Improved Thermal Control and Mechanical Property Evaluation for Multi-Dimensional Fused Filament Fabrication of Sandwich Cores

By

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A dissertation submitted to the University of Bristol in accordance with the requirements of the degree of DOCTOR OF PHILOSOPHY in the Faculty of Engineering.

OCTOBER 2018

Word count: approx. 61,500
Additive Manufacture (AM) is a technique capable of economically producing low volumes of complex components. Fused Filament Fabrication (FFF), a form of AM, successively deposits layers of extruded filament; the inter-layer bonds are typically the weakest regions the structure, with the strength determined by the deposition temperature and cooling rate. This thesis investigates its application to production of aerospace sandwich cores, through improved thermal control of the extruded temperature, the use of an industrial robotic arm for manipulation, and the mechanical properties of thin-walled components.

An investigation into the high speed thermal dynamics of the FFF process monitored the filament temperature, identifying a relationship with the recent time history of the feed rate, and a thermistor embedded in the nozzle better reflected the extruded temperature than a conventional, block-mounted thermistor. The application of a feed-forward controller greatly reduced fluctuations in the nozzle and filament temperature.

To overcome the “stacked” planes of inter-layer bonds produced by typical 3 axis FFF machines, the process was implemented on an 8 axis industrial robotic cell. This allowed for deposition of non-planar layers onto a cylinder and hemisphere, and the production of complex aerofoil cores.

This system was then used to evaluate the inter-layer bond strength of components produced with different bed orientations, relative to the gravity vector, and nozzle orientations, relative to the print bed. Results showed there was little effect of bed orientation on bond strength, but a significant effect of the nozzle orientation.

Additional testing identified the wall thickness affected the ductility of the failure under tension, with specimens of increasing wall thickness behaving closer to that expected of the bulk material. Similar results were observed for compressive testing of FFF cores, finding a similar specific compressive strength to the industrial-standard Nomex material, but a significantly higher compressive force.
This work was supported by the EPSRC Centre for Doctoral Training in Future Autonomous Robotic Systems (FARSCOPE) at the Bristol Robotics Laboratory (grant: EP/L015293/1). Additional travel grants were awarded by the SAMPE UK and Ireland Chapter and the Alumni Foundation – the author is very grateful for this support.

I would like to thank my supervisors, Dr. Carwyn Ward and Dr. Guido Herrmann, for their advice and support over the course of this project. Dr. Mike Elkington was instrumental in aiding the operation of the ABB robot, and the staff at ABB Robotic Support for answering my numerous questions on RAPID. Next, Dr. Julie Etches, the ACCIS lab support group, and the workshop technicians all provided invaluable assistance to aid the completion of this project. Jasper Kearney and Fionn Royer-Gray both assisted in this research through their undergraduate projects, with useful contributions and discussions.

The FARSCOPE CDT team, both the staff and the cohort members, were exceptional in motivating us and providing support where needed – the writing retreats at Engineers House provided ample pink wafer biscuits to finish the thesis. The other members of the ACT Cave are also very deserving of gratitude for their help, support, and coffee breaks. Its been great sharing an office with you all.

Having an amazing group around me outside of the University was a great help. My family, friends, and the sport of triathlon, have all provided welcome distractions to keep me on track over the course of the thesis. And finally a quote my family will appreciate:

Expectation wasn’t just about what people expected of you. It was about what you expected from yourself.

–Brandon Sanderson, Words of Radiance
I declare that the work in this dissertation was carried out in accordance with the requirements of the University’s Regulations and Code of Practice for Research Degree Programmes and that it has not been submitted for any other academic award. Except where indicated by specific reference in the text, the work is the candidate's own work. Work done in collaboration with, or with the assistance of, others, is indicated as such. Any views expressed in the dissertation are those of the author.

