Using dual-material additive manufacturing and electroplating techniques to produce minimal resistant circuitry inside a 3d printed product.

by

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Abstract

This research paper is an investigation to produce 3d printed parts that contain minimal resistance circuitry. This would allow for 3 dimensional circuits which could enhance product electronics instead of flat PCBs. this project tries to achieve this by electroplating conductive filament. Connection tracks are 3D printed from conductive filament on a fused deposition modelling (FDM) printer, this is then electroplated to make the connection tracks have minimal resistant. Conductive filaments have problems with impedance from the PLA insulating the copper inside the filament, causing breaks in the connection. Electroplating tries to overcome these breaks in connection. The experiment of this project takes 50mm by 20mm by 5mm test samples and electroplates them to make a quality connection. A quality connection is categorized by a low resistance, a good part coverage and a good chemical bond. A test sample was printed, and the resistance was measured to 4400Ω, this test sample was then electroplated, and the resistance dropped to 2Ω. A reliability study was undertaken on the best preforming test sample, repeating the test sample 5 times, and proving a reliable result. A case study outlined the reasons that minimal resistance is important in electronics and how electroplating conductive filament produces working circuitry. Electroplating overcame the breaks in connections that were in the conductive filament. Electroplating conductive filament can be used to produce 3D printed electronics.

Keywords: Electroplating, 3D Printing, 3D Printing Electronics.

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1 Introduction

This project aims to further the advancement of 3D printing electronics (Tan *et al.*, 2022) (JIM ROMEO, 2021) (Valentine *et al.*, 2017) (Espalin *et al.*, 2014) and has the potential to advance industries such as wearable electronics, embedded electronics, 3D printed bioelectronics (Tan *et al.*, 2022) (Valentine *et al.*, 2017) and space exploration (Espalin *et al.*, 2014). There are many methods to achieve 3D printed electronics including conductive filaments (Kwok *et al.*, 2017a), pick and place of components during printing (Espera *et al.*, 2019a) and conductive inks in material jetting printers (Roshanghias, Krivec and Baumgart, 2017) Each method has advantages and disadvantages, with the main problems being a reliable connection, software support and expense (Kwok *et al.*, 2017) (Espera *et al.*, 2019) (Roshanghias, Krivec and Baumgart, 2017).

Figure 1 - Structure of conductive channels

Using a FDM dual material printer to print conductive channels that are electroplated to produce minimal resistance connections. A potential design for conductive channels is shown in Fig.1 with the blue areas being non-conductive plastic and the green being conductive scaffolding for the electroplated connection. Electroplating could overcome the issue conductive filaments have with a potential break in the connection. Each layer of newly deposited metal, in time, could bridge the gap to regain connection (Fig.2).

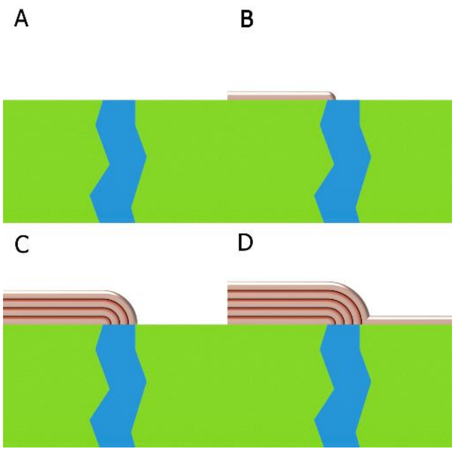

Figure 2 - Layers of deposited metal bridging a connection break (blue) through time during the electroplating process

1.1 Aims and Objectives

This project aims to produce minimal resistance connections inside of a fused deposition modelling (FDM) printed part. To achieve minimal resistance, the connections must have a resistance lower than 50Ω over a 100mm sample. The best performing samples will be repeated 5 times to check for reliable connections. The objective of this project is to produce parts with minimal resistance connections by changing the following variables:

- Electroplating voltage (V)
- Electroplating temperature (ºC)
- Electroplating tank agitation (rev/min)
- Electroplating distance between the anode and cathode (mm)
- Printer line width (mm)
- Printer layer height (mm)

Coverage of the metal plate is an important measurable when it comes to making reliable electrical connections. The exact coverage is hard to measure, it can however be estimated and rated into a banding system (Table 1). For this project to be successful, coverage must reach a rating of 5.

Table 1 - Percentage banding for coverage

Rating	1	2	3	4	5
Percentage band (%)	0%-20%	20%-40%	40%-60%	60%-80%	80%-100%

The strength of the chemical bond can also be rated out of 5. This is an indication to how well the metal has bonded to the plastic and is a good reference to the quality of the electroplate. A poor chemical bond can be for several reasons, including a poor plating surface (grease and oils on surface before plating) and surface burning (the voltage or current is too high, causing the plate to burn and flake off).

Connection breaks refers to the amount of electrically dead zones that do not connect to the rest of the plate. Connection breaks can be found by running a multi-meter across the plated part, an electrically dead zone is where the resistance becomes too high to measure. The plate is given a rating out of 5 based on the area taken up by these dead zones.

1.2 Structure of the Report

Chapter one introduces 3D printing electronics and electroplating and the theory behind electroplating, it also conveys the aims and objectives of this project. Chapter two is a literature review of the background around 3D printing electronics. Chapter three covers the method undertaken in this project, including the design of the experiment and manufacturer of experiment equipment, how the experiment was performed and a case study of a printed circuit. Chapter six discusses the results of this project. Chapter 7 concludes the project and compares the project to the project aims.

2 Literature Review

2.1 Theoretical Background

3D printers were once mainly used for rapid prototyping, companies are now looking into additive manufacturing to produce their company's final product (Baş, Elevli and Yapıcı, 2019), with some of the biggest manufacturing companies, "Mercedez Benz, BMW, IKEA, Ford" (Bayraktar, 2022) sharing their experiences, productions and saving when using 3D printing. Additive manufacturing had a market value of 13.7 billion in 2020 and is expected to reach 63.46 billion in 2026 (Mordor Intelligence, 2022). "By 2025, the medical, aerospace, and automotive industries are expected to contribute up to 51% of the total 3D printing market." (Joseph Flynt, 2019).

