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Technical Report 01/04

Rapid Prototyped Electronic Circuits

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1 PROJECT SUMMARY

The purpose of this project was to establish a technology which would enable a machine to self-replicate. The key to this technology was the ability to manufacture electro-mechanical parts (*i.e.* mechanical parts complete with included electronic circuits) in a single automated process. This would be the primary feature of a machine which could then go on to manufacture the elements required to make itself.

Existing rapid-prototyping (RP) technology lends itself to the manufacture of complete three-dimensional mechanical parts using one process. Therefore this project set out to discover the performance specifications of a Stratasys Dimension RP machine. The intention was to create electrical circuits by using casting channels for low melting-point alloys within components, so the RP technology was tested on all channel parameters. Research into the Stratasys Dimension RP machine performance proved that it was possible to create the components with the required casting channel specifications.

A successful circuit inclusion technique was discovered by using continuously heated equipment to inject molten Wood’s alloy into the casting channels. Whilst the injection technique was developed for prototype manufacturing, it also demonstrated that molten alloy distribution could be done accurately and yielded an excellent circuit quality. It was noted that the principle would lend itself well to the existing fused deposition method (FDM) RP technology as this already relies on melting materials at a distribution head to enable deposition.

The combination of the rapid-prototyping process to produce mechanical components with casting channels and the process of including the electrical circuits was labelled as RPEC technology (Rapid Prototyping Electrical Circuits).

This RPEC technology was then put to the test by attempting to build an autonomous robot using only RPEC techniques. The robot was a complete success. By fulfilling its requirement specification it proved that the RPEC technology worked.

The next development for the circuit inclusion element of RPEC will be to design and construct a motorised injection mechanism for the alloy which could deliver steady deposition on a motorised axis providing controllable deposition rates. This would be an important test to find out if the circuit inclusion method could be fully incorporated in an FDM RP machine. Should this succeed, at the result would be a useful machine also equipped with the potential to self-replicate.

2 TABLE OF CONTENTS

3 GLOSSARY

This section defines some terms which are commonly used throughout the report:

ABS	A plastic based on Acrylonitrile-Butadiene-Styrene copolymers; used as the build material in the Stratasys Dimension RP machine.
Bend alloy	See Wood's metal.
Casting channel	A groove in a component used to contain molten or powdered Wood's metal during the distribution process. These channels followed the basic shape and connectivity of the circuit.
Circuit casting	The action of depositing molten Wood's metal onto a component and allowing it to cool in the formation of an electrical circuit.
Circuit inclusion	The technology of manufacturing a physical component with an electrical circuit forming part of the component's structure.
FDM	Fused Deposition Method: a specific RP technique.
Infill	The RP process of filling the volume between critical surfaces of components with structural material.
Rapid prototyping (RP)	A technology which can create parts using fused deposition modelling. Components are designed using 3D solid modelling software package (e.g. SolidEdge) and then sent to the RP machine which will then automatically manufacture the component using ABS. All references within this document to RP refer to the fused deposition modelling technique. The machine used for this technique was the Stratasys Dimension rapid prototyping machine.
RPEC	Rapid Prototyped Electronic Circuits. The name of the technology whereby electrical circuit inclusion is possible with rapid prototyped components. This project was to devise techniques to create this technology.
Wood's metal	Low melting point (70 °C) alloy. Also know as bend alloy.

4 INTRODUCTION

The inspiration for this project was the concept of mechanical self-replication. Bowyer (2004) points out that the technology behind “a machine that could make a copy of itself” would have the benefit of exponential growth. No technology other than self-copying can do this and exponential growth is the fastest that is mathematically possible. For example, consider a machine that could make a copy of itself, at one machine per day. After one month there would be one machine for every man woman and child on the planet (raw materials permitting). These able machines would obviously have the capacity to make other products and the volume of produced goods would also multiple exponentially, quickly surpassing current mass production techniques.

With a view to creating this technology Bowyer states that such a machine would have to be capable of building three-dimensional objects from both an electrically insulating material and a conductor. With the technology at the time of writing it was assumed that the machine would have to be able to make all its components other than:

- Self tapping screws
- Brass bushes
- Lubricating grease
- Standard electronic chips such as microcontrollers and optical sensors
- A standard plug in low voltage power supply
- Stepper motors

It was also considered acceptable for a person to assemble the machine from those components and the standard parts.

Pain (2002) describes much earlier attempt at the integration of circuitry into functional components: in 1944 British engineer John Sargrove designed an automatic radio production line which he called ECME (Electronic Circuit-Making Equipment). In a bid to manufacture radios cheaply he dispensed with most of the hand-assembled bits by inventing a primitive chip – a slab of Bakelite with all the receiver’s electrical components and connections embedded in it. This was something which could be made easily by machines.

The starting point was a piece of Bakelite, moulded with a pattern of grooves and depressions on each side (Figure 2). When these were filled with molten zinc, they formed all the conductors, indictors, capacitors and resistors and so on that the receiver needed, all connected in exactly the right way. An operator sat at one end of the ECME line (a series of metal cabinets 20 metres long) feeding in the plates (Figure 1).

Figure 1: ECME production line in 1947

Figure 2: ECME bakelite chip

Despite economic success and unprecedented production rates, financial backing for ECME was lost as investors viewed such a high level of automation a threat to people’s livelihoods. Sadly only a few of the Bakelite boards survive in London’s Science Museum, and the ingenious machines which made them have been lost without trace.

At the time of writing the current technology most suited to building three-dimensional objects from an electrically insulating material was Rapid Prototyping (RP). RP is the collection of technologies that allow engineering components to be directly manufactured from descriptions of them held in a computer. Bath University has a fused deposition modelling (FDM) machine: a thin molten filament of ABS is deposited in the shape required. The process builds components up in layers. The resolution of the process is 100 µm. The result is physically strong enough to be used as components in prototype devices, and any shape that can be represented in a CAD system can be made, regardless of complexity, up to a cube with sides of 300 mm.

The idea behind the project described here was to combine Sargrove’s far-sighted idea of circuitry made by pouring molten metal into grooves in a plastic component with rapid prototyping to make the component. Initial experiments (Bowyer, 2003) showed that it was possible to incorporate a metal alloy (Wood's metal or Bend Alloy) into channels left for the purpose in a rapid-prototyped component simply by pouring it in. This was because the alloy's melting point (about 70 °C) is much lower than that of the RP polymer. This project will extend this idea to allow the construction of complete electronic circuits in three dimensions. This will be achieved by allowing channels for the metal in the rapid-prototyped part when it is made, along with cavities the correct shape for conventional electrical and electronic components such as resistors, capacitors, chips, small motors, and batteries.

This project attempts to formulate the basics of a process which would combine rapid prototyping techniques with Wood’s metal distribution techniques. The finished product will be a physically and electrically complete component with the potential to be manufactured from one single manufacturing process - a technology labelled in this report as RPEC (Rapid Prototyped Electronic Circuits). This would be a significant step towards mechanical self-replication.

5 SUMMARY OF WORK

In order to establish the technology of Rapid Prototyped Electronic Circuits (RPEC) it was necessary to conduct research in two major areas: RP machine limitations and circuit inclusion techniques. These areas were investigated in parallel. After summarising the findings, and specifying the technology, a design example was manufactured to demonstrate the potential of the technology. Figure 3 is a flowchart of the work carried out throughout the course of the project.

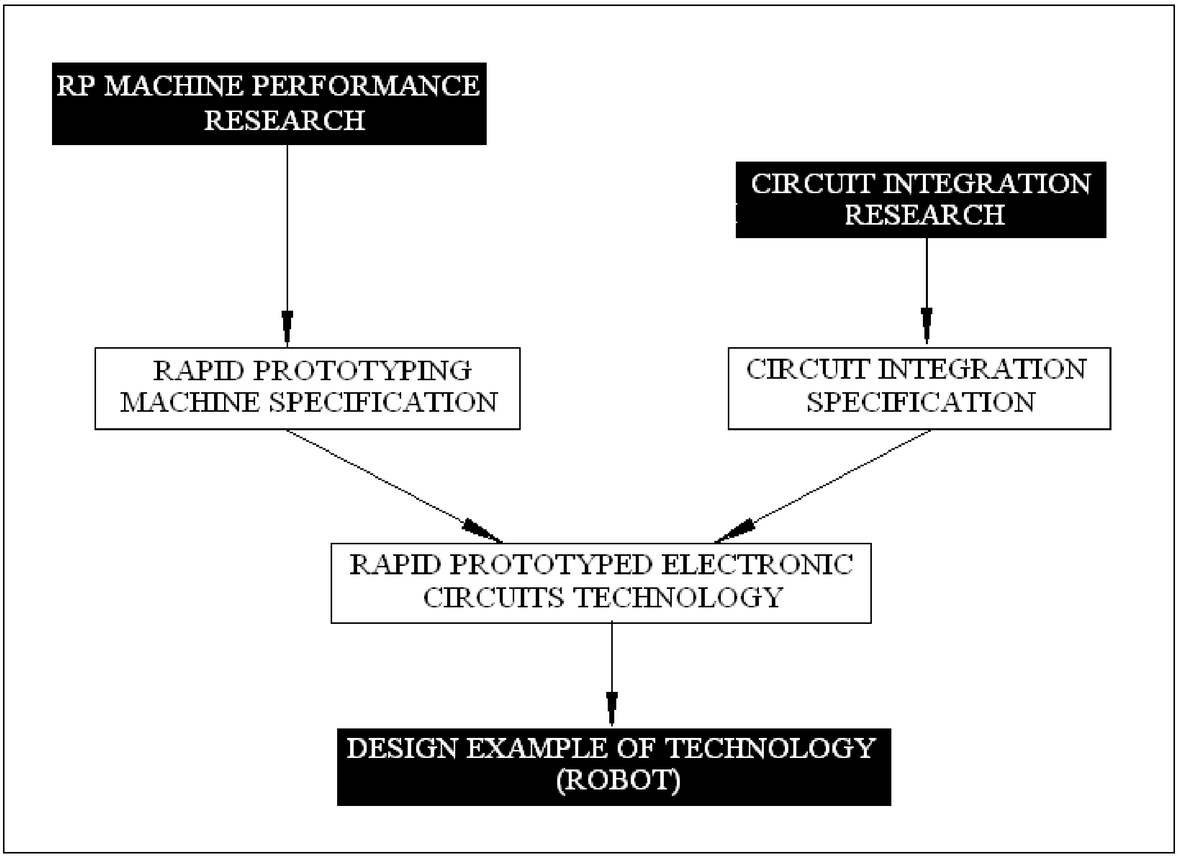


Figure 3: Flowchart of work carried out during the project. This breaks down into the three major areas (shown in black boxes).

This report is, therefore, written in three sections:

- RP machine performance research
- Circuit inclusion research
- Design example of the technology: An autonomous robot

Results are demonstrated and discussed locally for each section. A final discussion (concerned with the project as a whole) is presented at the end of the report.

6 RP MACHINE PERFORMANCE RESEARCH

6.1 Summary

Experiments were conducted on the Stratasys Dimension rapid-prototyping machine to establish its limitations with respect to the manufacturing components suitable for RPEC technology (*i.e.* components designs which could incorporate casting channels).

Experiments included investigations into:

- Casting channel parameters
- Support material requirements
- Minimum wall thickness
- Minimum hole diameter

Performance results proved that it was possible to create the casting channels required for the proposed RPEC technology.

Manufacture was also made more efficient by establishing the calibration zones needed by the RP machine. The machine builds components on foam plates, the location of which it needs to check by calibration before it starts a build. Placements of jobs were avoided in these areas to conserve the life of the machine’s foam plates.

6.2 Assumptions and references

This project used the Stratasys Dimension rapid-prototyping (RP) machine (a fused deposition modeller) for all its RP needs. Therefore this report assumes basic knowledge of how to use the RP machine. For detailed methods related to the use of this machine please refer to *Manual for Technical Report 01/04* (Sells, 2004).

All references within this document to the “RP machine” refer to the Stratasys Dimension rapid prototyping machine.

6.3 Introduction

This section attempts to research the limitations of the RP machine required to fulfil the first part of this requirement: the manufacture of three-dimensional objects from an electrically insulating material (i.e. the structural part of the component).

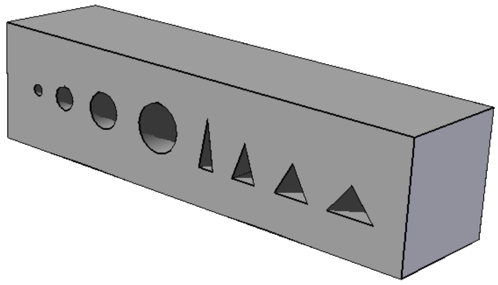
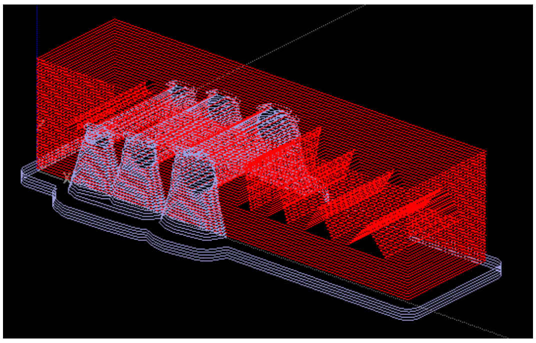
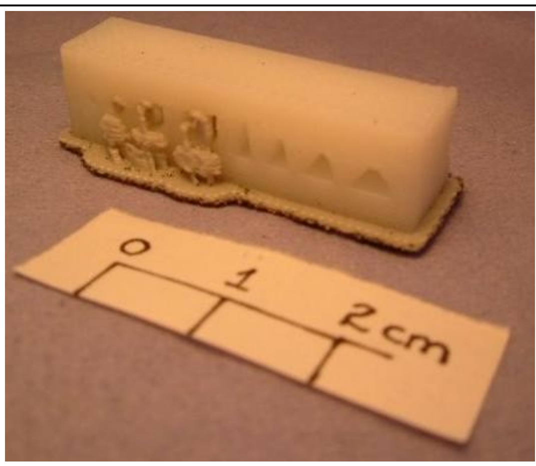
The assumed process of including circuits into components involved casting molten metal (Wood’s metal) into the structure required for an electronic circuit. This would require the incorporation of casting channels into the design of the component. These channels would hold and form the alloy in the desired shape during the casting process.

In order to cast successful circuits it was necessary to research the limitations of the RP machine with respect to channel geometries. This section, therefore, outlines experiments undertaken to generate a performance specification for the RP machine.

6.4 Rapid prototyping theory

Table 1 outlines the basic steps taken to manufacture a component using RP technology.

Table 1: Step by step demonstration of rapid prototyping manufacture process

Stage	Visualisation	Details
1		Design is created virtually using a 3D modeller.
2		The 3D model is pre-processed using a program from Startasys called Catalyst: the design is converted into tool paths for the RP machine to follow. Red lines represent component material. Blue lines represent any support material (required for overhangs).
3		Tool path information is sent to the RP modeller. The modeller is initiated and then left to manufacture the job.
4		When the RP modeller is finished, the component is unloaded and support material is peeled away to give the finished part. Here the support material can be seen under the part and in the holes at the left.

6.5 Experiment: Initial test of the RP machine's performance

6.5.1 Summary

This experiment was devised to gain familiarity with the rapid prototyping process and approximate an initial minimum casting channel width in a component design.

The experiment proved that casting channels incorporated into rapid prototype design were feasible and should be at least 0.9 mm wide to guarantee structural integrity. Further approximations suggested that support walls should be at least 0.3 mm thick, channel entrances from casting wells should be filleted and that the RP machine should be calibrated fully before manufacturing quality components.

6.5.2 Apparatus

- RP machine and accompanying Catalyst software
- Solid Edge r14 modelling software

6.5.3 Method

A test piece was designed using Solid Edge r14 (Figure 4 and Figure 5) consisting of seven channels (1.5mm deep) with widths ranging from 0.3 mm to 1.5 mm.

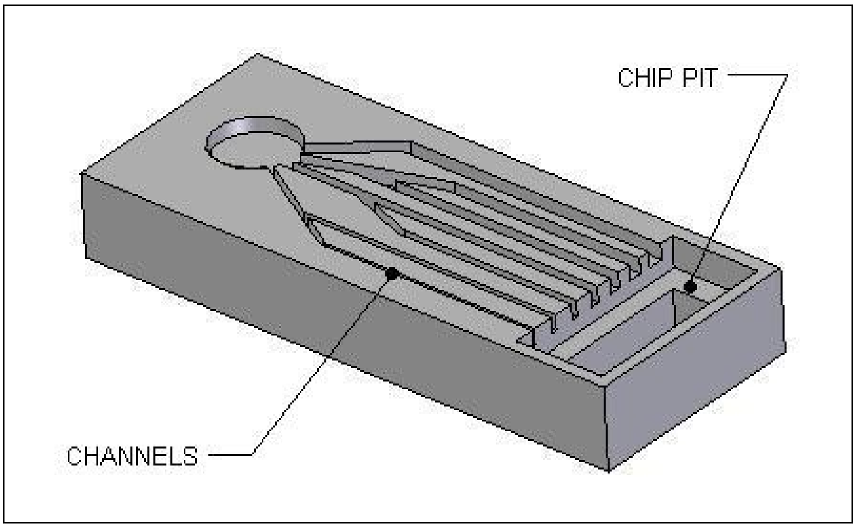


Figure 4: Isometric view of initial test piece

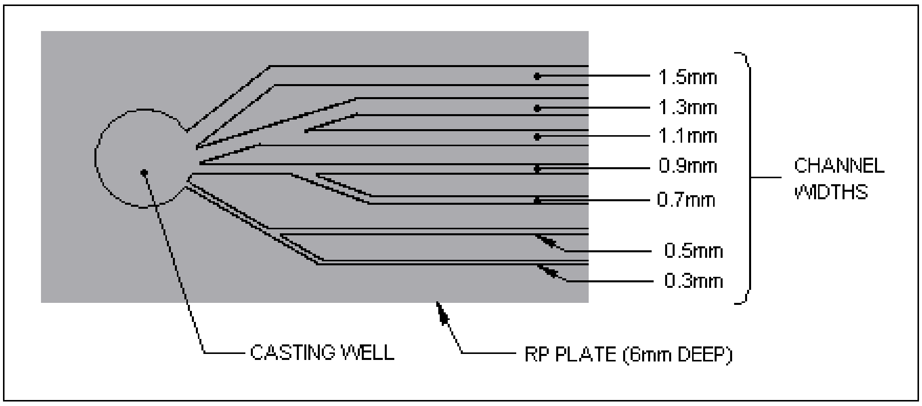


Figure 5: Plan view of channel widths ranging from 0.3mm to 1.5mm

The chip pit on Figure 4 was a part of the design intended to incorporate a standard DIL integrated circuit upside-down. Its pins would make contact with the solidified Wood's metal in the channels which would both hold the chip in and give it electrical connections.

Solid Edge was then used to save the 3D part file of the test piece as an STL file. The STL file was then loaded into Catalyst.

Table 2 shows the options set for the tool-path conversion within Catalyst.

Table 2: Data conversion parameters within Catalyst software

Field	Value
Modeller	Dimension
Build style	Standard
Part surface	Best vertical quality
Part interior style	Solid – fine
Support style	Sparse

Figure 6 shows the conversion of the STL file into lays for the RP machine.

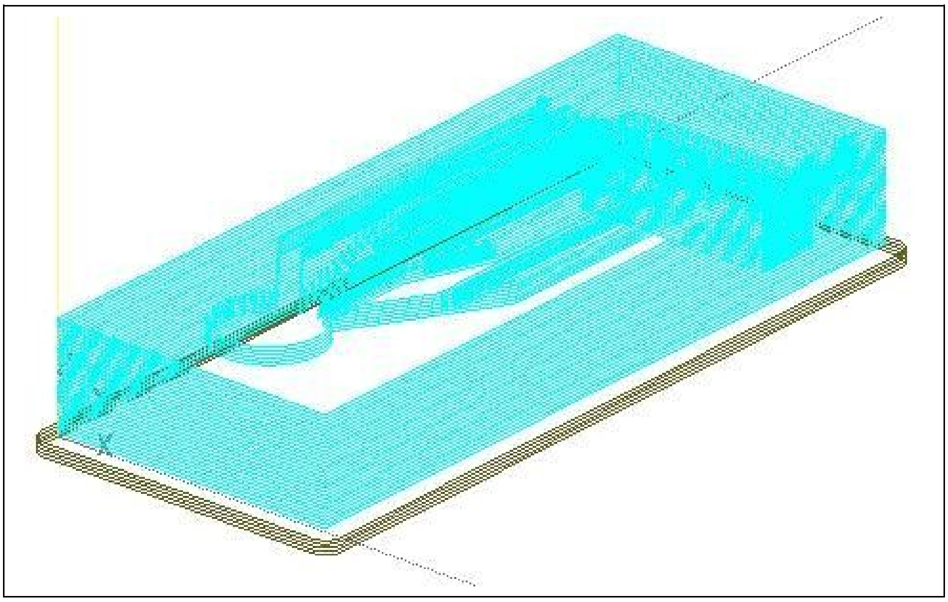


Figure 6: Analysis of test piece by Catalyst into tool-paths before sending to the RP machine.

The file was sent to the RP machine and manufactured. When completed, the piece was collected and analysed.

6.5.4 Results

Figure 7 is a photo of the finished component.

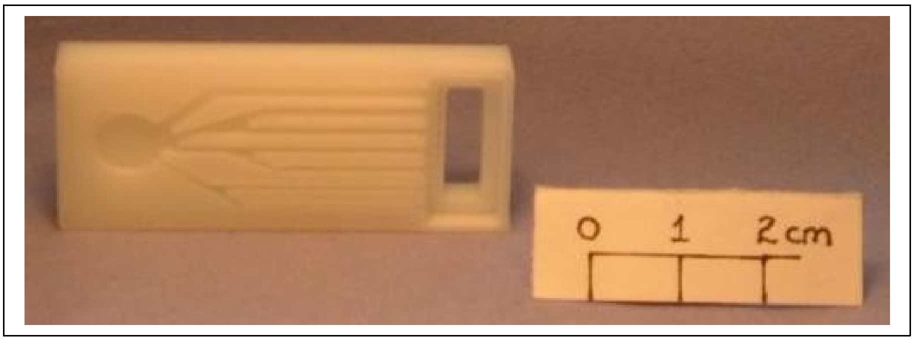


Figure 7: Manufactured test piece for initial RP performance test

Vertical quality (*i.e.* channel wall faces) was observed to be good: surface finish was smooth and the geometry was true.

Lack of infill (the RP process of filling the volume between critical surfaces of components with structural material) was found in every case behind faces which, during manufacture in the RP machine, had been orientated towards the back of the machine.

Terminal quality (*i.e.* ability for channel walls to end separately over a face) was poor, as demonstrated in Figure 8.

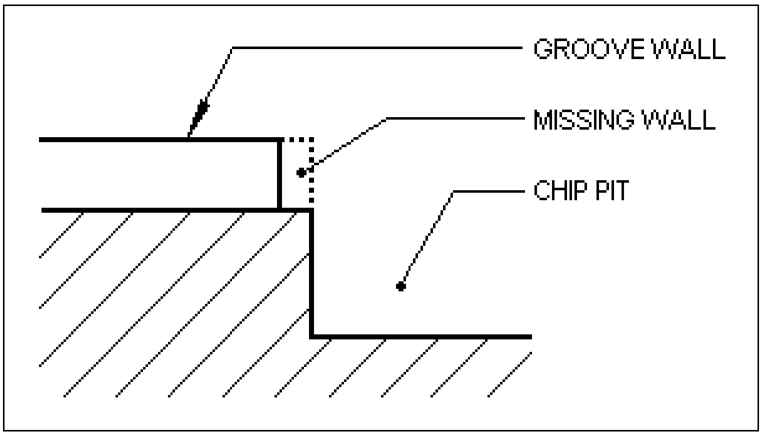


Figure 8: Demonstration of poor terminal quality. The channel walls were not flush with chip pit face. This was important as it allowed the potential for molten metal to escape the channel during the casting process, thus creating a short circuit.

Individual channel quality was recorded in Table 3.

Table 3: Observation of channel quality

Channel width (mm)	Result
1.5	Channel clear. Separating wall unfilled but previously identified on 'Catalyst'.
1.3	Channel clear
1.1	Channel clear
0.9	Channel clear
0.7	Channel clear. Entrance corner thrombosis.
0.5	Channel clear
0.3	Channel suffered from thrombosis at entrance corner and occasionally down length of channel

6.5.5 Discussion

This test demonstrated that it was possible to incorporate casting channels into the design of a rapid prototyped component. This test estimated that the minimum width for such a channel should be 0.9 mm. It was considered likely that channels thinner than 0.9 mm would suffer from thrombosis due to the resolution of the RP machine.

