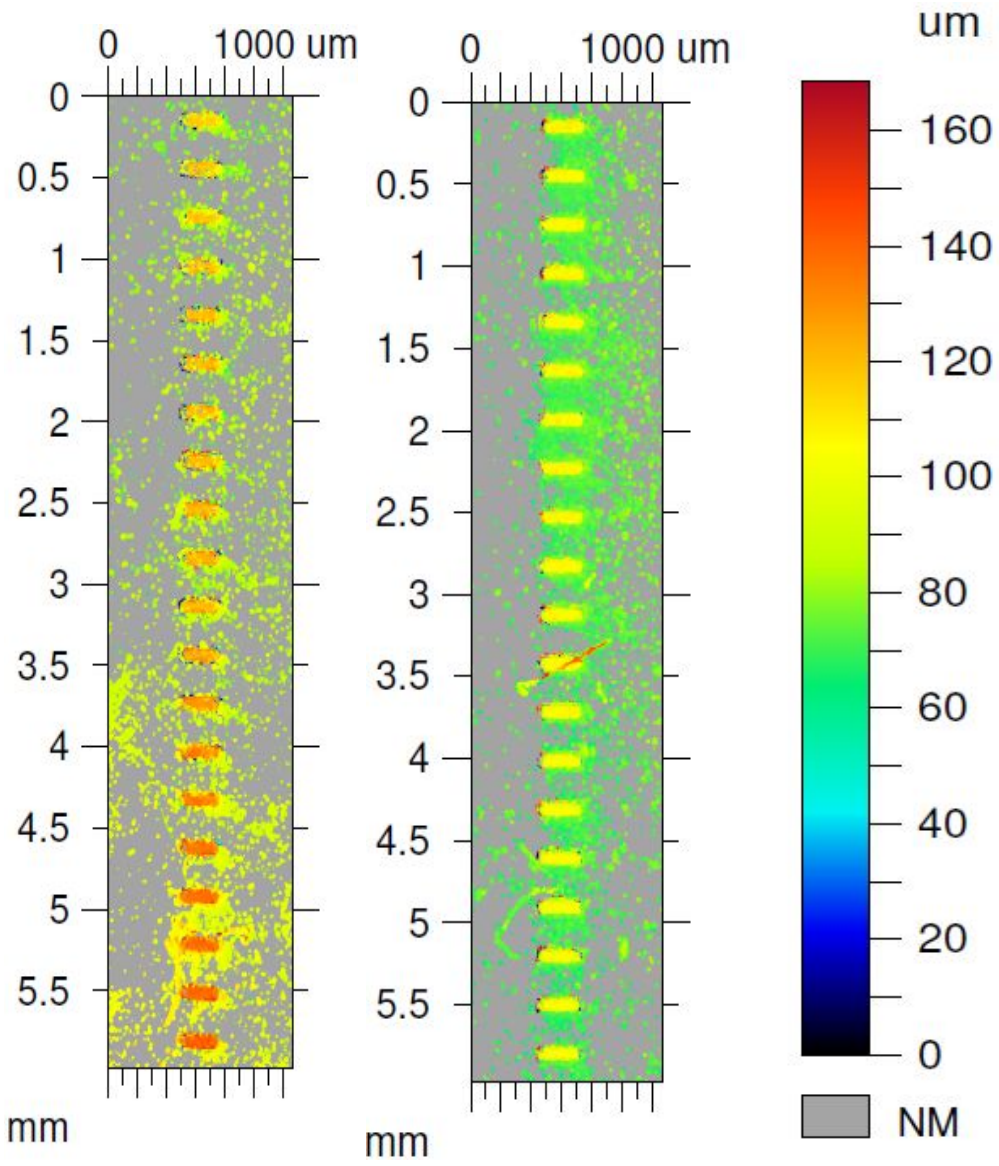


Figure 40: Top view of Stamp 4.1 (left) and Stamp 4.2 (right)

