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Additive Manufacturing of Functional Engineering Components

Rhys Owen Jones

A thesis submitted for the degree of Doctor of Philosophy

University of Bath

Department of Mechanical Engineering

June 2013

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Declaration of material from a previously submitted thesis and of work done in conjunction with others

The author has previously published a dissertation entitled “New RepRap Materials” for his Master of Engineering Undergraduate degree. The document detailed the implementation of new materials within the Fused Filament Fabrication process. The focus of the work was on researching the deposition of standard molten low melting point alloys injected into 3D printed ABS channels towards the end goal of producing electrical circuits. Whilst the work culminated in the production of a simple electrical circuit, poor control due to fundamental material properties resulted in diminished print quality and poor reliability. These issues inspired the work detailed in Chapter 5. This prior work is relevant to the main subject of the thesis, and it has been referenced accordingly where appropriate.

The work undertaken in this thesis falls under the umbrella of the wider RepRap project. Whilst the author’s contribution has been distinct and independent, other members of the RepRap project have made some contribution. Where appropriate, these contributions are explicitly outlined.
Abstract

Additive Manufacturing (AM) is a class of technologies whereby components are made in an additive, layer-by-layer fashion enabling production of complex parts in which complexity has little or no effect on cost. However typical components produced using these techniques are basic structural items with no major strength requirement and low geometric tolerances made from a single material. This thesis develops a low-cost Fused Filament Fabrication (FFF) based AM technique to produce functional parts. This is achieved by through researching and implementing new materials in combination and using precise control of infill tool paths for existing materials.

Robocasting has previously been shown to be extremely versatile, however is known to offer poorer build quality relative to its less-versatile counterparts. Research was undertaken to enable Robocasting to be combined with FFF to enable the print quality and practical benefits of FFF with the material flexibility of Robocasting. This resulted in the manufacture of several multiple-material components using the technique to demonstrate its potential.

In order to minimise the number of materials required to obtain desired properties, the effect of process parameters such as layer height, infill angle, and infill porosity were investigated. In total over an order of magnitude variation in Young’s modulus and tensile strength were achieved, enabling these properties to be actively controlled within the manufactured components.

Finally a novel non-eutectic low melting point alloy was developed to be compatible with the FFF process. Its greater viscosity compared to traditional eutectics resulted in improved print quality and the reliable deposition of electrically conductive track 0.57x0.25mm in cross-section. In addition the material is approximately three orders of magnitude more conductive that typical printable organic inks. A micro-controller was produced using the technique in conjunction with traditional electronics components. This represents the first time a functional electrical circuitry, with sufficient conductivity for the majority of applications and interfacing directly with standard electrical components, has been produced using a very low-cost AM technique such as FFF.
Abstract

The research undertaken builds components with substantially improved functionality relative to traditional AM products, enabling electromechanical components with varying mechanical and electrical properties. It is anticipated that this could substantially reduce the part-count for many engineering assemblies and open up Additive Manufacturing to many new applications.
List of Abbreviations

3DP  Three Dimensional Printing
ABS  Acrylonitrile Butadiene Styrene
AM   Additive Manufacturing
AMF  Additive Manufacturing File Format
ASTM American Society for Testing and Materials
CAD  Computer Aided Design
CAM  Computer Aided Manufacture
CNC  Computer Numerical Control
EBM  Electron Beam Melting
FDM  Fused Deposition Modelling, a commercial trademark of Stratasys Inc. detailing the FFF process
FFF  Fused Filament Fabrication
GCode CNC Programming Language
J-P  Jetted Photopolymer
LOM  Laminated Object Manufacture
MM   Single Jet Inkjet

\footnote{Despite extensive research, the exact reasoning behind this abbreviation has eluded the author; logically it should be SJI. However the term MM appears to be widespread and hence is used throughout this thesis}
**List of Abbreviations**

**PDMS** Polydimethylsiloxane

**PEEK** Polyether ether ketone

**PLA** Polylactic Acid

**PTFE** Polytetrafluoroethylene

**RepRap** Replicating Rapid Prototyper

**RFO** RepRap-Fab@Home Object File Format

**RP** Rapid Prototyping

**RPEC** Rapid Prototyping of Electronic Components

**RTV** Room Temperature Vulcanising

**SLA** Stereolithography

**SFF** Solid Free-form Fabrication

**SLS** Selective Laser Sintering

**STL** A file format defining a triangulated surface of a three dimensional object
1. Introduction

Additive Manufacturing (AM) and Rapid Manufacturing are often thought to be modern processes. The fundamental concept of manufacturing objects layer-by-layer is one of the oldest production techniques, dating back to at least the time of the pyramids. However general development within the field was minimal until the development of Computer Numerical Control (CNC) in the late 1950’s that enabled the creation of modern AM techniques.

Since the industrial revolution, focus has largely been placed on the other, more traditional, manufacturing methods, namely subtractive technologies such as milling and injection moulding and casting, which require subtractive techniques to create the moulds. This left prototyping to require skilled craftsmen, and needed part manufacture in multiple stages such as hand carving and other tedious, inaccurate and expensive processes.

Other manufacturing techniques such as injection moulding are the most efficient methods for mass production, high costs associated with tooling, setup and labour have left industry searching for techniques to ensure that processes are implemented on a “right first time” basis with minimised development time. Whilst the development of modern Computer Aided Design (CAD) has reduced some of these pressures, a real world solution is still desirable and hence AM techniques have been developed to suit this need. In the past decade however, improvements in the capability of AM and the reduction in costs has allowed AM to be increasingly used for production. Hence there is increasing demand to enable AM systems to produce functional components, however functionality is currently limited through a combination of resolution and achievable material properties.

All Additive Manufacturing systems function in a manner that allows greater part complexity relative to subtractive methods. An example of the complexity currently achievable with perhaps the most popular Additive Manufacturing technology, Fused Filament Fabrication, is shown in Figure 1.1.
1. Introduction

As with any manufacturing process, the best results are obtained when the characteristics of AM are actively considered during the design process. In the case of AM, components are often unnecessarily complex from a functional perspective, but allow material usage and build times to be minimised reducing cost. Fundamentally this ability to potentially have “complexity for free” is due to two major advantages relative to traditional methods [1]:

1. Additive Manufacturing is computationally simple - unlike subtractive techniques in which collisions between the tool head and the part always need to be modelled. With subtractive techniques further complexity comes from the choice of cut depths, spindle speeds, appropriate tools, cooling etc. Whilst AM does need to make some considerations of part geometry, in general they are substantially simpler.

2. Fixturing - Using subtractive techniques, additional fixturing is always needed to grip the part to react to cutting forces.

3. Toolhead access - In a layer-by-layer process, the deposition tool is always capable of accessing every area of the part within a given layer - hence this com-
1. Introduction

Whilst it is true that AM techniques potentially offer complex parts with little or no effect on cost, as with every manufacturing technique AM has a series of characteristics which should ideally be designed for. For the Fused Filament Fabrication AM technique, whereby material supplied in filament form is fed into a liquefier before being deposited, it is always preferable that the part is orientated such that the process isn’t attempting to deposit material in free air, or that overhangs are less than 45°. Subtractive processes have a similar set of design rules, which if ignored would result in the part being more expensive or perhaps non-machinable, whilst in AM processes the consequence may be a weaker, more expensive component requiring extra post processing or a secondary support material. Therefore additive techniques are more robust in this regard relative to their subtractive counterparts.

As previously stated, the essence of the Additive Manufacturing process is the production of components layer-by-layer, with each layer being a cross-section acquired from a CAD model. However the thickness of this layer implies that the final manufactured component is simply an approximation of the real data. Whilst no manufacturing technique is exact, and every manufacturing method produces parts which are simply approximations of the CAD model, AM introduces this additional approximation which is not present in other techniques. Hence one of the main disadvantages of Additive Manufacturing is that manufactured components are less accurate than their subtractive counterparts [1]. Further other issues exist which result in inaccuracies such as part warping and variation in material feedstock, these are discussed in Section 2.3.

To date the AM has been used with a reduced selection of compatible materials relative to the number traditionally available to engineers - limiting functionality. As highlighted in Section 2.3, many Additive Manufacturing process are fundamentally compatible with many materials, however until recent times all technologies have been solely developed by commercial organisations and academic institutions with close links to a relatively small number of partners in industry. Hence research into new materials has been constrained in part due to the lack of control over process parameters and the closed nature of available systems.

Despite the above limitations Additive Manufacturing has been historically adopted for prototyping. In recent times, reducing costs has allowed for the direct manufacturing of bespoke, high cost, intricate components such as in orthotics [2] and dentistry [3]. In short industry exploits the ability of Additive Manufacturing to produce single material components in small production sizes with complexity at “zero cost”, yet substantial benefits may be attained by exploiting the theoretical ability of AM to use multiple
1. Introduction

The use of multiple materials within Additive Manufacturing has been proposed almost since the technology’s inception, though their use to-date has mainly been in allowing a secondary support material to improve surface finish and versatility. The implementation of multiple materials in combination with new materials and novel material deposition strategies should allow the manufacture of components with graded, or anisotropic, or functional properties (or all three) simply by depositing different materials at different locations and in varying patterns to build single or multiple solids. For example a system capable of depositing an electrically conductive material, in combination with a traditional electrically insulating thermoplastic, would be capable of producing a circuit board. This technique could be expanded upon through additional materials to enable printed electronic components. As outlined in Chapter 2 this fundamental technique has already been implemented for the Jetted Photopolymer AM process by Objet Geometries and has allowed the manufacture of components with varying translucency, colour and strength/stiffness. Expanding this technique out to other processes will offer a wider range of material properties, and therefore allow more functional components.

Further to above potential new benefits, the traditional characteristics of AM still apply - namely the ability produce one-off complex, robust, low-cost components. This complexity would therefore enable such a circuit to also perform functions for which traditional AM parts would be used. This takes the technique beyond simply producing prototypes, and components with complex geometry and towards producing functional components. The design of an entire product/system around such a technology would have a profound effect on part count and give an associated reduction costs associated with assembly and packaging improvements enabling components that simply aren’t possible using traditional techniques. Given these benefits, this thesis aims to further develop AM processes to produce such functional components.

1.1. Research Hypothesis

This PhD aims to test the following hypothesis:

“Solid Freeform Fabrication processes are sufficiently versatile to manufacture low-cost functional electro-mechanical devices through the use of dissimilar materials and part geometry”
1. Introduction

In short, this research aims to improve Additive Manufacturing technology by enabling the manufacture of more functional components in a low-cost manner. However one may ask the question: “What is a functional component?” The Oxford English Dictionary defines function as:

“the mode of action by which (a component) fulfils its purpose. ” [4].

Arguably by this definition any part within a product or mechanical system provides some function, even if that function is purely aesthetic. Further a simple bracket could be manufactured that would provide some basic functionality due to its bulk geometry but would only need to possess uniform material properties. Within the context of this thesis, a more exacting engineering definition is used:

**Function - “ having a special activity, purpose, or task that is the result of more than bulk geometry”**

This PhD seeks to achieve the following goals:

1. To demonstrate the compatibility of different AM processes. In particular Robocasting, a technique similar to FFF but one that relies on a syringe in order to allow it to use paste materials [5], in parallel with Fused Filament Fabrication using fundamentally dissimilar materials.

2. To enable the control of bulk material properties through the control of mesostructure and print parameters.

3. To develop a novel cost-effective low melting point alloy compatible with the Fused Filament Fabrication and thermoplastics in order to enable the manufacture of electrical circuitry.

As detailed in the following chapter, some of the above goals have been partially achieved using very high end systems, their cost makes them unaffordable to many, and are only suitable for one off production runs for even for the most well-funded institutions. One could place an arbitrary limit on material costs - currently 3D printing materials are in the range of £30-60/kg - however such a metric does not consider the amount of material required for a given functionality. For many engineering components, parts are required to be a certain size, and thermoplastics have roughly a similar density and therefore such a metric is sensible. For others, e.g. electrical conductivity, a large range in conductivity is available, therefore one could foresee a situation where only a small amount of an expensive material is required to give the same functionality...
1. Introduction

as a large amount of cheap material and thus the total price comes out roughly equal. Whilst some metric could be used to consider both conductivity and cost, the exact limit would always be subjective and complex as a new metric would be required for every functional property. One of the goals of this thesis is that all developed solutions should be cost-effective. As will be outlined in the subsequent literature review, advancements have been made in the past few years in opening up AM technologies to those who have not been able to afford it, e.g. schools, students, small companies and home users. Given the difficulties outlined, within the context of this thesis low-cost simply implies that the technology developed is within the reach of schools, students, small companies and individuals.

These objectives have been informed through critical analysis of the literature which may be found in the subsequent Chapter.

1.2. Thesis Structure

After the literature review presented in Chapter 2, the research undertaken in this Thesis essentially has three bodies of work, whilst these have been undertaken separately in parallel on a practical basis, they are in fact heavily linked and essential to prove the hypothesis. Firstly Chapter 3 “Multi-material Development” details development of the multi-material AM system that combines the FFF and Robocasting processes. Whilst this alone represents a step forward in the available functionality that is achievable, there are drawbacks to this approach that ensures a complimentary solution is required.

Whilst using multiple materials allows for different functionality, if a design/system is to be optimised it is not unrealistic for a desired component to require many, many different material properties over the entire component. Achieving this only through multiple materials implies an extruder is required for every material property desired. From the perspectives of machine design and process complexity, such an approach simply isn’t practical or efficient. Therefore an alternative means of achieving a variation in material properties with just one material is required. Therefore Chapter 4 “Effect of mesoscale structure and print parameters on mechanical properties” investigates the range of properties that can be achieved by adjusting the porous mesostructure that makes up manufactured components. In doing so the mechanical properties achievable with one extruder has been shown to vary by an order of magnitude, and therefore may be used as a complementary technique.
1. Introduction

The final body of research work presented is entitled “Electrically Conductive Materials”. To summarise the literature review on the subject from the following chapter, to date excellent results are achievable using direct writing technologies, and poor quality has been achieved through Robocasting/FFF techniques. However direct writing techniques require extremely expensive silver based materials, and a fundamentally different process. Therefore such a technique cannot be implemented in parallel to the AM systems used in a low cost manner and the FFF/Robocasting techniques require a step change in resolution and control in order to produce functional circuits. This chapter researches techniques to substantially improve the quality attainable through low cost AM processes to enable printing of functional electronic circuitry.

Finally following the presentation of the research conducted, a discussion is presented and the conclusions are summarised.

![Figure 1.2.: Thesis Structure](image)

1.3. Contributions

The main contribution of this thesis is an Additive Manufacturing system capable of manufacturing multi-material components with varying engineering properties. Whilst other systems have been developed capable of using multi-materials, they either rely on extremely expensive technologies, use similar materials with a relatively narrow range of material properties, or they have been developed to use the Robocasting technique which offers reduced print quality relative to the alternatives.

All of the work undertaken used the RepRap project as a platform to enable the research. RepRap - short for Replicating Rapid Prototyper - is an on-going project to create a machine which is capable of producing a significant proportion of its own components. To date the project has focused on Fused Filament Fabrication as a tech-
nology to enable its goals - limiting the functionality attainable with present materials. All of the hardware and software developed by the project is released for free, under an open source licence, hence all hardware, software and electronics was easily modifiable to enable the research to be undertaken. More information about the RepRap project may be found in the next chapter.

A brief summary of the contributions of each chapter in this thesis is outlined below. Where relevant the individual contribution to a chapter is outlined and references are included to published papers based on the work undertaken:

- Chapter 1 - Introduction - This chapter provides an introduction to the field of Additive Manufacturing, explores the uses of Additive Manufacturing to date and the limitations of AM. The motivations behind this thesis are established, namely that low cost AM components to date offer little functionality beyond uniform properties and the implications of low-cost multi-material AM is substantial.

- Chapter 2 - Background - In this chapter the history and prior art of Additive Manufacturing are detailed. All significant Additive Manufacturing techniques are researched within the context of multiple materials. Recent developments investigating new materials are detailed. Fundamental problems and limitations of using multiple materials are researched e.g. file formats. The background to the RepRap project, its progress to date and an overview of research conducted by RepRap is also presented [6]. Based on the systems outlined, each fundamental AM technique is qualitatively analysed with respect to their ability to print a wide variety of materials, their capability of producing multi-material components, and their compatibility with other processes. It is concluded that Robocasting has already demonstrated the capability to deposit a wide range of materials, and is the most flexible technique available. Therefore by combining it with Fused Filament Fabrication a more useful system is created with a wider range of material properties achievable.

- Chapter 3 - Multi-material Development - The chapter explores the basic mechanical setup of the AM system. Whilst Robocasting has previously been shown to be compatible with FFF, to the best of the author’s knowledge this is the first instance where these two Additive Manufacturing processes have been combined in an automated fashion to form one machine. This chapter then details the implementation and calibration of this setup. Further the setup is sufficiently versatile that three FFF/Robocasting extruders may be used in any combination. This machine forms the basis of the test setup for the remainder of this thesis. The
1. Introduction

The chapter concludes with the manufacture of a component consisting of a robust polylactic acid inner core deposited by FFF, and a soft polydimethylsiloxane exterior shell. Outside of the work of this thesis, the concepts explored have been subsequently developed externally to manufacture multicolour FFF components.

- Chapter 4 - Effect of mesoscale structure and print parameters on mechanical properties - The implementation of additional extruders to allow a wider range of material properties comes with a few disadvantages, such as reduction in build volume, extra complication and care in mechanical setup to prevent nozzle collisions, and just increased complexity which reduces reliability. Therefore it is beneficial to reduce the total number of extruders within a given machine. As such research investigating other methods of achieving these material properties and in doing so improve reliability and build volume is desirable. One known technique is to alter the mesostructure of the manufactured parts by adjusting aspects of the extrusion tool path such as layer height, infill direction and porosity. This chapter investigates such print parameters with the aim of being able to define the required material properties, and through the results of this chapter select the appropriate print parameters. Whilst similar studies have been previously investigated for ABS on Stratasys systems, here the effect of build parameters on polylactic acid are investigated as it is known to be a better material for FFF in some regards - giving reduced warp, improved stiffness and wear resistance. Further a wider range of parameters are investigated compared to previous studies. Over an order of magnitude difference in structural properties such as Young’s modulus and ultimate tensile strength was achieved using the same build material.

- Chapter 5 - Electrically Conductive Materials - This chapter details the development of an electrically conductive material for Fused Filament Fabrication. As shown in the literature, previous printable conductive materials are either costly, have poor resistivity or have poor print quality. Whilst attempts have been previously made to print 60/40 solder amongst others, print quality has always been poor. In parallel to these attempts, research has previously been undertaken to attempt to enable FreeForm manufacturing of low melting point metals through using semi-solid materials and non-eutectics, such work has resulted in the manufacture of the thin walled components. Therefore the work undertaken in this chapter combines these two areas. The research presented in this chapter presents a new novel low cost electrically conductive alloy for FFF specifically for the purpose of electrical circuitry, and to be compatible with standard FFF thermoplastics. Potential solutions to previous issues highlighted in the liter-
1. Introduction

ature review were revisited, and it was elected to use a bespoke non-eutectic Sn/Bi/In alloy in order to reduce the effects of surface tension. Several extruder iterations were developed and optimised using finite element analysis to further improve print quality. After calibration a series of design rules were developed to ensure good quality prints. Finally a 3D-printed micro-controller was created using the technique; again this is the first time a complex functional electronic circuit has been produced using 3D printing techniques. A the time of writing, a paper based on the chapter entitled “Direct Metal Fused Filament Fabrication of Electrical Circuitry using RepRap” has been submitted and is under review.

• Chapter 6 - Discussion - Whilst some discussion is provided in each relevant chapter, this chapter looks at the technicalities and difficulties associated with combining all of the techniques and materials developed. Further the results are reviewed with respect to proving the author’s hypothesis.

• Chapter 7 - Conclusions - Conclusions are drawn about functional components manufactured by FFF and potential future work is discussed.
2. Background

Additive Manufacturing in its current form is the result of many technologies being developed in parallel. As a result methods that are used today each have their own strengths, weaknesses and applications. This section will explore the on-going development of Additive Manufacturing, including research into new materials, tuneable material properties, and the on-going transition to open-source technologies; whilst highlighting relevant research in the sector within the context of manufacturing functional engineering components.

2.1. Definitions

As will be detailed throughout the following chapter, the field of Additive Manufacturing is a sector that can trace its routes back to the 19th century. With the recent improvements in AM, revenues generated by the products and services of companies within the Additive Manufacturing industry are growing at the astounding rate of 29.4% per annum and stand at approximately $1.7 billion as of 2012 [7]. Further since the introduction of low cost open source 3D printers (the majority of which are RepRap derivatives), industry growth for low cost 3D printers in the $1000-2000 price bracket has been substantial, with growth of 294% per annum as of 2012. Unsurprisingly this has led to substantial developments in recent times, and some ambiguity in the terms used in field has arisen as a result. For clarity the author presents the following interpretations that will be used within this thesis. These definitions have been derived from Gibson et al. [1] and Chua et al. [8].

**Rapid Prototyping (RP)**

A term used across many industries to describe a mechanism for quickly producing a *representation* of a system or part before the final manufacturing process is established.
2. Background

This term is equally applicable to software development, where the term can be used in developing software in a piecewise fashion to allow clients to provide feedback during development. Arguably, this is a flawed definition. It does not reflect the improvements in output quality that have been occurring in recent times. This has led such technologies to become a more integral part of the manufacturing process; in some cases parts are manufactured by such techniques for inclusion in the final product.

Furthermore, the term rapid is a misdemeanour, particularly when for some systems and designs models can take several days to produce. A working group has recently been formed within American Society for Testing and Materials (ASTM) International to conceive a more appropriate term. At the time of writing, new terminology has not been defined; however recent ASTM standards refer to the term Additive Manufacturing. [1]

Additive Manufacturing (AM)

Additive Manufacturing refers to the collection of techniques which are capable of fabricating models, typically generated using a Computer Aided Design (CAD) package, in an additive fashion without the need for any complex process planning. The model is typically sliced into a series of two-dimensional layers, before being manufactured layer-by-layer.

Solid FreeForm Fabrication (SFF)

An alternative to the term Additive Manufacturing. The reference to the term FreeForm refers to ability of many AM systems to provide “complexity for free”, where for example a simple solid cube would have the same build time as a part with the same total volume but containing a complex mesostructure.

3D Printing (3DP)

The term 3D Printing refers to a subset of solid free-form fabrication and AM technologies which encompass the cheapest technologies.

Somewhat confusingly, 3D printing is also an alternative term for solvent jet printing (see Section 2.3), within the context of this thesis 3D printing will only refer to low
2. Background

cost solid free-form fabrication/AM systems.

2.2. Foundations of Additive Manufacturing

Whilst the concept of manufacturing objects in layers dates back to the building of the pyramids or coiled pottery, if not before, the underpinnings of modern Rapid Prototyping technologies may be traced back to the advent of photo-sculpture and topology. Much of the background presented here is based on Beaman’s summary [9].

**Photo-sculpture**

During the 19th century, attempts arose to create physical replicas of three-dimensional objects. One such attempt was undertaken by François Willème, whereby an object was placed at the centre of circular chamber and simultaneously photographed by 24 different cameras equidistantly spaced around the circumference. Silhouettes of these photographs would then be used by craftsmen to assist in the manufacture of three-dimensional models. In 1904 Baese developed a refinement on this technology, by employing the use of photosensitive gelatine, which when exposed to a graduated light source, expanded proportionally to the exposure time when treated with water [10].

Perhaps the earliest technique with direct parallels to a modern Rapid Prototyping technology, namely stereolithography, was developed by Munz in 1951 [11]. His system was centred on a transparent photo-emulsion that hardened when exposed light through a photographic negative. This photo-emulsion was contained within a large vat built on a piston as shown in Figure 2.1. After each layer was exposed, the piston descended allowing the next layer to be built on top of the previous layers. The result was that a 3D image of the object was steadily built in solid; this could be carved or chemically etched to create a 3D replica of the original.
2. Background

In 1892, Blanther developed and patented a novel method of manufacturing contour relief-maps [12]. The process consisted of impressing a contour line from a map onto a wax plate. Following this, Blanther proceeded to cut along this line, leaving a wax plate indicating a topographical area above a given altitude. This process was repeated for the remaining contour lines from the map, before stacking and smoothing these.
2. Background

wax plates. The process resulted in a three dimensional surface corresponding to the altitude indicated by the original contour lines. After creating a negative form of this surface, a regular map was then be pressed between these surfaces to create a three-dimensional contour relief map.

![Blanther's Contour Relief Map](image)

Figure 2.2.: Blanther's Contour Relief Map [12]

Whilst the methods of Blanther were furthered in the early 20th century by Perera, Zang and Gaskin, the fundamentals of the process were not substantially developed until the work of Matsubara in 1972 [9]. He proposed a topographical process based on photo-hardening resins, which involved coating powders such as graphite. These coated powders would be spread into a layer and heated to form a sheet of uniform thickness. Desired sections of this sheet would then be selectively hardened using a light source, before the unhardened sections of the sheet were dissolved by a suitable solvent, leaving one layer of the required geometry. This process could then be repeated to form multiple layers, which could be stacked together to form a three-dimensional mould.

The Birth of Modern Additive Manufacturing

Whilst there are other labour intensive methods besides those outlined in the preceding section which have similarities with modern AM, the first published account of a modern Additive Manufacturing process occurred in 1974. A joke was written by David
2. Background

Jones under the pen-name “Daedalus” in the New Scientist [13]. He proposed that a laser could be shone through a liquid monomer causing it to solidify. He further proposed that if the wavelength was accurately controlled, two lasers could be used such that cross-linking causing solidification would only occur where the beams intersected. These beams could then be made to trace out an object resulting in the manufacture of a 3D component. Despite the joke, a patent was applied for independently around the same time by Wyn Kelly Swainson for fundamentally the same concept, except rather than the lasers creating a 3D tool path, the part was formed layer-by-layer with the object being manufactured sitting on a piston and slowly lowered into the vat of monomer [14].

The first published practical implementation of AM was by Kodama who investigated three alternative processes to fabricate a 3D model [15]. The fundamental approach of all three methods was to use a commercial photo-hardening liquid. Upon UV illumination, unsaturated polyester within the liquid turned to a cross-linked polymer and solidified. The difference between each method lies in the approach used to accurately control the UV illumination:

1. A mask was implemented to control the exposure of the UV source. After the exposure of one layer, the model was then lowered into a liquid photopolymer vat in order to create the next layer

2. Implementing a mask-based approached as in 1), but locating the UV source and the mask at the bottom of the vat, and raising the model in order to create each layer.

3. Using an X-Y plotter, an optical fibre and lens to solidify a small segment of one layer accurately. The plotter scanned the cross-section of the model to solidify an entire layer fully. After the exposure of an entire layer the model would be lowered into a liquid vat to enable the production of the following layer.

Subsequent to this early development, the first commercial Additive Manufacturing system based on Stereolithography was released by Charles Hull and 3D systems in 1986.
2. Background

Figure 2.3.: Examples of Models Produced Using Kodama’s Techniques [15]

2.3. Modern Additive Manufacturing

Methods

Given that many RP techniques exist, this sections aims to perform a qualitative analysis on each with regards to its suitability to printing multiple materials. What follows is a literature review of the field. Before this analysis can be made however firstly the fundamental techniques of AM systems are presented in Table 2.1:
Table 2.1.: Descriptions of the Established Solid Free-Form Fabrication Technologies. Unless otherwise stated, illustrations are courtesy of Gibson et al. [1]

<table>
<thead>
<tr>
<th>Method</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stereolithography (SLA)</td>
<td>The process is built around a vat of liquid photopolymer, a laser beam and the appropriate optics, and a movable platform. At the start of the process, the platform is such that its surface is just below the surface of the photopolymer. The optics focus the laser onto the liquid surface, and proceed to scan a two-dimensional cross-section of the desired part causing the photopolymer to solidify. The entire platform drops to cover this section with more liquid. This process is then repeated until the complete part is manufactured.</td>
</tr>
<tr>
<td>Selective Laser Sintering (SLS)</td>
<td>A large quantity of powdered material is stored in a feed cartridge. A piston in the cartridge enables the upper surface height of the powder to be accurately adjusted. A roller is then capable of spreading powder from the feed cartridge onto the build platform. A laser beam, typically CO$_2$, traces over the powder, increasing its temperature above the material’s melting point enabling it to fuse together. A second piston controlling the height of the build platform is then lowered, to allow a further layer of powder to be deposited onto the build platform using the mechanism previously described. Unlike many other SFF technologies, the unfused powder in lower layers is able to support the part geometry in upper layers from deforming. Thus additional support material is not required for complex geometries.</td>
</tr>
<tr>
<td>Process</td>
<td>Description</td>
</tr>
<tr>
<td>-------------------------------</td>
<td>-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Single Jet Inkjet (MM)</td>
<td>Two single jets separately contain a plastic build material, and a wax support material, stored in heated reservoirs. Both jets move in X/Y directions whilst depositing droplets of each material at the appropriate positions. After deposition, the droplets rapidly drop in temperature causing them to solidify. Subsequently, a milling head removes a small amount of material from the top of the layer to ensure uniform thickness, whilst any swarf is collected by vacuum. The entire build platform then drops a small amount to allow the manufacture of another layer using the same process. Illustration is from the Worldwide guide to Rapid Prototyping. [16]</td>
</tr>
<tr>
<td>Jetted Photopolymer (J-P)</td>
<td>The Jetted Photopolymer process is very much a hybrid of traditional 2D ink-jet printing and Stereolithography. An array of ink-jet jetting heads is used to deposit a small layer of photo-curing material. Subsequently, the material is cured using UV light. This entire process occurs on a movable build tray that is lowered to enable the next layer to be manufactured. Typically other photo-curing materials or waxes are required for a support material. Illustration is from Objet Geometries Ltd. [17].</td>
</tr>
<tr>
<td>Laminated Object Manufacturing (LOM)</td>
<td>Material, typically paper, is supplied in sheet form on a roll. This material is fed over a platform and secured to a take up roll. A cross-section of the part is then cut using a CO₂ laser and then laminated. The platform is lowered, and fresh material is rolled over the build. This process continues to build subsequent layers. No support material is required as any excess material within the voids of the part is cross-hatched and can act as a support structure.</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Fused Filament Fabrication (FFF). Also known as Fused Deposition Modelling (FDM)</td>
<td>Material, typically thermoplastic, supplied in filament form, is fed into liquefier chamber where it is heated to a semi-liquid state and deposited through a nozzle onto a build platform. Upon leaving the nozzle, the material quickly solidifies. In a continuous process, the extruder is traversed in the X and Y axis relative to the bed to create a layer of the part. Typically a second extruder capable of depositing support material is also used in the process. This support may either be designed such that it is easy to breakaway in post processing, or alternatively may be soluble in a suitable solvent.</td>
</tr>
</tbody>
</table>
### Solvent Jet Printing (frequently referred to as Three-Dimensional (3D) Printing)

A powder spreader deposits an even layer of powder onto a build platform that is capable of movement in the Z axis. The machine then uses an Inkjet print head to deposit binder solution onto the loose powder to glue the powder together, to form a layer of the final part. Finally, the build piston is lowered, and the process repeated for the subsequent layers. Any unused powder is capable of supporting any layers above, thus no support material is required.

Image Courtesy of Hiemenz [18].

### Electron Beam Melting (EBM)

The process is centred around an electron beam gun, whereby a tungsten filament is heated until the point that it becomes incandescent. At this point, the filament produces a cloud of charged electrons. An anode, also contained within the gun, induces the electrons to travel through the gun at extremely high speed, approximately half the speed of light, towards the anode. Two sets of magnetic coils, one for focusing, one for position control, control this stream of electrons towards a desired point in a bed of powder. Upon hitting the powder, the electrons' kinetic energy is converted to thermal energy, melting the powder fusing it together. This beam is then traced over the powder to form one layer of part, before more powder is added and process repeated to build subsequent layers.

Image Courtesy of Hiemenz [18].
2. Background

Given the fundamental differences in the technologies available, it is unsurprising that each technique has different strengths and weaknesses. As such despite the versatility of Additive Manufacturing, each technique often has applications that best suit its strengths. A summary of these strength and weaknesses including typical costs, materials and applications is presented in Appendix A.

Fundamentals characteristics

Within Additive Manufacturing several different technologies exist, each with their own set of characteristics, capabilities and limitations. Common fundamental characteristics of most of these processes are set out below:

- Support material - Many AM processes require the use of a secondary support material in order to allow a model to be manufactured using a primary build material. This support material is typically removed manually by hand, which is time consuming, although water-soluble support materials are used in some processes. Further in many powder based techniques such as SLS or Solvent Jet Printing, unused power is used to support the main component, this powder may then be recycled for use as a build material in later prints. It is possible for some complex geometries that this support material can be physically impossible to remove or can damage the final model during removal. This is one of the few restrictions on part geometry within AM processes. An example of the part complexity achievable without support material for FFF (the technology used throughout this thesis) is shown in Figure 2.4. It should be noted that often prints such as this are possible without support material, provided they have no inverted surfaces, however surface finish is often diminished as a result. Without the use support material, post processing is not required and eliminates the risk of part breakage during material removal.
2. Background

![Complex part printed without support material, made on a RepRap by the author (left), diminished surface quality, highlighted in blue, at overhangs in excess of approximately 45° (right)](image)

- Costs and lead-times - In traditional subtractive processes, the overall size of the part has only an indirect effect on manufacturing time. Traditionally materials are comparatively cheap in comparison to machining time related to part complexity, tooling and fixturing costs, operator/programming time etc. However in many AM processes material throughput is roughly constant, thus the part cost is directly related to part volume with the only effect of part geometry being the use of additional support material. The lack of tooling and operational complexity makes the technique ideally suited to prototypes, hence its use in the development cycle to cut lead-time [8], however it results in part cost increasing substantially as part size increases. *i.e.* a part double the size costs approximately eight times the price and takes eight times as long to build.