SIGNED: .................................................... DATE: ..........................................
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<td>182</td>
</tr>
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<td>A.7</td>
<td>Schematic of the Directed Energy Deposition process</td>
<td>182</td>
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</table>
**NOMENCLATURE**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>ABS</td>
<td>Acrylonitrile butadiene styrene</td>
</tr>
<tr>
<td>AFP</td>
<td>Automated Fibre Placement</td>
</tr>
<tr>
<td>AM</td>
<td>Additive Manufacture</td>
</tr>
<tr>
<td>AMF</td>
<td>Additive Manufacturing Format</td>
</tr>
<tr>
<td>CAD</td>
<td>Computer Aided Design</td>
</tr>
<tr>
<td>CLAS</td>
<td>Curved Layer Adaptive Slicing</td>
</tr>
<tr>
<td>CLFFF</td>
<td>Curved Layer Fused Filament Fabrication</td>
</tr>
<tr>
<td>CMM</td>
<td>Coordinate Measuring Maching</td>
</tr>
<tr>
<td>CNC</td>
<td>Computer Numerically Controlled</td>
</tr>
<tr>
<td>DED</td>
<td>Directed Energy Deposition</td>
</tr>
<tr>
<td>DOF</td>
<td>Degree of Freedom</td>
</tr>
<tr>
<td>EU</td>
<td>European Union</td>
</tr>
<tr>
<td>FAA</td>
<td>Federal Aviation Administration</td>
</tr>
<tr>
<td>FDM</td>
<td>Fused Deposition Modelling (Stratasys Trademark)</td>
</tr>
<tr>
<td>FFF</td>
<td>Fused Filament Fabrication</td>
</tr>
<tr>
<td>FEA</td>
<td>Finite Element Analysis</td>
</tr>
<tr>
<td>FF</td>
<td>Feed-forward</td>
</tr>
<tr>
<td>IT</td>
<td>Information Technology</td>
</tr>
<tr>
<td>MDDL</td>
<td>Multi-Directional Layered Deposition</td>
</tr>
<tr>
<td>ME</td>
<td>Material Extrusion</td>
</tr>
<tr>
<td>PBF</td>
<td>Powder Bed Fusion</td>
</tr>
<tr>
<td>Prepreg</td>
<td>Pre-impregnated Fibre</td>
</tr>
<tr>
<td>PWM</td>
<td>Pulse Width Modulated</td>
</tr>
<tr>
<td>QA</td>
<td>Quality Assurance</td>
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<td>RM</td>
<td>Rapid Manufacturing</td>
</tr>
<tr>
<td>RP</td>
<td>Rapid Prototyping</td>
</tr>
<tr>
<td>STL</td>
<td>Standard Triangle Language</td>
</tr>
<tr>
<td>TCP</td>
<td>Tool Centre Point</td>
</tr>
</tbody>
</table>
Extruder: The deposition subsystem of an FFF machine comprised of a hotend and feed motor

Feed-forward: A control element using a source from the external environment
Feed rate: The speed at which filament is fed into the extruder hotend
Hotend: Heated section of the extruder, comprised of a nozzle, heater block, and heat sink
Prime: Sudden application of a positive feed rate to commence extrusion
Retract: Sudden application of a negative feed rate to cease extrusion
The modern world can be defined by the growing complexity of manufactured goods, from increasingly efficient jet aircraft to customised medical devices. A constant balance must be adopted between newer and more competitive technologies, and ensuring fulfilment of the design objectives and reliability in service. Additive manufacturing is a modern process capable of producing complex and cost-effective components, enabling rapid design iterations and a low volume production. The research presented in this thesis explores potential quality assurance aspects of Fused Deposition Modelling, a form of additive manufacture, and the increased design space afforded to a robotic arm-based extruder. This thesis will focus on its application to aerospace sandwich cores, which are high value products with low production volumes, and thus an ideal candidate process for AM.

Introducing the history and current trends of the additive manufacturing and composites industries, this section presents the scope of the research project and its applicability to the Aerospace sector. The aims and objectives of this project are shown, followed by a list of publications, and concludes with the structure of the remainder of this thesis.

1.1 Additive Manufacture

Additive Manufacture (AM), colloquially known as “3D Printing”, is formally defined by ISO52900 as a “process of joining materials to make parts from 3D model data, usually layer upon layer” [1], where a part can be produced directly from a Computer Aided Design (CAD) models. The use of raw material in powder or filament form is in contrast to subtractive manufacture, where a component is machined from a block of material. The Fused Filament Fabrication (FFF) process, as used over the course of this project, is depicted in Figure 1.1. A complete overview of AM processes is provided in Section 2.1.2 and illustrated in Appendix A.
CHAPTER 1. INTRODUCTION

Figure 1.1. Schematic of a typical FFF printer. (a) shows the filament supply, being drawn into the movable hotend by the extruder motor, (b), where it is melted and pushed through the nozzle (c). Deposited on a build platform, (e), movable in the z direction, the final part can be built up (f). To support the overhanging regions, support structures are necessary (d). Image from [2].