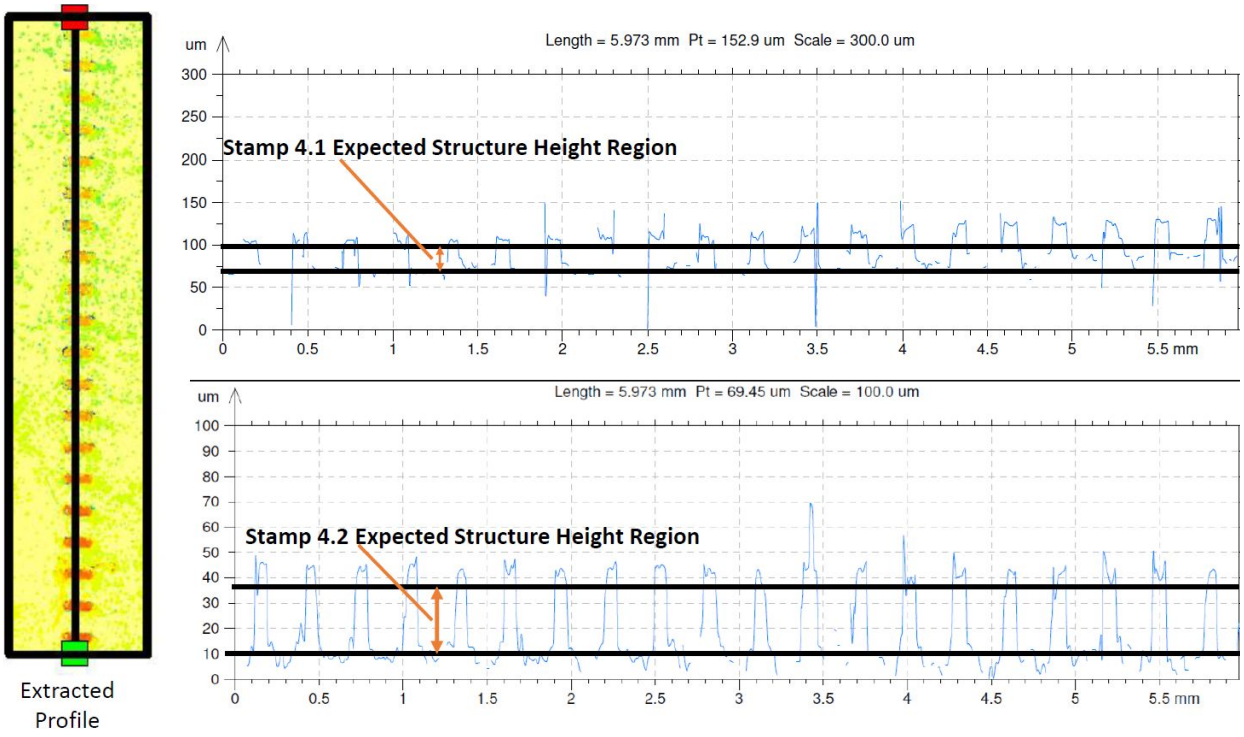


Figure 41: Stamp 4.1 (top) and stamp 4.2 cross-sectional profile comparison

Figure 42 shows a representation of the side profile of the structures on a stamp. As shown in **Figure 42**, the heights of the individual structures do not vary drastically from one end of the stamp to the other. The base of the stamp, however, exhibits a height difference between the ends of the stamp. This reveals that the unlevel nature is not attributed the structures, but rather the stamp base.

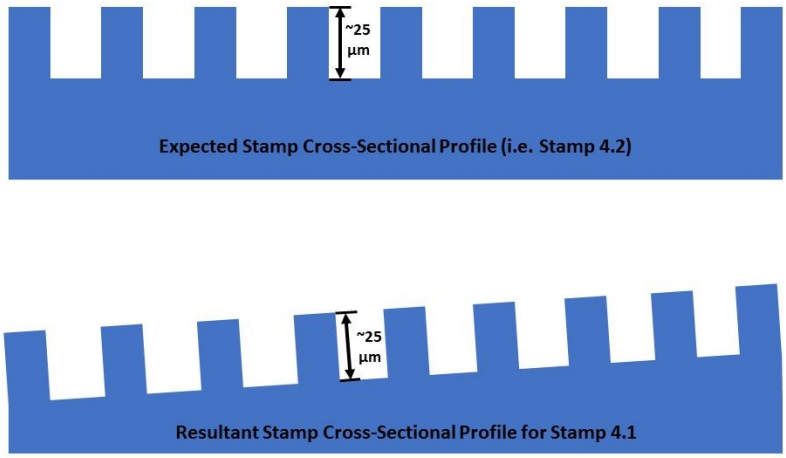


Figure 42: Side representation of structures on a stamp

Understanding that stamp 4.1 was not level confirmed that stage leveling could influence the visual characteristics of print quality. Leveling adjustments were made for subsequent trials to produce prints that complied with specifications outlined in **3.5.5a Visual Print Analysis**. A roll axis adjustment of 1500 microns was applied to the stage to compensate for the uneven nature of the stamp. The resultant print, which was produced under identical parameters as the left image in **Figure 39,** is shown in **Figure 43**.

