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I, Varun Sharan Kumar, hereby submit this original work as part of the requirements for the degree of Master of Science in Mechanical Engineering.

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Study of Binding Copper Powders by

Electrochemical Deposition

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By

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ABSTRACT

Additive manufacturing (AM) is a layer-by-layer manufacturing process that has a wide range of applications. Microparts manufactured by additive manufacturing are gaining prominence over traditional manufacturing methods due to their ability to process a wide range of materials, fabricate complex 3D microstructures and ease of use. AM processes have applications in diverse fields such as aerospace, automotive, medical devices and implants, electronics, and so on for fabricating complex microparts.

This work evaluates the feasibility of binding metal powders to enable a novel micro additive manufacturing method based on localized electro-deposition. A single layer of copper powders were glued together with the help of Nickel from the electrolyte as a binder using a completely in-house built CNC stage and controller. Images from scanning electron microscopy (SEM) and Optical microscope along with X-ray spectroscopy studies have shown the gluing of copper powders with Nickel acting as a binder element. Mechanical characterization was done on the glued part and yield strength values were obtained. Further, Taguchi studies have been conducted to investigate the optimal process parameters required for minimum diameter of glued spot, layer thickness and yield strength. Analysis of Variance (ANOVA) and signal-to-noise ratio were used to determine the important levels of process parameters and the results were then experimentally verified. A mathematical model is developed and verified to predict yield strength values of the deposit. Experimental verification of the model was performed using different substrates with the same deposition parameters to verify the substrate effects involved in the predicted hardness value. It was found that the deviations in the film hardness values of deposits on different substrates under the same deposition parameters were within 8% of each other.
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NOMENCLATURE

c            Constant
u            trial number
i            experiment number
\( y_u \)   mean response value
M            Overall mean of output factor
N_i          number of trials for experiment i
SN_i         Signal-to-noise ratio
\( \sigma \) yield strength of the bound part (MPa)
\( \Sigma \)  Summation
\( \eta_{ij} \) Average value corresponding to significant factor
\( \eta_{predicted} \)  Optimum value of output factor

\( H_c \)  Composite hardness (MPa)
\( H_f \)  Film hardness (MPa)
\( H_s \)  Substrate hardness (MPa)
\( A_f \)  Area on which \( H_f \) acts
\( A_s \)  Area on which \( H_s \) acts
\( P_{max} \) Maximum load (mN)

XIV
$A_p$ Projected area of contact at peak load

$m$ Amount of Nickel deposited at the cathode

$n$ Number of electrons in the electro chemical reaction of Nickel

$F$ Faraday’s constant (A-h/mol)

$I$ current that flows through the tank (A)

$I_p$ Pulse on current (A)

$d_f$ Duty factor

$T$ Time of deposition (s)

$H$ Indentation depth (mm)

$a$ Current efficiency ratio

$t$ Thickness of the film (mm)

$d$ Density of Nickel (g cm$^{-3}$)

$A_{ni}$ Area of deposition

$HV$ Vickers hardness (kgf/mm$^2$)

$\sigma$ Yield strength of the bound part (MPa)
1. Introduction

Due to the present push towards miniaturization of products in varied industries including medical, automotive, optics, biotechnology and electronics sectors, there is a need for improvement in micro and nanofabrication technologies [1, 2]. There exists a broad range of microfabrication technologies each having its own capabilities, applications and limitations [1, 3, 4]. Most of the microfabrication techniques are restricted when it comes to fabricating microproducts with diverse materials and complex 3D microstructures with high aspect ratios [5]. Recently though there have been improvements in micromanufacturing of 3D microstructures using different methods and materials. Some of these improvements include methods such as soft lithography [6], laser photoablation [7], localized electrochemical deposition [8], LIGA process [9, 10], electrochemical fabrication (EFAB) [11]. Most of the above processes (excluding EFAB) were developed for 2.5D micromanufacturing and hence are not suitable for producing a real 3D micropart. Micro additive manufacturing (AM) based on layer-by-layer manufacturing has been considered as an effective process that can manufacture true 3D microproducts [12].

1.1. Motivation for research

Additive manufacturing based on layer-by-layer technology is an effective process to fabricate 3D microparts. The current AM processes have a number of limitations when it comes to manufacturing microparts. The limitations are listed below:

Micro Stereo Lithography processes have a limitation of not fabricating a wider range of materials. They have limitations with minimum layer thickness due to viscosity and surface tension of the resin [13, 14]. Selective Micro Laser Sintering is a process which must be
performed in a vacuum chamber to avoid humidity and resulting oxidation[15]. Also there are limitations with respect to powder handling, part removal, and surface roughness. Since it is a thermal process, there are limitations with respect to thermal damage of the part. For the Selective laser Melting process, there are no specialized systems that can do micro manufacturing [16]. Inkjet printing is an AM process that employs layer-by-layer deposition of a liquid material in droplet form. A major limitation is the need of support structures for complex micro features. Also the removal of these support structures after the part is machined is a problem. 3D printing is another AM technology based on inkjet printing [17]. One of the problems of 3D printing is that the fluid which acts as the binder is ejected through a nozzle. The diameter of the orifice is usually less than 100 microns. Hence the binder should have low viscosity and high stability to prevent orifice clogging [18, 19]. Also, the jetting process must be performed in a low oxygen environment to prevent the formation of a surface oxide layer thus resulting in changes to the physical properties of the jet surface [20, 21].

To overcome the limitations currently present with respect to thermal damage, orifice clogging, support structures etc. in this research, a new micro AM process which is a combination of 3D printing and Localized electrochemical deposition (LECD) has been proposed.

1.2. Objective

The objectives of this research are:

1. Design and building of the micro CNC stage and controller
2. Establishing the feasibility of localized binding of metal powders using electro-chemical deposition
3. Investigation of the parameters affecting minimal diameter of deposition spot and layer thickness
4. Conducting an yield strength study on the glued part and investigating the parameters affecting yield strength of glued part
5. Formulating a mathematical model and verification for predicting yield strength of the glued part

1.3. Outline

The organization of the thesis is as follows: Chapter 1 gives a brief introduction into micro manufacturing and the motivation for the research. Chapter 2 is an in-depth literature review on the current trends in additive manufacturing with a focus on powder based AM technologies and LECD. Chapter 3 deals with establishing the feasibility of the proposed research idea. Chapter 4 explains in detail the system design and building of 3D micro CNC setup which is used in the research work. Chapter 5 explains the influence of process parameters on the diameter, layer thickness of deposition spot and yield strength of the glued part using Taguchi methodology. In chapter 6, a mathematical model is presented which gives accurate yield strength values. Chapter 7 lists the conclusions and future work.
2. Literature review

This chapter provides a detailed review of recent literature pertaining to this research.

2.1. 3D Micro Additive manufacturing

3D micro additive manufacturing can be categorized into three main groups [12]:

1. Scalable AM technologies – can be done for both macro and micro scale

2. 3D Direct writing (3DDW) – Developed for micro scale

3. Hybrid Processes

A classification of the different processes which come under the three main groups are shown in Figure 1 [12].

![Figure 1 - Classification of 3D micro additive manufacturing](image_url)
This research addresses some of the limitations based in powder based additive manufacturing methods. Hence, a detailed literature study is done on the existing powder based processes and their limitations. A classification of powder based additive manufacturing methods is shown in Figure 2.

![Diagram of powder based additive manufacturing methods](image)

**Figure 2 - Classification of powder based additive manufacturing**

### 2.1.1. Powder based additive manufacturing technologies - Melting

**Micro Selective laser sintering process (MLS)**

In this process, a high temperature laser sinters layers of very fine powder selectively. After each layer is sintered, a roller is used to spread a fresh layer of powder and the process is repeated [22]. Selective Micro Laser Sintering must be performed in a vacuum chamber to avoid humidity and resulting oxidation[15]. Also there are limitations with respect to powder handling, part
removal, and surface roughness. Since it is a thermal process, there are limitations with respect to thermal damage of the part [12].

Figure 3 (a) shows a MLS system with two powder coating rakes. These rakes help in controlling powder particle size and powder blend in each layer. Thus due to this system of rakes, multi or functional graded microparts can be manufactured. Figure 3 (b) and (c) show a multi material micropart made from copper and silver.

Selective laser melting (SLM)

This process is based on the MLS technique. Higher energy density lasers are used when compared with MLS thus resulting in complete melting of the metal powders [12]. For the Selective laser Melting process, there are no specialized systems that can do micro manufacturing [16].
Laser Engineered Net Shaping

Laser engineered net shaping is an additive manufacturing process which is mainly used for repairing parts. Here, metal powder are inserted at specific locations and a high-powered laser beam is used to melt the powder. This process is carried out in a closed chamber to prevent oxidation. A large variety of metals and combination of alloys can be used in this process. A major disadvantage with this process is the resultant residual stresses due to uneven heating and cooling processes [24-27]. A schematic of the process is shown in Figure 4.

![Figure 4 – Laser Engineered Net Shaping](image)

Electron Beam Melting

This process is similar to selective laser sintering but instead of a high temperature laser, an electron beam is used to melt layers of fine powder. This process takes place in a vacuum chamber to avoid oxidation and hence has been touted to be used in outer space applications [29]. Typically a 30 to 60 KV high voltage electron beam is used for this process.
2.1.2. Powder based additive manufacturing technologies – Binding

Prometal

Prometal is a powder based additive manufacturing technology which is mainly used for building tools and dies. The most commonly used powder is stainless steel. Since this is a binding process, a layer of metal powder is initially spread and liquid binder is deposited on top of it which binds the metal powder. This is repeated till a finished part is formed. Usually, sintering, infiltration and finishing processes are required to obtain a functional part [30].

