

ENGD3000

Electroplating of 3D printed components

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Abstract

This dissertation looks at the processes that go into electroplating and applying these methods to 3D printed parts made of PLA, with the ultimate aim to plate a simplistic geometry sufficiently enough to provide some form of usefulness in the form of conductivity. In the experiment carried out in this paper the researcher successfully plated Copper on to PLA allowing for a light weight, highly conductive product. Furthermore, this paper makes suggestion and key points that will be used in future experiments by analyzing the results obtained through the use of a microscope, scales and hand calculations.

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Nomenclature

ABS - Acrylonitrile Butadiene Styrene

CAD – Computer Aided Design

FDM - Fused Deposition Modelling

3D – 3 Dimensional

SLA – Stereolithography

STL – Standard Triangle Language

PLA - Polylactic acid

SLS -Selective Laser Sintering

DMLS – Direct Metal Laser Sintering

PolyJet – Polymer Jetting

MIT - Massachusetts Institute of Technology.

UV – Ultra-Violet

HD – High Definition

CLIP – Continuous Liquid Interface Production

BMW - Bayerische Motoren Werke AG

IBM - The International Business Machines Corporation

MATLAB – Matrix Laboratory

Gram-Equivalent- the quantity of a chemical element, group, or compound that has a mass in grams equal to the equivalent weight

Gram-molecular weight - the mass of one mole of a chemical compound equal in grams to the compound's molecular weight

Chapter 1 - Introduction

Products can now be produced more efficiently thanks to 3D printing. Creo parametric is a CAD tool used to design various products in 3D space, allowing for a wide range of editing tools that can allow for precision design. Furthermore, Creo parametric can make use of laser scanning that allow objects to be scanned into software. After the project is designed, the saved file is formatted to the corresponding G-code and printed. A 3D printed part is made by a printer that layers material (mostly plastic) upon one another by using a method known as FDM. Plastic Filament goes inside the 3D printer, where it heats the plastic to become molten and then placed upon the base plate of the printer as a starting point for the rest of the material to build up to the 3D model. Furthermore, the printers can operate automatically and will continue to do so until it runs out of material or finished the part.

During electroplating a layer of metallic material is applied to an object, like a 3D printed component. The phenomenon known as electrolysis is used to deposit metals to the targeted part. This allows for a material such as copper to adhere to the desired surface and coat it at a certain thickness. This coat of copper allows for the material to also have the properties that copper can provide. For instance, copper can be seen as quite a weak material in terms of tensile strength. So, if a light coat was applied to a stronger material not only would it be very conductive but it would also provide a larger tensile strength overall.

Electroplating and 3D printing work very well together as each discipline brings a lot of versatility to the table. 3D printing makes use of CAD software and all the advantages talked about above. Electroplating allows for the deposition of substrate onto the chosen material, in this case PLA, to imbue the overall products with the properties that come along with that material. The methodology that will be shown further below gives the technique that was used to achieve the overall aim of this paper. The options and market that was opened due to these two inventions coming together allows for better financial investments into a technological advancement that is reshaping how a lot production models are employed.

Chapter 2 - Background research

Section 2.0.1 - History of 3D printing from first being conceived to modern day.

This is when 3D printing began and the timeline only includes significant events [10]

Date: May 1981

Inventor: Dr Hideo Kodama

Institute: Nagoya Municipal Industrial Research Institute

Publishing Title: Rapid Prototyping technique

Description: His paper looked at a technique that would print each layer on top of one another. It involved printing photopolymers, which took use of a method that preceded stereolithography.

Date: 1984

Inventors: Engineers Alain Le Mehaute, Olivier de Witte and Jean Claude Andre

Institute: N/A

Description: Filed a patent for the Stereolithography process. They were to pioneer a new method that would revolutionize the manufacturing process. They didn't follow through with the invention as they felt there was no market for the invention.

Date: 1986-1987

Inventor: Charles 'Chuck' Hull

Description: filed a patent that introduced new features such as the STL file format and digital slicing. His process used ultraviolet light to cure the photopolymers. In 1987 Chuck opened a business called 3D systems and produced the first ever 3D printer called the SLA-1

It is arguable that either Chuck or Dr Kodama invented 3D printing. However, Chuck seems the better contender as he executed the design

Date: 1988

Inventor: Carl Deckard

Institute: University of Texas

Description: Filed a patent for SLS. This method uses a laser to sinter and harden deposits of plastic powder instead of UV light

Date: 1989

Inventor: Scott Crump

Institute: Stratasys

Description: Filed a patent for FDM. He would go to release the FDM 3D printer in 1991

Date: 1989

Inventor: Dr Hans Langer

Institute: EOS

Description: Pioneered DMLS in the mid-90's. DMLS makes use of a high-powered laser to sinter metallic powders together. He would go on to dominate the SLS market.

Date: 1993-95

Inventor: MIT

Institute: Massachusetts Institute of Technology.

Description: The first model made use of a plaster-based powder and starch materials as well as a water-based binder to print. This would become to be known as Binder Jetting.

Date: 1993-1994

Inventor: Royden Sanders

Institute: Solidscape

Description: Solidscape created 3D printers that made use of Wax to create moulds that would be used to make other objects out of more solid materials.

Date: 1998

Inventor: Objet Geometries

Institute: Objet Geometries

Description: Objet Geometries would introduce PolyJet 3D printing. This method makes use of multiple colours and materials to construct the object allowing for more versatility. Multiple droplets of polymer are deposited on to the base plater, where they are instantly cured using UV light. This was to be released in 2000.

Date: 1999

Inventor: N/A

Institute: Wake Forest Institute for Regenerative Medicine

Description: This was a massive breakthrough for the sector of 3D printing as they managed to 3D bio-print a human bladder, which they coated with the patients' cells to reduce the chance of the body rejecting the organ lowering the chances to close to zero.

Date: 2004-2005

Inventor: Dr Adrian Bowyer

Institute: University of Bath

Description: He had been inspired by 3D printing that led to ideas of self-replicating 3D printers

Date: 2005

Inventor: Zcorp

Institute: Zcorp

Description: Announcing the new Spectrum Z510 3D printer, which was the first 3D printer to print in colour in HD

Date: 2006

Inventor: Dr Behrokh Khoshnevis

Institute: University of Southern California

Description: Invented a huge 3D printer that could print houses in place. This new invention is a solution to help the housing crisis. The contour crafting system uses a crane to do the printing with concrete as the medium

Date: 2008

Inventor: Dr Adrian Bowyer

Institute: RepRap Movement

Description: With the release of Darwin RepRap 3D printer came the choice to self-replicate 3D printers at home as long as they have intermediate amount of technological and technical knowledge

Note: 3D printers have gone from being the size of entire rooms to now size that could fit on a desk

Date: 2008

Inventor: MakerBot

Institute: N/A

Description: Designed the website Thingiverse, which allowed users to upload their 3D designs for everyone to download and print.

Date: 2008

Inventor: Stratasys

Institute: Stratasys

Description: Invented a new material that was bio-compatible with the 3D printers that they produce.

Date: April 2009

Inventor: MakerBot

Institute: N/A

Description: MakerBot are massive supporters of Open sourcing and with their new printer called Cupcake CNC demand for these parts exploded as this allowed people to download the parts and construct the printers for themselves.

Date: 2009

Inventor: Organovo

Institute: Organovo

Description: Organovo managed to 3D print blood vessels allowing for the creation of organs such as hearts and kidneys.

Date: July 11th 2014

Inventor: Joseph and Philip Desimone

Institute: Carbon 3D

Description: Carbon 3D had a big focus on making 3D printers quicker by using a new technology known as CLIP and with this technology becoming available in 2015 it changed the landscape of 3D printers. It increased the overall speed of printing between 25-100 times faster.

Date: October 2015

Inventor: Desktop Metal

Institute: Desktop Metal

Description: BMD uses a very similar method to FDM but with metal allowing companies like Ford, google and BMW to print parts 10 times cheaper.

There are no more significant developments after this time.

Section 2.0.2 - History of Electroplating from first being conceived to modern day

Luigi Brugnatelli and Alessandro Volta

In 1805 Luigi Brugnatelli invented electroplating by making use of a voltaic pile discovered by his colleague Alessandro Volta in 1800. Pulling a quote from Belgian Journal of physics and Chemistry his methodology becomes clear. The quote is as followed “I have lately gilt in a complete manner two large silver medals, by bringing them into communication by means of a steel wire, with a negative pole of a voltaic pile, and keeping them one after the other immersed in ammoniuret of gold newly made and well saturated” [14]. Due to political problems at the time, Napoleon Bonaparte rebuffed Luigi’s work causing him to suppress any further work. It should be noted that without Alessandro’s invention of the portable electrochemical battery Luigi’s work would not have been as easy as it would have.

John wright

However, in 1845 John wright from Birmingham, England discovered that electroplating with gold and silver was best suited with Potassium Cyanide. Potassium Cyanide was good at electroplating as it staves off corrosion, helps to maintain a consistent metal ion level and contribute very well towards the conductivity of the plating solution [13].

The Elkington's

A number of other inventors were also in the midst of carrying out similar work with several patents being issued in 1840. Moreover, cousins Henry and George Richard Elkington managed to patent the electroplating process first and also bought the rights to John Wright’s process allowing the cousins to create a monopoly of electroplating for years to come [13].

Electroless Plating

Although Electroplating techniques today use a power source to induce the currents needed for the process, a process that would use its own chemical makeup as its own source of power for this process. In 1944, Abner Brenner and G.E. Riddell were experimenting with varied currents, substrates and additives when mixing their solutions to only discover by accident for second a time that they could plate nickel using sodium hypophosphite. This is due to Sodium hypophosphite acting as its own source of electrons. This method is now used in many applications today and uses lot of metals such as Cobalt, Copper, Gold and more [13].

The Silicon Age

As time marches on new technologies are being invented every day to meet the ever-growing demand for an easier life to live. In 1970 the birth of the Silicon age began with IBM now using electroplating in its computer chip production as well as various other techniques that can be found throughout history. Gold was now finding a more profound use in being plated on to circuit and fuel cells instead of aesthetic use [13].

Section 2.1 - Different areas of 3D Printers

There is many different type of 3D printers in the world with many more being invented in terms of usefulness. The list below will talk about some of the 3D printers already talked about and in use.

Section 2.1.1 - Food

Food is an everyday occurrence that all humans require for basic survival. A lot of time, energy and money is spent cooking and can become more difficult if people have allergies. Engineers at Columbian university [15] have managed to 3D print a cheesecake that is safe for consumption. The method still consists of printing layer by layer. However, the 3D printer uses what is known as “edible food inks” to create the cheesecakes that can be seen below in figure 1.



Figure 1 shows a 3D printed cheesecake

NASA hopes to one day to use this technology in their space station as to way to preserve food and give the astronauts of the station more options and customisability when it comes to their food choice. 3D printing food allows for a more affordable way for people to make food and allow for the same type of food, but with more empathises on making food that all can eat by simply printing without the foods people are allergic too.

Section 2.1.2 - Materials

As 3D printers get faster and more accurate through technologic advancements different materials are being used to construct new things. This can be seen very clear when reading the through the timeline. Some of these different materials are: various Metals, Concrete, Wood, Plastics, Resins, Powders and many more. It is clear that goal of 3D printing is to use any material that can be useful and make it easier to use [16].

Section 2.1.3 - Housing

As already discussed from in the timeline concrete housing is now a thing with a crane printing entire Concrete blocks in place using the Concrete as a medium. An example of this is a Russian company called Apis Cor, who are the first company to use this type of technology to construct buildings in 24 hours under any weather conditions. The housing crisis is a big issue faced by many people today and this innovation helps to mitigate and solve that problem. The next step for this form and all of 3D printing is to increase the speed without losing any quality in the form of structural integrity and allow for more customisability [17].

Section 2.1.4 - Medical

Everyone can agree that medical care is a big part of the world, ensuring people can live long healthy lives and providing inventions that will help repair all types of accidents from losing limbs to burns. A company currently using 3D printing to help their patients is Nidek Technologies, who are using 3D printed parts to construct their medical instruments. This makes the whole process quicker as they have moved away from metals to plastic fabrication allowing for a lot more versatility between prototypes and can get their products quicker to the market. There are also other areas that have greatly improved due to 3D printing and that is the creation of prosthetics. Before 3D printing companies would use metal and or wood as it was easier and cheaper. But this changed when 3D printing came along as instead of waiting for a cast to be formed and moulded to the patient's limb, they can now take a scan of the affected area and make any necessary changes to allow for a more form fitting prosthetic and be able to print out these customisable parts within hours as well as making it modular to allow for quick replacement [18].

Section 2.1.4.1 - Skin bio-printing

Every year 11 million people are inflicted by bodily harm in the form of burns, whether that be first degree burns or third-degree burns. Medical practitioners and research can go far and develop methods to help these victims recover from the most severe of accidents. However, with inventions like 3D printers in combination with advanced medical science, the recoverability of patients improves. A new advancement in printers now allows for the printing of skin cells on to the inflicted area. The

methodology allows for alterations to be made prior to the operation through the use of CAD files, tailoring each operation to the respective case. This process makes use of depositing living cells together with hydrogel-based scaffolds. To achieve the best results five steps have been determined:

Step 1: scanning or imaging of the inflicted area where the procedure will be performed

Step 2: Using the imaged results a model can be developed with CAD-CAM

Step 3: One or more cells can be used. However, this is dependent on the tissue to be printed with the biomaterial being carefully selected to ensure compatibility between the patient and the cells.

Step 4: The CAD/CAM files are sent to the bioprinter to begin the printing process.

Step 5: Let the cells mature [20]

Section 2.1.5 - Products for electroplating

A lot products required casts and moulds to be made before the product could be made to ensure all meets the specification as well as making prototypes that could potentially be costly. With the use of 3D printing products that are needed to be electroplated can be printed at no cost and then tested in solutions to see which mixture will provide the best results. Once this has been found then it can print in full size for mass production.