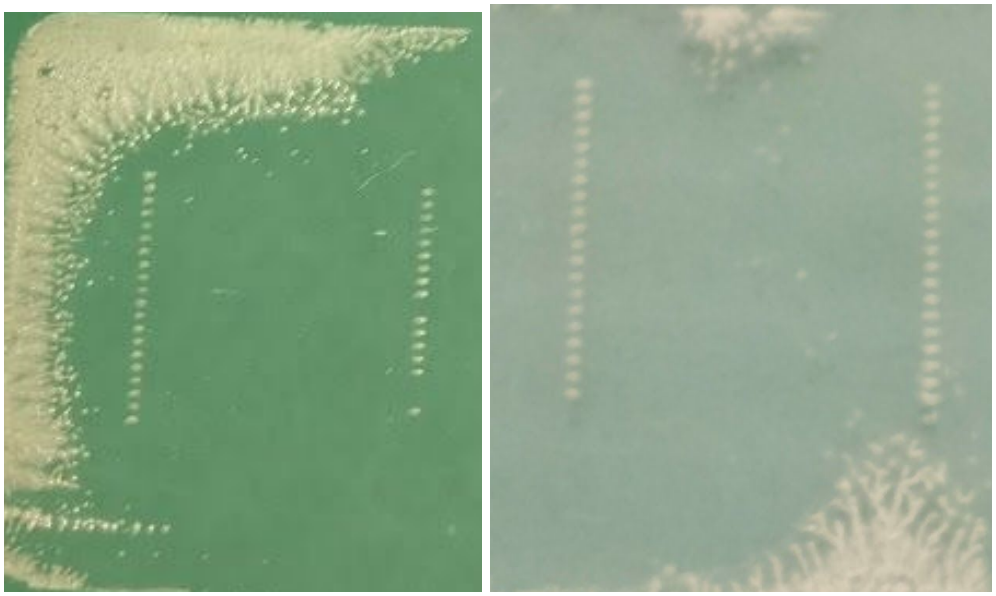


Figure 43: Print 4.1.1 (left) and Print 4.1.2(right; with 1500 micron roll axis adjustment)

This large adjustment improved the stage parallelism to the stamp, producing an acceptable print for further analysis.

Once proper alignment was determined for each stamp, small adjustments could be made to show the impact of inking angle on the final print. No direct correlation between small adjustments and print quality was found. Prints 4.2.7 and 4.2.10 were printed using identical parameters aside from the adjustment of 125 microns through the pitch dial and 125 microns through the roll dial. As seen in **Figure 44**, structures 10L and 11R from print 4.2.7 are visually equivalent to structures 10L and 11R, respectively, from print 4.2.10.

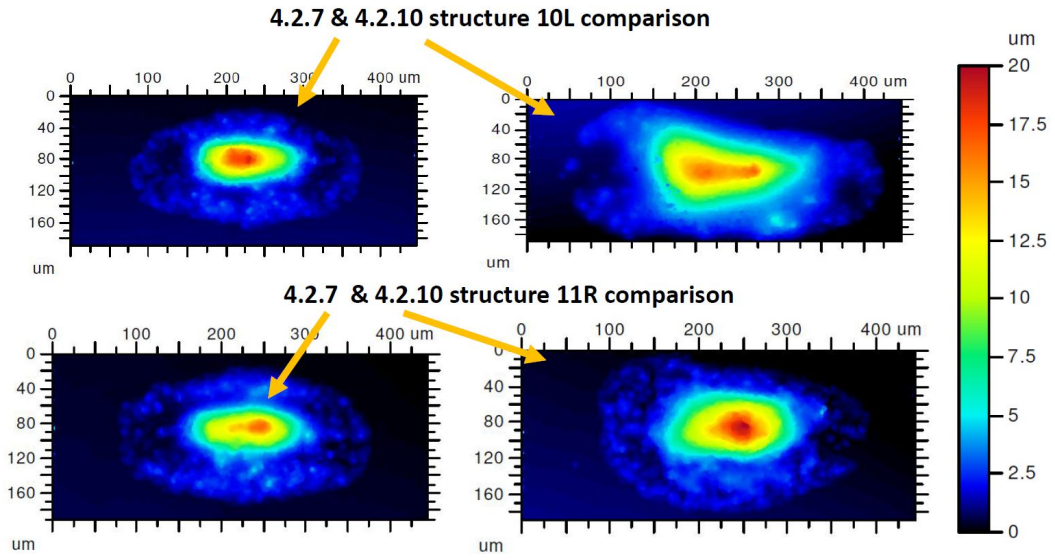


Figure 44: Multiple feature comparison after 125 µm roll axis and 125 µm pitch axis dial adjustment

Small adjustments were made up to 125 microns. A difference of 10% or less was measured in the dimensions in all directions when comparing adjusted prints to their non-adjusted counterpart. Therefore, adjustments of 125 microns or less do not have a significant impact on final prints.

4.3 Epoxy Spread

After the adhesive was printed, a second substrate was bonded to the original. Nine bonded samples were created with three different inking forces and bonding masses. The inking forces used were 0.45 N, 0.65 N, and 0.85 N. The masses used for bonding were 112 g, 166 g, and 212 g. These samples are outlined in **Table 7**.

Individual prints were measured after adhesion. These measurements were compared to the dimensions of the same prints before bonding to determine the spread resulting from the bonding, as seen in **Table 7**. As the spread was measured after bonding, the area of interest was between the two adhered glass microscope slides. Due to the microscope slide on top of the print,

a lower objective had to be used to avoid hitting the sample with the higher objective. This lower objective decreased the detail seen in the print, making measurement difficult. Negative spread values in **Table 7** were due to this constraint using the WLI. Epoxy spread was found to be due to two factors: epoxy peak height and sliding during adhesion. Epoxy spread due to sliding can be seen in **Figure 45**.