1.1.1 History and development of AM

Modern AM processes are derived from a number of older practices. Topography, the creation of 3D maps, was pioneered to create 3D terrain maps through clay modelling or the stacking of wax casts cut from contour lines; examples of raised relief map have been found from the Han Dynasty in China, dating from 206 BC-220 AD [3]. Photosculpture, developed by François Willème in 1864, could be considered the modern forerunner for modern 3D scanning and manufacture [4], where a rotating series of silhouettes were used as guides to carve a sculpture. A similar light-based technique, patented in 1922, used different intensities to cure variable depths of a gelatin slab [5].

The introduction of computers revolutionised manufacturing; subtractive Computer Numerical Control (CNC) machines in the 1940s provided an increase in the accuracy, repeatability, and productivity of factories. During the leaps in available computing power following Moore’s law, more complex toolpaths and control required for additive processes could be realised. An early paper in 1991 by Kruth [6] reviewed the processes available at the time, providing three classifications based on the state of the build material; powder, resin, and filament. The prevalence of GCode within the AM industry today is based on the initial conversion of CNC machines from subtractive to additive manufacture.

Directed Energy Deposition (DED) was introduced in the form of a welding tool to deposit
1.1. ADDITIVE MANUFACTURE

Figure 1.2. Comparison of production cost and volume for Selective Laser Sintering (SLS) AM process over conventional High Pressure Die-Casting (HPDC) for an aerospace landing strut Image from: [10] ©Springer

droplets of metal, with “Shape Welding” pioneered in Germany in the 1960s, producing large free standing structures [7]. This technique was used to produce large pressure vessels weighing up to 500 tonnes [7]. AM in its current form has been widely adopted in the form of Material Extrusion (ME), a process patented by Stratasys in 1992 under the trademark “Fused Deposition Modelling” [8].

AM was initially used for Rapid Prototyping (RP) during the design cycle. The ability to easily produce more complex components shortens design iterations, allows interface fit testing, and customers can gain an insight into the size, shape, and weight of the product [9]. Rapid Manufacturing (RM) applies RP into the manufacture of end use components; Figure 1.2 shows the same unit price is achieved per component for AM, whereas a conventionally manufactured component cost per component varies due to the tooling and setup costs [10]. This figure identifies key beneficiaries of AM would be industries with small production runs and high part complexity.

1.1.2 Current interest in AM

AM applications fall onto the “Hype Cycle”, a construct to estimate the expectation of a technology and its readiness for industrial use. Typically, new technologies are presented as a more complete solution, leading to a sudden rise and corresponding fall of expectations, before industry matures to find an optimum use within the technological constraints. A 2015 report by the European Commission located each application, and predicted which technologies are ready for industrial application through their position on the Hype Cycle, shown in Figure 1.3 [11]. This report showed AM as used for prototyping is mature and well understood, located within the Plateau of Productivity, whereas for manufacturing operations was just past the Peak of Inflated Expectations, and real limitations are hindering adoption.
In recent years, larger Aerospace corporations have become extensively involved in the AM industry; a key example is the acquisition of the controlling shares of two metal-based AM companies (Arcam and Concept Laser) by General Electric [12]. In conjunction with the exponential growth in metal AM system sales, as shown in Figure 1.4, the advantages afforded to AM for manufacturing are starting to be realised for use on airframes [13, 14].

Polymer AM has experienced slower adoption for manufacturing due to the lower strength of the inter-layer bonds [16, 17]. Stratasys has successfully qualified its ULTEM resin material for aircraft interior components, complying with the Federal Aviation Administration (FAA) Smoke and Toxicity Requirements [18], and has commercialised a printer with specialised hardware and software to aid the FAA and European Aviation Safety Agency (EASA) certification process [19]. A second major use of polymer AM within the Aerospace industry is the manufacture of composite tooling – moulds to ensure composite panels conform to the correct shape; the low-volume production requirements can enable economical repair of legacy aircraft [20].