- Surface finish - Surface finish is highly dependent on build orientation. Critical surfaces should always be parallel to the layer direction. However this is not always possible. Not doing this will result in a “staircase” effect along the surface due to the surface spanning several layers [19]. Even on the most accurate AM processes, layer heights are at least forty microns [16], resulting in a diminished surface finish relative to that available via machining. On more common processes layer heights can be as high as 0.3mm as shown in Appendix A resulting in a finish which is poor at best if build orientation is sub-optimal.

- Part distortion - Residual stresses can arise during material solidification as a
2. Background

result of the manufacturing processes. These residual stresses can be the result of many factors depending on the process in question. For example many processes rely on temperature to fuse material. Above a material’s glass transition point material contraction is minimal; however a substantial amount of contraction occurs between this glass temperature and room temperature. The resulting part distortion is geometry dependent, and hence is difficult to compensate for although research is on-going to model the process [20] and manufacturers have implemented heated build chambers in order to reduce the issue.

2.4. The RepRap Project and Self Replicating Machines

The topic of self-replicating machines has intrigued some of mankind’s greatest minds for generations. Descartes (1596 - 1650) said that humans were nothing more than complex machines [21], and that the body’s functions “follow from the mere arrangement of the machine’s organs every bit as naturally as the movements of a clock or other automaton follow from the arrangement of its counter-weights and wheels.” Fundamentally there are two potential approaches to artificial self-manufacture, which is to say the design of machines that are capable of manufacturing their own components to within engineering tolerances [21]:

1. Unit Growth or factory model: a collective of devices, each with a specific and limited purpose. Thus, each unit is not capable of reproduction, but as a group all are capable of manufacturing and assembling all components for every machine within the group.

2. Unit Replication, or ‘organismic’ model: the replicator is an independent device that utilises its surrounding environment to produce an identical copy of itself. Both the child, and the parent machine remain fertile.

Both allow exponential growth. As noted by von Neumann, any well stocked machine shop is capable of manufacturing all the tools required for another machine shop, and thus may be considered self-manufacturing system under the Unit Growth model. The difficulty with this is in the use of the term “well stocked”. Whilst adding further machines to the collective increases the potential for reproduction, yet more capability would be required to make these new machines. Thus, in practice this approach chases a receding target, and would require a substantial amount of space and resource; this
2. Background

would make it unattainable to all but the most well-funded institutions. Of course, human engineering considered as a whole is a Unit Growth model.

By contrast, a Unit Replication model is by definition self-contained and therefore not subjected to the limitations of the Unit Growth model. However, achievements in this sector have thus far been limited. This has mainly been due to the lack of a manufacturing technology sufficiently versatile to manufacture components with the various mechanical properties and geometries that would inevitably be required. The only major research effort that has actually achieved such a system that works in the world outside the laboratory is the RepRap project, of which this thesis is a part. The project argues that Additive Manufacturing techniques are the most versatile manufacturing techniques currently available, and therefore are the best suited to creating a self-manufacturing machine.

In 2004, Bowyer identified that one reason for the complexity of von Neumann’s proposals for producing a self-reproducing machine was due to its requirement to both assemble, and to produce, its constituent components [22]. He recognised that by removing the ability to self-assemble, instead relying on the dexterity of human beings, the design complexity would be reduced and such a machine could become reality. In addition, Bowyer identified solid free-form fabrication as a potential technology on which such a machine could be based. The decision to use SFF techniques rather than subtractive manufacturing was a simple one from an engineering perspective for the following reasons:

- Solid free-form fabrication requires substantially lower forces compared to subtractive manufacturing.

- Computationally, it is relatively simple to calculate movements of a Cartesian system for a solid free-form fabrication system compared to subtractive methods

- Of all the current manufacturing technologies, solid free-form fabrication has the greatest versatility in accordance with the requirements for a self-replicating kinematic machine defined by Freitas et al. [23]

Bowyer identified that many of the components of such a machine are widely available at minimal cost (e.g. nuts, bolts, motors, electronics etc.). He proposed the initial complexity of being able to produce these components was not worthwhile, both for technical reasons as well as maximising the ease of reproduction. However, with additional development, the percentage of self-manufactured parts is intended to increase as the machine’s capability improves. In addition, Bowyer took one further biomimetic
2. Background

principle from nature - evolution. All designs were released for free, under the terms of an open source GNU Library General Public licence, a copy of which may be found in Appendix C. The designs are available for modification and improvement over time; thus a RepRap is capable of producing both successive generations of machines and its own upgrades. In keeping with this philosophy, all work undertaken in this thesis has been released under the same licence.

An important decision was choosing the optimal solid free-form fabrication technology for self-reproduction. The FFF technique was chosen owing to its potential capability to work with multiple materials. This ability offers a corresponding potential increase in the self-manufactured part ratio. In addition, the RepRap team contended that a Fused-Filament-Fabrication-based machine could potentially be made using “low cost garden shed” methods.

Figure 2.5.: RepRap V1.0 - Darwin. The device is capable of self-manufacturing all parts shown in either white or green (except the thermal insulator on the extruder)

The fundamental concepts outlined above have since been developed into the first version of RepRap named “Darwin”, as shown in Figure 2.5, which was released to the public in late 2007. On 29th May 2008, the first complete working “child” machine was created from components made from a “parent” machine [24]. It is estimated that Darwin costs under $500 to build compared with $9,900 for the cheapest proprietary commercial 3D printer at the time [16].
2. Background

Materials and Extrusion Mechanisms

Initially, the RepRap team used polycaprolactone (PCL) polymer owing to its low melting point, thereby lowering the power consumption required for the extruder. Crucially however, its low coefficient of friction ensured that the polymer transport mechanism within the extruder needed to provide substantial amounts of grip. Thus, the resulting extruder design required multiple pinch wheels and therefore became unnecessarily complex [6].

![Image](image.png)

Figure 2.6.: The geared extruder design, showing front (left) and back (middle) views. In addition, a further modification implementing a PEEK bracket and a nozzle to encase the thermal barrier to reduce PTFE insulator swell is shown partially assembled (right)

Figure 2.6 shows a later iteration of the RepRap extruder design. The device has a gear ratio of 5:1 (using gears that RepRap is capable of producing for itself), in order to allow for increased control over the plastic filament feed. In this case, a single pinch wheel is employed, with a splined insert attached the driven gear compressing the plastic filament against an idler bearing. In addition, the position of this idler bearing is controlled by adjusting a series of compression springs at the front of the device. The compression springs ensure that the force acting on the filament remains approximately constant regardless of any small variations in filament diameter. The filament is fed into a thermal barrier, in this case PTFE due to its low friction and thermal conductivity coefficients, in order to prevent the heat from the nozzle spreading to the rest of the machine.

Following the thermal barrier, a brass nozzle with an orifice of 0.5mm is used to both heat and extrude the thermoplastic filament. This orifice diameter was chosen as it was deemed a good compromise between acceptable accuracy and reasonably fast build times.

Given the increased operating temperature of which the more recent extruder designs
were capable, other materials could potentially be used. Given the low friction coefficient of PCL, and the “stringy” nature of the extrudate, PCL was only capable of producing poor quality parts. Therefore, a transition was made to utilise Acrylonitrile Butadiene styrene (ABS) as is commonplace is other FFF systems.

Figure 2.7.: A comparison of the build quality, between ABS (left) and PLA (right) circa September 2009. Note the warping on the ABS part. [6]

Whilst ABS solved many of the problems initially reducing the quality of RepRap-made parts, one fundamental issue remained - part warping. Obviously the plastic filament needs to be heated to its melting point before solidifying when cooling. However, this cooling enables thermal contraction, and thus the bottoms of parts have the tendency to curl away from the build base, although this issue is reduced for small parts. Proprietary machines typically solve this issue by running the entire process within a heated chamber. However, it was deemed that incorporating a heated chamber into the design would increase the complexity of the design, and thus harm its ability to replicate.

In parallel, the use of Polylactic Acid (PLA) as a build material was being investigated by team-member Vik Olliver. PLA is a biologically sourced thermoplastic, which is biodegradable and more eco-friendly than oil-based polymers. It was discovered during this research that PLA suffers substantially less from contraction on cooling and is described by Bowyer as “the almost perfect” material for the Fused Filament Fabrication process. However it tends to “string”, leaving extrudate sticking out from the part surface due to in-air movements required during the build process; however this can be minimised by reversing the filament at the end of print moves.

Subsequently to this, a heated bed has been developed by the RepRap community. An aluminium build base is heated by a PCB or nichrome heater wire. This produces
similar effects to that of the heated build chamber used in commercial systems, but in a simple, low-cost manner. Subsequently this approach has been adopted by many low cost commercial FFF systems.

**RepRap II - Mendel**

A second-generation RepRap design, “Mendel”, was released in October 2009. The Mendel design focuses on reducing the amount of Cartesian frame to the design, and thus reduces the amount of “vitamin” (i.e. not self-printed) components required. In addition, Mendel incorporates rolling element bearings for constraint, resulting in a more robust and portable machine. However, at the inception of the work undertaken in this thesis, Mendel was only capable of using a single material during any build.
2. Background

Table 2.2.: RepRap Models Comparison Specifications, based on data provided by Jones et al. [6] and Sells [25]

<table>
<thead>
<tr>
<th>Technology</th>
<th>RepRap I: Darwin</th>
<th>RepRap II: Mendel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Price of all materials</td>
<td>€400</td>
<td>€400</td>
</tr>
<tr>
<td>Annual Service Cost</td>
<td>Oiling = €5. It is capable of printing its own replacement parts at material cost (minimal)</td>
<td></td>
</tr>
<tr>
<td>Size</td>
<td>600 mm (W) x 520 mm (D) x 650 mm (H)</td>
<td>500 mm (W) x 400 mm (D) x 360 mm (H)</td>
</tr>
<tr>
<td>Weight</td>
<td>14 kg</td>
<td>7.0 kg</td>
</tr>
<tr>
<td>Build Envelope</td>
<td>200 mm (W) x 150 mm (D) x 100 mm (H)</td>
<td>200 mm (W) x 200 mm (D) x 140 mm (H)</td>
</tr>
<tr>
<td>Materials</td>
<td>PLA, HDPE, ABS and HDPE.</td>
<td></td>
</tr>
<tr>
<td>Deposition rate</td>
<td>15.0cm³ per hour solid (test done for PLA, similar for others). Standard software settings translates this to 19.0cm³ build volume rate per hour</td>
<td></td>
</tr>
<tr>
<td>Positioning Accuracy</td>
<td>0.1mm</td>
<td></td>
</tr>
<tr>
<td>Accuracy</td>
<td>Diameter of nozzle 0.5 mm, 2 mm min. feature size, 0.1 mm positioning accuracy, layer thickness 0.3 mm</td>
<td></td>
</tr>
<tr>
<td>Finish</td>
<td>Poor</td>
<td></td>
</tr>
<tr>
<td>Volume of printed parts to replicate</td>
<td>1200cm³</td>
<td>1110cm³</td>
</tr>
</tbody>
</table>

Part Count Analysis

Up until the time RepRap was released, AM technology was prohibitively expensive for use as a manufacturing system, and therefore there are few examples of machines in which the parts to be made by AM were maximised. Systems have been used to manufacture individual components that typically could not be manufactured by an alternative method, but cases where entire machines have been designed to maximise the use of AM components are rare.
2. Background

Figure 2.9.: Darwin part count analysis including one extruder, both with fasteners (left) and without fasteners (right). It is assumed that each electronic assembly counts as one part. [24]

Figure 2.9, shows a part count analysis of the Darwin design conducted by Sells. Whilst the end goal of the RepRap project is to build a 3D printer that can build all of its components, the Darwin version has a self-manufacturing ratio of 48% (ignoring fasteners). Sells has identified that if the design was extended, to allow the extrusion of a resin, conductive alloy and a flexible polymer such as polydimethylsiloxane (silicone rubber), the self–manufacturing ratio could reach 94%.

The self-manufacturing ratio of Mendel is approximately the same as Darwin. Without any improvement in the deposition capability of the device, any change in replication count will solely be due to a design improvement. With RepRap thus far being unable to utilise functional materials, the functions of replicated parts are solely governed by their geometry. Thus, the replicated parts within the machine are typically structural components with no major strength requirement and low geometric tolerances such as clamps, mounting brackets, and course-pitch gears.

2.5. Multiple Material Additive Manufacturing and Functional Components

As mentioned previously, the use of multiple materials with Additive Manufacturing has been proposed almost since the technology’s inception. In some cases, the use of multiple materials is a fundamental element of how some AM process work: for example a secondary support material is a key element in the Fused Filament Fabrication
2. Background

process to enable more complex overhanging geometries to be created. This is often a different material to the primary build material (though most low-cost FFF systems use the primary build material for support as well, simply laying it down in a deliberately weak pattern).

In general, there are three potential techniques by which multiple materials may be implemented [1]:

- Two or more discrete materials may be deposited next to each other. Typically, systems of this type rely on adhesion between materials, although they may be bonded in some other fashion.

- An object can be created such that the part is inherently porous. Subsequently, this part may then be infiltrated by a second liquid material such as an adhesive. This technique is frequently used in the Solvent Jet Printing process to strengthen components.

- The AM process may utilise a feed material that itself is a blend of two or more constituent materials. Some systems also offer the ability to vary the ratio of these materials continuously to give functionally graded components. This technique has been previously demonstrated using EBM or SLS to manufacture nickel-titanium graded components amongst others. [26]

Many reasons are often cited as the driver for reasons for the AM industry to implement multiple materials, these include [1]:

- Improving mechanical properties - Additional materials can allow the bulk mechanical properties of produced parts to be finely controlled, for example tensile strength.

- Increased functionality - Multiple materials may enable parts containing different colours, electrical conductivity, stiffness or other properties. Further, these properties can vary either uniformly or discreetly throughout the component by placing the right combinations of materials in strategic locations.

- Improving the AM processes - Additional materials may assist with fabrication, e.g. support material.

This section aims to summarise research undertaken into the implementation of functional materials and multi-material techniques in the low cost 3D printing sector.
2. Background

Robocasting

In 1999, Joe Cesarano of the Sandia National Laboratory developed a new method of fabricating ceramics entitled Robocasting. Robocasting, often known as Paste Extrusion Freeforming (EFF) relies on a syringe to deposit a mixture of ceramic powder, water and chemical modifiers. The desired component is then built in an additive fashion - much like Fused Filament Fabrication - using a CNC-controlled positioning head and a pneumatically powered syringe. Typically a liquid-to-solid transition is then realised by solvent evaporation, UV curing or other methods [5]. After parts are formed using Robocasting, they must be dried and then sintered before they are ready for use.

Cesarano specifies that Robocasting slurry must meet three key criteria:

1. The slurry must be sufficiently pseudo-plastic to flow through a small orifice at modest shear rates,

2. It must be set-up into a “non-flowable” mass upon dispensing, and

3. The extrudate must be sufficiently robust to be able to withstand the weight of the above layers without defects.

Control of the build time proved to be critical. The build speed needed to closely match the speed at which respective layers transitioned from pseudo-plastic to dilatant. To assist with this transition, parts are typically built on a heated plate from at a temperature of 30 to 60°C. In the event that the drying rate was too slow, weight from the above neighbouring layers may lead to the yield stress being surpassed resulting in deformed layers with “slumping and non-uniform walls”. Equally drying too fast can result in de-laminating, warping and cracking.

Figure 2.10.: Robocasting [5]
2. Background

Cesarano concludes that for effective Robocasting five key parameters require precise control:

1. Viscosity and rheology of the slurry,
2. Drying kinetics of the extrudate,
3. Computer code for optimal machine instructions,
4. Percent solids in the ceramic powder slurry, and
5. The dispensing rate.

Similar conclusions to Cesarano’s above have also been made by Lu et al. [27]. A study was conducted on a polymer-based paste before the addition of alumina, LMT, quartz and graphite powders, in order to determine the effect on various parameters. Unsurprisingly, the results show that both powder type and the solvent volume fraction has a substantial effect on viscosity, and subsequently the required extrusion pressure (Figure 2.11).

At higher solvent volumes, viscosity remained reasonably stable with increasing shear rate, and thus was approximately Newtonian. However, with lower solvent fractions, all pastes showed shear-thinning properties (decreased viscosity with increasing shear rate) demonstrating pseudo-plasticity. Furthermore, all pastes were shown to have a critical value of ceramic volume fraction at which a substantial change in the paste viscosity occurs. Thus, an ideal paste should operate around this volume fraction during the deposition process, enabling a “low” viscosity paste to be easily extruded, before a loss of solvent and the associated substantial rise in viscosity and state change; enabling the layer to be sufficiently rigid to hold subsequently deposited layers.
2. Background

![Figure 2.11](image)

Figure 2.11.: Required extrusion pressure for constant volume flow rate for alumina paste with different solvent fractions [27]. Note the step change at 40% volume fraction

This work culminated in the creation of a variety of structures to show the strengths of the process. Of particular interest is an electromagnetic band-gap structure, whereby the ability of an object to transmit electromagnetic waves may be controlled by precisely adjusting the separation between infill segments (commonly referred to as roads).

Subsequently to these developments, the process has been further refined to function with up to four materials. The multi-material head consists of four independent material feeds in combination with a miniature mixing chamber and a rotatable paddle. An example of a graded two-material component produced on a dual feed mixing head showing a gradual 100% transition from one component material to the other is shown in Figure 2.12.

![Figure 2.12](image)

Figure 2.12.: Robocasting Multi-material Head (left) and a graded transition between two ceramic slurries (right)

Further, unlike Fused Filament Fabrication using thermoplastics, Robocasting is only
2. Background

capable of producing extremely basic structures without the use of support material. Whilst support is used for Fused Filament Fabrication, many complex shapes such as overhangs of up to 45° are possible without them. Therefore Cesarano’s multi-material head has been further employed to enable the deposition of a fugitive support material, which may later decompose during the sintering process.

A summary of the materials that have been employed for Robocasting is shown in Table 2.3.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Table 2.3.: Materials successfully demonstrated using Robocasting by Cesarano [5]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alumina (dense and porous)</td>
<td>PZT</td>
</tr>
<tr>
<td>$\text{Al}_2\text{O}_3$/TiCuSil Composites</td>
<td>Pozzolanic (ZnO)</td>
</tr>
<tr>
<td>$\text{Al}_2\text{O}_3$/Al Composites</td>
<td>Kaolin</td>
</tr>
<tr>
<td>$\text{Al}_2\text{O}_3$/Mo Composite</td>
<td>Stabilised Zirconia</td>
</tr>
<tr>
<td>Mullite</td>
<td>Mullite</td>
</tr>
<tr>
<td>Thick film, pastes, polymers and Epoxies</td>
<td>Silicon Nitride, PMN (In development)</td>
</tr>
</tbody>
</table>

In 2004 the work of Cesarano was furthered by Wang and Shaw [28]. They undertook a series of experiments to characterise porcelain slurries and in doing so opened up the Robocasting process to dental applications. Whilst the effect of material rheology on the extrudate quality/cross-sectional geometry has been studied by others, this is the first academic study of the dependency on extrusion parameters. Parameters investigated included extruder nozzle height, nozzle feed rate, extrusion rate, and critical nozzle height (i.e. first layer nozzle height). The supplied porcelain powder was found to contain large (>50μm) angular particles; hence it was milled to sub micrometer size. Finally a reference porcelain slurry was created by dispersing the milled powder in deionised water with a solid loading of 40 vol.%. The slurry was mixed for 24 hours in a mixer loader with $\text{Al}_2\text{O}_3$ balls to give a consistent slurry.

The pH value of the slurry was actively controlled as a method to control the material viscosity. This was possible thanks to the effect of pH on the Zeta Potential of the material. Zeta potential is a measurement of electro-kinetic potential energy in colloidal systems such as pastes and is, in essence, a measurement of stability of the system. Figure 2.13 shows the effect of pH on extrudate quality. It was shown the material was very stable at a pH of 9.3. This resulted in a very low viscosity fluid that demonstrated poor control when printing with a very shallow contact angle. As the pH approached 7.0, the material approached a Zeta Potential of 0mv which resulted in the material becoming shear-thinning with substantially greater viscosity. The resultant increase
in control results in minimal spreading and a contact angle of 90°, which is ideal for Robocasting.

Unsurprisingly, it was demonstrated that the nozzle height was a critical parameter. For a given extrusion speed, nozzle diameter and head feed-rate it is logical that there is a height below which the amount of material extruded will be too great and thus be forced to spread. Wang and Shaw propose that above this height the “cross-sectional geometry of the extrudate is only dictated by the rheological properties and wettability of the slurry”, with the contact angle being 90° at the ideal height for optimum print quality. The undertaken experiments appear to indicate the critical layer height obeys the following relationship:

\[
h_c = \frac{V_d}{\nu_n D_n}
\]  

(2.1)

Where \( h_c \) is the critical nozzle height in mm, \( V_d \) is the volume flow rate in cm\(^3\)/s, \( \nu_n \) is the nozzle feed rate in mm/s and \( D_n \) is the nozzle diameter in mm. It should however be noted that whilst the above holds true for porcelain, this has been shown not to be the case for chocolate [29], and therefore this relationship is likely material-dependent. In addition the effect of shear rate on contact angle was also investigated. However its effects were shown to be small relative to the other parameters investigated. But it was shown by Wang and Shaw that this relationship also enables the optimal nozzle feed rate to be calculated for a preset layer height, which further reinforces their claims.
2. Background

**Fab@Home**

Fab@home has the goal of creating a low cost rapid-prototyping machine, and was created by Cornell University after being inspired by the success of the RepRap project [30]. However, unlike RepRap there is no focus on self-replication, instead their aim is just to get as many people as possible to use so called “fabbers” [31].

Rather than a deposition tool specifically designed to use thermoplastics, two syringe-based extruders are typically employed to enable the Robocasting process, shown in Figure 2.14. The tool consists of a NEMA 8 stepper motor, with a rotor-mounted lead nut. A non-captive lead screw is then driven by the motor to drive a piston contained within the employed 10cc syringes, capable of producing a maximum force 90N.

Evan Malone, the lead developer in the Fab@Home team, initially investigated the use of a pneumatically powered dispensing system. However, this approach was abandoned as it was said to be, “tricky to find the right combination of nozzle diameter, material temperature, and dispensing pressure and pullback vacuum to use”. Therefore Malone argues that a volumetrically controlled system is more suitable to the Robocasting process.

A pneumatically controlled system requires that each material and nozzle combination would require a different set of operating parameters. However, pneumatic systems have a substantial advantage dealing with unwanted air which may become trapped within the pastes during loading. It is logical that the exact volume of air trapped will vary between pastes. Therefore when implementing a volumetrically controlled system, a preload would be required to enable deposition at the required rate, which would vary from build-to-build. Furthermore, pneumatic systems are used extensively in the dispensing industry, with many commercial systems available that deal with many of the same issues. Subsequently to the release of the Fab@home paste deposition tool, Makerbot and others have developed pneumatically driven paste extruders, in addition to the prior work already highlighted which would indicate that Malone’s argument is questionable.

### 2.5.1. Freeform Fabrication of Complete Electromechanical Devices

Perhaps the most relevant and comprehensive research into functional multi-material AM components was undertaken by Malone et al. In parallel to the development on
2. Background

![Image][1]

Figure 2.14.: The Fab@home syringe tool [32].

Fab@home, they looked to develop building blocks to enable the freeform manufacture of three dimensional, functional and electromechanical systems.

**Printable Zinc-Air Battery and Electrically Conductive Flexure Joints**

Whilst the manufacture of planar thin-film cells had already been achieved by Power Paper Ltd, Malone’s achievements represent the first example of a freeform three-dimensional energy storage device. Further, it is the first instance of a technique that is potentially capable of harnessing some of the major benefits of Additive Manufacturing such as complex geometry. Table 2.5 highlights the key materials used in fabricating the device.

<table>
<thead>
<tr>
<th>Component</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrolyte</td>
<td>8 Molar solution of potassium hydroxide and distilled water</td>
</tr>
<tr>
<td>Negative Terminal</td>
<td>Paste of methyl cellulose with copper (99% purity 2-5 µm) or silver (99% purity 1 µm)</td>
</tr>
<tr>
<td>Anode</td>
<td>Slurry of electrolyte with zinc (97.1% purity, dust) and surfactant</td>
</tr>
<tr>
<td>Separator</td>
<td>Paper, Rescor 740 insulating ceramic foam</td>
</tr>
<tr>
<td>Cathode Catalyst</td>
<td>Slurry of carbon black, manganese dioxide (MnO₂, 80-85% purity)</td>
</tr>
<tr>
<td>Cathode</td>
<td>Air</td>
</tr>
<tr>
<td>Positive terminal</td>
<td>Paste of methyl cellulose containing nickel (99% purity, 325 mesh), or copper or silver</td>
</tr>
</tbody>
</table>
As part of the work conducted, Malone entered into a process of optimising the basic anode and electrolyte chemicals and concentrations in order to ensure maximum performance. After several iterations, the optimum catalyst comprised 50% MnO$_2$, 44% 8M KOH, and 6% carbon black, with the separator layer consisting of 8M KOH.

The final design is shown in Figure 2.16.

In addition to optimising the materials used for the final cell performance, perhaps more relevant are the considerations taken in order to improve the extrusion performance. For the required conductive material, Pb-Sn solder was ruled out due to incompatible cell chemistry. Experiments were conducted mixing Methyl cellulose in 1:1 ratios by mass with Cu, Ni, and Ag powders [34]. For the separator material, surfactant, an additive to lower the surface tension, was added to several of the used materials to enable extrusion.

Qualitative experiments with methyl cellulose (MC) and metal power composite pastes reveals the dehydration of the MC gel may lead to shrinkage and cracking of the deposited paste, and also that adhesion to the substrate substantially deteriorates after dehydration. It is observed however that at no point has Malone investigated optimising the adhesion/joint between neighbouring materials through neither their respective geometries nor the effects of temperature that had been deemed critical by Cesarano.
2. Background

During fabrication experiments, Malone notes that a calibration process was undertaken for each material. This involves identifying a suitable syringe tip: a plastic tapered tip for viscous homogeneous and stainless steel parallel needles for multi-phase materials, though the reasons for this distinction are not elaborated on. Equally, orifice diameter was also varied, with increased sizes used for more viscous or phase-separation-prone material. Where possible, the smallest orifice diameter was chosen through which a material could be reliably extruded. Using this setup, estimates for key extrusion parameters were made, and iterated with the use of a test pattern until optimum results obtained.

When designing for this method, a key factor is that road height, established using the iterative process previously described, between material types may not necessarily match. Thus, when objects are sliced by the controlling software, no paths were generated for objects shorter than half the road height. Additionally, voids may occur due to height mismatches between neighbouring materials on adjacent layers.

Building on this work using carbon black to enable electrically conductive components, Malone investigated the manufacture of electrically conductive flexure joints. The joints consisted of ABS rigid end members, and a 1-part room-temperature vulcanising (RTV) silicone as the flexible joint. Carbon black was used to sufficiently increase the silicone’s viscosity such that it was freestanding upon extrusion. The device was shown to carry sufficient current to light an LED (10mA), but proved too fragile to survive real world use due to cracking and detachment of the conductive paste.
2. Background

![Freeform Fabricated ABS thermoplastic and silicone elastomer flexure joint][33]

**Electroactive Polymer Actuators**

Further elements of Malone’s library of compatible elements to produce electromechanical systems are actuators. At present substantial research has been done into the field of active materials capable of changing shape, volume or some other property in response to a signal. Malone concluded that whilst such materials exist, many are not compatible with the process implemented [33].

Given the materials and deposition patterns used in FFF, components have lower stiffness when compared to subtractively manufacture parts, so all materials that offered a high stress output but at a low strain were removed. Equally, the device needed to be compatible with the other components developed for Malone’s element library. Comparing these constraints to the proposed polymer properties leaves two potential material types, conducting polymers (CP) and Ionmeric Polymer-metal Composite Actuators (IMPC) [35].

Malone’s observes that conducting polymers are “appealing”, due to previous success in academia in printing electronics and sensors with them. A major difficulty encountered was the requirement for the actuator to function in air. Malone noted that to achieve air-operable actuators from conducting polymers, electrolyte must be used to enable their activation. Using a sample of $P_3OT$ (poly(3-octylthiophene-2,5-diyl)), a film was cast onto a PTFE substrate, and allowed to dry. The actuation of this, both in an electrolyte and when sandwiching an electrolyte for in-air operation was proven, although the device took in excess of four minutes to actuate.

Ionmeric Polymer-metal Composite Actuators are typically fabricated using a complex
process and are fundamentally based on a solid membrane usually used in proton-exchange-membrane fuel cells. These membranes typically have protons bound to anions within the polymer chains. A voltage across these electrodes enables actuation. However, this process does not lend itself to freeform fabrication due to the reliance on the pre-manufactured proton exchange membrane, which is beyond the capability of present AM technologies. A process previously developed was therefore used to enable the manufacture of IPMC actuators from a dispersion of Nafion particles in a solvent. Several materials were investigated for the required electrode, including conductive polymers, silver grease and metal powders. It was found that most of the materials suffered from chemical incompatibility, or contraction during evaporation of the solvent.

After these initial investigations, a series of experiments were conducted to improve the process of creating the Nafion IPMC actuators described above to enhance their performance and dispensability. In addition, a process was developed to enable the deposition of materials into an RTV silicone container onto which IPMC materials were cast.

In order to deposit liquid materials into wells contained within this silicone, the manufacturing planning software needed to be extended. Typically for AM process, parts are always created using the same layer height for each layer, and each layer is completed before the next begins. Up until this point, this had also been true for Fab@Home. Using a technique called “backfill deposition”, the silicone wells were given a greater priority than the surrounding materials. Thus, these wells could be completely manufactured before the extruder nozzle was lowered back into the well to enable deposition of the surrounding materials in a process similar to casting. The final manufacturing process enabled the production of the first ever freeform fabricated IPMC actuator. The device was capable of operating continuously in air for more than four hours and over 3000 cycles.

Figure 2.18.: Actuation of annealed Nafion/Hydrin Blend. Elapsed Time 45 seconds
2. Background

Figure 2.19.: Freeform fabricated IMPC. Shown is a cutaway CAD model (left), IMPC in its silicone well (top right), and after hydration and removal (bottom right) [33]

Freeform Fabricated of Organic Electrochemical Transistors and Relays

The achievements detailed thus far have focused on devices that enable the movement or flexure of mechanical systems through providing power, actuation and the appropriate electrical connections. However, if we were to study the electromechanical devices used in everyday life, most would be impossible without the appropriate control system. Therefore, a 100% printable transistor is a major step forward. Whilst printable transistors have been previously produced using ink-jet printing, Malone successfully demonstrated the first instance of a transistor was printed using solid free-form fabrication [36].

An Electrochemical Transistor (ECT) is unique in the field of organic electronics, in that the fundamental process is dependent on an electrochemical reaction triggered by an applied voltage to turn the device on and off. This enables the operating voltages to remain under 1V, and also ensures the device is not heavily sensitive to film thickness or any other dimensions\(^1\). Thus the lack of accuracy required makes ECTs an ideal candidate for an solid free-form fabrication transistor.

Whilst relays have previously been manufactured partially using AM in combination with electro discharge machining [37], Malone’s efforts focused on the creation of a relay solely using solid free-form fabrication without manual assembly [35]. The device built on prior work conducted in the manufacture of Malone’s IMPC actuator. In essence the relay used the IMPC to selectively close or open an electrical circuit by

\(^1\)Road width produced by a fab@home is limited to a resolution of 250micrometers
2. Background

breaking contact between electrically conductive surface electrodes. The housing of
the device was manufactured out of Silicone RTV, along with an IMPC mould which
would later be used for casting of the IMPC materials. The materials investigated for
other components of the relay are detailed in Table 2.6.

A significant difficulty, for which no solution was achieved, was that the IPMC mater-
ial cast poorly in the housing material. Thus, IMPCs produced tended to have “thick
and cracked” rims, which resulted in anode to cathode shorting and irregular material
layer thickness. Therefore the IMPC only produced low output force, and had poor
switch performance. Whilst the creation of a relay was possible after a substantial
amount of material and design optimisation, the performance of the device was poor,
with a load/input current gain of 1.05. As such, further work is required investigat-
ing improvements to IMPC casting, and the associated housing and actuator materials.
Once again, the IMPC material was cast onto a substrate at room temperature; despite
the prior work of Cesarano showing this the temperature of the substrate has a sub-
stantial effect of cracking and deposition quality. Therefore, the author of this thesis
believes implementing such a technique would offer substantial performance gains.

Table 2.6.: Table describing materials investigated for use in Malone’s solid free-form
fabrication electromechanical relay [35].