Inking Force Parameter	Trial 1 Bonding Force Applied: 1.10 N (112g)		Trial 2 Bonding Force Applied: 1.63 N (166g)		Trial 3 Bonding Force Applied: 2.08 N (212g)	
	Average Change in Length	Average Change in Width	Average Change in Length	Average Change in Width	Average Change in Length	Average Change in Width
0.45 N	-6.360	-3.225	12.275	5.700	30.855	-11.695
0.65 N	9.690	12.905	-0.120	58.925	17.900	16.685
0.85 N	37.710	23.215	18.360	50.565	5.055	24.585

Table 7: Average ink spread

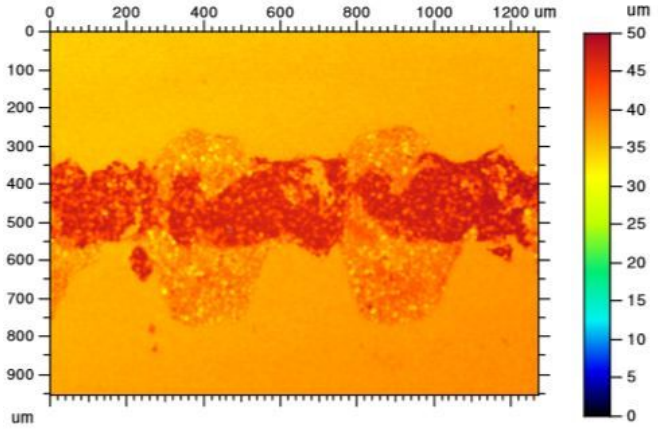


Figure 45: Print which slid during adhesion

Measurements, shown in **Table 7**, and optical examinations showed that the amount of ink applied in the original print was the largest factor impacting ink spread. Higher epoxy peaks resulted in larger epoxy spread when bonded. Structure 16 from print 6.2.12, shown in **Figure 46**, had an original peak of 23 μm, while structure 16 from print 6.2.13 had an original peak of 11 μm, as shown in **Figure 47**. As shown in **Figures 46** and **47**, structure 16 experienced more

spreading on print 6.2.12 compared to 6.2.13, even though print 6.2.13 was bonded using 212 g, while 6.2.12 was bonded with 166 g. The spreading experienced by structure 16 on print 6.2.12 was 41.72 µm, while only 29.16 µm on print 6.2.13.

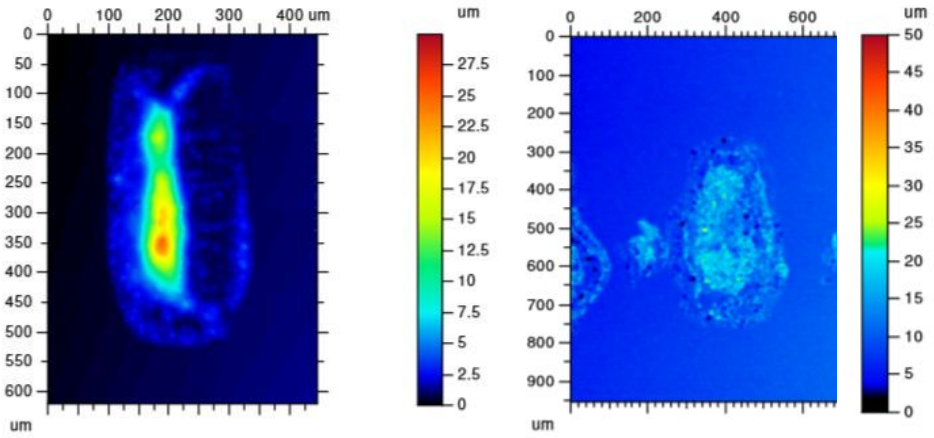


Figure 46: Print 6.2.12 Structure 16 (left) and Print 6.2.12 Structure 16 spread after bonding (right)

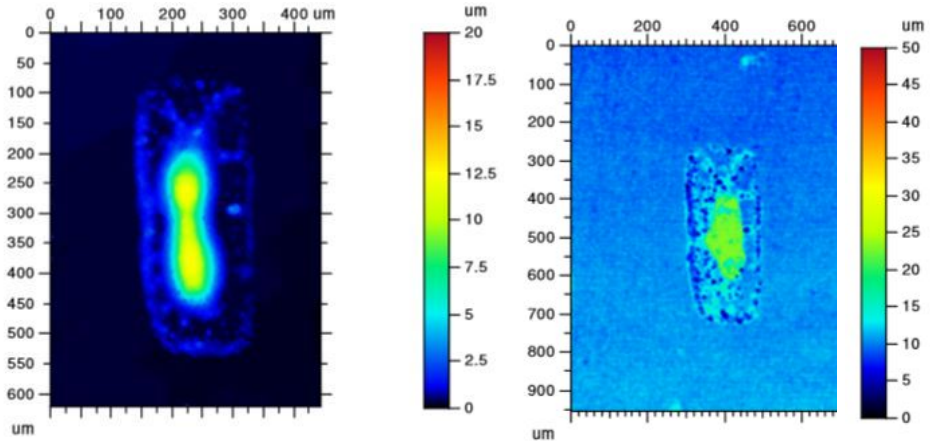


Figure 47: Print 6.2.13 Structure 16 (left) and Print 6.2.13 Structure 16 spread after bonding (right)

4.4 Shear Resistance

Shear tests were executed on all nine samples utilized for the pressed epoxy trials after curing per instructions in section **3.6.2 Epoxy Spread Testing**. All samples provided usable test data as shown in **Table 8**.