2.2. Micro 3D printing process (3DP)

3D printing (3DP) process which is based on inkjet technology was first developed at MIT[31]. Here, material ejected from the nozzle are deposited over a powder bed thereby solidifying the powder. The part is then lowered and a new layer of powder is spread over the previous layer and the process continues till the entire part is build[32]. The binder used in 3D printing is ejected out from a nozzle held at close proximity to the powder. A variation of 3D printing is direct inkjet printing where the powders are mixed with the binder beforehand. The powder-binder mixture is then ejected out from a nozzle and is subsequently cooled down by different processes to get the finished part.

The following steps are involved in developing any new 3D printing process:

2.2.1 Selection of powders

This is the first step in any 3D printing process. Involves selection of powder material, size of the powder particle, powder deposition method on the substrate and adding any additive if needed [33]. Particle size of the powder affects characteristics of the final part. Fine powders can give
thinner layers and minimum feature sizes whereas larger powders give a more homogeneous part [34, 35]. Powders can be either dry or wet deposited on to the substrate. Finer powders having particle diameter < 15 µm are wet deposited as a slurry. Larger powders of diameter ranging from 25 – 45 µm can be either wet or dry deposited on the substrate [34-37].

2.2.2. Selection of binder

An important aspect to look at here is the binder residue. Some binders like chloroform are known as fugitive binders as they don’t leave any trace behind. These binders do no contribute to the final strength of the part and hence a secondary process will be required to improve the strength of the part [38-40]. Other binders like plasters or cement leave a residue behind and hence contribute to the final strength of the part [37, 41].

2.2.3 Interaction between the powder and binder

This steps involves determining the weather the binder and the powder can interact with each other to form a homogeneous part. If the powder is hydrophobic and the binder is liquid based, there will be little interaction and hence the final part will be weak. Usually a compatibility testing is carried out before the actual process by inserting the binder on to the powder using a syringe and studying the interactions [37, 42].

2.2.4 Post processing of the part

This step involves removing the part from the powder bed and cleaning of the excess powders. Some of the ways that this can be achieved are through blowing, vacuuming, vibrating etc. [43, 44]. Post processing can also involve increasing the strength of the final part. This is done by either sintering the finished part or by a process called as infiltration [37, 45].

Some of the literature on parts achieved using micro 3DP is listed below:
Lu et al. have printed 3D mesh structures having 300 microns wire width. They have used gas-atomized Ti$_{35}$Ni$_{50}$Hf$_{15}$ (abbreviated as TiNiHf) powder having a mesh size of less than 635[46]. Lam et al. used a combination of cornstarch, dextran, and gelatin powders to print cylindrical scaffold designs. The binder/ink they used was natural polymers and plaster of paris in combination with a water-based ink[47]. Seitz et al. have used hydroxyapatite powder (HA) to fabricate 3D porous scaffolds for bone tissue engineering purposes. They have used a polymer based agent as the binder solution [48]. Ko et.al used 1-3 nm Au nano particles (NP) for direct inkjet printing. The NPs were dispersed in organic solvents like Toluene to form NP ink used for inkjet printing. A drop-on-demand inkjet head was used. Microstructures were then fabricated on glass or polymer substrate[49]. In all of the above techniques the binder or the binder – particle matrix is ejected out from a nozzle or printhead. A major limitation of using this kind of technique lies with the nozzle and the orifice diameter. The binder must have low viscosity to flow freely through the nozzle else orifice clogging can occur. Also the binder should be jetted out in a low oxygen environment to prevent the formation of a surface oxide layer thus resulting in undesirable changes to the physical properties of the part [18-21].

Figure 5 - 3D micro threads fabricated using 3DP process [12]
2.3. Localized electrochemical deposition (LECD)

Localized electrochemical deposition (LECD) has been considered as an effective process to fabricate 3D metallic microparts. The process was first introduced by Madden et al. who showed that when a tip of a sharp electrode placed in a plating bath is brought near a substrate and electric field is applied between the two, deposition happens which is localized to only the area below the electrode tip [8, 50]. Nickel micro-columns have been fabricated on a copper substrate using a non-soluble microelectrode (Platinum) as the anode[51]. Copper micro-columns were fabricated using LECD process and pulse electric supply instead of the traditional DC supply[52]. Chang et al. were able to fabricate Nickel micro-columns using a platinum microanode and Watts bath as the electrolyte. They also studied the effect of voltage on the surface morphologies of the fabricated nickel micro-columns[53]. Ultrasonic vibrations were introduced during LECD of nickel micro-columns and the results showed that the columns had a higher porosity when compared to columns fabricated without vibration[54].

2.4. Composite hardness model for yield strength study

The hardness value can be approximated to get a yield strength value of the part [55]. Since, the thickness of the deposit is very less, substrate effects come into play when measuring the hardness values of the part through Nanoindentation. Due to the small thickness, directly measured hardness values are usually influenced by the substrate. One way of overcoming this problem is by lowering the indentation load such that the substrate does not play a part in the measured value. This option too has limitations, since in most materials, the hardness cannot be defined by very small indentations [56]. A second approach is to separate the film hardness from
the composite hardness values. Several composite hardness models have been developed for this purpose [56-61]. Buckle’s model [62] was one of the earliest attempt that defined the measured hardness as the sum of hardness values within the plastic zone. The Jonsson-Hogmark is one of the earliest and most successful models that uses an area law of mixtures approach based on the load supporting film and substrate areas to model the composite hardness [57]. This model uses an uncomplicated geometrical approach to separate the substrate and film hardness contributions from the composite hardness value [59]. Another model developed by Burnett et al. [60, 61] is used in particular cases where indenter penetration depth is very low and is based off the volume law of mixtures. Chicot et al. proposed a composite hardness model which introduced a function related to the substrate and to the film hardness [59].

2.5. Outcome of literature review

In all of the techniques listed in the literature above, the binder or the binder – particle matrix is ejected out from a nozzle or printhead. A major limitation of using this kind of technique lies with the nozzle and the orifice diameter. The binder must have low viscosity to flow freely through the nozzle else orifice clogging can occur. Also the binder should be jetted out in a low oxygen environment to prevent the formation of a surface oxide layer thus resulting in undesirable changes to the physical properties of the part [18, 19] [20, 21].

It can also be seen from literature that there is thermal damage in the finished parts using MLS, LCVD because of the involvement of a high temperature laser. To overcome these limitations, a new process which uses metal generated through localized electrochemical deposition as the binder has been proposed.
3. System Design

This chapter explains in-depth, the building of the micro CNC stage and controller used for the gluing process. It also explains the software used for communicating with the stage and controller.

3.1. Introduction

The setup for the gluing process consists of an in-house built micro CNC stage and controller. The parts can be broken down into the actual stage which consists of 3 Zaber LSA Series Micro Motorized Linear Stages and the electrolyte tank (workpiece holder), the controller which consists of 3 DRV8824 Stepper Motor Driver, C10 bi-directional parallel port breakout board, and CNC spindle/tool holder.

3.2. Zaber LSA Series Micro Motorized Linear Stages

The objective was to build a 3 axis Micro CNC stage to carry out the experiments. For this purpose, 3 LSA series micro stages were used to form the 3 axes of the CNC stage. Figure 6 shows an individual axis of the LSA micro stage. 3 of these axes were custom fit and assembled to form the base of the CNC stage which can be seen in Figure 7.

The specifications of each individual axis are:

- Each axis can travel a maximum of 10mm
- < 25 nm microstep size
- Up to 10 mm/s speed and up to 3.5 kg thrust
• Driven by NEMA 08 stepper motors

The main advantages in choosing the Zaber linear stages are:

• These stages are driven by NEMA 08 stepper motors which are one of the smallest and most powerful stepper motors available.

• The 10 mm maximum axis travel is ideal for carrying out experiments at a micro scale.

• It can handle up to 3.5 kg thrust which is needed to support and move the electrolyte tank and workpiece holder fitted on top of it.

• The minimum movement of each axis is 1 micron. The feed rate is user defined and can range from a high of 32 mm/min to a low of about 1 micron/sec.

• The LSA stages are wired with a male D-sub 15 connector which is ideal to connect to a third party/custom built controller.

Figure 6 – Single axis of the micro stage
An electrolyte tank was machined at the workshop and placed on top of the stage. The tank holds the electrolyte and the substrate which acts as the cathode on which deposition takes place. The tank assembled on top of the stage is shown in Figure 17.

3.3. In-house built stepper motor controller

This section explains the need, components, assembly, and working of the in-house built stepper motor controller.

3.3.1 Need for In-house built stepper motor controller

The objective was to build a micro CNC stage which would be able to interact with an open source CNC software. The LSA micro stage uses a NEMA 08 stepper motor. This stepper motor
is one of the smallest and most powerful stepper motors available. Due to the size of the stepper motor, the rated current for the motor is very low (240 mA/phase). Hence, there were two main requirements for the controller:

1. The controller should be able to interact with an open source CNC software.

2. The controller should supply a rated current lower than the maximum current that NEMA 08 stepper motor can take i.e. less than 240 mA.