<table>
<thead>
<tr>
<th>Component</th>
<th>Anode, Cathode and Load Contacts</th>
<th>IMPC electrode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials</td>
<td>Conductive carbon cement, silver paint, silver-filled silicone RTV</td>
<td>Carbon black filled Nafion composite, Thermoplastic rubber/silver colloid composite, Ag-nanoparticle filled Nafion 0.7-1.3 um silver powder filled Nafion</td>
</tr>
</tbody>
</table>
2. Background

2.5.2. ChocALM

Whilst chocolate is not a material offering any engineering function, recent developments have occurred to enable the 3D printing of it in a process known as Chocolate Additive Layer Manufacture (ChocALM) [29]. Traditionally chocolate is manufactured through pouring liquid chocolate into moulds or over some filling at approximately 30°C. At this temperature the chocolate behaves as a fluid with significant viscosity, enabling control over it. Rheology testing was performed which confirmed the material possesses a fairly consistent viscosity between 32 and 37°C of 3.5-7 Pa.s.

Chocolate is an extremely complex material compared to traditional materials used by AM. There are six chocolate crystalline phases, and in order to ensure that the final product possesses the texture, taste and appearance that consumers demand, temperature control is critical throughout the extrusion process to ensure the final phase is correct. The ChocALM system consists of four separate processes:

1. A tempering unit for pre-tempering of the chocolate
2. A transportation system consisting of a lobe pump to deliver the material to the deposition head.
3. A deposition head for the extrusion of the chocolate consisting of an Archimedes

Figure 2.20.: Solid Free-form Fabrication Electromechanical Relay
2. Background

screw in combination with a simple circle nozzle of varying diameter.

4. An X-Y-Z positioning system

Unsurprisingly initial nozzle height was proven to be critical. Whilst Equation (2.1) suggested that the optimal nozzle height was 0.102mm, empirical testing showed the best results occurred at a build height of 2.9mm. Greater build heights would result in the material not adhering in corners and inaccurate parts being produced. Smaller layer heights produced thicker lines than intended, again resulting in poor prints. These results would suggest that the previous theory for optimum nozzle height by Wang and Shaw is material dependent, as mentioned above. In addition nozzle aperture size was shown to be critical, with poor results and inconsistent line diameter for a 1.0mm nozzle. Consistent lines were produced for 1.25 and 1.5mm nozzles, thus the reduced resolution associated with the 1.5mm nozzle led to the 1.25mm being used for optimum print quality. The results produced showed reasonable print through precise temperature control and therefore viscosity control, however it was concluded further work is required to improve control on deposition, develop an infill technique to manufacture dense parts, and to establish design constraints.

Figure 2.21.: Example ChocALM prints, (a) a heart and (b) the ChocALM logo

2.5.3. Rapid Prototyping of Electronic Components (RPEC)

The earliest work towards printed electronics using Additive Manufacturing techniques dates back to the work of Prinz et al. in 1998 [38]. Their technique known as Shape Deposition Manufacturing was in many ways the first Additive Manufacturing system capable of producing components which have functionality beyond that allowed by their shape. The system was extremely flexible and used both laser-based and FFF-like processes, however rather than simply being based on Additive Manufacturing,
2. Background

their apparatus also included subtractive milling tools. The combination of the two meant that components could be manufactured using the complexity of AM, before a subtractive machining operating could be performed in order to dramatically improve surface finish. Whilst many novel solutions were implemented, of particular interest is their ability to actively produce voids within printed structures to allow the embedding the pre-existing circuitry. An example of one such circuit is shown in Figure 2.22.

![Figure 2.22.: “Frogman” computer created using Shape Deposition Manufacturing [38]](image)

Outside of Additive Manufacturing manufacturing, printable electronics is already an area which is the focus of great amounts of research. Typically these technologies are based around direct-writing technologies using doped silver-based conductive inks. Therefore whilst they are capable of producing circuitry, they are incapable of producing the functional structural components that Additive Manufacturing allows. Further such conductive inks typically require annealing at temperatures (>200 °C) not traditionally compatible with low cost AM methods [39], although some modern inks are becoming available which require annealing at lower temperature (approx. 100 °C) and therefore are becoming compatible with some, but not all, AM materials [40].

Despite these issues with direct writing technologies, research is ongoing in the area to combine direct writing techniques and Additive Manufacturing. Lopes et al. implemented a hybrid SLA system capable of using a micro-dispensing pump to deposit silver based inks [40]. The system was shown to be able to develop 2D and 3D structures with embedded electronic circuits. However the usual SLA process was modified due to the required multiple start and stops of the SLA process, removal of uncured material and support structures and also to allow the insertion of components. Using the technique a successful 3D 555 timer circuit was manufactured. However many of the required modifications to the process were manual and hence a substantial amount
of research is required to automate the process. Further the author contends that combining two technologies which are so diverse will inevitably mean that such a system is cost prohibitive. In addition to the work of Lopes et al. a fundamentally similar solution was previously developed by Optomec Inc. [41] to be compatible with Stratasys FDM/FFF systems.

![Figure 2.23.: 555 Timer circuit produced using a hybrid SLA/ Direct Writing system by Lopes et al. [40]](image)

Whilst the research highlighted into using direct writing technologies above is of great relevance, other traditional methods in manufacturing electronics are of interest. In 1944, a British engineer named John Sargrove designed an automatic radio production line using a process he called ECME (Electronic Circuit Making Equipment) [42]. At the time, radios were still very expensive, and he required a method to reduce the labour costs associated with manufacturing and assembly. This led Sargrove to develop an early form of integrated circuit. His circuit was based around a piece of Bakelite that contained most of the radio’s electrical components. The Bakelite was moulded to contain a series of channels on each side (Figure 2.24). These channels were then filled with a zinc alloy to connect all of the electrical components contained within the Bakelite. As a result production costs fell dramatically whilst increasing production capacity.

![Figure 2.24.: ECME Production Line (left) and the ECME Bakelite Chip [42]](image)

Inspired by Sargrove’s work on ECME, Sells developed RPEC (Rapid Prototyping
of Electrical Circuits) techniques to allow the rapid prototyped ABS circuits (instead of the Bakelite circuits in ECME) with the aim of allowing RepRap to manufacture PCBs [43]. However, Sells required an alternative conductive material, as ABS has a lower melting point than that of zinc. Wood’s metal is a toxic alloy of tin, cadmium, lead and bismuth which possesses a very low melting point of just 70°C. Sells’ work focused on evaluating several methods of depositing the Wood’s metal. The most successful of these involved molten distribution, whereby the alloy was melted and injected using a syringe for deposition. At first, Sells attempted to heat the syringe before injecting the material. However, this technique was inadequate, with the material freezing in the nozzle just twenty seconds after filling. Sells iterated the design, by implementing a “jacket” of hot air around this syringe during the extrusion process. This was sufficient to prevent freezing. Upon extrusion, the alloy had the tendency to form molten droplets; this was attributed to the high surface tension of the material, and led to the material being difficult to manipulate once extruded. Whilst the molten material was injected into a rapid prototyped substrate, the injection process was done manually by hand. Nevertheless, Sells’ research culminated in the manufacture of a working robot, demonstrating the capability of RPEC [44].

![Image of a robot manufactured using RPEC techniques](image)

Figure 2.25.: Robot manufactured using RPEC techniques. The metal was deposited by hand. [44]

Subsequently, Sells work was furthered by the author of this thesis, by automatically depositing low melting point solders automatically into an ABS substrate. The extruder used consisted of a stainless steel needle with a 1.3mm diameter orifice, heated with nichrome wire in a similar fashion to standard RepRap thermoplastic extruders. A key finding was that the solders must be solid i.e. without flux. The presence of flux would enable the extrudate to separate into sections of conductive solder, and non-conductive flux rendering the track useless [45].

After testing several materials, 60/40 PB/Sn solder was used due to its availability in filament form. Interestingly, the melting point of the alloy (240°C) was substantially higher than that of the ABS substrate (105°C). Therefore the process was enabled by the
2. Background

The fact that thermoplastics generally have a specific heat capacity roughly ten times larger than that of the alloy. This resulted in less heat transfer to the thermoplastic than was initially expected, and thus only minimal deformation occurred to channels contained within the substrate providing wall thicknesses were greater than approximately 1mm.

Whilst reasonable build quality (Figure 2.26) was obtained for channels that were 2.6mm in width, this was deemed not sufficiently intricate to allow for useful circuits. After several iterations of the extrusion parameters, the device was capable to depositing alloy into 1.3mm diameter channels reasonably reliably, although build quality was reduced. Figure 2.26 shows a simple PCB manufactured that functions as an optoswitch circuit board. The device replaced another PCB from within the RepRap machine that created it, and functioned successfully.

It was concluded that further work needs to be undertaken to reduce the effects of surface tension though reducing the extruder orifice diameter, in order to enable more complex circuits and smaller components. Equally, it was somewhat tricky to solder in components after the PCB was manufactured. It is speculated that a rapid prototyped holder could be design to secure components within the plastic substrate during the production of the PCB, ensuring post soldering is not required.

![Figure 2.26: Example of RPEC build quality using 2.6mm channels (left), and the optoswitch PCB (right) [45]](image)

In addition to these attempts, others have taken place to allow direct metal deposition towards electrical circuitry. Malone et al. have also attempted direct solder deposition as shown in Figure 2.27; however published results appear to be of worse print quality that the RepRap prints outlined above [34]. It is claimed that the process has a small operating window for reasonable print quality, in which either it is possible to extrude lines with overlapping dilations in excess of 1mm in diameter, or thin continuous sections approximately 0.25mm in diameter. Further it is stated that poor wetting of the ABS substrate was achieved with this tin-lead solid solder, however it is proposed below that wetting may be improved through the use of indium-based solders.
2. Background

In parallel with this work investigating printing low melting point alloys directly towards electronics, previous efforts have been undertaken to research the printing of free form structures using FFF techniques. Agarwala et al. developed a technique known as FDMet [46] a binder burn out and sinter the metallic particles and remove the binder material. Therefore allowing structural metallic components to be produced, including components manufactured from stainless steel and tungsten carbide amongst others. However such a method implies that the burn out process destroys all plastic material, and therefore is not suitable for producing multi-material components and thus solutions are required to print using metallic materials directly.

Research into directly printing free form structures has already taken place. Conclusions have mirrored those outlined above into printed FFF electronics, namely the main issues arise due to surface tension and wetting. In an attempt to combat these issues, research has focused upon using non-eutectic materials. Unlike a lot of common metals, non-eutectics do not possess a sharp melting point, instead these materials transition through a paste-like semi-solid phase of solid metallic particles held within a liquid suspension. This results in a paste with significant viscosity and given that viscos-
ity is a much stronger force than surface tension should result in a more controllable fluid. Finke and Feenstra demonstrated that layers of semi-solid 40%Pb60%Sn could be deposited using such methods. It was concluded, unsurprisingly, that such materials were particularly sensitive to temperature and needed accurate temperature control in order obtain consistent properties [47]. Critically separation of liquid and solid phases was demonstrated during extruder retraction, and was shown to be related to shear rate. Again unsurprisingly, X-Y and nozzle feed rate were shown to be critical for geometric accuracy and interlayer bonding.

Further success was achieved by Rice et al. again a tin-based 85%Sb-15%Pb material was used however in addition to the more basic extruder used by Finke et al. a rotor was used to mix the slurry in order to improve consistency [48]. According to Rice et al. alloy with a 10% solid fraction has an apparent viscosity of the order of $10^{-1} \text{Pas}$, similar to olive oil, upon increasing this solid fraction to 50%, this rises to $10^2 \text{Pas}$, something comparable to tooth paste. Further the use of semi-solids ensures that the amount of thermal shrinkage to approximately one third compared to a traditional eutectic. In the author’s opinion, this is especially critically in a multi-material setup where such shrinkage would result in part deformation and head collisions. However the materials demonstrated to date have been with materials with an extrusion temperatures in the range of 200-250°C. Such temperatures are far above the glass point of PLA, the standard RepRap thermoplastic. This combined with the likely slow feed rates, high conductivity, and other work highlighted above with eutectic materials implies that lower temperature materials would be better suited to prevent thermoplastic substrate part deformation.

![Semi Solid Rheocaster](image_url)

Figure 2.29.: Rice et al.’s Semi Solid Rheocaster (left) and printed structures (right)
2.5.4. Digital Materials and Voxel Based AM

Voxel Based Additive Manufacturing

In addition to controlling raw material properties, attempts have been made to utilise the inherent flexibility of the AM process to adjust the internal structure in order to control the bulk material properties. Whilst this technique is used by most AM processes, this is in order to give a porous internal structure requiring less material and therefore speeding up build times. One such technique is voxel based Additive Manufacturing originally proposed by Gershenfeld [49].

As outlined previously, frequent difficulty obtaining the correct rheology and extrusion characteristics was encountered by Malone for materials when using Robocasting. Whilst substantial efforts have also gone into fabrication using ink-jet methods, even greater restrictions are placed on the material composition for them [50]. In essence, the process is a rapid assembler, capable of positioning and bonding pre-manufactured voxels (a term borrowed from computer graphics). The manufacture of such voxels would be achieved using traditional manufacturing technologies, and thus negates the difficulties with material rheology. In addition, it is proposed that “smart” voxels may be produced allowing active components such as transistors, photovoltaics and micro valves.

A key strength of the process is the ability to control the geometry of the voxel itself. A substantial investigation by Hiller [51], reveals that by controlling the shape of the voxel, they may automatically self-align and interlock during the assembly process. This potentially enables the fabricated components to more be accurate and repeatable than the positioning system of the 3D assembler.

Further still, the technology is capable of altering material properties using a variety of different methods. A substantial investigation was undertaken by Hiller to determine potential techniques. Hillier’s research, due to the early stages of the technique, was based on finite element analysis to enable a virtual tensile test.
2. Background

Interestingly, substantial variations in material properties and failure modes were possible, even for single material structures. Rightly, Hiller assumed that the manufacturing of the voxel would be subject to tolerances. It was found that as these tolerances were relaxed, the elastic modulus continuously decreased, and the initially brittle failure mode became more and more ductile. The effect was substantial, reducing the elastic modulus by approximately 66% for an error of just 10µm.

Given the sensitivity to error, the author of this thesis concludes that, to achieve a precise value of a given material property in practice would be, whilst possible, prohibitively expensive given the need to manufacture the quantity of voxels to the accuracy required. Further still, the number of voxel types required to give continuously variable material properties would ensure that printer design would be unnecessarily complex. Thus, Hiller’s efforts shifted to multiple materials.

Hiller found that by using a technique traditionally used in reprographics known as half-toning, a near-continuous variation in the bulk material properties may be produced, just by setting the desired percentage of each material, and randomly scattering the voxels within the component in the desired ratios.

Hiller found that using these techniques for a combination of acrylic and aluminium voxels, the elastic modulus varies exponentially as the amount of aluminium is increased (Figure 2.31). Perhaps more interesting was work undertaken combining aluminium, a material with a positive coefficient of thermal expansion (CTE), and zirconium tungstate (negative CTE). For a specific ratio, a material test sample was produced that was predicted to have a negligible thermal expansion or contraction. It is interesting to speculate on the potential similarities between this theoretical material and the Nobel-prize-winning 19th Century alloy Invar. Even today, the reasons for
2. Background

Invar’s very low coefficient of thermal expansion is not fully understood, though magnetic effects are postulated.

Figure 2.31.: Graphs showing the effect of half-toning for an aluminium/acrylic based structure on elastic modulus (left), and for an aluminium/zirconium tungstate structure on thermal expansion coefficient(right).

One final possibility was investigated by Hiller as a method for adjusting bulk material properties: altering the material micro-structure. Half-toning results in near isotropic material properties. For some configurations, an elastic modulus in excess of three times the value in the perpendicular direction was achieved, resulting in significant anisotropy. Using a similar technique an auxetic micro-structure was also demonstrated.

This author contends that, whilst Hiller’s results are fundamentally interesting, they are not suitable for practical implementation. Firstly, it seems that the difficulty of producing an “active” or smart voxel has just been offloaded to an external process. Secondly, it has been demonstrated that the manufacturing tolerances of these voxels are critical, and thus, given the number required, the process is likely to be prohibitively expensive. However, it remains to be seen whether the micro-structures demonstrated could be manufactured using traditional AM techniques, potentially offering similar results. Further still, substantial variations in bulk material properties were shown by adjusting joints between neighbouring voxels. Potentially this effect could be replicated in mechanical joints in multi-material structures created using more conventional multi-material AM techniques.
2. Background

Digital Materials

Whilst multiple materials have been used by commercial AM companies in order to improve the AM process (for example the infiltration of porous material with adhesive for solvent jet printing) the use of multiple materials to provide increased functionality by commercial vendors has been somewhat limited. The research mentioned thus far was done in academia. The only company at the time of writing to enable functional multiple material parts is Objet Geometries [17]. Example multi-material components manufactured using an Objet Connex system are shown in Figure 2.32.

Objet utilise the Jetted Photopolymer process to provide a mechanism to deposit droplets of photo-curable resin [1]. Where Objet’s techniques differ from others is that the resin can be mixed with differing ratios of curing agent to result in polymers with different Shore hardness ratings. Further, software developed by Objet enables varying Shore harnesses throughout different regions of the part creating what they describe as a digital material that parallels Hiller’s work with Voxel based AM. A typical example for a specific curing agent and photo-curing resin offers discrete variations in shore hardness from 40 - 95, and a corresponding change in tensile strength from 1 to 49MPa [52]. At the time of writing Objet are currently able to utilise 14 different materials, however through careful control and positioning of these materials 107 digital materials are possible enabling precise control over Shore hardness, stiffness, transparency and colour.

Figure 2.32.: Samples produced using the Objet Connex Family of 3D Printers. Tooth brush model with a rigid handle, and flexible bristles (left), a flexible tyre on a rigid rim (middle), a VW Beetle (right) complete with translucent lights, rigid body and flexible tyres and soft top [17]

Mechanical Characterisation of Fused Filament Fabrication

Research has already taken placing investigating the mechanical properties of FFF parts. A typical rectilinear infill pattern is shown in Figure 2.33. In order to fill com-
ponents, the angle of each layer of infill is perpendicular to the previous layer resulting in a structure with reasonably anisotropic material properties. Given that FFF employing ABS plastics has been available for many years, several studies already been undertaken to investigate the effect of the process and its associated build parameters on mechanical properties and the associated anisotropy. Ahn et al. investigated the effect of infill pattern/direction using Stratasys QuickSlice™ with an associated FDM 1650 machine [53]. Parameters investigated included infill orientation, extrusion size and extrusion temperature. It was concluded that the geometry in accordance with the standard method for measure plastic tensile properties, ASTM D638 [54], resulted in large stress concentrations due to infill terminating at the change in cross sectional area associated with the geometry, therefore ASTM D3039, a standard more typically used for polymer matrix composite materials was used instead. For components with approximately 0.08mm overlap between the infill and the perimeter, tensile strengths of between 65 and 72% relative to injection moulded FDM ABS P400 material were obtained, depending on the direction of the infill pattern. However it was concluded that in compression the FDM process was less critical and strength ranged from 80 to 90 per cent of the injection moulded samples.

Figure 2.33.: FFF Layup (right)

Bellini and Güçeri extended the above work by testing raw ABS 400 filament in single
extruded roads or lines in addition to tensile and flexural specimens [55]. They found that the extrusion process had a negligible effect on tensile strength and Young’s modulus with single road results being almost identical to the raw filament. However it was found that the maximum strain for the extruded road was only one third that of the raw filament. This reduction in maximum strain was attributed to orientation of the polymer during the extrusion process. When stretching the standard tensile test geometry many samples failed prematurely. It was proposed that these failures were due to a combination of inter-laminar defects due to over/under extrusion and poor surface roughness. However by varying the infill orientation it was found that a tensile strength of 7.6 – 16 MPa [56] was achievable with a corresponding stiffness of 970MPa – 1652MPa compared to 34.3Mpa and 19.0Mpa respectively for raw filament.

Ang et al. conducted similar experiments to Ahn et al., but furthered the investigation by studying the effect of porosity on compressive Young’s modulus and yield strength for a variety of tissue-engineering scaffolds manufactured out of Stratasys P400 ABS [57]. Five process parameters were investigated, giving a logarithmic relationship between porosity and yield stretch/stiffness. Unsurprisingly the strongest mechanical properties were exhibited in scaffolds with low porosity.

Hutmacher et al. used FFF to manufacture and analyse the mechanical properties of PCL [58]. It was found that a porosity of 58-77 % was achievable with a compressive stiffness ranging from 4-77MPa and yield strength from 0.4-3.6MPa. In both cases it was established that a power law existed linking these mechanical properties to scaffold porosity. Given that any relationship must be asymptotic at zero porosity, therefore any power (in the case of Ang et al.) or logarithmic law (in this case) must only be approximate and so only valid within the porosity range investigated.

Whilst all of the studies thus far have focused on the properties of ABS or PCL, no research has been conducted investigated into controlling the bulk properties of PLA using FFF. Given that PLA has substantially improved stiffness and deformation characteristics over those other materials it is an ideal material for 3D printing, and research into this area would be beneficial [6], [59]. Further all previous research has been conducted using commercial AM systems with a limited number of controllable parameters. Given the wider range of parameters available with RepRap, namely more extreme infill widths/porosities, flexible layer heights, multiple perimeters and solid layers, a wider range of bulk material properties is likely achievable. In doing so less build materials are required to achieve a given range of material properties.
2.5.5. File Formats

With the advent of the multi-material AM techniques previously outlined, a new challenge was imposed on the industry: how to digitally store CAD data such that information regarding mesostructure, material properties and other information may be recorded whilst remaining compatible with existing CAD systems? To date, the STL file format has established itself as the dominant file format for the AM industry, in part owing to its compatibility with all major CAD systems and 3D printers. However, the STL format only contains information regarding the surface of a part, and thus offers no method for representing internal colour, texture, material properties etc. The surface of a part is represented in a list of unstructured triangles, with each triangle being represented by 12 floating-point numbers. However, it is contended by Hiller and Lipson [60], that the format has not gained traction due to its technical merits, but because of its simplicity.

One consequence of the STL format is that each vertex must be stored repeatedly, once for each triangle that shares the vertex. This frequently generates voids in the surface owing to rounding errors. Thus, STLs often require pre-processing before being used in slicing software employed by AM machines in order to be usable.

Several alternative file formats have been proposed for use by the AM community. These are described in Table 2.7, which is based on an excellent summary by Hiller and Lipson [60].
2. Background

Table 2.7.: File Formats Proposed for use by the AM community from Hiller and Lipson [60]

<table>
<thead>
<tr>
<th>Format</th>
<th>Description</th>
<th>Advantages/Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>X3D(VRML)</td>
<td>Mesh based file formatted intended to enable the viewing of 3D content on the Internet</td>
<td>Includes information about 3D surface and its colour. However, also contains data intended for rendering such as transparency, animation etc. No provisions for defining multiple materials</td>
</tr>
<tr>
<td>STEP</td>
<td>Format intended for solid-model representation using extruded and swept solids, wire-frame and boolean modelling.</td>
<td>Complex</td>
</tr>
<tr>
<td>PLY</td>
<td>Format designed for use within the 3D scanning space by the storing of polygon meshes.</td>
<td>Capable of storing data relating to texture and colour. No definitions of material or micro-structure</td>
</tr>
<tr>
<td>SAT</td>
<td>Widely used for boundary representation objects in CAD packages</td>
<td>Format is based on the description of an objects internal topological data structure. This insures its difficult</td>
</tr>
<tr>
<td>OBJ</td>
<td>Mesh model format, Widely used for 3D modelling</td>
<td>No definitions of material or micro-structure</td>
</tr>
<tr>
<td>DXF</td>
<td>Widely used in CAD for 2D drafts, although capable of defining 3D triangle meshes</td>
<td>Intended for 2D use, therefore remain best suited for such.</td>
</tr>
<tr>
<td>3DS</td>
<td>Triangle mesh based format</td>
<td>Capable of colour and texture data. Limited to defining 65536 triangle and vertices's</td>
</tr>
<tr>
<td>SLC</td>
<td>Represents a 3D object by a series of 2D slices separated by fixed intervals in the Z plane.</td>
<td>A fixed Z spacing will inevitably cause problems between AM systems, as layer heights may vary.</td>
</tr>
</tbody>
</table>
2. Background

In addition to those outlined, two proprietary formats also exist that enable the storage of colour/material information. These are ZCorp’s ZPR (colour only), and Objet’s Objdf (material/colour). Typically, STLs or other formats may be converted to these types using the relevant vendor’s software. However, given the proprietary nature of these formats, using these with other vendor’s or open-source machines is not possible. Because of this, in addition to the aforementioned problems due to rounding errors, an alternative is required.

In 2011 the AMF format was approved by ASTM [61] to become the de facto replacement for STL [60]. It allows the inclusion of colour, material properties etc. The AMF format is based on the Extensible Mark-up Language (XML), and thus new features may be added to the format as required.

Further, AMF is capable of defining geometry as a mesh, and thus converting between STL and the proposed format becomes fairly easy. Equally, material properties may be graded to enable a continuous variation throughout the part. However, CAD software does not currently exist that is compatible with the format. Moreover (and rightly so) the format aims to be independent of vendors and AM systems. Thus material properties such as Young’s modulus are exactly defined, and so a substantial amount of research is required to investigate exactly how these properties are achieved for a given solid free-form fabrication process.

At the time of writing, uptake of the file format has been limited. Though major 3D printing hardware manufacturers and CAD companies were involved with the format’s creation, the format has not yet been implemented by any major piece of CAD software or any 3D printing hardware manufacturer.
2. Background

Multiple-material STL equivalent

One of the most critical limitations of the current STL format is the lack of support for multiple materials. With the AMF format, this minor extension introduces the \texttt{Palette} tag. Here, any number of materials may be defined by name and associated with a material ID. Other relevant attributes may also be added to each material. Then, within the \texttt{mesh} tags, additional \texttt{Region} tags can be added that reference different material indices. Since the vertex list is shared, no leaks are introduced at the boundaries between materials (Figure 2).

![AMF file Structure](60)

\[
\text{Figure 2.34.: AMF file Structure [60]}
\]

2.6. Critique of the literature and definition of objectives

To restate the hypothesis this thesis seeks to prove:

“Solid Freeform Fabrication processes are sufficiently versatile to manufacture functional electro-mechanical devices through the use of dissimilar materials and part geometry”

The literature review presents a number of new avenues for further research. Tool path planning was expected to be critical to fulfilling the author’s hypothesis. The literature review reveals that new materials in general tend to offer poor build quality for FFF in comparison to ABS/PLA. It was therefore logical that the use of these existing materials should be maximised, enabling the greatest resolution and opening the process to applications requiring high detail. It has already been shown that process parameters such as infill porosity substantially affect the mechanical properties of ABS. However the range of parameters investigated was small and the author contends that ABS is not the optimal build material owing to warping effects and its being generally weaker than alternatives. It was anticipated that conducting a study of these parameters for PLA and RepRap software will result in a wider range of potential properties and therefore open up more applications. Further the reduced warping effect of PLA is critical in a multi-
material setup as it reduces the risk of head collisions when using multiple tool heads and more accurate parts.

As has already been outlined, Robocasting has already demonstrated the capability to use a wide variety of active composite polymers and ceramics, and has already been shown capable of producing crude electromechanical components in a low cost, simple fashion. Therefore, this process also offers the best prospects of manufacturing more functional and complex components. However, with Fused Filament Fabrication already being shown to be able to produce approximately half of the components for such a machine in a low cost manner, discounting FFF is unwise.

Equally, the author would contend that the FFF process benefits from ease of material handling, and being capable of hundreds of hours of operation unattended. Conversely, the use of large syringes in current Robocasting systems compromises machine design (weight, volume required in the Cartesian robot etc.). Therefore, it is proposed the hybrid system would offer the most versatility whilst remaining practical; using FFF for large components where no specialist properties or active functions are required, and using Robocasting where such attributes are needed.

Furthermore the author contends that many of the other processes are incapable of a low cost implementation, often requiring expensive hard-to-source components e.g. CO$_2$ lasers. Excluding FFF and Robocasting the most functional and versatile techniques demonstrated to date are selective laser sintering, and jetted photopolymer. By definition jetted photopolymer requires the material to be deposited through an ink-jet nozzle. It is well established that such ink-jet heads are only capable of depositing materials in a very narrow viscosity range (1-40cp), this excluding JP from being able to deposit mixed composite materials and therefore limits the functionality. Further on a practical basis commercially available ink-jet heads are proprietary and the appropriate open control systems are not well established. However inherently the mechanics of a J-P system are fundamentally compatible with Robocasting and FFF, which could create an extremely versatile system. However issues exist with any multi-material setup, e.g. file handling, mechanical setup, process planning, which given the difficulty of developing a JP system, would be best initially tackled for just a FFF/Robocasting setup.

Selective laser sintering requires handling of fine powders. Traditionally powder is stored in a storage bin attached to a piston. The piston can move by a fixed amount before a separate roller deposits a fine powder layer on top of the existing layer before sintering as shown in Table 2.1. Therefore for a multi-material SLS system an alternative powder handling technique is required which is anticipated to be difficult,
2. Background

although some high end SLS systems use this technique. By using such a setup, the system becomes fundamentally similar to FFF and again opens the door to creating a hybrid system. However the flexibility of SLS lies in high melting point materials such as alloys, and these would be thermally incompatible with FFF and Robocasting. Similar properties to low temperature SLS materials such as Nylon are achievable through FFF, and hence this adds minimal functionality.

Robocasting techniques have already proven to be extremely versatile; however they are known to be slow, and in general the build quality achieved appears to be substantially worse than that from thermoplastic techniques. It is likely that this reduction in build quality is due to the fact that the materials have not been optimised for the process. Whilst some work has been presented to optimise the material viscosity through actively controlling pH for a given material, undertaking further work for a wide range of materials was unfeasible, has little or no novelty, and it was still doubtful whether or not thermoplastic-level quality could be achieved. Further there appear to be two distinct methods of paste extrusion: pressure driven or direct volumetric control, and whilst each has its own advantages in terms of packaging little is known about the effects of either on build quality. Given these issues it may be assumed that resolution attainable with paste base techniques would be poor and this would inevitably limit its use. However this further lends credence to the author’s hypothesis, by combining paste and thermoplastic techniques and carefully controlling the process order, it may be ensured that thermoplastic always adds some constraint to the pastes, thereby improving build quality. Therefore research should be undertaken to assess the compatibility of combining the FFF and Robocasting processes. Nevertheless key parameters for optimising Robocasting have been identified to be pH, viscosity, drying/curing kinetics, solid material volume fraction, dispensing rate and tool path planning.

Through combining Robocasting and FFF, it is anticipated that a wide range of materials may be used. However research to date to enable electrically conductive materials has yielded poor print quality to the extent that any reasonable circuit, regardless of resolution, has not been produced in an automatic fashion. The author has previously experimented with direct deposition of solder, and, whilst a circuit was produced using through-hole components, resolution was insufficient for basic microchips such as PDIP (2.54mm pin pitch). This was deemed essential in order to enable realistic functional circuits. Surface tension has been demonstrated to be the primary issue limiting print quality. Whilst low-surface-tension metals are available such as indium, they are prohibitively expensive, hence optimisation methods used in Robocasting would also prove useful - namely techniques to control material viscosity. Inspiration can however be drawn from the work presented investigating non-eutectic and semi-solid
2. Background

materials towards manufacturing free-form structures. Whilst the materials used to date are above a temperature which would cause thermal damage to PLA, the fundamental principles and quality achieved is promising however a lower temperature material would be ideally required.

Based on this analysis, the following objectives have been defined:

1. To demonstrate the compatibility of different AM processes. In particular Robocasting, a technique similar to FFF but one that relies on a syringe in order to allow it to use paste materials, in parallel with Fused Filament Fabrication using fundamentally dissimilar materials.

2. To enable the control of bulk material properties though the control of mesostructure and print parameters.

3. To develop a novel cost-effective low melting point alloy compatible with the Fused Filament Fabrication and thermoplastics in order to enable the manufacture of electrical circuitry.
3. Multi-material development

This work presented in this chapter details the process undertaken to enable the Robocasting and FFF processes to be combined. Whilst no new materials or techniques are developed, and therefore no new functionality is enabled, the work aims to demonstrate that the processes are inherently compatible whilst establishing the experimental setup and solving fundamental problems that enables the subsequent multi-material work in this thesis. As shown in the previous chapter, Robocasting and FFF are respectively capable of material properties not possible with the other. Hence whilst no new properties are obtained by combining the two, a wider range of properties are possible within the same printed component. In doing so part count will substantially be reduced relative to using both processes in isolation.

The work undertaken in this chapter may be broken down into three distinct sections:

- **Mechanical development** - Firstly development was needed to enable the use of multiple extruders to allow multi-material deposition. For simplicity, it was elected to develop the existing RepRap Mendel design rather than to develop a head changing system. The key element to this development was enabling three Bowden or paste extruder heads with independent height adjustment (details of these will be given below). Tool path planning traditionally used in FFF is basic, with head collisions not considered. It was deemed unlikely that extruders would be able to be manufactured and assembled to a sufficient tolerance to prevent head collisions with the part mid-build; hence height adjustment was incorporated into the design. Any offset between the extruders in the X and Y axis could be compensated for automatically in the tool path GCode. This flexibility was critical as at the time of development future extruder designs for pastes and low melting point alloys were unknown.

- **Robocasting development** - To enable the Robocasting process two fundamental paste deposition methods were evaluated experimentally. A volumetrically controlled method was shown to lack repeatability, despite having already been implemented in existing systems. This was attributed to variations in trapped
3. Multi-material development

air within the paste during the build and the prior syringe to syringe transfer, making attempts at calibration unrepeatable. Given that many potential materials contain solvents, simply using a vacuum chamber to ease this issue was not a solution. However, the alternative pneumatically driven process was shown to be repeatable to within 4%, within the repeatability of the more proven FFF process, and hence this was deemed to be suitable.