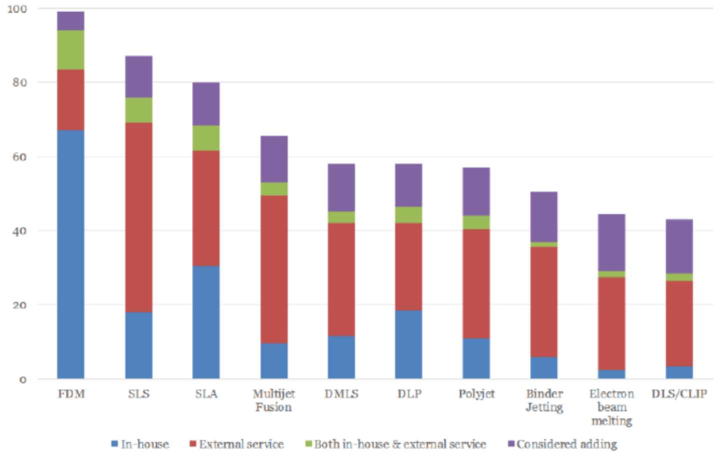

Figure 3 - Most used 3D printing technologies *(Statista, 2021)*

A survey was taken by Statista of the types of 3D printers that companies used (Fig.3), FDM was the most common type, with companies choosing to print in-house (Statista, 2021). This project will target towards FDM printers, although the same technic could be used on any type of 3D printer with the capacity to produce multi-material parts. Statista also researched into the most popular additive manufacturing material (Fig.4), Polylactic acid (PLA) is a third of all materials used on a 3D printer (Statista, 2020). This project will use PLA as a base material, but other base polymers could be used in future projects.

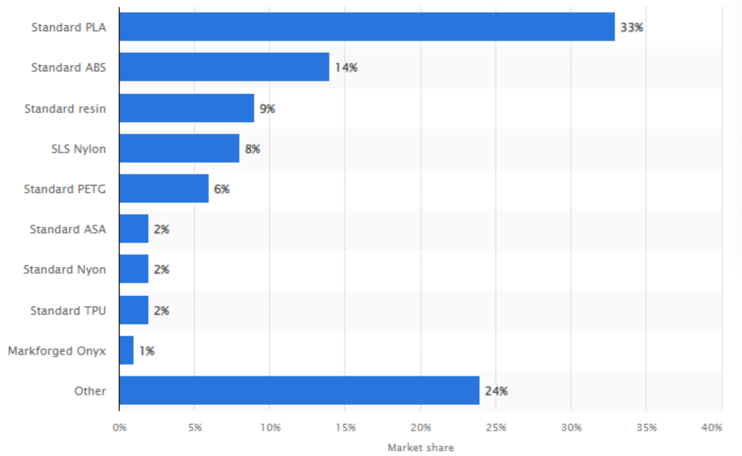

Figure 4 - Market share of materials in 3D printing *(Statista, 2020)*

It's widely considered that 3D printing electronics is the next advancement in additive manufacturing (Espera *et al.*, 2019b) (Lu, Lan and Liu, 2018) (Tan *et al.*, 2019).Electronic products had a market value of 1,191.2 billion in 2020 and expected to increase to 1,653.2 billion by 2025 (The Business Research Company, 2021). "3D-printing has a great potential to transform the electronics fabrication industry into a more adaptive and smart manufacturing practice" (Espera *et al.*, 2019).

The future trend of 3D printing electronics (Roach *et al.,* 2020) (Tan *et al.,* 2022) has benefits over the more traditional electronics manufacturing method, "such as simplified fabrication processes, increased design freedom, novel form factors, reduced weight, and lower prototyping and fabrication costs" (Tan *et al.,* 2022). Additive manufacturing electronics "aims to reduce wastage, time bottlenecks, costs, and increase efficiencies as compared to the conventional ways of fabricating electronics" (Tan *et al.,* 2019). 3D printed electronics can reduce the total time to produce a functional part, either a prototype or the final product, although 3D electronics doesn't have the same support from software's (Macdonald *et al.,* 2014). So far, all 3D printed electronics have been produced using more mechanical computer added design (CAD) packages (Macdonald *et al.,* 2014) (Tan *et al.,* 2022) (Liu *et al.,* 2018) for the electronic companies to adopt additive manufacturing specialist software would need to be produced. (Macdonald *et al.,* 2014) (Srinivasan and Muthuramalingam, 2021)

Research is being done into 3D printing electronics for wearable electronics, with success of printing with piezoelectric polymers to produce tactile sensors (Liu *et al.,* 2018). Space exploration is also an industry making strides into 3D printed electronics, their interest being to reduce volume taken by traditional printed circuit boards (PCB) electronics. NASA's Johnson Space Center 3D printed a signal conditioning circuit (Fig.5) with a 27% reduction in volume when compared to their original design (Macdonald *et al.,* 2014). "Comprehensive creation of non-conventional electronics such as flexible sensors, touch displays, smart labels, solar cells, digital posters, wearable devices, etc. are areas of development by Printed Electronics" (Srinivasan and Muthuramalingam, 2021)

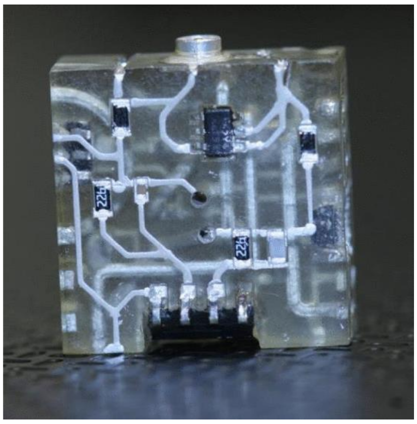

Figure 5 - 3D printed signal conditioning circuit

Research has been done to achieve 3D print electronics, with multiple methods to achieve this goal. One method is to use conductive inks and ink jet printers to print conductive tracks (Roshanghias, Krivec and Baumgart, 2017) (Fernandes *et al.,* 2020) Cost of ink jet printers and the conductive inks is the main drawback to companies adopting this method of printing electronics (Roshanghias, Krivec and Baumgart, 2017). Impedance is a limitation of conductive inkjet printers and restricts the printed circuit too small, low voltage applications (Fernandes *et al.,* 2020).

Computer numerical control (CNC) pick and placing of components into a 3D print, while printing, is another method to produce 3D printed electronics (Espera *et al.,* 2019). Although there is initial set up costs of the CNC pickers, the method to pick and place components is relatively inexpensive to produce printed electronics when compared to inkjet printing (Ahlers *et al.,* 2021) (Roshanghias, Krivec and Baumgart, 2017). There is little software support for integrating pick and place robots into 3D printing, and so far, 3D printing electronics using this method have been done manually (Ahlers *et al.,* 2021) (Espera *et al.,* 2019).