In a workshop on Rapid Technologies in 2009, Bourell et al. [21] identified a number of key areas for future development. Such requirements include process monitoring and control, involving exploration of the predictive process-structure-properties, and the integration of closed-
loop and adaptive control systems. Additionally, a better understanding and characterisation of the AM materials and machines was highlighted to aid industrial adoption.

### 1.1.3 Typical failure features

FFF components can exhibit a number of features during a print failure, with an example from the hobbyist level Makerbot Replicator 2 shown in Figure 1.5. The ridged upper surface of the print shows the failure was due to a nozzle blockage, either from a low extrusion temperature or foreign debris. A second defect related to the extrusion process is the sprue, caused from insufficient retraction during a travel movement; the retraction moves the melt front away from the nozzle orifice to reduce the “ooze”, which would cause sprue formation upon a rapid travel movement. A final defect is the peeling from the print bed due to the thermal contraction of the polymer. While this deformation is inevitable in extrusion processes due to the temperature change during the solidification process, the bed height must be accurately adjusted to ensure adhesion over the entire surface.

With a typical FFF printer, support structures are necessary to avoid the collapse of overhanging sections. This necessitates post-processing removal, typically manually achieved, although some soluble support materials are available. On the inside of the component, “infill” acts to support the upper layers, and can be set to different densities dependent on strength or build time requirements. Similar to the supports, the large “raft” on the bottom of the component increases the surface area to improve bed adhesion, requiring similar post-processing to remove.
1.2 Composite Materials

The joining of two or more dissimilar materials in a composite component can provide significant advantages over the traditional materials of metals, alloys, and wood. Over the past century, fibre reinforced plastics have combined stiff fibres with a ductile matrix for a variety of applications; notable use has been in the weight-sensitive Aerospace industry, with over 50% composite structural weight on modern airframes, as shown in Figure 1.6(a). For components requiring a high stiffness, core materials are placed between two face sheets to form a sandwich structure; by separating the in-plane load-bearing face sheets, stiffness can increase disproportionately to the weight, as shown by Figure 1.6(b) [22].

1.2.1 History and development of composite materials

The practice of combining dissimilar materials began in ancient times, with bricks made from a mud matrix and reinforced with straw. Complex composites were created by the Mongolians, comprising of a wooden core with strips of cattle horn and tendons glued to the inside and outside respectively to produce a powerful bow [24]. Functionally grading was exhibited in these weapons with different woods used for bending and non-bending sections.

First accidentally produced from the drawing of molten glass during the application of lettering to milk bottles, glass fibre started the era of modern composites. Initially used with a phenolic plastic matrix, this composite provided a flexible and cost-effective alternative for complex metal tooling. After the development of more advanced polymers and resins, fibreglass components were adopted for structural use on airframes during World War II; the surplus production at the end of the war motivated the expansion into a variety of markets [24].

It was during World War II that sandwich panels were also first used on the DeHavilland Mosquito, a British multi-purpose combat aircraft. With restrictions placed on metal use, the aircraft was designed with a monocoque fuselage made of balsa and plywood; the grain direction of the plywood was placed in the primary loading directions in a manner similar to modern fibre
1.2. COMPOSITE MATERIALS

**Figure 1.6.** (a) The percentage of structural weight of composite materials in the Airbus family of aircraft. Image ©Airbus [23]. (b) Benefits of sandwich construction for increased stiffness and strength with a marginal weight gain. Image ©Hexcel [22].
CHAPTER 1. INTRODUCTION

direction selection [25].

Composite use in aircraft has grown, as shown in Figure 1.6(a), alongside associated fabrication methods. Automation technologies, such as Automated Fibre Placement (AFP), have enabled faster manufacture of primary composite structures to maintain increasing production rates of the next generation aircraft. However, secondary structures still dominate the cost of an airframe despite their small size and weight; this is due to high levels of manual forming required [26].

1.2.2 Current interest in sandwich structures

A key objective in development for high performance applications are multi-functional composite components [23], where components fulfil structural requirements in addition to functionality such as damping, damage tolerance, and sensing. With sandwich structures comprising a substantial proportion of a modern airframe, reductions in production costs are vital, with such components making up to 70% of the cost of an aircraft wing while only 30% of the weight [27]. A significant proportion of this cost is due to the manual manufacturing process used for the complex composites [26], and high degrees of inter-component variability; the industry-standard Nomex honeycomb provides an excellent strength to weight ratio for its use in sandwich structures, as seen in Figure 1.6(b), but possesses poor manufacturability due to its low transverse strength [28].