It was also estimated that a minimum support wall thickness of 0.3 mm was required for a structurally sound wall.

Thrombosis was a problem at the thinner channel entrances. This was likely to be a design issue: entrances had sharp corners. One possible solution would be to fillet the entrance corners.

Lack of infill was found in every case behind faces orientated towards the back of the machine. There were a number of possible causes for this, the two most likely being:

- Number rounding error within the RP machine
- Calibration fault

Although it was difficult to avoid a number rounding error within the machine, it was realised that every effort should be taken to ensure that the calibration of the machine should be exact.

This problem was likely to be the linked to the shortfall of the channel walls at the chip terminals. It was noted that the following test should investigate a different orientation of the chip pit to verify this hypothesis.

6.5.6 Conclusion

It was noted from this test that casting channels incorporated into rapid prototype design on the RP machine should be at least 0.9 mm wide. Support walls should be at least 0.3 mm thick (assuming perfect infill). Channel entrances should be filleted. The RP machine should be calibrated fully before manufacturing quality components to ensure even infill.

6.6 Experiment: Casting channel parameter test

6.6.1 Summary

A component with different channel geometries was designed and made on the RP machine. The channels were then observed, analysed and conclusions were drawn.

This experiment identified that poor in-fill quality only applied to faces orientated towards the back of the RP machine during manufacture. Thus the operator should avoid orientating critical faces towards the back of the machine (*e.g.* chip terminals) until RP machine correction/calibration.

Other results concluded that channel length and corner radii did not influence the integrity of the component or the channels. Channels were structurally sound at a minimum width of 1.1 mm (a refined result from Section 6.5). Channels were structurally sound up to and including sharp corners of 150°. Channels depths were as shallow as 0.25 mm without influencing channel integrity. Inverse drafts were used up to and including 10° without influencing integrity or requiring support material.

It was noted that a further test should be conducted to investigate the possibility of printing horizontal, triangular roofed holes to increase the possible geometries available for making circuits that are fully three-dimensional..

6.6.2 Introduction

This test was designed to confirm previous results from Section 6.5, regarding channel width and to explore more casting channel parameters:

- Channel filleting
- Chip pit orientation
- Channel depth
- Channel profile
- Channel length
- Channel path corner angle

6.6.3 Apparatus

- RP machine with accompanying Catalyst software
- Solid Edge r14 modelling software

6.6.4 Method

A test piece was designed using Solid Edge r14 (Figure 9 and Figure 10). The piece was then manufactured using an identical method to that described in Section 6.5.3 with the exception that the chip pit was aligned with the length facing the side of the machine during manufacture (a 90 ° rotation clockwise rotation compared to the alignment of the test piece manufactured in Section 6.5).

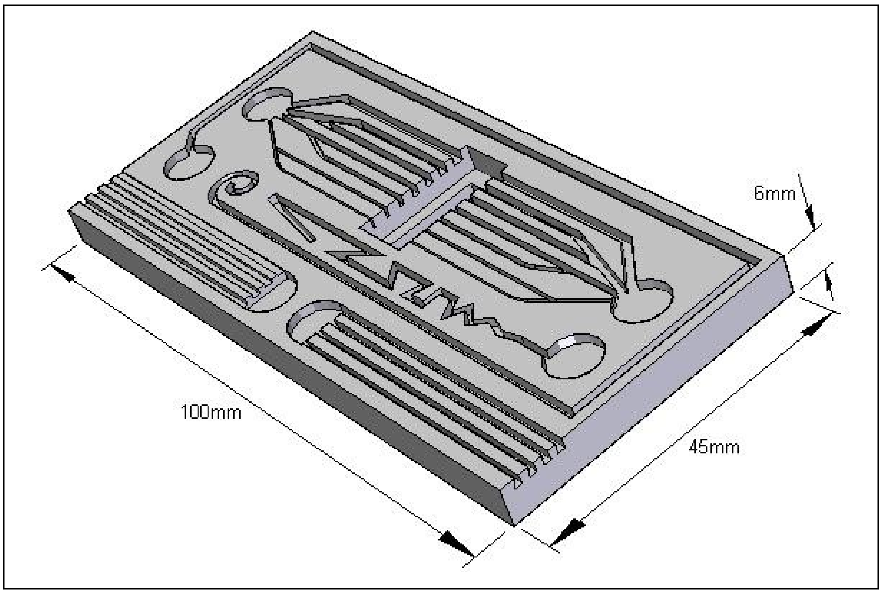


Figure 9: Isometric view of test plate including channels under test, chip pit and casting wells

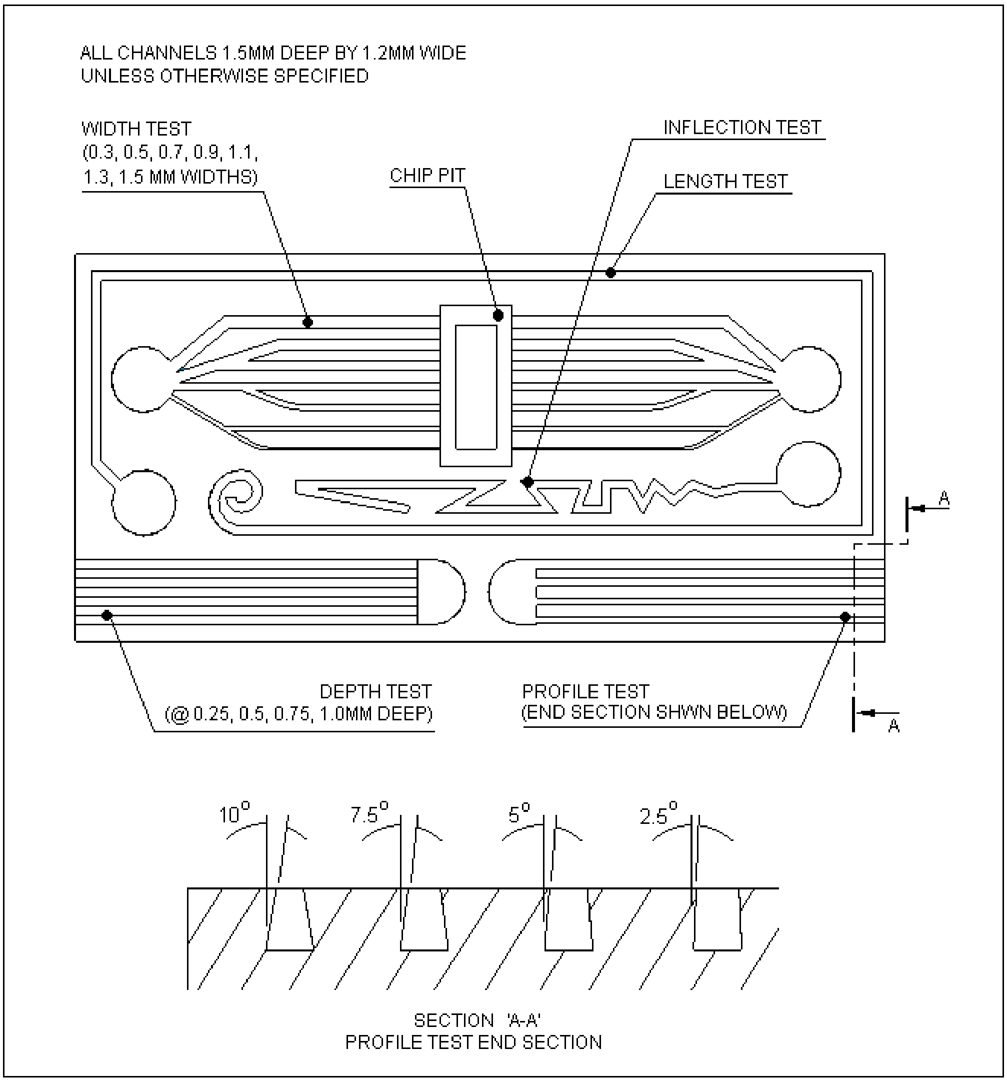


Figure 10: Identification of different channel tests within test piece

6.6.5 *Results*

This section assesses the quality of the test piece (Figure 11).

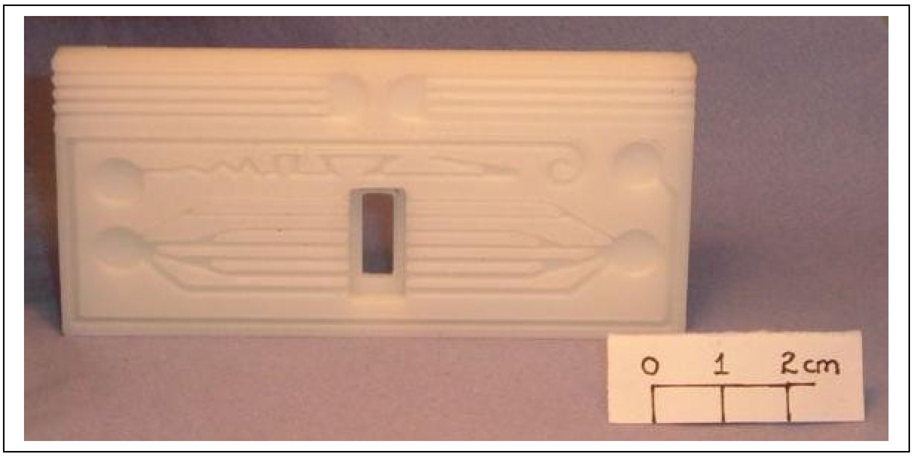


Figure 11: Finished test piece for casting channel parameter analysis

Vertical quality (i.e. channel wall faces) was observed to be good: surface finish was smooth and geometry was true.

Areas of in-fill were poor in areas on all faces pointing towards the back of the machine.

Terminal quality was excellent i.e. groove wall was sufficiently flush with the chip pit wall (Figure 12).

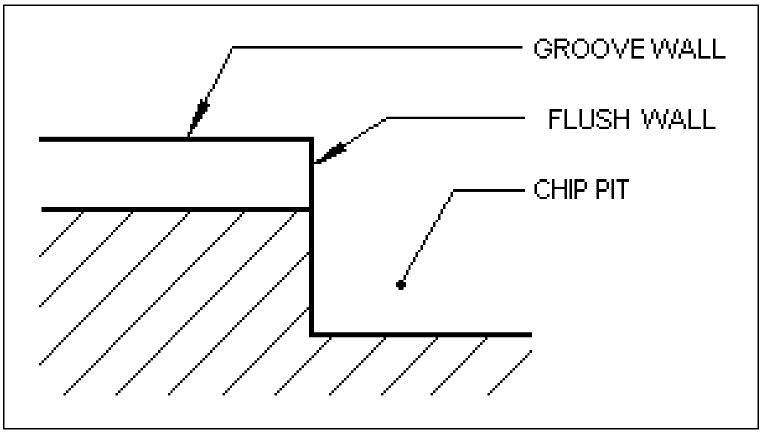


Figure 12: Demonstration of good terminal quality. The channel walls in all cases were flush with chip pit face preventing the possibility of molten metal escaping the channel before making contact with the chip terminal during casting.

Individual channel quality was recorded in Table 4.

Table 4: Observation of channel quality (areas referenced in Figure 5)

Test	**Variation**	**Result**
Length	-	Channel clear along 250 mm length including spiral test at the path end.
Width	1.5 mm (left)	Channel clear
	1.5 mm (right)	Channel clear
	1.3 mm (left)	Channel clear
	1.3 mm (right)	Channel clear
	1.1 mm (left)	Channel clear
	1.1 mm (right)	Channel clear
	0.9 mm (left)	Slight thrombosis
	0.9 mm (right)	Channel clear
	0.7 mm (left)	Slight entrance thrombosis
	0.7 mm (right)	Channel clear. No entrance thrombosis.
	0.5 mm (left)	Slight entrance thrombosis
	0.5 mm (right)	Lead tunnel overly thin. Channel thrombosis.
	0.3 mm (left)	Zero entrance thrombosis. Heavy channel thrombosis.
	0.3 mm (right)	Zero entrance thrombosis. Heavy channel thrombosis.
Inflection	-	All inflections up to and including 150° sufficient
Depth	0.25 deep	Channel maintains integrity
	0.50 deep	Channel maintains integrity
	0.75 deep	Channel maintains integrity
	1.00 deep	Channel maintains integrity
Inverse Draft	2.5°	Channel maintains integrity. Zero support material required.
	5.0°	Channel maintains integrity. Zero support material required.
	7.5°	Channel maintains integrity. Zero support material required.

Test	Variation	Result
	10.0°	Channel maintains integrity. Zero support material required.

6.6.6 Discussion

The consistent orientation of the poor in-fill areas indicated that the RP machine was generally poor at in-fill to all faces pointing towards the back of the machine. Until the machine could be correctly re-calibrated, this was noted as a problem to be avoided by avoiding orientation of critical faces towards the back of the machine.

Further observations indicated that channels of 1.2 mm width could be successfully made to distances of 250 mm at all radii.

Results generally indicated that filleting entrance corners reduced the risk of thrombi.

Repeating the width test (similar to that of Section 6.5) indicated a lack of confidence in the 0.9 mm width channels after an identification of a slight thrombosis in one of the two 0.9 mm width channels. Results indicated a channel width of 1.1 mm was the minimum to guarantee structural integrity.

Channel inflection (path cornering) was tested up to 150° without failure.

Depth tests were encouraging, channel integrity was maintained at a depth of 0.25 mm.

Inverse draft channels maintained integrity up to and including 10° and required no support material. This was an excellent and unexpected result which demanded a further test into the possibility of printing horizontal, triangular roofed holes.

6.6.7 Conclusion

From this test it was noted that the operator should avoid orientating critical faces (e.g. chip terminals) towards the back of the machine until the RP machine could be calibrated fully.

Channel length and corner radii did not influence integrity. Channels were structurally sound at a minimum width of 1.1 mm (a refined result from Section 6.5). Channels were structurally sound up to and including sharp corners of 150°. Channels depths were as shallow as 0.25 mm without influencing channel integrity. Inverse drafts were used up to and including 10° without influencing integrity or requiring support material. Channel entrances required fillets to avoid thrombi.

A further test should be conducted to investigate the possibility of printing horizontal, triangular roofed holes.

6.7 Experiment: Support material requirements

6.7.1 Summary

A test piece with varying triangular hole geometries was designed. This was then tested on Catalyst and the support material requirement conditions were analysed.

It was noted that the RP machine could cater for overhangs in the model design of up to and including 45 ° away from the vertical axis. Support material was required for overhangs greater than or equal to 46 ° away from the vertical axis.

This result was crucial to the casting channel specification as it accurately defined the geometrical specification of horizontal holes which could be made without using support material.

6.7.2 Introduction

Section 6.6 identified the discovery that the use of slight inverse draft angles did not induce the use of support material. This indicated the possibility of a triangular roofed horizontal hole which would not require support material.

This test was designed to investigate the parameters of horizontal triangular roofed holes in rapid prototyped components.

6.7.3 Apparatus

- Catalyst software
- Solid Edge r14 modelling software

6.7.4 Method

A test piece was designed using Solid Edge r14 (Figure 13 and Figure 14).

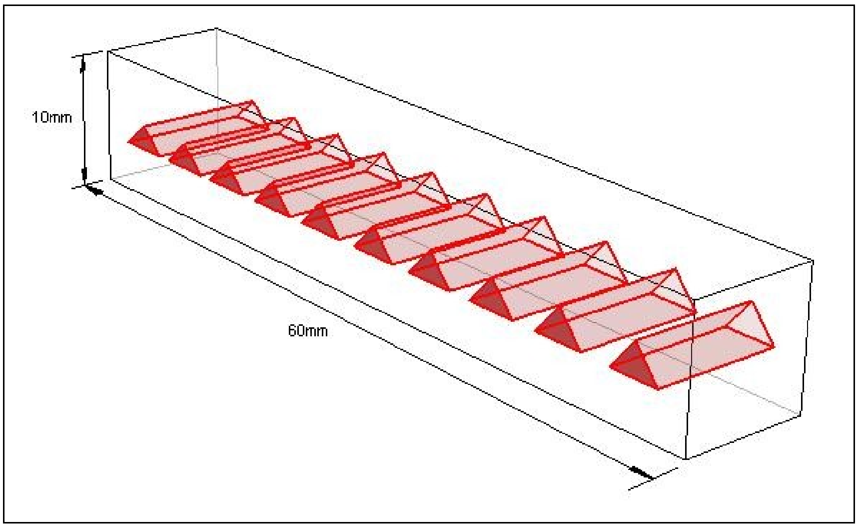


Figure 13: Isometric view of the horizontal hole test plate including holes (shaded red) under test

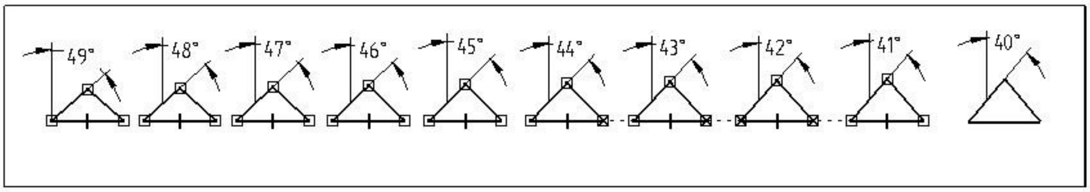


Figure 14: End view dimensions of the hole profiles under test

The piece was then loaded into the Catalyst software and support material needs were identified.

6.7.5 Results

Figure 15 shows the lay up defined by Catalyst to manufacture the test piece.

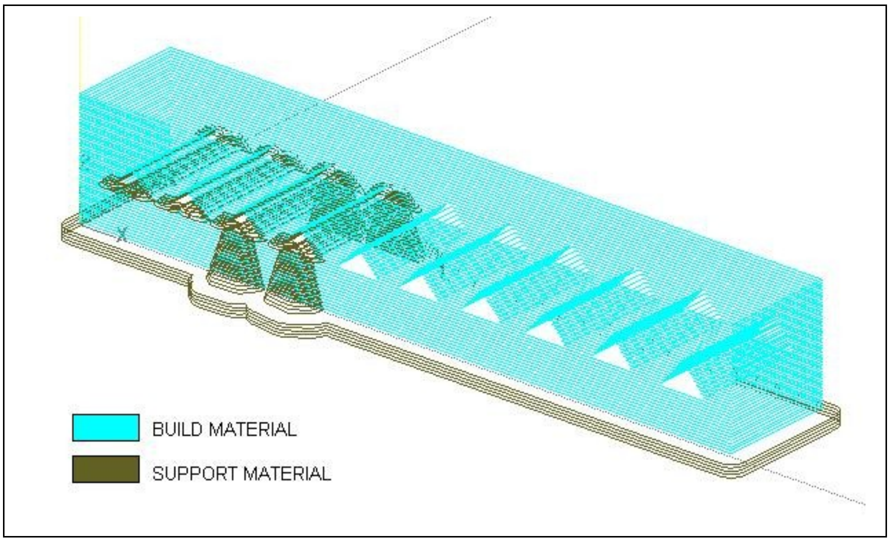


Figure 15: Lay ups required to manufacture the test piece

Individual hole status was recorded in Table 5.

Table 5: Observation of support material requirements for the test piece

Hole	Overhang angle (°)	Support material required?
1	49	Yes
2	48	Yes
3	47	Yes
4	46	Yes
5	45	No
6	44	No
7	43	No
8	42	No
9	41	No
10	40	No

6.7.6 Discussion

Catalyst was efficient at defining the limitations of the RP machine. It was clear that the machine could not build elements of a model with overhangs over and including 46° away from the vertical build axis without using support material.

This result was crucial to the casting channel specification as it accurately defined the geometries of horizontal holes (which must be made without using support material).

6.7.7 Conclusion

The RP machine built overhangs up to and including 45° away from the vertical axis without using support material. This enabled the production of a horizontal hole of triangular profile.

6.8 Experiment: Minimum wall thickness

6.8.1 Summary

By using a test plate designed specifically with increasing wall thicknesses, Catalyst was able to identify the minimum achievable wall thickness on the RP machine to be 0.4 mm. Observations of the physical product yielded excellent wall quality with a tolerance of approximately ± 0.1 mm.

6.8.2 Introduction

In order to cast molten metal proud of the component surface for contact situations a method was devised to incorporate a chip-away mould (or “fence”) to form a temporary casting channel (see Section 8.8.2). Thus the molten metal could be cast into the fence then exposed (after solidification) by peeling the fence away. In order to make effective fencing it was necessary to find the minimum wall thickness which could be made by the RP machine.

6.8.3 Apparatus

- RP machine with accompanying Catalyst software
- Solid Edge r14 modelling software

6.8.4 Method

A test piece with varying wall thickness was designed using Solid Edge r14 (Figure 16 Figure 17).

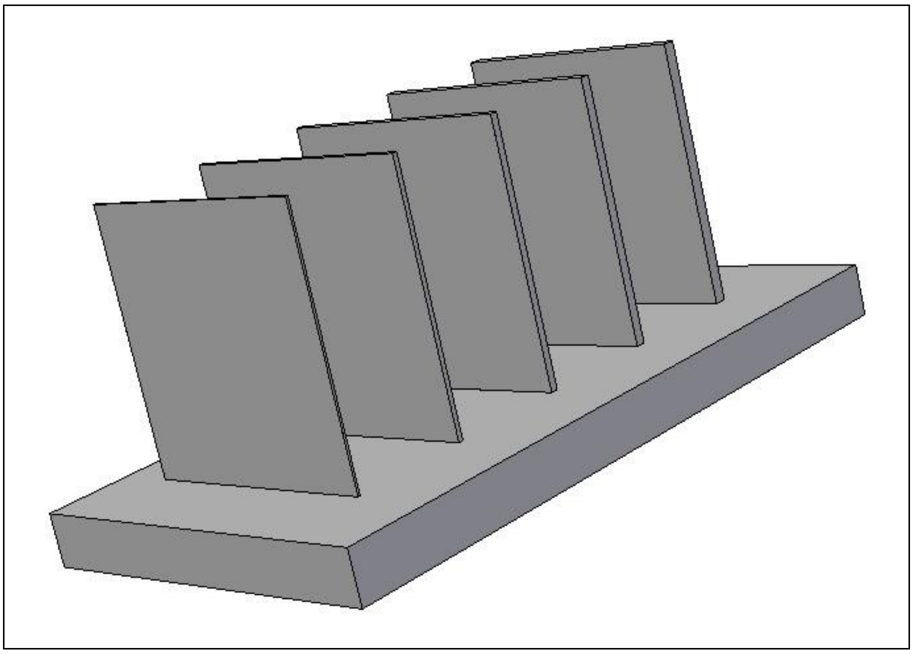


Figure 16: Isometric view of test plate including thin walls under test

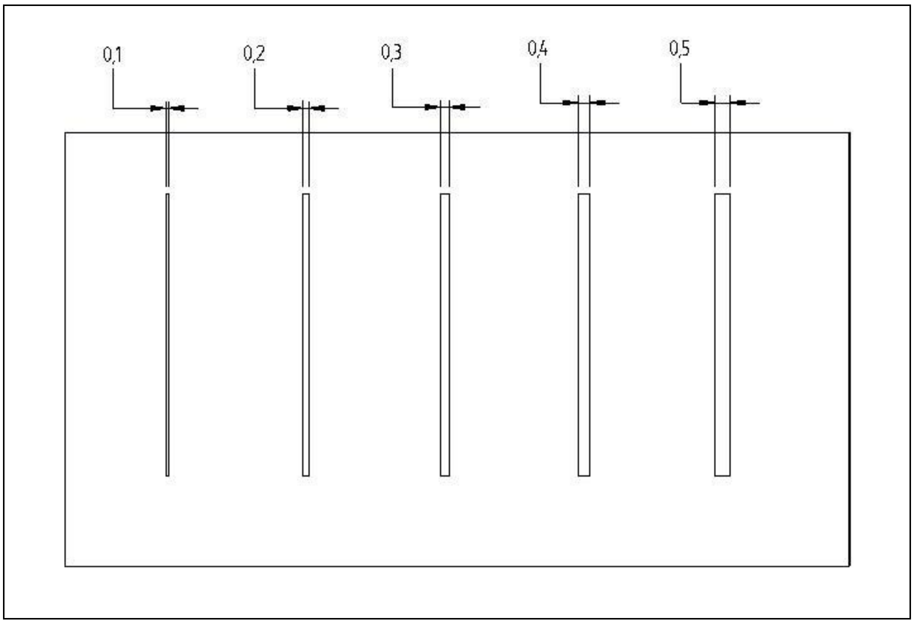


Figure 17: Identification of different channel tests within test piece

The piece was then manufactured using an identical method to that described in Section 6.5).