Before building the final controller, several alternatives (readily available controllers) were tried and tested. Below is a list of some of the controllers which were tested with the micro stage:

The first controller which was tested was the TB6560 stepper motor controller. This was a low cost controller available on eBay. The controller interfaced with a PC computer through a parallel port. This meant that it would be able to interact with the open source CNC software and hence control the motor through G codes. The controller is shown in Figure 8. The major drawback with this controller was the minimum rated current that it could deliver was 1.5A which was very high for the NEMA 08 stepper motors. Hence this controller would overheat the stepper motors during regular operation and would eventually burn the stepper motors.
The second controller which was tested was the Gecko drives G540 controller. This is a popular controller shown in Figure 9 with a very good build quality that is most often used for controlling CNC stages. This controller again interfaces with a PC through a parallel port. Even though the rated current for this controller ranges from 0 – 3.5A, the amount of current supplied to the motors cannot be controlled to a specific value. Hence the stepper motors would eventually heat up and prolonged use would burn the motors.
There were controllers from Zaber, the company which manufactured the LSA micro stage and Allegro micro systems which were considered. These controllers are built to operate with a NEMA 08 stepper motor supplying a rated current well below the 240 mA maximum value for the motors. But these controllers have an RS-32 connector to interact with the PC. These connectors do not work with the open source CNC software.

Hence, there was a need to build a low current stepper motor controller which would be able to interface with an open source CNC software.
3.3.2 Components and assembly

To control the 3 axes of the CNC stage, 3, DRV8824 Stepper Motor Driver Carrier, Low Current breakout boards were used. The main advantage of this board is that it has a trimming potentiometer which helps in controlling the amount of current sent to the stepper motor. Figure 10 shows the DRV8824 board along with the trimming potentiometer.

![Trimming potentiometer](image)

By adjusting the potentiometer and measuring the Voltage value at the “ref” pin, the current limit can be set using the relation:

\[
\text{Current limit} = V_{\text{ref}} \times 0.61
\]

Hence, to set a current limit of 200 mA which is below the rated current of 240 mA for the NEMA 08 stepper motors, the potentiometer needs to be set in a position where the Voltage measured at the \( V_{\text{ref}} \) pin is 0.33 V.
The 3 individual controllers were soldered on to a bread board with the wiring diagram shown in Figure 11.

![Wiring diagram for DRV8824](image)

**Figure 11 - Wiring diagram for DRV8824**

The soldered controllers are shown in Figure 12.

![Soldered controller](image)

**Figure 12- Soldered controller**
Once the issue with supplying low current to the motors was sorted out, the next step which was making the controller compatible with an open source CNC software was addressed. For the controller to work with a CNC software and thereby move the stage using G codes; it has to be interfaced with the PC preferably through a parallel port.

For this, the C10 Bi-directional parallel port breakout board was used. This board which is shown in Figure 13 provides an easy way of interfacing outputs and inputs through a parallel port. The outputs for the Step/Direction signals from the soldered controller are used as inputs to the breakout board. The breakout board then sends these output signals through the parallel port to a PC based CNC controller. This helps in controlling the stage through G codes.

Figure 13 - C10 Parallel port breakout board
3.4. CNC controlled spindle/tool holder

Once the stage with the electrolyte tank and controller were built, the next step was to build a tool holder. The tool which acts as the anode during deposition might be rotated depending upon the experiments. Hence there was a need to have a spindle which would be controlled by the CNC software which would double up as a tool holder. Depending upon the experiment the tool could be rotated by including rotation in the CNC program or keep the tool stationary.

To achieve this, a CNC controlled spindle and controller were used. The spindle used in the system is a 400W PWM speed controlled spindle which was bought on Amazon. The spindle has a controller which was wired to the C10 breakout board to interface with the CNC software. The spindle and controller are shown in Figure 14.
The fixture to hold the spindle in place was machined in the workshop. The spindle mounted on the machined fixture is shown in Figure 17.

3.5. CNC software

There were a couple of CNC software that were tried and tested for use with the stage and controller. The first one was LinuxCNC which is open source software under the GNU licensing scheme. As the name indicates this software works only on Linux based operating systems and was tested on Ubuntu. The software worked well in controlling the stage and spindle. This software is slightly more complicated and time consuming in defining the initial settings and calibration for individual axis. The advantages are that each and every aspect of the software is completely user customizable and hence offers a great deal of features for operating a CNC stage. The software UI for LinuxCNC is shown in Figure 15.

![Figure 15 - UI for LinuxCNC](image-url)
The second software which was used was Mach3. This software is a Windows based CNC software. Mach3 has an easier user interface and calibration system when compared to LinuxCNC. It is more intuitive and has all the features needed to control a stage and spindle using G codes. Mach3 was chosen as the software used to control the CNC stage and spindle in this work. A typical Mach3 UI is shown below in Figure 16.

![Mach3 UI](image)

Figure 16- UI for Mach3

The complete setup along with the micro CNC stage, electrolyte tank, stepper motor controller, C10 breakout board, spindle/tool holder, and Mach3 software is shown in Figure 17.
Figure 17 - Complete experimental setup
4. Feasibility Study

4.1. **Principle of Gluing of metal powders by electrochemical deposition**

The process developed in this research combines the principles of 3D printing and localized electrochemical deposition (LECD) to present a novel micro additive manufacturing technique. A single layer is experimented and studied in this work to demonstrate the feasibility of the proposed approach. Copper powder is spread on a substrate immersed in an electrolyte bath and the tip of an electrode is brought near it. Electric field is passed and the circuit is completed. Nickel from the electrolyte is deposited locally below the tip of the microanode. This results in the copper powder located below the electrode to be glued by the nickel deposit which acts as a binder. Figure 18 shows the schematic of the gluing process.

![Figure 18 - Schematic of gluing process](image)

M + A -
TOOL ELECTRODE
(M) (+)
METAL SUBSTRATE (-)
At Tool
M (s) → M+ (aq) +e-
Horizontal Feed
ELECTROLYTE
INSULATION
At Layer-in-progress
M+ (aq) +e → M↓
Binder Material
Completed Layers
METAL POWDER
METAL SUBSTRATE (-)
4.2. Experimental Setup

The experimental setup for this process is explained in detail in chapter 3. The experimental setup used for the gluing process can be seen in Figure 17.

4.3. Experimental Details

A platinum tool of 250 microns diameter was used as the anode. The tool was coated on the sides with an insulating material with only the tip exposed. A copper plate was used as the substrate (cathode). The substrate was fine polished using different size sandpapers to get a smooth uniform finish. The substrate was then washed with deionized water and cleaned in an acetone ultrasonic bath for 3 minutes to rid it off any surface contaminants that might be present. Copper powder of grit size 325 or 44 microns was used for the experiments. It was found that powders having a grit size of more than 25 microns are suitable for both dry and wet deposition methods [63]. The substrate along with the copper powder was placed inside the electrolyte cell. A pulsed power supply was chosen for this process to achieve localized deposition. Watts bath was the electrolyte chosen for the experiments, the composition of which is listed in

Table 1.

<table>
<thead>
<tr>
<th>Chemical</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nickel Sulphate (NiSO(_4).6H(_2)O)</td>
<td>240 g/l</td>
</tr>
<tr>
<td>Nickel Chloride (NiCl(_2).6H(_2)O)</td>
<td>45 g/l</td>
</tr>
<tr>
<td>Boric acid (H(_3)BO(_3))</td>
<td>30 g/l</td>
</tr>
</tbody>
</table>
The initial experiments were conducted with a copper substrate. The experimental conditions used are given in Table 2. All the initial experiments conducted had a pulse on time of 20ms and a duty factor of 23%. The inter-electrode gap was fixed at 20 microns for the initial set of experiments. The experimental parameters used are listed in Table 2.

With regard to the copper powder, several experiments were conducted to come up with the best way of placing the copper powder on the substrate. Initially copper powder was loosely placed on the substrate. This procedure had several problems, chief among them was the powder being displaced as and when the electrolyte was introduced.

After many trials and going through literature, making the powder into a paste or slurry were tested [33]. Loose copper powder was mixed with DI water and applied on top of the substrate. When electrolyte was introduced into this system, the problem with copper powder being displaced was solved. This system was tested with the initial experiments and the results showed that Nickel was being deposited on the copper powder.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrode (Anode)</td>
<td>Platinum tool of 250 microns dia.</td>
</tr>
<tr>
<td>Substrate (cathode)</td>
<td>Polished copper plate (25mm*25mm)</td>
</tr>
<tr>
<td>Electrolyte</td>
<td>Watts bath</td>
</tr>
<tr>
<td>Voltage</td>
<td>8V</td>
</tr>
<tr>
<td>Duty Factor</td>
<td>23%</td>
</tr>
<tr>
<td>Pulse on time</td>
<td>20 ms</td>
</tr>
<tr>
<td>Gap</td>
<td>20 microns</td>
</tr>
</tbody>
</table>
4.4. Preliminary Results

The glued specimen were observed under an optical microscope. Three samples were experimented on with three different substrates. Sample A, B and C with copper, brass and glass substrates respectively. An optical microscope image of plain copper powders can be seen in Figure 20 shows the nickel deposition on sample A. It is clearly observed that nickel is deposited over the copper powder. SEM image of the deposition spot for sample A is shown in Figure 21. Figure 22 shows the images for sample B wherein brass has been used as a substrate.