Section 2.2 - In-depth look at Electroplating

When it comes to electroplating the overall method can be generalised and put into layman's terms of simply applying a useful layer over the product to provide a better product.

Section 2.2.1 - Electrochemistry and Faraday's Law

To begin to understand electroplating fully a dive into Faraday and his constant has to be established. Faradays' idea was to send a current through a series that had multiple electrolytes connected and comparatively weigh all the different materials that are separated in a given time, but with the same current. After multiple studies were carried out by various scientist all using the same methodology of applying a given quantity of electricity through a solution of electrolyte and then proceeding to weigh the metals that have deposited on the cathode. The mean value from all these experiments being carried out came to 1.1183 milligrams of silver deposited on the cathode. However, it is more convenient to use gram-molecular weight when using univalent and gram-equivalent weight for polyvalent ions. For all intended purposes Silver will be used as it is the element that is mostly referred to when determining other elements. Thus, silvers atomic weight gives us a value of 107.93 in terms of oxygens atomic mass being 16. Dividing the amount of the silver deposited on the cathode by the atomic weight of silver in terms of oxygen gives Faraday's constant of ~96,500 coulombs.

Chapter 3 - Literature Review

[1] used rectangular shapes with a hole in the mid-upper section of the shape as their chosen sample for conducting of the experiment, which was made out of ABS. The main aim of A. Islam, H. N. Hansen and P. T. Tang's research was to look at how surface structure and topology impacts the overall quality

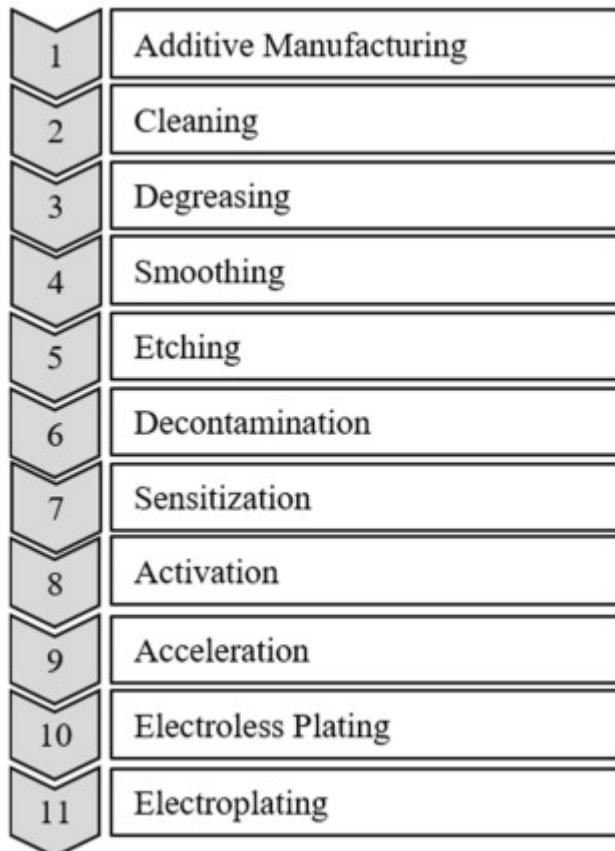


Figure 2 shows the methodology used throughout the experiment

The preparation of the surface used a single cut-off machine known as Discotom 6 by struers Inc. Parts 1 and 3 that used Discotom for the cuts were further cut using the microtome with the sections having an overall thickness of 70 µm. To confirm the composition of coatings an EDX was used, which was provided by Bruker XFlash detector 410-M and uses Esprit software.

When thin slices were prepared a transmitted light microscope called Axioscope 5 by Carl Zeiss Microscopy Deutschland GmbH was used. And lastly when looking at the surface roughness of the product a laser scanning microscope was used called the LEXT OLS5000 (MS) by Olympus Deutschland GmbH. This microscope also provided images with colour.

The results found showed cavities between the single strands as a result of the FDM process, which in turn created a leaky surface mainly found on the top side of the samples. And lastly the researchers identified the pre-surface treatment as the most important part of the entire process.

[2] paper looks for a more direct method for the electroplating of plastic, ultimately looking to stop the need for slow and economically inefficient process such as electroless metal deposition, painting with

of an electroplated product. They made use of different types of microscopes such as transmission light microscope, laser scan microscope and scanning electron microscope. The rectangles were made of certified ABS Terluran GP-35. They chose to print simplistic shapes as the printing of more complex shapes will require further optimization of the manufacturing and post treatment process. Using varied literatures and their own knowledge, A. Islam, H. N. Hansen and P. T. Tang followed the steps of preparation, etching, electroless plating of nickel and then electroplating of nickel. See figure 2.

conductive inks and PVD coating. The researchers decided on using Schulte-Tinco 50 from A. Schulman Inc., USA. They chose this particular one as it showed the highest conductivity from all the options they could choose from and posed really good mechanical properties. Their analysis made use of a Alicona infinite Focus microscope.

Prior to the plating of the different metals on to the plastic various methods were tried to prepare the surface for adhesion of the metals. These methods were non-treated, grinded, milled and Wet-blasted to try and find the best surface preparation leading to the best coverage for metal plating. Overall, Wet-blasted was found to provide the best result.

The experiment used acidic Copper bath comprised of sulphuric acid and Copper Sulphate that underwent 3 A/DM² and was timed for 6 mins. Further carrying out more experiments to find the best conditions for plating was 8 A/dm² for 11 minutes. However, with these optimal conditions only 12% of the sample was covered with metal of the total area. As can be seen in (figure 3) the non-treated area was found to have weak adhesion between the plated metal and the plastic. Whereas, the surface treated area showed much greater adhesion between the plastic and the metal.

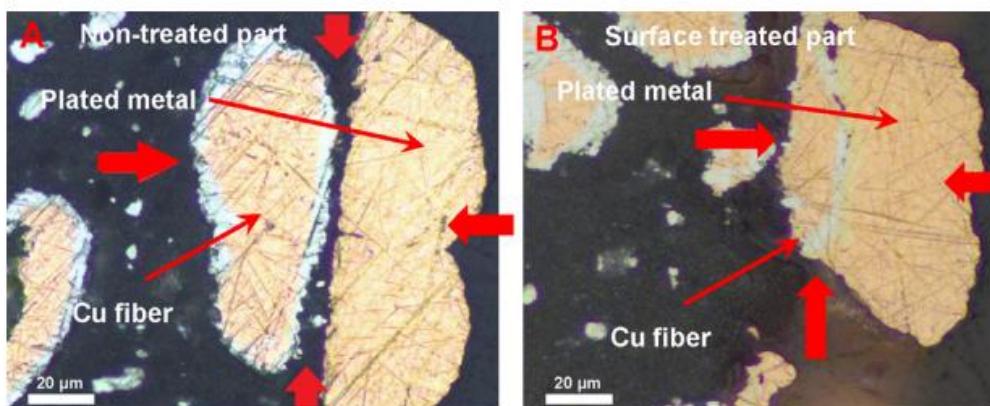


Figure 3 shows a microscopic view of the surface

The researchers also carried out the same experiment except with Nickel instead of copper as Nickel offered better protection against the corrosion, solderability and strong surface uniformity. The Nickel bath consisted of Nickel Sulfamate and boric acid with the bath being low-stress and low-speed bath due to the chemicals. The analysis of the Nickel plate showed better surface coverage than copper did. With Nickel being at 64% and Copper at 45%.

Finally, the researchers found conductive plastic composites provided a strong enough conductivity without the use of a more direct way to make the plastic more conductive. When it came to testing the conductivity of the surface the Wet-blasted Nickel-plated parts showed a 70% increase than that of its counterpart. Nickel plated came to 1.2e+6 S/m, while Copper came to 9e+5 S/m.

Chapter 4 - Problem statement

The main problem of using plastic is that it can be very weak and easily susceptible to heat and wear. To help solve these problems Electroplating was introduced allowing for more complex geometries to be printed and then electroplated with a chosen metal allowing for the light weight and easy to print plastics with the strength, corrosion resistance or conductivity of that metal. This all depends of what metal is chosen as each metal has its own advantages and disadvantages, so choosing the metal is entirely based on the situation that arises.

Section 4.1 - Aim

To design and successfully electroplate 3D printed components, while providing a way for the process to be optimised

Section 4.2 - Objectives

- To devise a method to electroplate 3D printed components
- To allow the reader to gain an understanding of what the project is about and how the main aim has been achieved
- To conduct research in-depth and gain a better understanding of electroplating
- To produce calculations to confirm the difference for theoretical and actual results
- To devise an optimised method for electroplating copper

Section 4.3 - Deliverables

- A MATLAB script to compute the different values such as Current efficiency, Thickness and many more
- A setup that is optimised using rigs and jigs for electroplating 3D printed components
- To create an applied coat greater than 1 micron thick
- A comprehensive comparison of theoretical and actual results obtained

Chapter 5 – Project Management

- Every two weeks a meeting was setup to update the supervisor
- A logbook was created to show the key parts (See appendix A)
- A work breakdown structure was made to show an overview of the experiment (See appendix B)
- A Gantt chart was created to allow for the project to be carried out in a timely manner (See appendix C)

The Gantt chart was mostly followed with some unforeseen occurrences such as the 3D printers not working as intended as well needing to order more supplies.

Chapter 6 – Methodology

Note: This experiment followed the guidelines set out by COSH, with the experiment being conducted under controlled conditions. Furthermore, to carry out this experiment requires access to the chemicals below and 3D printers.

Section 6.1 - Electroplating Plastic

Electroplating followed the same Risk assessment, equipment and safety equipment. The differences that occurred are the measurements for the bath, the rig that was used and the steps taken to achieve the final products. This will be listed below:

Section 6.1.1 - Safety equipment

- 1 pair of latex gloves
- 1 pair of goggles
- 1 lab coat

Section 6.1.2 - Risk assessment

Risk	Cause	Severity (1-10)	Likelihood (1-10)	Management
Breakage	Knocking beaker off a table	4	3	Use a dustpan and brush to clean it up
Spillage (water)	Spilling or breaking the beaker	5	3	Use a mop or tissue
Spillage (Chemical)	Spilling or breaking the beaker	5	3	Use a mop
Eye irritation	Wiping the eyes after contact with the chemicals	4	2	Wash eyes out with clean water. Seek medical attention
Skin irritation	Getting chemicals on exposed skin	3	4	Wash skin with water. Seek medical attention

Table 1 shows the risk assessment for the carried-out experiment

Section 6.1.3 - Pre-calculations and background knowledge

Before the experiment can be carried out, calculations need to be completed to determine the theoretical thickness you want the applied layer to be. To do this Faraday's first and second law of electrolysis is used.

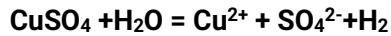
The first of Faraday's laws states that during electrolysis [20] "the amount of chemical reaction which occurs at any electrode under the influence of electrical energy is proportional to the quantity of electricity passed through the electrolyte".

The second Faraday's law for electrolysis states [20] "that if the same amount of electricity is passed through different electrolytes, the masses of ions deposited at the electrodes are directly proportional to their chemical equivalents".

Copper's properties		
Name	Value	Units
Density	8.96	g/cm ³
Atomic weight	63.54	Atomic mass unit
Valency	2	Positive
Molecular Weight	159.62	g/mol

Table 2 shows a table for the relevant properties of copper

To get the valency of copper the use of the chemical reaction formula below will be used:



Note: Hydrogen will be released as a gas, making it negligible

So, for copper it can be seen that it is Cu²⁺. therefore, its valency is +2.

Using this equation and finding the answer allows for electroplating to be more accurate and can be calculated a lot easier. **Note:** A supplementary MATLAB script will be provided for calculating Thickness, current efficiency, Rate of plating and total percentage difference (Appendix F).

Section 6.1.4 - Equipment

200 g Copper sulphate anhydrous

600 ml distilled water

1 g of sulphuric acid

1 ppm chloride

rig

4 copper pipes (Diameter 1.4 cm, Height 14.2 cm)

Copper wire

Power supply unit

Crocodile clips two

Two wires

Arbitrary 3D plastic part (PLA was used)

Conductive Copper spray

Beaker 1 litre

Section 6.1.5 - Method

The rig is 3D printed using PLA with the dimensions and design seen in (appendix D). This experiment used a hollow cylinder (appendix D) that was 3D printed.

Step 1: Measure 600 ml of distilled water into the beaker. Then add 200 grams of copper sulphate anhydrous and stir until fully dissolved, while stirring add 1 gram of sulphuric acid and after stirring some more add 1 PPM of chloride. Lastly stir for another 1-2 minutes. Finally leave to stand for a day with any form of protection to protect the mixture. You should get a nice blue colour (appendix E).

Step 2: While the mixture is standing for the day, have the 3D printer print off test shapes and a rig, if you so require. Print the test shapes off first as they will require spray painting of a conductive copper spray.

Step 3: Once the test shapes are printed off, spray paint them with the Conductive Copper spray with an even coating. Allow to dry naturally as the applied heat will warp the shape.

Step 4: Once everything in the previous steps have been completed place the copper pipes within the rig and use any form to keep them hanging in place. Wrap copper wire around the pipes and use copper wire around the printed shapes. Ensure the two wires do not touch each other as it may ruin the results.

Step 5: Using the crocodile clips attach them to the copper wires. The negative should be connected to the wire wrapped around the part that is being plated and the positive connect to the wire wrapped around the pipes.

Step 6: Set the power supply to 1 volt or 2 amps and allow to run for 1 hour. Use a timer to ensure accurate results. Once the time is up turn off the power supply, disconnect the clips and check how much is plated. Repeat this step two more times. Make sure to take the weight at interval. The values for the voltage and time do not need to be followed and are simply stating what the researcher did to achieve the results below.