6.8.5 Results

Figure 18 demonstrates that the only walls ≤ 0.4 mm thickness would be processed in the lay-up procedure.

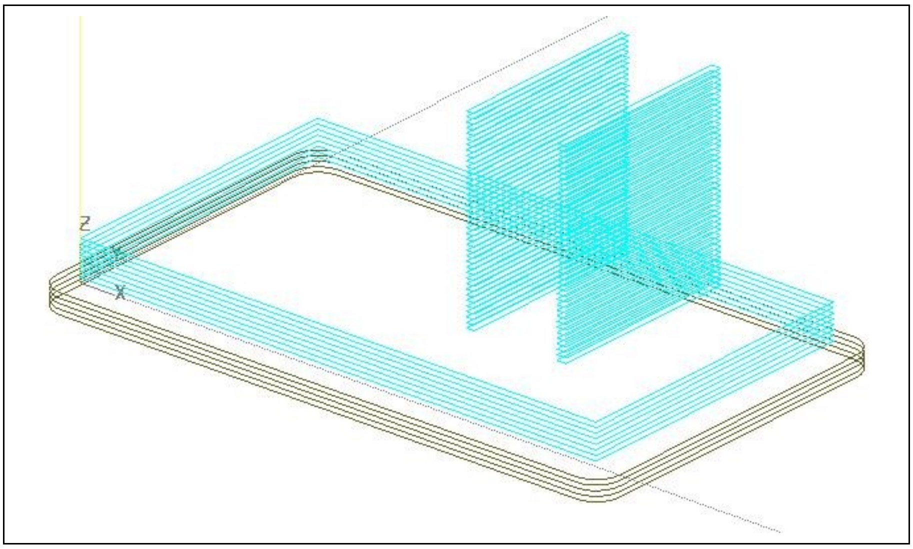


Figure 18: Catalyst translation of solid models to layers, omitting walls ≤ 0.4 mm thickness

Figure 19 and Figure 20 demonstrates that the wall quality was generally clean and subject to a tolerance of approximately ± 0.1 mm.

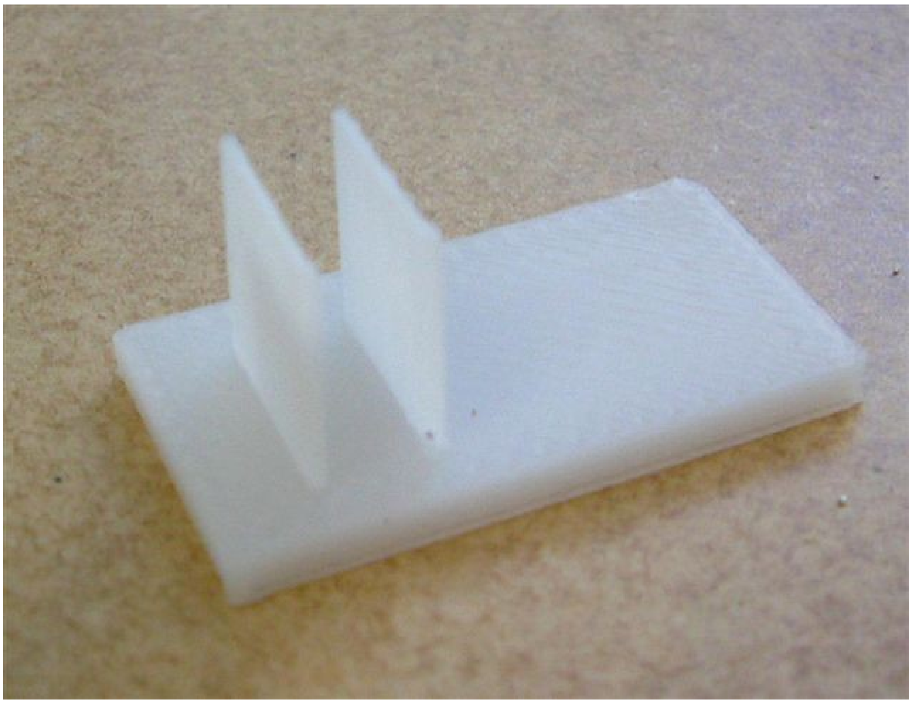


Figure 19: Physical component made by RP machine from Catalyst translation of model.

Figure 20: Magnification of processed thin walls made on test piece (plan view). 0.4 mm thickness is on top, 0.5 mm thickness is bottom.

6.8.6 Discussion

This test established the minimum wall thickness manufactured by the RP machine to be 0.4 mm. The quality of the walls at this thickness was observed to be excellent, with an estimated tolerance of ± 0.1 mm. This result proved essential to the technique known as ‘fencing’ (see Section 8.8.2).

It should be noted, however, that the test piece was aligned with critical faces aligned with the axes of the RP machine. Due to the limit of the machines tolerance it would be less certain that the minimum wall thickness would be as low as 0.4 mm should the faces be orientated at 45 ° or other angles to the machine's axes. This should be investigated.

6.8.7 Conclusion

The RP machine was able to manufacture walls to a minimum thickness of 0.4 mm (± 0.1 mm).

6.9 Experiment: Minimum hole diameter

6.9.1 Summary

This experiment was devised to identify the integrity of small holes made in components on the RP machine. By creating a test plate and analysing it, it was possible to determine that the smallest possible hole with 100 % reliability was ø 1.0 mm.

6.9.2 Introduction

It was necessary to have placement holes in the bottom of the casting channels to hold the electrical components upright and in the correct position during circuit filling (see Section 8.8.5). Thus it was necessary to determine the minimum achievable hole diameter on the RP machine.

6.9.3 Method

A test piece with varying hole diameters was designed using Solid Edge r14 (Figure 21 and Figure 22).

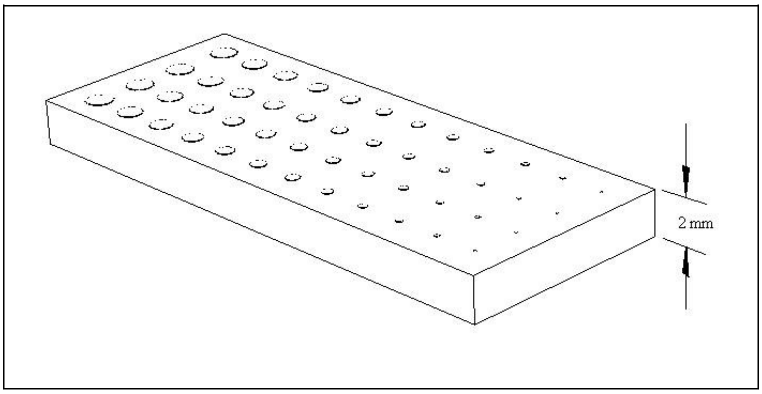


Figure 21: Isometric view of test plate showing open holes of varying diameter

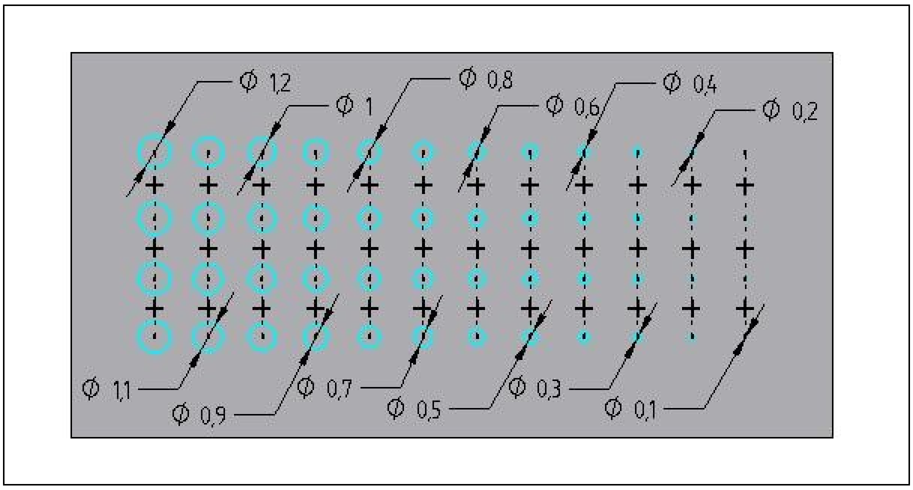


Figure 22: Identification of hole diameters. Hole repeated in four columns to evaluate repeatability.

The piece was then manufactured using an identical method to that described in Section 6.5. The holes were then analysed.

6.9.4 Results

Figure 23 is a magnification of the completed test piece.

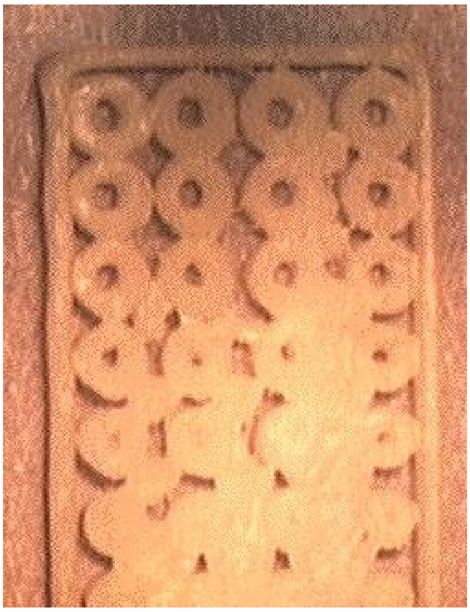


Figure 23: Small hole test piece. Top row ø 1.2 mm, decreasing by 0.1 mm diameter per row. The lower holes omitted from photo because all holes were blind below fifth row (ø 0.8 mm).

The hole qualities were recorded in Table 6.

Table 6: Hole quality

Hole ø (mm)	Processed by catalyst?	Hole quality			
		1	2	3	4
1.2	Yes	Clear	Clear	Clear	Clear
1.1	Yes	Clear	Clear	Clear	Clear
1.0	Yes	Clear	Clear	Clear	Clear
0.9	Yes	Clear	Clear	Thrombosis	Clear
0.8	Yes	Thrombosis	Blind	Blind	Blind
0.7	Yes	Blind	Blind	Blind	Blind
0.6	Yes	Blind	Blind	Blind	Blind
0.5	Yes	Blind	Blind	Blind	Blind
0.4	Yes	Blind	Blind	Blind	Blind
0.3	Yes	Blind	Blind	Blind	Blind
0.2	Yes	Blind	Blind	Blind	Blind
0.1	Yes	Blind	Blind	Blind	Blind

6.9.5 Discussion

Results showed that holes of diameter 0.8 mm or less were not structurally sound. 75% of ø 0.9 mm holes were structurally sound, and 100 % of holes ø 1.0 mm and above were sound. It was noted that components should not be designed with holes smaller than ø 1.0 mm.

It was noticed that infill was missing in areas with closely packed features. This was noted as a consideration for future design.

6.9.6 Conclusion

Components with holes smaller than 1.0 mm were not reliable in terms of quality. Infill was missing in areas with closely packed features. This was noted as a consideration for future design.

6.10 Experiment: Calibration zone locations

6.10.1 Summary

The RP machine builds components on disposable foam plates. This investigation was conducted to maximise the efficiency of the foam plate usage. After rough approximation techniques a calibration zone map was generated. This map was used to ensure that jobs were not initialised over the calibration zones, thus increasing the life of the foam plates.

6.10.2 Introduction

In order for the Stratasys Dimension rapid prototyping machine to function precisely it calibrates the print head in relation to the foam plate surface at the start of every job.

After loading the machine with the foam plate and instigating the job the plate is raised to printing level and the printing unit is sent along a path over the plate. The plate is raised into the unit at four different locations along the path, depressing a switch on the print unit which is used to calculate the surface geometry of the plate.

Removing a part from the foam often forms cavities in the surface local to the origination of the part. Due to the nature of machine's use, jobs are often done on used plates which introduces the possibility of false calibration i.e. depression of the switch on a cavity surface abnormal to the geometry of the surface majority, created from job removal.

This investigation was designed to map the calibration zones and was useful to ensure that the placement of jobs was kept outside these zones.

6.10.3 Method

The RP machine calibration process was observed.

Foam and print unit geometries were measured using a ruler.

Print head limits were found by measuring the co-ordinates of a job footprint. This job was sent from Catalyst intended to be laid in the extreme front left corner of the foam plate. It was assumed that the print head extremes were to be symmetrical.

6.10.4 Results

Calibration paths were consistent throughout all jobs.

The footprint of a job placed in the extreme front left corner was found to be 15 mm from the front edge and 10 mm from the left edge.

Geometries, assumptions and resulting estimations of the print unit path are displayed in Figure 24.

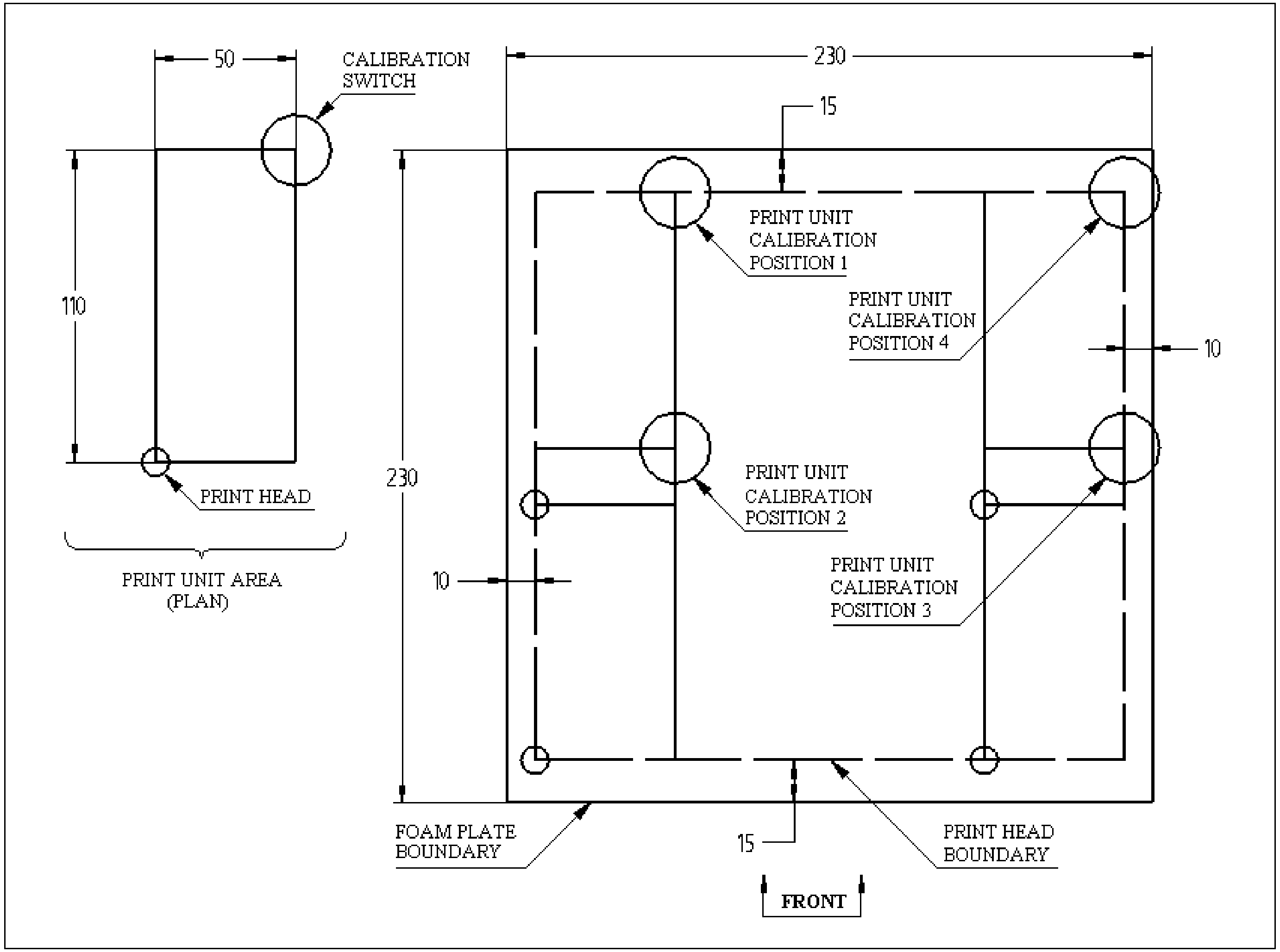


Figure 24: Geometry assumptions used to calculate the calibration zones on the plate

Figure 25 summarises the estimated locations of the calibration zones (given an approximate ± 12.5 mm tolerance for measuring error, resulting in ø 25 mm area per zone).

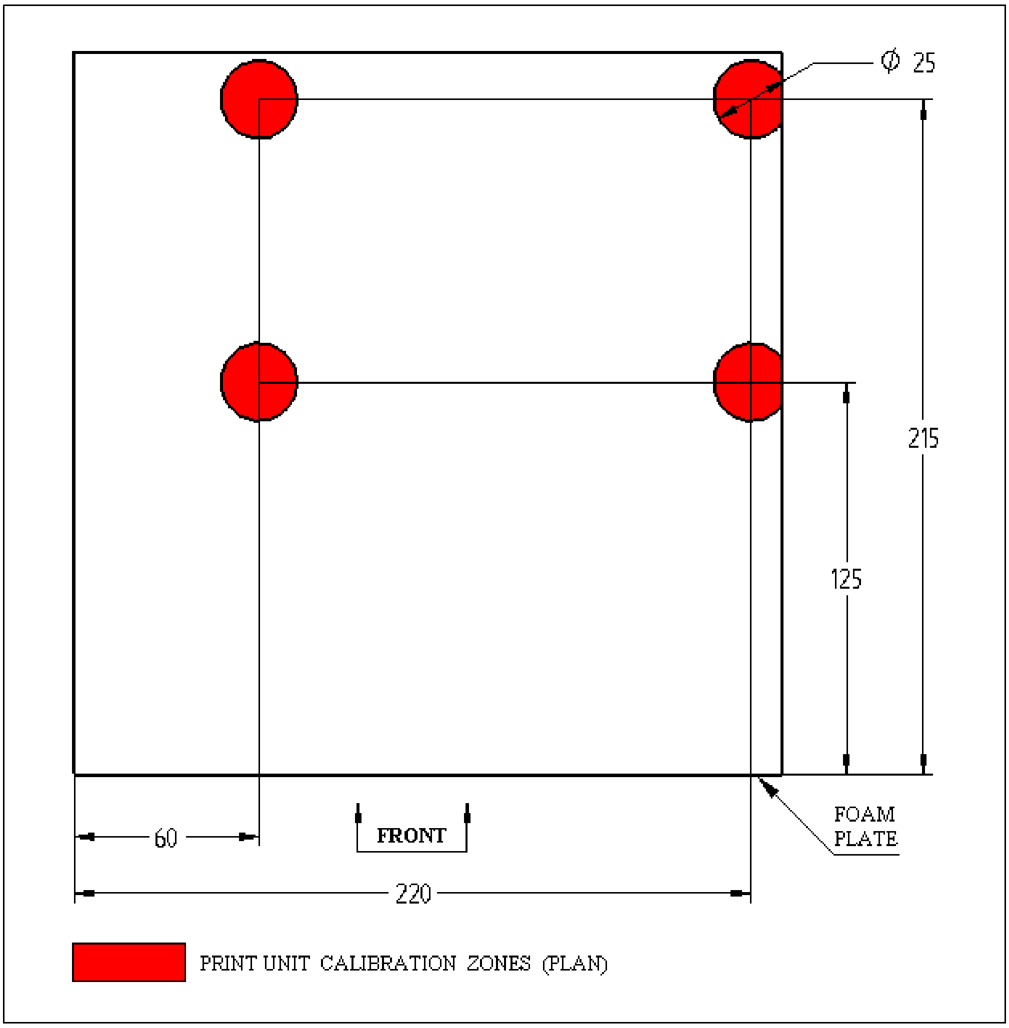


Figure 25: Estimates of calibration zones on plate

6.10.5 Discussion

Observations yielded consistent calibration zones (defined in Figure 25).

These were regarded as estimates and it was noted that further research was required to narrow the tolerance of the calibration zones. However, the calibration map was considered a useful tool to conserve the life of the foam plates.

It was also noted that an overlay method would be useful at the job placement stage (within Catalyst) to ensure that printing would avoid the calibration zone.

6.10.6 Conclusion

The generation of the calibration zone map proved to be a useful tool to conserve the life of the foam plates.

6.11 Discussion of RP machine performance research

This section of research was found to be extremely useful to define the minimum specification for all components for use within RPEC technology when using the Stratasys Dimension RP machine.

Perhaps the most important research was the casting channel parameter test. Casting channels were considered to be the crux of the RPEC technology and therefore it was essential to specify these parameters. The basic minimum width requirement for a casting channel (estimated to be 1.0 mm) was considered a suitable width for the typical casting process. This was an extremely encouraging result as it meant that the first element of RPEC technology was possible.

This project saw the first real investigation into the specific requirements for support material on the Stratasys Dimension RP machine. It was discovered that the critical overhang angle was much larger than expected (45 ° away from the vertical) and this enabled two important facilities.

- The ability to manufacture holes on a horizontal build plane using a triangular profile
- Efficient RP design of parts with overhang features

The discovery of a reliable minimum wall thickness was important for the advanced casting technique used in practical applications called ‘fencing’ (see Section 8.8.2). The manufacture of tall thin walls over a thin section of support material enabled the potential to design temporary casting channel features. The fencing could then be removed due to the flex from the thin wall and the brittleness of the support material section to reveal an exposed terminal with accurate tolerances. The technique was a faster and more flexible alternative to the previous use of separate plug moulds, and was crucial to the design of push fit installations for components such as batteries and microchips.

The specification of a minimum hole diameter was crucial to the practical application of spot melt installations (see Section 8.8.5). For permanent installations electrical components could be integrated into the circuit by pushing the electrical connections into the hole while the local volume of the circuit material was liquid. This hole would serve as a locator for the component while the circuit alloy froze around the connection.

Mapping the calibration zones required for the RP machine meant that jobs could be planned efficiently, extending the life of the foam plated.

It is important to remember that despite the fact that specifications were established for components to be made on the Stratasys Dimension RP machine, this should by no means restrict component designs for other machines or RP technologies.

6.12 Conclusion for RP machine performance research

Research into the Stratasys Dimension RP machine performance proved that it was possible to create the casting channels required for the RPEC technology.

Results yielded a specification for components to be used in RPEC. Experimentation covered and successfully defined:

- Casting channel parameters
- Support material requirements
- Minimum wall thickness
- Minimum hole diameter

Manufacture was also made more efficient by establishing the calibration zones needed by the RP machine. Placements of jobs were avoided in these areas to conserve the life of the foam plates.

6.13 RP machine performance specification reference

Please refer to *Manual for Technical Report 01/04: Rapid Prototyping Electronic Circuits* (Sells, 2004). This summary condenses all of the conclusions from Section 6 to form a minimum requirement specification - essential when designing RP components for electrical circuits. It has not been included in this section in order to eliminate possibility of uncontrolled update issues (which would undoubtedly occur if there were multiple copies of this specification).

7 CIRCUIT INCLUSION RESEARCH

7.1 Summary

This section analyses different methods of distributing Wood's metal into the casting channels of rapid prototyped components. The objective was to define a technique capable of integrating electronic circuits into mechanical parts in a manner which could be adopted easily by a rapid prototyping machine. This process would then be used to complete the second half of the RPEC technology.

The most successful alloy distribution method used continuously heated equipment to inject molten Wood's metal into the casting channels. The resultant circuit quality was good, and the process was considered acceptable for RPEC technology.

The high surface tension of the alloy allowed manipulation of the casting channels up to a 20 ° incline without disturbing the circuit.

Whilst the injection technique was developed for prototype manufacturing it demonstrated that molten alloy distribution could be done accurately and yielded an excellent circuit quality. It was noted that the principle would lend itself well to existing rapid prototyping technology which already relies on melting materials at a distribution head to enable deposition.

7.2 Introduction

After establishing the minimum specifications of the structural components (see Section 6), it was considered feasible to integrate the circuits into the rapid-prototyped parts by distributing Wood's metal into the casting channels. The essential technique to create the circuit would involve the use of Wood's metal as the conductive material. This alloy has a lower melting point (70 °C) than the ABS used for RP components. Therefore the alloy has the potential to be melted and distributed into the casting channels without harming the structural integrity of the component. The alloy can then be allowed to solidify to form the circuit. Two potential processes were investigated to achieve this goal:

- Molten distribution: deposition of molten Wood's metal into the casting channels.
- Solid particle distribution followed by flash melting: deposition of solid Wood's metal powder into the casting channels followed by heating the component over 70 °C to melt and fuse the powder and bond the circuit.