Printing with conductive filaments is a method to produce 3D printed electronics (Kwok *et al.,* 2017). Conductive filaments do not need specialised machines or expensive materials and therefore are inexpensive to produce electronics when compared to other methods. (MSNJ, 2022) (Kwok *et al.,* 2017). Conductive filaments are produced by adding a conductive filler, such as copper or graphene into the hopper of a screwed extruder (Kwok *et al.,* 2017b). Particles of the conductive filler align to make an electrical connection (Kwok *et al.,* 2017) (Rocha *et al.,* 2021). Conductive filaments have relatively high impedance, this is due to the base polymer insulating the conductive particles (Rocha *et al.,* 2021). Copper conductive filaments have a resistivity of $1.0\text{x}10^{-3}$ $\Omega\cdot$m (MSNJ, 2022) when compared to copper of $1.7\text{x}10^{-8}$ $\Omega\cdot$m (Anne Marie Helmenstine, 2019), this restricts the printed circuit to low voltage, low current, and low complexity (Kwok *et al.,* 2017) (Rocha *et al.,* 2021).

Minimal resistance wires are needed to produce complex circuits, this is due to losses in power across the length of the wire. Losses in voltage can be calculated from the resistivity of the conductive filament, using arbitrary values for current, length and radius, of 1Amp, 50mm and 1.5mm respectively. Using Equation 1 and a resistivity of $1.0\text{x}10^{-3}$ Ω·m for the conductive filament (MSNJ, 2022), the voltage drop across a 50mm length can be calculated to 7.073V. Using the same values for the current, length and radius, for a minimal resistance material (copper) having a resistivity of $1.7\text{x}10^{-8}$ Ω·m (Anne Marie Helmenstine, 2019), the voltage drop can be calculated to 0.000120V.

Equation 1 - Voltage losses over a conductor *(StackExchange, 2014) (Tesla Scientific, 2022)*

$$V = I \cdot \frac{\rho \cdot L}{\pi r^2}$$

V = Voltage losses (V)
I = Current across wire (Amps)
ρ = The resistivity of the conductor (Ω·m)
L = Length of wire (m)
r = Radius of wire (m)

Having wires that don't have minimal resistance is also problematic when using basic sensors that work by a change in resistance in the component, such as potentiometers (POT) (Ravi Teja, 2021). POTs are mainly used in a voltage divider circuit (Ravi Teja, 2021), by using non minimal resistance wires its equivalent to adding resistors to each side, this would decrease the sensitivity of the senor as it can only affect a small portion of the overall resistance in the circuit. A decrease in sensitivity would be for all sensors that use resistance to measure something.

This project tries to produce minimal resistance connections by electroplating conductive filament. Fig.6 shows a typical electroplating set up, a power supply forces a cathode to gain a negative charge, this attracts positive metal ions from the electrolyte, which leaves negative ions, the circuit is completed when the negative ions rip positive metal ions from the sacrificed metal, the anode (Electroplating.net, 2010) (Rachel Keatley, 2020).

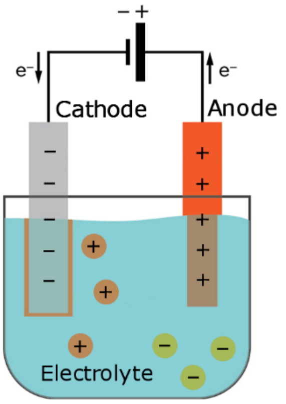

Figure 6 - Electroplating process

Research was done into resistivities of metals (Table 2), although silver has a high resistivity value (Terence Bell, 2020), copper is chosen for this project as both the conductive filler inside the conductive filament and the plating metal. Copper is chosen over silver because is more affordable, more readily available (Megan Rows, 2022), and easier to electroplate (Vaněčková *et al.*, 2020).

Table 2 - Resistivities of metals

Material	Resistivity (Ω • m)
Silver	1.59×10^{-8}
Copper	1.68×10^{-8}
Gold	2.44×10^{-8}
Aluminium	2.82×10^{-8}
Zinc	5.95×10^{-8}
Iron	9.58×10^{-8}

2.2 Related Research

The first study done in selectively electroplating, dual material 3D prints was done in 2018 (Angel *et al.*, 2018), this study did not focus on producing electronics but instead looked to achieve parts with multiple materials, for instance "a magnetic metal such as nickel and a highly conductive one such as copper" (Angel *et al.*, 2018). The experiment of (Angel *et al.*, 2018)had a custom-made clamping system, so that copper foil could have a good contact with the conductive filament (Fig.7).

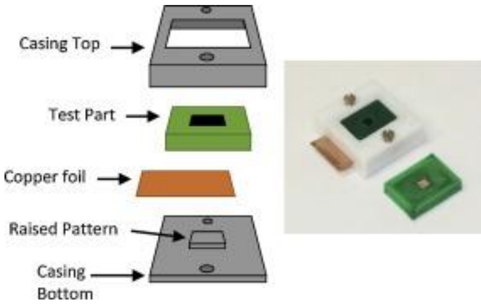

Figure 7 - Clamping system from (Angel et al., *2018)*

(Angel *et al.*, 2018) does not share all the variables on which it used in their experiment, variables that are shared are a current of 1Amp, the concentration of copper sulphate and the type of conductive filament used (Electrifi). Results can be seen in Fig.8 where different geometries were electroplated, looking at plating in stages for different sections, and even melting the plastic to see the metal plates that remain.

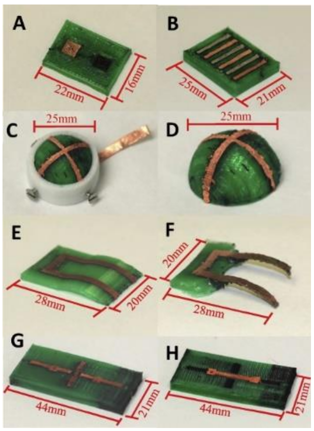

Figure 8 - Results of (Angel et al., *2018)*

In 2019, more research was done to achieve the goal of 3D printing electronics (Lazarus *et al.*, 2019). The aim of this research was to produce a 555 timer oscillator circuit, which is "based on an resistor-capacitor exponential decay to switch between two threshold voltages" (Lazarus *et al.*, 2019), this means circuit resistance is important to get the correct timing decay. This experiment shares the variables used to print and electroplate the timing circuit, with an importance on the electroplating electrolyte temperature of 34ºC. Fig.9 shows the process of the experiment untaken in (Lazarus *et al.*, 2019).