Figure 23 shows gluing of copper powders on a glass (nonconductive) substrate.

![Optical microscope image of plain copper powder](image-url)
Figure 20 - Sample A – Copper powder glued by nickel binder on a copper substrate

Figure 21 - Sample A – SEM image of deposition spot
Figure 22 - Sample B - Copper powder glued by nickel binder on a brass substrate

Figure 23 - Sample C - Copper powder glued by nickel binder on a glass (nonconductive) substrate
Energy-dispersive X ray spectroscopy (EDX) technique was used to examine the copper powder and deposition spot. These results are shown below. The chemical composition of both can be seen in Table 3 and Table 4. In Figure 24, which is the EDX of plain copper powder, it can be seen that there is no noticeable Nickel present. For the EDX on the deposition spot in Figure 25, a nickel spike can be clearly seen in the results along with the copper powder. This shows that nickel is acting as a binder in gluing the copper powders.

![EDX spectrum](image)

Figure 24 - EDX of copper powder shows negligible presence of nickel
Figure 25 - EDX of the glued spot clearly shows the presence of nickel which acts as a binder in gluing the copper powders.

Table 3 - Chemical composition of plain copper powder

<table>
<thead>
<tr>
<th>Element</th>
<th>Wt %</th>
<th>At %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>92.48</td>
<td>82.84</td>
</tr>
<tr>
<td>Oxygen</td>
<td>03.68</td>
<td>13.08</td>
</tr>
<tr>
<td>Silicon</td>
<td>00.43</td>
<td>00.77</td>
</tr>
<tr>
<td>Nickel</td>
<td>03.41</td>
<td>03.31</td>
</tr>
</tbody>
</table>

Table 4 - Chemical composition of glued region (deposition spot)

<table>
<thead>
<tr>
<th>Element</th>
<th>Wt %</th>
<th>At %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>85.60</td>
<td>78.08</td>
</tr>
<tr>
<td>Oxygen</td>
<td>02.77</td>
<td>10.02</td>
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<tr>
<td>Silicon</td>
<td>00.51</td>
<td>00.91</td>
</tr>
<tr>
<td>Nickel</td>
<td>11.12</td>
<td>03.31</td>
</tr>
</tbody>
</table>
Thus, a novel micro additive manufacturing method was proposed and experiments were carried out using a completely in-house built micro CNC stage. Gluing of copper powders was carried out using nickel from electro chemical deposition as a binder. Images from scanning electron microscopy (SEM) and Optical microscope along with X-ray spectroscopy studies show the gluing of copper powders with nickel as a binder element.
5. Design of experiments to study the effect of process parameters

After the feasibility of the idea was established, experiments were carried out to optimize the process parameters which would give smallest diameter of deposition and minimum layer thickness of deposition. Ideally, in localized electrochemical deposition, the diameter of a deposition spot must be as close to the diameter of the tool being used. This will be advantageous in binding true 3D parts together. Also the thickness or height of deposition is a very important parameter that needs to be controlled. The thickness of the binder plays a vital role in the strength and surface finish of the part [12, 64]. In traditional 3D printing, the binder is dispensed of a nozzle and hence the amount of binder being deposited can be easily controlled. In our process the binder is being generated through electrochemical reactions and hence we need to find the ideal process parameters to get minimum amount of binder generated and hence have better control over the process. Taguchi methodology was used to optimize the process parameters.

5.1 Taguchi Methodology for design of experiments

The Taguchi method provides a systematic and efficient methodology for process optimization. The Taguchi reduces variation in a process through robust design of experiments. Instead of having to test all possible combinations like the factorial design, the Taguchi method tests pairs of combinations [65]. Orthogonal arrays and Signal-to-noise ratios are used as part of this process. Orthogonal arrays give a way of conducting the minimal number of experiments which could give the full information of all the factors that affect the performance parameter. Signal-to-
noise ratios give an indication of the effect of changing one process parameter on the entire process.

There are three quality characteristics used by Taguchi namely, smaller-the-better, nominal-the-best, and larger-the-better. In this study, the objective was to reduce the diameter of deposition and get a minimum layer thickness of binder deposited. Hence smaller-the-better quality characteristic has been used in this study.

5.1.2. Selection of process parameters

Numerous experiments were conducted to narrow down on process parameters and their levels. These experiments helped in better understanding the process and narrowing down on the chosen output and process parameters. Listed below are a details of the experiments conducted and how they eventually led to narrowing down the parameters.

Initial experiments were conducted to get the voltage values. It was observed that at a bias over 8V, the deposition was too vigorous and uncontrolled. The result was that the copper powder below the anode was displaced due to the bubbling effect and hence deposition of Nickel on the copper powder was not taking place. Also the experiments conducted at a bias of less than 2V showed little or no deposition. Eventually, it was found that a bias between the range of 3-5 V was giving the best deposition [53]. Initially, width of deposition was considered as one of the output factors instead of diameter of deposition. Voltage, speed of X-Y axis, duty factor, and gap were taken as the input parameters. A line of 1mm was drawn along the X or Y direction and then its width was measured. Ideally the width of the line should be as close to the diameter of
the tool to get a controlled deposition, An L18 orthogonal array was selected. Orthogonal arrays and how they are selected is explained in detail in the next section.

A total of 18 experiments were done and the width of deposition measured. The input factors used and L18 array with the deposition width values are shown in Table 5 and Table 6 respectively.

Table 5 - Input parameters for width of deposition

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: Gap (µm)</td>
<td>10</td>
<td>20</td>
<td>-</td>
</tr>
<tr>
<td>B: Speed (µm/sec)</td>
<td>5</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>C: Voltage (V)</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>D: Duty factor (%)</td>
<td>10</td>
<td>40</td>
<td>70</td>
</tr>
</tbody>
</table>

Table 6 - L18 array for width of deposition

<table>
<thead>
<tr>
<th>Gap</th>
<th>Speed</th>
<th>Voltage</th>
<th>Duty</th>
<th>Width of deposition (µm)</th>
</tr>
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<td>2</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>1110</td>
</tr>
</tbody>
</table>
The width of deposition was measured using an optical microscope. A few of the images obtained are shown in Figure 26.

![Figure 26 - Image of width of deposition](image)

The major drawback for measuring the width for the gluing process was that the deposition was not uniform. As seen in Figure 26, the deposit appears broken and uneven (not a straight line). Hence measuring a constant value for the width was very difficult.

There were several reasons for why the deposit was uneven. Below is the explanation for the same.
Due to the copper powder being manually applied on the substrate, the surface on which deposition was taking place was not uniform. The gap between the tool and the substrate was set at either 10 or 20 microns depending upon the trial number in the array. At such small distances, when the tool was moved in either the X or Y direction, there was contact between the tool and the substrate. Hence when the tool touched the substrate there was a short circuit and no deposition took place. Eventually as the tool moved along the axis, there were places in which the tool and substrate were not touching and deposition occurred in those places. Hence the deposition appeared to be jagged and not a straight line. This was more prevalent at slower speeds of 5 µm/sec than at relatively higher speeds of 10 µm/sec.

Hence, using speed as an input factor and width of deposition as an output factor were not feasible.

The study was modified to include diameter of deposition as an output factor instead of width and pulse on time as input factor in the place of speed. It was found from literature that having on time along with duty factor gave a better understanding of the process parameters than just having duty factor. Also on time helps in localizing the deposition and hence was more suitable for the study.

Gap (A), on time (B), Voltage (C) and duty factor (D) were selected as the input factors. It is seen from literature that a smaller on time gives a localized deposition when compared to higher on times. Hence on times of 0.2, 0.4, and 0.6 ms were used as the levels. The gap between the electrodes was set at 10 and 20µm with the duty factor set at 10, 40 and 70%.
Table 7 - Process parameters with different levels

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: Gap (μm)</td>
<td>10</td>
<td>20</td>
<td>-</td>
</tr>
<tr>
<td>B: On Time (ms)</td>
<td>0.2</td>
<td>0.4</td>
<td>0.6</td>
</tr>
<tr>
<td>C: Voltage (V)</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>D: Duty factor (%)</td>
<td>10</td>
<td>40</td>
<td>70</td>
</tr>
</tbody>
</table>

5.1.3. Selection of orthogonal array

The selection of the orthogonal array depends on the total number of degrees of freedom of the process parameters. Degrees of freedom are defined as the no. of comparisons that need to be made to determine the ideal level. In this study, 3 parameters are having three levels each and 1 parameter has 2 levels. Hence the total no. of DOF is 7. The orthogonal array selected must have an equal or greater no. of DOF [66]. For this study, the L18 orthogonal array was selected.

Table 8 shows the layout of the L₁₈ orthogonal array.
Table 8 - Layout of L18 orthogonal array

<table>
<thead>
<tr>
<th>Exp. No.</th>
<th>Gap</th>
<th>On time</th>
<th>Voltage</th>
<th>Duty</th>
<th>Diameter</th>
<th>Height</th>
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<td>2</td>
<td>1</td>
<td>269</td>
<td>65</td>
</tr>
<tr>
<td>18</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>1523</td>
<td>60</td>
</tr>
</tbody>
</table>
5.1.4. Analysis and Discussion of Experimental results

As mentioned earlier there are three types of performance characteristics namely, smaller-the-better, nominal-the best, and larger-the-better. In this study, smaller-the-better characteristic has been used. An optical microscope was used to determine the diameter of deposition spot. A circle was fit along the region of deposition to get the diameter of the spot.