7.3 Experiment: Simple molten alloy distribution

7.3.1 Summary

A simple test piece was used for casting. Wood's metal (melting point 70 °C) was heated until molten, poured from a beaker into a casting well within the test piece and then distributed along the channels using a thin copper strip.

The results of the forged circuits were poor due to premature solidification of the metal. This made the process extremely difficult to perfect.

7.3.2 Introduction

The initial intended process incorporated casting channels into the design of the component as the first stage. The final stage assumed pouring molten metal into the channels thus casting an electronic circuit.

In order to cast successful circuits it was necessary to gain familiarity with the casting process. This experiment attempted the casting process using basic techniques.

7.3.3 Apparatus

- Leather gloves
- Thin copper strip (approximately 0.5mm wide)
- 1 cc Wood's metal
- Hacksaw
- Glass beaker
- Incubator
- Casting test piece from the experiment defined in Section 6.5 (detailed in Figure 26 and Figure 27).

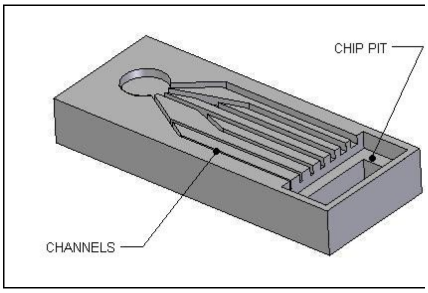


Figure 26: Casting test piece

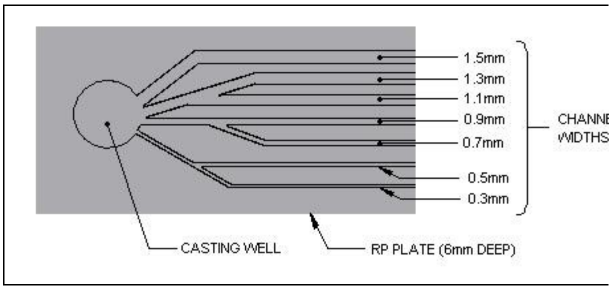


Figure 27: Casting channel width details

7.3.4 Method

The incubator was pre-heated to 85 °C.

A clear work space was made and the casting test piece was laid out on the bench.

The Wood's metal was cut from stock to the required volume using a hacksaw.

The volume of alloy was inserted into the beaker and then allowed to acclimatise in the incubator for 1.5 hours (i.e. until molten).

Gloves were worn at this point. Once the alloy was molten the beaker was extracted from the incubator using the leather gloves.

The beaker was then carried to the casting test piece and molten alloy was poured into the casting well.

The copper strip was used to drag the molten alloy down the casting channels.

Once distributed along the channels the molten alloy was allowed to cool and solidify.

7.3.5 Results

7.3.5.1 Procedural success

It was noted that the distribution of the liquid alloy from the casting well to the channels within the test piece was extremely difficult. A large amount of surface tension was noted within the molten alloy – this was detrimental to distribution.

The cooling rate was noted to be extremely fast under ambient conditions. This meant that the alloy was only molten for approximately 20 seconds.

7.3.5.2 Casting quality

This section assesses the quality of the forged circuits (Figure 28).

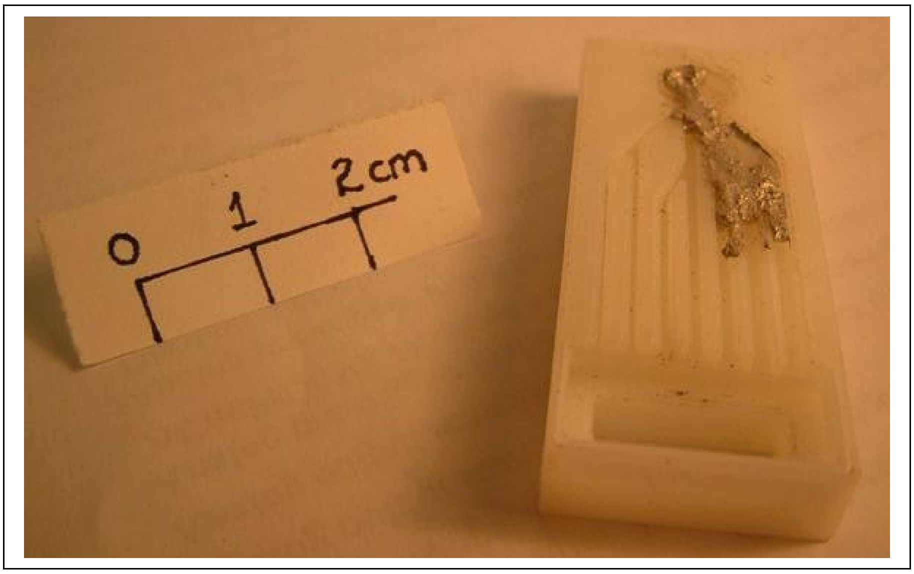


Figure 28: Initial casting piece

Owing to the short time available for the casting of the circuits (only 20 seconds due to premature solidification) it was not possible to distribute the metal into channels other than those listed in Table 7.

Table 7: Observations of the casting channels used for forging the test circuits

Channel width (mm)	Result
1.5	50% complete along length, uneven, overspill into adjacent channel
1.3	50% complete along length, uneven, overspill into adjacent channel
1.1	50% complete along length, uneven, overspill into adjacent channel
0.9	10% complete along length, uneven, overspill into adjacent channel

7.3.6 Discussion

Owing to the premature solidification it was considered unfair to analyse and compare the performance of the Wood's metal forged circuits between casting channel widths.

This test demonstrated that the casting process of molten Wood's metal was difficult and required more thought and preparation. The primary problem encountered during this test was premature freezing of the Wood's metal.

It was noted throughout the course of the experiment that there were many opportunities to stem the freezing rate. Potential improvements are listed below:

- Pre-heat the casting test piece with the molten alloy
- Pour the circuits on a hot plate set-up
- Using a soldering iron to aid distribution
- Use pre-heated syringes to distribute the molten alloy along the casting channels

A large amount of surface tension was noted within the molten alloy, making distribution problematic. It was considered that there would be a number of ways to solve this:

- Change the composition of the alloy to reduce the surface tension
- Apply a coating to the casting channels to allow them to be wet by the alloy and break the tension
- Apply the alloy to the channel in cold powder form and flash melt it
- Refine the existing technique to reduce the impact of surface tension

7.3.7 Conclusion

Simple distribution of molten alloy using a beaker was not suitable for the casting process. The method suffered from inaccurate distribution and premature freezing of the alloy.

It was noted that more consideration was required to prevent cooling of the alloy at all stages. Measures could also be taken to improve the surface tension characteristics of the alloy.

7.4 Experiment: Pre-heated molten distribution equipment

7.4.1 Summary

This experiment attempted to cast Wood's metal into casting channels of a rapid prototyped test piece. From the lessons learnt in Section 7.3 test equipment was preheated where possible to prevent premature freezing. A needle and syringe was also used to improve the accuracy of the deposition.

The alloy was kept molten for approximately 60 seconds. Syringe deposition was observed to be more accurate but pre-heating did not delay the freezing for long enough, thus general distribution was poor or incomplete.

7.4.2 Introduction

This experiment was designed to refine the casting method by using suggested modifications in Section 7.3.6 to delay the solidification of the molten alloy:

- Pre-heating the casting test piece in parallel with the molten alloy
- Forging the circuits on a hot plate set-up
- Using a soldering iron to aid distribution
- Using a pre-heated syringe to distribute the molten alloy along the casting channels

7.4.3 Apparatus

- Two pairs of disposable latex gloves
- Hacksaw
- 1 ml Wood's metal
- Glass petri dish
- Incubator
- Dri-block D8-3 hotplate
- 5 ml BD Plastipak syringe
- 500 µm x 16 mm Monoject needle to accommodate 5ml syringe
- Test piece (Figure 29 and Figure 30)

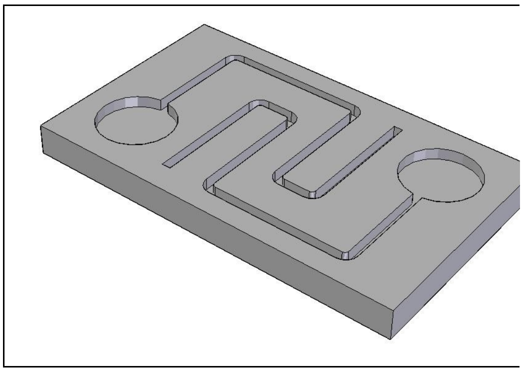


Figure 29: Casting test piece

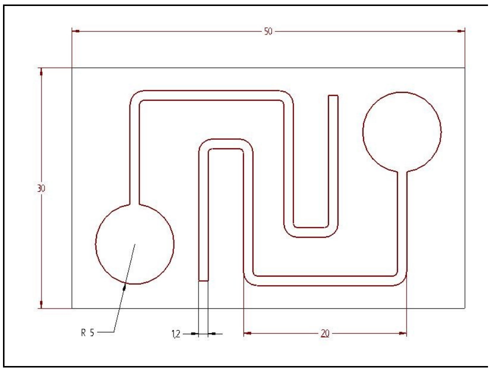


Figure 30: Casting channel details

7.4.4 Method

The incubator was pre-heated to 90 °C.

The hotplate was pre-heated to 90°C.

The required volume of alloy was cut from stock to using a hacksaw, and then placed on the Petri dish.

The following was loaded into the incubator for 1 hour (until everything had acclimatised to 90 °C): casting test piece, syringe, needle, Wood’s metal and petri dish.

Gloves were worn at this point, and the soldering iron was switched on.

The incubator was opened, and whilst still in the incubator Wood’s metal was drawn into the syringe (without the needle) and laid to rest on the petri dish.

The casting test piece was quickly transferred to the hotplate.

The syringe was transferred to the hot plate and molten alloy was injected into the first casting well on the test piece. The soldering iron was used to drag the molten metal along the casting channels.

The syringe was then transferred back to the incubator, the nozzle cleaned and the needle installed. The syringe was transferred to the hot plate and molten alloy was injected into the second casting well of the test piece.

Procedural observations were recorded.

The incubator and hotplate were switched off and the casting test piece was allowed to cool.

Observations of forging quality were recorded.

7.4.5 Results

7.4.5.1 Procedural analysis

Molten alloy within the syringes remained molten for approximately 40 seconds.

When molten, the alloy flowed freely from the syringe when required. The drop size from the orifice varied between approximately 1 mm and 3 mm.

Excluding one attempt, molten metal could not be ejected through the needle due to premature freezing causing blockage within the needle. On the one brief success at this trial molten alloy was ejected in thin, accurately-directed and uniform stream.

Molten metal in contact with the casting test piece remained molten while the hotplate was on (at 90 °C).

Distribution of the molten alloy from the casting well to the channels within the test piece using the soldering iron was compromised because the tip exceeded the melting point of the test piece material, thus it destroyed the integrity of the casting channels.

7.4.5.2 Casting quality

This section assesses the quality of the forged circuits (Figure 31).

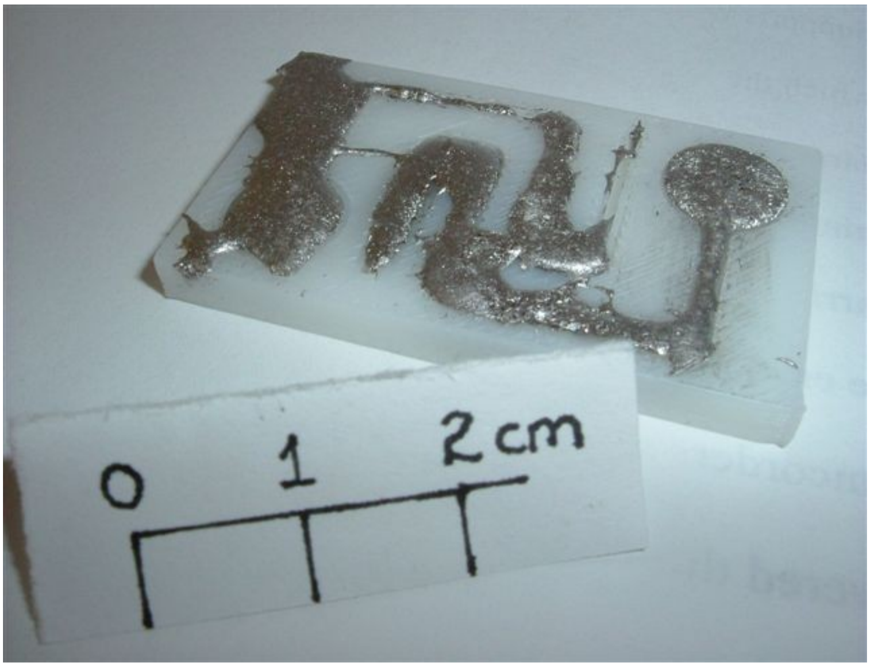


Figure 31: Casting result after using pre-heated equipment

Channels were disfigured and forged circuits in nearly all areas were either spilling out of the channels or incomplete.

7.4.6 Discussion

Preheating the syringes was successful in the respect that it was possible to draw up the molten alloy and eject it where necessary. However, the nature of its use meant that despite being used above the hotplate the cold ambient temperature eventually disabled its use by freezing the alloy.

The use of the syringe and needle (when operational) certainly enabled more accurate deposition. It is therefore worth investigating a continuously heated syringe assembly to enable continuous molten deposition.

The use of the hotplate to maintain the temperature of the casting piece was a success. Deposited alloy remained molten until the hot plate was switched off which was extremely useful to manipulate the distribution.

The soldering iron was successful in the respect that it moved the molten alloy around within the circuits freely. However, its excessive temperature melted the casting channel material and so needed to be moderated.

Overall the steps taken to maintain the alloy above its melting point meant an improvement of 60 seconds working time. However, this was not enough and it was noted that further temperature control was required of the deposition and distribution equipment.

7.4.7 Conclusion

Modifications to equipment using pre-heated treatment were not enough to yield enough distribution time. It was noted that the experiment should be repeated using continuously heated equipment to eliminate the possibility of alloy freezing at any stage of the process.

7.5 Experiment: Continuously heated equipment for molten distribution

7.5.1 Summary

This experiment attempted to inject molten Wood's metal into casting channels of a rapid prototyped test piece. From the lessons of previous experiments, all test equipment was continuously heated. It was found that the use of a syringe hot jacket complemented the use of the hot plate to completely eliminate the problem of premature freezing.

The thin needle also enabled accurate deposition which eliminated the need for casting wells and a distribution aid (e.g. soldering iron) and also reduced major spills. The best performance was found when the casting channel was slightly overfilled before using the syringe to apply suction to the alloy. This drew the alloy into the channel and gave excellent consistency to the circuit quality.

The results from this experiment yielded circuits of a high quality. This indicated that the continuously heated injection process was viable for casting electronic circuits using molten Wood's metal.

7.5.2 Introduction

This experiment was designed to test the use of a continuously heated needle and syringe assembly specifically designed for the task of injecting molten Wood's metal into the casting channels of a rapid prototyped component.

7.5.3 Apparatus

- Two pairs of disposable latex gloves
- Hacksaw
- 1 ml Wood's metal
- Glass petri dish
- Techne Dri-Block D8-3 hot plate oven
- 5 ml BD Plastipak syringe
- 500 µm x 16 mm Monoject needle to accommodate 5ml syringe
- Test piece as described in Section 7.4.3.
- RS200-2531 pneumatic in-line air heater (750 Watts)
- Syringe hot-jacket (Figure 32 and Figure 33)
- Thermocouple

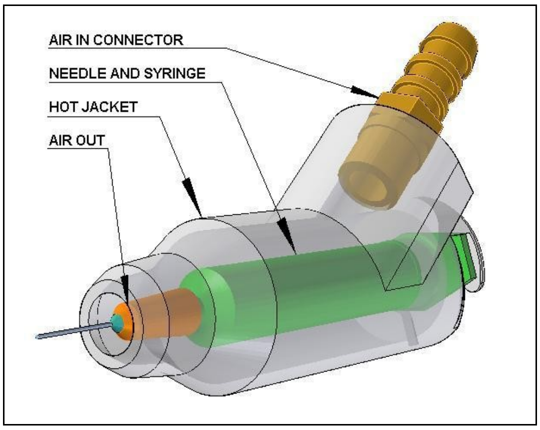


Figure 32: Hot-jacket assembly designed to maintain needle and syringe in excess of 70 °C (front view)

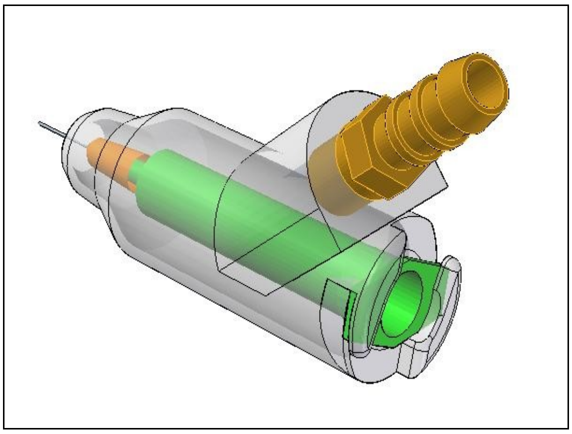


Figure 33: Hot-jacket assembly (rear view)

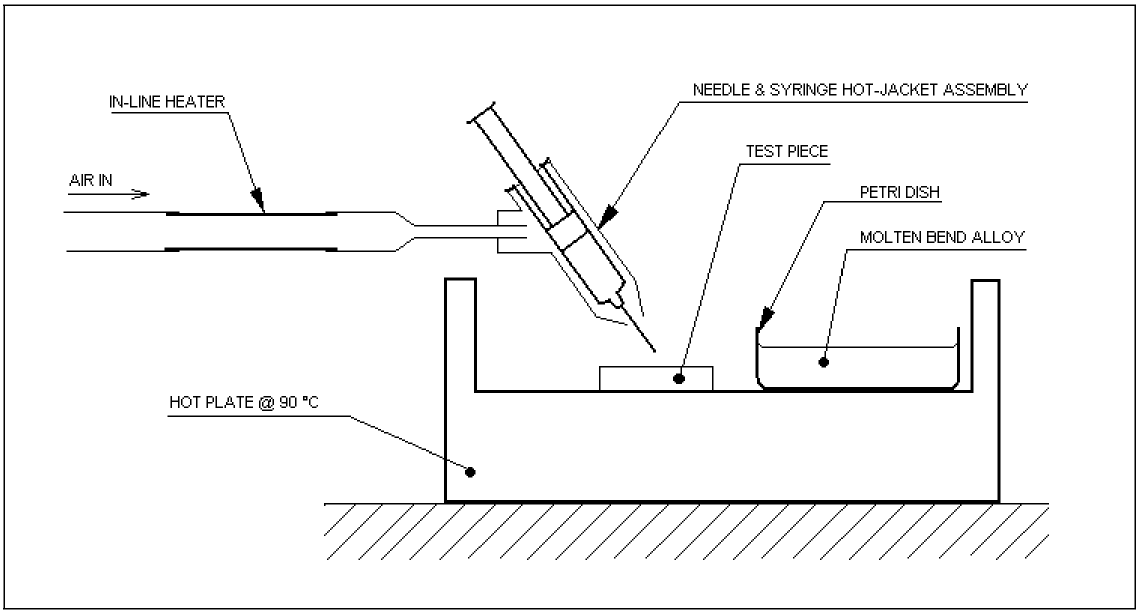


Figure 34: Apparatus set-up for the injection process

7.5.4 Method

The hotplate was pre-heated to 90°C.

The required volume of Wood’s metal was cut from stock to using a hacksaw, and then placed on the Petri dish.

The following was loaded onto the hotplate for 15 minutes (until everything had acclimatised): casting test piece and Wood’s metal in petri dish. During this heating time the lid on the hot plate was closed to achieve 90 °C faster.

Gloves were worn at this point.

A needle and syringe were assembled and loaded into the hot-jacket. The assembly was preheated for five minutes using an air pressure of approximately 6 psi and a voltage over the in-line heater of approximately 120 Volts. A thermocouple was use to maintain an exit air-flow temperature (from the hot-jacket) of approximately 90 °C.

Once the apparatus on the hotplate had acclimatised to 90 °C, the hot jacket air pressure was reduced to approximately 0.5 psi (so the airflow would not blow away the alloy) and the voltage over the heater reduced to 80 Volts (reduced under low airflow conditions to achieve an air-over-needle temperature of 80 °C).

Molten alloy was sucked into the syringe from the petri dish and than injected into the test piece as demonstrated in Figure 34.

Procedural observations were recorded.

The hotplate was switched off and the casting test piece was allowed to cool.

Observations into forging quality were recorded.

7.5.5 Results

7.5.5.1 Procedural analysis

Handling of the hot jacket assembly was sufficiently ergonomic as demonstrated in Figure 35.

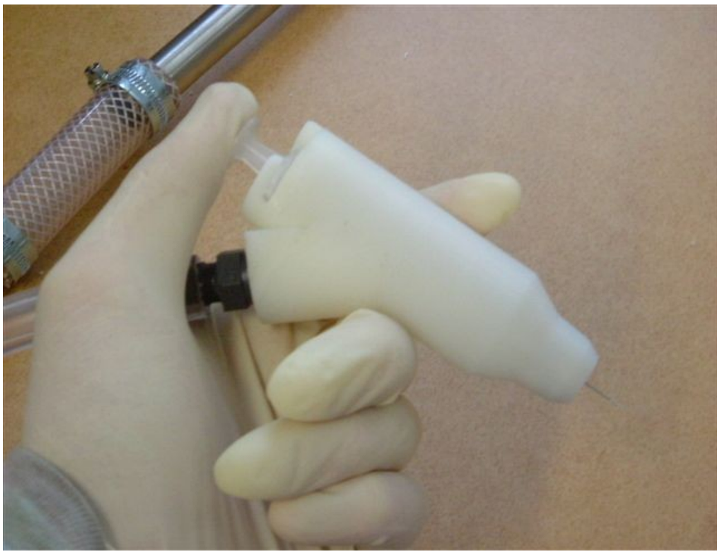


Figure 35: Hot jacket handling

Drawing the molten metal required a large amount of suction from the syringe, however, premature freezing did not cause a blockage.

Ejection of the molten alloy into the casting channels through the 500 µm needle resulted in much less overspill than the previous experiment (Section 7.4) which had used the 2 mm diameter syringe without the needle. Accurate deposition was also possible. However more control was needed to ensure an even distribution.

Surface tension made distribution within the channel awkward, however, it was discovered that the best technique was to overfill the channel slightly, followed by a small amount of suction from the syringe to draw the molten alloy down into the channel. This gave an excellent even consistency to the circuit (Figure 38).

It was not necessary to fill the casting wells to forge the circuit as the needle deposited the alloy accurately enough.

The circuit was able to be manipulated at any time during the experiment because it was molten for the duration that the hotplate was on.

7.5.5.2 Forging quality

Figure 36 demonstrates a clear improvement using the equipment in this experiment:

- Channels suffered much less overspill
- Channel integrity was maintained because none of the equipment exceeded the melting point of the casting test piece

- Casting wells were not required for distribution
- Circuit consistency was generally even

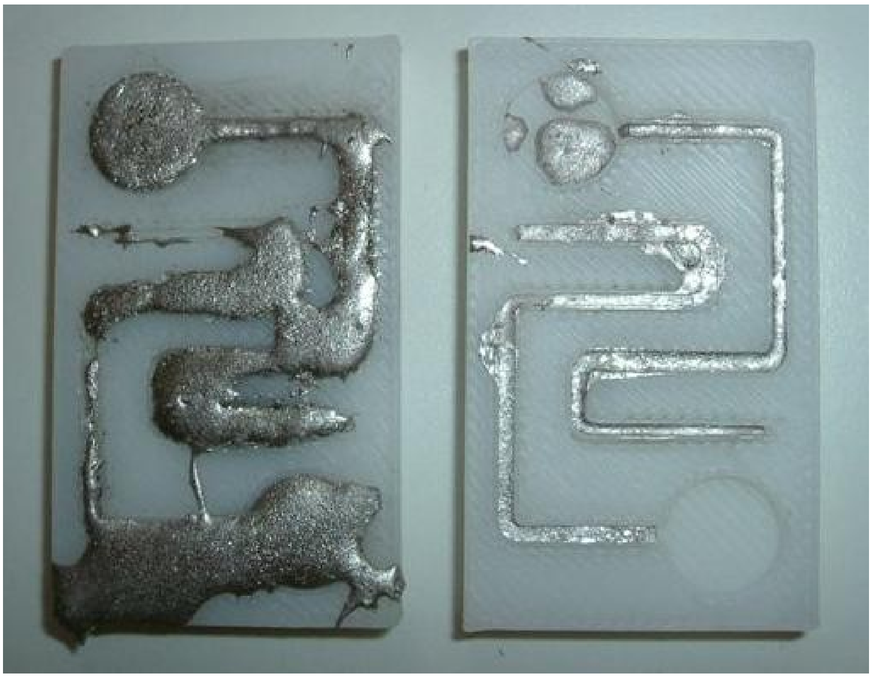


Figure 36: Comparison between alloy distribution using 2000 µm syringe orifice from experiment described in Section 7.4 (left) and the 500 µm needle orifice used in this experiment (right).