- **Control system** - At the time of implementation, computational techniques to handle multiple materials/properties were not established. Whilst the AMF format had been proposed, no CAD software had implemented the standard, hence an alternative was required. Bowyer proposed to use multiple STL files, as are commonplace within Additive Manufacturing. However STL files are only capable of storing geometric data. Hence other properties were manually assigned once for each file prior to tool-path generation.

Consequently, these developments enabled the manufacture of a multi-material component comprising of both PDMS and PLA. Further the fundamental mechanical setup has been developed externally, and three material FFF components have been manufactured; examples of which are provided at the end of this chapter. To the author’s knowledge, this is the first instance of Robocasting and Fused Filament Fabrication processes being combined in an automated fashion, and thus it was shown the test setup implemented was fit for its purpose. Given the pressure-based technique used, research was conducted to assess the effect of mixing powders with PDMS to enable functional composite materials. In practice it is noted that tuning FFF is typically empirical and therefore process parameters are adjusted based on visual appearance and experience.

### 3.1. Design Brief

Work was to be undertaken to the following design brief:

A new 3D printer, or substantial modifications to an existing printer, should be designed to manufacture multi-material 3D complex electromechanical components using solid free-form fabrication processes. The printer should be considered a test bed to:

- enable the characterisation of the implemented solid free-form fabrication processes
### 3. Multi-material development

- be sufficiently flexible to use the materials required for the manufacture of complex electro-mechanical components.

A specification, in accordance with this design brief, was written and may be found below:

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Quantity</td>
<td>1 Off for research purposes, Final implementations to be released to the RepRap community</td>
</tr>
<tr>
<td>2 Life Span</td>
<td>3 years of experimental use</td>
</tr>
<tr>
<td>3 Machine Materials</td>
<td>Ideally materials already used by RepRap: Self tapping screws, Brass bushes, Rolling element bearings, simple linear bearings, Studding, Lubricating grease, Standard RepRap Electronics, Standard plug in low voltage power supply, Stepper motors, Timing belts, Any other components which could be simply replaced with the stock materials/electromechanical in later versions of the RepRap machine. In short, low cost easy to require materials that are available worldwide.</td>
</tr>
<tr>
<td>4 Ergonomics</td>
<td>Machine to be driven by the standard RepRap Host software. Extruder heads should be easily replaced</td>
</tr>
<tr>
<td>5 Cost</td>
<td>Below £450 for the entire machine</td>
</tr>
<tr>
<td>6 SFF Process</td>
<td>The designs should be compatible with both Robocasting, and FFF.</td>
</tr>
<tr>
<td>7 FFF Specification</td>
<td>FFF extruder should remain compatible with already developed materials used in the RepRap project when fed with 3mm filament. 0.5mm Nozzle orifice. Typical working temperatures of 190-240°C. Build speeds to be established</td>
</tr>
<tr>
<td>8 Robocasting Specification</td>
<td>Syringe based. Pneumatically or volumetrically controlled. Variable interchangeable tips as determined by the material. Build speed - material dependent and to be established.</td>
</tr>
<tr>
<td>9 Extruder Handling</td>
<td>Up to three extruders. Easily replaceable, and adjustable to take account of manufacturing and assembling tolerances</td>
</tr>
<tr>
<td>10 Power sources</td>
<td>12v DC and 6 bar air pressure</td>
</tr>
<tr>
<td>11 Aesthetics</td>
<td>All wiring, filament should be neatly tied/fed to the extruder</td>
</tr>
<tr>
<td>12 Performance</td>
<td>Build volume should be at least 150x150x100mm for all three extruders</td>
</tr>
<tr>
<td>13 Manufacturing Process</td>
<td>Where possible, all parts should be made using FFF technology to minimise manufacturing time</td>
</tr>
<tr>
<td>14 Maintenance</td>
<td>Maintenance before each use is acceptable.</td>
</tr>
<tr>
<td>15 Noise levels</td>
<td>Avoid loud noise where possible</td>
</tr>
<tr>
<td>16 Substrate heating</td>
<td>A heated bed capable of 100W should be used to minimise part warp</td>
</tr>
</tbody>
</table>
3. Multi-material development

It should be noted that throughout this thesis FFF is used heavily to manufacture components for the experimental setup. The main reason for this is to minimise development time, however an added benefit of using this is encourage external development by the RepRap community and also to give the reader an indication of the functionality attainable with Fused Filament Fabrication.

3.2. Mechanical Concepts

For RepRap to be able to use multiple materials, research and design efforts may be broken down into two distinct areas:


2. Development and characterisation of the required extruders.

In reality, neither of these requirements may be developed independently of the other. However, to improve the clarity of this thesis, the results will be presented separately.

3.2.1. Cartesian Robot Development

Three concepts were considered for the Cartesian robot. Firstly, a head changer proposed by Sells for implementation with minimal modification to the standard RepRap design was considered. The standard RepRap Mendel is shown in Figure 3.1. For the remainder of this thesis, the machine axes are identified according to the diagram shown.
Two provisional areas are highlighted showing potential free space for extruder docks and are shown in Figure 3.2. Sells proposed a series of docks secured to the top gantry of the Mendel design. It was proposed that a either a magnetic or mechanical locking attachment system would enable extruders to be stored in the docks and easily secured to the X axis when required. One potential problem with head changers in traditional subtractive processes is the reduced rigidity of the tool-head mount. It was anticipated that would be a non-issue for the following reasons:

- Fundamental forces at the extruder tip due to deposition are minimal.
- Forces applied by the filament supply dragging on the carriage can be significant.
3. Multi-material development

if tangling of the filament supply occurs, however this is a non-issue providing a good filament handling mechanism is used (e.g. a spool).

• The quickest accelerations during a print are approximately 0.17g, requiring a reaction force of approximately 1.7N for a typical extruder (mass \(\approx 1\)kg) [62]. Whilst this is minimal, the peak accelerations occur during non-printing travel moves. They are required to reduce the risk of extruder ooze, improving print quality and reducing print time. However this is tuneable through other parameters, such as filament retraction before the move, and hence there is some flexibility to reduce these forces.

Figure 3.2.: Potential locations for extruder docks

The author observes that whilst this method allows for a head changer with minimal modifications to the standard frame, a substantial loss in build volume in the Z direction is inevitable. The concept is dependent on the operating extruder being able to operate directly underneath the docked extruders. Given that each standard Mendel extruder is approximately 125mm tall, at least this value will be lost from the Z build volume; leaving just 15mm build height at standard dimensions without allowing for clearance for filament feed and cabling. Further it is observed that unlike thermoplastic, a paste extruder stores its material in a syringe within the working volume of the machine. Hence build volume is likely to be reduced further.

Clearly, the mechanical design would need to be enlarged in the Z direction, which, whilst possible, would entail substantial work as this would also imply increasing the Y build volume given the machine’s equilateral prism design. In addition strengthening the overall design would probably be needed. Thus this approach was deemed too risky when coupled with development work that would be needed to ensurerepeatable
3. Multi-material development

and accurate docking of the heads.

An alternate derivative of this design is to dock extruders at either end of the X axis as shown in Figures 3.2 and 3.3. Instead of docking on a gantry parallel to the X axis, the author proposed a pair of gantries at either end of the X-axis also indicated in Figure 3.2. The concept would allow a pair of extruders, one above another, at either of the Z-axis, thus allowing four extruders. However, this design would require a fundamental redesign of the machine. Firstly suitable supports for the gantries would be required, in addition to lengthening the X-axis to maintain build volume. It should be noted that this lengthening this axis does not come with as much risk as Sells’ design, as the X-axis may be altered independently of Y and Z. Nevertheless, difficulties with docking repeatability are still likely. Further, the dimensions of the Robocasting and alloy extruder were unknown, thus making an integrated and complex concept such as this difficult. However this fundamental concept has been subsequently proven by Dustan [62], but concerns regarding extruder design flexibility in the future remain.
3. Multi-material development

Figure 3.3.: Alternative Head Changer Concept

Magnets located at four corners of both sections of the carriage. A series of wedges provide constrain all motion in lateral and longitudinal planes.

X axis widened, and carriage recessed to allow for collection of docked extruders.

Symmetric geometry allows for extruders to be docked at either end of the Cartesian robot whilst minimising loss in build volume.
3. Multi-material development
3. **Multi-material development**

One final alternative remained: a redesign of the extruder carriage. Given that support material is required for Robocasting, at least three extruders are required. Therefore, to avoid a substantial loss in build volume, the volume of each extruder must be reduced. An alternative remains, whereby the filament drive mechanism is decoupled from the extruder itself, and the filament guided to the hot end by a stiff low friction Bowden tube as shown in Figure 3.4. It should be noted that such a setup was highly experimental at the time of implementation, but at the time of writing is commonplace in RepRap machines. Never-the-less there are potential draw backs to such a setup:

- Stretching of the tubing may affect print quality due to hysteresis, particularly during in transient conditions.

- The stiffness of the tubing will place extra lateral loading onto the X carriage.

- Increased motor torque is required to overcome friction

![Figure 3.4.: Bowden extruder setup](image-url)
3. Multi-material development

Despite these disadvantages, some limited testing has previously been conducted with some success [63]. Taking this approach would enable each extruder to take up less volume by allowing the drive mechanism to be external to the machine, and mounting three extruders simultaneously would be possible.

One consideration which must be made is the effect of manufacturing and assembly tolerances. In order to prevent nozzle collisions when having all multiple heads on a gantry, all must be working at the exact same nozzle height relative to the build platform. Given the manufacturing techniques, this is unlikely to be possible without adjustment. Therefore the reduced weight and size of a Bowden extruder allows a simple spring mechanism to be used as detailed in Figure 3.5
3. Multi-material development

Figure 3.5.: Multiple Extruder Carriage

Bearings moved inside X-Carriage to improve packaging - Allows a greater internal volume for extruders for a given spacing between the X-axis smooth rods.

X Axis belt clamps - Belt path changed from outside to inside the carriage - Improves packaging allowing more working volume for extruders for a given belt path.

Extruder mounting system - Arranged in equilateral triangle for optimal packaging, Captive nuts on the reverse side allows for easy attachment. Intermediate springs on secondary extruders allow for height/offset adjustment.

Extruder mounting plate - requires the extruder drive mechanism to be decoupled from the extruder itself, using either a pneumatic or bowden system. Extruder spacing lessened reducing offsets between extruders and therefore potential for inaccuracies.
3. Multi-material development

Given the unknowns associated with Robocasting, an integrated approach such as the head changer concepts was thought to be insufficiently versatile to allow for modifications to the system as the process is developed. Therefore it was proposed that Bowden approach would be best suited for research. The concept previously outlined was developed into the system shown in Figure 3.6. The design offers the capability of handling three extruders, providing their maximum diameter is 16mm. Given this, work transferred to developing a paste and thermoplastic extruder compatible with this system.

![Implemented MultiExtruder Extruder Carriage](image)

Figure 3.6.: Implemented MultiExtruder Extruder Carriage

3.3. Thermoplastic Extruder Development

Following the concept outlined previously, a Bowden thermoplastic extruder was designed and implemented into the system, shown in Figure 3.7, based on the Bowyer’s geared extruder. After a short amount of testing extrusion stopped despite the drive mechanism appearing to work correctly. It was found that the PTFE tubing, which was held using adhesive, was secured insufficiently at the extruder end of the system. Further development, based on the work of de Bruijn, was conducted to improve this joint by threading the outside of the tube using an appropriately sized die. A nut could then be used for fixing. However, despite this method working successfully for de Bruijn [63], a similar failure mode to that previously described occurred again.
3. Multi-material development

Subsequent testing reveals the walls of the PTFE tubing were insufficiently stiff and thus the thread disengaged from the nut. After changing the tubing wall thickness to 1.6mm, this problem was solved.

Using this design, it was found that the extruder oozed substantially compared to standard RepRap designs. Whilst RepRap extruders typically ooze a small amount, reversing the filament a small distance at the end of a run typically solves this issue. However increasing this reverse by nearly a factor of three (approximately 4mm of filament) compared to direct-coupled extruders made the effect compatible to that achievable to a standard RepRap design at the time of development. If the extruder is left at operating temperature for a long period (>20seconds) oozing could still occur. Whilst this result would be acceptable for a standard single material print, some consideration had to be made for multi-material prints - namely allowing for different tool-heads to be used. Unlike a single material print, where the head is constantly in operation during the entire print, during a multi-material print a transition must occur between tool heads. During this period, a significant amount of extruder ooze will occur. Whilst extra filament reversal reduces this, some ooze is still apparent. It was proposed that the thermoplastic extruder should cool to an idling temperature when not in use. However this temperature should be maximised to reduce print times whilst ensuring no ooze occurs whilst at this temperature. Through experimentation this temperature was found to be 120°C, however ooze still occurred in the transition. Fundamentally it was proposed to solve this through two fundamental means.

Firstly a barrier could be printed around the object, during this transition time ooze would still occur and whilst this is happening the nozzle can move outside of this bar-
3. Multi-material development

Due to the elevated idle temperature any ooze would remain soft. Upon reaching the idle temperature, the build could continue and the barrier would prevent any ooze from hitting the print.

In order to reduce the possibility of ooze, the time taken to cool the extruder from its operating temperature to this idling temperature should be minimised through reducing thermal mass. Two fundamental heating strategies are established within RepRap, nichrome heating wire and enamel wire-wound power resistors. The use of a power resistor requires a comparatively large heating block in order to contain it, and hence has a large thermal mass allowing stable temperatures with simple bang-bang heating control. Implementations using nichrome wire typically wrap the wire around the extruder nozzle before coating it in an insulator such as Kapton tape or ceramic putty. The resulting extruders typically have minimal thermal mass and are capable of reaching operating temperature very quickly (under 10 seconds); however the low thermal mass also ensures that the more complex PID control is vital to allow consistent temperatures. Given this benefit nichrome heating wire was used for the extruder used throughout this chapter, although a heated block setup was used for subsequent chapters due to the reduced tool head changes required in the work undertaken.

Whilst the print quality using the setup described was comparable to output of RepRap machines at the time of development, the added complexity of a multi-material print places additional emphasis on print quality. At the time, rough uneven top layers were produced by RepRap machines, for a single material if the nozzle were to collide with any undesired material, it could simply melt thorough it with no substantial side effects. However in a multi-material printer some FFF extruders would be operating at an idling temperature, which would be insufficient to melt through these dilations. Further paste extruders would be operating at room temperature exacerbating the issue. Finally when using functional materials, e.g. magnetic or conductive, unwanted material in the wrong area of the print could result in a failure because the wrong functional material was in the wrong place.

Hence in order to improve print quality further the raw filament diameter was reduced from 3mm to 1.75mm, a comparable filament size to that used on commercial FFF printers. This reduction in filament diameter leads to several major benefits, all of which lead to improved print quality:

- Increased filament drive accuracy - The reduction in filament diameter means that the filament needs to travel approximately three times further in order to extrude a similar volume. This results in a more precise, accurate and controllable filament drive which operates at substantially lower forces, improving consist-
3. Multi-material development

- Reduced flexural stiffness - The reduced diameter results in the flexural stiffness decreasing by almost a factor of nine. Coupled with the lower extrusion forces this results in substantially less hysteresis and stretching of the Bowden tubing. This leads to a significant improvement extruder control during transient conditions.

After these modifications it was deemed that whilst print quality was acceptable to allow research to continue, although still poor relative to that attainable at the time of writing. It should be noted that compared to the print quality achievable on commercial AM systems, and modern day RepRap’s print quality was still poor even for standard single-material prints. The author estimates that at the time of publication of this thesis approximately 20-30000 open source 3D printers will have been produced, many operated by skilled, technically minded users who are constantly upgrading them. Throughout the author’s PhD significant developments have been made on tool path planning, firmware optimisation, extruder design (including the reduction in filament diameter highlighted) and general hardware which have made basic print quality comparable with, or often better than, commercial FFF/FDM AM systems. However significant progress is still to be made to tool path and support material generation to enable similar quality complex geometry prints. Therefore it is concluded that should this research be revisited with a modern setup, these issues are expected to be significantly reduced.

3.4. Robocasting Development

As has previously been described, two techniques are prevalent in Robocasting: either pneumatic or volumetric control. The literature review established that on first appearance, both of these have their advantages and disadvantages. Pneumatically controlled systems typically deal very well with the inclusion of air in the deposited pastes, whereas volumetrically controlled systems are force independent, and thus should ensure fewer setup changes between pastes of different viscosity etc. Therefore, given this the lack of clarity in determining the optimal solution, it was decided to pursue each path independently.
3. Multi-material development

3.4.1. Volumetrically Driven Paste Extruder

In order to allow three extruders without a substantial loss of build volume and without a major redesign of the Cartesian robot, it was required that all extruders needed to be very compact. Therefore, using a design where the motor was directly coupled to the piston, such as the Fab@Home system shown in Figure 2.14, was not an available option. An alternative was to use the thermoplastic Bowden drive mechanism described previously. Rather than feed the thermoplastic filament into a heated extruder nozzle, a piston was to be secured to the end of the filament, and in turn displaced a paste in a syringe as shown in Figure 3.8. Naturally, this concept would reduce the stiffness of the overall system in the process. Given that the force required for extrusion for a given nozzle orifice would increase substantially as the syringe diameter increased, it was unclear at what syringe size this reduction in stiffness would become an issue.

During testing, it was found that a significant preload needed to be used in order to get the required flow rates. Equally, and like the thermoplastic designs, a reverse parameter was used to stop flow when required. For 3cc syringes, acceptable results were achieved, but it was deemed this volume was not suitable to produce usefully large components. Upon scaling the design to 10cc syringes, it was found that the preload varied from test to test by up to 50% to get the required flow rates. It was also found that if the drive mechanism slipped due to the high extrusion forces this preload would be removed. This would result in a substantial reduction in extrusion rates and produce unsatisfactory results. Further, an incorrect filament feed rate could build up or remove the preload even with the smallest error.
3. Multi-material development

Given the lack of success with these initial experiments, this work was abandoned and work concentrated on the pneumatic concept. However the concept has been subsequently implemented on another open source 3D printer as shown in Figure 3.9.

![Figure 3.9.: Ultimaker syringe extruder by Joris van Tubergen using the concept proposed by the author. [64]](image)

3.4.2. Pneumatically Driven Paste Extruder

Breaking down the pneumatically driven systems described in Section 2.3 gives several areas of work:

1. Dispensing Components
2. A valve to control air flow
3. The mains air supply

Given the aim of creating a self-manufacturing machine, wherever possible, components and assembly were to be manufactured using FFF which RepRap can currently achieve. It was decided that manufacturing dispensing components and the air supply system required a degree of capability and accuracy not currently possible. However, a concept for creating a part self-manufactured valve was jointly developed by the author and Patrick Haufe \(^1\), and is shown in its completed form in Figure 3.10.

The device consists of a dual shaft DC motor, with one shaft connected to a cam, and

\(^1\)In addition, the firmware to control the device was developed mainly by Bowyer, in collaboration with the author
the other connected to an opto-switch flag (not shown). As the cam rotates, a printed spring is compressed, blocking and releasing air flow running through silicone tubing on the opposite side of the spring. The flag passes through an optoswitch to enable the RepRap software to know when the cam is at the points where the valve is open or closed.

Figure 3.10.: Rapid Prototyped Valve. All parts in green are produced using Fused Filament Fabrication

Critically, the design does not simply disconnect the air supply in the off position. This would leave the syringe at an elevated pressure resulting in unwanted extrusion. A second valve is used to ensure that this excess pressure is release to the atmosphere reducing this unwanted material. In testing, the device has proved to be successful, and capable of functioning at pressures in excess of 2 bar (limited by air supply). Further, the time lag that is inevitable in the opening/closing action is easily accounted for in RepRap’s software. Given the success of the valve, work shifted to investigating the repeatability of extrusion using the device.

Given the constant-force nature of a pneumatically driven process, a series of experiments were conducted to establish the effect of externalities on volume flow rate. The material extruded was polydimethylsiloxane (PDMS). The extruded mass was recorded for a variety of experimental parameters. It was found that test-to-test variation due to different, although the same specification, pistons, tips, and syringe barrels resulted in a variation in the flow rate of 3%, with an average flow rate of $1.1 \text{cm}^3/\text{min}$ at 1.6bar when using 18 Gauge (0.838mm ID) 2mm long steel tips and a 10cc syringe.

\(^2\)Henkel Unibond “super” bathroom sealant
3. Multi-material development

It is logical that the wall friction will vary as volume of paste contained within syringe changes. Given the constant-force method implemented, this change in friction will result in a change in the flow rate. Figure 3.11 shows the result of an investigation into this variation, using the test setup previously described. It was found that the variation did not exceed 4% from the average under any circumstances. Further, Newton’s law of viscosity states the anticipated reduction in wall friction should vary linearly with contact area, and therefore volume for a syringe of constant cross-section. Thus, this linear reduction in wall friction should result in a proportional increase in flow rate with reduced volume in the syringe. It can be seen the results are broadly linear, matching expectations.

Based on the typical thermoplastic filament tolerances, (within 0.1mm diameter), a flow-rate variation of up to 10% is seen between filament batches. Despite this variation acceptable results are still achieved without further tuning as Fused Filament Fabrication is an inherently forgiving process. Whilst Robocasting utilises a different extrusion method and materials, the fundamental process is similar to FFF. Further, the pressure during these tests was manually controlled by hand, and thus would account for some of the error.
3. Multi-material development

Given these facts, it was anticipated that the achieved results would be acceptable and therefore a pneumatic system was chosen to be favoured over the aforementioned volumetric system. Hence an iterative process was undertaken whereby known key parameters were empirically adjusted to give optimal build quality for the test setup previously described. A description of these parameters along their optimal values may be found in Table 3.1.

Table 3.1.: Critical Build Quality Parameters for Paste Extrusion

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Final Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>ValveDelayForLayer(ms)</td>
<td>For the first time the extruder is used on each layer, the delay between opening the valve and starting to move the extruder head.</td>
<td>200</td>
</tr>
<tr>
<td>ValveDelayForPolygon (ms)</td>
<td>As above but for each successive valve opening for the remained of the layer</td>
<td>200</td>
</tr>
<tr>
<td>Valve Over Run (mm)</td>
<td>The distance before the end of a road sequence to close the extruder valve.</td>
<td>2</td>
</tr>
<tr>
<td>Extrusion Pressure (bar)</td>
<td>Pressure used during extrusion to enable the build of required parts</td>
<td>1.6</td>
</tr>
<tr>
<td>FastXYFeedrate (mm/min)</td>
<td>Speed at which the extruder plots. Other parameters exist that enable acceleration, these were disabled for Robocasting.</td>
<td>1000</td>
</tr>
<tr>
<td>Extrusion Height (mm)</td>
<td>The depth of each layer. Must be identical for all extruders</td>
<td>0.3</td>
</tr>
<tr>
<td>Extrusion Infill Width (mm)</td>
<td>Gap between in the zig-zag pattern used for fine infill on the exterior walls of an object</td>
<td>0.8</td>
</tr>
<tr>
<td>Extrusion Size (mm)</td>
<td>Modelled Width of extruded roads</td>
<td>0.8</td>
</tr>
<tr>
<td>Infill Overlap (mm)</td>
<td>Amount to overlap infill and outline. Ensures both are welded together.</td>
<td>0.2</td>
</tr>
</tbody>
</table>
3. **Multi-material development**

![Image of multi-material part](image)

Figure 3.12.: An intermediate result whilst tuning the Robocasting process for PDMS (left) and the final build quality achieved (Right). Part measures 20x20mm

Figure 3.12 shows an example of some of the results achieved during the empirical tuning process described. It can be seen that several “strings” are apparent at some of the edges of the part. This is attributed to the relatively high viscosity of the paste, and in-air non-extruding movements of the extruder “stirring” deposited material. It is anticipated that the results could be further improved through improved tool path planning. For example before an in-air movement, the entire extruder lifted a small amount to prevent this mixing. Never-the-less, the final result shown was deemed sufficient to attempt a true multi-material part.
3. Multi-material development

3.4.3. Ideal material properties

Thinking of the mechanical setup developed, it is worthwhile to consider the effect of material properties on extrusion quality. As outlined in the Literature Review, Cesarano stated that it was a material requirement that it be extruded into a non-flowable mass. To put this in engineering terms, some limit of shear stress must be reached before any shear actually occurs. As stated previously, development pace in Additive Manufacturing is relentless, and several Robocasting systems have been developed. However the subjective print quality of both the system developed in this thesis and others appears to be highly variable. Whilst these prints are on different systems, and therefore some variation would be expected, the range of print quality seen is far beyond what one would expect.

To date there has been no fundamental study on a wide range Robocasting materials and the effect of material properties on print quality, and such a study remains a matter for further work. The author proposes that the fundamental reason for this wide range of print quality is due to a wide variety of flow regimes possible in pastes. Whilst several regimes are also possible for plastics, it is hypothesised that as plastics quickly harden once extruded, the print quality is not affected by subsequent printing of the part. The major flow regimes for fluids under steady-shear conditions are shown in Figure 3.13, and detailed descriptions of each regime are outlined below together with the hypothesised side effect on print quality; where available a representative print is included to give the reader an indication of print quality.

Figure 3.13.: Characterisation of fluids based on their steady-shear flow curves [65]
3. Multi-material development

Based on Table 3.3, it is hypothesised that the order of preference of flow regime is as follows:

1. Bingham Plastic
2. Shear-thinning
3. Newtonian
4. Shear-thickening.

Whilst these proposed ideals are subjectively reinforced in the small sample set shown, it is recommend this is a matter for further research.
<table>
<thead>
<tr>
<th>Flow Regime and Typical Materials</th>
<th>Description</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Newtonian Materials: Water</td>
<td>Differential viscosity and coefficient of viscosity are constant with shear rate</td>
<td>Low stresses result in shear and deformation. Implies that each layer must be cured after printing before moving to the next. Response is linear which should result in easy tuning of material flow rates in a pneumatic/constant force setup.</td>
</tr>
<tr>
<td>2 Shear-thickening Materials: Typically starch suspensions and “Silly putty”</td>
<td>Differential viscosity and coefficient of viscosity increase continuously with shear rate.</td>
<td>Low stresses result in shear and deformation. Implies that each layer must be cured after printing before moving to the next. Response is non-linear making tuning difficult</td>
</tr>
<tr>
<td>3.4</td>
<td>Shear-thinning (pseudo-plastic) with yield response Materials: PDMS, Adhesives, Also standard FFF thermoplastics e.g. ABS/PLA</td>
<td>Differential viscosity and coefficient of viscosity decrease continuously with shear rate</td>
</tr>
<tr>
<td>5.6</td>
<td>Bingham plastic (ideal) (non-ideal) Materials: Clay, Chocolate</td>
<td>Obeys the relation ( \sigma = \sigma_B + \eta_{pl} \dot{\gamma} ), Once above the Bingham yield stress the differential viscosity, ( \eta_{pl} ), is constant, while the coefficient of viscosity decreases continuously to some limiting value at infinite shear rate.</td>
</tr>
</tbody>
</table>
3. Multi-material development

3.5. Electronics and Software

Whilst the author was the first person to investigate printing in multi-materials with a RepRap, it has been a goal of the project since its inception, and hence to some degree electronics and software already designed had taken into consideration multi-material requirements. Whilst the author did some firmware and software development, namely coding to allow extruder offsets and control logic for the developed paste extruder, the majority of the work was done by others. As these contributions are essential to reproducing the author's work, these developments are summarised in this section.

3.5.1. Software

The RepRap is operating through a host PC. The PC program, RepRap Host, is written in Java to ensure compatibility between operating systems. The software, originally written by Bowyer, McAuliffe and others, takes a model file in the STL file format, and slices it into layers, before saving the tool-paths as a GCode file. This GCode is then sent by a separate module, developed by Bowyer and McAuliffe, to the electronics for interpretation by “fiveD” firmware, also developed by Bowyer. A screen shot of the software in operation is shown in Figure 3.14. Key parameters for paste extrusion are detailed in Table 3.1, similar parameters exist for plastic extrusion with additional parameters for extrusion temperature and retractions for non-printing moves. A copy of the source code for the firmware and software has been included on the DVD accompanying this thesis.
Two issues arose with regards to how to handle a multiple material part. Firstly, and critically, the question remained of exactly how to define a two-material part. Given the premature status of multi-material file formats, and the lack of compatibility with existing software, implementing a fundamentally new format would be unwise. Therefore using the STL format was the preferred option. It was decided that separate STL files were to define each material within the part. Specifically STL files contained an internal coordinate system which is used to define the part.

Ordinarily the exact coordinates of where the part may within this system is ignored, and only the relative coordinates of the facets are used to define the shape. It was proposed by Bowyer to use this coordinate system to define the relative position between parts/materials during a build as indicated in Figure 3.15. Upon loading an STL into the Java host software, print parameters appropriate for that STL may be chosen. Hence multiple STLs can be loaded defining one part in total, with each STL defining a different material or print parameters of the final part. In addition Bowyer also implemented a technique that enables all of the required part files, the relevant material and extruder information, and the relative position within the build volume within one file, known as an RFO (RepRap and Fab@Home Object, originally proposed by Zach Smith) file [66]. The file is essentially a ZIP file, containing the required STLs and a legend file of Extensible Markup Language (XML) to define the materials and the positions.

Secondly, the controlling software that generates tool paths based on this geometrical
3. Multi-material development

data was incapable of dealing with offsets between different extruders. At that stage of development, RepRap host was not capable of extruder offsets, and given the software’s complexity\textsuperscript{3} it was decided to simply detect when a tool head change is required and offset the coordinates in the GCode using a post processing script. Such a program was written by the author in collaboration with Gerrit Wyen. A copy of this program may be found on the DVD that accompanies this thesis.

\textsuperscript{3}and the author’s programming ability
3. Multi-material development

Figure 3.15.: Approach to handling multi-materials with STLs. Two separate files (left and centre) combine to give one multi-material part (right).
3. Multi-material development

3.5.2. Electronics

The test setup in this chapter uses the “RepRap Generation 3” electronics developed by Zach Smith. The system consists of a central motherboard, powered by an ATMEL ATMEGA644P microprocessor. In addition to this central motherboard, three breakout stepper driver modules are used for powering the stepper motors and a further three opto-endstops are used in combination with homing flags on the axes to allow the setting of a datum point. Finally one “RepRap Extruder controller” is required per extruder up to a maximum of four. These extruder controllers consist of an Atmel ATMEGA168. The separate microprocessor on the extruder controller allows it to process tasks with minimal communication with the main Motherboard. A basic overview of this setup is shown in Figure 3.16.

This implementation was used for all the experiments detailed in this chapter. For the work detailed in subsequent chapters a RepRap RAMPS 1.3 board, developed by Russell, was used. The main benefit of this board is the inclusion of micro-stepping on the stepper drivers, allowing smoother operation and better print quality. Further the designs used an ATMEL 2560P powered Arduino Mega board which means all of the functionality of the GEN 3 system is included on just one break out board. A detailed schematic maybe found in Appendix D.

![Figure 3.16.: RepRap Gen 3 Electronics Diagram](image)
3. Multi-material development

3.5.3. Effect of Additives

As previously mentioned, one of the main benefits of Robocasting is the ability to mix composite materials using functional powders. However some consideration has to be made to the effect on the printing process. As highlighted in the literature review, additives have been used by Fab@home to stiffen PDMS such that it is free standing, and therefore gives better print quality, in addition to using powders for functional properties.

Whilst some success has already been achieved in 3D printing IPMC (Ionic Polymer Metal Composite) actuators, the author contends that the displacements achieved are insufficient for most electro-mechanical devices and rely on expensive and rare materials. In addition, if we were to study the devices used by society in day-to-day life the majority would be implemented either using electric motors or solenoids. Whilst such devices require complex geometries, it can be said that 3D printing technologies lend themselves to producing such intricate components. For these reasons the development of a ferrite material compatible with Robocasting was useful, both to gain the additional functional properties, but also to assess the effect of the powder on the process. Unlike the volumetric technique developed by Fab@home, the pneumatic method will likely need to run at higher pressures to achieve the same flow rate with additives due to the increased viscosity. However it has been established by Fab@Home that other parameters need adjusting even in the volumetrically controlled setup for optimum print quality, e.g. line width, retractions etc.

Given the experience already gained at this stage of research, it was decided to mix ferrite powders with the PDMS previously implemented to make a flexible magnetic material. If required the composition of the material could be adjusted to allow the extrusion characteristics as well as the magnetic properties to be controlled. Research thus far has focused on assessing the effect of material composition on extrusion characteristics for 300 mesh iron powder and PDMS.

Figure 3.17 shows the results of the investigation conducted so far using a similar setup to that previously described. It can be seen that at low weight percent of iron powder, flow rates decrease linearly with increasing powder content. This has been attributed to the increase in viscosity associated with the addition of powder. The extrudate produced, being silicone based, allows for substantial deflections, estimated at 2-3cm for thin filaments, when in the presence of a 10mm dia. x 3mm neodymium magnet. Therefore these results are promising, and the measurements taken allow calculation

\[4\] Purchased from Pyrotechnic Supplies
3. Multi-material development

of the parameters needed to calculate the required deposition path.

Figure 3.17.: Graph showing the effects of iron quantity in the composite material on the extrusion rate. Tests are conducted using 300 mesh iron powder in a 10cc syringe loaded with 4cc of material at 1.6bar over a five minute period.