**Output Parameter 1 - Diameter of deposition spot**

![Image showing experiment results](image-url)
For smaller-the-better quality characteristic, the signal-to-noise (S/N) ratio was calculated using,

\[ SN_i = -10 \log \left( \sum_{u=1}^{N_i} \frac{y_u^2}{N_i} \right) \]

As shown in [67, 68], where \( y_u \) is the mean response value, \( u \) is the trial number, \( i \) is the experiment number and \( N_i \) is the number of trials for experiment \( i \).

ANOVA was conducted to determine the factors are important to the performance characteristic. It was performed at 95% confidence level.

The result of ANOVA is shown in Table 9.
Table 9 - ANOVA for diameter of deposition spot

<table>
<thead>
<tr>
<th>Source</th>
<th>DOF</th>
<th>Sum of Squares</th>
<th>Mean square</th>
<th>F ratio</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: Gap</td>
<td>1</td>
<td>0.985</td>
<td>0.985</td>
<td>0.21</td>
<td>0.653</td>
</tr>
<tr>
<td>B: On time</td>
<td>2</td>
<td>1.032</td>
<td>0.516</td>
<td>0.11</td>
<td>0.895</td>
</tr>
<tr>
<td>C: Voltage</td>
<td>2</td>
<td>108.989</td>
<td>54.494</td>
<td>11.87</td>
<td>0.002</td>
</tr>
<tr>
<td>D: Duty factor</td>
<td>2</td>
<td>329.232</td>
<td>164.616</td>
<td>35.85</td>
<td>0.001</td>
</tr>
<tr>
<td>Error</td>
<td>10</td>
<td>45.92</td>
<td>4.592</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>17</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The P value and F ratio indicate the statistical significance of each factor. P value is less than 0.05 for both Voltage and Duty Factor. This indicates that these factors have a statistically significant impact on the diameter of deposition at 95% confidence level. This is consistent with what was observed during the experiments. A higher voltage coupled with a high duty factor resulted in a very large deposition area with vigorous bubbling which would invariably disperse the copper powder. A relatively lower voltage and duty factor gave a controlled deposition spot with minimum dispersion of copper powder due to bubbling. The F ratio is more than 4.5 for both Voltage and Duty Factor. This indicates that the response variable (diameter) changes significantly with variation in the levels of Voltage and Duty factor in the range of selected levels.

The S/N ratio is given in Table 10. The ratios reveal that a Gap of 20 μm (Level2), on time of 0.2 ms (Level1), Voltage of 3V (Level1) and a Duty factor of 10% (Level1) are the optimum parameters for a highly localized deposition spot. As explained earlier a lower voltage and duty factor helps in getting a highly localized deposition spot with the smallest diameter.
The optimum value of diameter of deposition spot can be computed as,

\[ \eta_{predicted} = M + \sum (\eta_{ij} - M) \]

Where M is the overall mean of diameter of deposition and \( \eta_{ij} \) is the average value corresponding to significant factor.

Confirmation experiments were used to corroborate the analysis results. The experimented and predicted values for diameter of deposition are shown in Table 11.

Table 10 - S/N ratio for diameter of deposition spot

<table>
<thead>
<tr>
<th>Factor</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>-58.51</td>
<td>-58.04</td>
<td>-</td>
</tr>
<tr>
<td>B</td>
<td>-57.95</td>
<td>-58.35</td>
<td>-58.52</td>
</tr>
<tr>
<td>C</td>
<td>-55.67</td>
<td>-57.57</td>
<td>-61.58</td>
</tr>
<tr>
<td>D</td>
<td>-52.23</td>
<td>-61.26</td>
<td>-61.33</td>
</tr>
</tbody>
</table>

Table 11 - Confirmation experiments

<table>
<thead>
<tr>
<th>Predicted</th>
<th>Experimented</th>
</tr>
</thead>
<tbody>
<tr>
<td>A2B1C1D1</td>
<td>A2B1C1D1</td>
</tr>
<tr>
<td>165.503</td>
<td>163</td>
</tr>
</tbody>
</table>
5.1.5 Control Limits for comparing predicted and experimented values

While comparing the predicted and experimented values, 2 sigma control limits were used to validate the values got from experimentation. 2 sigma limits basically gives an upper and a lower limit and are based off of the predicted value. If the experimented value obtained is within these limits, this would mean that for 2 sigma control limit the experimented value holds good with respect to the predicted value. This also indicates that the experimented value is good at 95 % confidence level if it falls in-between the control limits.

2 sigma control limit = Mean of the predicted value ± Standard Deviation of the predicted value

In this case,

2 sigma limits = 165.503 ± 4

From this, the Upper control limit is 169.503 and the lower control limit is 161.503.

Since the value obtained from experimentation is 163 which lies within the limits calculated, the experimented values hold good at 2 sigma control limits.

Figure 28 and Figure 29 show the images for the diameter of deposition spot for the confirmation experiment.
Output Parameter 2 - Height of deposition

The Mitutoyo Surftest SJ-410 Series profilometer was used to measure the height of deposition. Smaller-the-better quality characteristic was used to calculate the signal-to-noise (S/N) ratios.
ANOVA was performed to find out the significant parameters at 95% confidence levels. Data points were obtained from the profilometer which were then plotted using Matlab to get a graph depicting the height of deposition.

Figure 30 - Height of deposition (Expt. No.1)

Figure 31 - Height of deposition (Expt. No.4)
Table 12 - ANOVA for height of deposition

<table>
<thead>
<tr>
<th>Source</th>
<th>DOF</th>
<th>Sum of Squares</th>
<th>Mean square</th>
<th>F ratio</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: Gap</td>
<td>1</td>
<td>13.3</td>
<td>13.303</td>
<td>1.2</td>
<td>0.299</td>
</tr>
<tr>
<td>B: On time</td>
<td>2</td>
<td>17.74</td>
<td>8.869</td>
<td>0.8</td>
<td>0.477</td>
</tr>
<tr>
<td>C: Voltage</td>
<td>2</td>
<td>98.67</td>
<td>49.337</td>
<td>4.51</td>
<td>0.042</td>
</tr>
<tr>
<td>D: Duty factor</td>
<td>2</td>
<td>14.38</td>
<td>7.188</td>
<td>0.65</td>
<td>0.544</td>
</tr>
<tr>
<td>Error</td>
<td>10</td>
<td>111.05</td>
<td>11.105</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>17</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The P value and F ratio indicate the statistical significance of each factor. P value is less than 0.05 for Voltage. This indicates that this factor has a statistically significant impact on the height of deposition at 95% confidence level. The F ratio is more than 4.5 for Voltage. This indicates that the response variable (height of deposition) changes significantly with variation in the levels of Voltage in the range of selected levels.

The S/N ratio is given in Table 13.

The ratios reveal that a Gap of 10 µm (Level1), on time of 0.2 ms (Level1), Voltage of 4V (Level2) and a Duty factor of 70% (Level3) are the optimum parameters to obtain minimum height of deposition.
Table 13 - S/N ratio for diameter of deposition spot

<table>
<thead>
<tr>
<th>Factor</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>-28.43</td>
<td>-30.14</td>
<td>-</td>
</tr>
<tr>
<td>B</td>
<td>-28.12</td>
<td>-29.19</td>
<td>-30.55</td>
</tr>
<tr>
<td>C</td>
<td>-28.59</td>
<td>-26.63</td>
<td>-32.44</td>
</tr>
<tr>
<td>D</td>
<td>-30.03</td>
<td>-29.8</td>
<td>-28.03</td>
</tr>
</tbody>
</table>

Confirmation experiments were used to corroborate the analysis results. The experimented and predicted values for diameter of deposition are shown in Table 14.

Table 14 - Confirmation Experiments

<table>
<thead>
<tr>
<th>Predicted</th>
<th>Experimented</th>
</tr>
</thead>
<tbody>
<tr>
<td>A2B1C1D1</td>
<td>A2B1C1D1</td>
</tr>
<tr>
<td>12.55</td>
<td>14</td>
</tr>
</tbody>
</table>

Again, 2 sigma control limits were used to calculate the upper and lower limits for the experimented value.

2 sigma control limit = Mean of the predicted value ± Standard Deviation of the predicted value
The mean and Standard Deviation of the predicted values were 12.55 and 3.2 respectively. From this, the upper limit was found to be 15.75 and the lower limit was 9.35. Since the experimented value of 14 was within the limits set, it was concluded that the experimented value holds good at 2 sigma control characteristic.

Thus the study on the effect of process parameters on diameter of deposition and height of deposition revealed the following:

1. Orthogonally designed experiments were performed and subsequent statistical analysis indicated that Voltage and Duty factor has maximum influence on the diameter of deposition and in-turn the diameter of copper powder glued.
2. The validation results confirmed that shorter pulse on-time with low voltage and duty factor coupled with a higher inter-electrode gap gave the smallest diameter of deposition and hence the smallest diameter of glued metal powders.
3. Voltage was found to have the maximum influence on the height or layer thickness of deposition.
4. The validation results confirmed that shorter pulse on-time with high duty factor and medium voltage coupled with a smaller inter-electrode gap gave a minimum height or layer thickness of deposition.