Chapter 8 - Results

The results below are taken using different instruments:

Section 8.1 - Results from MATLABS, actual weighing and Microscope

Plastic with paint	A	B	C	D	E	F
Weight (grams)	1.1	0.6	0.2	1.2	0.6	0.2
Height (mm)	24	17.5	12	24	17.5	12
Diameter (mm)	24	18	12	24	18	12
Radius (mm)	12	9	6	12	9	6
Surface area (mm ²)	1809.55	989.601	452.38	1809.55	989.601	452.38
Theoretical Thickness (um)	86.5051	79.0903	174.2412	86.5051	79.0903	174.2412
Actual Thickness (um)	175	189.9	173	111.3	75.9	32.5
Percentage error	50.56851	58.35161	0.717457	22.28	4.2	436.12
Resistance of copper plating	0.1	0.1	0.1	0.1	0.1	0.1

Table 3 shows the characteristics as well the final results of the experiment

Second run at 1 Volt for 1 hour	2nd hour		
Name	A	B	C
Weight prior to next plating (g)	1.5	0.6	0.3
Weight after plating (g)	2.2	0.9	0.4
Difference in percent (%)	37.83	33	28.57

Table 4 shows the 1st experiment at 1 volt for 1 hour

1st experiment			
First run at 1 volt for 1 hour		1st hour	
Name	A	B	C
Weight prior to plating (g)	1.1	0.6	0.2
Weight after plating (g)	1.5	0.6	0.3
Difference in percent (%)	30.76	0	40

Table 5 shows the results after the second hour

Third run at 1 Volt for 1 hour	3rd hour		
Name	A	B	C
Weight prior to next plating (g)	2.2	0.9	0.4
Weight after plating (g)	2.2	1	0.45
Difference in percent (%)	0	10.52	11.76

Table 6 shows the results for the last hour

2nd experiment			
First run at 0.2 volt for 1 hour	1st hour		
Name	D	E	F
Weight prior to plating (g)	1.2	0.6	0.2
Weight after plating (g)	1.7	0.7	0.34
Difference in percent (%)	34.4	15.3	51.8

Table 7 shows the second experiment for 0.2 volts for 1 hour

Second run at 0.2 Volt for 1 hour	2nd hour		
Name	D	E	F
Weight prior to next plating (g)	1.7	0.7	0.34
Weight after plating (g)	1.75	0.75	0.34
Difference in percent (%)	2.89	6.89	0

Table 8 shows the results for the second hour

Third run at 0.2 Volt for 1 hour	3rd hour		
Name	D	E	F
Weight prior to next plating (g)	1.75	0.75	0.34
Weight after plating (g)	1.8	0.82	0.35
Difference in percent (%)	2.89	8.9	2.89

Table 9 shows the results the third hour

Weight of Copper (ii) Sulphate (g)	200
Moles of Copper (ii) Sulphate (Mol)	1.25
Volume of distilled water (dm3)	0.6
Concentration (mol/dm3)	2.083333333

Table 10 shows the concentration of the mixture

Percentage weight increase overall (%)	A	B	C	D	E	F
	100	50	76.92	40	30	54.54
Current Efficiency (%)	14.061	14.06	6.3274	8.433	61.8	21.08
Rate of plating (um)	0.0344	0.0629	0.062	0.0207	0.0138	0.0207

Table 11 shows the current efficiency, rate of plating and weight increase overall