3.6. Combining the Robocasting and FFF processes to allow the manufacture of multi-material components

At this stage of research, both thermoplastic and paste extruders had been independently implemented. However, work needed to be undertaken in order to allow for the control process to deal with each extruder simultaneously. The final test setup is show in Figure 3.18.
3. Multi-material development

An attempt was made to create a simple cube, using transparent PLA thermoplastic for the exterior, and white PDMS for the interior infill. The produced part may be seen in Figure 3.19. Given the weak external shell and the PDMS interior, the walls of the part are capable of significant deflection (approximately 3mm); however it was observed that the part suffered from de-lamination at the corners. It is anticipated that this may be resolved by increasing the exterior wall thickness from its current value of 0.7mm.

Subsequently, the part shown in Figure 3.20 was manufactured. It is a pair of PLA tweezers with PDMS grips. In order to minimise the effect of unwanted oozing described previously, a small barrier was built around the tweezers, and thus prevent any unwanted extrudate from hitting the part during head movements.
It was observed during the manufacturing of the part that the extrusion of paste stopped approximately 75% through the build. The nozzle was replaced mid-build, enabling the part to finish building satisfactorily. On closer inspection, it was discovered that the thermoplastic build quality was poor, with several lumps of the surface of the part. Typically this isn’t an issue given the stiffness of the thermoplastic extruder. However, for the paste extruder in this test, a tapered plastic tip was used to maximise the flow rates. This tip ran over these uneven areas and the nozzle orifice deformed, leading to increased pressures being required for similar flow rates. Subsequently, steel tips were used and so far the problem has not arisen again. Equally, in order to confirm this diagnosis it has been shown that running the PDMS extruder independently in a clamp stand for similar time periods does not result in the same problem. Whilst this is a potential solution for PDMS, other higher viscosity materials will require higher pressures to achieve similar flow rates which may not be possible. Therefore in order to improve thermoplastic build quality several steps were taken to reduce the issue:

1. Filament diameter reduced to 1.75mm from 3mm - The non-linearity of extrusion is in part due to hysteresis owing to stretching of the Bowden tubing. This stretching is caused by the extrusion forces, by reducing the filament diameter to 1.75mm, extrusion forces are reduced to 1/3 of the forces required to 3mm filament reducing hysteresis.
3. **Multi-material development**

2. Retraction speeds increased - Due the “spring” effect of the Bowden tube, some unwanted extrusion occurs at the end of moves in the transient period as the extrusion pressure is unloaded. Increasing the potential reversal speeds by reducing extruder gear ratio from 5:1 to 3:1 with a corresponding increase in retraction speed from 18 to 40mm/s, reduces the amount of unwanted extrusion - improving print quality.

After the above changes, the system has shown to be resilient to the failure mode described. Subsequent to this research, substantial amounts of work have been undertaken to allow for software compensation of Bowden tube hysteresis. It is anticipated that between these software improvements, and the mechanical changes described, the effect would be a non-issue should the work be repeated, however this has not been tested.

Following the research undertaken in this chapter, the fundamental multi-head mechanical setup has been further developed by the author focusing on three material/three colour FFF printing. Examples of the prints achieved using this setup is shown in Figure 3.21

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5This work was undertaken by RepRap Pro Ltd. At the time of writing, the author is in their employ
3. Multi-material development

Figure 3.21.: RepRapPro Tricolour Mendel Prints, Love Sculpture (top), Dice (Middle) and Traffic Cone (Bottom)
3.7. Conclusions

This chapter presents the development of an hybrid Additive Manufacturing system capable of both Fused Filament Fabrication and Robocasting, in doing the wide choice of materials compatible with Robocasting are combined with the traditional engineering properties and practicality of the FFF process. Research was undertaken investigating two fundamental approaches to the Robocasting process, volumetric and pressure-driven control. It was concluded that volumetric control offered poor repeatability, with problems arising due to trapped air contained within the material. It was found through testing that pressure-driven control was robust against this failure mode; however it is susceptible to changes in flow rate between materials due to different material viscosities.

A standard “Bowden” FFF setup was adopted. Critically it was concluded that adjustment of all extruders was vital in order to prevent collisions with manufactured components. Given the lack of support for multi-materials by industry at the time of development, an approach was proposed for handling multi-material components using existing standards and file formats and this was implemented by Bowyer to enable further work.

Several issues arose due to unwanted extrusion during tool-head changes and poor print quality. Hence improvements were made to the mechanics to minimise these issues e.g. switching to 1.75mm filament. The final workflow for the print strategy used is shown in Figure 3.22.

The system implemented was sufficiently versatile that three FFF/Robocasting extruders could be used in any combination. It forms the basis of the test rig for the remainder of this thesis. A complex, by traditional standards, component was manufactured consisting of a robust polylactic acid inner core deposited by FFF, and a soft polydimethylsiloxane exterior shell. The component would be impossible to manufacture using traditional low volume manufacturing techniques in one shot, with only two shot injection moulding being capable of manufacturing the part in quantity.
3. Multi-material development

Start

Heat all extruders to thermoplastic extruders to idling temperature

Increase Z by one layer height

Print external barrier offset 2 mm from main part

Extruder required in this layer of part

Print portions of layer in this material

Set Primary extruder to extrusion temperature

Extruder required in this layer of part

Print portions of layer in this material

Retract, move away from component into free space

Set extruder to idling temperature

Other materials required in layer

Prime away from component

Print layer in given material

Recover from retraction

Set extruder to idling temperature

Print Finished

End

Turn off all extruders

Yes

No

Figure 3.22.: Deposition Strategy
4. Effect of Mesoscale Structure and Print Parameters on Bulk Mechanical Properties

Given the inherent versatility of AM techniques, it is clearly a good idea to exploit that versatility as much as possible with each material used, and only then to add extra materials as needed. This is because such exploitation can be achieved purely through software and parameter changes, without changing the hard engineering of the AM machine itself. The multi-material system described in the last chapter will be returned to later. But this chapter is devoted to a study intended to minimise the need for multi-materials in the first place.

In creating a multiple material AM system the question will be inevitably asked, how many different materials can such a system use? Perhaps a more pertinent question would be: how many materials are required to achieve a broad range of mechanical, functional and other properties? It is a standard technique within engineering to actively select materials in order to give the required properties for a part to perform a given function. Such properties may be needed in order to meet requirements for weight, strength, stiffness or other mechanical properties. The number of materials used to date with AM processes is substantially less than subtractive techniques, and as such a narrower spectrum of raw material properties are available. Therefore a complimentary technique is required in order to maximise the range of effective material properties by some other means.

Further being able to actively vary the mechanical properties throughout a component may offer many desirable characteristics not possible traditionally. Consider a simple strain gauge, traditionally a compromise has to be met between achieving good resolution and accuracy, whilst also being able to deal with large strains. A strain gauge which is made of a varying stiffness material would offer a non-linear response; therefore it is possible that high precision and accuracy could be achieved over small strains, whilst less accurate measurements could be achieved over a larger range where tradi-
tional strain gauges would fail. Such properties are unattainable with more traditional techniques.

Searching for methods to maximise the range of bulk material properties achievable with a limited range of materials is desirable even if a wider range of materials becomes compatible with AM techniques. Implementing extra materials has significant consequences as outlined below:

- Print volume is reduced
- Some change over process is inevitably required for priming/heating of extra extruders. In doing so build time is increased and can result in unwanted oozing issues described previously
- AM systems become more intricate, increasing costs and reducing reliability
- Tool-path generation becomes more complex

Given these difficulties, the requirement for an alternative method of obtaining a wider range of materials properties is increased further.

A common misconception with Additive Manufacturing lies with the expected manufacturing time. This misconception is in part based on Additive Manufacturing’s namesake, Rapid Prototyping, and also due to its use in reducing design cycle time. However speeding up the design cycle is not due to the speed of the AM process, but due to the lack of tooling required and the consequent ability to quickly iterate designs. The AM process itself may take hours or even days to produce a complicated part. In order to combat these long build times, AM’s inherent flexibility is used to create a complex porous mesostructure within a solid external shell that enables reduced cost in exchange for impaired mechanical properties.

Lanza et al. have shown that mechanical properties of the component may be controlled by varying porosity, infill overlap, layer thickness and road thickness amongst others for Stratasys Acrylonitrile Butadiene Styrene (ABS) material. Whilst many parameters may be controlled using this proprietary system, RepRap enables the use of a much wider range of values for these parameters.

This chapter seeks to answer the question of what mechanical properties may be achieved by varying these build parameters. When a variation in only mechanical properties are required, the use of this technique will substantially reduce the number of materials
4. Effect of Mesoscale Structure and Print Parameters on Bulk Mechanical Properties

needed; enabling other functional materials to be used that cannot be substituted by part geometry alone (for example, a conductive one). In addition, through varying bulk mechanical properties through only varying process parameters also opens up other potential properties not available through the use of separate materials. Process parameters could be continuously varied through a component, giving different stiffnesses in different locations within the part. Such a technique therefore opens up new applications in many areas.

As already mentioned, several detailed studies have already taken place investigating the effect of print parameters the work undertaken to date has focused on the limited number of parameters tuneable using proprietary Stratasys software and ABS material. Little effort has been made into researching other potential parameters or indeed other FFF thermoplastic materials, even when many consider polylactic acid (PLA) to be better suited to the FFF process. This chapter investigates the effect of the more varied print parameters allowable with open source software in combination with PLA. Further comparisons are drawn with the results of studies already undertaken for ABS. Finally conclusions are drawn about the appropriateness this technique within the context of multi-materials.

4.1. Print Parameters

Fundamentally all FFF systems use similar parameters to describe exactly how an object is sliced into layers and tools paths are generated. For the research in this chapter the open-source software “Slic3r” [67] has been used for tool-path generation.

The reason for this change from the RepRap host used previously in this thesis is due to the fact that the subtleties included in RepRap host to allow multiple materials are not required, and Slic3r is more widely adopted and so would maximise the impact of this research. Further the prints generated with Slic3r and its accompanying firmware typically offer higher quality prints, implying more robust and repeatable results. For comparison however, one basic set of results generated by RepRap host is included.

A schematic showing the typical rectilinear infill with infill direction alternating every layer is shown in Figure 4.1:
Whilst every slicing software offers different settings and parameters, in general they share several key attributes. These may be broken down as shown in Table 4.1. A list of other non-critical print parameters may be found in Appendix E.1 and E.2.
Many of the above parameters have been investigated previously for ABS [55] [57], albeit in a limited manner. However, whilst the consequences of adjusting these parameters have been investigated, they have not been researched with the goal of defining print parameters based on a desirable material property. Whilst this change in emphasis is subtle, it does shed some light on a certain parameters that would be unwise to actively control when others are available - specifically it implies that it is not just the ability to control a property which should be considered, but also its sensitivity. Further several parameters are known to have a substantial effect on print quality, rather

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extrusion infill width/ infill percentage</td>
<td>The spacing between neighbouring roads of infill - directly controlling the effective porosity. Some software calculates this based on a desired infill percentage and Extrusion size</td>
</tr>
<tr>
<td>Extrusion size (Road/Line width)</td>
<td>The theoretical width of each line of infill.</td>
</tr>
<tr>
<td>Layer height</td>
<td>The height of each layer, directly effects the cross-section of the infill line, and therefore contact area between layers. Directly impacts resolution and print time.</td>
</tr>
<tr>
<td>Infill overlap</td>
<td>The effective overlap between each infill road and the perimeter of the object</td>
</tr>
<tr>
<td>Number of shells/perimeters</td>
<td>The number of perimeters that are to be built before creating the infill. Effectively controls the thickness of the shell that surrounds the object. Often used to improve appearance in order to prevent a seam where the extruder starts and stops.</td>
</tr>
<tr>
<td>Layers of solid fill</td>
<td>Whilst the interior of a part is porous to save print time, typically exposed layers are solid both to improve appearance and mechanical properties. This parameters defines the number of exposed solid before that start of porous fill.</td>
</tr>
<tr>
<td>Extrusion temperature</td>
<td>Extruder operating temperature</td>
</tr>
<tr>
<td>Infill angle</td>
<td>The angle of the infill relative to some origin, typically this alternates every layer such that the direction of one layer is perpendicular to the previous/next layer in order to improve mechanical properties</td>
</tr>
</tbody>
</table>

4. Effect of Mesoscale Structure and Print Parameters on Bulk Mechanical Properties

Table 4.1.: Key FFF Print Parameters
than just speed/strength. Therefore when other parameters are likely to be available to achieve the same desired properties, actively controlling parameters which effect quality would be unwise.

Based on the above considerations, two of the highlighted key parameters may be discounted. Specifically infill overlap - the amount a line of infill overlaps the perimeter - is known to effect surface finish/quality at high overlaps. Further the amount of variation in overlap available is very small, in the range of 0.2mm. Therefore with the mechanics available, accurately controlling this parameter is not achievable, as the true value would be subject to interactions with other parameters e.g. overshoot as a result of print speed. Further this kind of variation in overlap could occur through other natural variations such as filament tolerances causing a wider than intended extrusion size. However the sensitivity to this overlap value may be seen within the test-to-test variation within other sample sets in this study.

Secondly, extrusion temperature is already known to have an effect of welding between roads/layers, resulting in de-lamination if too cold, or excessive-ooze/poor-print-quality if too hot. However the optimal extrusion temperature is known to vary between material suppliers, or even between colours. Also the thermal stability of extruders is often poor, fluctuating up to 10°C in the author’s experience. Hence given all of these issues, it was deemed unwise to use extrusion temperature when alternatives are available.

One final parameter considered is the number of solid layers to print, to give good quality exterior surfaces, before starting the porous internal structure. These were anticipated to have a substantial effect on the mechanical properties. However their effect will be dependent on the overall geometry of the part. For example a part that consists of only a few layers will be dominated by the solid fill, where as a very tall part will have minimal solid fill. Therefore for the purpose of these tests no solid layers were to be produced, and the fill will be uniform throughout the part. However 100% dense samples will be produced and therefore representative data for just the solid layers will be obtained during testing. This variation may then be accounted for during the design process in real world use.

4.2. Material Considerations and Scope

The work undertaken in this chapter is specifically on the material properties achievable for polylactic acid (PLA); however in a broader context the fundamental techniques are available for any 3D printed material. However, different materials fail in
substantially different ways. e.g. fracture failure modes may be brittle or ductile and so on; and some materials weld to themselves better than others. PLA for instance is known to weld substantially better than ABS, and this is one of the original reasons for using it as a build material. These fundamental differences in material properties may have a substantial effect in the trends observed. Therefore were appropriate comparisons are drawn to other studies using ABS.

4.3. Experimental Methods

PLA printed samples used in this investigation were fabricated used a standard RepRap Mendel FFF 3D printer in combination with the “Slic3r” software. The software first takes an STL file, slices this into a series of layers before computing the required infill patterns and to save the results as G-Code NC control files in order to control the RepRap machine. The printing parameters used are shown in Table 4.2 these represent typical build parameters, these were used for every data set with just one variable/parameter from Table 4.2 adjusted in addition to infill percentage.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extrusion Temperature</td>
<td>200 °C</td>
</tr>
<tr>
<td>Infill Percentage</td>
<td>10-100%</td>
</tr>
<tr>
<td>Extrusion size</td>
<td>0.5mm</td>
</tr>
<tr>
<td>Feed rate</td>
<td>30mm/s</td>
</tr>
<tr>
<td>Number of Shells</td>
<td>1</td>
</tr>
<tr>
<td>Layer height</td>
<td>0.25mm</td>
</tr>
<tr>
<td>Infill Angle</td>
<td>45°</td>
</tr>
</tbody>
</table>

All samples were built in accordance with the EN ISO527-2:1996 standard. Faberdashery or Makerbot Natural/transparent PLA 4043D filament of diameter 1.75mm was used, depending on the experiment in question, however all results within a given dataset are from the same supplier. The porosity of the sample was calculated from the theoretical material density (1.24g/cc) and the geometric bulk density measured in accordance with ISO 18754:2003. Any variation in the sample geometry due to manufacturing tolerances and thermal contraction were compensated by using by using actual cross-sectional areas and volumes measured. The tensile mechanical properties of the samples were measured using an Instron 3369. Three samples for each configuration were tested at a test speed of 2mm/min using a 1Kn load cell and a Instron
Figure 4.2: EN ISO 527-2:1996 Test Sample
2630 extensometer (50mm gauge length) to a load equivalent to 1% UTS. This experimental setup is shown in Figure 4.3. Finally the samples were fractured at a test speed of 5mm/min using a 5kN load cell. Test data was collected using Instron Bluehill Materials Software.

![Test setup for Young’s modulus measurement](image)

**Figure 4.3.: Test setup for Young’s modulus measurement**

In order to establish reference mechanical properties values for 4043D PLA, cast tensile test samples were prepared by a process based on EN ISO 527-2:1996. First a CNC mould was manufactured to the same dimensions as those to be produced via the FFF technique. A vacuum oven, preheated to 170°C, was used to cast an excess of Natureworks Ingeo 4043D PLA pellets for three hours to ensure degradation of the polymer was kept to a minimum and to reduce the presence of voids within the material. Finally the excess material was removed and stress concentrations reduced by polishing the sample. As with the samples produced by FFF, variations in geometry due to the manufacturing process and other thermal effects are normalised via the measurement of cross-sectional area when calculating stress.
During preliminary test it was found that samples could occasionally fail prematurely as has been reported in prior studies with ABS; with the fracture surface occurring inside the shoulder of the sample outside of the gauge length as shown in Figure 4.4 leading to an invalid result. Two potential reasons for this problem were hypothesised. Firstly it was suspected that this may be due to an artificially high stress concentration where the infill meets the perimeter. It can been seen that all cracks propagated from the radiused transition between the gauge length and the shoulder as seen in Figure 4.4. The exact angle between fill and the perimeter would be dependent on both the infill percentage and also the fill angle itself. This could account for the preliminary variation seen between test samples. Also it was hypothesised that the Instron grips were placing undesirable stress concentrations on the porous structure, also leading to premature failure. In order to combat this, the shoulder samples were covered in duct tape - a standard technique in materials testing - to more evenly distribute the stress. Subsequent to this modification to the experimental setup the number of premature fractures reduced substantially.

One other minor subtlety was noted during early testing. For stiffness testing an extensometer was clipped to the test piece using either a spring or an elastic band. Regardless of the clamping force applied by the springs, some slippage occurred during measurement leading to discontinuous inaccurate results. It was proposed that this was simply due to the low friction of PLA, and the even print surface achieved. Therefore a small amount of tape was applied to the gauge length where the extensometer attached to improve grip. Subsequent to this no problems were noted with the experimental setup. Examples of the final test samples, complete with the modifications described, are shown in Figure 4.5.
4. Effect of Mesoscale Structure and Print Parameters on Bulk Mechanical Properties

4.4. Results and Analysis

Normalisation

One important consideration is the effect of the printed external shell on the mechanical properties of the printed component and its effect on the apparent porosity of the sample in question. Consider an infinitely large sample with a 20% infill percentage, the effect of a printed wall at the edges would have a negligible effect on porosity and therefore theoretically such a sample would have a 20% bulk porosity also. However in more typical scenarios the exterior wall represents a significant fraction of the overall cross-section and therefore would artificially increase bulk porosity at low infill percentages.

In order to obtain a fair comparison between samples, and to remove other variations such as filament tolerance, all presented results use bulk porosity instead of infill percentage. This also has the added benefit of taking into account the exact quantity of material used and therefore gives a measure of the most efficient way to obtain given properties in terms of build time/volume. The porosity of the samples were calculated using Equation 4.1.

Whilst the mass of the sample was measured analytically, and the PLA density was provided by the manufacturer, Natureworks, the variation in bulk volume of each sample needed to be taken into account. Given the complex shape, measuring the part volume exactly for every sample would be difficult. Hence a 100% dense sample was
modelled in CAD and the volume was found to be $11750\text{mm}^3$, the bulk dimensions of the actual test samples were then measured, and this volume scaled accordingly to accommodate the small differences as accurately as possible.

\[
\text{Porosity} = (1 - \frac{\text{Mass}}{\text{Bulk Volume} \times \text{Density}})
\]

As is standard engineering practice, all load and extension data was normalised into stress and strain using equations 4.2 and 4.3. This enables the data accumulated in this study to be applied to other geometries.

\[
\text{Stress } \sigma = \frac{\text{Load}}{\text{Cross Sectional Area}}
\]

\[
\text{Strain } \epsilon = \frac{\text{Extension}}{\text{Gauge Length}}
\]

Table 4.3 shows the results acquired from the mechanical testing of the cast PLA pellets in order to establish base line results. The stiffness values correspond well compared to the values reported in other studies, although the ultimate tensile strength is marginally higher than reported by both the manufacturer and compared to other reputable sources [68] [69].

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young's Modulus, $E$</td>
<td>$3.4\pm0.12$</td>
<td>GPa</td>
</tr>
<tr>
<td>Strength at 1% Yield, $\sigma_{1%}$</td>
<td>$19.4\pm0.7$</td>
<td>MPa</td>
</tr>
<tr>
<td>Ultimate Tensile Strength, $\sigma_{UT}$</td>
<td>$63.8\pm3.8$</td>
<td>MPa</td>
</tr>
<tr>
<td>Elongation at failure, $\epsilon_f$</td>
<td>$4.06\pm0.41$</td>
<td>%</td>
</tr>
</tbody>
</table>

Typical fracture surfaces for a range of infill percentages are shown in Figure 4.6. As can been seen, the direction of the fracture surface lies perpendicular to the direction of stress. This is a fundamental characteristic of the brittle fracture failure mode. Further weight is lent to this conclusion by examining a typical stress-strain graph as shown in Figure 4.7. It may be seen that across the vast majority of test samples the amount of plastic deformation once the ultimate tensile strength has been reached is minimal, indicating brittle fracture.
Figure 4.6.: Fracture surfaces of PLA samples with 6, 54 and 72% porosity (left to right)
4. Effect of Mesoscale Structure and Print Parameters on Bulk Mechanical Properties

Figure 4.7.: Typical stress-strain curve. Result is for a 100% 45º infill, 0.25mm layer and 0.5mm infill width sample

4.4.1. Effect of Infill percentage

Figure 4.8 depicts the effect of varying the theoretical infill percentage on the bulk porosity for every sample within this study. Unsurprisingly it may be seen that the relationship is linear, with bulk porosity approaching 0% as the infill percentage approaches 100%. However, it can also be seen that there is a reasonably large variation in porosity of approximately 10% for a given infill percentage. It is hypothesised that this variation is due to a number of causes. Firstly there is known to be a substantial variation in the input filament diameter: the manufacturers typically quote a nominal diameter of 1.75mm but a tolerance of +/-0.1mm. This alone would theoretically result in a variation of +/- 11% from the nominal. However in practice the measured diameter was found to be 1.72-1.77mm.

In addition, further variation occurs due to subtle variations in infill pattern due to a combination of infill parameters, part geometry and Slic3r’s algorithms. In an ideal scenario, individual lines of infill are connected at the perimeters as highlighted in Figure 4.9. Using this strategy minimises the amount of retractions/extruder start/stops
4. Effect of Mesoscale Structure and Print Parameters on Bulk Mechanical Properties

and therefore reduces print time. However for some part geometries breaks in the infill occur resulting in single lines of infill. This would result in a reduction in porosity over the part.

![Figure 4.8.: Effect of infill percentage on porosity](image)

![Figure 4.9.: Infill pattern highlighting optional roads between infill lines](image)
It may also be seen that as the number of perimeters is increased, bulk porosity decreases. This is due to the thickening of the solid shell that surrounds the part, even though the internal porosity remains the same. Owing to the method used porosity is averaged over the entirety of the part.

Given these factors, further weight is lent to the author’s prior statements on the importance of normalisation in this study. Therefore all results from this point onwards will be recorded against measured porosity instead of the infill percentage input parameter. Alternative plots against infill percentage may be found on the DVD accompanying this thesis. However the equations for the trend lines to convert between infill percentage and porosity are presented below. In all cases the coefficient of determination was of the order of 98-99% indicating a very strong correlation. Therefore it may be concluded that these results are adequate to convert the relationships presented in the rest of this chapter.

\[
\text{Host bulk porosity} = -0.8153x + 0.8526 \\
\text{Slic3r 1 perimeter porosity} = -0.903x + 0.8846 \\
\text{Slic3r 2 perimeters porosity} = -0.8255x + 0.8066 \\
\text{Slic3r 3 perimeters porosity} = -0.7555x + 0.7386
\]

where \(x\) is the theoretical infill percentage
4. Effect of Mesoscale Structure and Print Parameters on Bulk Mechanical Properties

Figure 4.10.: Baseline results showing the effect of porosity on ultimate tensile strength - Remove host incorrect data from regression.

Figure 4.11 shows the effect of varying infill percentage alone for both Slic3r, using the settings shown in Table 3.14, and also baseline data for RepRap host slicing software. Ultimate tensile strength appears to increase exponentially as the bulk porosity decreases, as is well established in the literature for porous materials. Further, between slicers, results are near identical at high porosities; however UTS appears to increase more readily with decreasing porosity for Host, reaching approximately 52MPa at 11% porosity. Slic3r achieves a similar peak UTS at approximately 2% porosity. These peak UTS values are significantly less than 63.8MPa achieved through casting. The error between the estimated zero porosity data and the cast results may be attributed to the anisotropy inherent in the infill direction’s being 45° to the applied load, and to stress concentrations where the infill patterns meet the exterior perimeter. Further, despite the author’s best efforts, a 0% porosity sample was not able to be printed which would reduce the peak UTS achieved further still. In total almost an order of magnitude variation was achieved in this sample set, ranging from 57 MPa down to 6 MPa.

It is theorised that the reason for this discrepancy between slicers is due to the difference in part quality achieved with each. Given that the data presented here is just baseline data before further variations in other parameters in addition to infill percentage later, equations representing the lines of best fit may be found with later results.
Slic3r uses a novel method for calibration relative to RepRap host. Within the RepRap firmware in the machine itself, every axis including the extruder simply uses a fixed constant to interpret how many times the stepper motor should be stepped per millimetre of movement on the axis. RepRap host is set such that 1mm move on the extruder axis should produce a 1mm long line of extrusion. This enables code to be easily hand written e.g. A 1mm move in the X axis would result in a corresponding 1mm in the extruder axis. However this makes calibration iterative, dependent on a lot of factors including nozzle size, filament diameter/variation etc. Slic3r on the other hand treats the extruder axis as filament input; this is comparatively trivial to calibrate and hence part quality is typically higher. It is suspected that due to the poorer surface quality of host prints (indeed the least porous were 0.5mm taller indicating overfill) part measurements were inaccurate leading to poor porosity calculations.

Figure 4.11.: Baseline results showing the effect of porosity on Young’s modulus

Figure 4.11 shows a similar set of results for Young’s modulus. Again a similar effect is seen, with regression analysis indicating an exponential fit with a very high coefficient of determination value of 0.96 from both sets of software. Again with host software, the Young’s modulus increases faster than Slic3r with the bulk porosity, again due the effect previously outlined. In total approximately an order of magnitude variation was achieved between approximately 3.3GPA and 0.35-0.52 GPA depending on the soft-

\footnote{This method was actually first implemented by another, now legacy piece of software called “Skeinforge”}

1
ware in question. Relative to the UTS test results, the data is less well correlated with
more variation, although the trend is still clear. This is a standard conclusion in ma-
terials testing: due to the increased complexity of the testing procedure for stiffness
testing there is simply more room for error. Typically stiffness measurements are aver-
aged over a large number of samples. Given the scope and sheer number of parameters
in this study, fewer samples than typical were used, however some averaging is still
apparent due to the regression analysis studying the effect of porosity on every data
set.

In all data presented in this study, strong correlations between bulk porosity and UTS/Young’s
modulus were achieved. In most cases excellent fits could be applied assuming either
an exponential or logarithmic fit; and logarithmic fits have been used in other studies.
However for a logarithmic fit such a relationship would imply infinite strength/stiffness
at zero porosity which is clearly invalid. It was elected that an exponential fit were
more appropriate.

4.4.2. Effect of Perimeters

Figure 4.12.: Effect of the number of perimeters and porosity on ultimate tensile
strength
4. Effect of Mesoscale Structure and Print Parameters on Bulk Mechanical Properties

Figure 4.12 demonstrates the effect of increasing the number of perimeters on the ultimate tensile strength. It may be seen that at high porosities, increasing the number of perimeters substantially increases the ultimate tensile strength; however the benefit decreases with decreasing porosity. At the extreme case of a high porosity sample, three perimeters results in gain of approximately 6MPa relative to one perimeter. This trend is logical, based on the trends already demonstrated that strength increases exponentially with decreasing porosity, increasing by almost a factor of ten over the bulk porosities investigated. However at high bulk porosities the trend is relatively flat. Therefore making the already porous interior fill slightly more porous has a small effect on strength, however redistributing that material to the edges increases the amount of 0% porosity material - which is significantly stronger. The results of regression analysis for this data set are presented below:

\[
\sigma_{1P} = 52.089e^{-2.923\phi} \\
R^2 = 0.9908 \\
\sigma_{2P} = 52.835e^{-2.316\phi} \\
R^2 = 0.9761 \\
\sigma_{3P} = 56.298e^{-2.233\phi} \\
R^2 = 0.9804
\]

Where \( \phi \) is the porosity percentage and \( P \) is the number of perimeters

The increase in strength with the number of perimeters at high bulk porosities is interesting. Bulk porosity is an effective measure of the total amount of material within the sample. Therefore it may be concluded that increasing the number of perimeters allows for faster prints, assuming material deposition rate is roughly constant, for an equivalent part strength or higher strengths with the same amount of material/print time. It should also be noted that less variation in UTS is achieved over the sample set as the number of perimeters is increased. Therefore given the underlying goal of this thesis, the widest possible properties should be achievable, and hence one perimeter achieves the weakest structural properties and is still a useful technique.

Clearly based on the presented correlations, and the nature of exponential fits, the underlying relationship is as follows:
4. Effect of Mesoscale Structure and Print Parameters on Bulk Mechanical Properties

\[ \sigma = \sigma_{UTS}e^{K\phi} \]

Where \( \phi \) is the porosity percentage, \( \sigma_{UTS} \) is the ultimate tensile strength at 0% porosity, and \( K \) is a constant dependant on the print parameters.

Figure 4.13.: Effect of number of perimeters and porosity on Young’s modulus

Figure 4.13 shows that varying the number of perimeters has a similar effect on Young’s modulus. In total a range of approximately 3.3-0.5GPa was achievable, with more perimeters resulting in a stiffer structure at high porosities with a negligible effect at low porosities, and a benefit of approximately 0.5GPa at high porosities between the most/least perimeters. Similar conclusions may be drawn on optimising print time/material as with the stress results. Results of the regression analysis are presented below:

\[ E_{1P} = 3.2296e^{-2.767\phi} \]
\[ R^2 = 0.9629 \]
\[ E_{2P} = 3.056e^{-2.068\phi} \]
4. Effect of Mesoscale Structure and Print Parameters on Bulk Mechanical Properties

\[ R^2 = 0.9107 \]
\[ E_{3P} = 3.15e^{-1.863\phi} \]
\[ R^2 = 0.9931 \]

Where \( \phi \) is the porosity percentage, and \( P \) is the number of perimeters.

Again based on these correlations and the fundamental nature of an exponential curve, it is clear than in the general case the relationship takes the form:

\[ E = E_0 e^{k\phi} \]

Where \( \phi \) is the porosity percentage, \( E_0 \) is Young’s modulus for a 0% porosity sample, and \( K \) is a constant dependent on the print parameters.

4.4.3. Effect of Extrusion Size

Figures 4.14 and 4.15 show the effect of varying the extrusion size from 0.5-0.7mm. As the infill percentage is the controlled parameter, the spacing between infill roads is automatically adjusted in order to compensate for the increased extrusion width and to keep the infill percentage constant in accordance with Equation 4.8.

\[ \text{Infill Spacing} = \frac{\text{Extrusion Size}}{\text{Infill Percentage}} \quad (4.8) \]
4. Effect of Mesoscale Structure and Print Parameters on Bulk Mechanical Properties

Figure 4.14.: Effect of extrusion size and porosity on ultimate tensile strength

Figure 4.15.: Effect of extrusion size and porosity on Young’s modulus
4. Effect of Mesoscale Structure and Print Parameters on Bulk Mechanical Properties

It can be seen that extrusion size has an almost negligible effect on either ultimate tensile strength or Young’s modulus. The variation seen is within what would be expected for test-to-test variation, approximately 2MPa and 0.1GPa in each case.

Regression analysis indicates a progressive, but small, increase in both UTS and Young’s modulus with increasing extrusion size. As the increase is so slight test-to-test variation cannot be ruled out. However an increase in the mechanical properties with extrusion size would not be unsurprising, particularly for high porosity samples.

It is a fundamental characteristic of the infill pattern used, that the plastic must form a bridge across the infill of the previously layer. As the infill percentage decreases, so does this bridging distance. However there is a limit to distance that can be bridged without severely affecting the quality of the extrusion, typically the infill will either break up or be of an inconsistent cross-section. SEM images of two porosity samples are shown in Figure 4.16 which indicates this effect. In the author’s experience, increasing the infill width relative to standard settings within reason improves bridging as the width. Therefore having a more consistent cross-section would reduce stress concentrations and logically improve the mechanical properties.

Further a change in the mechanical properties would be unsurprising, given that changing the line width would change the aspect ratio of the extrusion, and in doing so change the contact patch between layers. But the sample size in this set is simply too small to give a reliable conclusion given the minimal variation. In addition, an increase in line width would increase the perimeter width also and allows parallels to be drawn to the results previously presented on the effect of the number of perimeters used - and further reinforces this observation. However within the context of the aims of this chapter, it can be said the variation is negligible compared to test-to-test variation, hence this is not a controllable parameter and is not suitable for tuning print properties.