5.2 Study on the effect of process parameters on the yield strength of the glued part

Characterization studies were performed on the glued part to find out its yield strength. A CSM Nanoindentation tester (NHT) was used to carry out the tests. Figure 32 shows a picture of the
CSM tester used. The tester gave a hardness value in the form of a Vickers Hardness number (HV). The HV number was correlated to get approximated yield strength values using the following relationship:

\[ \sigma \sim H_v \times c \]

\[ \sigma = \text{yield strength of the glued part}, \ c = 3.33 \text{ and } H_v = \text{Vickers hardness} \]

Figure 32 - CSM Nanoindentation tester

5.2.1. Taguchi methodology for design of experiments

Taguchi method has been used to study the effect of process parameters. An L18 orthogonal array has been used for this study. The criteria for selection of orthogonal arrays and the Taguchi methodology have been explained in detail in chapter 5.
5.3. Analysis and discussion of experimental results

For the study, 3 replicates were performed for a total of 18*3 = 54 experiments. In this study, the objective was to get the best yield strength value for the glued part. Hence, smaller-the-better quality characteristic has been used.

5.3.1. 1st replicate

The 1st sets of 18 experiments were performed and the yield strength values were measured.

The L18 array and yield strength values for the 1st replicate are shown in Table 15,
ANOVA was performed to determine significant factors affecting yield strength. The ANOVA results can be seen in Table 16. P-value and F ratio give the statistical significance of each factor. Since none of the factors have a P-value less than 0.05 and f ratio greater than 4.5, none of the factors were found to be significant.
Table 16 - ANOVA for yield strength - 1st replicate

<table>
<thead>
<tr>
<th>Source</th>
<th>DOF</th>
<th>Sum of Squares</th>
<th>Mean square</th>
<th>F ratio</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: Gap</td>
<td>1</td>
<td>195.6</td>
<td>195.6</td>
<td>1.05</td>
<td>0.331</td>
</tr>
<tr>
<td>B: On time</td>
<td>2</td>
<td>413.29</td>
<td>206.65</td>
<td>1.11</td>
<td>0.368</td>
</tr>
<tr>
<td>C: Voltage</td>
<td>2</td>
<td>82.67</td>
<td>41.34</td>
<td>0.22</td>
<td>0.805</td>
</tr>
<tr>
<td>D: Duty factor</td>
<td>2</td>
<td>20.75</td>
<td>10.37</td>
<td>0.06</td>
<td>0.946</td>
</tr>
<tr>
<td>Error</td>
<td>10</td>
<td>1870.02</td>
<td>187</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>17</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

5.3.2. 2nd replicate

A second set of 18 experiments were carried out and yield strength values were measured. The L18 array with the yield strength values are shown in Table 17.

Table 17 - L18 array for 2nd replicate

<table>
<thead>
<tr>
<th>Exp. No.</th>
<th>Gap</th>
<th>On time</th>
<th>Voltage</th>
<th>Duty</th>
<th>Yield strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>409.59</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>116.55</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>49.95</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>46.62</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>139.86</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>13.32</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>63.27</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>6.66</td>
</tr>
<tr>
<td>9</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>93.24</td>
</tr>
<tr>
<td>10</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>33.3</td>
</tr>
<tr>
<td>11</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>126.54</td>
</tr>
</tbody>
</table>
In the ANOVA table for the 2nd replicate, it can be seen that the P-value and f ratio for duty cycle is less than 0.5 and greater than 4.5 respectively. Hence duty factor was found to be a statistically significant factor affecting the yield strength of the glued part.

### 5.3.3. 3rd replicate

A 3rd set of experiments were done to verify the design as both the 1st and 2nd replicates gave varying ANOVA values. The L18 array with the yield strength values are shown in Table 19.
Table 19 - L18 array for 3rd replicate

<table>
<thead>
<tr>
<th>Exp. No.</th>
<th>Gap</th>
<th>On time</th>
<th>Voltage</th>
<th>Duty</th>
<th>Yield strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>352.68</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>186.48</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>3.33</td>
</tr>
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<td>4</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>29.97</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>199.8</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>6.66</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>126.54</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>19.98</td>
</tr>
<tr>
<td>9</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>116.55</td>
</tr>
<tr>
<td>10</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>83.25</td>
</tr>
<tr>
<td>11</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>149.85</td>
</tr>
<tr>
<td>12</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>76.59</td>
</tr>
<tr>
<td>13</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>6.66</td>
</tr>
<tr>
<td>14</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>16.65</td>
</tr>
<tr>
<td>15</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>66.6</td>
</tr>
<tr>
<td>16</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>99.9</td>
</tr>
<tr>
<td>17</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>266.4</td>
</tr>
<tr>
<td>18</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>83.25</td>
</tr>
</tbody>
</table>
Table 20 - ANOVA for yield strength - 3rd replicate

<table>
<thead>
<tr>
<th>Source</th>
<th>DOF</th>
<th>Sum of Squares</th>
<th>Mean square</th>
<th>F ratio</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: Gap</td>
<td>1</td>
<td>5.92</td>
<td>5.92</td>
<td>0.06</td>
<td>0.811</td>
</tr>
<tr>
<td>B: On time</td>
<td>2</td>
<td>466.06</td>
<td>233.028</td>
<td>2.37</td>
<td>0.144</td>
</tr>
<tr>
<td>C: Voltage</td>
<td>2</td>
<td>261.11</td>
<td>130.554</td>
<td>1.33</td>
<td>0.308</td>
</tr>
<tr>
<td>D: Duty factor</td>
<td>2</td>
<td>877.47</td>
<td>438.73</td>
<td>4.74</td>
<td>0.041</td>
</tr>
<tr>
<td>Error</td>
<td>10</td>
<td>983.65</td>
<td>98.365</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>17</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The ANOVA values for the 3rd replicate show that P-value is less than 0.05 for duty factor. This indicates that this factor has a statistically significant impact on the yield strength of the glued part at 95% confidence level. Also the f ratio is higher than 4.5. This indicates that the response variable (yield strength) changes significantly with variation in the levels of Duty factor in the range of selected levels. Hence the 2nd and 3rd replicates are in agreement with each other.

A higher duty factor results in a rough deposit having a loose structure. The deposit appears as an aggregate of loose powders. This adversely affects the yield strength of the glued part. This is in accordance with literature on LECD wherein it has been proved that high duty factors tend to give loose deposits[52]. Also a higher duty factor results in a very large deposition area with vigorous bubbling which would invariably disperse the copper powder. This tends to affect the yield strength of the glued part.
Table 21 - S/N ratio for yield strength of the glued part (3rd replicate)

<table>
<thead>
<tr>
<th>Factor</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>34.84</td>
<td>35.99</td>
<td>-</td>
</tr>
<tr>
<td>B</td>
<td>38.63</td>
<td>28.23</td>
<td>39.38</td>
</tr>
<tr>
<td>C</td>
<td>37.12</td>
<td>38.98</td>
<td>30.13</td>
</tr>
<tr>
<td>D</td>
<td>42.61</td>
<td>37.67</td>
<td>25.96</td>
</tr>
</tbody>
</table>

The S/N ratio is given in Table 21.
The ratios reveal that a Gap of 20 µm (Level2), on time of 0.6 ms (Level3), Voltage of 4V (Level2) and a Duty factor of 10% (Level1) are the optimum parameters for maximum yield strength of the glued part. As mentioned earlier, a low duty factor with medium voltage gives the glued part which has the best yield strength value.

Confirmation Experiments

It is noted that the optimal combination of parameters i.e. Gap of 20 µm (Level2), On time of 0.6 ms (Level3), Voltage of 4V (Level2) and a Duty factor of 10% (Level1) coincidentally match with one of the experiments in the orthogonal array (Trial 4). Hence no Confirmation experiments are needed to verify the design [67, 69].
Confirmation experiments were still carried out to verify the analysis results. The experimented and predicted values for yield strength are shown in Table 22.

<table>
<thead>
<tr>
<th>Prediction</th>
<th>Experimentation</th>
</tr>
</thead>
<tbody>
<tr>
<td>A2B1C1D1</td>
<td>A2B1C1D1</td>
</tr>
<tr>
<td>198</td>
<td>233</td>
</tr>
</tbody>
</table>

Thus the study on the effect of process parameters on yield strength of the glued part revealed the following:

1. Duty factor was found to be the most significant factor influencing the yield strength of the glued part.
2. A longer pulse on-time with medium voltage and a low duty factor value coupled with a high inter-electrode gap gave the best yield strength values in the glued part.
3. Confirmation experiments were not needed since the optimal combination of parameters coincidentally matched with one of the experiments in the orthogonal array.
6. Mathematical modeling for estimation of film hardness of the deposit

The yield strength study in the previous chapter takes into account the composite hardness of the specimen to calculate the yield strength. This is good for getting a basic understanding of the strength of the glued part. To get more accurate values, the film/substrate hardness of the deposit needs to be measured which can then be approximated to get accurate yield strength values of the deposit. For this, a composite hardness model is used. In this case the model used is the Jonsson-Hogmark model [57].