Wider industrial applications are pushing for “Bigger, Faster, Cheaper” parts for applications such as wind turbines, where offshore blades are over 80 m long and weigh in excess of 35 metric tons, and the automotive industry with its constant drive for lowering CO\textsubscript{2} emissions [29]. To reduce the cost and increase the functionality of composite components, new developments in materials and manufacturing processes are necessary.

1.3 Aim and Objectives

Adoption of AM processes would aid composite manufacture, with the increased design space and reduced manufacturing cost over conventional core materials. This thesis investigates quality control aspects of filament temperature during the extrusion process, as would be required for part certification, and the implementation, use, and mechanical properties of printing with an industrial robotic arm, and the research can be summarised by the question:

How can the mechanical quality of FFF components be improved through thermal- and multi-DOF- control for the manufacture of sandwich cores?

This research question was divided into three regions of interest. First, the bonding between layers is highly dependent on deposition temperature; there has been little work on the true extruded temperature of the filament. Next, knowledge of the mechanical properties of the FFF components is required for its application, both as a material, and in comparison to competitor
core materials. Finally, the implementation and programming of a multi-DOF FFF system is required to demonstrate and evaluate curved layer components and its application of core manufacture.

These three regions evaluating the thermal, mechanical, and implementation of FFF provided the following objectives:
CHAPTER 1. INTRODUCTION

**Aim:** To investigate thermal control of the FFF process and evaluate mechanical properties of thin-walled FFF components.

**Objectives:**

- Analyse the filament temperature during the extrusion process to identify and implement improved control strategies.
- Compare the performance of a core produced with AM to aerospace-grade Nomex honeycomb.
- Analyse the effect of utilising the higher degrees of freedom of a robotic arm on mechanical properties of FFF components.
- Demonstrate toolpath generation afforded to the high degree of freedom manufacturing systems.

1.4 List of Publications

Table 1.1 lists papers published over the course of this project, and links are provided to supporting multimedia of the robot operation in Table 1.2.
## 1.4. LIST OF PUBLICATIONS

<table>
<thead>
<tr>
<th>Publication type</th>
<th>Associated chapter(s)</th>
<th>Reference</th>
</tr>
</thead>
</table>
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Table 1.2. Supporting media available on YouTube.

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<tr>
<th>Title</th>
<th>Description</th>
<th>Hyperlink</th>
</tr>
</thead>
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<tr>
<td>Curved Layer FDM with a robotic arm</td>
<td>Supporting video for ECCM18</td>
<td>[Link]</td>
</tr>
<tr>
<td>Robotic FDM orientation tests</td>
<td>Supporting video for Chapter 7. NB: Private video, requires URL for access.</td>
<td>[Link]</td>
</tr>
<tr>
<td>Arm-based 3D Printing for composite repair</td>
<td>Demonstration of composite repair manufacture</td>
<td>[Link]</td>
</tr>
</tbody>
</table>

1.5 Thesis outline

This thesis begins with a literature review in Chapter 2, introducing the broad topics of AM and composite manufacture. This discusses recent academic literature and industrial research into AM, allowing construction of a Venn diagram, Figure 2.14, which summarises the research completed into the overlapping regions of design space, quality assurance methods, and part properties. Table 2.6 links the remaining chapters of this thesis to the related literature review sections, and the associated region of this Venn diagram.

The first section of research examines the filament temperature during the extrusion process; Chapter 3 investigates the high speed dynamics of the filament temperature during step changes in feed rate, and the start/stop process. Monitoring of the filament temperature was conducted with a thermal camera and a nozzle-based thermistor, rather than the traditional block-mounted thermistor.

Chapter 4 builds on the previously identified trends to implement advanced thermal control methods of a delay compensation through a Smith Predictor and feed rate compensation through feed-forward control. This presents the modelling of thermal dynamics, implementation of these controllers, and evaluation with a variable feed rate signal.