Figure 4.16.: Fracture surfaces for 54 and 72% porosity samples, 0.5mm extrusion size (left to right)
4. Effect of Mesoscale Structure and Print Parameters on Bulk Mechanical Properties

Results of the regression analysis for all subsequent experiments are presented in Table 4.4.

4.4.4. Effect of Layer Height

Figures 4.17 and 4.18 demonstrate the effect of varying layer height on UTS and Young’s modulus respectively. As with the results for extrusion size, whilst some effect is seen when looking at trend lines from regression analysis, a small variation is apparent. A minimal increase of approximately 5MPa/0.5Gpa in both UTS and Young’s modulus is apparent as the layer height decreases. Besides test-to-test variation, the only hypothesis for this that the author can provide is a change in aspect ratio similar to the effect seen with line width. However, what can be said is that any variation is only apparent with a large sample size, and that any the total variation is within the normal range of what would be expected due to test-to-test variation. Further, layer height has a substantial effect on part quality and therefore sacrificing this in order to allow for the control of bulk properties would be unwise when other parameters are available.

Figure 4.17.: Effect of layer height and porosity on ultimate tensile strength
4. Effect of Mesoscale Structure and Print Parameters on Bulk Mechanical Properties

4.4.5. Effect of Infill Angle

Figure 4.18.: Effect of layer height and porosity on Young’s modulus

Figure 4.19.: Effect of infill angle and porosity on ultimate tensile strength
4. Effect of Mesoscale Structure and Print Parameters on Bulk Mechanical Properties

As with all other experiments conducted in this chapter, the infill pattern alternated every layer such that the infill of one layer is perpendicular to the previous layer. Nearly every manufacturer producing FFF AM systems uses this technique in order to reduce anisotropy. This is due to isotropic mechanical properties typically being more desirable. Within the context of attempting to engineer the mesostructure to obtain exact mechanical properties this allows process complexity to be reduced, which is to say that infill angle does not need to be considered at the component design stage.

For a basic part, such as the test pieces used in these experiments, the external geometry of the component is largely consistent, and when referring to infill angle the author means the angle relative to the gauge length. For a part with a complex external shape, this relative angle between the infill and the perimeter would be constantly changing. Hence, should anisotropic properties by obtained, the material properties achieved becomes a function of the external shape of the part. Whilst this issue is not insurmountable by altering the infill angle within a layer, and indeed the flexibility of Additive Manufacturing easily lends itself to allowing this technique to establish this effect, the process becomes more complex. But potentially this opens the door to using the technique described to have varying properties in different directions.

Figures 4.19 and 4.20 show the effect of infill angle on ultimate tensile strength and Young’s modulus. As can be seen, especially for UTS, infill angle has a minimal effect, indicating the properties obtained are isotropic. For UTS, a variation of approximately 1-2MPa was seen across the entire range of fill angles. For Young’s modulus, variation was grater at approximately 0.5GPa, however this is within the range expected compared to other results presented. One curious result however was that it is clear that 0° results are approximately 10% stiffer across the range of porosities, but with no clear trend across the other infill angles. It is anticipated that this is a result of reduced stress concentrations where the perimeter meets the infill as the infill is always perpendicular the perimeter. However, should this be the case, this is only achievable of samples of simple geometry with current infill algorithms. Curiously this same effect is not seen for UTS, which, should the underlying reason be due to stress concentrations, would be expected to give a similar effect. Given the consistency of the UTS results, and the robustness of UTS results relative to stiffness, this result is inconclusive.

The result that 3D printed PLA is isotropic is curious in comparison to work by Ang et al. [57], Ahn et al [53] and Bellini and Güçeri [55], where in all cases Stratasys ABS P400 was found to suffer a 5-7% reduction in both strength and stiffness depending on the infill orientation. It is hypothesised that this is due to a fundamental difference between ABS and PLA. ABS is known to not weld to itself particularly readily, hence
layer de-lamination is often found in large ABS prints. PLA on the other hand is known to weld to itself with ease. One critical area within a print is the weld between the perimeter and the infill due to the stress concentrations present with the sudden change in geometry. Given that infill angle would change this contact patch between the infill and the perimeter, it is likely that the weld is also affected. Given that ABS is already known to be sensitive in this area, it is a possible cause for the anisotropy seen in the literature.

![Figure 4.20: Effect of infill angle and porosity on Young’s modulus](image)

**4.5. Universality of the results**

When discussing the validity of the results achieved, two specific questions should be considered:

- How applicable are the results over a wide range of geometries?
- Over what range of print parameters and FFF setups are the results applicable?
4. Effect of Mesoscale Structure and Print Parameters on Bulk Mechanical Properties

To address the first question, one must consider basic materials testing theory in combination with the results obtained. Normalisation is a standard technique used within materials testing in order to allow test results to be applied to a wide range of geometries, and is the reason for using stress and strain over load and extension. However materials are typically uniform and therefore this technique is appropriate for any geometry.

However the conclusions of this study are that the exterior solid shell dominates the mechanical properties of a porous structure. Given that the results measured are only bulk values, these bulk results will be dominated by this exterior shell, and therefore the results obtained are only accurate to structures with similar geometry i.e. 10mm gauge width. However due to the flexibility of Additive Manufacturing processes, a potential solution to this problem lies within the tool-path-planning technique. It should be possible to include an internal diaphragm within the infill of the component, similar to an exterior wall. In doing so the results obtained should be more applicable to any geometry. Therefore further work should be undertaken, both to investigate how applicable the results of this study are across other geometries, and to investigate potential techniques such as the one just mentioned to reduce the effect of part geometry.

To consider how applicable the results obtained are to other FFF setups, one needs to consider the approach taken in this study. Fundamentally at least two possible techniques exist in setting the parameters to be investigated:

1. Design of experiments - Where by every parameter is adjusted simultaneously, and

2. OFAT - One factor at a time.

Using the design of experiments approach yields a benefit in that as every parameter is adjusted simultaneously, the effect of parameter interactions may also be measured at the expense of a more complicated analysis. But it was elected for test simplicity to use the OFAT approach. However the final results show that infill angle, layer height, and extrusion size have a negligible effect on the mechanical properties, and any effect lies within test-to-test variation; with only bulk porosity and number of perimeters having any significant effect. Therefore it can be concluded that a full data set exists for each of these factors, and their relevant interactions. As such results are applicable to any similar test setup.
4. Effect of Mesoscale Structure and Print Parameters on Bulk Mechanical Properties

4.6. Discussion

To summarise, throughout this study ultimate tensile strengths of 6.3 - 60.3MPa have been achieved with corresponding Young’s modulus values of 0.42 - 4.06GPa. However these stiffest values are larger than those either measured independently through casting or those provided by the manufacturer. Therefore these are invalid samples, and in reality a stiffness range of 0.42-3.32Gpa is achievable using the technique. Most interestingly, the maximum strength values achieved are almost identical to the cast values, or the manufacturer’s data sheet, implying that no loss of part strength occurs during the printing process. This is a key conclusion, and differs from the ABS studies conducted in the literature where approximately a 30% loss in part strength occurs. The reason for this discrepancy is hypothesised to be due to its ability to readily weld to itself, the higher extrusion temperature relative to its glass point, and also the fact that it has very low viscosity relative to ABS when molten allowing it to take the shape of neighbouring structures/walls readily.

To restate the intention of this chapter, it is always been known, and often demonstrated for ABS, that bulk material properties may be varied with FFF by varying print parameters. However to date only ABS has been investigated using FFF, and using a limited set of print parameters relative to those available with open source tools. Further the work conducted to date has been undertaken within the context of investigating the material properties achieved for a given set of parameters. The work undertaken here, whilst in some ways more thorough due to the increased number of parameters and a different material, has a different scope with the goal to define the material properties required and in turn define the ideal print parameters. This subtle difference presents a few implications when analysing results.

Firstly the robustness of the process should be considered at all times. Specifically, if the part properties are particularly sensitive to a given parameter, the effect of variations within the printing process should be considered such that an estimate can be made of exactly how reliably that property may be achieved print-to-print, and perhaps more critically between machines. To some extent these variations have been taken into account of in this study, for example variations in filament diameter within a given batch have been considered through repeats; some variation may still occur between batches as the nominal diameter inevitably varies.

Secondly the efficiency of the process should be considered, such that the minimum amount of material is required to achieve a given property both to reduce print time and material costs. As previously mentioned this is one reason why all results have
4. Effect of Mesoscale Structure and Print Parameters on Bulk Mechanical Properties

Table 4.4 shows an overview of the properties achieved for all parameters with the exception of infill angle as this was shown to have no effect. To summarise the results presented, it has been found that only the number of perimeters and the bulk porosity have any meaningful effect on the mechanical properties of a component. Whilst other parameters investigated (Layer Height, Infill Width) were shown to have some effect, that effect was only highlighted through a large number of tests, and any change in the properties seen was well within test-to-test variation. Therefore such parameters are not suitable for use in actively controlling component properties.

4.6.1. Implementation and Design guidelines

To restate the results of this study so far, it has been shown that the bulk of the parameters investigated have a minimal effect, and where they have been shown to have an effect, this may only been seen with repeated tests and the magnitude lies within test to test variation anyway. The two significant parameters are number of external perimeters and infill percentage to affect the bulk porosity. Therefore to maximise part strength for a given print time, and produce the most efficient part, the number of perimeters should be maximised (i.e 3) and the infill percentage selected accordingly in order to give the desired material properties. Design guidelines on how to achieve given UTS/Stiffness by adjusting porosity are presented in Tables 4.5 & 4.6:

<table>
<thead>
<tr>
<th>UTS Required (MPa)</th>
<th>No Of Perimeters</th>
<th>Porosity Required</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.9 - 60</td>
<td>3</td>
<td>$\frac{-1}{2.923} \ln \frac{\sigma}{52.089}$</td>
</tr>
<tr>
<td>12.3 - 13.9</td>
<td>2</td>
<td>$\frac{-1}{2.923} \ln \frac{\sigma}{52.089}$</td>
</tr>
<tr>
<td>6.3 - 12.3</td>
<td>1</td>
<td>$\frac{-1}{2.923} \ln \frac{\sigma}{52.089}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>E Required (GPa)</th>
<th>No Of Perimeters</th>
<th>Porosity Required</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1 - 3.3</td>
<td>3</td>
<td>$\frac{-1}{1.803} \ln \frac{E}{3.15}$</td>
</tr>
<tr>
<td>0.92 - 1.1</td>
<td>2</td>
<td>$\frac{-1}{3.085} \ln \frac{E}{3.056}$</td>
</tr>
<tr>
<td>0.56 - 0.92</td>
<td>1</td>
<td>$\frac{-1}{2.707} \ln \frac{E}{3.2286}$</td>
</tr>
</tbody>
</table>

It has been previously stated that the material deposition rate in the FFF process is independent of the component geometry. Given that porosity is therefore directly related
Table 4.4.: Summary of properties achieved

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Variable</th>
<th>UTS Range(MPa)</th>
<th>E Range(GPa)</th>
<th>$\sigma$</th>
<th>$R^2$</th>
<th>$E$</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perimeters</td>
<td>1</td>
<td>6.3-56.1</td>
<td>0.56-3.29</td>
<td>52.089e^{-2.923}</td>
<td>0.9908</td>
<td>3.2296e^{-2.767}</td>
<td>0.9629</td>
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<td>52.089e^{-2.828}</td>
<td>0.9761</td>
<td>3.056e^{-2.068}</td>
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<td>0.9908</td>
<td>3.2296e^{-2.767}</td>
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<td>3.3989e^{-3.212}</td>
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to the printed material volume and given the non-linear relationship between strength, stiffness and porosity it is clear that an optimum efficiency exists; whereby a maximum strength is achieved for a given print time or material quantity used. Whilst it is not surprising that both strength and stiffness increase with decreasing porosity, at higher porosities it can be seen that change in porosity has such a small effect on strength that is almost negligible.

For RepRap devices interior infill percentage is typically 20-25%. Although this may be varied to obtain the required strength for the part, typically operators adjust this parameter very little, perhaps by 10-20% at most. From the data obtained in this investigation this implies that infill porosity is in the range of approximately 60% with a corresponding strength 8.5MPa and stiffness of 0.55GPa for the standard print settings used. Further a decrease in porosity by 10% results in print time increasing 10%, despite the mechanical properties only changing by approximately 3.5MPa and 0.2GPa respectively. However due to the non-linear relationships demonstrated a similar decrease in porosity between 0/10% results in an improvement of approximately 12MPa and 0.8GPa. Therefore a more efficient strategy would be to make use of the non-linear relationship demonstrated by increasing the number of solid exterior layers when additional strength is required but maintaining the sparse interior. Further it is also visible from the results presented that improved mechanical properties are achieved for a given amount of material/porosity as the number of exterior perimeters are increased; in the extreme case approximately 90% improvement is seen between the one and three perimeter samples at high porosities. Therefore, when actively choosing parameters, the number of perimeters should be maximised in order to increase process efficiency before using infill percentage/bulk porosity to obtain the exact value.

Despite these guidelines, significant progress still needs to be made to understand exactly how this process can be practically implemented. For example, traditional tools such as Finite Element Analysis need development in order to be able to design for components with tuneable material properties with fixed external geometry. Furthermore, whilst the AMF CAD file format discussed in Section 2.5.5 is in the process of being adopted and is capable of storing required strength data in CAD files, no major CAD system has implemented this facility at the time of writing. Never-the-less the technique outlined demonstrates the potential for components to have tuneable mechanical properties and in doing so allows for components to have the minimum possible strength whilst still performing the desired function. Designing components in such a manner ensures the components are built in the quickest time possible with the least amount of material; this in part combats two of the biggest disadvantages of AM - slow print time and high material costs.
4. Effect of Mesoscale Structure and Print Parameters on Bulk Mechanical Properties

4.7. Conclusions

The work presented in the chapter represents the first study investigating the mechanical properties of components manufactured using Fused Filament Fabrication in PLA. In total almost an order of magnitude variation was achieved in both Ultimate tensile strength and Young’s modulus. Comparing the results to those achieved in other studies for ABS, it is clear that PLA is more suited to tuning isotropic mechanical properties. Critically no loss of the peak mechanical properties was recorded compared to cast data. This is in comparison to more traditional FFF materials such as ABS, where up to a 30% loss in strength has been seen in the literature. The results achieved in this study PLA are more robust, with fewer parameters affecting the properties attained with the results shown to be more isotropic and less susceptible to changes of infill angle. Finally design guides have been presented detailing how this technique may be implemented in a practical manner.
5. Electrically conductive materials

Perhaps the most touted application for multi-material 3D printing is being able to manufacture three-dimensional circuitry. As described in Sections 2.5.1 and 2.5.3, previous attempts have been made to print 3D circuitry using Rapid Prototyping techniques. However each method demonstrated thus far has significant drawbacks. The earliest examples within the field of 3D printed electronics dates back to the work of Prinz et al., using Shape Deposition Modelling to embed pre-existing circuitry into printed structures [38]. To date research into directly printing the circuits themselves has focused on direct writing technologies, typically based around a silver-doped ink or polymer [39].

These technologies produce distinct electrical circuits; whereas an Additive Manufacturing system could incorporate electrical circuitry within a structural housing that could potentially fulfil some other function. In addition traditional direct-writing conductive materials, whilst offering excellent print quality, are often prohibitively expensive due to the required silver content. Further the most conductive inks often require annealing at temperatures in excess of 300°C post-printing in order to lower the trace resistance substantially. This annealing would inevitably damage the surrounding printing plastic material and thus is not compatible with low cost FFF 3D printing.

Despite these problems significant progress has been made in this area by Lopes et al, who successfully combined Stereolithography and the direct writing process, and have produced 3D structural electronics with the process including a 555 timer circuit [40]. Despite the success of the technique, the direct writing approach – relying on expensive silver loaded inks, and combining two fundamentally different complex processes ensures the method is costly. Hence a low cost alternative is desirable even if such a technique is not as flexible as that developed by Lopes et al.

Malone et al. demonstrate a method for depositing conductive pastes and resins using a bespoke syringe extruder similar to that developed in Chapter 3. However this paste-
5. Electrically conductive materials

Based method gives a resistivity that is in excess of two orders of magnitude greater than traditional conductors such as copper, and as such the technique is only suitable to circuits requiring extremely low power. Further, the use of non-metallic materials implies that traditional soldering techniques would no longer be effective, thus alternatives (such as conductive glues) would need to be used.

A further technique has previously been developed by the author that directly deposits low melting point eutectic alloys into plastic channels. However significant problems arose due to the high surface tension of the alloys used. As outlined in Chapter 2, significant efforts have been placed into allowing FFF techniques to function with metals and are mentioned even in the earliest Fused Deposition Modelling patents [70]. Whilst much of this work has focused around metal/plastic composite materials [46] [71], attempts to directly print metals single material metal structures has also been undertaken. Rice et al. proposed the use of semi-solid slurries and non-eutectic materials in order to maximise build quality [48]. Significant progress was made using a tin/lead non-eutectic solder. Temperature control was shown to be critical, with the slurry deposited needing to fall within the semi-solid regime in order for two layers to bond sufficiently. Nevertheless free-form single wall objects were successfully manufactured using the technique. A similar approach was taken by Finke and Feenstra who demonstrated that the rheology of materials in this semi-solid region responds significantly with changes in temperature hence accurate temperature control was again shown to be critical, in addition attempts were made to model extrusion forces of such a system. [47]

To summarise the work undertaken to date, some success has been obtained using non-eutectics and semi-solids to manufacture single wall structures, and in parallel some success has been achieved printing conductors however print quality has been poor. This chapter presents Direct Metal Fused Filament Fabrication (DMF³), a novel technique to create circuit boards with Additive Manufacturing. The process presented in this chapter details the development of a conductive material which is compatible with Polylactic acid thermoplastic build material whilst utilising the semi-solid techniques described above to allow low cost electronic circuitry.

Whilst the advantages/disadvantages of a multi-material component have already been discussed, it is worth noting that the benefits of the technology are even more profound within the field of electronics. If a true 3D circuit is possible a wide number of technical and physiological problems facing the electronics industry could be eased, examples of which are outlined below:

1. Ergonomics and Packaging - With the ever growing competition between elec-
5. **Electrically conductive materials**

electronics manufacturers, consumers are often looking for features outside of a product’s core functionality to distinguish it from its direct competitors. One example of this could be ergonomics. Traditional electronics are limited by a two dimensional process: typical circuit boards are square and flat. However the most ergonomic shapes are typically curved to match features of the human body. Therefore a compromise is often needed to incorporate ergonomic features because voids are inevitably required resulting in a less optimal design occupying a larger volume and therefore a less desirable end product. In addition to this increased volume, other trade-offs arise such as increased expense due to greater material requirement, higher carbon emissions associated with shipping due to increased packaging size and so on.

2. Component protection - Common problems with exposed circuitry are electrical shorting between neighbouring components due to undesired conductive material in contact with the board and mechanical damage due to the poor structural properties of PCB materials. A true 3D circuit would be capable of housing track and components within a protective matrix reducing these risks. However, whilst a lack of access provides benefits in terms of reliability, it equally prevents maintenance, repairs and tuning of adjustable components if the board is not designed correctly\(^1\).

3. Consumer prototyping - Perhaps the biggest benefit of traditional printing technologies is the ability to reproduce images which would require a technical ability that is beyond the end user’s aptitude, or would require a great deal of training. An automated AM system capable of producing 3D circuitry would be able to produce complex electrical systems, and providing the design is provided in a suitable form the end user would require almost no understanding of how the underlying system functions.

4. Compatibility - As outlined in Section 2.16, some functional electrical components have already been manufactured using 3D printing technologies including resistors, capacitors, and batteries amongst others. The efficiencies of such components have been poor and components often use expensive or exotic materials which are not readily available. Therefore in the interim any system capable of depositing both conductive tracks and an insulating material should in addition be compatible with a wide range of existing electrical components.

5. Recycling - Electronics manufacturers are coming under increasing pressure

\(^{1}\)In practice such components should be left exposed or protected by a separate cover.
from both consumers and legislators to substantially reduce the amount of waste associated with manufacturing electronic goods [72]. Whilst a 3D printing system located at the point of use for the required circuit would inevitably reduce emissions and costs associated with transport and packaging, end of life recycling would be more difficult and requires a new technique due to the components being potentially encased in plastic.

5. **Electrically conductive materials**

5.1. **Process Development**

The research work undertaken for this chapter may be split into two distinct sections: materials, and extrusion techniques. Whilst in practice these sections were not developed independently of each other, this chapter is laid out as such in order to improve readability.

5.1.1. **Material Considerations**

As shown in Section 2.5.3 previous attempts at using low melting point alloys in an FFF process have been partially successful, in some instances creating functional circuits albeit of extremely poor quality. This lack of control has previously been associated with the strong cohesive forces of the materials used i.e. surface tension, and therefore in this section it is aimed to analyse the fundamental origins before attempting to minimise the effect.

Fundamentally surface tension is the result of intermolecular forces with liquids and results in droplets attempting to minimise their surface area for a given volume when placed on flat surfaces. Practically contact angle through the droplet to this flat surface is used to calculate a systems surface energy. When a liquid droplet is placed upon a solid surface, two distinct equilibrium regimes are possible. In the event that a liquid is very strongly attracted to the surface, such as that between water and a strong hydrophilic material the contact angle be zero degrees and complete wetting will be achieved as shown in Figure 5.1c. In addition partial wetting is also possible as seen in Figure 5.1a, this occurs when weak attraction is present such as that between a hydrophobic flat surface and water and will result in poor wetting with a contact angle that in excess of 90°.
5. Electrically conductive materials

Figure 5.1.: A small liquid droplet in equilibrium on a flat horizontal surface. Both (a) and (b) indicate partial wetting, with (b) indicating greater wetting relative to (a) with (c) indicating complete wetting of the flat surface $\theta_e = 0^\circ$ [73].

Figure 5.2.: Measurement of contact angle. $\theta$ depicts contact angle, LV surface free energy between liquid and vapour, SV surface free energy between solid and vapour and LS interfacial free energy between liquid and solid [73].

Figure 5.2 depicts the measurement of the contact angle from the solid surface through the droplet to the boundary between the droplet and the surrounding vapour. The degree of wetting is dependent on the surface/interfacial free energy between the liquid/surrounding vapour LV, liquid and the solid sheet LS, and the solid and the surrounding vapour. In the case of FFF, an additional two parameters to be considered are introduced into the system. Given the consistent flow out of the nozzle, any molten
metal is likely to be simultaneously contacting both the insulating material onto which it is to be placed in addition to the nozzle. Therefore the interfacial energy between the extruder nozzle and the molten alloy, and the surface free energy between the extruder nozzle and the surrounding vapour needed to be considered. In order to maximise material control it is theorised that the attraction between the alloy and the nozzle should be minimised resulting in a large contact angle.

Due to the layer-by-layer process through which FFF functions, it is required that both the conductive and insulating materials operate at the same build height. Therefore this determines that the insulating material should in fact take the form of female channels. Given that RepRap already functioned with plastics which were electrically insulating (although not characterised) it was highly likely that these materials will offer better build quality compared to the alloys which are being developed in this chapter. Therefore by maximising the attraction between the alloy and the plastic material would encourage wetting and the alloy to take the form of the channel. Typically high energy surfaces are materials such as metals, glasses and ceramics and possess strong chemical bonding such as covalent or metallic bonding where as low energy surfaces are held together by physical forces such as hydrogen bonds or van de Waal forces. Given that our thermoplastic material would typically fall into this latter category it is important to consider alternative means of improving wetting:

- **Wetting agents** – A wetting agent is a type surfactant which lowers the surface energy of a liquid material to lower than that of the substrate allowing wetting of the surface to occur. These wetting agents are usually found in solder flux. However prior work highlighted that upon extrusion of flux containing solders the extrudate had the tendency to separate into non-conductive flux and conductive solder resulting in an electrical breakage.

- **Composite plastics** - Additives were already used within the thermoplastic feedstock used in Fused Filament Fabrication in order to vary the colour, improve extrusion properties or to alter the mechanical properties of the component amongst others. Research has already been undertaken in order to investigate using metal-filled polymer composites in order to increase the Young’s Modulus and other mechanical properties of the material [71]. This material would almost certainly have an increased surface energy and therefore was likely to improve wettability. One side effect of such an approach would be that the resistivity of the insulating layer would substantially decrease, however this could possibly be countered with a third layer of undoped plastic, with only the layer in contact with the metal being a composite. Whilst the exact resistivity of such a composite was difficult
with simple models becoming valid due to percolation theory. Percolation theory states that at some volume fraction known as the percolation threshold a connected network of conductive particles spans the sample resulting in a significant and sudden drop in the resistivity. In addition to the volume fraction the bulk resistivity has been shown to be highly dependent on particle size and shape which makes resistivity even more difficult to predict [74]. Never-the-less iron polymer composites have been produced with a negligible decrease in resistivity up to a volume fraction of almost 10% giving the potential for a substantial increase in bulk surface energy.

Given that both that the use of surfactants and composite plastics to lower surface energy are independent of the fundamental alloy, it was elected to first minimise the effects of surface tension for the alloy and using these methods later if required.

Several metallic materials exist which exhibit low surface tension namely indium and gallium. However such materials are prohibitively expensive with indium costing approximately $600/kg unprocessed in bulk [75], however retail prices are substantially more for processed high purity samples – currently £285 for just 50g; [76]. Whilst it was true that in a final working solution, the actual amount of alloy required is expected to be small given the resolution and conductivity that is expected to be achieved, and therefore the resulting cost is expected to be reasonable. The shear amount of testing and material required to reach that stage results in using significant amounts of indium/gallium and therefore was unfeasible.

In an ideal system, the flow properties of the alloy would match those of already-used thermoplastics. Typically FFF processes employ amorphous thermoplastics, which is to say that the plastic gradually transitions into its molten state with temperature, enabling the plastic’s viscosity to be controlled. Whilst amorphous alloys exist, and indeed their use within the FDM process is patented although no results have been published [77]. Some existing amorphous alloys are available in the approximate temperature ranges required e.g. $Mg_{80}$Ni$_{10}$Nd$_{10}$, $La_{66}$Al$_{14}$Cu$_{20}$ [78], but these rely on exotic expensive materials at which price point silver loaded direct writing techniques are already suitable.

Several considerations were made when selecting the appropriate alloy for the process:

1. The extrusion temperature of the molten alloy should be compatible with our thermoplastic substrate, in this case Natureworks 4043D polylactic acid, to allow multi-material printing. The specific heat capacity of most low-melting-point alloys relative to the polymer build material is approximately one order of
5. **Electrically conductive materials**

magnitude lower. Thus the extrusion temperature may be significantly above the thermoplastic’s glass point of 60°C [79] without thermal damage.

2. It would be desirable for metal tracks to be covered by thermoplastics (e.t. for electrical insulation), and thus the melting point should be sufficiently high for the plastic not to melt underlying metallic track during plastic extrusion (which has an extrusion temperature of 180-200°C).

3. Based on conclusions by Sells, surface tension should be minimised both through material selection and viscosity control. Therefore it would desirable to have precise control of the material viscosity.

Non-eutectic alloys are very common and it was proposed that amorphous-like properties can be achieved by carefully specifying a non-eutectic alloy. Much like amorphous materials, non-eutectic alloys do not have a sharp melting point; instead they transition through a paste-like state consisting of solid particles within a liquid suspension. Therefore, the underlying viscosity of the material could be controlled by adjusting the ratio of solid-to-liquid material through temperature regulation and alloy selection. Doing this would sufficiently improve quality sufficient to enable circuitry in the same manner as such techniques have allowed free form structures as shown by Rice *et al.* [48] and Finke and Feenstra [47]. This chapter demonstrates that by using this technique the effects of surface tension previously shown may be reduced resulting in a substantial improvement in print quality, enabling the manufacture of simple electrical circuitry.

Figure 5.3 shows a typical phase diagram illustrating the relation between material composition, temperature and material state for a binary alloy system. L stands for liquid phase, A and B are the constituent materials and $\alpha$ and $\beta$ are their respective solid phases. Consider a particular composition, C, on cooling, freezing begins at $T_2$ where the first solid material, $\beta$, beings to form. As temperature is decreased further the amount of B in the liquid is reduced as more solid is produced until finally the alloy completely solidifies at $T_1$. The amount of solid material at a given temperature and for a given composition may be calculated using the Lever Rule, Equation 5.1; where $a$ is the distance on the graph from a given composition C to the liquidous phase L, and $b$ is the distance from C to the solid phase $\beta$ for a given temperature. Through using this rule the solid-to-liquid ratio can be controlled through alloy composition and temperature control, enabling material properties suitable for printing.
5. Electrically conductive materials

![Binary phase diagram](image)

Figure 5.3.: A typical binary phase diagram

\[
\text{Solid}\% = \frac{b}{a + b} \quad (5.1)
\]

Given that viscosity is a substantially stronger force than surface tension, it was anticipated that the use of a non-eutectic would reduce these effects in accordance with the research already conducted by Rice et al. [48]. As the quantity of solid material in the non-eutectic would decrease with temperature, increasing its viscosity, it would also be desirable if this gradient was as shallow as possible such that the greatest possible amount of control over viscosity was obtained. Whilst materials exist that feature some of the above properties, none were found to be readily available within a similar melting point to that of PLA. Given this, it was proposed that a bespoke alloy would be the best solution.

### 5.1.2. Material Selection process

The process of material selection was driven by several key factors. Firstly, it was essential that phase diagrams were readily available in order to drive the selection process. This limits the range of potential materials simply as there is a lack of data for materials within this temperature range due to their relatively rare nature. Of the systems available, it was elected to use a tin/bismuth/indium system was for several reasons,
5. Electrically conductive materials

firstly well known eutectic alloys such as Lens Alloy, Field’s metal exist based on this systems with most of the above properties, finally the system is simplistic compared to other quaternary alloys.

An alternative constituent material which suits a low melting point alloy is lead, and is traditionally used in electrical solders. However recent legislation has eliminated the use of lead in consumer electronics in Europe due to mild health side effects therefore the use of lead was ruled out.

Upon deciding on a tin/bismuth/indium system, only one phase diagram was available that allowed a system that operated within the required temperature range, namely a Bi-In-Sn system for a mass ratio of tin to bismuth of 30/70. Figure 5.4 presents this data.

![Bi-In-Sn Phase Diagram](image)

Figure 5.4.: Bi-In-Sn Phase Diagram. Vertical Section at mass ratio Sn/Bi=30/70, plotted in at. %

Upon obtaining an appropriate phase diagram, the exact ratio of materials needed to be decided. The fundamental property governing this decision was achieving an appropriate solid/liquid ratio when molten and therefore an appropriate viscosity. A high viscosity is desirable in as far as it allows the most control over surface tension effects, and also the phase diagram shows that viscosity is less susceptible to temperature fluctuations in the high viscosity region of the diagram. However such a high viscosity
Electrically conductive materials

also implies a large amount of shear on the extruder which can potentially cause damage. Given the many unknowns at this stage of the research, an iterative approach to alloy selection was required. Based on these compromises, it was estimated that an alloy with an 80% solid ratio at the melt transition would be appropriate, which was to be evaluated through practical testing and iterated if required.

The selected alloy began to melt at approx. 130°C before entering a solely liquidous phase at 195°C. It was found that the extruder temperature needed to be 150°C to allow consistent extrusion. It was proposed the higher than anticipated extrusion temperature was due to the high solid-to-liquid ratio. After a minimal amount printing, dross formation, a tin/bismuth powder confirmed through energy-dispersive x-ray spectroscopy (Figure 5.5) was observed within the extruder which led to blockages. Further the high solid ratio at the beginning of the melt transition placed a large amount of shear on a low friction PTFE liner contained within the extruder, which led to failure after minimal printing. Therefore the solid ratio at the melt point was reduced to approximately 50% resulting in an alloy composition of 57.98% Sn 39.9% Bi 2.1% In (Alloy 2), with melt region of approximately 130 -150°C. This enabled a lower minimum extrusion temperature of 135°C, reducing the rate of dross formation and reduced shear at the melt transition eliminating these failure modes.

Figure 5.5.: SEM Imagery of 69.9%Sn 29.2% Bi 0.8% In. showing crystals of the tin rich phase + eutectic (left) and tin/bismuth dross formation (right)

5.1.3. Filament Manufacture

In an ideal scenario the following measurements would be conducted in the raw filament form as it would be used in the final process in addition to post extrusion. Given the relativity small quantities of material that was to be used in this research, having raw material extruded into an appropriate form was uneconomic, furthermore the exact geometry of the filament feed required was unknown, thus an alternative method was
5. Electrically conductive materials

Fortuitously the used alloys have an unforeseen benefit in that the low melting point also eases handling and thus casting the materials becomes possible with inexpensive and easy to obtain equipment. Given the thermoset properties, fairly high specific heat capacity and availability of silicone tubing, a syringe was used to cast the alloy into the tubing. Upon cooling this could be simply split open with scalpel to leave alloy filament of the required diameter. Heating the material into the pure liquidous phase is vital for material consistency, without this step the alloy forms a paste like substance of liquid alloy with solid tin particles. Upon refreezing this liquid composition will then refreeze to a different material composition possessing different material properties.