Section 8.2 - Microscopic results – First set of results

Sample A

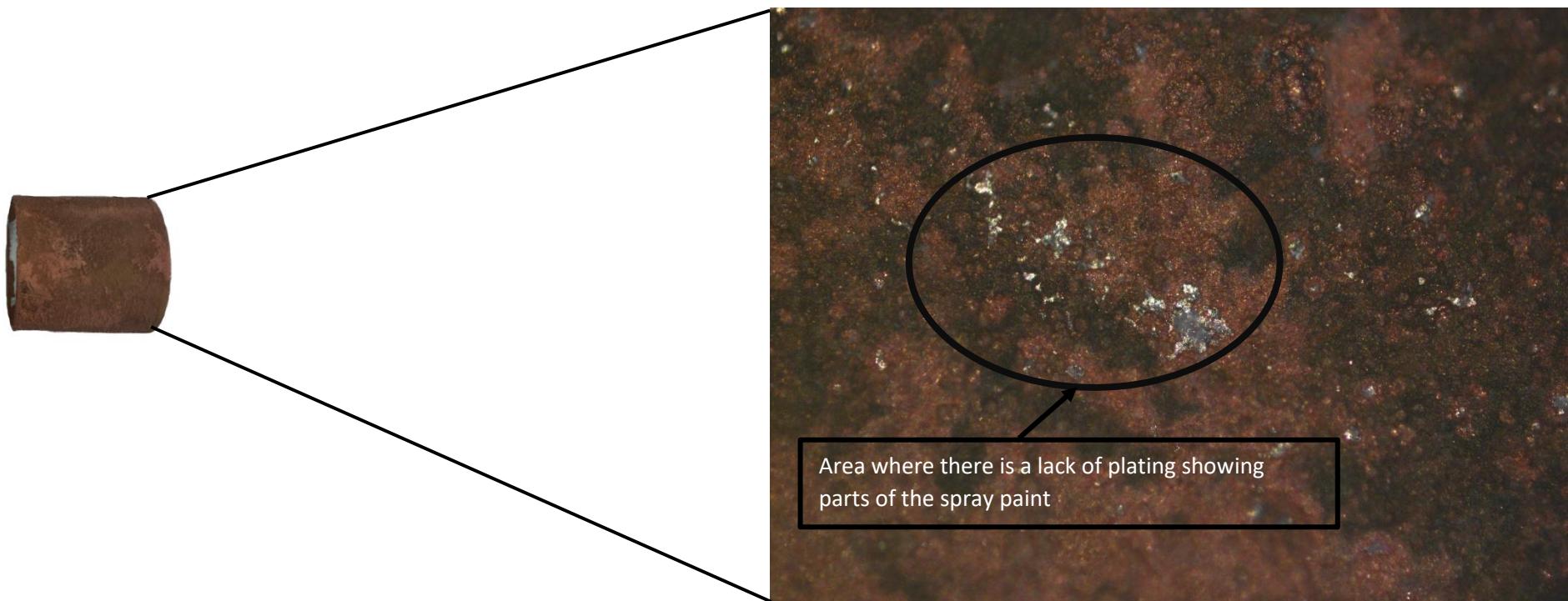


Figure 4 shows a microscopic view of sample A's surface

Sample B



Figure 5 shows a microscopic view of sample B's surface

Sample C

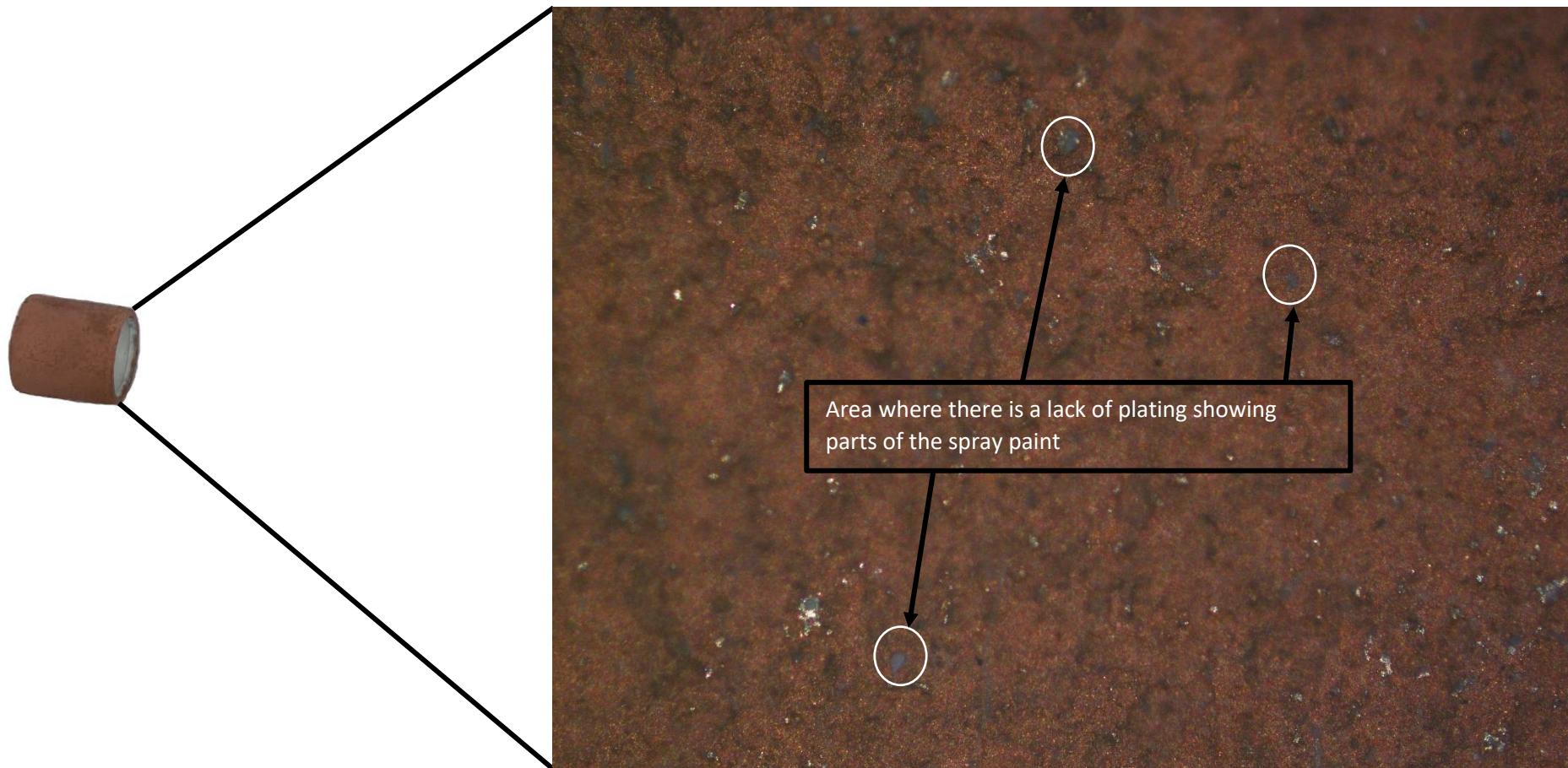


Figure 6 shows a microscopic view of sample C's surface

Cross section of samples A, B and C

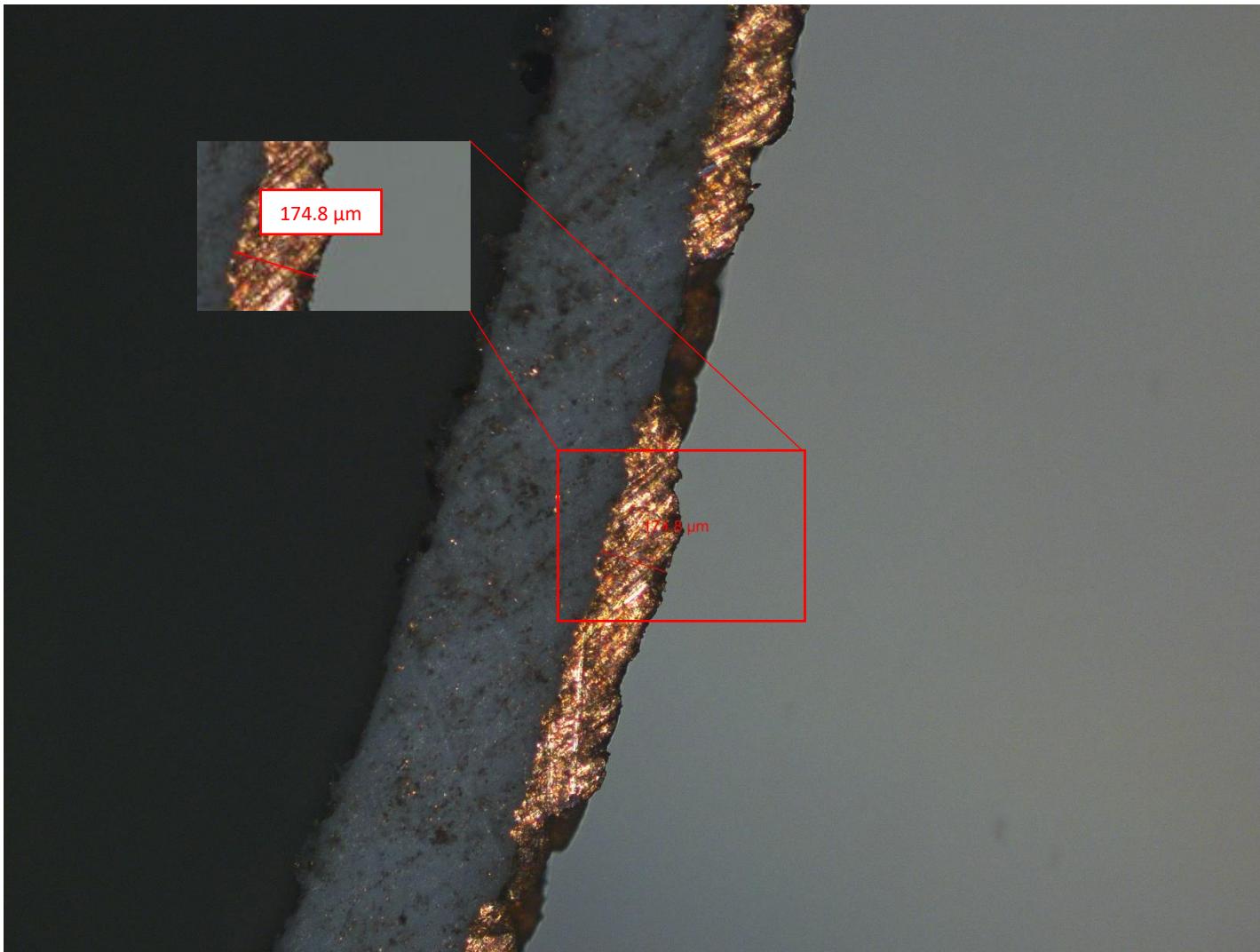


Figure 7 shows the cross section of sample A

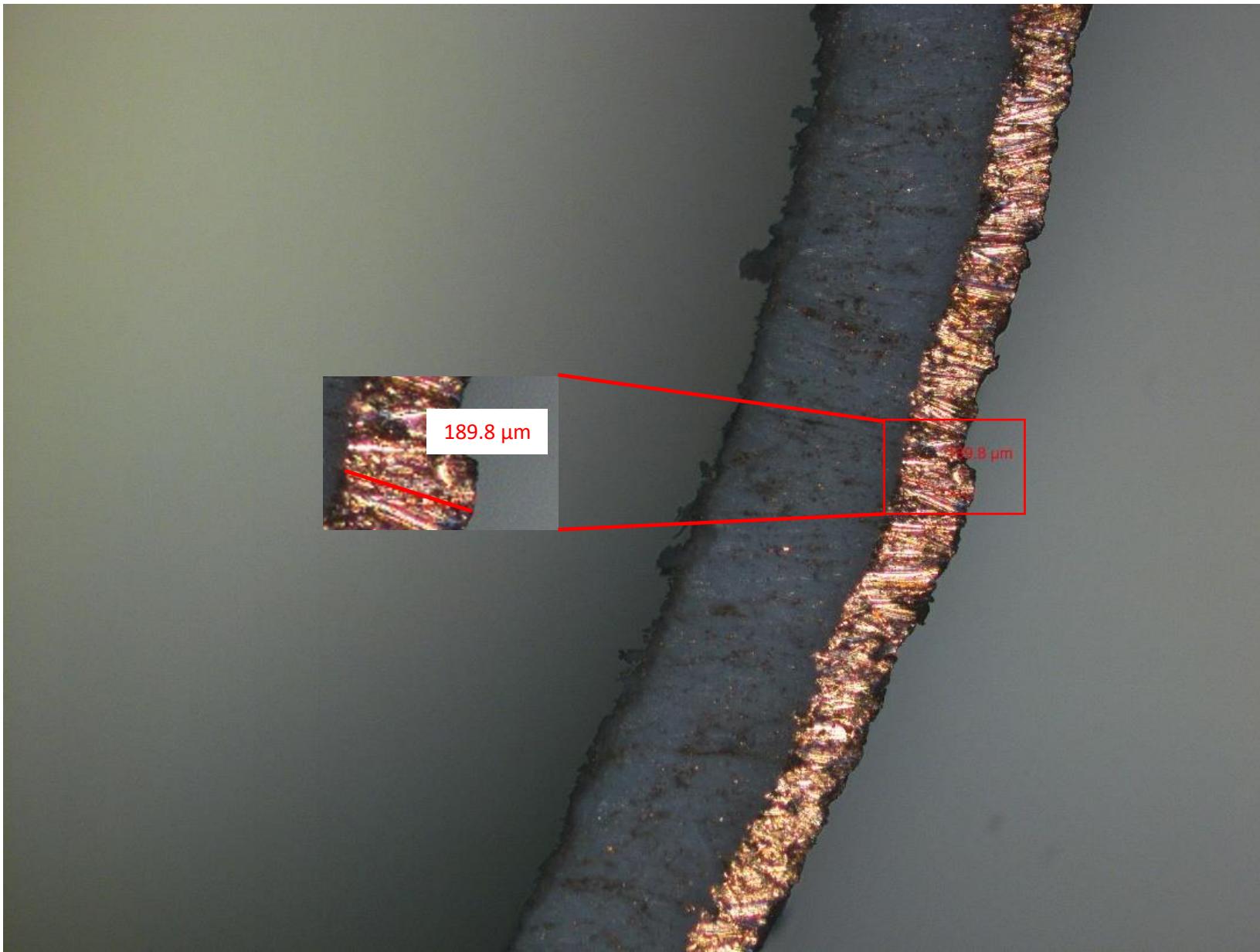


Figure 8 shows the cross section of sample B



Figure 9 shows the cross section of sample C

Section 8.3 - Second set of results

Sample D



Figure 10 shows the surface area of sample D

Sample E

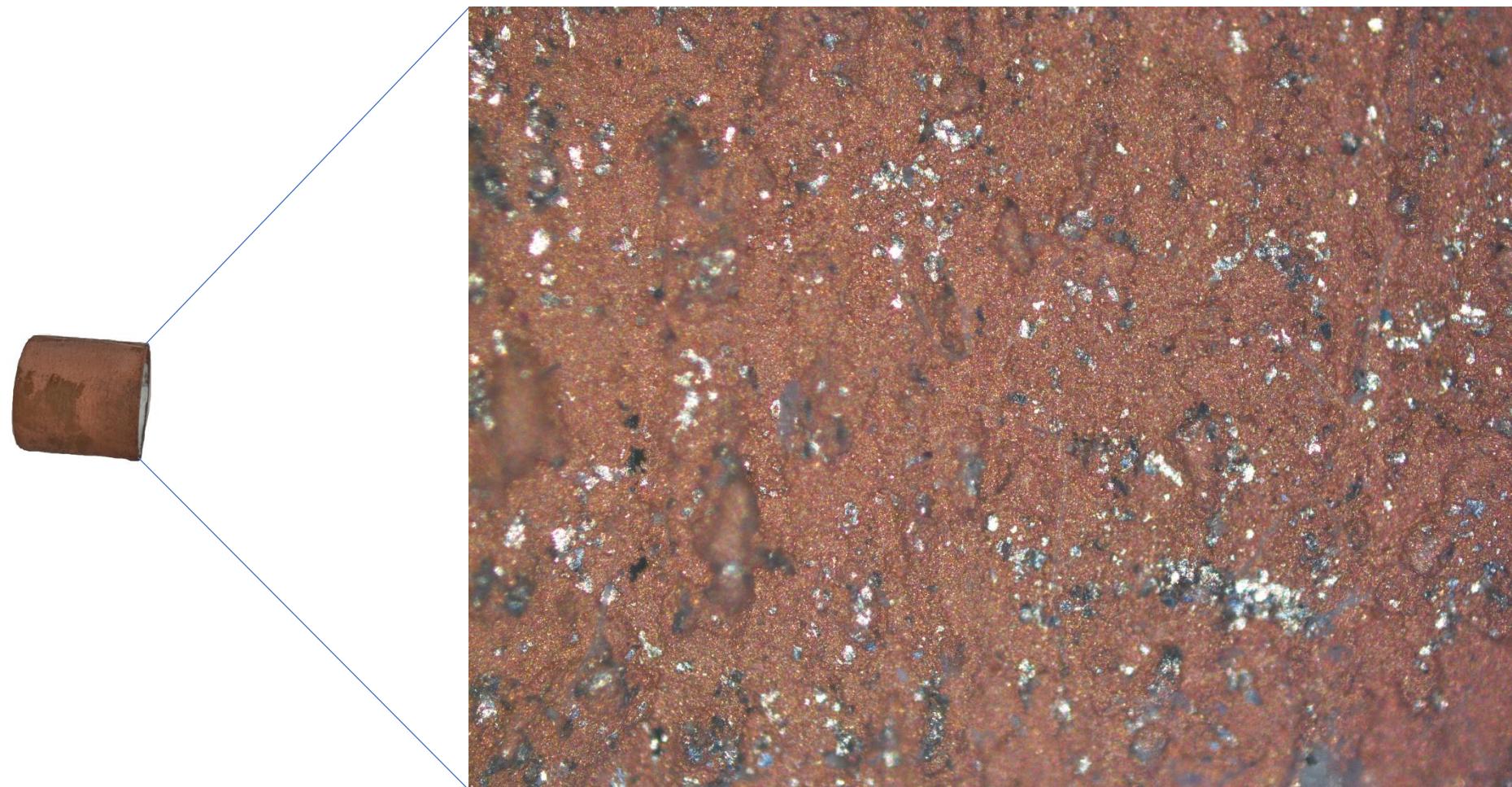


Figure 11 shows the surface area of sample E

Sample F

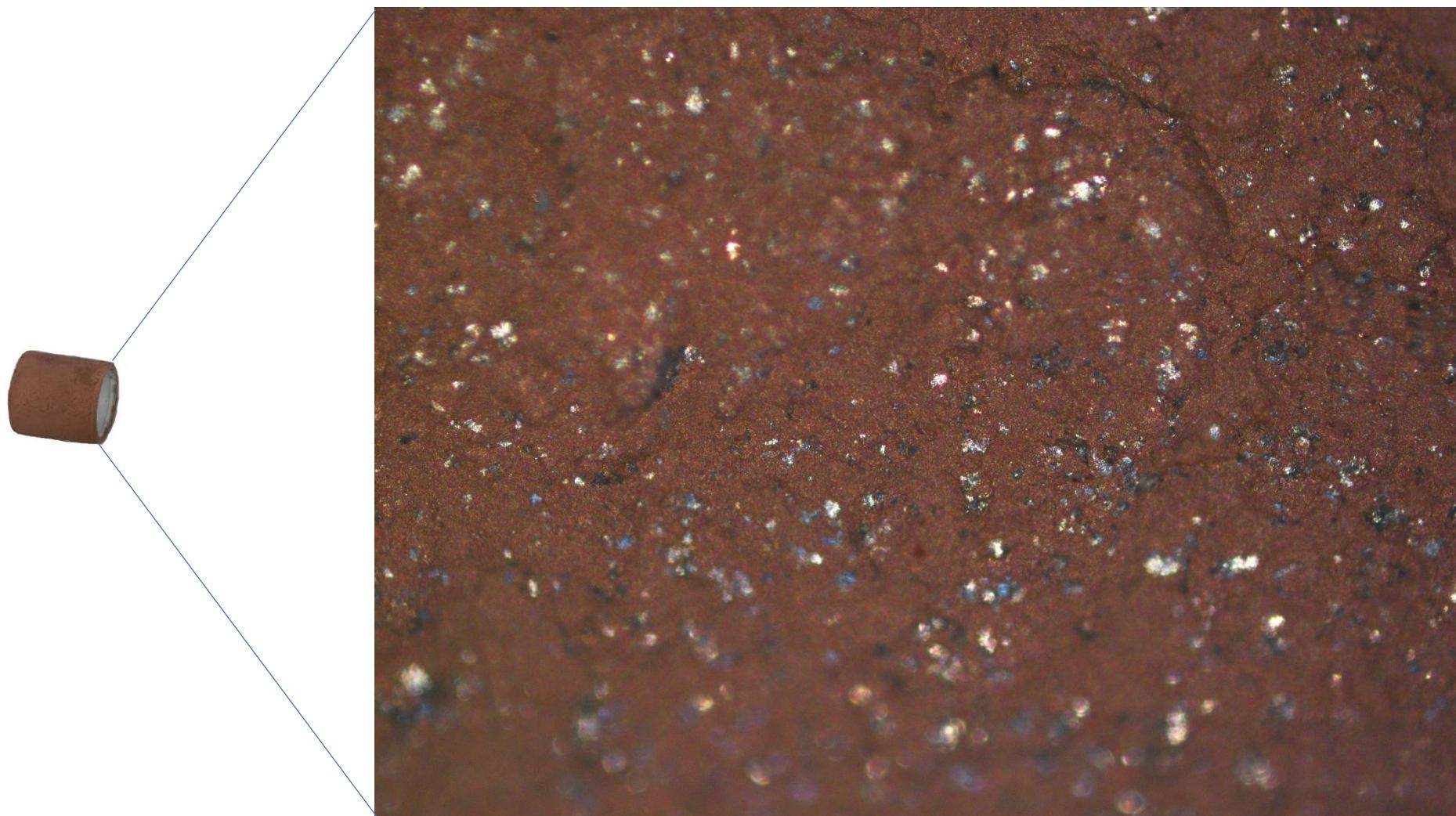


Figure 12 shows the surface area of sample F

Cross section of samples D, E and F

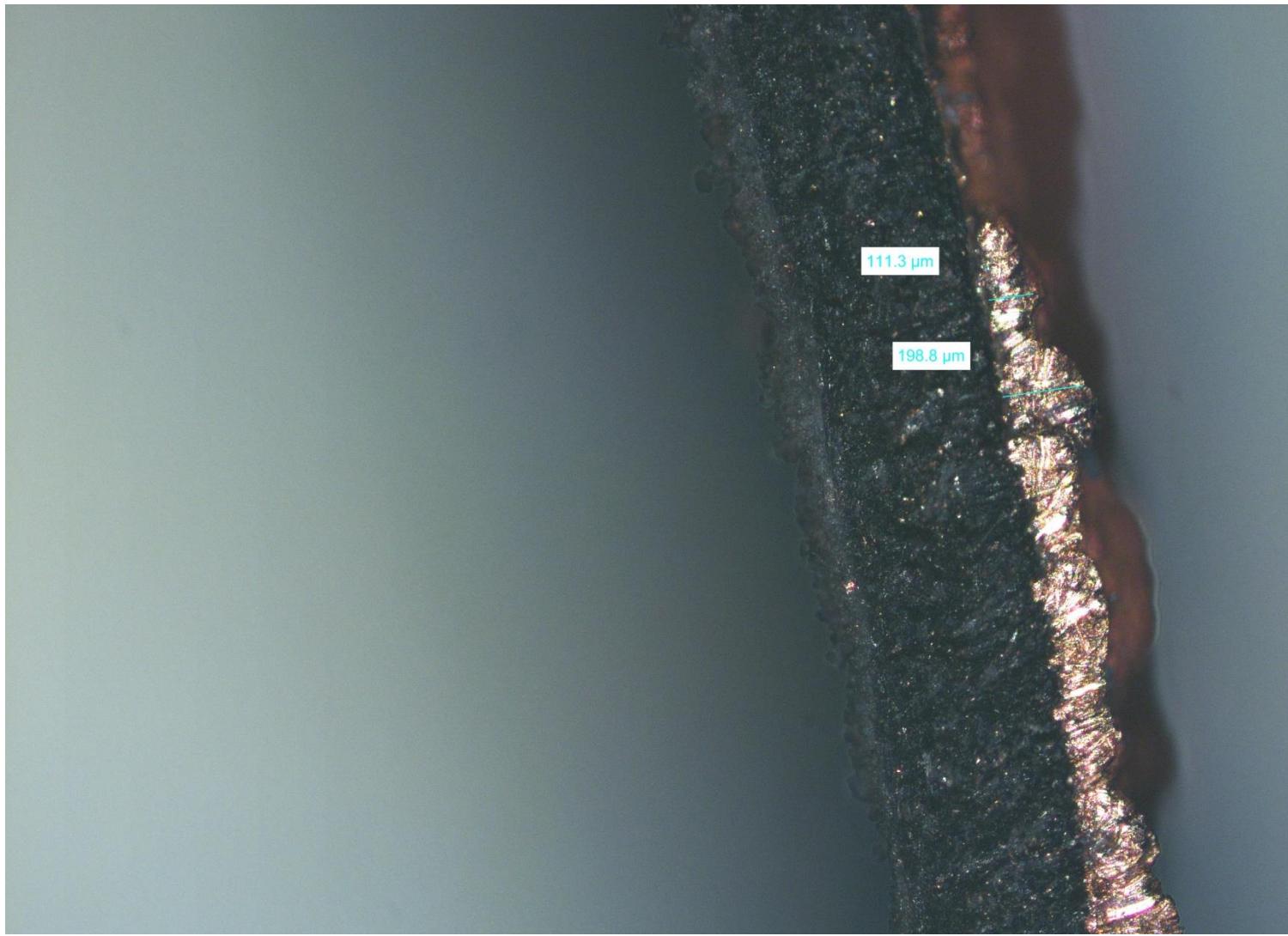


Figure 13 shows the cross section of sample D

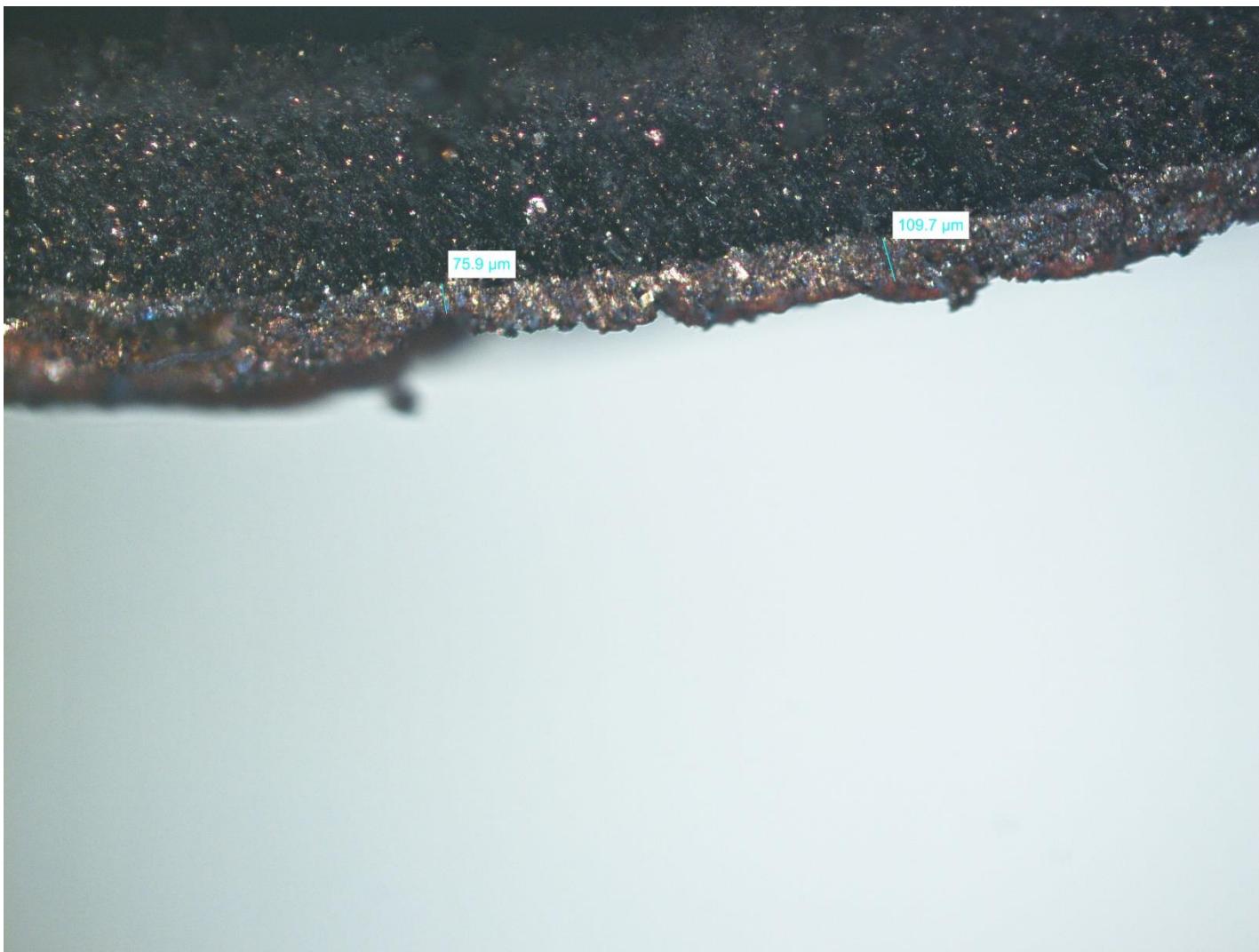


Figure 14 shows the cross section of sample E



Figure 15 shows the cross section of sample F

Chapter 9 - Discussion

One of the main problems of using a non-coated metal is that the properties on a singular metal has disadvantages such as being more susceptible to corrosion, tarnishing, erosion and many more. With the use of electroplating, a protection layer can be applied to the underlying material by applying a new surface layer that will have the qualities needed to prevent this. This problem can also be applied to 3D printed component especially as plastics tend to be weak compared to metals. So, coating a 3D printed component with a metal allows for the creation of a light object with the best properties of that chosen metal. A main example of this is what is being carried out in this experiment. Plastic is not that conductive when it comes to electricity. However, they are much lighter than most metals, So plating with layers of Copper allows for the product to be light and conductive.

Section 9.1 - Hand Calculations and MATLAB scripts

The methodology used to calculate the results consisted of hand calculations as well as MATLAB scripts. The hand calculations were done first and respectively looked over multiple times to ensure no errors were made as this error might translate over to the MATLAB scripts. Once the hand calculations were confirmed to be right, the script was also produced following the same equations and ran with the same parameters, allowing for confirmation that the MATLAB scripts are correct. To further automate and create an ease of use for the researcher and the readers, the scripts feature functions allowing the user to change any of the parameters they need, allowing for quicker calculations instead of constant hand calculations. Furthermore, the script also makes use of an excel spreadsheet with the vital information needed for the theoretical calculations across a good range of the main elements used in electroplating (See appendix F).

Section 9.2 - Material choice and Rig design

The researcher selected PLA over ABS and Nylon as this experiment required strength, stiffness as well as printability over other factors. Resistance such as Corrosion and Heat are negligible in this experiment. So, the advantages ABS and Nylon are not considered due to these factors. The Rig went through multiple iterations with small adjustments being made. The first step consisted of measuring the diameter of the beaker that will be used as this will allow for a decent fit that will be needed to hold the copper pipes and the sample in place. The Rig consisted of four holes with a diameter of 17 mm and an extruded bottom face of 12.8 mm (see appendix E) this was designed this way to ensure the copper pipes would stand relatively straight to where it sits. The holes were placed at 45-degree angles to keep the distance between one another the same as well as keeping the sample in the middle. Furthermore, the central hole has a diameter of 10 mm allowing for enough room for the wire that will be used for the current to connect with the sample.

Section 9.3 - Spray Painting

Making use of a spraying room provided by De Montfort university, the samples were sprayed with a conductive Silver coated Copper spray from Mg chemicals. However, this method proved to be lacking as the first set of experiments failed to plate properly due to the number of layers. The main problem that occurred from the spray can was that the liquid had a high viscosity due to its composition. And the pressure of the spray further harmed the initial samples by applying too much force to the surface causing the liquid to not dry on the spot it was intended for as well as applying more would simply move the liquid. Furthermore, a hair dryer was used to help the drying process of the paint, however this warped the plastic, so allowing for it to naturally dry was chosen. To change this the next set of samples were painted on by spraying a large amount of the liquid on the cardboard and dipping the brush allowing for much more controllability, allowing the research to have much more freedom on how much is coated and the number of layers. The overall look of the new plated samples turned out a lot better than prior ones (see Appendix E).