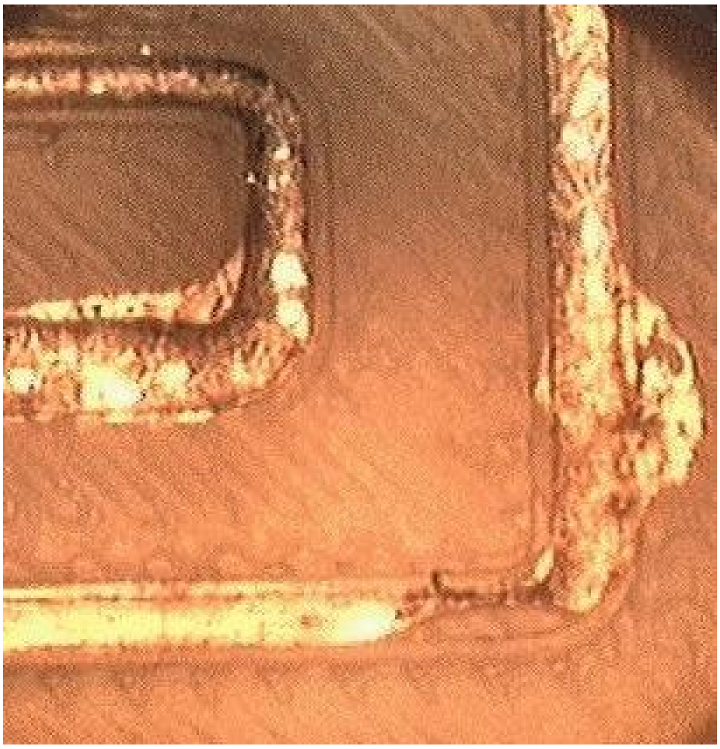


Figure 37: Identification of over-spilled areas using the 500 µm needle

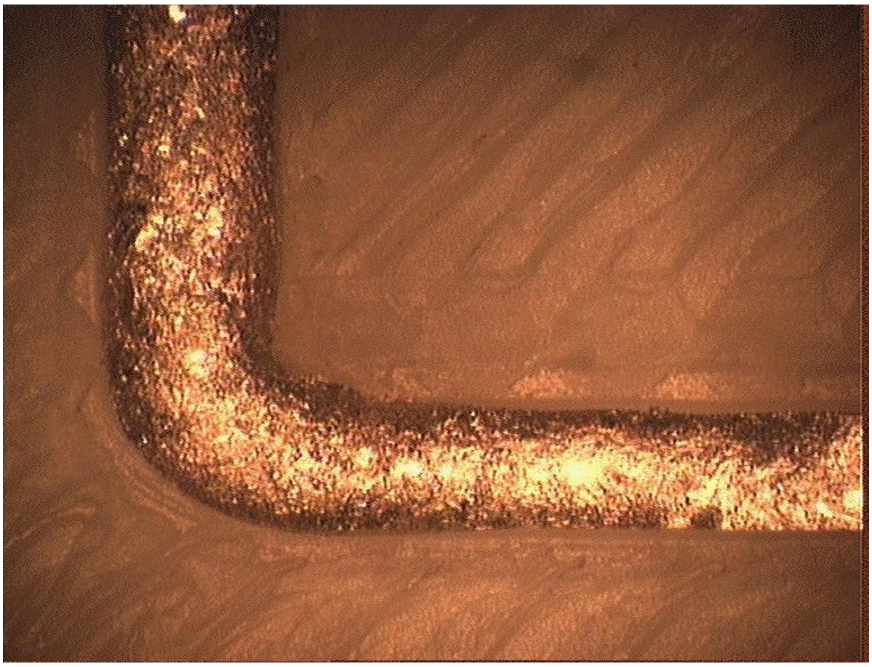


Figure 38: Magnification of forged circuit around 90 ° bend (channel width 1.2 mm). Circuit is consistent and does not suffer from overspill.

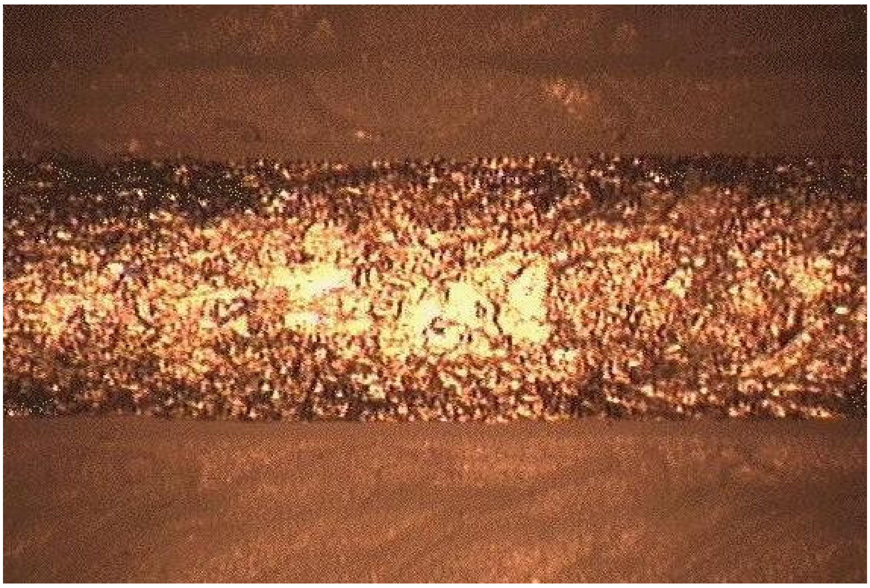


Figure 39: Magnification of forged circuit along straight channel (width 1.2 mm). Central light reflection indicates concave top surface.

7.5.6 Discussion

The hot jacket assembly yielded a process with the potential to cast reliable circuits.

The accuracy of the deposition eliminated the need for casting wells to be incorporated into the design.

The best results were achieved when the casting channel was slightly overfilled before applying suction to draw the alloy down into the channel. The resultant consistency of the circuits was generally good.

Slight overspills in areas were all due to inexperience with the technique. Due to the complete elimination of premature freezing this process showed a potential to be perfected and improved upon.

7.5.7 Conclusion

This experiment proved that the hot jacket assembly had the potential to be a viable process for casting electronic circuits using molten Wood’s metal.

7.6 Experiment: Metalised casting channels

7.6.1 Summary

This experiment attempted to inject molten Wood's metal into casting channels of a rapid prototyped test piece. The casting channels were metalised before casting in the hope that this would overcome some of the surface tension problems by enabling the alloy to wet to the channel surface.

Unfortunately the metalisation process did not yield any significant improvements for the molten alloy distribution

7.6.2 Introduction

This experiment was designed to test the effectiveness of pre-treating the casting channels by metalising them. This was intended to overcome the surface tension within the alloy, noted in Section 7.3, by enabling the alloy to wet to the side of the channels.

7.6.3 Apparatus

- Two pairs of disposable latex gloves
- Hacksaw
- 1 ml Wood's metal
- Glass petri dish
- Techne Dri-Block D8-3 hot plate oven
- 5 ml BD Plastipak syringe
- 500 µm x 16 mm Monoject needle to accommodate 5ml syringe
- RS200-2531 pneumatic in-line air heater (750 Watts)
- Syringe hot-jacket
- Thermocouple
- Test piece as described in Section 7.4.3.
- Gold sputtering machine.

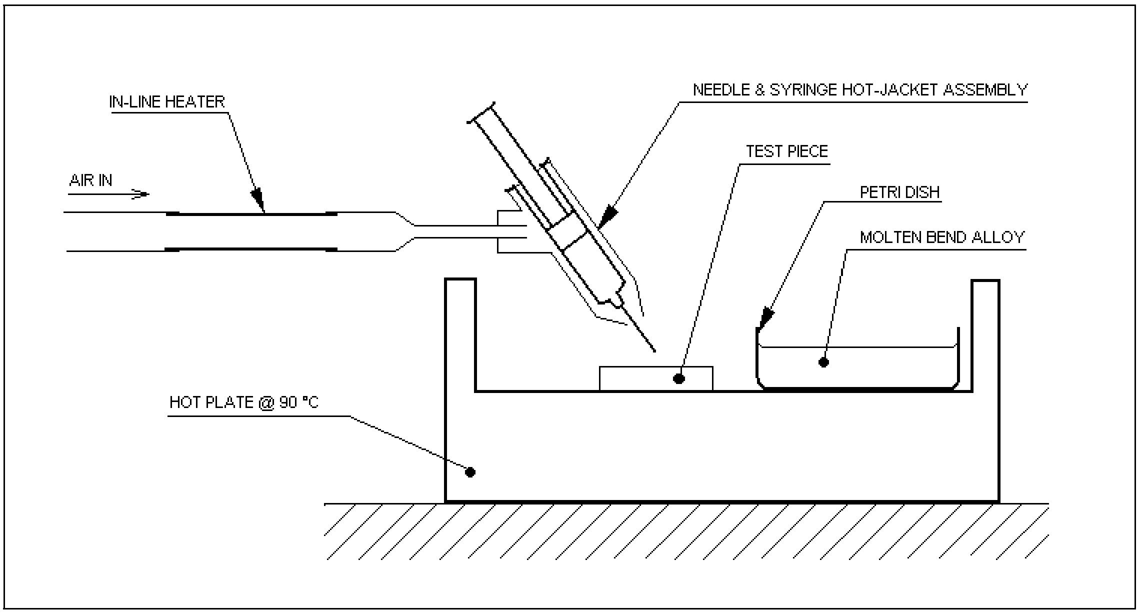


Figure 40: Apparatus set-up for the injection process

7.6.4 Method

7.6.4.1 Test piece preparation

The test piece was cleaned with detergent, dried and then inserted into the gold sputtering machine. A layer of approximately 10 µm was applied to the top surface of the test piece

Figure 41: Gold sputtering machine

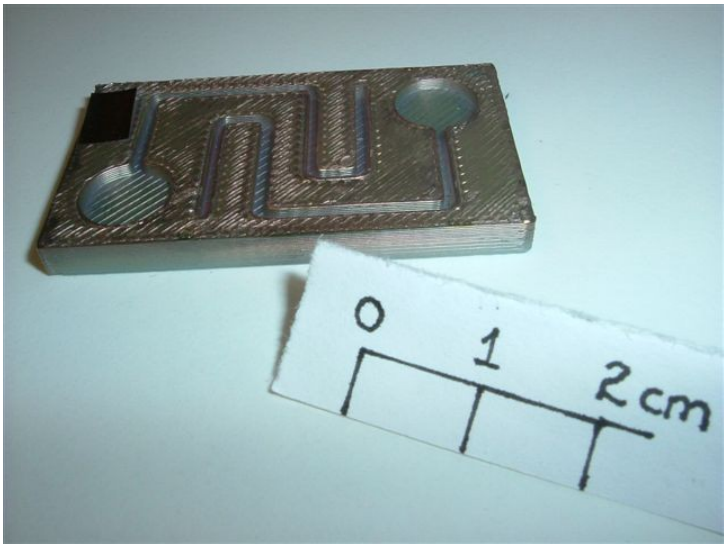


Figure 42: Treated test piece with 10 µm gold coating

7.6.4.2 Casting method

The casting method was identical to that defined in Section 7.5.

7.6.5 Results

7.6.5.1 Procedural analysis

The ability to distribute the alloy within the test piece on the metalised channels was not significantly easier than on the un-treated channels.

Wetting was not observed.

7.6.5.2 Forging quality

Overspill and circuit characteristics were similar to those found previously with no visible improvement due to the metalisation.

Figure 43: Magnification of casting channel on metalised test piece (casting channel width 1.2 mm)

7.6.6 Discussion

There were no visible improvements by metalising the casting channels.

This was partially due to the nature of the test. The initial test process required an implement to drag the molten alloy from the casting well along the channels. Surface tension made this problematic and thus the idea of metalising the casting channels was conceived. However, because the dragging element had been eliminated with accurate deposition by using a needle and syringe the distribution advantages of metalising the channels were not pronounced.

It was thought that metalising the channels might also improve the quality of the circuit. However magnification has shown no distinct benefit. This is likely to be due to the fact that the thickness of the gold filament was surmounted by the surface roughness of the channel. Also the vertical faces of the channels were exposed to less metalisation due to the unavoidable orientation of the test piece during the sputtering process.

7.6.7 Conclusion

Metalising the channels did not improve the casting process or circuit quality and need not be included in further tests.

7.7 Experiment: Wood's metal powder manufacture

7.7.1 Summary

This experiment was devised to manufacture Wood's metal powder from ingot stock which would then be tested as an alternative method to forging an electronic circuit.

Once the alloy had been melted, air was blown through a Venturi spray nozzle to blow small globules of molten alloy into a bucket of cold water. The globules solidified on contact with the water and were collected using filtration technique. This test featured a hot air supply to prevent premature freezing and blockages.

The use of the hot air proved a complete success and the quality of the powder collected was found to be ideal for cold casting (particle diameters ranging from 50 µm to 1000 µm diameter).

The manufacture process could be refined by using a more efficient apparatus geometry to minimise waste.

7.7.2 Introduction

The intended circuit inclusion process incorporated casting channels into the design of the component and, on completion, poured molten metal into the channels thus casting an electronic circuit. Following problems with surface tension of the molten alloy (noted in Section 7.3.6) it was thought that using a cold casting method (i.e. powder distribution followed by flash melting) might be a alternative solution.

This test was devised to investigate the potential of creating Wood's metal powder using a Venturi spray nozzle. This test featured a hot air supply to ensure all elements of the apparatus in contact with the alloy were above 70 °C to avoid premature freezing and blockage.

7.7.3 Apparatus

- Leather gloves
- Wood's metal ingot
- Aluminium block of high thermal mass
- Hacksaw
- Glass Petri dish
- Techne Dri-Block DB-3 Hotplate
- Cold water (ambient temperature)
- Bucket
- RS 200-2531 in-line air heater

- Venturi spray nozzle (material inlet pipe: ø 2 mm x 18 mm, air outlet pipe: ø 5mm) connected to hot air supply with regulator
- Filter paper and funnel

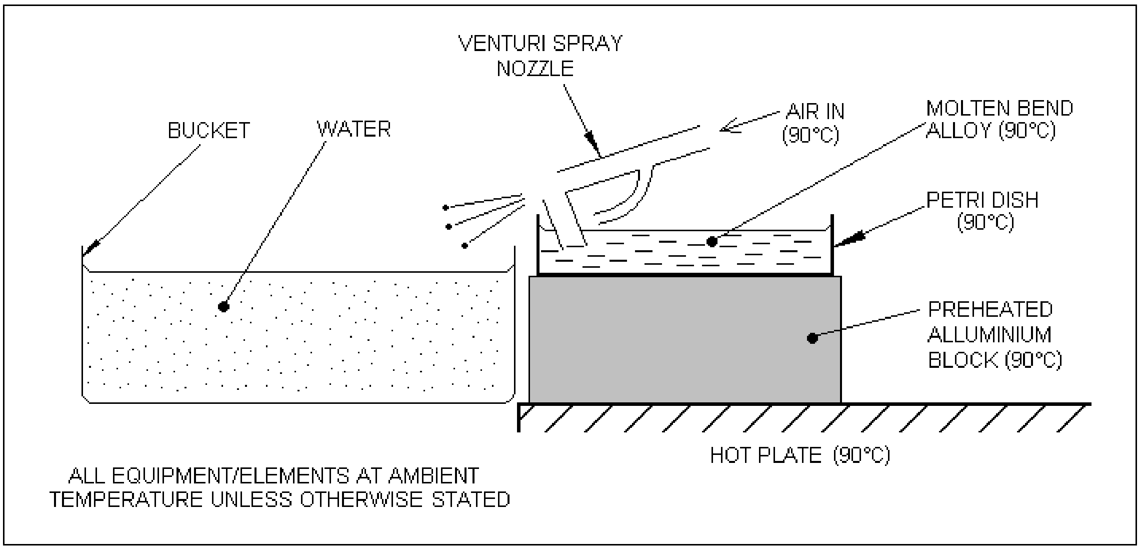


Figure 44: Apparatus set-up to manufacture Wood's metal powder from molten stock

Figure 45 demonstrates Venturi spray nozzle and an extra heating line.

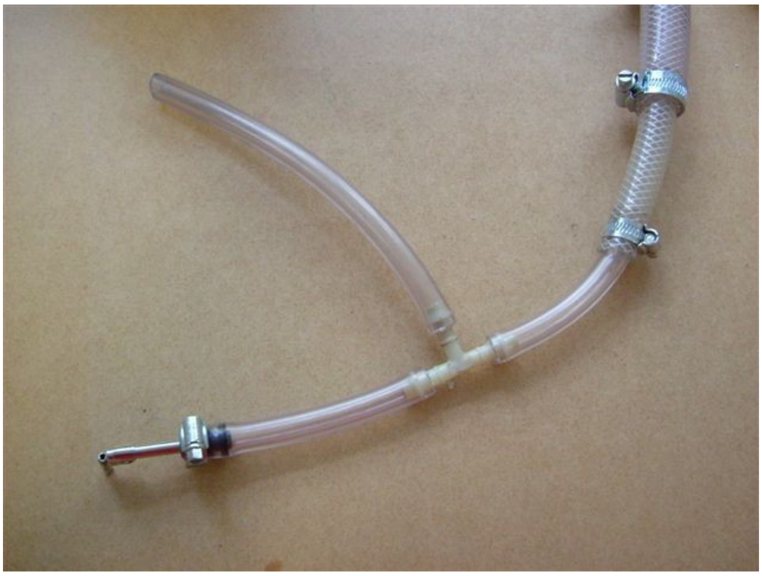


Figure 45: Venturi nozzle and extra heating line setup featuring t-connector to split the heated air line

7.7.4 *Method*

The hotplate was pre-heated to 90 °C.

The Wood's metal was cut from stock to 2 cm^3 using a hacksaw.

The volume of alloy was inserted into the petri dish and then allowed to acclimatise in the hotplate for until molten (approximately 30 minutes).

A clear workspace was made, the bucket was filled with water and the Venturi spray nozzle was connected to the air supply. The in-line heater was connected between the supply and the nozzle. A heating line was connected between the heater and the nozzle (Figure 45).

Gloves were worn. The air supply was turned on to 7 psi and the heater was supplied with 140 Volts.

A thermocouple was used to check the temperature of the air from the nozzle to be approximately 90 °C.

Once the alloy was molten the petri dish was mounted on the aluminium block to be above the level of the hot plate.

The apparatus was assembled as shown in Figure 44. The heating line was directed over the material intake pipe on the nozzle to bring to approximately 90 °C.

The material intake tube was lowered into the molten alloy whilst aiming the output nozzle towards the bucket and the air supply pressure was gradually increased. Meanwhile the heating line was directed over the material intake orifice.

Once completed the air supply was switched off.

The bucket was drained through a sieve. Particles were collected in filter paper and funnel and allowed to dry.

Particles were then observed and analysed.

7.7.5 Results

7.7.5.1 Procedural success

There were no premature freezing incidents, and therefore no blockages during manufacture. The heating line was simple to use and effective at maintaining the temperatures of both the alloy and the material intake pipe.

Waste was high due to an awkward makeshift set-up. Figure 46 demonstrates waste on the hotplate, sides of the water bucket and surrounding areas.

Figure 46: Physical apparatus set-up

It was noted that the movement of particles at high speed required the use of safety goggles.

7.7.5.2 Visual results

37.5 g of Wood’s metal particles were collected from the bucket. These were found to range from approximately 50 µm to 1000 µm in diameter (Figure 47).

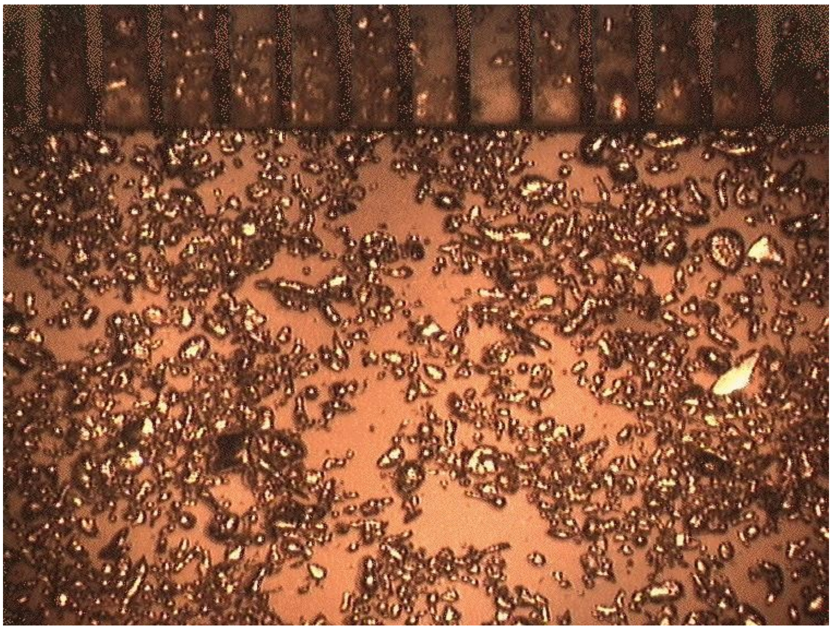


Figure 47: Magnification of solidified alloy particles (powder). Vertical lines on top of photo represent 1 mm increments.

7.7.6 Discussion

The procedure was a success. This is testament to the efforts made to maintain all elements of the apparatus in contact with the molten alloy above 70 °C.

The process should be refined further by configuring the apparatus to achieve a better spray geometry. This will greatly reduce the waste.

Larger particles were later removed easily with a fine sieve.

7.7.7 Conclusion

The use of hot air in the Venturi nozzle made the process of Wood's metal powder manufacture viable.

Should more powder be required, this process should be used with a more efficient apparatus geometry to minimise waste.

7.8 Experiment: Powder distribution and flash melting

7.8.1 Summary

This experiment attempted to cast Wood's metal into the casting channels of a rapid prototyped test piece. This was done by packing powdered Wood's metal into the test piece casting channels and then heating the entire test piece briefly above the melting point of the alloy.

Owing to high surface tension properties of the alloy, flash melting was ineffective at creating a uniform structure circuit from the powder. This meant that the circuit was unacceptably weak.

7.8.2 Introduction

The intended circuit inclusion process incorporated casting channels into the design of the component and, on completion, poured molten metal into the channels thus casting an electronic circuit. Following problems with surface tension of the molten alloy (noted in Section 7.3.6) it was thought that using a cold casting method (i.e. powder distribution followed by flash melting) might offer an alternative solution.

This test used the alloy powder from the experiment defined in Section 7.7. The powder was distributed into the channels and then briefly heated above 70 °C to melt and bond the circuit before being allowed to freeze.

7.8.3 Apparatus

- Two pairs of disposable latex gloves
- Wood's metal powder from the experiment defined in Section 7.7
- Test piece as described in Section 7.4.3.
- Techne Dri-Block D8-3 hot plate oven

7.8.4 Method

The hotplate was pre-heated to 90°C.

Wood's metal powder was poured over the test piece and any excess was shaken off the test piece.

The test piece was placed in the hotplate and the lid was lowered.

After 15 minutes the hotplate was switched off and the casting test piece was allowed to cool.

Observations into forging quality were recorded.

7.8.5 Results

7.8.5.1 Procedural analysis

Filling the casting channels was a simple process because the powder was cold and could be manipulated manually. However, due to the rough texture of the top surface of the test piece it was extremely difficult to remove particles of alloy which escaped the channel during distribution.