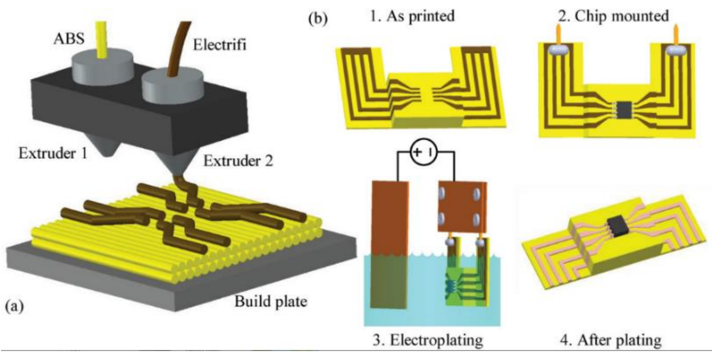

Figure 9 - Process undertaken in (Lazarus et al., *2019)*

(Lazarus *et al.*, 2019) used the addition of additives "Cl−–PEG (polyethylene glycol)–MPSA (sodium 3-mercapto-1-propanesulfonate)–JGB (Janus Green B)" to improve plating. Lazarus et al., only noted a change in shininess when using additives, which had no effect on the resistance across the circuit, Fig.10 shows the experiment results with (Fig.10.b) and without (Fig.10.a) additives.

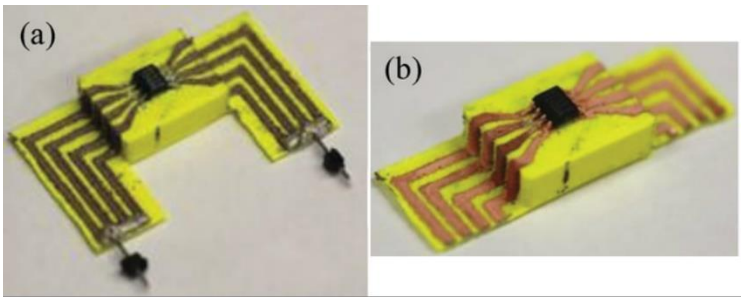

Figure 10 - Results of (Lazarus et al., 2019) (a) without additives, (b) with additives

Both pieces of research had success with 3D printing electronics, this is believed to be because both experiments use Multi3D Electrifi Conductive Filament (Multi3D, 2022) which has a resistivity of 6 x 10^{-6} and is best on the market (Multi3D, 2022). Electrifi cost $2150.00 per kilogram, if 3D printing is to be adopted by manufacturing companies to produce electronics, the price would have to be reduced or a different filament is chosen with a higher resistivity. Lazarus et al., measured a resistance of 23.8Ω across a 20mm by 20mm printed plated, a similar size plate was printed from MSNJ's conductive filament (MSNJ, 2022) and a resistance was measured to be 1900Ω, MSNJ's conductive filament costs £69.99 per kilogram (Multi3D, 2022). MSNJ's conductive filament will be used for this project as it is more affordable and more inline with the filament companies would use if 3D printing electronics was adopted.

3 Method and Theory

3.1 Experiment Set-up

Before designing the experiment, research and testing was completed, this discovered both the variables that will have the biggest effects on the plated connection, and the typical ranges of variables that could be expected. Researched (Saleh *et al.*, 2004) showed that the voltage, current, solution agitation, solution temperature and the distance between the anode and cathode had the greatest effect on electroplating (Table 3). Research (Jaksic and Desai, 2019) also showed that layer height, line width and printing temperature had the greatest effects on the connections made inside the print (Table 3).

Table 3 - Variable ranges

Variables		Range	
		Lower	High
Electroplating	Voltage	6V	24V
	Current	0.8A	1.5A
	Solution Agitation	off	on
	Solution Temperature	22 ºC	34 ºC
	Electrode Distance	Na	
3D Printing	Line Width	0.3mm	0.5mm
	Layer Height	0.12mm	0.24mm
	Print Temp	200 ºC	230 ºC

Testing was completed on the electroplating variables to discover the expected range, this was untaken in the set-up shown in Fig.11. Table 3 shows the ranges can be expected in the electroplating process. Additives were also highlighted in the research of having a big effect on the quality, finish, and coverage of the plated connection (Miura and Honma, 2003). Due to time constraints testing a range of additives would be outside the scope of this project.

Figure 12 - The set-up to discover the expected ranges

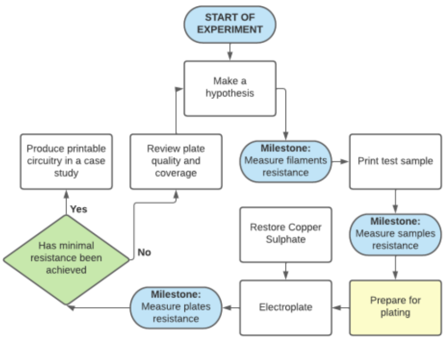

Figure 11 - Flowchart of experiment process

This project had a flexible experiment process as different hypothesis were made to achieve the main objective of producing printable circuitry. Hypothesises were made based on previous knowledge collected from either past samples or research. The experiment mainly followed the process seen in Fig.12, samples of 50mm in length (Appendix A) were chosen to speed up testing and printing times whilst being easy to convert to the 100mm standard. Samples were printed on a Ender 3 from conductive filament produced by MSNJ with a resistivity of $1.0\text{x}10^{-3}$ Ω·m (MSNJ, 2022) when compared to copper of $1.7\text{x}10^{-8}$ Ω·m (Anne Marie Helmenstine, 2019). Gloves were used when handling samples, this was to minimise adding oils to the plating surface. The test samples were then prepared to be plated this could involve being cleaned or sanded. The printed test samples were immediately added to a custom-built electroplating tank (Fig.13), this reduced human contact. The initial custom-built tank design (Appendix B) had to be changed, so the variables could be controlled more reliably. The electroplating tanks were designed to accommodate variable ranges discovered in preliminary testing. Once the test samples had been plated, resistance, coverage, connection brecks and chemical bonds were recorded.