Section 9.4 - Microscope Method

Using a Nikon Eclipse LV150N Microscope the above pictures were able to be obtained with each sample (see appendix E) being placed under the microscope at 50x magnification, it has become clear that the overall solution works very well with majority of the surface being plated. The finish of the surface is very fine and smooth allowing for the next plating process, if chosen to do so. However, this process does not exclude that the method is not completely efficient with the highest coming out as 14% for the largest and middle-sized sample. The lowest being 6% for the smallest sample as found by the MATLAB script (see table 3) for the first experiment. It is clear from figures 4-6 and 10-12 that there are small areas that have either been partially plated or not at all. This can be down to many reasons such as the way the researcher has placed the samples into the liquid with the Copper wire stopping parts of the surface to plate. To mitigate this, the wire was moved to a plated area after every 1-hour interval to ensure that any parts left over got relatively the same treatment. Furthermore, the placement of where the sample sits can affect the overall performance of the plating. It is well known that thickness of plating is proportional to plating time as well as proportional to the distance between the electrode. This can present a problem as the researcher cannot be sure if the sample sat equal distance to the all four Copper pipes throughout the entirety of the experiment.

Section 9.5 - Discussion

Section 9.5.1 - First set of results

It should however be noted that it is clear surface area affects the overall quality of the plating with the area being un-plated getting worse from sample C to Sample A. This can be seen clearly with the naked eye. Moreover, each sample received the exact same time, voltage and setup. The only clear difference is the size of the samples. Even though the concentrations may be five times higher than optimal amount or 2 times higher than the border amount to be used each sample went under the same conditions.

Moreover, since the experiments used the same current as well as having varied surface areas, it has become clear that an increase in current is needed for larger surface areas as they have more area for it to plate, in turn meaning using more copper from the copper solution.

Due to plastic being used and thickness as well as the shape the edges were sanded to allow the removal of excess Copper giving a clear surface, while maintaining the structural integrity of the shape and the Copper. This decision has allowed for the measuring of the thickness ensuring accuracy and allowing any further plating in chosen to do so. The results can be seen in figure 7-9 and 13-15. The original weight of sample A without plating is 1.1 grams with the overall weight after plating coming to 2.2 grams that gives a weight increase of 100 percent (see table 3). However, the most interesting part of electroplating is the thickness of the plating as there is a huge difference between the theoretical calculations and the actual thickness. As can be seen in the actual thickness found by the microscope is 175 μm compared to the theoretical results that proposed the thickness would be 86.5 μm thick, this is a percentage error of 50.5 percent. The same trend can be concluded for sample B as the original weight prior to plating was 0.6 gram with the final weight after plating coming to 1 gram that is an increase in weight roughly around 50 percent. The thickness calculated to 79.09 μm with the actual thickness being 189.9 μm , this gives a percentage error of 57 percent. However, sample C had the most interesting findings as it had an initial weight of 0.2 grams and landed on 0.45 grams after plating, this leads to a weight increase of 76.92 percent. The actual thickness was very close with the theoretical calculations. The theoretical came to 174.24 μm and the actual thickness was 173 μm , that gives a difference of 0.7 percent difference. Now looking at the difference between the current efficiency sample A had an efficiency of 14 percent, Sample B has an efficiency of 14.09 percent and sample C has an efficiency of 6.3 percent (see figures 7-9).

From the discussions that have been carried out, it slowly enlightens the possibilities that could have affected the overall method of the electroplating process. Firstly, surfaces area does not directly correlate to the thickness of the plating in this experiment as all samples, which are varied sizes plated relatively close to one another. So far, the biggest impact that can be determined is the time, current and the concentration used for the experiments. All three samples spent 3 hours in total being electroplated as time is considered a major contributing factor towards thickness, it is clear this holds true. As most other factors have been eliminated and the thickness of each sample are close to one another with sample A being 175 μm , sample B being 189.9 μm and sample C being 173 μm (see table 3).