Results of tensile testing to identify the effect of wall thickness on the inter-layer bonding properties of FFF components are discussed in Chapter 5. FFF cores were compared to the industry standard Nomex core in compression, comparing ultimate tensile stress and specific ultimate tensile stress.

Chapter 6 begins the examination and implementation of multi-dimensional FFF, comparing the structural layouts of different FFF printers, before describing the developed system using an industrial robotic arm. Toolpath generation methods for cylindrical and curved substrates are presented, and the manufacture of curved layer aerofoil cores is demonstrated.

With the increased flexibility afforded to a robotic arm, a novel study of FFF material properties is described in Chapter 7, investigating bond strength through tensile testing with a variety of print bed and nozzle angles.

A discussion of the research is presented in Chapter 8, covering the themes of thermal control, mechanical properties, and robotic implementation. To provide industrial context, a cost
comparison between machined Nomex, traditional AM, and the robotic AM system is presented, followed by a Technology Readiness Level (TRL) assessment of the developed system.

Finally, the conclusions, limitations of the research, and further work are presented in Chapter 9.
Additive Manufacture (AM) is a topic of ongoing research in both academia and industry. This chapter introduces the main research themes within the field of AM, and its application to producing composite sandwich structures. A brief overview of the advanced manufacturing industry is provided, followed by a summary of the main research areas within sandwich panel production and polymer-based FFF, and the current work on quality assurance and control. Finally, advanced FFF processes are discussed, before concluding with the identification of research gaps within this field.

It should be noted there is a wealth of information available on forums for 3D printing and composite manufacture which has not been assessed over the course of this literature review. While this provides a range of background knowledge and practical help for both fields, they do not significantly contribute to the forefront of research.

2.1 State of the advanced manufacturing industry

Manufacturing is vital to the modern economy comprising of international supply chains with a worldwide value of $11.4 trillion [30]. It is often described as experiencing the 4th industrial revolution; termed Industrie 4.0 by the seminal German report [31]. Following from the previous industrial revolutions of mechanised steam power (1700s), mass production and electricity (mid-1800s), and increased automation and Information Technology (IT) (1970s), this revolution involves advanced automation, data acquisition and analysis [31]. Adoption of Industrie 4.0 allows devices to autonomously communicate along the value chain, including those extrinsic to the company to allow for more efficient integration of manufacturing operations.

AM fits within this paradigm through the potential for high levels of component customisation, allowing for increasing production line flexibility, and a reduction in inventory storage cost [32].
CHAPTER 2. LITERATURE REVIEW

With the increased geometric complexity achievable within AM components, the part count can be reduced to provide both time and cost savings [9]. The AM industry currently represents less than 0.05% of the global manufacturing industry, showing a significant potential for increased adoption.

2.1.1 Research funding and centres

With this strong economic motivation for the industrial adoption of AM, there has been significant research and the development of research hubs around the world. The European Union (EU) is actively pursuing Industrie 4.0, providing €500 million for “digital innovation hubs”, and €270 million for research into “factories of the future” [31].

The UK Additive Manufacturing Roadmap [30] noted only 17% of UK firms had experience with AM technologies, compared to 24% in China and 37% in Germany. This was tackled in the UK through establishment of high value manufacturing “catapult centres”, including the National Centre for Additive Manufacturing, to provide training and research for industry.

The most comprehensive report was produced by the America Makes & ANSI Additive Manufacturing Standardization Collaborative (AMSC) in 2017 [33], providing guidance for industrial development and adoption of AM. To identify research needs, four subgroups investigated precursor materials, process control, post-processing, and finished material properties, providing recommendations categorised into low, medium, and high priorities.

Corresponding with the industrial adoption, there has been increasing numbers of publications in academic literature; Figure 2.1 shows the number of papers with key words of “3D Printing” or “Additive Manufacture” listed on the Web of Science.