The need for this model is explained below:

- Substrate effects will be involved while measuring the hardness of thin films/deposits which have a thickness less than 100 µm
- The measured hardness value is the composite hardness value containing both the film and substrate hardness
- By using this model we can find the film hardness and hence find a better yield strength value

Hence, this model helps in finding the film or deposit hardness independent of the substrate hardness.

6.2 Process Modeling

The Jonsson - Hogmark model is used as a base model to calculate the deposit thickness. The Jonsson – Hogmark model is given as follows:

\[ H_c = \frac{A_f}{A} * H_f + \frac{A_s}{A} * H_s \]  \hspace{1cm} (1)
where, $H_c$ = composite hardness, $H_f$ = Film hardness, $H_s$ = Substrate hardness, $A_f$ = area on which $H_f$ acts, $A_s$ = area on which $H_s$ acts,

\[ A = A_f + A_s \]  \hspace{1cm} (2)

\[ \frac{A_f}{A} = 2C \frac{t}{h} - C^2 \left( \frac{t}{h} \right)^2 \]  \hspace{1cm} (3)

\[ \frac{A_s}{A} = 1 - \frac{A_f}{A} \]  \hspace{1cm} (4)

Where, $t$ = thickness of film, $h$ = depth of indentation, $C = (\sin(22))^2$ for deposition on hard substrates [57].

The process modeling part consists of 3 steps:

6.2.1 Step 1 – Calculating the composite hardness

Composite hardness was calculated using the Oliver-Pharr method from a load – displacement curve. The load – displacement curve is obtained by carrying out Nano indentation experiments on the deposit. Figure 33 shows a typical load – displacement curve that is obtained through Nano indentation. The composite hardness $H_c$ can be calculated by the following steps:

Composite hardness can be calculated as

\[ H_c = \frac{P_{\text{max}}}{A} \]  \hspace{1cm} (5)

Where, $P_{\text{max}}$ = maximum load, $A$ = projected area of contact at peak load

\[ A = F(h_c) \]  \hspace{1cm} (6)

\[ h_c = h_{\text{max}} - h_s \]  \hspace{1cm} (7)

\[ h_s = \frac{(\pi - 2)}{\pi} * (h - h_f) \]  \hspace{1cm} (8)
\[ (h - h_f) = 2 \frac{P}{S} \tag{9} \]

\[ h_s = \varepsilon \frac{P_{\text{max}}}{S} \tag{10} \]

where \( \varepsilon = 0.72 \)

Substituting the above in eq. 2 we get the composite hardness value

Figure 33 - Schematic of load versus indenter displacement data where, \( P_{\text{max}} \): maximum load, \( h_{\text{max}} \): indenter displacement at peak load, \( h_f \): the final depth of the contact impression after unloading and \( S \): initial unloading stiffness [70]

6.2.2 Step 2 – Calculating the thickness of the film

From Faraday’s Law
\[ M = \text{atomic weight of nickel} = 58.69, \ n = \]

\[ \text{no. of electrons in the electro chemical reaction of nickel} = 2, \ F = \text{Faradays constant} = 26.799 \text{ A} - \text{h}, \ a = \text{current efficiency ratio}, \ I = \text{current that flows through the tank and} \ T = \text{time of deposition} = 20 \text{ seconds} \]

For pulse plating I is given as:

\[ I = I_p \times df \]

where: \( I_p = \text{pulse current}, \ df = \text{duty factor} \)

The current efficiency ratio \( a \) is given as:

\[ a = \frac{(\text{actual mass of deposition})}{(\text{theoretical mass of deposition})} \times 100 \]

\( a \) is found to be 95.5% for most Ni plating solutions.

Substituting the above values in Equation 11

\[ m = \frac{(58.69)}{(2 \times 26.799)} \times a \times (I_p \times df) \times T \]

\[ m = 1.095 \times a \times (I_p \times df) \times T \quad (12) \]

Also from Faraday’s law, the thickness of the deposition \( t \) is given as

\[ t = \frac{(m \times 100)}{dA_{ni}} \quad (13) \]

where, \( m = \text{amount of Nickel deposited at the cathode} \ (m = 1.095 \times aIT), \ d = \text{density of nickel} = 8.907 \text{ g cm}^{-3} \) and \( A_{ni} = \text{area of deposition} \).

Substituting the above values in Equation (13),
6.2.3 Step 3 - Finding the hardness of the deposit

Substituting the above equations in (1), by appropriate expressions from Eqs (3), (4), (5) and (14), the model for the film or deposit hardness can be formulated as,

\[
H_c = 2C \frac{t}{h} - C^2 \left( \frac{t}{h} \right)^2 \cdot H_f + \left[ 1 - 2C \frac{t}{h} - C^2 \left( \frac{t}{h} \right)^2 \right] \cdot H_s
\]

\[
H_c = 2C \frac{\left(11.74 \times (I_p \times df) \times T\right)}{A_{ni}} - C^2 \left( \frac{\left(11.74 \times (I_p \times df) \times T\right)}{A_{ni}} \right)^2 \cdot H_f
\]

\[
+ \left[ 1 - \left( \frac{\left(11.74 \times (I_p \times df) \times T\right)}{2C \frac{A_{ni}}{h}} \right) - C^2 \left( \frac{\left(11.74 \times (I_p \times df) \times T\right)}{A_{ni}} \right)^2 \right] \cdot H_s
\]

Solving for \(H_f\)

\[
H_f = \left[ \frac{P_{\text{max}}}{A} \frac{1 - 2C \times \left[ \frac{\left(11.74 \times (I_p \times df) \times T\right)}{A_{ni}} \right] \times h - C^2 \left[ \frac{\left(11.74 \times (I_p \times df) \times T\right)^2}{A_{ni}} \right] \times h^2}{2C \times \left[ \frac{\left(11.74 \times (I_p \times df) \times T\right)}{A_{ni}} \right] \times h - C^2 \left[ \frac{\left(11.74 \times (I_p \times df) \times T\right)^2}{A_{ni}} \right] \times h^2} \right] \times H_s
\]  

(15)

The above equation gives the film or deposit hardness. This expression takes into account the substrate hardness and is based on the thickness of the deposit calculated by Faraday's law.
6.3. Process model validation by experimentation

The in-house built experimental setup used for the electrochemical binding process is shown in Figure 17. Two substrates – Brass and Aluminum were used to carry out experimental verification of the above developed hardness model. Three sets of process parameters as shown in Table 23 are selected and deposition experiments are carried out on both Brass and Aluminum substrates.

Table 23 - Process parameters for deposition used in model validation

<table>
<thead>
<tr>
<th>Set #</th>
<th>Gap</th>
<th>Voltage</th>
<th>Duty Factor</th>
<th>On time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>5</td>
<td>10</td>
<td>0.6</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>4</td>
<td>70</td>
<td>0.4</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>4</td>
<td>40</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Nanoindentation tests were conducted on the deposited samples. A load-displacement curve was plotted based on the nanoindentation data, and the composite hardness values were calculated using the Oliver-Pharr method. The thickness of the film was calculated using equation 14. It can be seen from the Figure 34 that the film hardness values calculated by the model are in close agreement (3-8%) with each other for both Aluminum and Brass substrates at the same process parameters. This shows that the substrate effects which are involved in a composite hardness value have been removed thus giving an accurate film or deposit hardness value.
Using this, the film hardness value has been approximated to get a Vickers hardness number which is in turn used to get an accurate yield strength value of the deposit. The Vickers hardness value is calculated from the following relationship [71]:

\[
HV = 0.0945 \times H_f
\]  

(16)

Where \(HV = \) Vickers hardness (kgf/mm\(^2\)); \(H = \) Film hardness (MPa)

The yield strength values are then correlated to the Vickers hardness values through the following relationship [55]:

\[
\sigma \sim HV \times c
\]  

(17)

where \(\sigma = \text{yield strength of the glued part (MPa)}\), \(c = 0.33\) and \(HV = \text{Vickers hardness (kgf/mm}^2\))

Figure 35 shows the Vickers hardness values for both Brass and Aluminum substrates. Figure 36 shows a comparison of the yield strength values for both Brass and Aluminum substrates.
A mathematical model was developed in this chapter to predict the deposit hardness for electrochemically bound parts. Experimental verification was done using two substrates – Brass and Aluminum with similar deposition parameters and hardness values were calculated. It was found that the film hardness values for both the substrates under similar deposition parameters were in close agreement with each other (3 – 8%). The hardness values were further used to determine the yield strength of the deposit.
7. Conclusions and future work

7.1. Conclusions

A novel micro additive manufacturing method is proposed and experiments are carried out using a completely in-house built micro CNC stage. Gluing of copper powders were carried out using Nickel from electro chemical deposition as a binder. Images from scanning electron microscopy (SEM) and Optical microscope along with X-ray spectroscopy studies show the gluing of copper powders with Nickel as a binder element. Yield strength studies were conducted to find out the strength of the glued part. Further Taguchi studies were carried out to optimize the process parameters and the following conclusions could be drawn:

1. Orthogonally designed experiments were performed and subsequent statistical analysis indicated that Voltage and Duty factor has maximum influence on the diameter of deposition and in-turn the diameter of copper powder glued.

2. The validation results confirmed that shorter pulse on-time with low voltage and duty factor coupled with a higher inter-electrode gap gave the smallest diameter of deposition and hence the smallest diameter of glued metal powders.