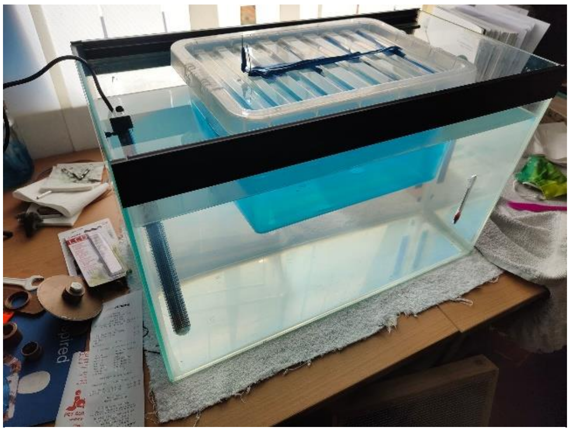

Figure 13 - Custom-built electroplating tank

3.2 *Method Break Down*

- **Make a hypothesis**
  Estimate the variables based on previous knowledge gained (Literature or past tests).

- **Measure filaments resistance**
  The resistance of the filament is measured to track resistance changes throughout the process.

- **Print test sample**
  A test sample is printed (Appendix A), the print surface is cleaned before printing and gloves are used when handling the print to reduce contact oils.

- **Measure samples resistance**
  The resistance of the printed test sample is measured to track resistance changes throughout the process. A multimeter is used to measure the resistance from corner to corner along the 50mm edge, the best edge is then recorded.

- **Prepare for plating**
  In Fig.12 this task is indicated in yellow as it's an optional task. This task depends on the latest hypothesis, examples being a sample cleaning task or sanding the test sample to achieve a smoother surface.

- **Restore Copper Sulphate**
  Fresh copper sulphate is added until the solution is saturated this gives the best possible chance for a successful electroplate.

- **Electroplate**
  The test samples are then placed into the tank and electroplated until there's no visual changes (the plated layer can get thicker, but no new area is being plated). How the test sample is positioned in the tank depends on the latest hypothesis, for example periodically rotated, continually rotated or stationary.

- **Measure plates resistance**
  The resistance of the plated test sample is measured to track resistance changes throughout the process. A multimeter is used to measure the resistance from corner to corner along the 50mm edge, the best edge is then recorded. Whilst one probe of the multimeter is placed on the corner of the test sample the other is moved across the piece to find electrically dead zones.

- **Has minimal resistance been achieved?**
  Has the recorded resistance for the plated test sample achieved minimal resistance, a resistance less than 50Ω?

- **Review plate quality and coverage**
  The plate quality of the test sample is reviewed, and the coverage of copper connection is compared.

- **Refining the variables**
  Tasks are repeated for different variables such as Voltage, Current and Solution agitation.

3.3 *Experiment*

The variables for the first test sample can be found in Table 4, these variables are estimated from literature research and preliminary testing.

Table 4 - The variables of the experiment

Test Number	Printing			Preparation	Electroplating					
	Line width	Layer height	Print Temp		Voltage	Current	EP Temp	Part Rotation	Electro distance	Time (mins)
T1	0.4	0.2	215	None	12	1	34	None	18.5	10
T2	0.4	0.2	215	None	18	1	34	None	10.5	60
T3	0.4	0.2	215	None	24	1	34	Rotation	10.5	20
T4	0.4	0.2	215	None	24	1	34	None	10.5	60
T5	0.4	0.2	215	None	24	1	34	None	10.5	60
T6	0.4	0.2	215	None	24	1	34	Rotation	6.5	60
T7	0.4	0.2	215	None	6	1	34	Periodically	6.5	180
T8	0.3	0.16	215	Sanding	24	1	34	Rotation	6.5	60
T9	0.4	0.2	215	None	24	3	34	Rotation	6.5	60
T10	0.4	0.2	215	None	12	3	34	Rotation	6.5	300

It was initially thought that the further away the anode and cathode were, the more even the final plate would be. T1 proved this not to be the case (Fig.14) and T2 tried to get more power to the cathode by increasing the voltage and the distance between the electrodes. Fig.15 shows that power was increased to the test sample, and this influenced the chemical bond of the plate but did not improve the coverage.

Figure 14 - T1 test sample

Figure 15 - T2 test sample

Rotating sample T3 tried to improve the coverage of the plate. Although coverage was improved (Fig.16) it was noticed that the most plating happened to the test sample in areas that were closest to the surface of the solution, however this area was also the area furthest from the metal contact. There were two theories that could explain T3s coverage, firstly it could be because electricity favours the path of least resistance, and when close to the metal contact it passes through the metal instead of the test sample. Secondly T3s coverage could be due to a higher concentration of copper sulphate at the top of the solution.

Figure 16 - T3 test sample

Figure 17 - T4 test sample

T4 tried to address the first theory about T3s coverage, this was achieved by making a plate that had contact points that were away from the plate (Fig.17). T4 however was a step backwards as there was very little plating, this was thought to be because the resistance was too high to get the necessary power to the measurable plate. The second theory of T3s coverage was reinforced by T4 as the only plating happened on the sides of the connectors, just below the solution surface.

T5 (Fig.18) was plated close to the surface to support T3s coverage theory. T5 plated with the same coverage as T3 but achieved a better chemical bond, however this time the area that plated most was the area closest to the anode.

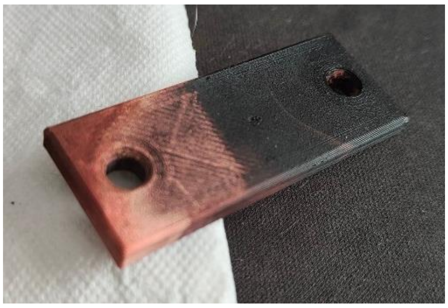

Figure 18 - T5 test sample

Figure 19 - T6 test sample

T6 (Fig.19) was plated closer to the anode and was rotated at the centre of the test sample, whilst also staying close to solution surface. Bubbles were noticed stuck on the underside of the test sample which were stopping the copper sulphate from plating those areas, these bubbles were being produced from the metal contacts.

T7 (Fig.20) tried to slow down the plating speed on the metal and periodically rotate and release the trapped bubbles. Bubbles didn’t build up, but coverage was decreased.

Figure 20 - T7 test sample

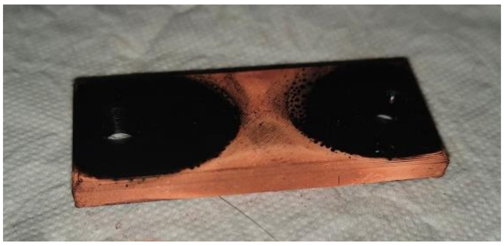

Figure 21 - T8 test sample

T8 (Fig.21) tested the effects of surface finish. Line width and layer height were decreased to improve the surface finish of the test sample. The test sample was sanded before plating to further increase the finish.