Inking Force Parameter	Trial 1 Bonding Force Applied: 1.10 N (112g)	Trial 2 Bonding Force Applied: 1.63 N (166g)	Trial 3 Bonding Force Applied: 2.08 N (212g)
0.45 N	0.47 N	1.85 N	2.67 N
0.65 N	0.62 N	1.72 N	2.80 N
0.85 N	1.43 N	2.07 N	3.32 N

Table 8: Shear force test data

Data reveal that as the inking force in the printing process increased, the shear force also increased, as seen in **Table 8**. Similarly, as the bonding force increased the overall shear forces increased across all samples.

Using the highest sample shear strength (3.32 N), the shear stress (**τ**) was calculated using the equation:

$$\tau = Force/Parallel\ Area$$

Equation 3: Shear stress

This value was determined to be 150 psi when considering the cross-sectional area of the applied epoxy was approximately 0.005 square inches. When compared to the theoretical lap shear stress listed on the EPO-TEK H2OS data sheet in **Appendix B** of 1,240 psi, the actual value is 1/8th the expected value. Throughout these trials, structures may not have been fully transferring all of the ink to the substrate. Additionally, an area over estimate or the gaps between structures may have affected the final result.

4.5 Resistivity Trials

A resistivity test was utilized to determine if adhesion by microcontact printing with a conductive epoxy could establish electrical continuity across conductive contacts, as shown in **Figure 48**.

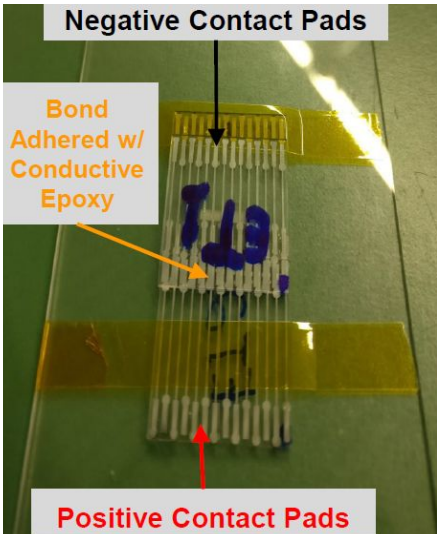


Figure 48: Conductive chips bonded for resistivity testing

The stamp utilized to apply conductive epoxy to the conductive chips had structures designed for the flex prints with contact pads that were 300 µm wide. The aluminum contact pads on the miniature chips used for resistivity testing were 635 µm wide. Therefore, using the camera on the microcontact printing tool, two stamp structures were aligned with the first contact on the chip. While print alignment was not successful on the remaining pads, epoxy was applied to both chips on the first contact successfully. After the bonding and curing processes, a multimeter was used to determine if electrical conductivity had been established across the set of contacts. A resistance reading of 0.96 kOhms was obtained through the multimeter measurement, confirming the epoxy facilitated electrical continuity between two chips.

4.6 Time Constraints

Time proved to be a critical factor in each individual processing step. However, the impact of time was heavily observed in the epoxy pot life and the printing time.

4.6.1 Epoxy Pot Life

Both EPO-TEK H2OE-PFC and EPO-TEK H2OS had pot lives of three days. After three days viscosity changes by 20%. Therefore, it became important to note the time after mixing the two components of the epoxy at which printing occurred. In order to maintain consistency and efficiently isolate variables, all trials were performed with epoxy mixed within 36 hours of the print.

4.6.2 Printing Time

The amount of time between inking and printing was an influential factor. In order to ensure that ink was being applied evenly to all structures, inked stamps were observed under the WLI. This showed that while the applied ink would peak towards the center of the structure, the entire structure was completely covered. However, these measurements took approximately 30 minutes per stamp, increasing the amount of time between inking and printing. As seen in **Figure 49**, prints created within thirty minutes between inking and printing transferred ink from fewer structures than those created within two minutes between inking and printing.