3. Voltage was found to have the maximum influence on the height or layer thickness of deposition.

4. The validation results confirmed that shorter pulse on-time with high duty factor and medium voltage coupled with a smaller inter-electrode gap gave a minimum height or layer thickness of deposition.
5. Duty factor was found to be the most significant factor influencing the yield strength of deposition.

6. A longer pulse on-time with medium voltage and a low duty factor value coupled with a high inter-electrode gap gave the best yield strength values in the glued part.

Further, a mathematical model was developed in this chapter to predict the deposit hardness for electrochemically bound parts. Experimental verification was done using two substrates – Brass and Aluminum with similar deposition parameters and hardness values were calculated. It was found that the film hardness values for both the substrates under similar deposition parameters were in close agreement with each other (3 – 8%). The hardness values were further used to determine the yield strength of the deposit.

7.2. Future work

In the present work, only a single layer of powders have been glued. Future work can incorporate gluing of multiple layers of powders to produce a fully functional micro 3D part. Configuring the system to utilize a CAD model of the desired part and automatically extract G codes and carry out the gluing process. Further study on the mechanical strength (tensile strength) of the glued part can be conducted.


[68] Ross, P. J., 1988, "Taguchi techniques for quality engineering: loss function, orthogonal experiments, parameter and tolerance design."
[69] Phadke, M. S., 1995, Quality engineering using robust design, Prentice Hall PTR.
APPENDIX A: PUBLICATIONS


CPT at A&B Foundry and Machining

As part of my Master’s degree at the university, I undertook a 4 month Internship at A&B Foundry and Machining in Franklin, Ohio working as a Quality Engineer. The place I worked at was a sand casting foundry manufacturing rough aluminum castings according to the AS9100 Rev C standards. My goals at the start of the internship and the timeline to achieve the same were as follows:

Goals and Timeline:

1. To learn the existing quality standards and testing procedures – November 2\textsuperscript{nd} – December 5\textsuperscript{th}
2. To learn existing manufacturing processes – November 2\textsuperscript{nd} – December 20\textsuperscript{th}
3. Develop new processes and products to satisfy customer needs – November 2\textsuperscript{nd} – January 3\textsuperscript{rd}
4. Work on integrating the new process and products with the existing quality standards – November 2\textsuperscript{nd} – March 1\textsuperscript{st}

Below I will explain how I went about achieving the goals and the role they played in helping me better understand my research and the importance of engineering and quality control in general.

1). to learn the existing quality standards and testing procedures

The first part of my internship consisted of learning the existing quality standards and testing procedures used in certifying sand casted aluminum parts. Any casting that were shipped to the customer had to have the following testing done on them and the values had to be within the drawing specified ASTM, AA, and MIL-STD specifications:
- Mechanical testing

Each casting had a separate set of test bars that were poured which were then tested for Ultimate tensile strength, yield strength and hardness. The values observed were then compared with existing specifications as per the customer requirements to validate the casting. This step would help generate a material test certificate which was sent out along with the shipped casting.

Working in the melt lab conducting the testing experiments helped me gain invaluable real world experience on how material testing plays a vital role in any finished product. My thesis has a section dedicated to mechanical characterization and finding out the hardness of electro-deposits and working on mechanical testing at the foundry helped me better justify and understand the need for testing in any new product.

![Figure 37 - Brinell hardness Tester](image_url)
2). to learn existing manufacturing processes

My internship was done at an aluminum casting manufacturing foundry. I was exposed to the traditional manufacturing processes like sand casting, finish grinding, and welding.

**Sand Casting:**

- **Pattern Making** – A pattern or tooling of each casting is made before any job is begun in a foundry. Herein we used wood working to make a pattern for the mold making process. I helped in CAD modeling the pattern along with the rigging and gating to help the pattern makers visualize their ideas. Based on their inputs the final model and drawing were created and these were used by the pattern makers to build the tooling.
Mold making:

Once the pattern was made, they were then set into a mold by the molders using chemical sand. Since the sand plays a major role in the integrity of the casting, I helped carry out sand testing to check the strength and grain fineness of the sand being used. Based on my test results, the amount of binder added to sand was varied and the mold was prepared.

Figure 39 - Sand mold with the pattern before pouring
Figure 40 - Sand strength tester

Figure 41 - Grain fineness sieve shaker
Melting:

Once the mold was ready, molten metal was poured in to the mold. Before the metal could be poured, each metal pot had to be tested to check the chemistry present in them. For this I would take a small disc shaped sample from the pot of molten metal and do a spectrometer analysis of the disc. Once the analysis was completed, I would check the chemistry of the metal and compare it with the customer requirements based on ASTM, AA specifications. If the chemistry was found to be within specification, the go ahead would be given for the mold to be poured.

Cut-Off and Shakeout

The mold was then allowed to cool down and extra metal and sand were cut and shook out to get the casting.
Finish Grinding

The casting was then finish ground based on customer specifications. Since the facility only manufactured rough aluminum castings which the customer would then machine, the amount of material removed was of prime importance. Each customer had different specifications based on the drawing provided which gave the amount minimum amount of machine stock needed on the casting. I would analyze the drawing and based on the information I provided the grinders would carry out finish grinding.

Welding

Welding was only done when the casting had certain defects which could not be repaired through grinding. Again, each customer would have their own rules and regulations on whether welding could be carried out or not. Hence based on the specifications, the welding of the casting was done to fix surface defects like holes and porosity.

The sand casting process helped me utilize and sharpen my CAD modeling skills based on real time drawings given by the pattern makers. Since CAD modeling is a vital part in any 3D printing process, this helped me sharpen my skills and better understand the real time work in an industrial setting. Also, I was able to understand the need for chemical analysis on any new product or part. The feasibility part of my thesis has a detailed section on carrying EDX experiments on the electrodeposits to confirm the chemistry of the deposits. My experience at the foundry helped me appreciate the need for this section in my thesis. Overall the casting process helped me understand the importance of an engineering drawing and how to read and make sense of GD&T.
3). Develop new processes and products to satisfy customer needs. Work on integrating the new process and products with the existing quality standards.

During my time at the foundry I had the opportunity to work with a new customer who wanted castings made with a material that we had never used before. Hence we had to go about finding the best way to satisfy the customer’s requirement along with making sure that the product could be made within the process capabilities we had.

For this, I had meetings with the production managers, section leads, and quality inspectors to see what capabilities our facility had. Keeping that in mind we came upon the best way to manufacture this casting to meet the customer’s requirement. We reached a conclusion that since the mechanical properties required for this casting were lower than any casting we had ever
made that we would not heat treat the castings. Also, we had to model a completely different rigging and gating to best suit the molding of this casting. We modeled different designs and tested the accuracy of each design and the pros and cons associated with it. Finally a design was selected and the casting was manufactured. Mechanical testing results were within the customer specifications. We were able to achieve this without scrapping any molds or castings and deliver the part on time to the customer.

This helped me in visualizing how a process should be designed. This helped me understand that customer requirements change continuously and that the process should be flexible enough to adapt to these changes. Since my thesis is on 3D printing wherein complicated CAD models need to be printed based on the requirements, I was able to appreciate and understand the need for flexibility in a process and to think outside the box to meet the customer requirements.

Overall my experience working as a Quality Engineer was highly rewarding giving me valuable real world inputs. I was able to better understand and appreciate the need for mechanical and chemical testing and its importance in bringing out any new product into the market. My exposure with real time CAD modeling based on rough drawings provided by the pattern makers gave me a thorough understanding of how drawing and modeling play a vital role in manufacturing and quality. The ability to tweak a process based on the customer requirements and specifications gave me an in-depth understanding on the challenges that would arise when developing new products and processes. These experiences also directly related to my thesis since I have detailed mechanical and characterizations along with CAD modeling included in my research work and helped me better appreciate the need for the same.
Application of research in the CPT at A&B Foundry and Machining

In this section, the application of my research in the castings that were manufactured during my CPT at A&B foundry is discussed.

Once a rough aluminum casting is made, it is then machined by the customer according to their requirements and specifications. Many times once the machine stock area is removed the castings have tint holes on the surface which are not suitable for the application that the customer needs it for. These holes may be a result of careless machining practices or could be sand holes due to improper mold placement. Majority of the times, the customer returns these casting back to the facility and asks for a new part to be manufactured. This results in significant financial loss since the casting has to be manufactured with all the expenses being in-house.

There are different type of holes that can develop on the surface. Some of them are macroscopic in nature and cannot be repaired by welding as it would affect the integrity of the castings. These parts would have to be scrapped and re made. But sometimes we do come across castings which have smaller holes on the surface. Since welding or grinding is the only expertise that the facility has to repair holes and since welding or grinding on a machined casting destroys the integrity of the casting, the parts are scrapped.

This is where my research area of localized electrochemical deposition can be applied to fill these microscopic holes without affecting the integrity of the casting. A schematic below explains the mechanism involved in this process:
By depositing locally using LECD, the integrity of the machined casting is not affected. This process can help reduce the scrap rate of the facility and also save the company from financial losses.

To demonstrate the feasibility of the proposed idea, experiments were done in the lab on Brass and Aluminum plates. A blind hole was made on these plates and their profile was plotted using a profilometer. Deposition experiments were carried out on the region of the hole and the profile was plotted again. The results showed that deposition at the spot of the hole filled up the hole thereby eliminating the surface defect present.
Surface profile of plate with blind hole

Surface profile of hole repaired with deposition