7.8.5.2 Forging quality

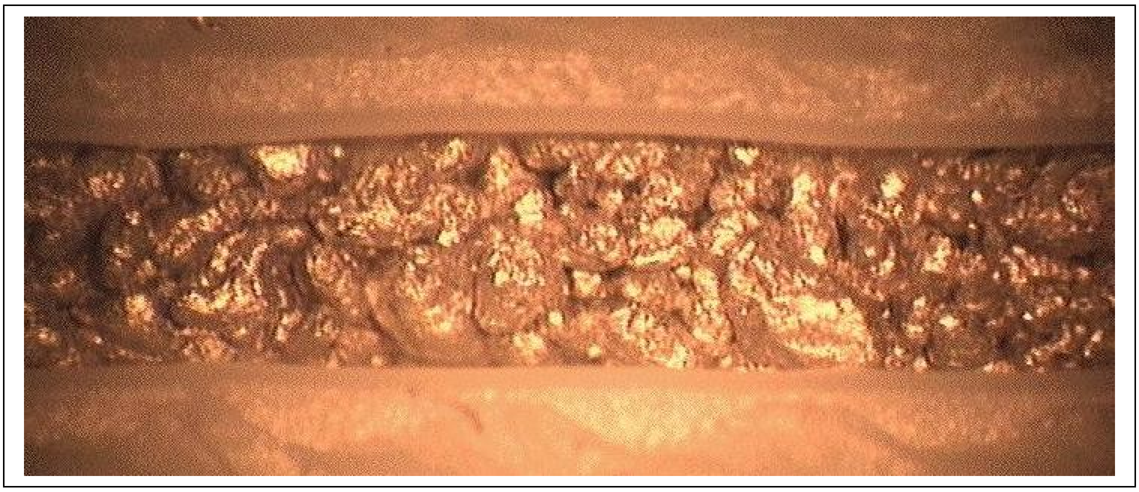


Figure 48: Close magnification of circuit (channel @ 1.2 mm width) made from powdered alloy after flash melting. Note powdered structure still remains despite heating.

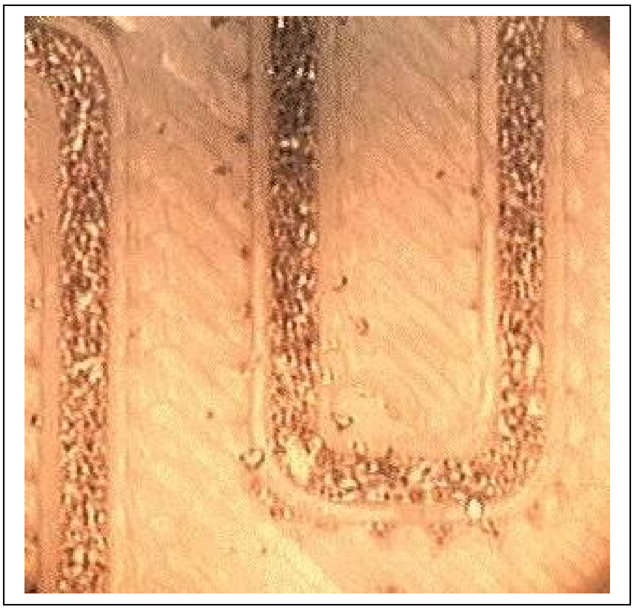


Figure 49: General view of powdered circuit after flash melting

When the test piece was exposed to a light shock force the circuit quickly disintegrated, fell apart and emptied out of the casting channel.

7.8.6 Discussion

Despite initial benefits of simple distribution due to manageable temperatures, it was noted that removing rogue powder particles was extremely difficult.

From observations it was obvious that, despite melting, the individual particles maintained their several structure. This was likely due to the high surface tension of the alloy. Unfortunately, the granular structure greatly weakened the circuit.

7.8.7 Conclusion

Owing to high surface tension properties of the alloy, flash melting was ineffective at creating a uniform structure circuit from the powder. This meant that the circuit was unacceptably weak.

7.9 Experiment: Maximum channel incline

7.9.1 Summary

This experiment was devised to identify the maximum channel incline allowable to maintain a stagnant fluid state of molten Wood’s metal post-injection.

Injection trials were conducted by using channel inclines of increasing severity on a test plate. The maximum channel incline which could maintain a stagnant fluid state was found to be 20°. This should be taken into account during circuit design.

7.9.2 Introduction

In order to continue a circuit between levels it was thought that there might be a necessity to incorporate inclined channels into the design. This test was designed to determine the maximum channel incline allowable to maintain a stagnant fluid state of molten Wood’s metal post-injection.

It was noted in previous tests that the Wood’s metal had a high surface tension value. The ability to cast molten alloy into a stagnant state, whilst on an incline, takes advantage of this property.

It was also noted that there were several factors which would affect this value: channel cross sectional area, channel geometry, length, surface finish and alloy temperature. Whilst it was considered important to investigate these factors, this test was designed to establish basic preliminary data, with every effort isolating the incline angle as the only variable.

7.9.3 Method

A test piece with varying channel inclines was designed (Figure 50 and Figure 51).

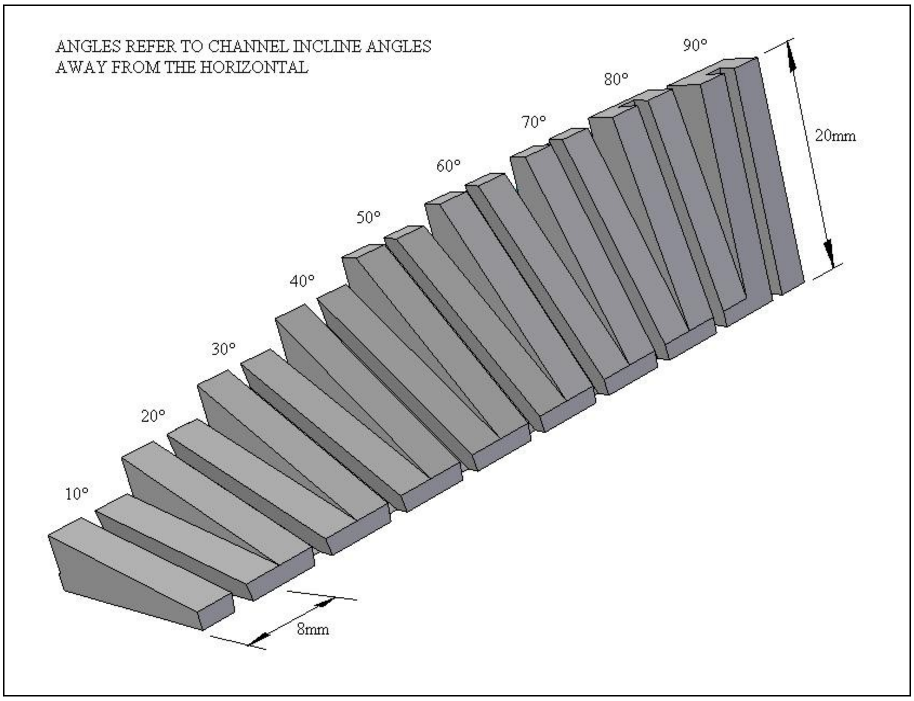


Figure 50: Isometric view of test plate showing increasing channel inclines of 20 mm length

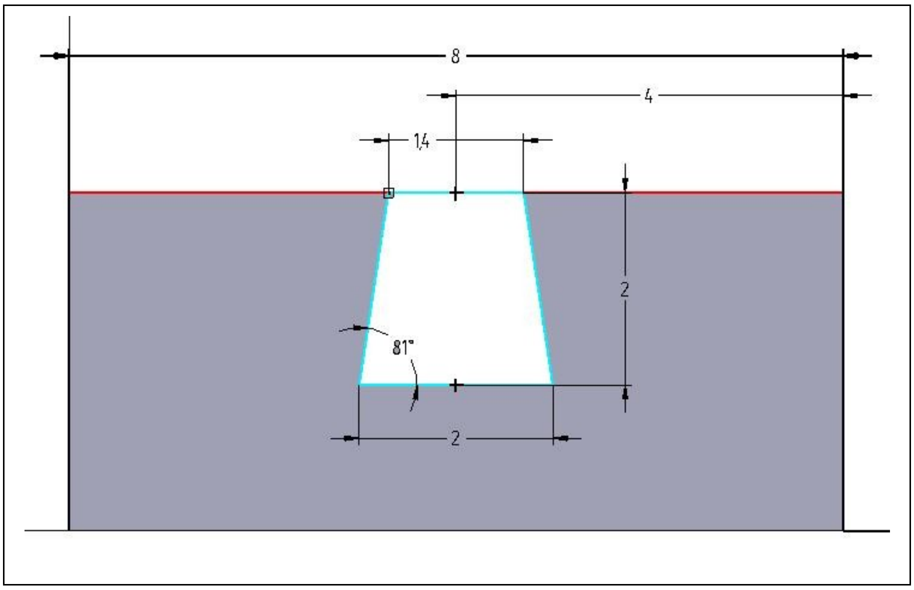


Figure 51: Identification of cross section channel geometry consistent between inclines

The piece was then manufactured on the RP machine using an identical method to that described in Section 6.5. Alloy was injected into the channels as defined in Section 7.5.

Injection was started 2 mm from the top of each channel and worked downwards.

7.9.4 Results

Casting quality was recorded in Table 8.

Table 8: Casting results for increasing channel inclines

Channel	Incline angle from the horizontal	State on injection? (Stagnant/fluid)	Response to suction forming with syringe	Channel quality on solidification
1	10°	Stagnant	Good	Good
2	20°	Stagnant	Good	Top of casting was lited back towards the horizontal.
3	30°	Fluid	Fluid escaped	Thin alloy film remained
4	40°	Fluid	Fluid escaped	Thin alloy film remained
5	50°	Test abandoned		
6	60°			
7	70°			
8	80°			
9	90°			

7.9.5 Discussion

It was clear that casting under the conditions defined within this experiment should not have been attempted on channels with a greater incline of 20 °.

This eliminated the possibility of using inclined channels as a link between circuits of different altitudes.

However, the fact that casting was possible for inclines of 10 ° and to some extents 20 ° was encouraging for the sensitivity of the injection process.

7.9.6 Conclusion

This test concluded that channels should not be inclined above 20 ° from the horizontal during the casting process.

7.10 Discussion for Circuit inclusion

Two different basic circuit inclusion techniques were tested and analysed.

The first technique for including circuits in rapid prototyped components was molten distribution. After testing several different methods, the final solution used continuously heated equipment to prevent premature freezing and a needle and syringe to ensure accurate deposition. Custom equipment was designed to enable continuous heating using a hot air. The results of the finished circuit using this technique were extremely positive. Circuits were robust and simple to cast into the channels.

The only distribution problem using this technique was because of the high surface tension within the alloy. This made it difficult for the alloy to flow along the casting channels. One attempt to relieve this problem was made by using a gold sputtering machine to metalise the casting channels. Unfortunately this did not make any significant difference to relieving the problem.

However, it was noted that the high surface tension was on occasion quite useful. This property meant that a liquid section of alloy within a channel could maintain its shape up to an incline of approximately 20 °. This meant that handling procedures (while it was in mid-casting process) was not a problem as it was quite difficult to disturb the molten-state circuit.

The second integration technique involved the distribution of Wood’s metal powder into the casting channel before heating the component briefly above 70 °C. Whilst a good powder manufacture technique was established, there was a major problem with the distribution technique. Because of the high surface tension the alloy particles would maintain their shape even when molten, only binding with other alloy particles at point contacts. This resulted in circuits with granulated structures which were extremely weak.

The continuously heated injection method, whilst appropriate for the prototype stage, demonstrated an important principle which could well be incorporated into the production phase. The proof that it was possible to distribute molten alloy from a point inspired the thought that it would be possible to use a similar distribution head within the machine to automate the process. Seeing as this is exactly how the Stratasys Dimension rapid prototyping machine works for the deposition of its structural and support materials, it was noted that the adoption of the technique into existing technology was a real possibility.

7.11 Conclusion for Circuit inclusion

A successful circuit inclusion technique was discovered by using continuously heated equipment to inject molten Wood's metal into the casting channels. The resultant circuit quality was acceptable for it to be adopted as part of RPEC technology.

The high surface tension of the alloy allowed manipulation of the casting channels up to a 20 ° incline without disturbing the circuit.

Whilst the injection technique was developed for prototype manufacturing it demonstrated that molten alloy distribution could be done accurately and yielded an excellent circuit quality. It was noted that the principle would lend itself well to existing rapid prototyping technology which already relies on melting materials at a distribution head to enable deposition.

7.12 Circuit inclusion specification reference

Please refer to *Manual for Technical Report 01/04: Rapid Prototyping Electronic Circuits* (Sells, 2004). This summary condenses all of the conclusions from Section 7 to form a circuit inclusion specification. It has not been included here in this section to eliminate possibility of uncontrolled update issues (which would undoubtedly occur if there were multiple copies of this specification).

8 DESIGN EXAMPLE OF RPEC TECHNOLOGY: ROBOT

8.1 Summary

A simple robot design was chosen to demonstrate the RPEC technology. Whilst there was a need for the robot to perform an interesting function the emphasis was not on the implications of this function. The purpose of the robot was simply to demonstrate that an electro-mechanical system could be manufactured using only RPEC technology and its allowable exceptions (supply of standard electrical components and simple manual assembly).

Modular construction techniques were used to enable research in to the complex elements of the design and limit failure impact. However, the complete manufacturing success of the final components indicated that component manufacture need not be modular for production purposes. This was encouraging for the future scale-up of RPEC technology.

Further research was carried out to install standard electronic components (*e.g.* capacitors, microchips and motors), resulting in the development of two new specialised techniques: ‘fencing’ and ‘spot-melting’. These ensured the reliable and functional installations of standard electrical components.

The robot was a complete success. It fulfilled 100% of its requirement specification thus proving that RPEC technology worked.

This exercise highlighted the point that the next development for the circuit inclusion element of RPEC would therefore be to design and construct a motorised injection mechanism which could deliver steady state deposition on a motorised axis providing constant velocity.

8.2 Design Brief

The robot was expected to move forward on a smooth flat surface until it collided with a stationary object. On collision it was to recognise that a collision had occurred and pause. The robot was to reverse, rotate 45° and then continue reversing until the next collision at which point the function had to be repeated. It was expected that the decisions based on the input were to be controlled using a pre-programmed IC microcontroller.

8.3 Robot specification

8.3.1 Rules of Manufacture

The robot had to be manufactured using RPEC technology.

Six standard elements (as defined by Bowyer, 2004) were allowed to be incorporated into the design if needed:

- Self tapping screws
- Brass bushes
- Lubricating grease
- Standard electronic chips such as microcontrollers and optical sensors
- A standard plug in low voltage power supply
- Stepper motors

People were allowed to perform basic assembly procedures.

8.4 Electronic solution

8.4.1 Functional description

The motor was powered directly through a PIC microcontroller using output channel C. The pre-programmed microcontroller took sensory information through channel B. The contact sensor comprised of a metal loop, which on contact with an obstacle would be pushed into a terminal on the robot base thus completing a circuit. All robot movement was controlled through the microcontroller. The circuit was powered using 3 x AAA batteries (total: 4.5 V).

8.4.2 Required Inventory

Table 9: Inventory items for robot

Description	**RS Code**	**Qty**
IC, Microcontroller, PIC16F73-I/SP	467-1347	1
Diode, Switching, 1N4148A52A	436-7341	8
Capacitor, metallised polyester, film, min, encapsulated, 100Vdc, 0.1uF	115-578	2
Capacitor, tantalum, radial wire ended, 5mm pitch, 10V, 100uF	262-4850	1
Instrument motor	245-6095	2
Resonator, 4MHz, CST4.00MGW	179-3725	1
Switch, toggle, ultra min, gold contacts, PCB, plain bush, vertical, SPCO, On-On	448-0781	1
Connectors	-	6

8.4.3 IC 16F73 microcontroller pin diagram (reference for Figure 53)

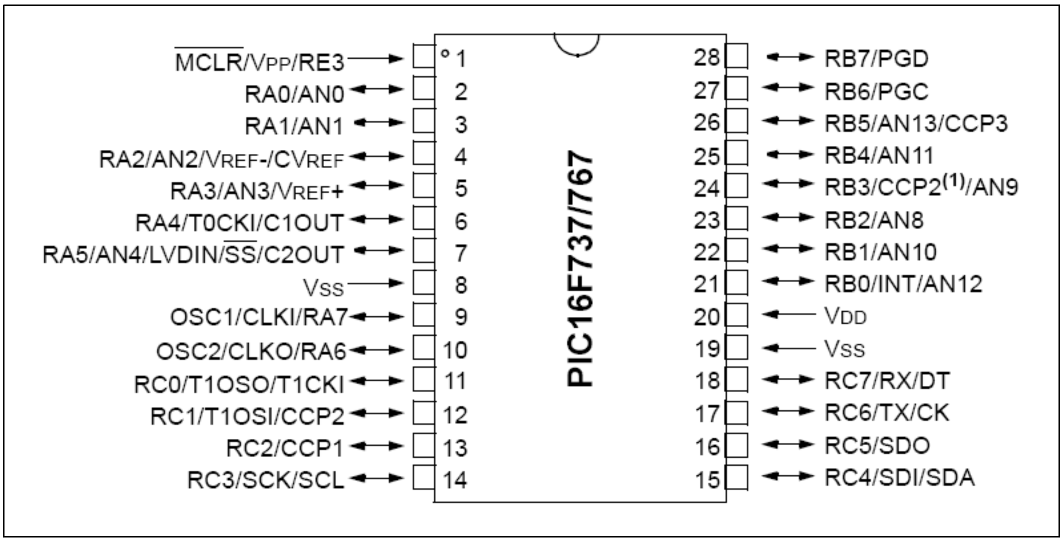


Figure 52: IC 16F73 microcontroller pin diagram

8.4.4 Circuit diagram for the robot

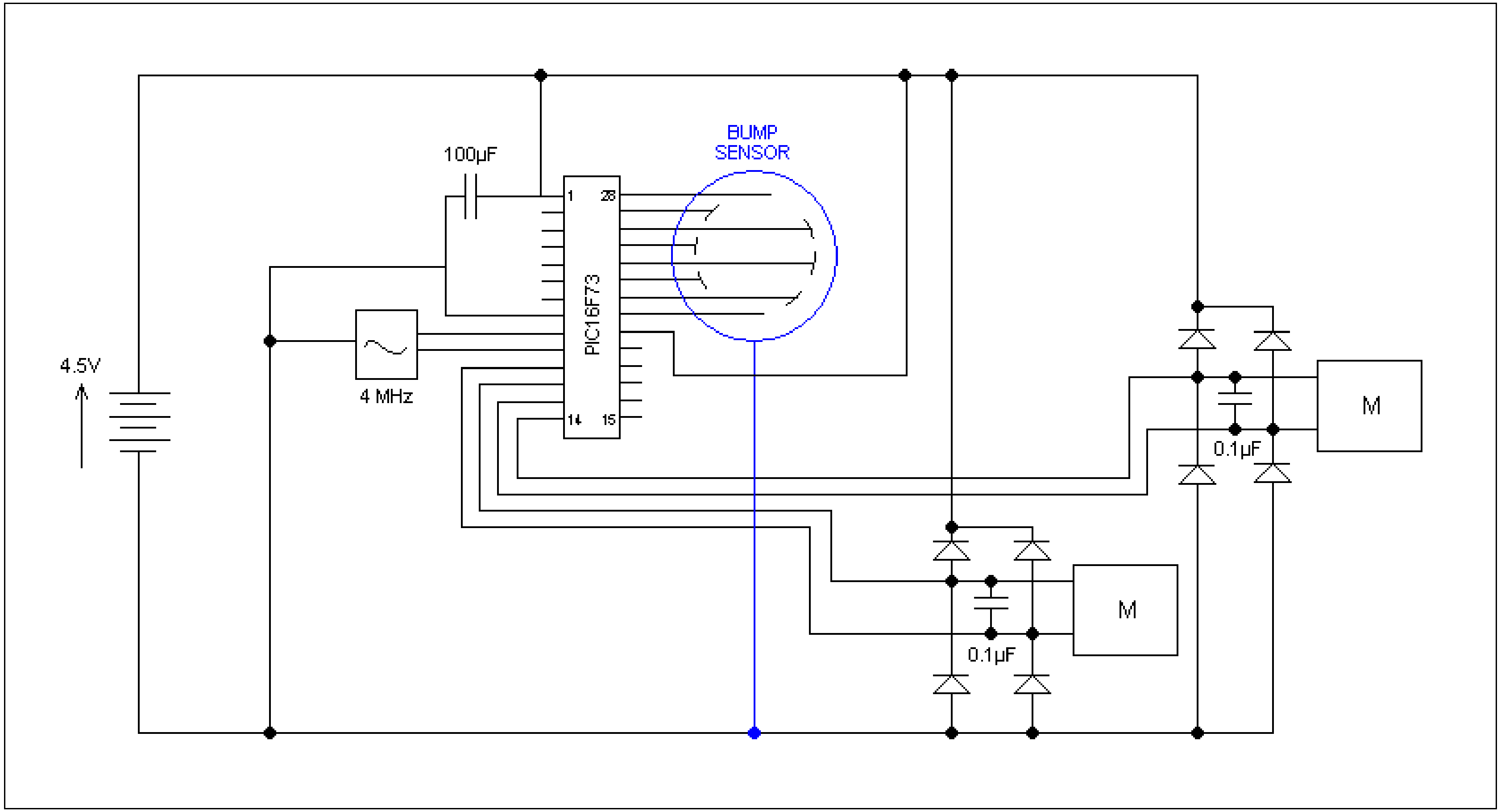


Figure 53: Robot circuit using input/output current from the IC microcontroller

8.5 Basic Design

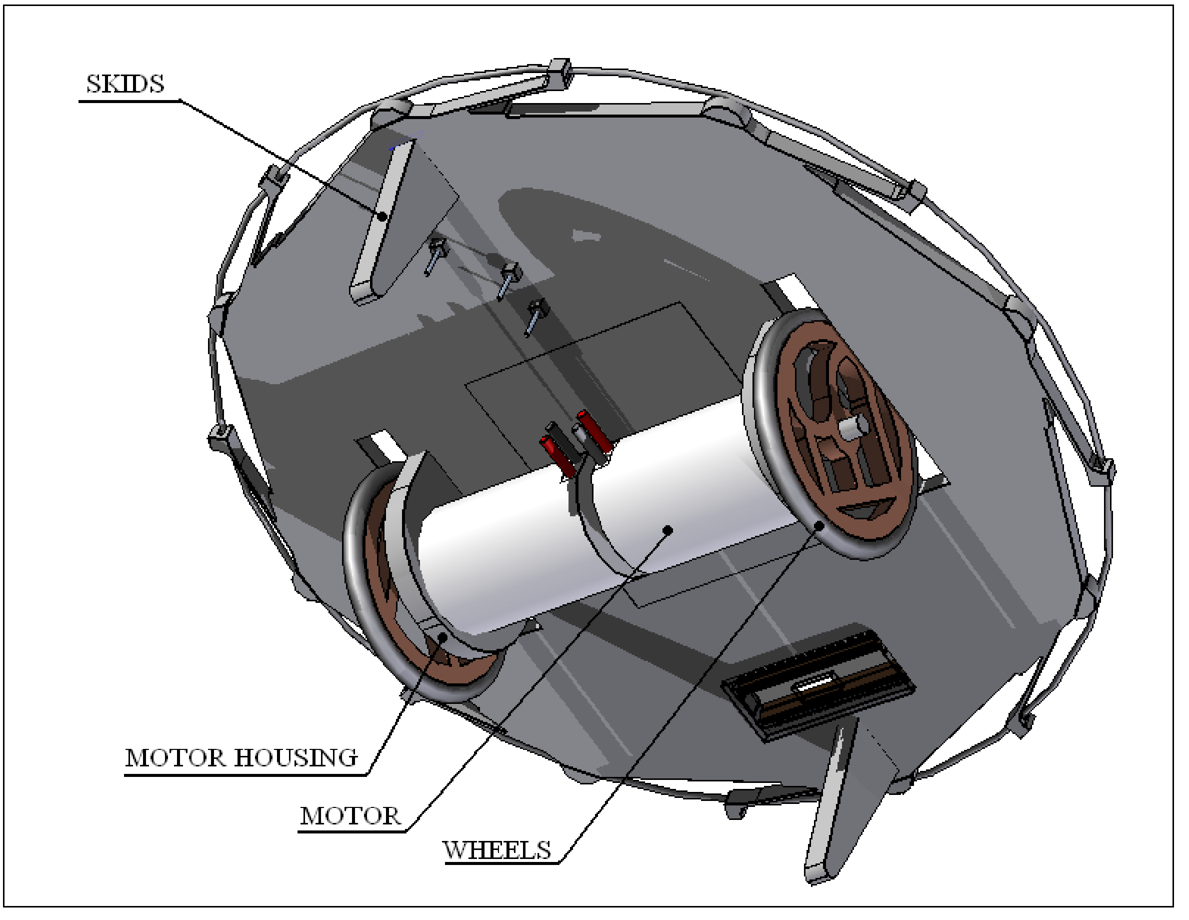


Figure 54: Underside of robot with identified features

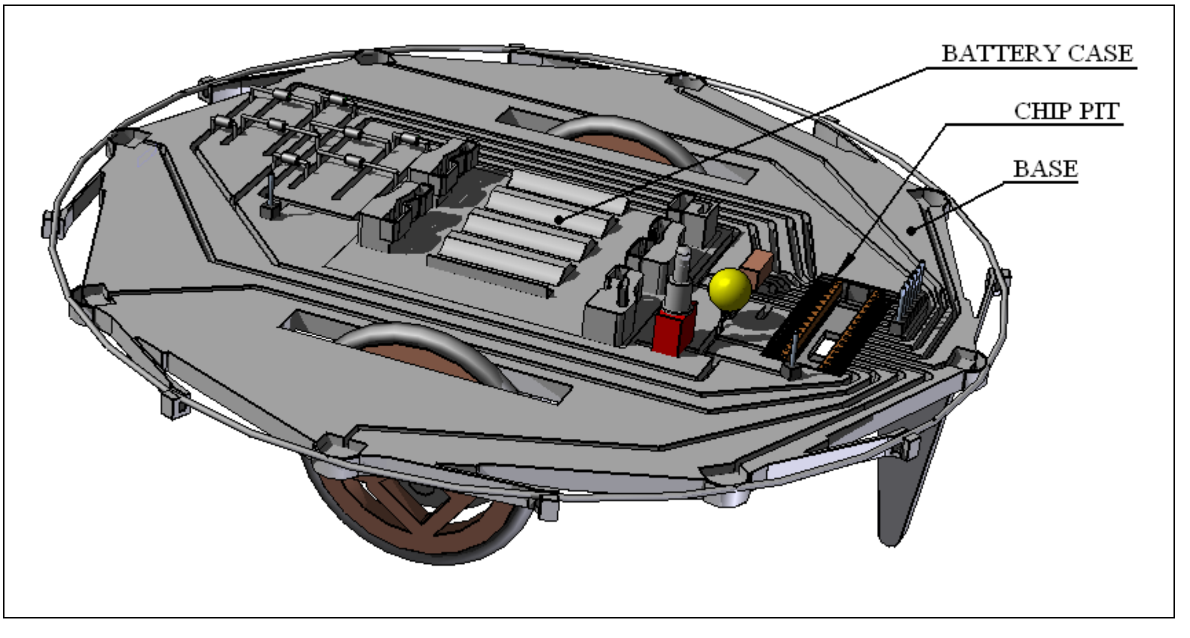


Figure 55: Topside of robot with identified features

8.6 Method of manufacture – outline

The robot was designed on Solid Edge (Figure 54 and Figure 55).