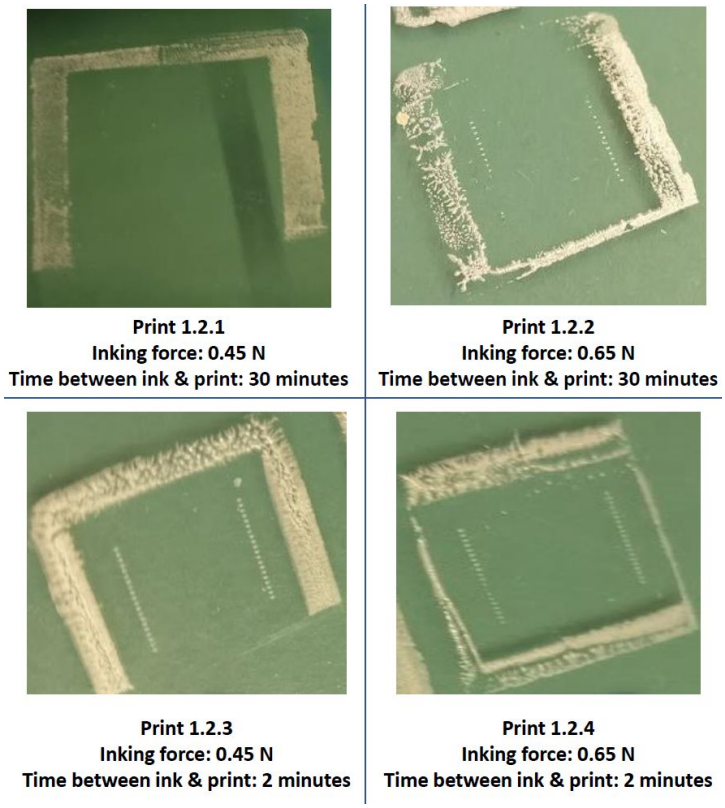


Figure 49: Comparisons of the effect of time between inking a stamp and printing

5.0 Conclusion

The goal of this project was to use microcontact printing to bond a miniature circuit chip and a flex print using a conductive epoxy. This goal was broken down into two objectives. The first objective was to optimize the microcontact printing process for a conductive epoxy on a glass substrate. This was done by considering the tool properties that had the potential to impact print quality.

The second objective was to apply the optimized parameters to the desired application, bonding the flex print and miniature circuit chip. The desire to use microcontact printing as opposed to soldering stems from the size and production rate constraints of soldering. Shear strength and resistivity tests could be completed to determine if adhesion by microcontact printing has characteristics comparable to those of soldering. While these tests were completed, their values were not compared to those of soldering due to the wide variety of soldering techniques used in industry. The data collected during shear strength and resistivity tests showed that, if optimized, adhesion by microcontact printing has the potential to match adhesion by soldering.

Microcontact printing process refinement led to the development of a method that produced repeatable and usable prints. The execution of a structured test plan determined which mechanical properties influenced the quality of a final print. These results showed that the force applied throughout the printing process, both during inking and printing, was not a singular ideal force, but instead had to fall within a window of acceptable forces. This window of acceptable forces depends on the size of the structures on the stamp. The stamp created to print the pattern

required to bond the miniature circuit chips to flex prints had an acceptable force window of 0.45 N to 0.85 N.

After exploring forces, focus was placed on the alignment and relative parallel nature of the stage to the print head of the microcontact printing tool. In order to produce successful prints, each stamp, once attached to the print head, had to be aligned using adjustment dials on the roll and pitch axes of the tool stage. These combined refinements created a baseline from which further adjustments could be made. Further adjustment up to 125 microns had negligible impacts on the dimensions of the final print. All prints created with stamps that had been properly aligned fell within the size tolerance set by the pads on the miniature circuit chips.

The refined inking force and alignment parameters were used to print epoxy to conduct shear strength and electrical conductivity tests for the desired application. The maximum shear strength measured was 3.32 N and the measured resistivity was 0.96 kOhms. While the microcontact printing process is not yet fully optimized, this data revealed that with time and more resources, using microcontact printing to apply conductive epoxy establishing electrical connections could be an innovative, alternative solution to current soldering techniques.

6.0 Future Work

When considering the results collected throughout this project, the following future work is recommended.

6.1 Parameter Limits

Due to the time constraints of this project, only three parameters were considered: ink pad thickness, inking force, and inking angle. In order to fully optimize this process in the future, the remaining parameters discussed during this report (i.e. printing force, angle, and time) should be optimized following the methods used for this project.

6.2 Stamp Holder on μCP tool

When a stamp is loaded onto the μCP tool print head, there is no consistent hard stop or set position for the stamp to be aligned with each time. Between each new print creation, the stamp must be cleaned, which requires removal from the tool. The stamp is then placed back onto the print head and secured with the vacuum. However, there is no guarantee that the alignment is consistent with previous trials and that force will be measured/applied to the stamp in the same manner. To remove this potential source of error, a stamp holder on the μCP tool print head for the current design of the PDMS stamps is recommended to provide a consistent position.

6.3 μCP Tool Calibration & Alignment

The current μCP tool does not possess a method of determining the parallelism of the tool stage to the print head. A digital solution to monitoring this factor could be the implementation of gyro sensors and encoders on the μCP stage and print head to compare the angular positions of

the subsystems. A digital readout indicator could be displayed on the Labview GUI to provide the user with information about relative positions.

6.4 Utilizing Flex Prints with Non-Solder Stopping Contacts

A constraint defined late in the timeline of this project was the existence of solder stop on the flex prints for the desired application. This solder stop lined the width of the flex print and had a height of approximately 20-30 μm. Therefore, electrical continuity could not be established when two components were adhered together. Future work done on this project should be done using flex prints with non-solder stopping contacts.

6.5 Surface Functionalization/Wettability

Due to the time constraints of this project, the main focus was to specifically assess the impact of mechanical properties on print quality. Thus, the wettability of the glass substrate and miniature conductive chips was never assessed. Printing was done on both glass substrates and aluminum contact pads, which have different wetting properties. Therefore, methods of functionalization should be developed for both to increase the hydrophilicity of the surface.