When T6 and T8 were being plated arcing was occurring between the rotor and spring connector, this was not the case for T7. Preliminary testing showed that electroplating stopped at 1.5 Amps, research on arcing showed that the current was spiking above this when arcing was present. T9 (Fig.22) raised the current to 3 Amps, above the preliminary testing range.

Figure 22 - T9 test sample

Figure 23 - T10 test sample

T9 still had rings of non-plated area around the metal contact points. T10 (Fig.23) reduced the voltage whilst keeping the high current to slow down the process to try and cover these areas.

Coverage of the copper plating seemed to be a main struggle of this experiment. Although out of scope of this project, it was decided to introduce an inhibitor additive to the copper sulphate, in hopes to give the plate more coverage. Inhibitors work by disturbing the direct flow of current to the anode and allowing the plating object to plate more evenly (Lai *et al.*, 2018). Polyoxyethylene glycol was added to variables used in T9, Fig.24 shows the outcome.

Figure 24 - T9 with additives test sample

3.4 *Case Study*

A circuit was produced using the variables from the T9 test sample. A 12V power supply was connected by 2 70mm 3D printed tracks, with a cross section of 5mm by 5mm, to a 9V-12V strip light.

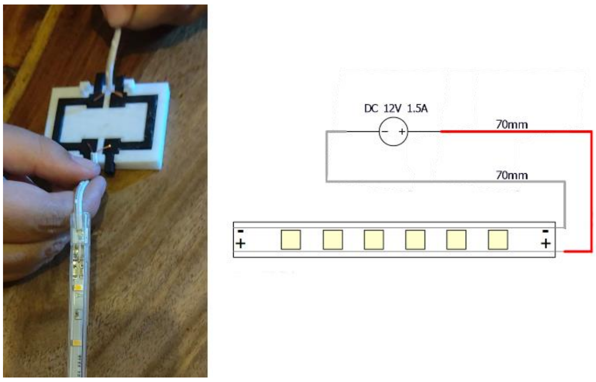

Figure 25 - Case study circuit

Fig.25 shows the case study circuit before the connections have been electroplated. When the strip lights were connected by only the conductive filament, the lights did not turn. Using a multimeter a voltage of 0.04V was measured across the strip lights (Fig.26), which is not inside its functional range (9V-12V). 11.96V were taken by the resistance of the 70mm connections.

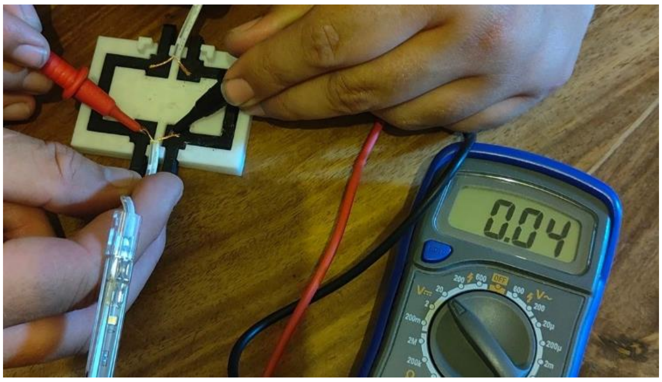

Figure 26 - Voltage drop across the strip lights

4 Results

4.1 Results of Experiment

Over the course of the experiment there is a struggle to get the necessary power form the anode to the cathode. T1's defining variable is the distance between the electrodes, with this and a relatively low current and voltage, T1 had a thin copper layer that had little coverage (Table 5). Even though the little plating, resistance still decreased between milestones. It was believed that between the probes of the multimeter a connection was being made across the copper plate and the conductive filament, reducing the resistance across the test samples edge.

Table 5 - Results of experiment

Test Number	Resistances (5cm)			Chemical bond	Coverage	Connection breaks	Success
	Filament	After Print	After Plate				
T1	7300	4700	1500	2	2	1	Bad
T2	7200	3400	10600	4	1	1	Bad
T3	7400	5100	1300	3	3	2	Okay
T4	7300	3500	3400	2	1	2	Bad
T5	7400	4600	4200	4	3	2	Okay
T6	7200	5300	10	5	4	3	Good
T7	7300	4600	3100	5	2	1	Okay
T8	7400	4000	40	5	4	3	Good
T9	7500	4400	2	5	5	4	Very Good
T10	7300	3800	20	4	5	4	Good

T2 increased the power getting to the cathode when compared to T1, this increased the chemical bond of the plate, but the plating area became more localised, with similar amount of electrically dead areas. T2 was the only test sample that had a resistance increase from after printing to after plating. The resistance increase was believed to be due to electrical dead zones that isolated the sides of the test sample.

T3 was the first test sample to rotate the part to increase coverage. Coverage was increased and was thickest in areas closer to the surface of the copper sulphate, this was also the area furthest from the metal contacts. Resistance decreased when compared to T1, but it was negligible towards the goal of minimal resistance.

T4 had contacts above the copper sulphates surface, so that current would not flow through the metal before the test sample. T4 had little plating on the measurable plating area but instead had plating on the connection handles (Fig.27). T4 reinforced the belief that plating happens more readily towards the surface of the solution, it was believed that this was due to a higher concentration of copper sulphate toward the surface as the copper surface dropped out of solution with the acetic acid (vinegar). Little plating took place on the measurable plate of the test sample, and this led to negligible reduction in resistance.

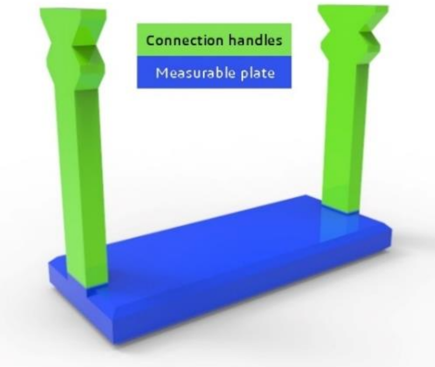

Figure 27 - T4 area breakdown

T5 had little visual differences to T3. The resistance was the biggest difference, T5 had negligible change in resistance from after printing to after plating.

The power reaching the cathode was increased in T6 by reducing the distance between the electrodes. The power increase was enough to plate over half of the test sample, this led to a copper plated connection path that span the length of T6. T6 was the first test sample that had an electroplated path, and this was evident in the resistance of 10Ω compared to the previous best T3 with 1300Ω

The power received by the cathode was lowered for T7 and left for a longer period of time, in hopes to give better coverage over the test sample. In practice lowering the voltage drastically reduced the coverage of the copper plate. Without the necessary coverage a plated copper connection is not achievable.