Battery case, chip pit and base were manufactured using the RP machine and assembled using a solvent based adhesive (refer to Figure 54 and Figure 55 for identification of features).

Circuit inclusion was performed as defined in Section 7. Due to the large footprint of the base it was not possible to heat the base on the hotplate as per usual. Therefore a 10 mm thick mild steel plate was heated to 100 °C in an incubator and then used as a temporary hotplate.

Motor housing, skids and wheels were manufactured using the RP machine and installed using a solvent based adhesive.

All standard electronic components were installed as defined in Table 10. For a push fit installation: The component was pushed firmly into place (see Section 8.8.2). For spot re-melt: A soldering iron was used to spot-melt a point along the circuit. Flux was added to the connection of the standard component to aid contact. This connection was then inserted into the molten area. The molten area was allowed to solidify, thus installing the connection (see Section 8.8.5).

Table 10: Method of installation of standard electronic components into the integrated circuit

Part	**Installation method**
IC, Microcontroller, PIC16F73-I/SP	Push fit
Diode, Switching, 1N4148A52A	Spot melt
Capacitor, metallised polyester, film, min, encapsulated, 100Vdc, 0.1uF	Spot melt
Capacitor, tantalum, radial wire ended, 5mm pitch, 10V, 100uF	Spot melt
Instrument motor	M3 screws
Resonator, 4MHz, CST4.00MGW	Spot melt
Switch, toggle, ultra min, gold contacts, PCB, plain bush, vertical, SPCO, On-On	Spot melt

The sensor loop was soldered together and placed on the outer sprung arms of the base.

Bridge wires were manually fitted to connectors.

Batteries were manually installed (push fit) and the robot was tested.

Results were observed and recorded.

8.7 Result

8.7.1 The finished robot

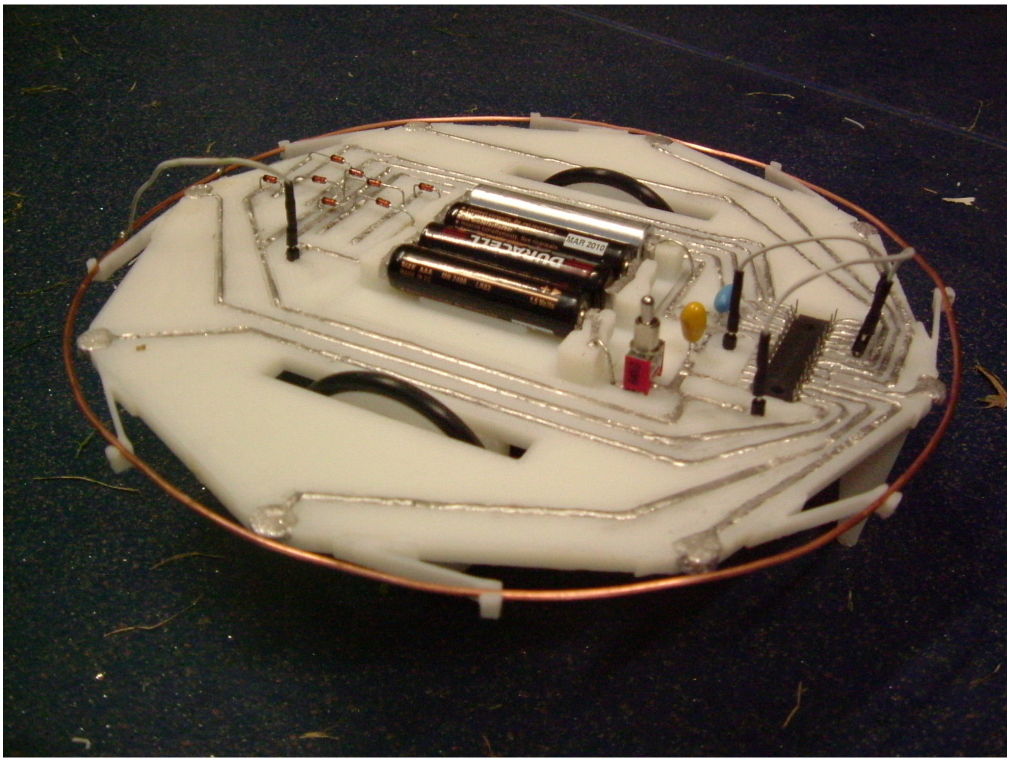


Figure 56: Photograph of finished robot

8.7.2 Performance

The robot successfully accomplished all requirements outlined in the specification from Section 8.3.

Note: The 0.1µF capacitors were removed for the circuit in order for the electronic system to work. The reason for this problem was, at the time of writing, undetermined.

8.7.3 Procedural

All components made on the RP machine worked first time. The modular manufacturing approach was intended to save the entire component should any of the features fail. The fact that there were no failures meant that it would have been feasible to make the structural part of the robot in one shot.

Circuit inclusion was successful with only two exceptions:

- The large size of the base meant that the hotplate could not be used. The modified heating method (a large pre-heated mild steel plate) did not have the same effect as continuously heated hotplate, however, this did not hinder the process excessively.

- Long lengths of circuits sometimes proved tricky due to the surface tension of the alloy. Occasionally bubbles of alloy on previously laid sections of the circuit would swell up and threaten to spill out of the channel. This was remedied by inserting the needle into the bubble and sucking alloy out of the area to reduce the swelling and restore the circuit.

8.7.4 Circuit quality

The circuit quality in all areas was sound and robust. This was the most important result for the project as it proved that the RPEC technology, as a whole, was sufficiently defined.

8.8 Component integration

8.8.1 Structural Modular assembly

After the design work had been completed for the robot a modular assembly technique was chosen (Figure 57). The decision to take this approach was made for three reasons:

- Efficiency: modular assembly reduced the need for support material. The flat base on top of legs would have required a large amount of support material.
- Failure impact reduction: some features were very complex and there was a risk that they would not be manufactured correctly first time. Making the robots in modules meant that a failure would be contained within its module rather than compromising the whole robot.
- Modular design: complex elements (e.g. chip pit and battery case) had been designed in a modular fashion due to the fact that each one had been made separately, analysed and modified. Thus the modularised design files lent themselves to a modularised assembly.

The modularised approach was ideal for the prototyping stage. However, there were no circumstances which prevented a single shot manufacture for production. The fact that there were no failures during manufacture was encouraging for this possibility.

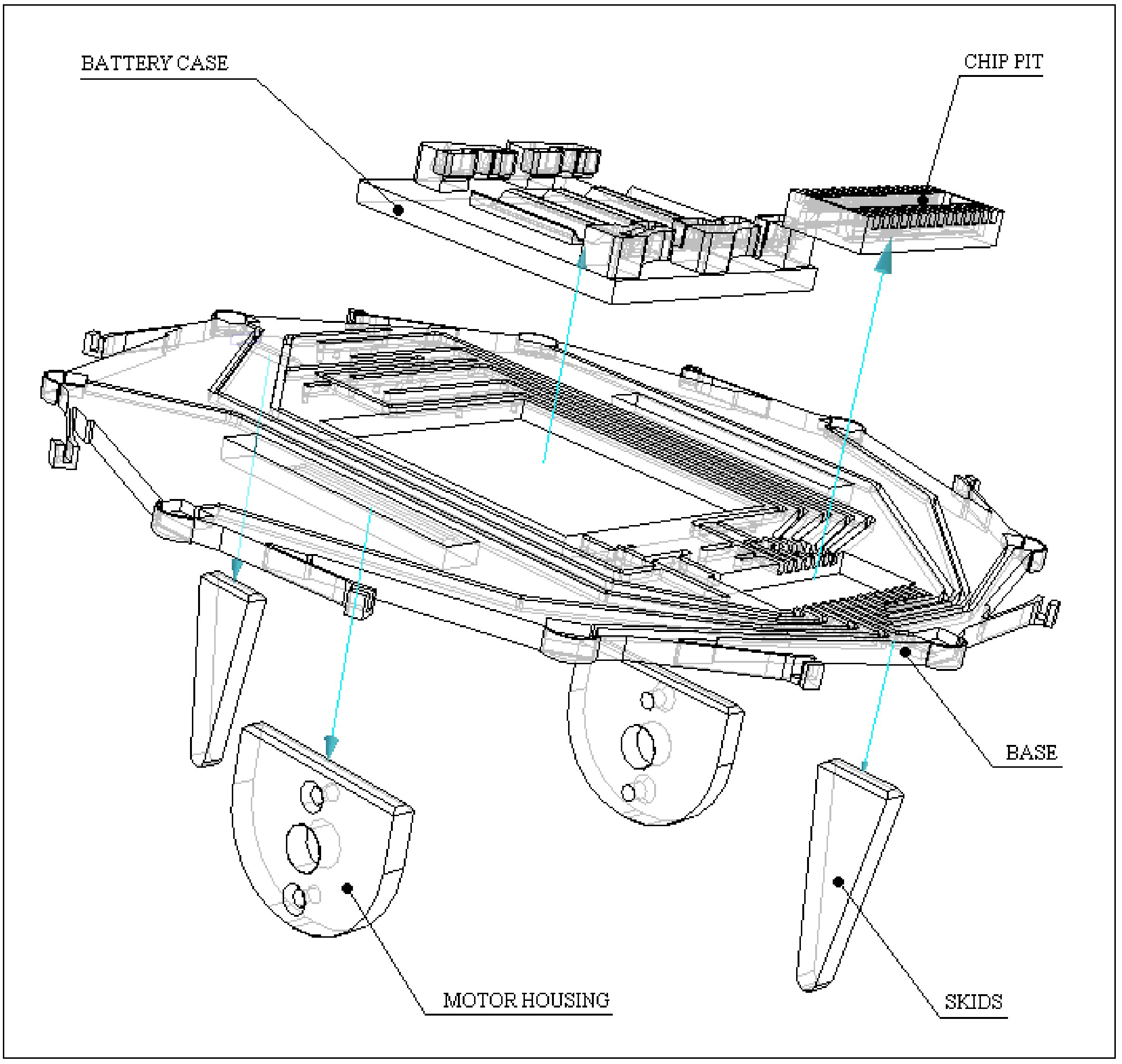


Figure 57: Exploded view of robot assembly

8.8.2 Push fit installations

A appropriate fitting procedure for some standards components (e.g. microchips, batteries etc.) into the prototyped circuit was the push fit, for the following reasons:

- It was possible to replace the component without altering the physical state of the circuit – ideal for research-based manufacture
- The process of inserting the component into the circuit was simple

In order to create push fits for electrical components it was necessary to cast the molten alloy outside the physical boundaries of the circuit channel to ensure that a good electrical contact could be made with the electrical component connections.

This was achieved by using a simple method labelled “fencing”. Temporary supports (fences) were built into the design of the component and left in place during casting. The design of the fence allowed the containment of the Wood’s metal in an accurate position until alloy solidification has occurred. Once the alloy solidified the fencing was removed (manually peeled away) to reveal an exposed alloy terminal.

The key to making fencing which could be easily removed was to design it as a floating part. Thus Catalyst will automatically include chip-away support material to support the fencing. This made the fencing strong enough for casting purposes and also guaranteed an easy removal of the fencing at the contact point with the component proper through the support material interface.

Fencing designs followed the specifications outlined in Section 6.13.

8.8.3 Push fit example: battery case

8.8.3.1 Battery case description

The battery case was designed to hold the batteries and connect them to the circuit (Figure 58). Sprung arms were incorporated to enable a push fit for the batteries into the case. Cups were included to secure the batteries as much as possible.

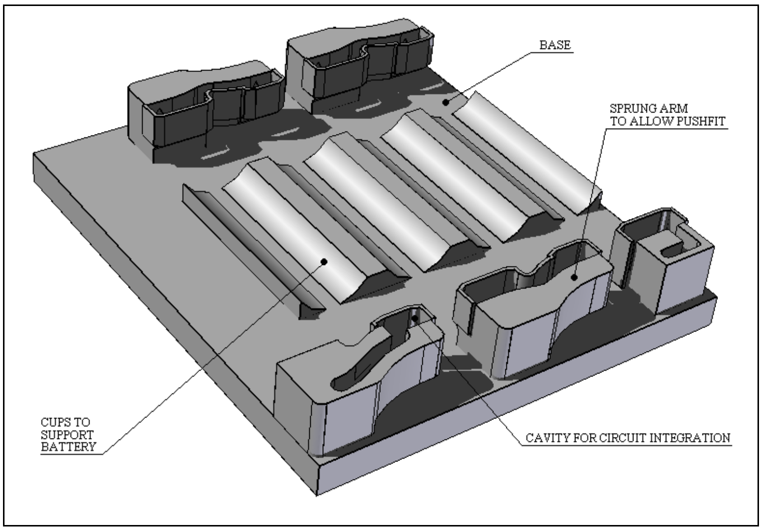


Figure 58: Battery case design features

In order to connect the batteries in series it was necessary to have exposed terminals on the springs. Thus fencing was included in the design as shown (in blue) in Figure 59.

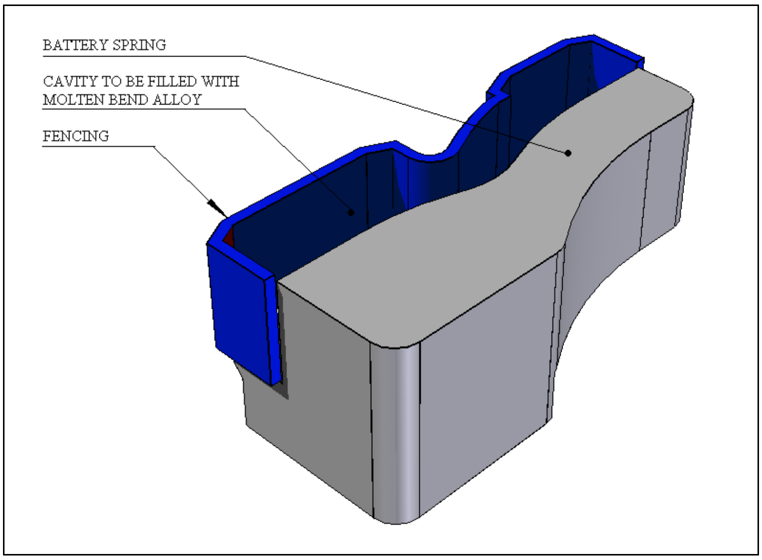


Figure 59: Fencing highlighted in blue. Note this fencing is floating. This forced Catalyst to incorporate chip-away support material into the lay-up below the fencing, to ensure that it broke away easily after casting.

8.8.3.2 Push fit accuracy

The measured length for a standard AAA battery was 44 mm ± 0.05 mm. The unsprung distance between the terminals was therefore designed to be approximately 0.3 mm shorter to maintain a push fit on the battery. The terminal fit had to be accurate to within approximately ± 0.1 mm to guarantee a push fit. The fencing technique was able to achieve this terminal accuracy.

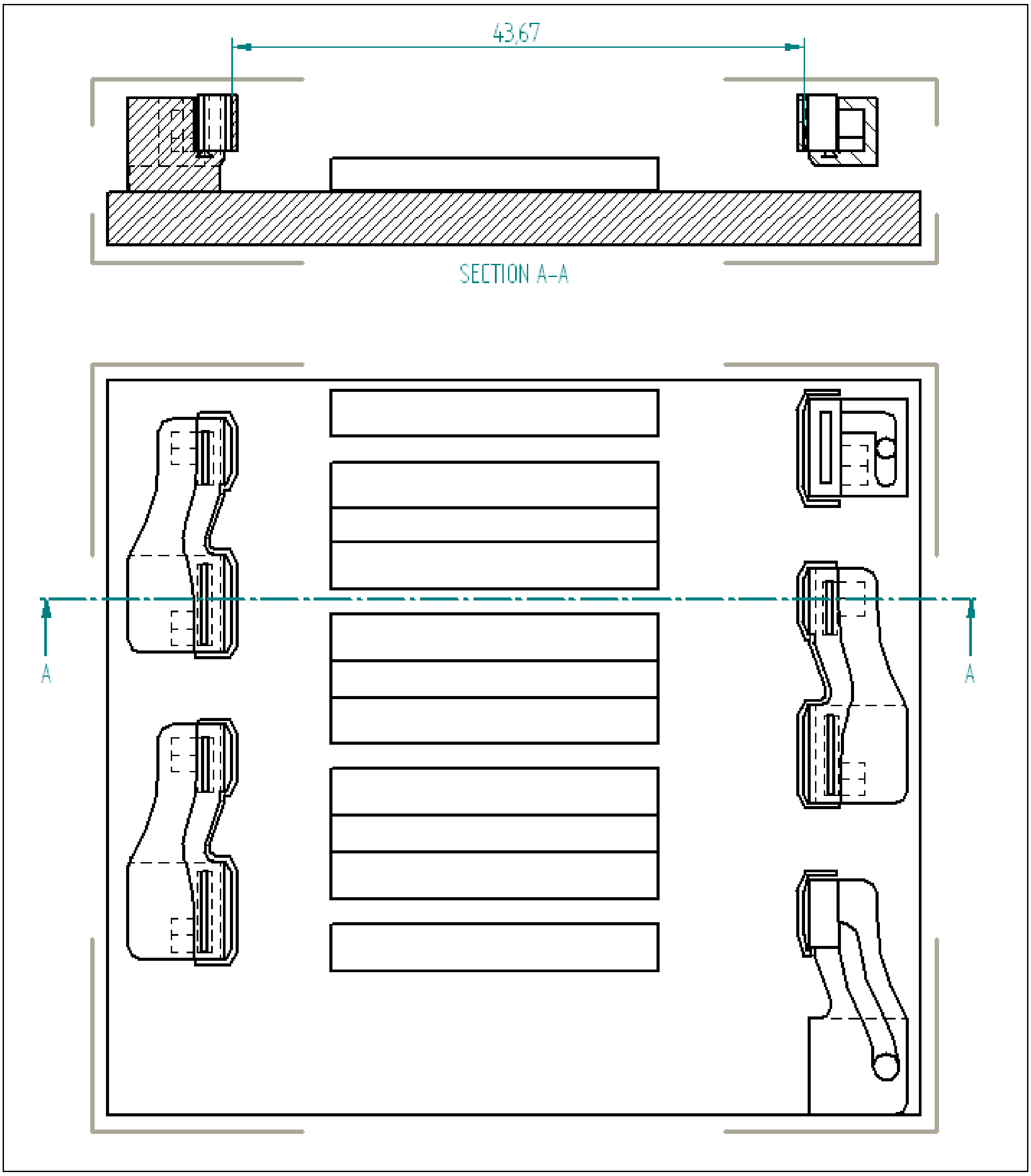
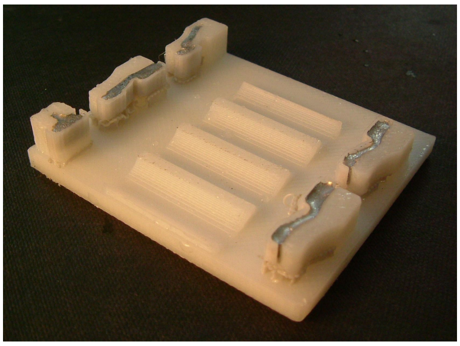
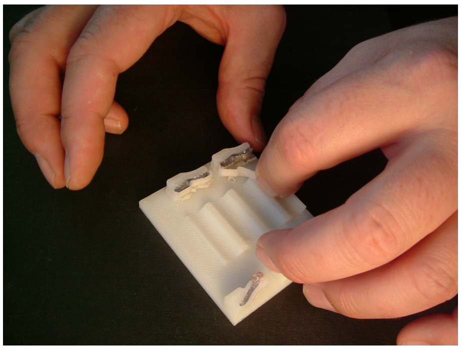


Figure 60: Definition of the critical dimension on the battery case. Distance between terminals defined the type of fit the battery would have. The terminal fit had to be accurate to within approximately ± 0.1 mm to guarantee a push fit. The fencing technique was able to achieve this accuracy.

Using the fencing in RPEC: demonstrates how the fencing technique was incorporated into the RPEC process for the battery case.

Table 11: Procedure for making the battery case

Stage	Photograph	Description
1		Circuit was integrated using method defined in Section 7
2		Alloy was allowed to solidify
3		After solidification the fencing was peeled away to reveal the exposed terminals
4		Batteries were pushed in to place (the aluminium `battery’ is there because it was not known in advance if the robot was to operate at 6v or 4.5v).

8.8.3.3 Anchoring

Due to the removal of material it was necessary to ensure that the solidified element did not become detached from the major component. For this reason cavities were incorporated into the component design which locked the alloy into local support material (Figure 61).

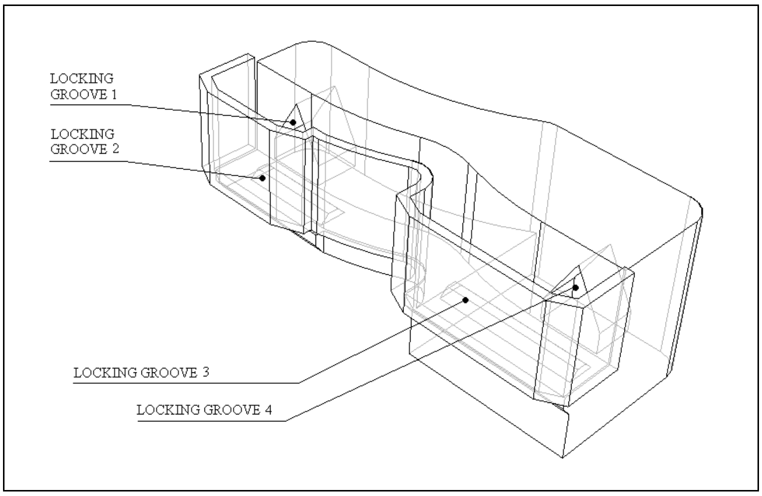


Figure 61: Locking cavities were built into the battery spring to ensure that the metal component did not detach from the major component.

8.8.4 Push fit example: chip pit

8.8.4.1 Chip pit description

The chip pit was designed to hold the microcontroller and connect it to the circuit (Figure 62).