Given that the proposed extruder would control the linear material feed rate, the process is subject to errors due to variation in the filament diameter. Given that the filament was not to be produced by traditional methods, understanding the extent to which the diameter changers was critical. Therefore, three sample of the alloy was heated to in excess of 200°C using a hot plate and an infra-red thermometer before casting into 2mm silicone tubing. Each sample produced was in excess of 200mm and a callipers was used to measure the diameter five times along the length of each sample, the results of which are shown in Figure 5.6

![Figure 5.6: Alloy Filament Consistency](image)

Despite the nominal internal diameter of the silicone tubing being 2mm, it was found the actual average filament diameter was found to be 1.95mm and the diameter was
found to be within +/-1% of the average both over the entire length of each filament and across samples. The variation in nominal diameter was attributed to thermal contraction of both the silicone and the tubing on cooling to room temperature. In volume terms the variation in filament diameter equates to a worst case of over extruding 2.8% extra material or under extruding 2.3% relative to average values. This was considered to be within the tolerances of the overall process and these values are typical of what could be expected for typical thermoplastic filament and therefore the technique is suitable for the proposed use.

5.2. Material Characterisation

As outlined in Section 2.5.3, many attempts have already been made at creating conductive materials for printed circuitry. Mostly these materials have been created through doping electrical insulators such as ink or plastics with extremely conductive materials such as silver. Despite the very high conductivity of the conductive element, the resultant composite materials still possess a high resistivity e.g. SS-26 a silver-filled RTV Silicone posses a resistivity of $5 \times 10^{-3}\Omega \text{ cm}$ [33], five orders of magnitude greater than its constituent conductive material. Thus whilst such an approach would be fairly trivial to implement in 3D printing by combining Silver with the standard RepRap build materials, the resultant materials would be prohibitively expensive and only suitable to the most low power circuits. Furthermore a significant amount of electrical energy is wasted due to the heating of the electrical connectors reducing the efficiency of the circuit. Given that the glass point of Polylactic acid is in the range of 50-60°C, it is within the realms of possibility that such heating could damage the surrounded printed part over long periods. In the following section the proposed materials are tested for key electrical properties in order to assess their suitability for the proposed process.

5.2.1. Theory

4-point resistance measurement method

Resistance is the measure of a materials ability to impede the flow of current. However the resistance of a material is a function of its geometry. Thus resistance needs to be homogenised with respect to its length and cross-sectional area in order to allow a true comparison between materials, the resulting parameter is the materials resistivity $\rho$: 
5. Electrically conductive materials

\[ \rho = \frac{RA}{L} \] (5.2)

Where \( R \) is the measured resistance, \( A \) is the cross-sectional area of the sample and \( L \) is the length.

Given that metals such as the one proposed have fairly low resistivities, the accuracy of test setup is of critical importance. In particular the resistance of the electrical contacts between the test equipment and the samples and connecting wires have the potential to significantly skew the results.

The four-point resistance measured is the standard for testing receptivity of low resist- ance test samples [80]. As the name implies four points of contact are used as opposed to the two point used in more crude setups.

In both the two and four point resistance measurement test setups, the resistance is simply measured using Ohm’s law i.e. sending a force current across the sample before measuring voltage across it. In the case of the two point setup, the force current travels along the same wires as those used to do the sensing; hence the resistance of the wire creates a voltage drop and therefore an inaccurate measurement value. However the four point test rig used a different set of wires for measuring and thus the measurement is not affected by the voltage drop across the current carrying wires. Hence the resistance of the connecting wires does not affect measured value, and thus an accurate value of resistance for only the test sample is obtained.

5.2.2. Experimental Method and Results

In accordance with BS 5714:1979, a gauge length of at least 300mm is required for accurate results. In addition the test specimen must “take the form of any shape possessing smooth, straight sides and of substantially uniform cross-sectional area”, this is in order to accurately convert the measured resistance into resistivity using Equation 5.2. [80]

However as previously mentioned at least a 300mm test sample is required to conform with the appropriate British Standard, and a maximum length of approximately 200mm was manufactured using the method outlined, and therefore an alternative needed for resistivity testing.
5. Electrically conductive materials

A Keithley 2400 source meter was used to apply a current of 100mA through a Gwin- stek LCR-06A 4-wire test fixture to a series of 2mm diameter alloy filament samples produced through the method previously outlined. The length of the test samples varied between 225 and 290mm, which does not comply with the 300mm minimum specified in the standard; however the manufacturing method did not enable longer samples to be produced. An average resistivity of $6.22 \times 10^{-7} \Omega m$ was obtained. Despite the test sample length being below that stated in the relevant standard, the low standard deviation (Table 5.1) lends credibility in the results. Upon repeating the experiment with 60/40 lead/ tin flux-free solder, a resistivity of $1.78 \times 10^{-7} \Omega m$ was recorded, which corresponds to values established in the existing literature [81].

Table 5.1.: Resistivity of printable materials – Typical ink resistivities are from Molesa [82]

<table>
<thead>
<tr>
<th>Material</th>
<th>Resistivity(Ωm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DMF$^3$</td>
<td>$6.22 \times 10^{-7}$</td>
</tr>
<tr>
<td>60/40 Pb/Sn Solder</td>
<td>$1.78 \times 10^{-7}$</td>
</tr>
<tr>
<td>Organic Printable Inks</td>
<td>$3.3 \times 10^{-4} - 5 \times 10^{-5}$</td>
</tr>
<tr>
<td>Metallic/Binder Ink</td>
<td>$1.3 \times 10^{-6} - 2.5 \times 10^{-7}$</td>
</tr>
<tr>
<td>Nanocrystal Ink (Au)</td>
<td>$1.0 \times 10^{-7} - 3.3 \times 10^{-8}$</td>
</tr>
</tbody>
</table>

5.3. Filament Drive

Unlike the paste and plastic extruders implemented in Chapter 3, it was decided that the metal filament should be directly driven into the hot nozzle i.e. without the flexible Bowden tubing; several reasons were behind this decision:

1. At the time of development, the maximum filament diameter which would result in sufficient quality was unknown. Given that the system has a fixed resolution in terms of filament travel, reducing the filament diameter would have two effects. Firstly more filament travel would be required to deposit the same amount of material. Secondly a benefit is achieved in terms of the efficiency of heating achieved. From basic thermodynamics the energy to heat a given volume of material is proportional to its specific heat capacity, and the rate at which material may be heated is proportional to the surface area of the melt chamber. Thus given that as the filament diameter is decreased the volume of material (i.e. $\propto D^3$) decreases quicker than the surface area (i.e.$\propto D$) a net benefit is achieved in terms of the heating efficiency. Given the unknown filament diameter, the ideal design needed to be compatible with a variety of filament diameters. A Bowden setup
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would require mechanical design changes to account for this change whereas a regular direct drive setup is more flexible.

2. Given the previous poor control previously achieved by direct metal deposition, any inaccuracies in the process were to be minimised. Stretching of the low friction plastic tubing connecting the extruder drive and the nozzle in plastic setups is already known to reduce print quality. Given the increased stiffness of metal filament relative to plastic this errors would be increased further.

3. Metals are have the potential to be more brittle than thermoplastics, Forcing metal filament through the radius of the Bowden tube was likely to result in snapping of the filament, whilst this would reduce quality anyway this would also result in extruder reversals (traditionally used to stop unwanted material deposition in travel moves) having zero effect.

To the best of the authors knowledge, several different filament drive concepts have been trialled since the inception of RepRap whilst there has been no significant research into determining the best mechanism for driving thermoplastics, the simultaneous testing of many different drive concepts by the open source Rapid Prototyping community has determined that using a bolt which is then hobbed to include fine pitched gear teeth around its shank. Whilst this approach is well proven for plastics, due the increased strength and lower ductility it was unknown whether this approach would be suitable for driving the metal filament. Therefore, the extruder design shown in Figure 5.8 was designed using such a bolt with the intention of using it to drive the metal filament, and evaluated experimentally.

At the time of writing, two fundamental different approaches may be used by RepRap to control flow rate through the extruder. RepRap controls motion through the use of GCode, using 5 axes, X,Y,Z (Cartesian coordinates), E(Extruder Dimension) and F (tool-head feed rate). A typical line of GCode is shown below:

\[
G1 X10 Y10 Z0 E10 F1500;
\]

The “G1” command simply initiates a controlled move, in this case to X10 Y10 Z10 whilst moving the extruder axis 10mm at a feed rate of 1500mm/min. It is important to that this feed rate is not necessarily what the tool head performs. Modern firmwares are capable of acceleration, but rather than controlling this acceleration in the GCode, acceleration is controlled based on linear acceleration and jerk parameters contained within firmware. Even with thermoplastics which have excellent dynamic control,
Herringbone/double helical gears are utilised to give a smoother drive compared to standard spur gears. In theory they also imply reduced backlash which in turn reduces the amount of filament reversal before non-extruding moves reducing filament wear. Sprung idler bearing to ensure consistent grip despite changes in filament diameter.

Nema 17 200 steps/rev stepper motor drive with gear ratio of 43/13. Theoretical resolution of 0.034° when 1/16 microstepping.

“Hobbed” bolt filament drive as has become the de facto standard in RepRap extruders.

Two thru holes to enable extruder hot end (not shown) to be bolted to the drive mechanism.

Figure 5.7.: Alloy extruder drive mechanism
5. Electrically conductive materials

Effects of acceleration are often seen in the print quality. This is essentially due to latency between input at the extruder drive and output at the nozzle. The result of this is that the extruder effectively under extrudes under acceleration and over extrudes upon deceleration.

The firmware interprets GCode commands using a fixed constant to translate motion in millimetres into extruder steps:

\[ \text{Motors steps} = \text{Motors steps per mm} \times \text{Distance in mm} \quad (5.3) \]

Whilst the above is trivial for the axes of a machine, two different approaches are possible to enable motion control of the extruder:

- E axis defines road length i.e. displacement of the extruder head in a print move
- E axis defines filament travel

Each of the above techniques has their own benefits. Defining the axis in terms of road length allows for easy hand coding. However it ensures that the “Steps per mm” constant is dependent on a number of print parameters such as layer height, line thickness and filament diameter etc. and therefore calibration becomes empirical. Whereas filament travel is easy to measure experimentally, and therefore inaccuracies in the filament drive manufacture can be easily accounted for, however hand coding becomes more difficult. Given that the reliability of the extruder drive had not been established for metals, especially given their increased hardness relative to plastics, it was elected to use the latter approach, and simply convert between each system using (5.4) as a baseline.

\[ \text{Motors steps per mm of road} = \frac{\text{Road cross sectional area} \times \text{Motor steps per mm of filament}}{\text{Cross sectional area of filament}} \quad (5.4) \]

\[ \frac{\text{Motors steps per mm of filament}}{\text{Steps per motor revolution} \times \text{Microstepping Factor} \times \text{Gear Ratio}} = \frac{\text{Contact Diameter} \times \pi}{\text{}} \quad (5.5) \]

\[ \text{Motors steps per mm of filament} = \frac{200 \times 16 \times \frac{41}{13}}{8 \times \pi} \approx 420 \quad (5.6) \]
5. Electrically conductive materials

For the 8mm stainless steel drive gear used, using (5.5) the quantity of steps required in order to drive one millimetre of filament was found to be 420. However through empirical testing, the actual number was found to be 434. This variation is due to a variation in the contact diameter due to errors in the manufacturing process of the hobbed bolt. In order to establish the repeatability of the mechanism, a simple experiment was conducted repeatedly travel over a 100mm section of filament at 200mm/min, the results of which are shown in Figure 5.8. Repeatedly running over the same section of filament was thought to be the worst case scenario as it would subject the filament to wear which would happen, albeit in a small amount, during filament reversals during printing. In total over the 2000mm distance of filament travel during the test, a maximum error of approximately 1mm/1% was seen. In the author’s experience this is well within the range that would be expected with FFF thermoplastics and therefore it was deemed that this was sufficient.

![Figure 5.8.: Alloy extruder drive consistency. Stroke +/-100mm. Speed 200mm/min.](image)

5.4. Extruder Nozzle Design

In addition to the extruder drive mechanism, considerable effort was placed onto the hot end designs. Preliminary testing showed the material inertness was of critical importance. As shown in Figure 5.9 substantial nozzle wear was apparent after very little running. This was attributed to the molten alloy acting as a solvent slowly dissolv-
5. Electrically conductive materials

ing the brass nozzle. This resulted in an uneven nozzle geometry with a larger wetted perimeter between the molten material and the nozzle than was anticipated and print parameters required constant adjustment. In the design used for the majority of tests shown in this paper, anodised 6061 aluminium was used due to the presence of the chemically resistant oxide layer due to the anodising. Subsequently stainless steel has also proven to be suitable through a similar mechanism.

Figure 5.9.: Brass nozzle solubility

From the literature review it is clear there is some disparity in approach from existing research, Rice et al. implemented a rotor to ensure the fluid is well mixed which was not utilised by Finke and Feenstra [48] [47]. Based on this, it was elected to start with the simplest solution, i.e. no rotor. This decision is especially critically in the multi-head setup design, given the packaging constraints of the design. From initial trials using a standard RepRap extruder, it was shown that the amount of molten material within the nozzle was critical. Using a standard setup with a melt zone of approximately 30mm would result in sections of track of reasonable quality, before large dilations as shown in Figure 5.10. These dilations were attributed to the material being able to be extruded under its own weight because of the increased density relative to traditional plastics. In order to optimise the melt zone, empirical and finite element analysis was employed to develop the extruder design shown in Figure 5.11. It should be noted that other extruder designs were experimentally trialled, however they have been left out of this chapter to improve readability. A detailed account of these designs may be found in the Appendix. A comparative study was undertaken for several extruder iterations using finite element analysis using the parameters shown in Table 5.2. Figure 5.12 shows the predicted steady-state extruder temperature as a function of displacement from the extruder tip. It should be noted that the filament temperature was not modelled as many of its thermal properties were unknown; however the surrounding extruder temperature is still a reasonable measure of the melt zone. It can be seen that relative to the initial design, the melt zone is substantially reduced to approximately 6mm and enables the build quality shown in Figure 5.14.
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Table 5.2.: Finite Element Analysis Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact Resistance</td>
<td>5K/W</td>
</tr>
<tr>
<td>Convection Coefficient</td>
<td>10 (W/m^2)/K</td>
</tr>
<tr>
<td>Bulk Ambient Temperature</td>
<td>293K</td>
</tr>
<tr>
<td>Heater Block Temperature</td>
<td>423K</td>
</tr>
</tbody>
</table>

Figure 5.10.: Poor initial results, note the radiuses corners and dilations

Figure 5.11.: Final Nozzle Design

Aluminium nozzle – stepper to allow design to be clamped to the drive mechanism

O-ring to prevent material leakage

0.5mm orifice

PEEK insulator to prevent thermal conduction to the drive mechanism, containing PTFE tubing to allow for a low friction filament guide.

Aluminium heater block – Containing 100K thermistor and a 6.8Ω vitreous enamel wire wound resistor heating element (not shown).
Figure 5.12.: Predicted extruder temperature as a function of displacement from the nozzle orifice.
5. Electrically conductive materials

Figure 5.13.: Extruder Nozzle FEA, Standard RepRap (left) and final DMF3 nozzle(right)

Figure 5.14.: Example of attained print quality, track width 0.57mm
5. Electrically conductive materials

5.5. Print Results

On average a track with of 0.57mm was achieved in steady state conditions with a standard deviation of 0.052. This result compares favourably to the 1.24mm track width achieved on average by other studies [83]. Despite this initial success, dilations in extrusion were apparent at rapid changes in direction as can be seen in Figure 5.14. The average width of these dilations was 0.97mm with a standard deviation of 0.05. This was attributed to a surface tension effect in combination with an interaction between extruder dynamics and path geometry.

5.5.1. Tool Path Generation

In order to combat these issues with extrusion dilation, substantial modifications were undertaken to the tool path generation process. Ignoring side effects of surface tension an extruder will lay down materially equally on either side of the tool path. This fundamental problem is also apparent for arcs and circles with less material being required on the inside compared to the outside. However as derived below the exact amount of overfill is related to both the arc radius and the extrusion thickness.

\[
\text{Inner Segment Area} = \pi\left(r^2 - \left(r - \frac{t}{2}\right)^2\right) \tag{5.7}
\]

Figure 5.15.: Extrusion overfill for a right angle (left) and an arc (right)
5. *Electrically conductive materials*

Total Area Extruded = \(2\pi rt\) \hfill (5.8)

Inner Arc Percent Fill = \[
\frac{\pi rt}{\pi(r^2 - (r - \frac{t}{2})^2)}
\] \hfill (5.9)

Inputting the measured steady state extrusion width of 0.57mm into (5.9) gives the result shown in Figure 5.16. It can be seen that there is a substantial drop off in the amount of extrusion overfill as the arc radius increases, from double the required volume of material for a radius of 0.25mm down to just 10% over extrusion by a radius of just 1.3mm. As would be expected the fill volume approaches 100% as the radius approaches infinity i.e. a straight line. Given that this error substantially decreases with arc radius experiments were undertaken to assess this effect in practice. As previously described a series of channels were used with a rectangular cross-section of 0.7x0.25mm. The corner radius was increased in 0.5mm steps. Unfortunately the mechanical setup and file formats used are unable to interpret the concept of arcs and radiuses, thus curves are broken down into a series of small segments.

Figure 5.16.: Inner arc segment rill ratio v. arc radius for an extrusion thickness of 0.57mm
Matlab was used to convert the required arcs required into line segments as illustrated in Figure 5.17. The positional error associated with simplification may be calculated using (5.10). The total number of line segments was controlled such that this error is less than the known accuracy of the Cartesian setup i.e. 0.1mm. Ensuring the total number of arc segments is kept within sensible limits was deemed important due to limitations with the control electronics resulting in jerky and inconsistent motion.

Table 5.3 depicts the print quality achieved for various corner radii. It can be seen that corner dilation is substantially reduced when a radius is introduced, upon increasing this radius to in excess of 1.5mm dilation is no longer visibly apparent for a track thickness of 0.57mm. As previously mentioned, the amount of overfill is also related to track thickness, it is anticipated that with further work to reduce this overfilling effect, the technique may be opened up to be compatible more intricate component packages.

\[ \text{Error} = R \cos \frac{\theta}{2} \]  

(5.10)
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<table>
<thead>
<tr>
<th>Corner Radius (mm)</th>
<th>Corner Radius (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>2.5</td>
</tr>
<tr>
<td>1.0</td>
<td>3.0</td>
</tr>
<tr>
<td>1.5</td>
<td>3.5</td>
</tr>
<tr>
<td>2.0</td>
<td>4.0</td>
</tr>
</tbody>
</table>

5.5.2. 3D Circuitry

Finally a series of trials were performed attempting to cover printed alloy tracks with PLA thermoplastic. PLA was used as it warps less than other available materials (such as ABS), and in doing so minimising the risk of extruder head collisions that is possible in a multi-material setup. However difficulties arose due to the high temperature and specific heat of the thermoplastic. These caused thermal damage creating critical track breakages. Upon closer inspection it was observed that the alloy actually overfilled by approximately 0.1-0.2mm above its neighbouring thermoplastic layer. Increasing the layer height of the plastic interface layer from 0.25 to 0.5mm solved the problem of thermal damage. However this resulted in more complicated tool path planning as the dual extruder heads were no longer operating at the same layer height, giving a potential for nozzle collisions with the build. It is anticipated that through the use of a head changer difficulties with nozzle collisions may be eased. Further attempts were made to deposit multiple layers of alloy track effectively creating a vertical circuitry; however the reliability of connection between mating layers proved to be poor. Therefore further work is required in this area in order to improve reliability.
5. Electrically conductive materials

Figure 5.18.: Attempts at track covering - 0.25mm layer height interface layer (left), 0.5mm (centre) and completed (right)

In order to interface with standard electronic components the substrate was designed such that the components were installed inverted, with pins recessed into the substrate such that pins were flush with the bottom of the rectangular alloy channel. This ensured that extruders were always operating at the same layer height. Simple PDIP 2.54mm pitch and through-hole components were shown to be compatible with this process. However consistent welding between alloy tracks and component pins was not achieved. Thus connections were always ensured manually by hand.

5.6. Design Rules

Based on the experiments outline, design guidelines are presented in Table 5.4. It should be noted that these rules are not hard and fast, however pushing the boundaries of these specifications will result in reduced print quality and reliability.
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<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel geometry</td>
<td>0.7x0.25mm designed, 0.5x0.25mm printed</td>
</tr>
<tr>
<td>Corners</td>
<td>Should be filleted to a radius of 1.5mm.</td>
</tr>
<tr>
<td>Track width</td>
<td>0.57mm</td>
</tr>
<tr>
<td>Minimum track pitch</td>
<td>2.54mm (PDIP)</td>
</tr>
<tr>
<td>Alloy extruder temperature</td>
<td>150°C</td>
</tr>
<tr>
<td>Print feed rate</td>
<td>150mm/min</td>
</tr>
<tr>
<td>Extruder steps per mm of track</td>
<td>40 steps per mm</td>
</tr>
<tr>
<td>Filament retraction at the end of print moves</td>
<td>equivalent to 5mm of printed track</td>
</tr>
<tr>
<td>Component legs</td>
<td>Should be recessed such that they lie flush with the printed channels. Components should be manually connected to printed tracks after alloy deposition</td>
</tr>
<tr>
<td>Extruder over-run</td>
<td>2mm without material deposition to prevent electrical shorting</td>
</tr>
<tr>
<td>Layer height</td>
<td>Typical 0.25mm Insulating interface layer 0.5mm</td>
</tr>
</tbody>
</table>

5.7. Proof of concept PCB

In order to properly evaluate the design rules established in the previous section, a basic circuit was printed using the technique. The board selected was a micro-controller based upon the Arduino platform known as the Sanguino. The schematic for the micro-controller is shown Figure 5.19. All components within the design are either through-hole or, in the case of the micro-controller, a 40 pin PDIP chip with a pin pitch of 2.54mm.

In total two of these circuits have been manufactured using our technique, both inserting pre-tinned and fluxed components into their respective printed polymer channels before printing the alloy track. Reliable connection to component pins was not always achieved automatically; so a few connections were touched with a soldering iron for both methods. In addition the standard Sanguino circuit was simplified to remove any non-essential elements, such as components enabling the user to reset the micro-controller without power cycling. Also only four of the 32 controllable pins are connected giving three exposed pins and one further pin to drive an LED.
Despite the previous research, the attempt highlighted several requirements not previously investigated. Firstly mounting two extruders on the same tool gantry defines that each individual extruder must be operating on the same layer. Therefore this defines components with tall electrical pins should be recessed into the insulating substrate such that the top surface of the connector is flush with the bottom of the respective channel and any non-essential protruding component housing is removed as shown in Figure 5.19.

Further problems became apparent owing to compromises made in the mechanical arrangement. As previously mentioned a Bowden thermoplastic extruder drive was selected to ease packaging of the alloy deposition head on the RepRap’s moving carriage and to minimise axis weight. However this added a spring element into the drive system because of the elasticity of the Bowden tubing. Thus when extrusion was no longer required this spring element still needed to be unloaded by reversing the filament drive, resulting in a small dilation of the deposited thermoplastic. Owing to the increased complexity of the substrate relative to tests outlined thus far, many more reversals were required and thus the issue became more apparent. Fortuitously the STL-slicing program used typically placed these dilations adjacent to component pins, thus chamfering the pin entrances eased the issue.
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5.7.1. Component and Track Connections

One other issue highlighted by the circuit’s manufacture was obtaining reliable T connections between two tracks to enable parallel circuitry. Initially experiments were undertaken to investigate overrunning track to ensure the track connection. However results proved inconsistent either leaving a critical gap in a track or giving large dilation which swelled substantially above the desired layer height. When this dilation was covered with thermoplastic molten alloy was smeared around the circuit poten- tially shorting components. Both of these failures more were critical. However, by using a 1.5mm track bend radius to make a T join by joining the two tracks tangen- tially the surface contact area between tracks is maximised and using this technique neat joins have been repeatedly achieved.

5.7.2. Component Placement

Two potential options are available for component placement:

1. The substrate is printed, printed tracks laid before the components are inserted and connected manually

2. The substrate is printed, and components are then inserted prior to the printing of the track

This latter option potentially allows for the components to automatically be soldered into place. Hence this technique, if combined with an automated pick and place ma- chine which is common in industry, would allow for automated manufacture of PCBs. This method was trialled, and reliable component connections were never achieved (approximately 50% of joints were poor). However poor joint could be manually in- spected and repaired. It is suspected that in part the reason for this poor quality is due to the step change that occurs in substrate between the PLA channels, and the legs of the components. Whilst it is anticipated that this would be improved with further research, for the majority of experiments, it was preferable to insert the components after laying the track. Doing so ensured a consistent substrate and the disadvantage of having to manually solder connections was a non-issue given that a large number of joints would need to be repaired with the automated option.
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5.7.3. Final PCB Manufacture

Given the difficulties encountered in connecting mating layers automatically, these were deposited and the connection between mating layers was ensured by hand before the complete board was enclosed by using a porous 0.5mm thick interface layer as previously described. Stages of board manufacturer, including the micro-controller running a standard LED blink program is shown in Figure 5.20.

Figure 5.20.: Micro-controller manufacturing steps
5. Electrically conductive materials

5.8. Conclusions

The chapter shows for the first time an FFF method to build electrical circuits with a cost-effective RP process that has been shown to be capable of directly interfacing with existing electrical components. The developed process enables the fabrication of electrical devices embedded within RP mechanical structures.

A bespoke non-eutectic alloy was designed to be thermally compatible with polylactic acid, whilst offering improved control based on previous success manufacturing free-form structures using semi-solid materials. Minimising the melt transition of the extruder and material selection was shown to be critical in order to improve transient response and in order to ensure extruder reliability.

A novel extruder design in order to maximise control through minimising the melt zone guidelines were obtained through experimentation and Finite Element Analysis in order to minimise defects and dilations. Optimised tool path generation by limiting corner radii to 1.5mm was shown to be critical in preventing corner dilations. Conductive circuit track of 0.57mm width was produced using the methods developed, a significant improvement on similar techniques seen in the literature. The technique has been shown to be compatible with existing PDIP and through-hole electrical components. The electrical resistivity of the final alloy was shown to be $6.22 \times 10^{-7}\Omega m$, approximately two orders of magnitude better than typical inkjet direct writing conductors. A process map summarising the research methodology is shown in Figure 5.21.
Finally a micro-controller circuit was built using the technique developed whereby both conductive traces were deposited and components directly soldered automatically. Whilst this was successful, and represents the first circuit produced using low cost FFF technology, more effort is required to improve component interfacing reliability.
6. Conclusions

To give an overview of the work presented, Chapter 1 introduced Additive Manufacturing, its benefits and limitations before suggesting that the capability and functionality of the components produced would be dramatically improved if multi-material components could be manufactured. Additive Manufacturing techniques were further examined in Chapter 2, particularly within the context of multiple materials and functionality. It was concluded that two fundamental techniques - Robocasting and FFF - were inherently compatible and therefore creating a system capable of using both would dramatically increase functionality. Chapter 3 documents the mechanical, software and general process research and development towards such a system. Further techniques to improve the functionality of these raw processes are shown in subsequent chapters. Specifically Chapter 4 details research undertaken to maximise the range of mechanical properties achievable with a single material. Finally Chapter 5 summarised the research undertaken developing the FFF process to be compatible with a conductive alloy, the chapter culminated in the manufacture of a complex functional circuit.

6.1. Review of progress with respect to Aims and Objectives

6.1.1. Progress with respect to objectives

The author attempted to achieve three objectives initially outlined in Section 1.1. For the reader’s convenience these are presented again below:

1. To demonstrate the compatibility of different AM processes. In particular Robocasting, a technique similar to FFF but one that relies on a syringe in order to allow it to use paste materials [5], in parallel with Fused Filament Fabrication using fundamentally dissimilar materials.
2. To enable the control of bulk material properties through the control of mesostructure and print parameters.

3. To develop a novel cost-effective low melting point alloy compatible with the Fused Filament Fabrication and thermoplastics in order to enable the manufacture of electrical circuitry.

All of the above objectives have been achieved and evidence for this may be found in the relevant chapters within this thesis. Together this substantially improves the functionality of the components achievable using low cost Additive Manufacturing techniques, the extent to which functionality has been improved is discussed in the following section.

6.2. Hypothesis support

To restate the author’s hypothesis:

“Solid Freeform Fabrication processes are sufficiently versatile to manufacture functional electro-mechanical devices through the use of dissimilar materials and part geometry”

Functional within the above hypothesis, refers to functional within the engineering context beyond that achievable through geometry alone.

Each chapter within this thesis provides some novel proof of the hypothesis, a summary of the contribution of proof for each chapter is outlined below:

- Multi-material Development - This chapter details the development of a system capable of using both FFF and Robocasting within the same fundamental process. The mechanics, electronics and tool path planning for such a system are all developed. Finally a two-material part is manufactured from PDMS and PLA. This partially supports the hypothesis. The process developed enables inherently dissimilar materials to be used, and opens up FFF to all of the electrical properties previously achieved by Malone.

- Effect of Mesoscale Structure and Print Parameters on Bulk Mechanical Properties - This chapter details research undertaken investigating the range of mechanical properties available by varying part mesostructure for polylactic acid, in
6. Conclusions

doing so this research allows the mechanical properties of a part to be tuned improving functionality - and provides proof towards the author’s hypothesis

- Electrically conductive materials - The work undertaken in this chapter investigates a potential method for creating electrical circuitry using Additive Manufacturing techniques. A novel non-eutectic low melting point alloy and associated extruder is developed towards the goal of minimising surface tension, which has been previously highlighted as a major issue in the literature. All previous attempts have to use additive techniques to create circuitry have resulted in extremely poor conductivity limiting functionality. The chapter demonstrates that the fundamental technique is compatible with existing PDIP and through-hole electrical components, and results in the production of micro-controller using the technique - directly supporting that author’s hypothesis that an electrical component is possible

6.2.1. Outcomes and Key Conclusions

Each chapter of research undertaken offers some key conclusions and research outcomes that prove vital to conduct 3D printing of functional electro-mechanical components using FFF and Robocasting. These Key findings are summarised in this section.

Firstly an essential research outcome has been to demonstrate the repeatability of the Pneumatic Robocasting process. Whilst Robocasting is in many ways an old method, it was unclear from the literature whether a pneumatic or a volumetric driven process is more suited to FFF. Chapter 3 has demonstrated this repeatability to within 5% for the pneumatic process, and the volumetric process proved to be inconsistent due to trapped air within the printing medium

The study investigating the mechanical properties of PLA demonstrated the robustness of PLA vs. other materials for the FFF process for the first time. Other studies with other materials find a substantial drop in the mechanical performance of the material vs. cast or injection moulded samples. This has proven not to be the case for PLA, due it its ability to weld to itself so readily. PLA has also been shown to be highly suitable to tuning mechanical properties in a way that other materials are not. PLA offers more repeatable, robust result, with fewer parameters affecting performance. This simplicity relative to other materials ensures that the technique may be implemented in a practical manner. Finally, the range of properties achievable using the technique with PLA is
6. Conclusions

substantially greater than other materials further demonstrating its suitability to the technique.

Finally the chapter investigating electrically conductive materials demonstrated the importance of non-eutectics towards directly printing metals with FFF. The print quality and resolution achieved (0.57mm) is substantially greater than seen in the literature with more typical low melting point metals. The importance of anodising was also shown to be vital in order to prevent the FFF extruder itself being dissolved by the molten material. The chapter also represents the first time tool path planning has been optimised for FFF metal printing and design guides for the technique have been presented. It was concluded that the corner radius of the tool path needed to be controlled in order to prevent dilations, with 1.5mm being the minimum corner radius achievable whilst maintaining consistent extrusion. During the several iterations of extruder designed, the importance of maintaining a very small melt zone has been shown to be key in order to have the maximum amount of control of the molten material

6.3. Limitations and Issues

Whilst some discussion occurs within the relevant chapters of this thesis regarding limitations and issues with the process, this section seeks to highlight and discuss potential issues with a multi-material Additive Manufacturing process that are not covered elsewhere in this thesis.

6.3.1. Recycling and End of life

In recent times there is increasing legislation and consumer demand for designers to consider the process at the end of a components working life. With rising material costs, and environmental concerns there is increasing emphasis on being able to recycle components from within a product. For traditional manufacturing techniques the process should be designed at the conception of the component. Whilst this is true for AM, traditional AM has the potential to manufacture multiple-part products which are physically impossible to disassemble (equally they don’t actually require assembly in the first place). Further using the techniques developed in this thesis, functional multiple-material products may be manufactured of which are technically one part - albeit one that is composed of many materials with a complex structure. Three potential solutions which go part the way to solving this are outlined below:
6. Conclusions

• Centrifugation- In the case of non-thermoplastics used in AM, typically the materials have substantial variations in density. In this case they could be heated to their melting point and centrifuged to separate these materials based on density before recycling using traditional methods.

• Fractional distillation - Many materials used in AM have differing melting/boiling points. Therefore fractional distillation may be used in a similar way as it is used to separate crude oil into its constituent components.

• Solvents - For thermoplastics with similar densities and melting points, solvents may be used to dissolve one specific thermoplastic leaving the others in the part intact. This solvent/plastic solution may then be resynthesised into the original thermoplastic.

Using the above techniques, it is anticipated that the majority of components could be recycled into their constituent materials, however further research is required to develop these processes and prove its effectiveness.

6.3.2. Repair

It is inevitable that some parts may become damaged during their working life. In the case of electrical circuits, components may need to be swapped or often access is required to components for tuning e.g. a potentiometer. Again the drawbacks of the method developed should be considered during the design process, namely that access to such components is not guaranteed using the techniques outlined. Aside from considering this access during the design process, and it is trivial for AM process to leaves holes in an external casing to ensure access and solve the problem, the author is unable to offer any further techniques to ease this issue. However it should be considered that by having electrical and other components encased within a robust plastic housing substantially reduces the risk of failure to begin with. Therefore manufacturers simply having modular complex components which need to be replaced entirely may not be an issue - particularly if the recycling methods outlined could be achieved.