Section 9.5.2 - Comparing first and second set of results

As can be seen in the second set of results (section 8.3) it is clear that these results are much nicer in terms of plating. However, the decrease in voltage has left the surface of the samples with a lot less area being plated, this is to be expected. As discussed, a drop in current will lead to less Copper plating and

essentially slow down the electroplating process therefore requiring a longer time period to reach the thickness and the coverage that the first set of examples reached. The other parameters were kept the same in terms of concentration, time and characteristics of the samples. This drop in plating can be seen from the results table (see table 3). This difference in weight due to the current can be seen when comparing the first and second experiment. Sample D and A both had an initial value of 1.1 grams with sample D stopping at 1.8 grams whereas sample a stopped at 2.2 grams. This is 0.4 grams less than the first experiment. Furthermore, sample B and E both started at 0.6 grams with a slow increase in weight over the time periods. However, sample E stopped at 0.82 grams, whereas sample B stopped at 1 gram and lastly Sample C and F both started at an initial weight of 0.2 grams with sample C stopping at 0.45 grams compared to 0.35 grams for sample F. To further show this difference an overall weight percentage was calculated that can be seen in table 11. Another set of results further leading to this answer is the rate of plating that clearly show a correlation between current and rate of plating. This further confirms that surface area does not directly affect the rate of plating with the plating only being affected by current and time. As a higher current means less time needed to fully plate the samples. This reasoning can apply the other way with more time and less current.

Chapter 10 - Critical Analysis

The overall scope of the experiment was achieved to a sufficient standard that can be considered a success. Although prior experimental runs proved unfruitful, they acted as a learning curve and allowed for the researcher of the experiment to gain more insight into how electroplating works. It can be seen how the overall experiment methodology has improved leading to the results in Chapter 8. There may be deviations between the theoretical and actual values. But this can be down to many oversights that will be stated further on.

The overall efficiency of the process as calculated by (table 11) show there was something wrong with the process and required further investigation. The current efficiency can be down to many things.

Section 10.1 - Concentration

Firstly, the concentration of the solution was five times higher the amount it should have been. It has been found [21] that the best concentration was 0.4 mol/dm^3 , whereas the concentration of the solution used in this was 2 mol/dm^3 . Furthermore, this experiment used 1 volt for the entire test and this is right on the limit of the recommended voltage for copper electroplating. It is agreed during electroplating that Thermodynamic control dominates the overall experiment, that is if the experiment is in near-equilibrium conditions, which is the main part of this experiment. Due to this rule when high voltage and a high concentration are put together the efficiency will suffer as metal ions in the near-electrode will be exhausted quickly. This rule was followed for the second set of results at 0.2 volts and clearly showed time should be considered more as a lower voltage and longer time can produce better results, if regularly checked.

Section 10.2 - Pre-Processing

It is clear that pre-processing plays a vital role in achieving really good results for plating, especially if the experiment was to use other metals. The next experiment should consist of some form of pre-processing such as Wet-blasting, sanding down to smooth the material or etching the surface. However, wet-blasting is better as it allows for better adhesion between the metal and plastic as found by [2]. Furthermore, the researchers found a conductive plastic composite could prove beneficial in cutting down the overall need for a layer of conductive spray. Therefore, reducing the time it takes to plate as well as preparing the respective facilities needed to spray paint.

Section 10.3 - Rig design

The design of the Rig could be more optimised as one of the main problems with the Rig is that the sample would not sit central between the four Copper pipes. This creates an efficiency problem as the closer copper pipes will use a lot more copper than that of its counter parts leading to the closer pipes running out quicker.

Section 10.4 - MATLABS and hand calculations

Theoretical calculations do not take into account the concentration of the mixture due to this; theoretical results should be taken with caution. It is due to this failure to take into account that the theoretical calculations have a massive percentage error. Another reason for the deviation is because of the placement of the samples, due to the sample not maintaining a centralised placement leads to each side being uneven in terms of plating. This can be seen from the second set experiments as illustrated by the microscopic pictures (see figures D and E). This could mean that the theoretical calculations are in fact correct, but the way the experiment was carried out caused the errors that have occurred. However, that is not to say these calculations do not have a place as these are calculated prior to the experiment. But as can be seen with the MATLAB scripts it is easier to adjust and completely gets rid of the need for paper. Furthermore, if future advancements allow for more precise answers in determining the theoretical results than the script can be easily updated for this.

Chapter 11 - Conclusion

In conclusion the aim to plate Copper onto plastic was successful as can be seen above in chapter 8. However, an optimised method was only achieved theoretically through calculations and a stronger understanding of the processes that go into electroplating. With this knowledge the next experiment will include the changes talked about on Chapter 12 below. And lastly all aims and deliverables have been met.

Chapter 12 – Recommendations

- Use pre-processing to prepare the surfaces for plating as this will allow for better adhesion and therefore better plating efficiency
- The Rig should be re-designed in such a way that does not hinder the distances between the sample to be plated as well as the Copper pipes.
- The Rig should also feature an extrusion that will hold the sample allowing for easier extraction.
- All experiments should make use of titanium wires as this will not become brittle as found with copper wiring.
- The concentration should be lowered to 0.4 mol/dm^3 to allow for better efficiency for the plating process
- Use a conductive copper composite to reduce the overall time the experiment takes

Chapter 13 - Conflict of interest

The author declared no conflicting interests

Chapter 14 - References

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Chapter 15 – Appendices

Appendix A - Logbook

Date: 5/10/2022

Time: 14:10

Created logbook. Going to start looking at what is required for Project specification and ethics form.

Date: 06/10/2022

Time: 14:00

Started to create a rough idea of what materials I will need and questions to answer for the project.
Will be approved upon at a later date

Date: 11/10/2022

Time: 14:00-15:00

Met up with my supervisor and discussed the project and what is wanted and expected out of the project. Went over the details of the project with a fine-tooth comb. Waiting for the 14th, so Richard knows if any other students will be assigned to the project before discussing anything further.

Date: 13/10/2022

Time: 11:00

Updating project Specification to be more specific and to the standards expected of students

Date: 8/10/2022

Time: 16:46

Put in the request for the ordering of the silver coated conductive copper spray ill be requiring.

Date: 13/12/2022

Time: 8:00

Finished the interim report

Date: 16/1/2023

Time: 14:00

Met up with my supervisor to discuss progress and printers that can be used for the Rig

Date: 3/2/2023

Time: 14:00

Met up with my supervisor to start the initial experiment

Date: 4/3/2023

Time: 10:00

Began my second experiment making adjustments from the 1st experiment

Date: 30/3/2023

Time: 12:00

Began my third experiment after some success plating from my 2nd experiment

Date: 15/4/2023

Time: 10:00-21:00

Conducted background researcher in terms of history of 3D printer and electroplating

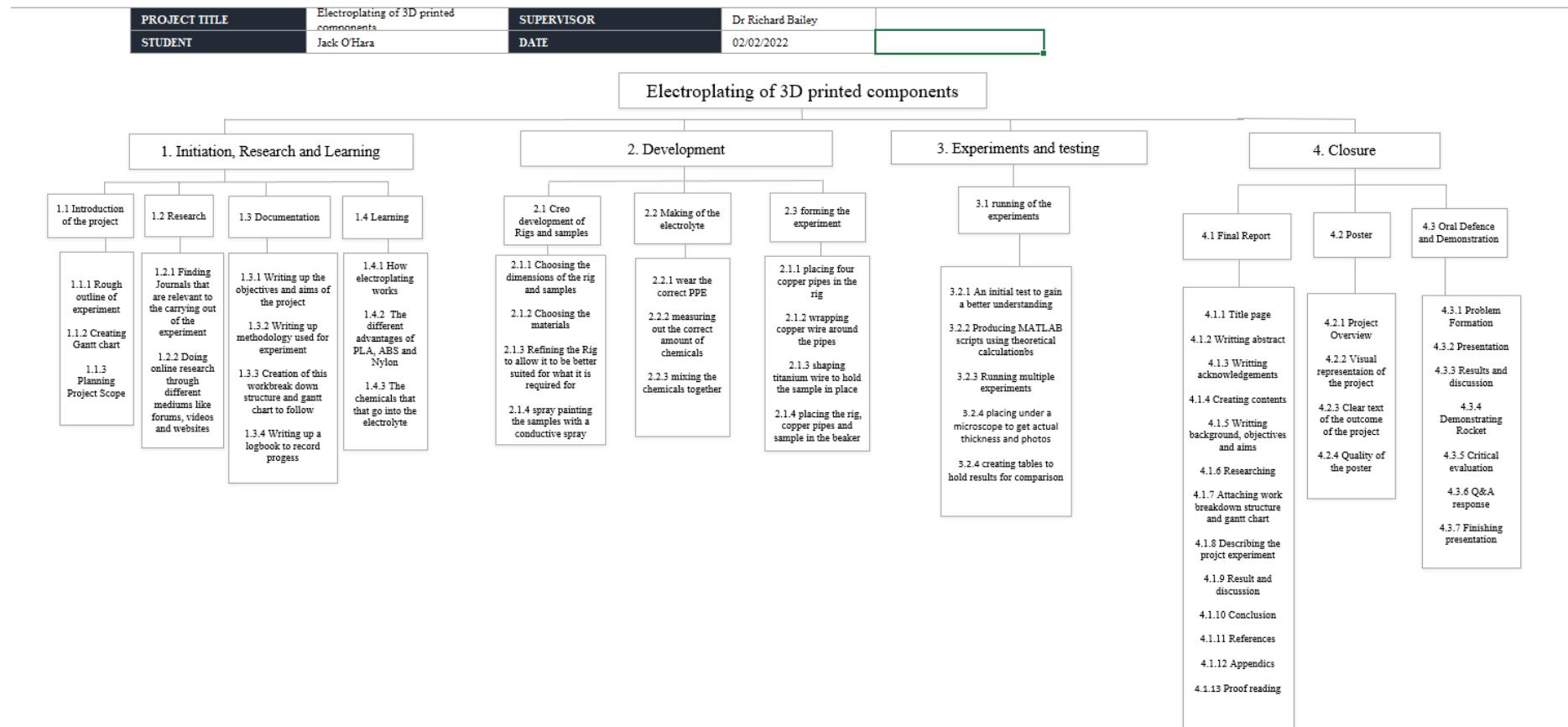
Date: 17/5/2023

Time: 10:00-19:00

Conducting a fourth experiment and finishing write up as well as captions

Appendix B – Work breakdown structure

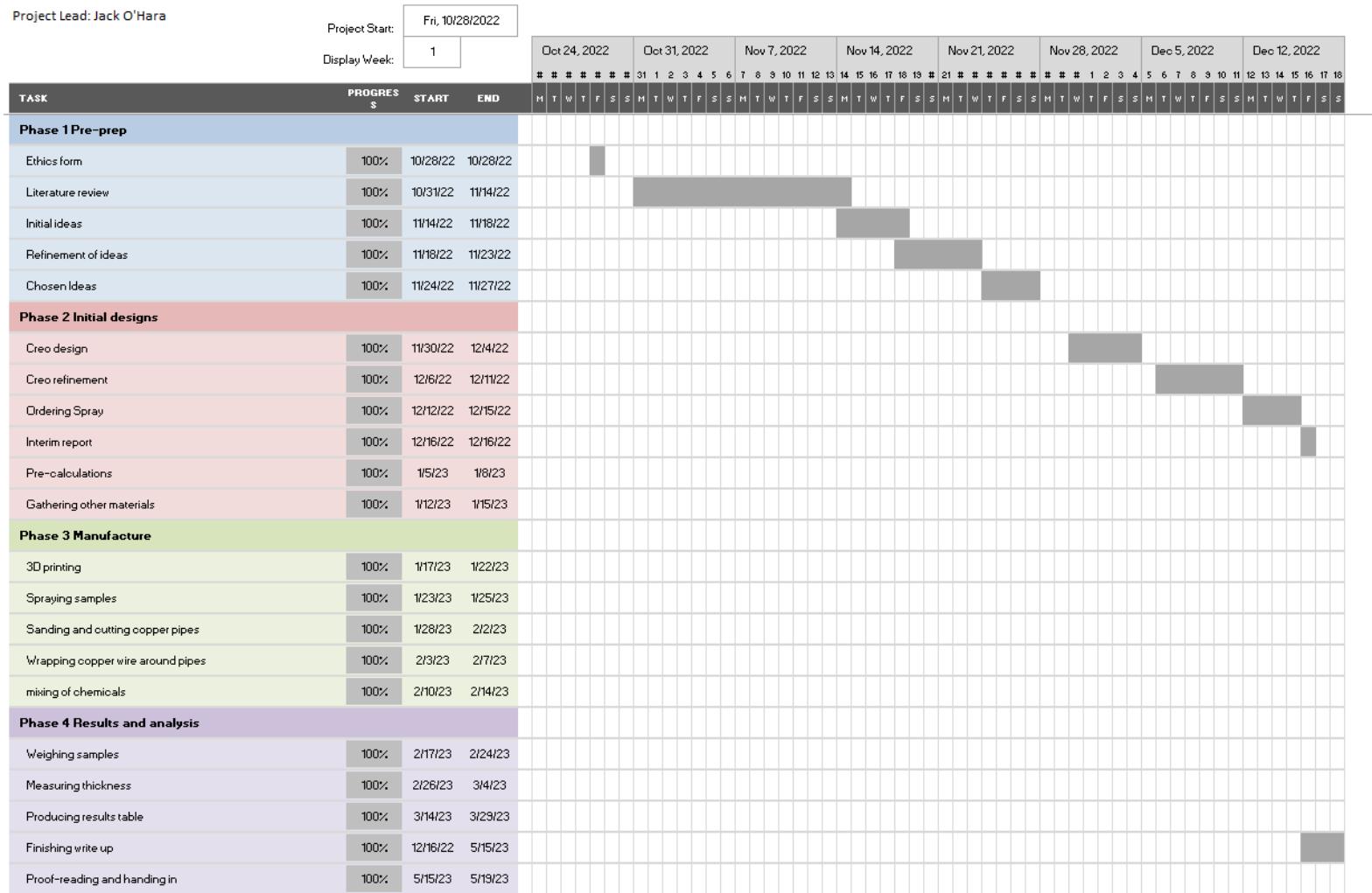
Work Breakdown Structure



Appendix C – Gantt chart

ELECTROPLATING OF 3D PRINTED PARTS

SIMPLE GANTT CHART by Vertex42.com
<https://www.vertex42.com/ExcelTemplates/simple-gantt-chart.html>