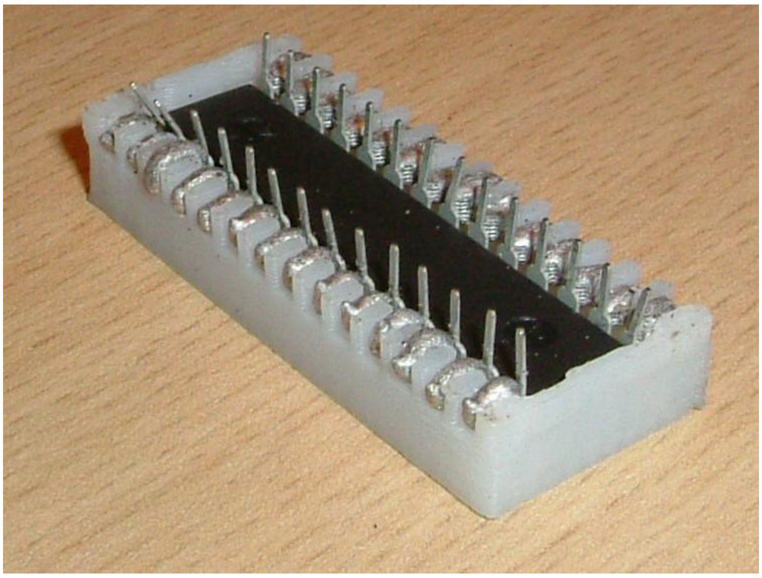


Figure 62: Chip pit module complete with microcontroller. Terminals (silver colour) were use to connect the chip to the rest of the circuit.

In order to connect the chip it was necessary to have exposed terminals protruding into the chip pit. Thus fencing was included in the design as shown in Figure 63.

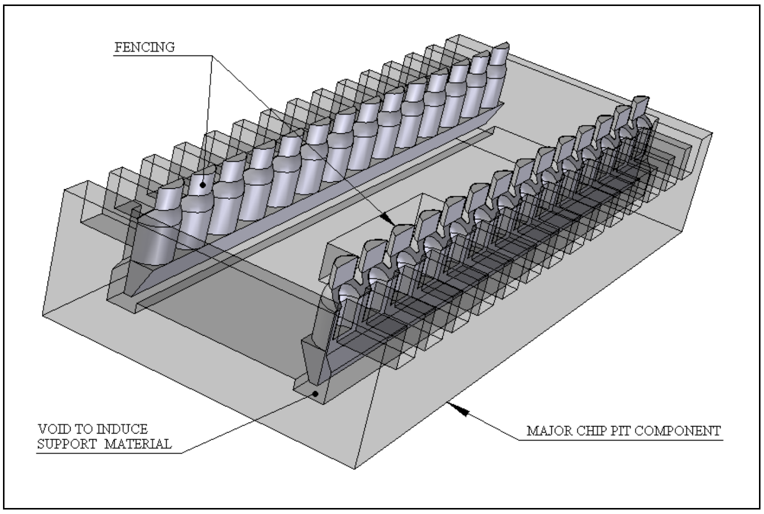


Figure 63: Chip pit (transparent black) complete with two strips of fencing (silver) which shaped 28 terminals. Note the void deliberately created under the fencing strips to induce support material as a base for the fencing.

The shape of the terminal was also critical to making the push fit a success. In order to push the chip in to the pit, the top surfaces of the terminals had to be rounded. Figure 64 demonstrates how this was made possible by adding a domed detail to the cavity in the fencing element.

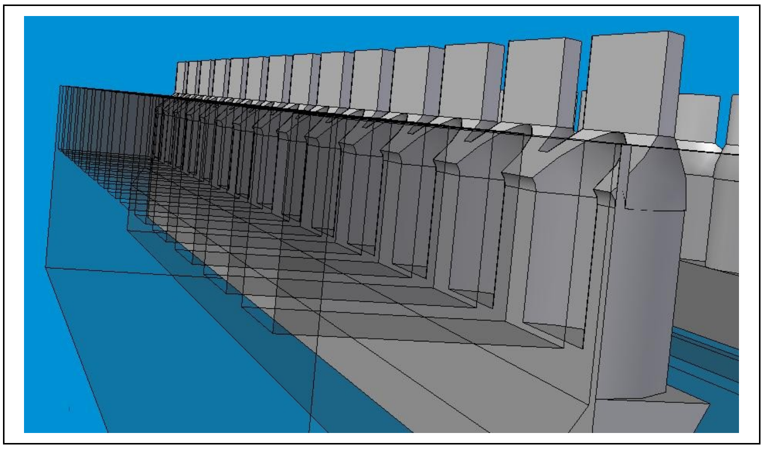
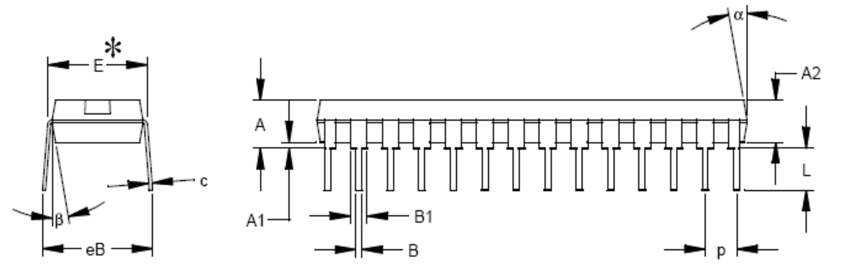


Figure 64: Chip pit fencing (grey) which allowed detailed casting profiling

8.8.4.2 Push fit accuracy

The dimensions for a PIC16F73-I/SP microcontroller were analysed (Figure 65). The unsprung distance between the terminals was therefore designed to be approximately 0.2 mm tighter to maintain a push fit on the chip. The terminal fit had to be accurate to within approximately ± 0.1 mm to guarantee a push fit. The fencing technique was able to achieve this terminal accuracy.



		Units	MILLIMETERS		
	Dimension Limits		MIN	NOM	MAX
	Number of Pins	n		28	
	Pitch	p		2.54	
	Top to Seating Plane	A	3.56	3.81	4.06
	Molded Package Thickness	A2	3.18	3.30	3.43
	Base to Seating Plane	A1	0.38		
*	Shoulder to Shoulder Width	E	7.62	7.87	8.26
	Molded Package Width	E1	6.99	7.24	7.49
	Overall Length	D	34.16	34.67	35.18
	Tip to Seating Plane	L	3.18	3.30	3.43
	Lead Thickness	c	0.20	0.29	0.38
	Upper Lead Width	B1	1.02	1.33	1.65
	Lower Lead Width	B	0.41	0.48	0.56
	Overall Row Spacing §	eB	8.13	8.89	10.92
	Mold Draft Angle Top	α	5	10	15
	Mold Draft Angle Bottom	β	5	10	15

Figure 65: Dimensions for a PIC16F73-I/SP microcontroller. Note * dimension.

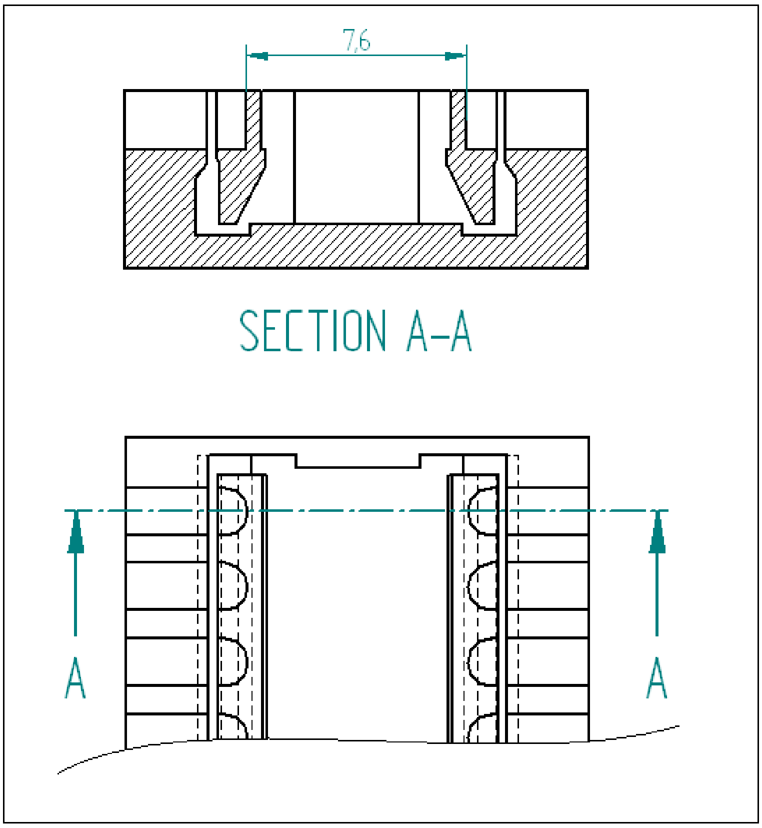


Figure 66: Critical dimension for the chip pit. Terminal distance was 7.6 mm. This forced the chip legs together creating a push fit.

8.8.5 Spot melt installations

For permanent installations (i.e. components which need not be replaced frequently) electrical components were integrated into the circuit by pushing the electrical connections into a support hole while the local volume of the circuit material was liquid. This hole would serve as a locator for the component while the circuit alloy froze around the connection.

The circuit could be accurately spot melted with a soldering iron. Experiments showed that for a 30 W iron, 60 V was required to generate a temperature of 90 °C at the tip.

Flux was also found to be essential to create a good electrical seal. Connections were therefore dipped into the flux before being inserted into the molten alloy.

8.8.6 Spot melt example: diodes

Figure 67 and Figure 68 show how support holes were used effectively to enable accurate spot melt installation of diodes.

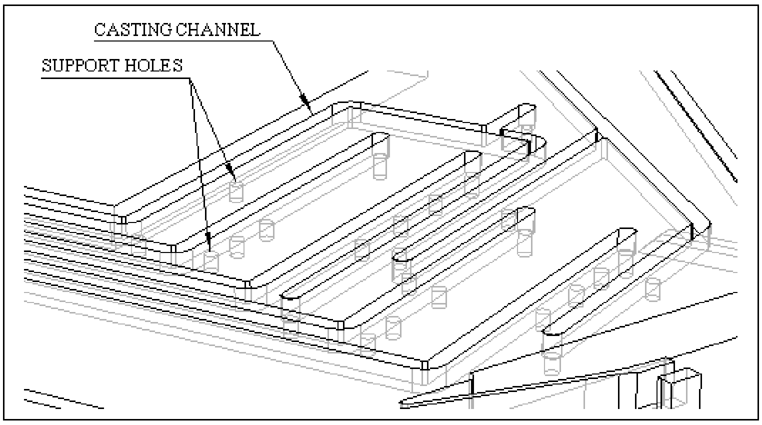


Figure 67: Support holes in casting channels of robot base

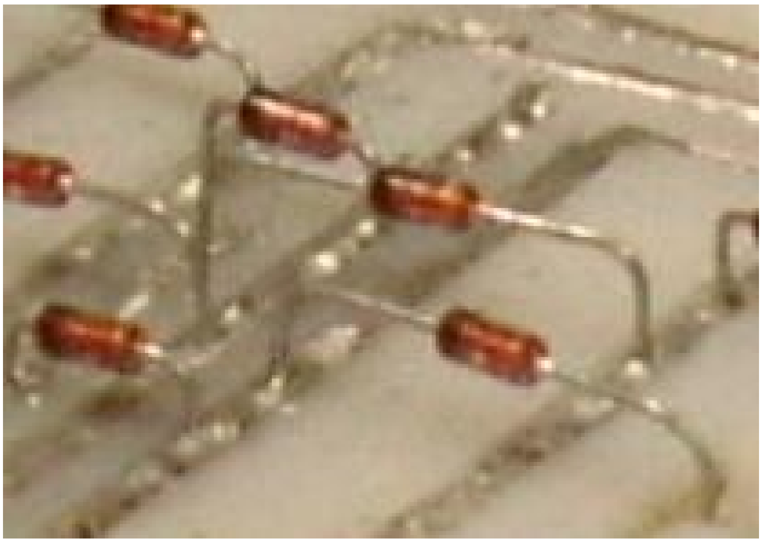


Figure 68: Semiconductors integrated into the circuit by spot melting

8.9 Design example discussion

The robot was constructed and completed using RPEC techniques only and it achieved all of the tasks it had been designed to do. Although the ability to drive forwards, recognise when it had hit something and then go then other way was impressive, this was by no means the robot's greatest achievement. By incorporating many different electrical elements and enabling them to work as a fully functional circuit the robot proved that the RPEC technology developed in this project actually worked.

The hindrance of not having a hotplate large enough was largely overcome using a pre-heated thermal plate. The inability for this equipment to maintain its temperature meant that the injection process had time constraints. It was likely that the imperfect manual motion of moving the syringe down the casting channel, and the non-uniform alloy ejection rate were the main causes for this swelling. The inevitable haste due to the time constraints only made this worse.

The next development for the circuit inclusion element of RPEC would therefore be to design and construct a motorised injection mechanism which could deliver steady deposition on a motorised axis providing constant fill rates.

The modular construction technique worked well. It allowed simple development of awkward elements and was a necessary precaution against the impact of component failure during the prototyping stages. On the final production run it was encouraging to note that there were no manufacturing failures, indicating that the modular process (at a later production stage) could be dropped in favour of a single manufacturing run.

A significant amount of research went into the push fit elements: the chip pit and the battery case. The fencing technique was found to be extremely useful for prototyping purposes as it enabled fast, single stage mould design. The fencing techniques were refined to a high level to produce push fit elements which were both accurate and highly repeatable. This was difficult because the required tolerances were usually at the limit of the RP machine's ability. It was expected that with improving RP technology the fencing technique becomes a prominent part of RPEC technology. Whilst fencing was designed on an individual basis for each different interface, it is encouraging to note that due to the high level of standardisation within electrical component design it is conceivable that a finite number of push fit modules could be designed to cover 99 % of interface situations. This would be extremely important at the advanced stages of RPEC implementation.

Simple soldering techniques were found to be extremely useful at permanent installation of some electrical parts. This was another inherent advantage of using a low melting point alloy.

Altogether the manufacture of the robot proved that RPEC technology was a fast and effective way of making a fully functional electro-mechanical device. By solving the integration problems of electronic circuits it put the potential of rapid prototyping technology into a new sphere.

8.10 Design example conclusion

The robot was a complete success. By fulfilling its requirement specification it proved that RPEC technology worked. Modular construction techniques enabled research into the complex push-fit elements. The complete manufacturing success of the final components indicated that component manufacture need not be modular for production purposes.

Research in the push-fit installation area led to an important technique labelled “fencing” – this enabled the fast and accurate production of temporary alloy moulds which was an essential part of providing a reliable push fit interface for the circuit. Soldering techniques were also discovered to be possible for more permanent components.

The only procedural problem (circuit swelling during injection) was likely due to human error. The next development for the circuit inclusion element of RPEC would therefore be to design and construct a motorised injection mechanism which could deliver steady state deposition on a motorised axis providing constant velocity.

9 PROJECT DISCUSSION

This discussion was written to summarise previous discussions of Section 6.11 and Section 7.10.

This project successfully defined RPEC technology by specifying two major elements used together to manufacture electro-mechanical components.

The mechanical requirement was fulfilled using rapid prototyping technology. This involved testing the performance of an RP machine to establish whether it would be capable of manufacturing intricate casting channels and associated geometries. Research established a detailed component specification for RPEC technology and also discovered new potentials for the machine (critical overhang angles, horizontal holes and efficient job placement).

The electrical requirement was fulfilled by using continuously heated equipment to inject molten Wood's metal into the casting channels. Results suggested that the molten circuits were stable up to a 20 ° incline. It was noted that the principle would lend itself well to the existing fused deposition method (FDM) RP technology which already relies on melting materials at a distribution head to enable deposition. Research established that powder distribution followed by flash melting was not suitable and that metalised channel surfaces did not aid molten distribution under injection conditions.

The design example (robot) was fully functional and wholly reliable. This was testament to the quality of the techniques defined for the RPEC technology. With a real application came new techniques to add to the RPEC knowledge. The installation of electrical components demanded two different installation techniques: push fit and spot melt. Both areas required research and lead to the discovery of two new techniques to achieve the requirements (fencing and hole location).

The next development for the circuit inclusion element of RPEC would be to design and construct a motorised injection mechanism which could deliver steady state deposition on a motorised axis providing constant velocity. This would be an important assessment as to whether the circuit inclusion method could be fully adopted by an FDM RP machine. Should this ever happen, we would be looking at a useful machine equipped with the potential to self-replicate.

10 PROJECT CONCLUSION

This project was entirely successful at defining a preliminary technology which could potentially be used to enable machines to self-replicate.

The technology was achieved by establishing the limitations of an FDM RP machine and combining that with a continuously heated injection technique which integrated electronic circuits into the RP components.

The combined technologies (labelled RPEC technology) was proven to be successful after manufacturing an autonomous robot using its techniques.

The next development for the circuit inclusion element of RPEC would be to design and construct a motorised injection mechanism which could deliver steady state deposition on a motorised axis providing constant fill rate. This would be an important test as to whether the circuit inclusion method could be fully adopted by an FDM RP machine. Should this ever happen, we would be looking at the first ever machine equipped with the potential to self-replicate.

11 ACKNOWLEDGEMENTS

My profound thanks go towards Dr Bowyer for his continual support, inspiration and guidance throughout the project, the Mechanical Engineering Department at the University of Bath for its facilities, The Nuffield Foundation for awarding me with the grant to do this project, Mr J Brewster for putting up with my elementary questions about electronics, Mr H Jones for finding and fixing things together and Mr C Davey for donating some very useful kit. Also to Miss A Thatcher for getting me up to university every morning and Miss J Clements for having the patience to let me write this f*cking report!

12 REFERENCES

12.1 Literature

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Bowyer, A. (2004): *The biology of Direct Writing and Rapid Prototyping*. [Online] Available at http://staff.bath.ac.uk/ensab/rapid-prototyping/ (accessed October 28 2004).

Sells, E. (2004): Manual for Technical Report 01/04: *Rapid Prototyping Electronic Circuits*. Bath: University of Bath

Pain, S. (2002): The chunkiest chip. *NewScientist*, 19 October 2002, pp. 60-61.

12.2 Table references

12.3 Figure references

13 APPENDICES

13.1 Rapid prototype machine manufacturers

Stratasys Inc
14950 Martin Drive
Eden Prairie
MN 55344USA
T: 952 937 3000
F: 952 937 0070
E: support@stratasys.com
W: www.stratasys.com

13.2 Wood's metal supplier

Lowden Metals Ltd
Unit 7
Harvey Works Industrial Estate
Shelah Rd
Halesowen
West Midlands
B633P6
T: 01215013596
F: 01215855162
E: www.lowden-metals.co.uk

13.3 Syringe manufacturer

Becton Dickinson UK Ltd
Between Towns Road
Cowley
Oxford
OX4 3LY
UK

13.4 Needle manufacturer

Tyco Healthcare UK Ltd
Northern Ireland
BT52 7AP
01329 224226
(Contact: Tracey Sandleberry)

13.5 Hot-jacket design critical dimensions

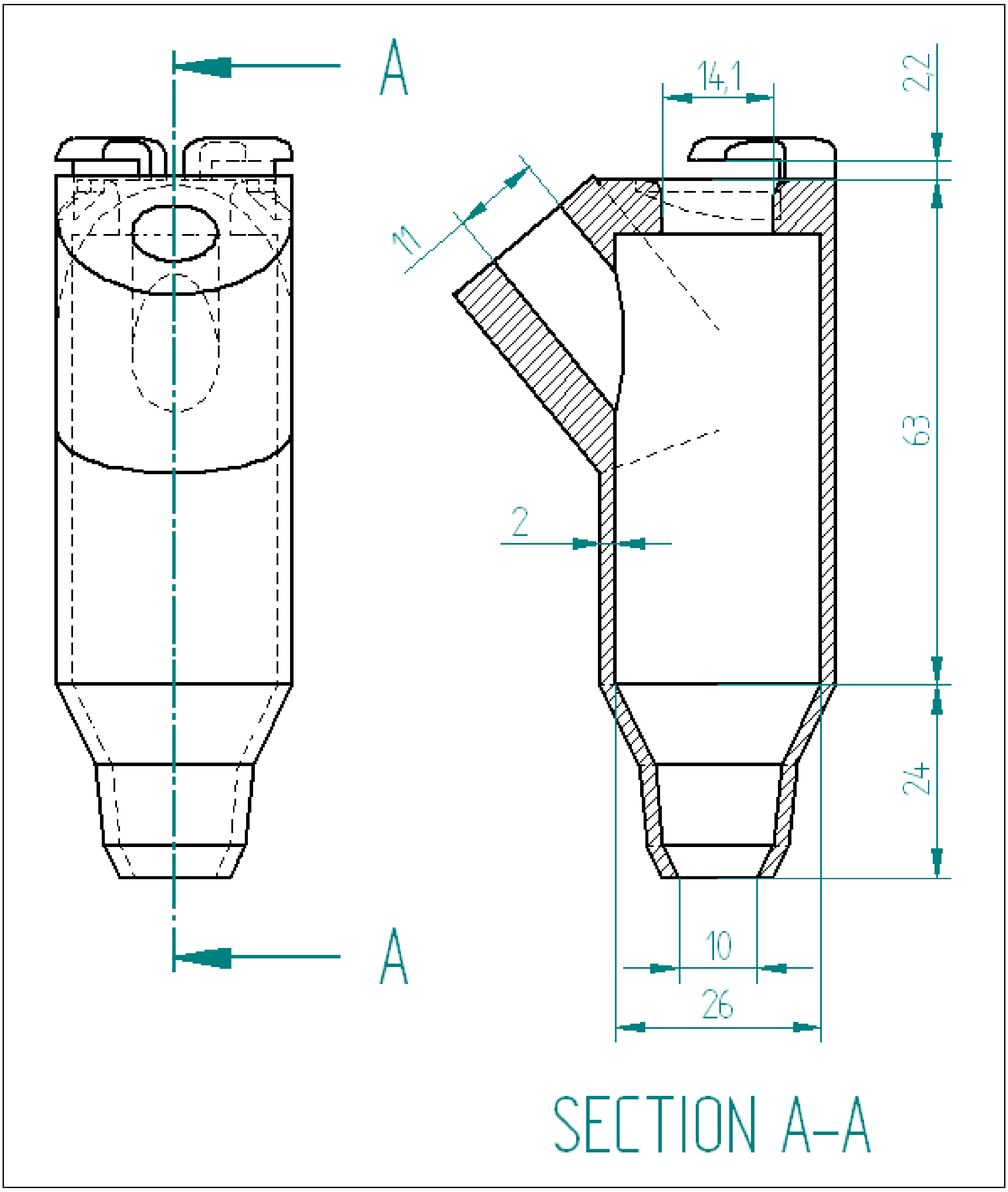

Figure 69: Critical dimensions for the hot-jacket design

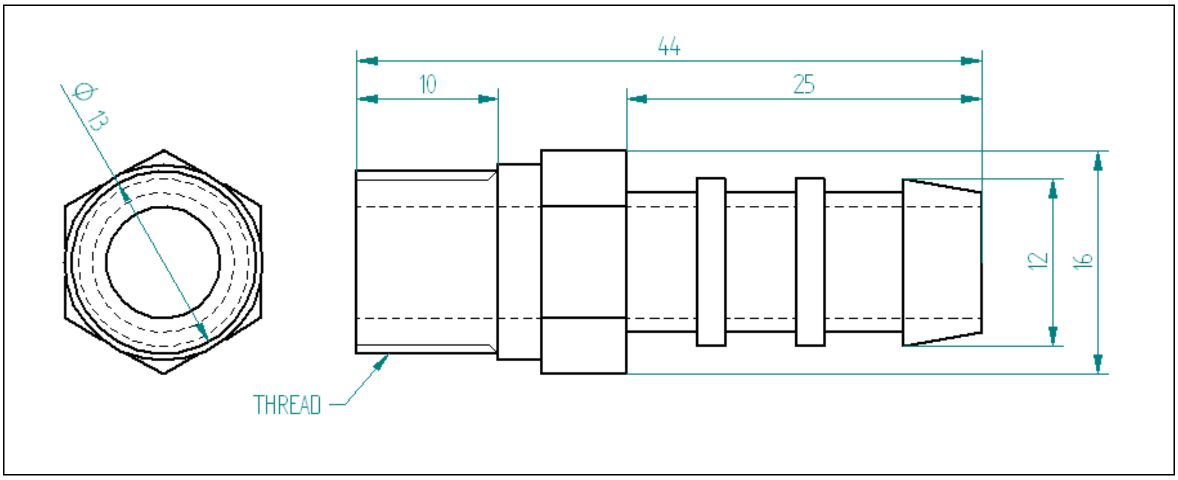

Figure 70: Critical dimensions for the air connector required to fit the hot-jacket