6.3.3. Interface geometries and material adhesion

All of the materials used in this thesis were able to naturally adhere to one another. However whilst this is the case for a lot of amphorous thermoplastics, this is not
guaranteed. However, through the appropriate interface geometry and the use of the casting-like backfill deposition technique it is possible that materials that do not naturally adhere may still be used however research needs to go into this area.

6.3.4. Thermal properties

Whilst Robocasting is capable of using thermosets, FFF is traditionally used with thermoplastic materials. Assuming the adhesion already highlighted is a non-issue, further problems may arise due to different thermal properties. As highlighted when developing a low melting point alloy, having incompatible thermal properties may lead to thermal damage to the substrate material. Therefore the extrusion temperature of mating thermoplastics should be similar. Further the glass point of each material is critical, both to indicate when thermal damage occurs, and also to reduce the possibility of part warping. Should the temperatures of the required plastics not be similar, it is possible that the use of a robocast thermoset intermediate diaphragm of a secondary material would be enough to prevent thermal damage to the lower melting point material. Indeed, a possible use of the author’s systems would be to introduce such intermediate diaphragms into complex parts made from dissimilar materials to increase the range of operating temperatures and differential expansions that they could withstand in use.

6.3.5. Surface finish and part quality

Even when a functional property is achievable with Additive Manufacturing techniques, the current limitation of reduced quality and surface finish relative to subtractive techniques is still undoubtedly an issue. Without a substantial improvement in accuracy for low cost AM, high tolerance surfaces such as bearing fits are not possible. However in recent times the part quality achievable has increased substantially and continues to do so. Therefore as this improvement continues, surface finish becomes less and less of an issue although at what point the rate of increase in quality levels out remains to be seen.
6. Conclusions

6.4. Future development

The research undertaken in this thesis dramatically improves the potential functional properties available to designers. However development is still required to improve the range of material properties available and research is required to minimise the consequences of this process. Therefore further work is recommended into the following areas:

- Further research is placed into improving build quality of low melting point alloys - namely investigating other formulations of alloys to improve wetting, viscosity and extrusion properties. Another potential technique already outlined is to improve the surface energies of the relevant materials, namely to reduce the attraction the nozzle via a PTFE coating and the use of a polymer/metallic composite substrate. In doing so this may open the process to SMT components allowing more intricate, functional circuits.

- Investigate potential methods to extend the work conducted to enable true three dimensional circuitry.

- Further research should be conducted to extend the range of properties available with the raw FFF/Robocasting single material processes. For example further research into ceramics and resins to enable components to be produced which are more robust at high temperatures.

- Establish the effect of mesostructure on other materials such as polycarbonate, ABS, low melting point alloys and robocast materials and also to assess the feasibility of the technique across a wider range of geometries and build orientations.

- Research should be placed investigating the effect of multi-material AM on product life cycle and recycling methods.

- The effect of the inclusion of a rotor when extruding non-eutectic semi-solids towards printing electronics, as used by Rice et al. for freeform structures, should be evaluated and its effect on extrusion quality assessed [48]
6. Conclusions

6.5. Final comments

The methods developed in this thesis provide techniques to produce functional electro-mechanical systems using Additive Manufacturing techniques. Whilst further research is required to obtain yet more functionality, through careful tool path planning and material selection, the methods developed allow the manufacture of components with tuneable mechanical properties in addition to allowing the integrated electrical circuitry using Additive Manufacturing methods. This potentially enables a profound reduction in the part count of many engineering systems. Using these techniques example functional components have been manufactured including components that would traditionally require two-part injection moulding, which would be impossible to prototype using existing methods, and a printed micro-controller.
References


References


References


References


[47] S Finke and FK Feenstra. Solid freeform fabrication by extrusion and deposition
References


[58] D W Hutmacher, T Schantz, I Zein, K W Ng, S H Teoh, and K C Tan. Mechan-
References


[69] Donald Garlotta. A Literature Review of Poly (Lactic Acid). *Journal of Poly-
References


A. Comparison of common AM techniques
### Comparison of common AM techniques [16] [24]

<table>
<thead>
<tr>
<th>Method</th>
<th>Stereolithography</th>
<th>Selective Laser Sintering</th>
<th>Single Jet Inkjet</th>
<th>Jetted Photopolymer</th>
<th>Fused Filament Fabrication</th>
<th>Solvent Jet Printing</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Vendor</strong></td>
<td>3D Systems</td>
<td>EOS GmbH</td>
<td>Solidscape (Stratasys)</td>
<td>Objet Geometries (Stratasys)</td>
<td>Stratasys/RepRap</td>
<td>Zcorp(3D Systems)</td>
</tr>
<tr>
<td><strong>Typical Cost</strong></td>
<td>$75K-800K</td>
<td>$200K-1M</td>
<td>$46-80K</td>
<td>$20K-300K</td>
<td>$500-300K</td>
<td>$15-70K</td>
</tr>
<tr>
<td><strong>Layer Thickness (mm)</strong></td>
<td>0.05</td>
<td>0.1</td>
<td>0.006</td>
<td>0.028</td>
<td>0.1-0.4</td>
<td>0.089</td>
</tr>
<tr>
<td><strong>Accuracy</strong></td>
<td>very good</td>
<td>good</td>
<td>excellent</td>
<td>good to very good</td>
<td>fair</td>
<td>fair</td>
</tr>
<tr>
<td><strong>Speed</strong></td>
<td>average</td>
<td>average to good</td>
<td>poor</td>
<td>good</td>
<td>poor</td>
<td>Excellent</td>
</tr>
<tr>
<td><strong>Surface Finish</strong></td>
<td>very good</td>
<td>good to very good</td>
<td>excellent</td>
<td>good to very good</td>
<td>fair</td>
<td>fair</td>
</tr>
<tr>
<td><strong>Strengths</strong></td>
<td>large part size, accuracy</td>
<td>accuracy, wide range of materials</td>
<td>accuracy, finish, office OK</td>
<td>accuracy and finish, office OK, multiple materials already commercially available</td>
<td>office OK price, materials</td>
<td>speed, office OK, price, colour</td>
</tr>
<tr>
<td><strong>Weaknesses</strong></td>
<td>post processing is required Messy liquids</td>
<td>size and weight, system price, surface finish, awkward powder handling</td>
<td>speed, limited materials, part size</td>
<td>post processing</td>
<td>speed</td>
<td>limited materials, fragile parts, finish</td>
</tr>
<tr>
<td>-------------------------------</td>
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<td>-------------------------------------------------------------------------------------------------</td>
<td>-------------------------------------------------------------------------------------------------</td>
<td>-------------------------------------------------------------------------------------------------</td>
<td>-------------------------------------------------------------------------------------------------</td>
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</tr>
<tr>
<td>Material Cost $/Kg</td>
<td>$170-$240</td>
<td>Plastics $70 -140</td>
<td>$220</td>
<td>$385</td>
<td>$80-500</td>
<td>starch: $0.35 / cu in plater: $0.60 / cu in + infiltrant :$0.35 / cu in</td>
</tr>
<tr>
<td>Applications</td>
<td>Fit and form testing</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td>Trade show and marketing models</td>
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<td></td>
<td>Rapid manufacturing of small detailed parts</td>
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<td></td>
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<tr>
<td></td>
<td>Fabrication of specialised manufacturing tools</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td></td>
<td>Patterns for investment casting, urethane and RTV moulding</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Slightly less detailed parts and models for fit and form testing compared to photopolymer-based methods |
| Rapid manufacturing of parts, including larger items such as air ducts |
| Parts with snap-fits and living hinges |
| Parts which are durable and use true engineering plastics |
| Patterns for investment casting |

| Most detailed parts and models available using additive technologies for fit and form testing |
| Patterns for investment casting, especially jewelry and fine items, such as medical devices |
| Patterns for urethane and RTV moulding |

| Very detailed parts and models for fit and form testing |
| Trade show and marketing parts and models |
| Patterns for investment casting, especially jewelry and fine items |
| Patterns for urethane and RTV moulding |
| Color industrial design models have been demonstrated and are known to be under development |

| Detailed parts and models for fit and form testing using engineering plastics |
| Detailed parts for patient- and food-contacting applications |
| Plastic parts for higher-temperature applications |
| Trade show and marketing parts and models |
| Rapid manufacturing of small detailed parts |
| Patterns for investment casting |
| Fabrication of specialized manufacturing tools |
| Patterns for urethane and RTV moulding |

| Concept models |
| Parts for limited functional testing |
| Color models for FEA and other engineering related applications |
| Architectural and landscape models |
| Color industrial design models, especially consumer goods and packaging |
| Castings |
B. Research Publications

B.1. Journal papers


B.2. Conference Papers


B.3. Open Source Publications


support material based on PVA to be deposited using the robocasting process.
http://blog.reprap.org/2009/12/soluble-support-material.html

• “Paste Extruder, the first test” January 2010. Detailed description and analysis
of preliminary results of the volumetric paste extruder used in this Thesis

• Publication of paste extruder design files. March 2010.
http://sourceforge.net/p/reprap/code/HEAD/tree/trunk/users/Rhys/Paste-extruder/

• “Bowden Paste Extruder” Publication of results and discussion regarding the
volumetric paste extruder detailed in Chapter 3.
http://blog.reprap.org/2010/03/bowden-paste-extruder.html

• “Mendel MultiExtruder Carriage” June 2010. Publication of the design files of
the Multiextruder setup detailed in Chapter 3.
http://www.thingiverse.com/thing:3594

• “Mendel Multiple Materials” Discussion regarding first multi-material prints.

• Publication of program to modify tool path GCode allow for offsets between
http://sourceforge.net/p/reprap/code/HEAD/tree/trunk/users/Rhys/Gcodeoffset/

• “RepRapping Two Materials into One Object” Details changes required to pro-
cess planning.
http://blog.reprap.org/2010/08/siliconepla-tweezers.html

• “PLA Silicone Tweezers” August 2010. Design files for the first Multimaterial
print are made readily available.
http://www.thingiverse.com/thing:3715

• “Improved Mendel X Motor Bracket” September 2010 – Publication of an im-
proved RepRap Mendel X Motor mount to eliminate belt fatigue
http://www.thingiverse.com/thing:4209

• “Herringbone Geared Extruder” December 2010. Publication of the Alloy fila-
ment drive mechanism, also compatible with standard thermoplastics.
http://www.thingiverse.com/thing:5111
B. Research Publications


• “Some more printed circuitry” April 2012. Documents the process of creating the first printed PCB detailed in Chapter 5, together with final alloy composition, extruder design etc. http://blog.reprap.org/2012/04/some-more-printed-circuitry.html • “Printed circuitry all covered up” June 2012. Documents the issues discussed in Chapter 5 with regards to covering printed track. http://blog.reprap.org/2012/06/printed-circuitry-all-covered-up.html
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D. RepRap Ramps 1.3 Schematic
E. Slicing Settings

E.1. Slic3r standard software preferences
acceleration = 0
bed_size = 200,200
bed_temperature = 0
bridge_fan_speed = 100
bridge_flow_ratio = 1
bridge_speed = 35
brim_width = 0
complete_objects = 0
cooling = 0
disable_fan_first_layers = 1
duplicate = 1
duplicate_distance = 3
duplicate_grid = 1,1
duplicate_gcode = G1 X65 Y150 F4000.0
end_gcode = ;feed for start of next move
external_perimeter_speed = 100%
extra_perimeters = 1
extruder_clearance_height = 20
extruder_clearance_radius = 20
extrusion_axis = E
extrusion_multiplier = 1
extrusion_width = 0
fan_always_on = 0
fan_below_layer_time = 60
filament_diameter = 1.75
fill_angle = 45
fill_density = 0.15
fill_pattern = rectilinear
first_layer_bed_temperature = 0
first_layer_extrusion_width = 0
first_layer_height = 100%
first_layer_speed = 50%
first_layer_temperature = 200
g0 = 0
gcode_arcs = 0
gcode_comments = 0
gcode_flavor = reprap
infill_acceleration = 50
infill_every_layers = 1
infill_extrusion_width = 0
infill_speed = 35
layer_gcode =
layer_height = 0.25
max_fan_speed = 100
min_fan_speed = 35
min_print_speed = 10
notes =
nozzle_diameter = 0.5
output_filename_format = [input_filename_base].gcode
perimeter_acceleration = 25
perimeter_speed = 25
perimeters = 2
perimeters_extrusion_width = 0
post_process =
print_center = 35,100
randomize_start = 1
retract_before_travel = 0.9
retract_length = 2.5
retract_lift = 0
retract_restart_extra = 0.1
retract_speed = 30
rotate = 0
scale = 1
skirt_distance = 3
skirt_height = 1
skirts = 1
slowdown_below_layer_time = 15
small_perimeter_speed = 25
solid_fill_pattern = rectilinear
solid_infill_speed = 35
solid_layers = 4
start_gcode = G28 ; home all axes
support_material = 0
support_material_angle = 0
support_material_pattern = rectilinear
support_material_spacing = 2.5
support_material_threshold = 45
support_material_tool = 0
temperature = 200
threads = 2
top_solid_infill_speed = 50
travel_speed = 150
use_relative_e_distances =
z_offset = 0
E. Slicing Settings

E.2. Host software standard preferences

Preference definitions may be found at :http://reprap.org/wiki/Java_Software_Preferences_File
#RepRap machine parameters. See
http://objects.reprap.org/wiki/Java_Software_Preferences_File

#Thu Oct 20 18:23:43 BST 2011
BaudRate=57600
BedTemperature(C)=65
CommsDebug=true
Debug=true
DisplaySimulation=false
DumpX(mm)=0
DumpY(mm)=0
Extruder0_Address=0
Extruder0_ArcCompensationFactor(0..)=8
Extruder0_ArcShortSides(0..)=1
Extruder0_ColourB(0..1)=0.6
Extruder0_ColourG(0..1)=0.3
Extruder0_ColourR(0..1)=0.3
Extruder0_CoolingPeriod(s)=-1
Extruder0_EvenHatchDirection(degrees)=45
Extruder0_ExtrudeRatio(0..)=1
Extruder0_ExtrusionBroadWidth(mm)=-1
Extruder0_ExtrusionDelayForLayer(ms)=50
Extruder0_ExtrusionDelayForPolygon(ms)=50
Extruder0_ExtrusionFoundationWidth(mm)=2
Extruder0_ExtrusionHeight(mm)=0.25
Extruder0_ExtrusionInfillWidth(mm)=0.5
Extruder0_ExtrusionLastFoundationWidth(mm)=2
Extruder0_ExtrusionOverRun(mm)=1.5
Extruder0_ExtrusionPWM(0..1)=-1
Extruder0_ExtrusionSize(mm)=0.5
Extruder0_ExtrusionSpeed(mm/minute)=1500
Extruder0_ExtrusionTemp(C)=220
Extruder0_FastEFeedrate(mm/minute)=7000.0
Extruder0_FastXYFeedrate(mm/minute)=1500.0
Extruder0_InFillMaterialType(name)=PLA-infill
Extruder0_InfillOverlap(mm)=0.2
Extruder0_InfillSpeed(0..1)=1
Extruder0_Lift(mm)=0
Extruder0_MaterialType(name)=PLA
Extruder0_MaxAcceleration(mm/minute/minute)=1200000.0
Extruder0_MiddleStart=true
Extruder0_NumberOfShells(0..N)=2
Extruder0_OddHatchDirection(degrees)=-45
Extruder0_OffsetX(mm)=0
Extruder0_OffsetY(mm)=0
Extruder0_OffsetZ(mm)=0
Extruder0_OutlineSpeed(0..1)=0.9
Extruder0_Purge(ms)=0
Extruder0_Reverse(ms)=2000
Extruder0_SlowXYFeedrate(mm/minute)=1500.0
Extruder0_SupportMaterialType(name)=null
Extruder0_ValveDelayForLayer(ms)=200
Extruder0_ValveDelayForPolygon(ms)=200
Extruder0_ValveOverRun(mm)=-1
Extruder0_ValvePulseTime(ms)=-500
Extruder1_Address=0
Extruder1_ArcCompensationFactor(0..)=8
Extruder1_ArcShortSides(0..)=1
Extruder1_ColourB(0..1)=0.3
Extruder1_ColourG(0..1)=0.6
Extruder1_ColourR(0..1)=0.9
Extruder1_CoolingPeriod(s)=-1
Extruder1_EvenHatchDirection(degrees)=45
Extruder1_ExtrudeRatio(0..)=1
Extruder1_ExtrusionBroadWidth(mm)=2.5
Extruder1_ExtrusionDelayForLayer(ms)=150
Extruder1_ExtrusionDelayForPolygon(ms)=50
Extruder1_ExtrusionFoundationWidth(mm)=2
Extruder1_ExtrusionHeight(mm)=0.25
Extruder1_ExtrusionInfillWidth(mm)=2
Extruder1_ExtrusionLastFoundationWidth(mm)=1
Extruder1_ExtrusionOverRun(mm)=3
Extruder1_ExtrusionPWM(0..1)=-1
Extruder1_ExtrusionSize(mm)=0.5
Extruder1_ExtrusionSpeed(mm/minute)=1500
Extruder1_ExtrusionTemp(C)=205
Extruder1_FastEFeedrate(mm/minute)=22000.0
Extruder1_FastXYFeedrate(mm/minute)=1500.0
Extruder1_InFillMaterialType(name)=PLA-support
Extruder1_InfillOverlap(mm)=0
Extruder1_InfillSpeed(0..1)=1
Extruder1_Lift(mm)=0
Extruder1_MaterialType(name)=PLA-support
Extruder1_MaxAcceleration(mm/minute/minute)=1200000.0
Extruder1_MiddleStart=true
Extruder1_NumberOfShells(0..N)=0
Extruder1_OddHatchDirection(degrees)=45
Extruder1_OffsetX(mm)=0
Extruder1_OffsetY(mm)=0
Extruder1_OffsetZ(mm)=0
Extruder1_OutlineSpeed(0..1)=0.9
Extruder1_Purge(ms)=30000
Extruder1_Reverse(ms)=1500
Extruder1_SlowXYFeedrate(mm/minute)=1500.0
Extruder1_SupportMaterialType(name)=null
Extruder1_ValveDelayForLayer(ms)=200
Extruder1_ValveDelayForPolygon(ms)=200
Extruder1_ValveOverRun(mm)=2
Extruder1_ValvePulseTime(ms)=-500
Extruder2_Address=0
Extruder2_ArcCompensationFactor(0..)=8
Extruder2_ArcShortSides(0..)=1
Extruder2_ColourB(0..1)=0.3
Extruder2_ColourG(0..1)=0.8
Extruder2_ColourR(0..1)=0.3
Extruder2_CoolingPeriod(s)=-1
Extruder2_EvenHatchDirection(degrees)=45
Extruder2_ExtrudeRatio(0..)=1
Extruder2_ExtrusionBroadWidth(mm)=6
Extruder2_ExtrusionDelayForLayer(ms)=50
Extruder2_ExtrusionDelayForPolygon(ms)=50
Extruder2_ExtrusionFoundationWidth(mm)=2
Extruder2_ExtrusionHeight(mm)=0.25
Extruder2_ExtrusionInfillWidth(mm)=1.5
Extruder2_ExtrusionLastFoundationWidth(mm)=2
Extruder2_ExtrusionOverRun(mm)=1.5
Extruder2_ExtrusionPWM(0..1)=1
Extruder2_ExtrusionSize(mm)=0.5
Extruder2_ExtrusionSpeed(mm/minute)=1500
Extruder2_ExtrusionTemp(C)=205
Extruder2_FastEFeedrate(mm/minute)=7000.0
Extruder2_FastXYFeedrate(mm/minute)=1500.0
Extruder2_InFillMaterialType(name)=PLA-infill
Extruder2_InfillOverlap(mm)=0.2
Extruder2_InfillSpeed(0..1)=1
Extruder2_Lift(mm)=0
Extruder2_MaterialType(name)=PLA-infill
Extruder2_MaxAcceleration(mm/minute/minute)=1200000.0
Extruder2_MiddleStart=true
Extruder2_NumberOfShells(0..N)=1
Extruder2_OddHatchDirection(degrees)=-45
Extruder2_OffsetX(mm)=0
Extruder2_OffsetY(mm)=0
Extruder2_OffsetZ(mm)=0
Extruder2_OutlineSpeed(0..1)=0.9
Extruder2_Purge(ms)=30000
Extruder2_Reverse(ms)=2000
Extruder2_SeparationOutlineSpeed(0..1)=1
Extruder2_SlowXYFeedrate(mm/minute)=1500.0
Extruder2_SupportMaterialType(name)=null
Extruder2_ValveDelayForLayer(ms)=200
Extruder2_ValveDelayForPolygon(ms)=200
Extruder2_ValveOverRun(mm)=2
Extruder2_ValvePulseTime(ms)=-500
Extruder3_Address=1
Extruder3_ArcCompensationFactor(0..)=8
Extruder3_ArcShortSides(0..)=1
Extruder3_ColourB(0..1)=0.3
Extruder3_ColourG(0..1)=0.3
Extruder3_ColourR(0..1)=0.3
Extruder3_CoolingPeriod(s)=0.1
Extruder3_EvenHatchDirection(degrees)=45
Extruder3_ExtrudeRatio(0..)=1
Extruder3_ExtrusionBroadWidth(mm)=6
Extruder3_ExtrusionDelayForLayer(ms)=600
Extruder3_ExtrusionDelayForPolygon(ms)=500
Extruder3_ExtrusionFoundationWidth(mm)=2
Extruder3_ExtrusionHeight(mm)=0.25
Extruder3_ExtrusionInfillWidth(mm)=1.5
Extruder3_ExtrusionLastFoundationWidth(mm)=2
Extruder3_ExtrusionOverRun(mm)=0
Extruder3_ExtrusionPWM(0..1)=-1
Extruder3_ExtrusionSize(mm)=0.3
Extruder3_ExtrusionSpeed(mm/minute)=1500
Extruder3_ExtrusionTemp(C)=0
Extruder3_FastEFeedrate(mm/minute)=8000.0
Extruder3_FastXYFeedrate(mm/minute)=1500.0
Extruder3_InFillMaterialType(name)=null
Extruder3_InfillOverlap(mm)=0.2
Extruder3_InfillSpeed(0..1)=0.9
Extruder3_Lift(mm)=0
Extruder3_MaterialType(name)=Alloy
Extruder3_MaxAcceleration(mm/minute/minute)=1200000.0
Extruder3_MiddleStart=true
Extruder3_NumberOfShells(0..N)=1
Extruder3_OddHatchDirection(degrees)=-45
Extruder3_OffsetX(mm)=0
Extruder3_OffsetY(mm)=0
Extruder3_OffsetZ(mm)=0
Extruder3_OutlineSpeed(0..1)=0.9
Extruder3_Purge(ms)=10000
Extruder3_Reverse(ms)=400
Extruder3_SeparationOutlineSpeed(0..1)=1
Extruder3_SlowXYFeedrate(mm/minute)=1500.0
Extruder3_SupportMaterialType(name)=null
Extruder3_ValveDelayForLayer(ms)=200
Extruder3_ValveDelayForPolygon(ms)=200
Extruder3_ValveOverRun(mm)=2
Extruder3_ValvePulseTime(ms)=500
FinishX(mm)=10
FinishY(mm)=190
FiveD=true
FoundationLayers=0
GCodeUseSerial=false
InterLayerCooling=false
MaximumFeedrateX(mm/minute)=1500
MaximumFeedrateY(mm/minute)=1500
MaximumFeedrateZ(mm/minute)=50
MaxXYAcceleration(mm/minute/minute)=1200000
MaxZAcceleration(mm/minute/minute)=3000
NumberOfExtruders=4
PathOptimise=true
Port(name)=/dev/ttyUSB1
RepRap_Machine=GCodeRepRap
Shield=false
SlowXYFeedrate(mm/minute)=1500.0
SlowZFeedrate(mm/minute)=50.0
WorkingX(mm)=300
WorkingY(mm)=300
WorkingZ(mm)=300
F. Alloy Extruder Iterations

Here all extruder designs trialled are detailed. Initially a standard RepRap design based on 3mm filament (iteration 1), was trialled however the solubility problems detailed in the relevant chapter were observed, similar problems were shown with an aluminium nozzle (iteration 2). Whilst these fundamental problems were resolved, PTFE extruders were developed (iteration 3 and 4), to combat the low thermal conductivity of PTFE the melt zone was initially increased to 70mm however problems arose with poor control. Namely transient performance was poor with puddles of material often being deposited. Hence the filament diameter was reduced to 2mm to reduce thermal mass - improving transient performance, and the melt zone reduced to 60mm. This was sufficient to trial the 2nd material iteration discussed in the relevant chapter. Finally a more compact and robust design was developed based on an anodised nozzle in order to eliminate the solubility issues with an extremely compact melt zone.

F.1. Final Alloy Extruder
<table>
<thead>
<tr>
<th>Part Number</th>
<th>Part Name</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>PEEK Insulator</td>
</tr>
<tr>
<td>2</td>
<td>Aluminum Heater Block</td>
</tr>
<tr>
<td>3</td>
<td>Aluminium Nozzle</td>
</tr>
<tr>
<td>4</td>
<td>4x2 PTFE Liner</td>
</tr>
<tr>
<td>5</td>
<td>O Ring</td>
</tr>
</tbody>
</table>

**SECTION A-A**

**Dimension:**
- 18
- 24
- 58.6

**Notes:**
- DO NOT SCALE DRAWING
- UNLESS OTHERWISE SPECIFIED:
  - SCALE: 1:1
  - WEIGHT:
  - TITLE: Final Extruder Assembly
  - SIZE: A
  - DWG. NO.: 0001
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<td>TOLERANCES:</td>
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<tr>
<td>LINEAR +/-0.1MM</td>
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<td>INTERPRET GEOMETRIC</td>
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<td>TOLERANCING PER:</td>
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<td>USED ON</td>
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<td>APPLICATION</td>
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<td>DO NOT SCALE DRAWING</td>
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</tr>
</tbody>
</table>

**Title:** Aluminium Heater Block

**Size:** A

**Drawing Number:** 0001

**Scale:** 2:1

**Comments:**
0.5x2mm Orifice

SECTION A-A

Aluminium Nozzle

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN MM
TOLERANCES:
FRACTIONAL:
LINEAR +/- 0.1MM

APPLICATION
USED ON NEXT ASSY

5 4 3 2 1

Aluminium
Nozzle
UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN MM
TOLERANCES:
FRACTIONAL
LINEAR: +/- 0.1MM

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

NEXT ASSY
USED ON
FINISH

APPLICATION
DO NOT SCALE DRAWING

TITLE:

PEEK Insulator

SIZE
A

DWG. NO.
0001

REV

SCALE: 2:1
WEIGHT:

SHEET 1 OF 1
F. Alloy Extruder Iterations

F.2. Standard RepRap Extruder (Iteration 1)
Brass Heater Block

Dimensions are in mm

Material: Brass

Interpret geometric tolerancing per:

UNLESS OTHERWISE SPECIFIED:

- Dimensions are in mm
- Tolerances:
  - Fractional: ±0.1
  - Angular: Mach Bendl
  - Linear: ±0.1

Finish and material:

Next Assy Used On Finish

Application Do Not Scale Drawing

SCALE: 2:1

REVDWG. NO. A
SIZE DWG. NO. 0001

UNLESS OTHERWISE SPECIFIED:
Brass Nozzle

Dimensions in mm

- Diameter: 9.4 mm
- Length: 18 mm
- Orifice: 0.5 mm, 1 mm deep

Section A-A

Notes:
- Do not scale drawing
- Unless otherwise specified, scale 2:1
- Dimension tolerances:
  - Angular: ±0.1°
  - Linear: ±0.1 mm

Application:
- Used on next assembly

Title:
Brass Nozzle

Drawn:
0001

Sheet 1 of 1
F.3. Standard RepRap Extruder with Aluminium Nozzle (Iteration 2)
Part Number | Part Name
---|---
1 | PEEK Insulator
2 | Brass Heater Block
3 | Aluminium Nozzle
4 | 6x4x36 PTFE Tubing

**SECTION A-A**

**Iteration 2**

**Assembly**

**UNLESS OTHERWISE SPECIFIED:**

- DIMENSIONS ARE IN MM
- TOLERANCES:
  - FRACTIONAL ± 0
  - LINEAR: ± 0.1

**INTERPRET GEOMETRIC TOLERANCING PER:**

- MACH
- BEND
- LINEAR: ± 0.1

**APPLICATION**

- USED ON
- FINISH

**NEXT ASSY**

- DO NOT SCALE DRAWING

**DRAWN**

- DRAWN
- CHECKED
- ENG APPR.
- MFG APPR.

**COMMENTS:**

**TITLE:**

Iteration 2

Assembly

**SIZE**

A

**DWG. NO.**

0001

**REV**

A

**SCALE:** 1:1

**WEIGHT:**

**SHEET:** 1 OF 1
Aluminium Nozzle

Dimensions are in mm. Tolerances: Fractional ± 0.1, Angular ± 0.1°, Linear ± 0.1

Interpret geometric tolerancing per:

Material: Aluminium

Application: Used on nextassy

Finish: DO NOT SCALE DRAWING

Scale: 2:1

Weight: 0001

Sheet 1 of 1
F.4. Initial PTFE Nozzle Extruder (Iteration 3)
<table>
<thead>
<tr>
<th>Part Number</th>
<th>Part Name</th>
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<tbody>
<tr>
<td>1</td>
<td>Brass Inner Heater</td>
</tr>
<tr>
<td>2</td>
<td>Brass Outer Heater</td>
</tr>
<tr>
<td>3</td>
<td>PTFE Nozzle Insert</td>
</tr>
<tr>
<td>4</td>
<td>PEEK Insulator</td>
</tr>
<tr>
<td>5</td>
<td>4x3x90 PTFE Liner</td>
</tr>
</tbody>
</table>

SECTION A-A

Iteration 3
Assembly

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
FRACTIONAL: ±
ANGULAR: MACH.
LINEAR: ±0.1

INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL

NEXT ASSY
USED ON
FINISH

APPLICATION
DO NOT SCALE DRAWING

DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:

SIZE: A
DWG. NO.: 0001
REV:
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
Brass Outer Heater

Dimensions are in mm
Tolerances:
- Fractional
- Angular: Mach
- Linear: +/- 0.1

Interpret geometric tolerancing per:

Material

Title: Brass Outer Heater

Title: Brass Outer Heater

Title: Brass Outer Heater

Title: Brass Outer Heater

Title: Brass Outer Heater

Title: Brass Outer Heater

Title: Brass Outer Heater

Title: Brass Outer Heater
PTFE Nozzle Insert

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN MM
TOLERANCES:
FRACTIONAL ± 1
ANGULAR: MACH ± 1
LINEAR +/- 0.1

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

TITLE:

DRAWN:
CHECKED:
ENG APPR.:
MFG APPR.:
Q.A.

COMMENTS:

Q.A.  MFG  APPR.  ENG  APPR.  CHECKED  DRAWN

NEX ASSY  USED ON  FINISH

APPLICATION  DO NOT SCALE DRAWING

SCALE: 10:1  WEIGHT:  SHEET 1 OF 1
F. Alloy Extruder Iterations

F.5. Final PTFE Nozzle Extruder (Iteration 4)
### PART LIST

<table>
<thead>
<tr>
<th>Part Number</th>
<th>Part Description</th>
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</thead>
<tbody>
<tr>
<td>1</td>
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<tr>
<td>2</td>
<td>Brass Outer Heater</td>
</tr>
<tr>
<td>3</td>
<td>PTFE Nozzle Insert</td>
</tr>
<tr>
<td>4</td>
<td>PEEK Insulator</td>
</tr>
<tr>
<td>5</td>
<td>4x2x80 PTFE Liner</td>
</tr>
</tbody>
</table>

### SECTION A-A

1. Brass Inner Heater
2. Brass Outer Heater
3. PTFE Nozzle Insert
4. PEEK Insulator
5. 4x2x80 PTFE Liner

---

**UNLESS OTHERWISE SPECIFIED:**

- **DIMENSIONS ARE IN MM**
- **TOLERANCES:**
  - FRACTIONAL
  - ANGULAR: MACH
  - LINEAR: ±0.1

**INTERPRET GEOMETRIC TOLERANCING PER:**

**MATERIAL**

**APPLICATION**

**NEXT ASSY**

**USED ON**

**FINISH**

**DO NOT SCALE DRAWING**

---

**TITLE:** Iteration 4 Assembly

**SIZE:** A

**DWG. NO.:** 0001

**REV:** A

**SCALE:** 1:1

**WEIGHT:**

**SHEET:** 1 OF 1
PTFE Nozzle Insert

SECTION A-A

DIMENSIONS ARE IN MM
TOLERANCES:
FRACTIONAL: ± 0.1
ANGULAR: MACH
LINEAR +/− 0.1

INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL

NEXT ASSY
USED ON
FINISH

APPLICATION
DO NOT SCALE DRAWING

UNLESS OTHERWISE SPECIFIED:

TITLE:
PTFE Nozzle Insert

SIZE A
DWG. NO. 0001
REW

SCALE: 10:1
WEIGHT:
SHEET 1 OF 1

NAME DATE
DRAWN CHECKED
ENG APPR. MFG APPR.
Q.A. COMMENTS:

5 4 3 2 1
PTFE Nozzle
Insert