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Project Lead: Jack O'Hara

Eri 10/28/2022

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Project Lead: Jack O'Hara

Project Start: Fri, 10/28/2022

Display Week: 17

TASK	PROGRES %	START	END	Feb 13, 2023		Feb 20, 2023		Feb 27, 2023		Mar 6, 2023		Mar 13, 2023		Mar 20, 2023		Mar 27, 2023		Apr 3, 2023											
				M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	F	S
Phase 1 Pre-prep																													
Ethics form	100%	10/28/22	10/28/22																										
Literature review	100%	10/31/22	11/14/22																										
Initial ideas	100%	11/14/22	11/18/22																										
Refinement of ideas	100%	11/18/22	11/23/22																										
Chosen Ideas	100%	11/24/22	11/27/22																										
Phase 2 Initial designs																													
Creo design	100%	11/30/22	12/4/22																										
Creo refinement	100%	12/6/22	12/11/22																										
Ordering Spray	100%	12/12/22	12/15/22																										
Interim report	100%	12/16/22	12/16/22																										
Pre-calculations	100%	1/5/23	1/8/23																										
Gathering other materials	100%	1/12/23	1/15/23																										
Phase 3 Manufacture																													
3D printing	100%	1/17/23	1/22/23																										
Spraying samples	100%	1/23/23	1/25/23																										
Sanding and cutting copper pipes	100%	1/28/23	2/2/23																										
Wrapping copper wire around pipes	100%	2/3/23	2/7/23																										
Mixing of chemicals	100%	2/10/23	2/14/23																										
Phase 4 Results and analysis																													
Weighing samples	100%	2/17/23	2/24/23																										
Measuring thickness	100%	2/26/23	3/4/23																										
Producing results table	100%	3/14/23	3/29/23																										
Finishing write up	100%	4/16/23	5/15/23																										
Proof-reading and handing in	100%	5/15/23	5/19/23																										

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SIMPLE GANTT CHART by Vertex42.c

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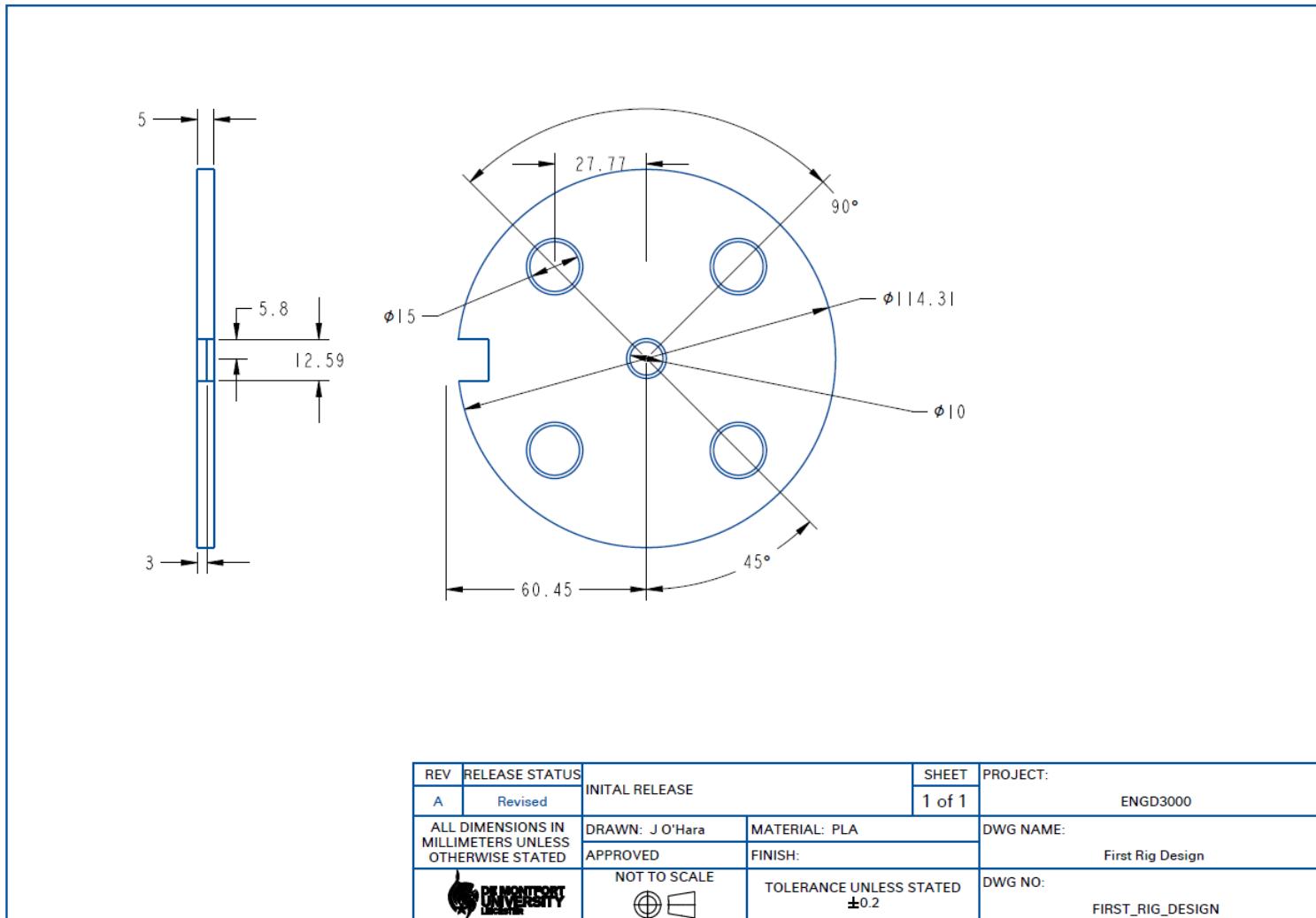
Project Lead: Jack O'Hara