Appendices

Appendix A: EPO-TEK H2OE-PFC Data Sheet

EPOXY TECHNOLOGY

EPO-TEK® H20E-PFC

Technical Data Sheet

For Reference Only

Electrically Conductive, Silver Epoxy

Date: Sep 2013
Rev: VIII

Recommended Cure: **150°C / 1 Hour**

No. of Components:	Two
Mix Ratio by Weight:	1 : 1
Specific Gravity:	Part A: 2.88 Part B: 3.31
Pot Life:	3 Days
Shelf Life:	One year at room temperature

Minimum Alternative Cure(s):
may not achieve performance properties below
175°C / 45 Seconds
150°C / 5 Minutes
120°C / 15 Minutes
80°C / 3 Hours

NOTE: Container(s) should be kept closed when not in use. Filled systems should be stirred thoroughly before mixing and prior to use.

Product Description: EPO-TEK® H20E-PFC is a two component, semiconductor grade epoxy, designed for flip chip interconnects using a solder-free joining method.

Typical Properties:

To be used as a guide only, not as a specification. Different batches, conditions & applications yield differing results.
*Cure condition: 150°C/1 Hour * denotes test on lot acceptance basis Data below is not guaranteed.*

PHYSICAL PROPERTIES:			
* Color (before cure):		Part A: Silver Part B: Silver	
* Consistency		Smooth thixotropic paste	
* Viscosity (23°C): @ 100 rpm		3,000 - 4,000	cPs
Thixotropic Index:		6.69	
* Glass Transition Temp:		≥ 80	°C (Dynamic Cure:20-200°C/ISO 25 Min; Ramp -10-200°C @ 20°C/Min)
Coefficient of Thermal Expansion (CTE):			
	Below Tg:	48 x 10^{-6}	in/in°C
	Above Tg:	106 x 10^{-6}	in/in°C
Shore D Hardness:		50	
Lap Shear @ 23°C:		850	psi
Die Shear @ 23°C:		≥ 5	Kg 1,700 psi
Degradation Temp:		407	°C
Weight Loss:	@ 200°C	0.46	%
	@ 250°C	1.02	%
	@ 300°C	1.78	%
OperatingTemp:	: Continuous:	- 55°C	to 225°C
	Intermittent:	- 55°C	to 325°C
Storage Modulus:		921,254	psi
Ion Content:	Cl:	199	ppm NA^+: 12 ppm
	NH_4^+:	349	ppm K^+: 12 ppm
* Particle Size:		≤ 20	microns

ELECTRICAL AND THERMAL PROPERTIES:		
Thermal Conductivity:	3.2	W/mK
* Volume Resistivity @ 23°C:	≤ 0.0004	Ohm-cm

Appendix B: EPO-TEK H2OS Data Sheet

EPOXY TECHNOLOGY

EPO-TEK® H20S
Technical Data Sheet
For Reference Only

Electrically Conductive, Silver Epoxy for Die Stamping

Number of Components:	Two
Mix Ratio By Weight:	1:1
Specific Gravity:	
Part A	1.74
Part B	3.07
Pot Life:	3 Days
Shelf Life:	One year at room temperature

Minimum Bond Line Cure Schedule*:

175°C	45 Seconds
150°C	5 Minutes
120°C	15 Minutes
100°C	45 Minutes
80°C	90 Minutes

*Note: Container(s) should be kept closed when not in use. For filled systems, mix contents of each container (A & B) thoroughly before mixing the two together. *Please see Applications Note available on our website.*

Product Description:

EPO-TEK® H20S is a modified version of EPO-TEK® H20E, designed primarily for die stamping and dispensing techniques for chip bonding. EPO-TEK® H20S is a highly reliable, two component, silver-filled epoxy with a smooth, thixotropic consistency. In addition to the high electrical conductivity, the short curing cycles, the proven reliability, and the convenient mix ratio, EPO-TEK® H20S is extremely simple to use.

EPO-TEK® H20S Advantages & Application Notes:

- Especially recommended for use in high speed epoxy chip bonding systems where fast cures are highly desirable.
- Suggested for JEDEC Level III and II plastic IC packaging.
- The low temperature cure makes it ideal for flex circuitry and other low stress applications.
- It is used extensively for bonding quartz crystal oscillators and other stress sensitive chips.
- Used for die and SMD bonding inside hybrid/hermetic packages such as DIP and TO-Cans; also EMI/Rf shielding of micro-electronics.
- Ideal for making ITO electrical contacts in LCD packaging; and suggested for LED die-attach.