T8 improved the surface finish of the print before plating, including sanding to get the best possible finish. This had negligible effect on the finished plate when compared to T6, with both 10Ω (T6) and 40Ω (T8) inside specification of this project.

With coverage of the plate a main struggle of this project, T9 increases the current. The current is raised to 3 Amps, giving more power to the cathode, and increasing the coverage to more than 80%. 2 ohms was measured from corner to corner meaning there was a pure copper connection plated onto the 3D printed part. Rings were left around the metal connections, which backs a previous theory, that when close to the metal connections the current is drawn to the path of least resistance and not through the test sample.

For T10 the voltage was drop and the test sample left for a longer period in hopes to plate the rings left in T9. T10 did not plate these areas, and had a worse chemical bond, as when the plate left the electroplating tank, the top layer flaked away. Results in Table 5 were taken on the remaining bonded plate.

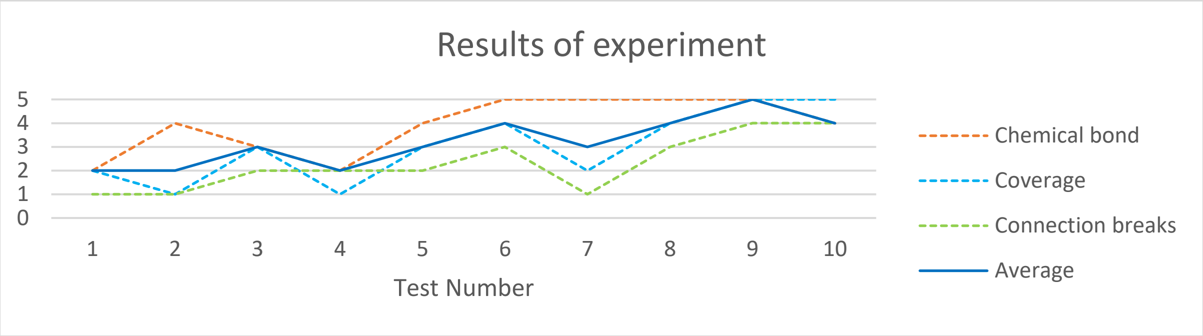

Figure 28 - Graphical results of experiment

Fig.28 shows that T9 was the best preforming test sample. It was decided to repeat T9 variables with the introduction of an inhibitor (Polyoxyethylene glycol), this was to try and improve coverage. The inhibitor reduced the power reaching the cathode and therefore the quality of the plate was reduced, Table 6 shows the results of this test. There was low coverage, and by chance one edge of the test sample had been completely electroplated, hence the relatively low resistance when compared to other test samples with similar coverage.

Table 6 - Results of experiment with added additives

Resistances (5cm)			Chemical bond	Coverage	Connection breaks	Success
Filament	After Print	After Plate				
7400	4100	110	5	2	3	Okay

4.2 *Results of Case Study*

A case study was completed to show the benefits of electroplating the conductive filament tracks to produce minimal resistance circuitry.

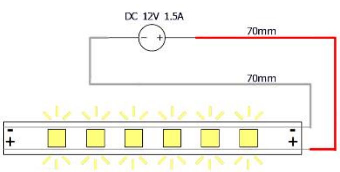

Figure 29 - Case study once tracks have been electroplated

Fig.29 show the working circuit once the 70mm tracks had been plated. A multimeter measured 11.86V across the strip lights (Fig.30), which is inside their functional range of 9V-12V, hence the lights turned on. The plated copper allowed more voltage to reach the strip lights, compared to the 0.04V with just the conductive filament carrying the current.

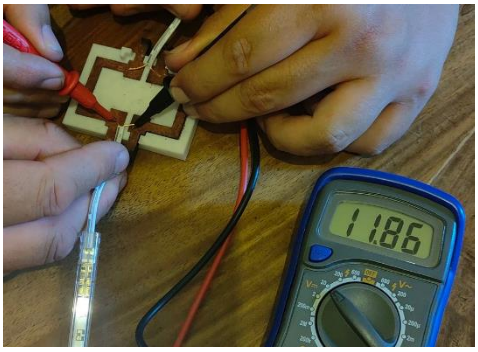

Figure 30 - Voltage drop across the strip lights after electroplating

4.3 Reliability of the Results

To validate the results a repeatability study was undertaken, by repeating the best preforming test sample 5 times, spread over the course of a week and ran at different times to ensure the environment as not involved in the results. T9 was the best preforming test sample and was therefore chosen in the repeatability study (Table 7).

Table 7 - Reliability of the results

Test Number	Resistances (5cm)			Chemical bond	Coverage	Connection breaks	Success
	Filament	After print	After plate				
T9.1	7200	4400	2	5	5	4	Very Good
T9.2	7500	5400	50	5	3	5	Good
T9.3	7300	4900	10	5	4	4	Good
T9.4	7300	5200	30	5	4	4	Good
T9.5	7400	3700	0.3	5	5	5	Very Good
Average	7340	4720	18.46	5	4.2	4.4	Very Good
SD	101.9804	611.2283	18.97489	0	0.748331	0.489898	

All 5 test samples had a final resistance less than or equal to 50Ω, as specified in the aims of this project. Out of these 5 repeated tests, T9.2 was the worst preforming test sample (Fig.31) as it was only able to cover between 40-60% of the test sample. The drop in coverage is believed to be from a raise in environment temperature over 34 degree and therefore raising the temperature of the electrolyte, above the temperature set by the tank heater. T9.5 was the first test sample to achieve the top band rating in chemical bond, coverage and connection breaks, it was also the first test sample to have a resistance lower than 1Ω.

Figure 31 - Reliability of the results

Fig.32 shows how repeatable this experiment is, with most of the data points between 4 and 5 and only the coverage of T9.2 being outside this range. The standard deviations for this repeatable study also support that the experiment undertaken as part of this project is reliable, with the standard deviation for the final resistance, chemical bond, coverage and connection breaks being 19, 0, 0.75 and 0.49 respectively.