2.1.2 AM Processes

Additive Manufacture is defined by ISO52900 as a “process of joining materials to make parts from 3D model data, usually layer upon layer” [1], allowing the build up of parts as opposed to subtractive machining of raw material. Seven classifications of AM processes were identified, related to the feed material form and the method used for joining layers [1]. These are summarised in Table 2.1, along with examples of commercial machine manufacturers. Appendix A provides images describing each process, and Fused Filament Fabrication, as used in this project, was shown in Figure 1.1. Typical polymers used for FFF are polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS).
2.1. STATE OF THE ADVANCED MANUFACTURING INDUSTRY

Figure 2.1. Published papers with topics listed as “3D Printing” or “Additive Manufacture” (Web of Science, data range 1970-2017).
<table>
<thead>
<tr>
<th>Categories</th>
<th>Printed substrate</th>
<th>Strengths/Weaknesses</th>
<th>Commercial Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material Extrusion</td>
<td>Thermoplastics, Ceramic slurries, Metal pastes</td>
<td>Inexpensive, multi-material Limited part resolution, poor surface finish</td>
<td>Ultimaker, Stratasys</td>
</tr>
<tr>
<td>Powder Bed Fusion</td>
<td>Polymer/Polyamides, Atomised metal powder, ceramic powder</td>
<td>High accuracy, Fully dense parts, High specific strength suitability for powder recycling Requires anchor and support structures</td>
<td>Arcam, Concept Laser</td>
</tr>
<tr>
<td>Vat Polymerisation</td>
<td>Photopolymer, Ceramics</td>
<td>Smooth surface finish, poor durability (esp. when exposed to UV)</td>
<td>Formlabs, Carbon 3D</td>
</tr>
<tr>
<td>Material Jetting</td>
<td>Photopolymer, Wax</td>
<td>Multi-material printing, good surface finish Low strength</td>
<td>Stratasys PolyJet, XJET</td>
</tr>
<tr>
<td>Binder Jetting</td>
<td>Polymer, Ceramic, or Metal Powders</td>
<td>Full-colour objects, wide material selection High porosity, requires infiltration during post-processing</td>
<td>ExOne, Viridis3D</td>
</tr>
<tr>
<td>Sheet Lamination</td>
<td>Plastic Film, Metallic Sheet, Paper</td>
<td>Excellent surface finish, low cost materials Post-processing difficulties</td>
<td>Mcor, Helisys</td>
</tr>
<tr>
<td>Directed Energy Deposition</td>
<td>Molten metal wire or powder</td>
<td>Good control of grain structure Requires extensive post-processing</td>
<td>Mx3D, Sciaky</td>
</tr>
</tbody>
</table>
2.2 Sandwich panel manufacture and research

Sandwich panels are commonly used as secondary structures within the Aerospace industry due to the advantageous properties of high stiffness, suitability for complex geometries, and low mass [26]; Figure 2.2 shows the high level of composite use on the A350 airframe. A major barrier in industries with higher production volumes, such as automotive, is the cost and manufacturing time of complex sandwich panels; such parts can contribute 70% of the cost at just 30% of the weight of an aircraft wing [26, 27]. An example of a complex sandwich panel is shown in Figure 2.3.

Typically manufactured through manual layup, there are multiple sources of component variability and defects [34], leading to high scrap and rework rates [35]. One major error source is the low transverse strength of Nomex honeycomb structures; while they have excellent strength the the vertical direction under compression, they are easily deformed through side loads [28, 36, 37]. Such side loading is common during the layup of the top skin as it is manipulated and draped to conform to complex surface geometries [38].

2.2.1 Conventional sandwich manufacture

Honeycomb structures have been observed at a wide variety of scales in nature, from the hexagonal honeycomb built by bees to the arrangement of carbon atoms in graphene; applications across a range of fields from architecture to biomedicine were explored in a broad paper by
Manufacture of Nomex honeycomb for core material use is typically performed with the expansion method, where successive sheets of Aramid fibre sheets are layered with offset adhesive nodes; spacing between the adhesive layers determines the cell size. This process produces hexagonal honeycomb in a rectangular sheet, which would be transported to the customer for machining and layup.

To begin the sandwich panel manufacture, sheets of pre-impregnated fibres (prepreg) are defrosted from the storage temperature, cut into shape, and kitted into the required sections. The core material is machined and stabilised through addition of an adhesive to the surface to reduce the chances of crushing; an additional cure is sometimes required for this process. Retention onto the build plate and avoidance of cell deformation is provided by a separate medium to provide extra support; images of typical machining errors of uncut fibres and wall tearing were presented by Jaafar et al. After material preparation, the bottom skin is manually deposited, core placed, and then the top skin draped; the manual draping process has been extensively studied by Elkington et al. The completed component is then bagged and cured in an autoclave under pressure. Significant research efforts are underway to adopt a conventional oven over an autoclave, which could save approximately 30% of labour hours required for manufacture.