Fri, 10/28/2022

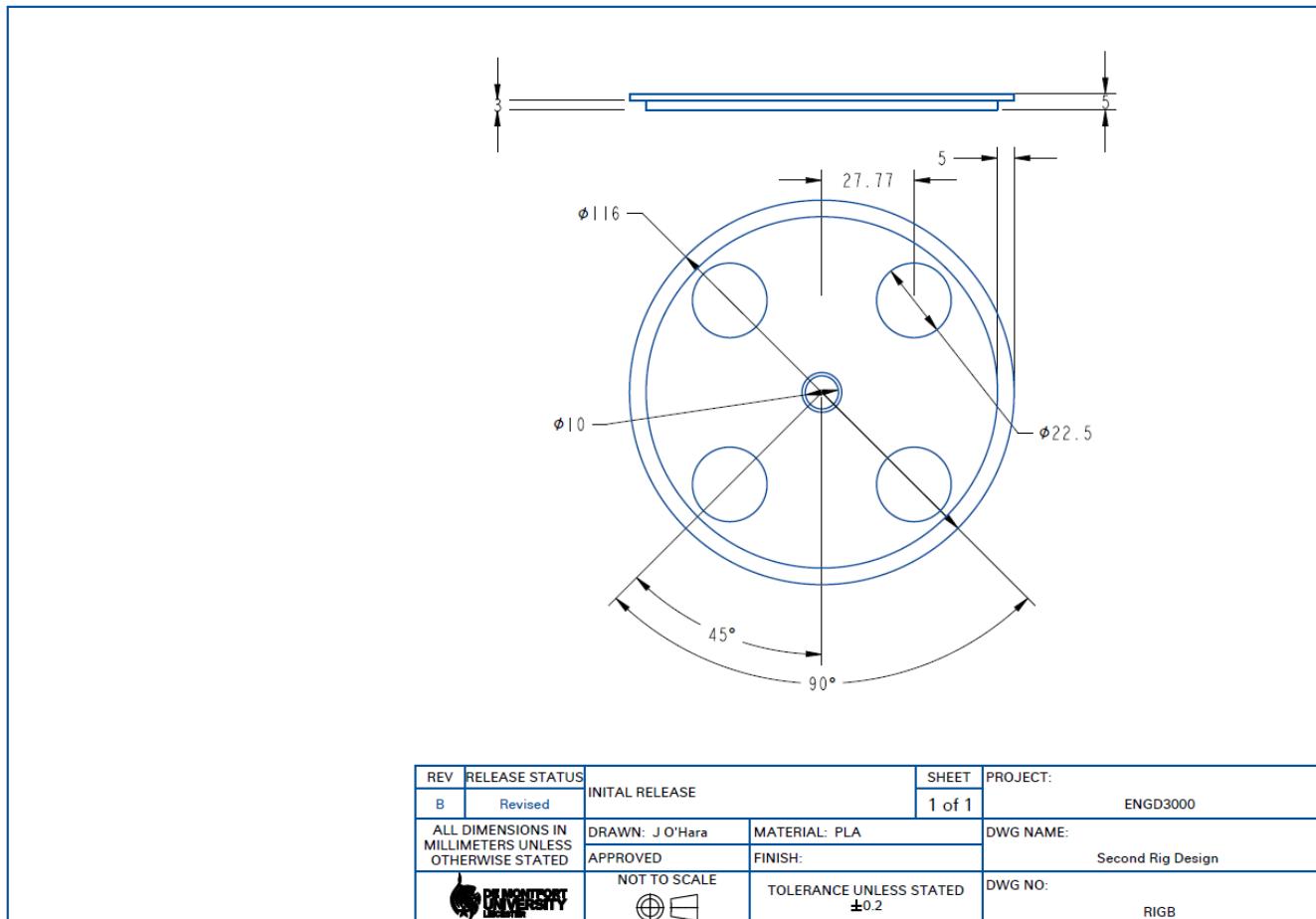
Display Week: 24

Appendix D – Drawings

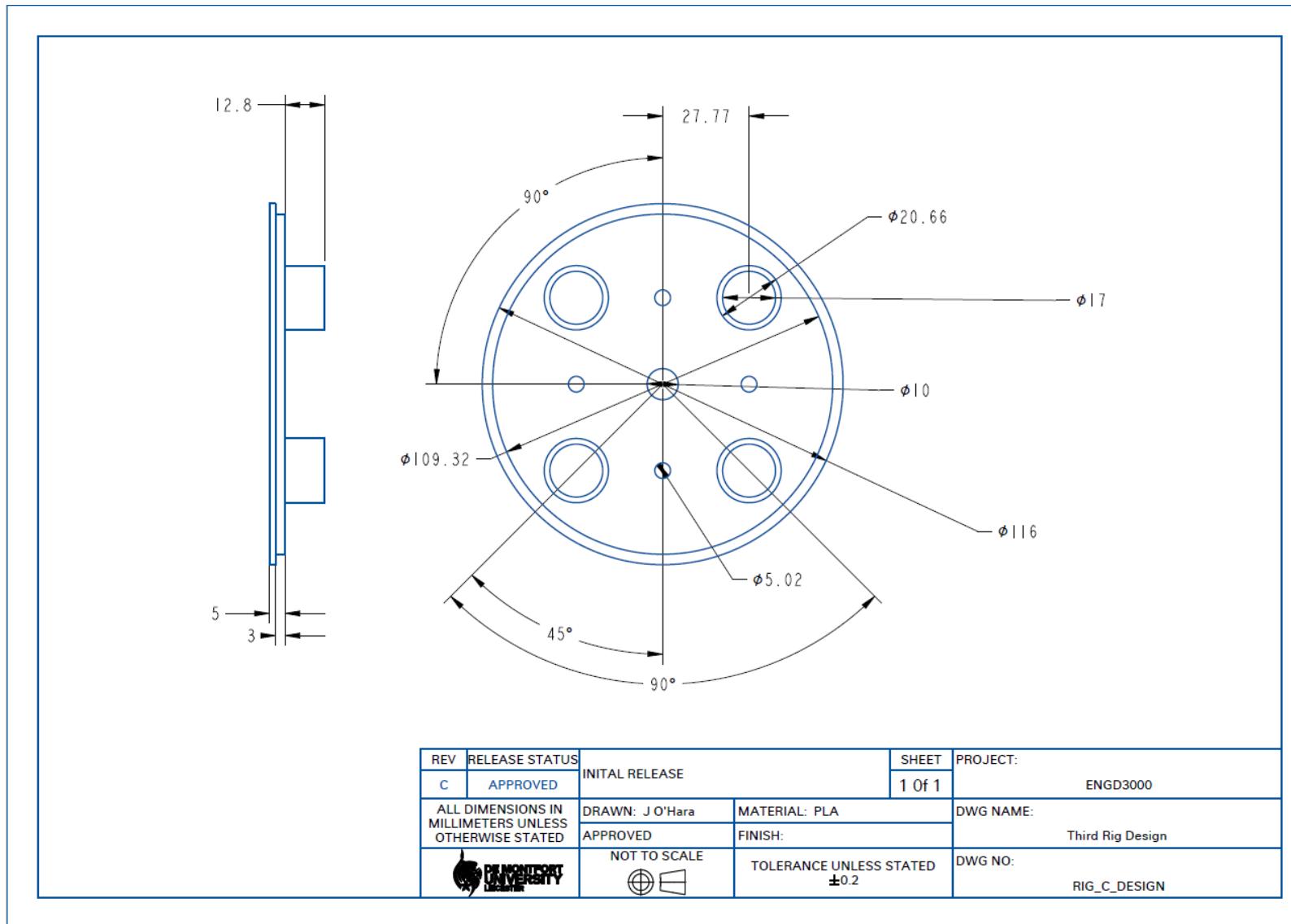
Rig design A



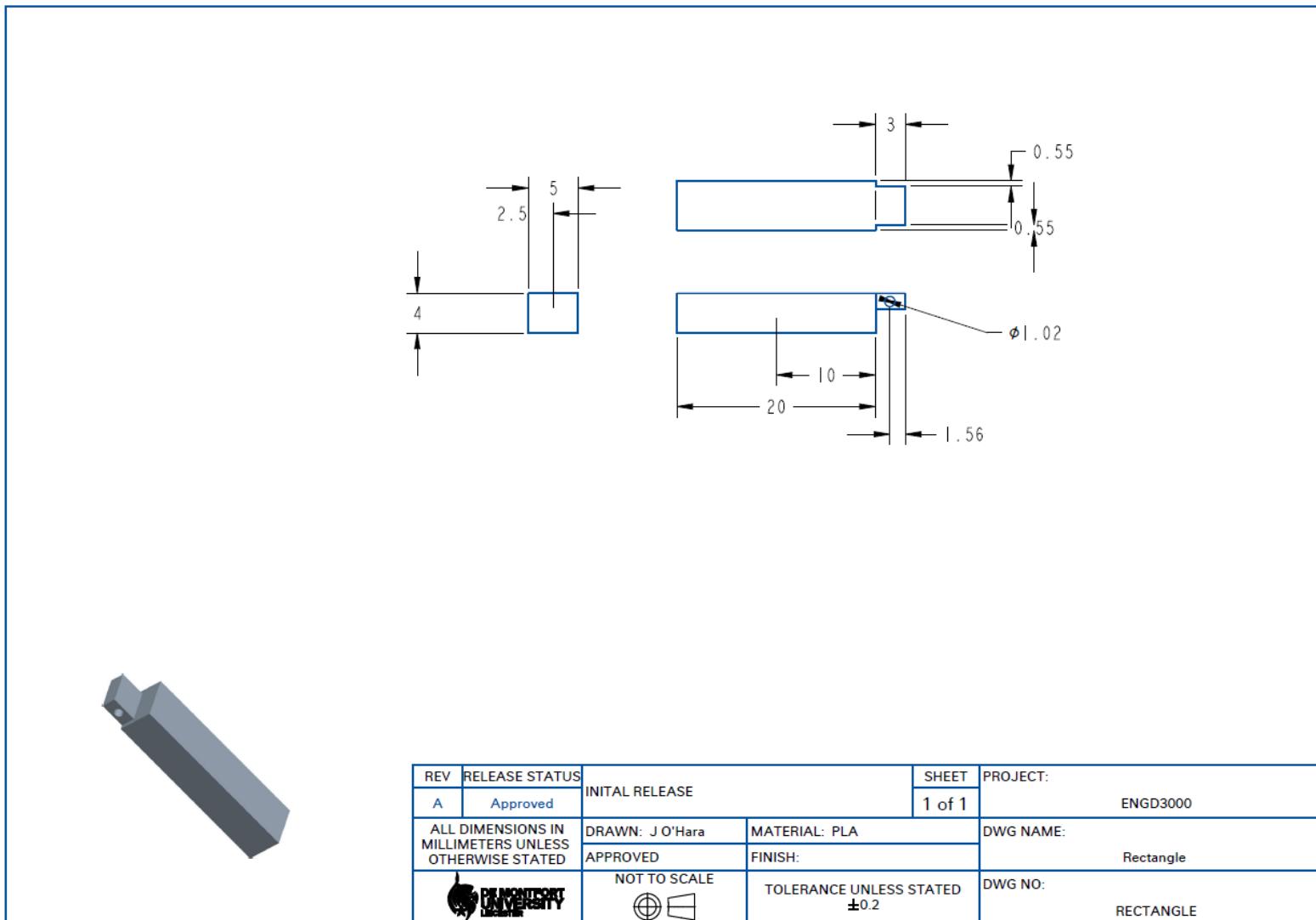
Rig design B



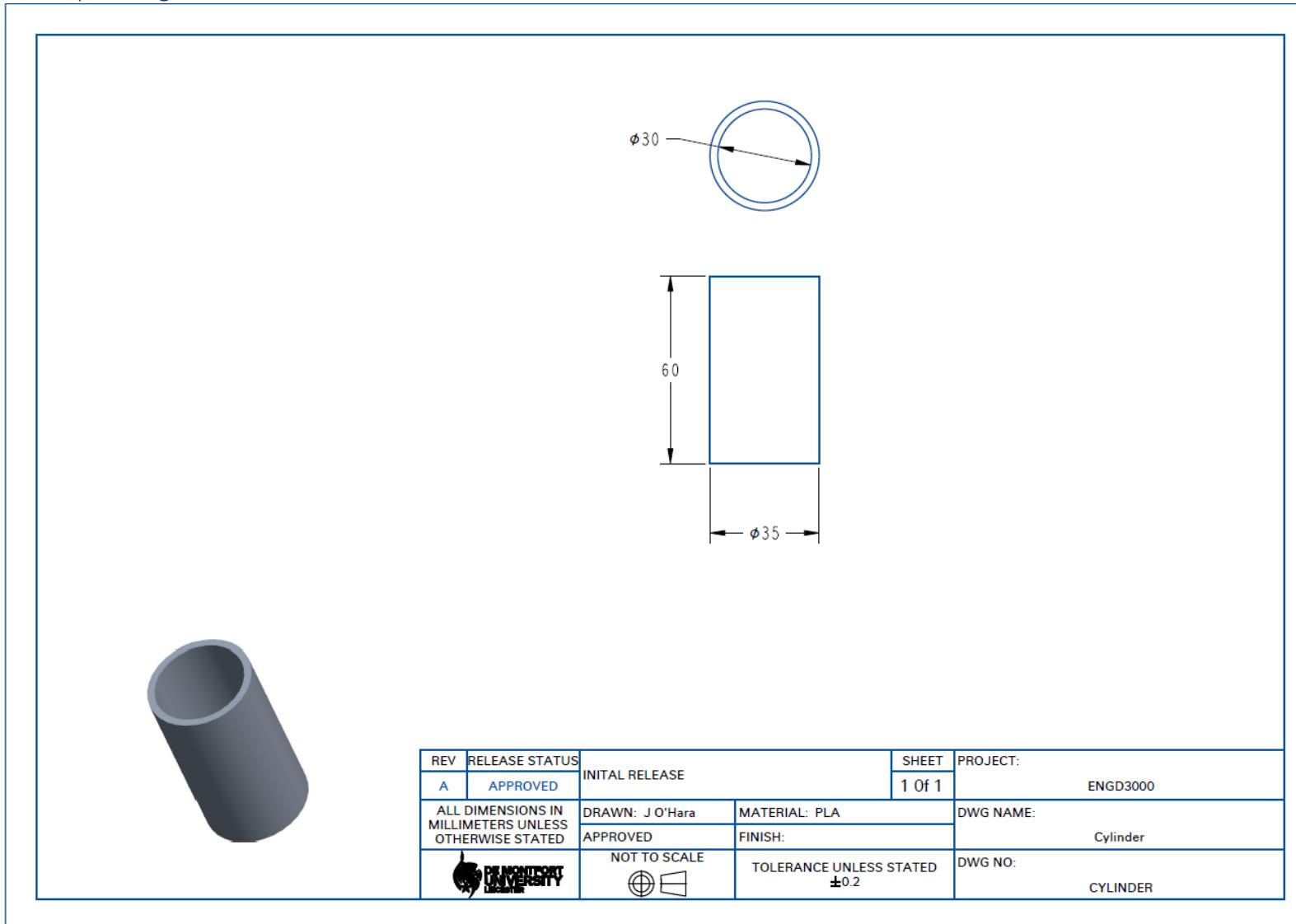
Rig design C



Rectangular sample design



Cylindrical sample design



Appendix E – various photos

Photo of Rig A

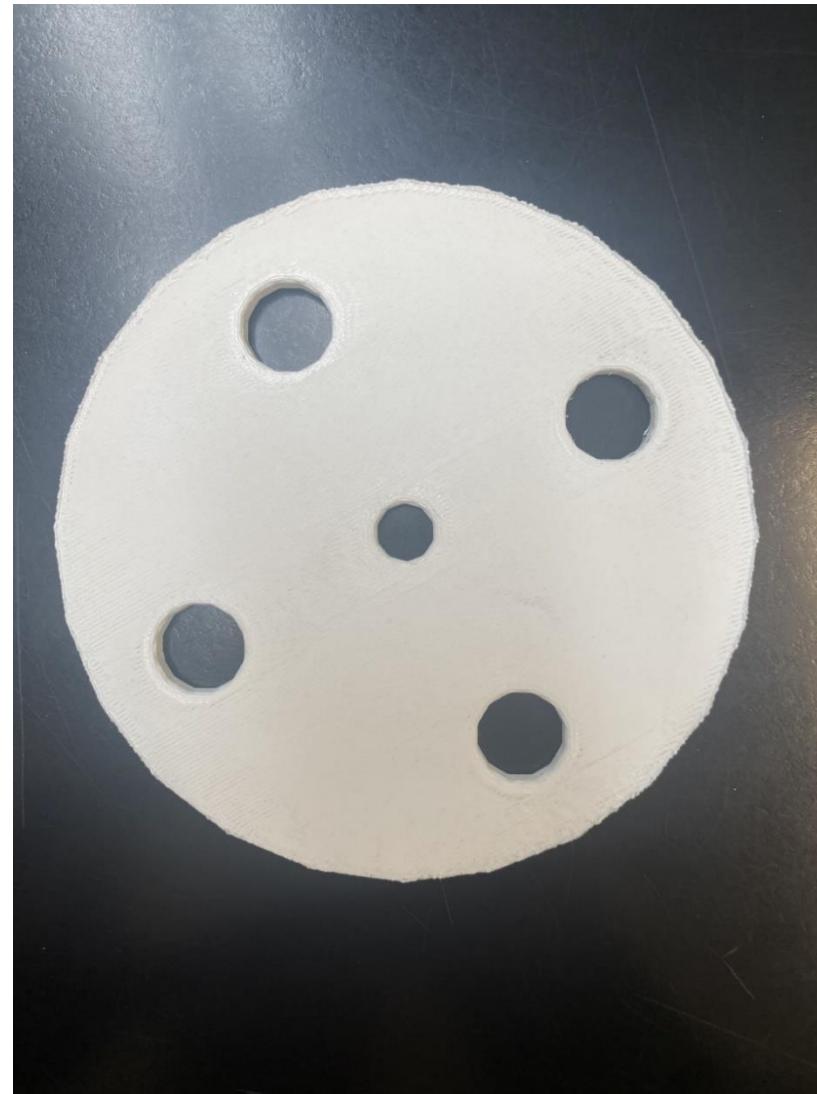


Photo of Rig B



Photo of Rectangular samples



Photo of first experiment



Photo of first experimental samples spray painted



Photo of second experimental samples spray painted



Photo of first experimental samples plated



Photo of solution getting filtered



Device used to the weight after 1 hour intervals



Microscope used to get the pictures in chapter 8



Appendix F – the MATLAB Script used for the theoretical calculations

% HOW THE SCRIPT WORKS

```
% First input the correct the values. Some values you will need to input  
% from your own experiment such as weights. others can be pulled from the  
% table provided
```

```
clear, clc
```

```
disp('Find below a table of the most used elements in terms of electroplating')
```

```
% VariableNamingRule
```

```
Metalprop = readtable("metalprop.xlsx","VariableNamingRule","preserve");  
head(Metalprop,10)
```

```
%% setting the initial paramenters
```

```
IW = 1.2; % Initial Weight (grams)
```

```
FW = 1.8; % Final Weight (grams)
```

```
C = 63.554; % Atomic weight Copper
```

```
rho = 8.92; % Density of copper (g/cm3)
```

```
n = 2; % Charge
```

```
Volume = 600; % solvent in ml
```

```
cop = 200; % grams of chosen composite
```

```
t = 3; % hours
```

```
T = t*3600; % seconds
```

```
I = 2; % Amps
```

```
%% Area characteristics (mm)
```

```
h = 24; % height
```

```
D = 24; % diameter
```

```
%% Ideal values (function part)
```

```
A = Thick(C,rho,n,h,D,cop,Volume,T,I,FW,IW);
```

```
%% This script works out the amps needed for a certain thickness based on a set amount of time
```

```
function Thickness = Thick (C,rho,n,h,D,cop,Volume,T,I,FW,IW)
```

```
% Variables
```

```
pi = 3.14159; % Value of the constant Pi
```

```
F = 96500; % Faradays Constant
```

```
%% Area characteristics (mm)
```

```
R = D/2; % Radius mm
```

%% Surface Area

$sf = 2 * \pi * R * h;$ % surface area (mm²)

$SF = sf / 10;$ % surface area (cm²)

%% Calculating the theoretical thickness

$TW = (I * T * C) / (n * F);$ % Theoretical Weight

$CW = FW - IW;$ % change in weight

$CE = CW / TW;$

$Ce = CE * 100;$

$Thickness = ((10000 * TW) / (\rho * SF)) * CE;$

`disp('The theoretical thickness in um is')`

`disp(Thickness)`

`disp('The current efficiency in percent is')`

`disp(Ce)`

```
%% Parameters set
```

```
mol = 0.006265; % number of moles for 1 gram of Copper Sulphate
```

```
% Choosing the concentration in mol/dm3. Advised range is 0 - 1 (mol/dm3)
```

```
vol = Volume/1000; % converting from cm3 to dm3
```

```
moles = cop*mol; % Total moles of Copper(II) Sulphate
```

```
conc = moles/vol; % Concentration of mixutre
```

```
disp('The concertration in mol/dm^3 is')
```

```
disp(conc)
```

```
%% Rate of Plating (um/min)
```

```
R = ((600000*I*C)/(n*F*rho*SF))*CE;
```

```
disp('The rate of plating in um/min is')
```

```
disp(R)
```

```
%% Total Percentage calculator
```

```
PDC = ((FW-IW)/((FW+IW)/2))*100;
```

```
disp('The total percentage difference is')
```

```
disp(PDC)
```

```
end
```