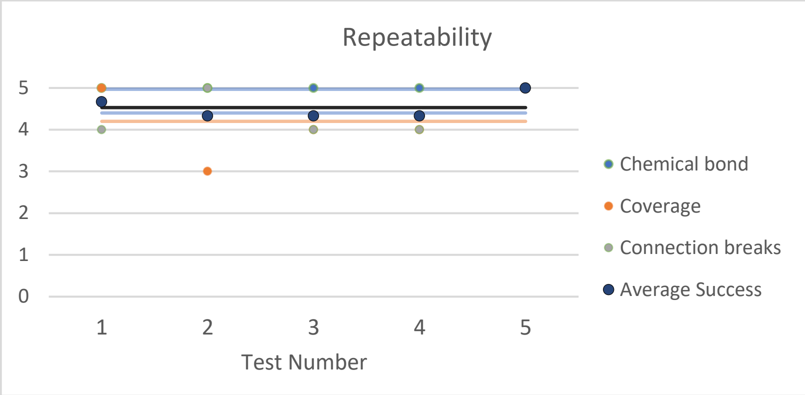

Figure 32 - Graphical reliability of the results

5 Discussion

Samples T6, T8, T9 and T10 all plated to have a resistance lower than 50Ω, which is lower than the resistance set out to achieve in the aims of this project. While 4 test samples achieved minimal resistance, only T9 and T10 had a coverage more than 80% to achieve the objective of this project. Both T9 and T10 are a success for the aims and objectives of this project, but T9 had a plate with a better chemical bond than T10, meaning T9 was a success for this project. T9 was repeated 5 times to prove reliability with all test samples having a resistance lower than 50Ω.

The results of this project show that it is possible to use electroplating to convert 3D printed conductive filament to minimal resistance circuits. Fig 33 shows the correlation between coverage and connection breaks, proving that electroplating the conductive filament can overcome breaks in connection. Excluding T8 all printer setting were the same and therefore would have started with theoretically the same amount of electrically dead area. The results of this experiment show that as the plated area increased, the amount of electrically dead areas decreased. If electroplating was not bridging the gap across connection breaks, each test sample would have had the same amount of electrically dead area, Fig 33 shows this is not the case.

Test Number	Coverage	Connection breaks
1	2	1
2	1	1
3	3	2
4	1	2
5	3	2
6	4	3
7	2	1
8	4	3
9	5	4
10	5	4

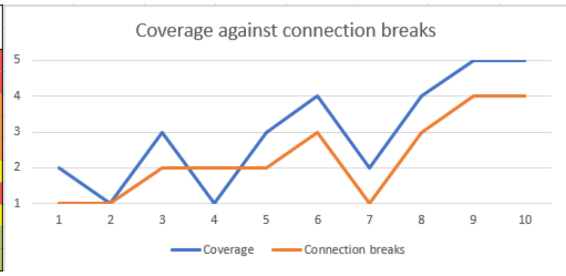

Figure 33 - Coverage against connection breaks

Both Angel et al., (2018) and Lazarus et al., (2019) has similar success to this project. This project uses a cheaper conductive filament with a higher resistivity showing that electroplating conductive filament works for even affordable filaments. Future research could be done to find this highest resistivity, because as resistivity increases the cost of filament decreases. As part of this project a case study was undertaken, Angel et al., (2018) and Lazarus et al., (2019) also had circuits that proved a drop in resistance for the plated parts, like the results of this project. The variables used to produce minimal resistance were not shared in Angel et al., (2018) or Lazarus et al., (2019) as a great emphasis was placed on discovering the process.

Electroplating internal features were a limitation of this project, as the amount of agitation needed to affect these features was greater than the possible agitation in the current configuration of the electroplating tank. The electroplating tank in appendix B tried to have a greater solution agitation, but this compromised the stability of other variables such as electrolyte temperature. Future research could be done to plate internal features using a better specification of electroplating tank.

Electrolyte additives were not inside the scope of this project, this was due to the number of different additives on the market against the time constrains of this project. Although not using additives was a limitation of this project, this experiment proved that plating was possible without the use of additives. Future research could eb done to find the effects of additives on the electroplating quality.

6 Conclusion

This project proves it is possible to reliably print electronics using electroplated conductive filament to make minimal resistance connections. Conductive filaments have a problem to make connections without high resistance, but they have enough conductivity to allow the connections to be electroplated. This experiment uses a cheaper filament which has a higher resistivity when compared to past experiments (Lazarus *et al.*, 2019) (Angel *et al.*, 2018). This project was classed as a success as the main aims were met, a connection with less than 50Ω over a 50mm length, and 80% of a 50mm by 20mm by 5mm (Appendix B) test sample covered by a coper plating. The best test sample had a resistance of 4440Ω with just conductive filament, once electroplated the resistance was reduced to 2Ω, creating a minimal resistance connection. A reliability study was done on this test sample, with final resistances having a standard deviation of 19Ω around an average 18.5Ω.

Many things were learnt on this project, one being the importance of a controlled environment for reliable results. Electroplating is exothermic, meaning it produces heat, and chemical reaction inside electroplating is more reactive with a higher temperature. It was difficult to control the temperature inside the electrolyte especially when room temperatures fluctuate between 10^{o}C and 40^{o}C. An industrial electroplating tank would resolve this for future projects. Chemical safety was a learning curve of this project, with the use of coper sulphate and acetic acid having to think about transportation, safety while using, storing when not in use and disposal after the project. Making sure PPE was worn when handling chemicals or items they came into contact with. Although the general process of electroplating was known before the start of the project, the deeper chemistry was learnt whist designing the experiment for this research. The electroplating tank was designed without knowing the process in detail, if it was known the tank would have been designed to allow for multiple anodes to improve the plate and reduce the need for electrolyte agitation.

The project was a success and could lead to new types of research in the future, including plating internal features, the effects of additives and the highest resistivity in conductive filament to still electroplate.

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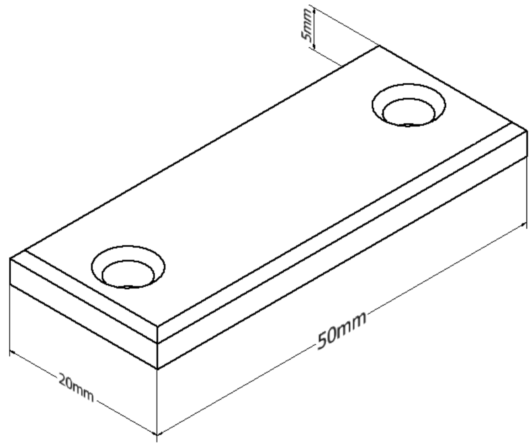
Appendices

Appendix A



Appendix C