Typical Properties: *(To be used as a guide only, not as a specification. Data below is not guaranteed. Different batches, conditions and applications yield differing results; Cure condition: 150°C/1 hour; * denotes test on lot acceptance basis)*

Physical Properties:

*Color: Part A: Silver Part B: Silver
*Consistency: Smooth, thixotropic paste
*Viscosity (@100 RPM/23°C): 1,800 – 2,800 cPs
Thixotropic Index: 5
*Glass Transition Temp.(Tg): ≥ 80°C (Dynamic Cure 20—200°C /ISO 25 Min; Ramp -10-200°C @ 20°C/Min)
Coefficient of Thermal Expansion (CTE):
Below Tg: 31 x 10^{-6} in/in/°C
Above Tg: 120 x 10^{-6} in/in/°C
Shore D Hardness: 64
Lap Shear Strength @ 23°C: 1,240 psi
Die Shear Strength @ 23°C: ≥ 5 Kg / 1,700 psi
Degradation Temp. (TGA): 414°C

Weight Loss:
@ 200°C: 0.40%
@ 250°C: 0.60%
@ 300°C: 1.37%
Operating Temp:
Continuous: - 55°C to 200°C
Intermittent: - 55°C to 300°C
Storage Modulus @ 23°C: 339,720 psi
Ions: Cl^- 162 ppm
Na^+ 0 ppm
NH_4^+ 282 ppm
K^+ 4 ppm
*Particle Size: ≤ 20 Microns

Electrical Properties:

*Volume Resistivity @ 23°C: ≤ 0.0005 Ohm-cm

Thermal Properties:

Thermal Conductivity: 3.25 W/mK

EPOXY TECHNOLOGY, INC.
14 Fortune Drive, Billerica, MA 01821-3972 Phone: 978.667.3805 Fax: 978.663.9782
www.EPOTEK.com

Epoxies and Adhesives for Demanding Applications™

Rev. X
Sep 2011

References

B Michel, A Bernard, A Bietsch, & E Delamarche. (2001). Printing meets lithography: Soft approaches to high-resolution printing. *IBM Journal of Research and Development, 45*(5), 697. Retrieved from ProQuest Computer Science Journals database. Retrieved from https://search.proquest.com/docview/220685049

Burgués-Ceballos, I., Stella, M., Lacharmoise, P., & Martínez-Ferrero, E. (2014). Towards industrialization of polymer solar cells: Material processing for upscaling. *J. Mater. Chem. A, 2*(42), 17711-17722. doi:10.1039/C4TA03780D

Chai, X., Kobayashi, T., & Fujii, N. (1999). Ultrasound-associated cleaning of polymeric membranes for water treatment. *Separation and Purification Technology, 15*(2), 139-146. doi:10.1016/S1383-5866(98)00091-4

Epoxy Technology. (2015). Cure Matters: Determining the Proper Cure Schedule. Retrieved from http://www.epotek.com/site/files/brochures/pdfs/Cure_Matters_Final.pdf

Glasmästar, K., Gold, J., Andersson, A., Sutherland, D. S., & Kasemo, B. (2003). Silicone transfer during microcontact printing. *Langmuir, 19*(13), 5475-5483. doi:10.1021/la026558x

Han, J., Messina, K., & Switalla, N. (2016). *Modification of microcontact printing process for adhesive and conductive ink printing *

Kim, B., K Peterson, E T K, & Papautsky, I. (2004). Long-term stability of plasma oxidized PDMS surfaces. *Conference Proceedings : ... Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE Engineering in Medicine and Biology Society. Annual Conference, 7*, 5013. Retrieved from PubMed database. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/17271441

Krebs, F. C. (2009). Fabrication and processing of polymer solar cells: A review of printing and coating techniques. *Solar Energy Materials and Solar Cells, 93*(4), 394-412. doi:10.1016/j.solmat.2008.10.004

*Microcontact printing tool * Unpublished manuscript.

Nobel Media. (2014). The history of the integrated circuit. Retrieved from https://www.nobelprize.org/educational/physics/integrated_circuit/history/

Peters Group. (2017). ELPEMER SD 2463 FLEX-HF. Retrieved from https://www.pragoboard.cz/download/sd2463_eng.pdf

Polymerization *Encyclopoedia Britannica,* Retrieved from http://academic.eb.com.ezproxy.wpi.edu/levels/collegiate/article/polymerization/60701

*Processes microcontact printing * Unpublished manuscript.

Swain, S. K., & Isayev, A. I. (2009). PA6/clay nanocomposites by continuous sonication process. *Journal of Applied Polymer Science, 114*(4), 2378-2387. doi:10.1002/app.30827

Tyco Electronics Corporation. (2013). Quick reference guide standard flexible printed circuit (FPC). Retrieved from http://www.mouser.com/pdfdocs/TEConnectivityFPCStandardQuickReferenceGuide.PDF

Underwriters Laboratories. (2017). Polyimide (PI) Plastic. Retrieved from https://plastics.ulprospector.com/generics/32/polyimide-pi

Xia, Y., & Whitesides, G. M. (2010). Soft lithography. *Angewandte Chemie International Edition, 37*(5), 550-575. doi:AID-ANIE550>3.0.CO;2-G

Yang, L., Shirahata, N., Saini, G., Zhang, F., Pei, L., Asplund, M. C., et al. (2009). Effect of surface free energy on PDMS transfer in microcontact printing and its application to

ToF-SIMS to probe surface energies. *Langmuir : The ACS Journal of Surfaces and Colloids, 25*(10), 5674. Retrieved from PubMed database. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/19358590