To produce complex geometries, automated machining processes are required to shape the Nomex core, with the large difference between the in-plane and out-of-plane properties leading to difficulties in dimensional accuracy. In a seminal work on core properties, Foo et al. studied...
2.2. SANDWICH PANEL MANUFACTURE AND RESEARCH

investigate the in-plane tensile and compressive properties of Nomex honeycomb, identifying the
anisotropic in-plane elastic modulus as 0.44 and 0.48 Nmm$^{-2}$, and the out-of-plane compressive
elastic modulus as 120.68 Nmm$^{-2}$. Other issues in the machining of Nomex honeycomb were
identified by Liu et al. [44] include difficulties in retention onto a build plate, poor surface quality,
and a high level of fibrous dust requiring Personal Protective Equipment (PPE) for workers and
post-processing for removal.

An additional difficulty is that of joining panels, as discussed in [41, Chapter 14], with
additional reinforcement required to assist the transfer of loads through the panel skin, typically
requiring prefabricated joints and fasteners to be bonded to the surface. An FAA guidance
document on composite manufacture [45, Chapter 7] describes the process for manufacturing such
inserts, requiring the application of skin stiffening and potting resin, as shown in Figure 2.3(a).
Functional grading would provide additional local stiffening of the core, but Nomex honeycomb
is of uniform cell size, so such implementation would require the splicing of multiple cores
presenting similar issues of skin stiffening, potting resin, and additional fabrication steps.

2.2.2 Application of AM for core manufacture

Additive Manufacture has been previously explored for use in composite repair at the University
of Bristol, as part of a project with the Defence Science and Technology Laboratory (DSTL) [46].
The initial preparation was identical to that recommended by the FAA [45, Chapter 7], where a
section was removed about the damaged section. A laser scanner identified the location and size
of this area, and the FFF core deposited in situ, before the application of potting resin and the
top skin; this process is shown in Figure 2.4.

The repair using the FFF core had superior mechanical properties to an equivalent con-
ventional repair core, however it can be seen there is a significant gap between the repair and
sandwich cores for the potting resin to fill; this was a limitation of the size of the nozzle on
the FFF printer. This project was expanded by the thesis author to demonstrate the end-to-end
manufacture of a sandwich panel, with use of silicon pads for the pick and place layup of the
bottom skin, the FFF production of the core, and the pick and place layup of the top skin [47].

Riss et al. of the Fraunhofer Institute for Machine Tools and Forming Technologies [48],
produced a double-curvature core with wall thickness optimised for localised load cases. This
demonstrated a key advantage of the formability of FFF components, as difficulties arise in
producing such curvatures with honeycomb due to its anticlastic properties. Other advantages of
FFF were also stated as the ability to use “snap-in” connectors to join core sections to produce
parts larger than the printer volume.

Türk et al. [49] demonstrated the potential benefit of AM cores through the redesign of an
aircraft instrument panel from machined aluminium to a composite sandwich. This achieved a
40% weight reduction and 50% reduction in part count.

The Oak Ridge National Laboratory (ORNL) has developed a slicer, a software package to
convert CAD models into AM toolpaths, capable of optimising the honeycomb density within an aerofoil wing, where a smaller cell size is used in the root of the wing where higher loading would be experienced [50, 51]. One difficulty encountered during the generation of this structure was toolpath optimisation, as conventional slicers would produce walls from two deposition passes; such a toolpath would not produce the most lightweight structure, as discussed in Chapter 5. A solution to toolpath generation for such complex, single-walled components was found through a solver of the Chinese Postman Problem by Dreifus et al. [52]. In this problem category, a route was identified to traverse each edge of a graph a single time to produce the lowest density structure.

Industrial interest has been shown by Boeing in 2002, with the filing of a patent entitled “Honeycomb cores for aerospace applications” [53], describing use of AM technologies to produce thermoplastic cores for specialised Radar Cross Section (RCS) applications. This patent also conceptualised snap-in connectors to join sections of printed core similar to those proposed by
2.3 POLYMER FFF

Riss et al. [48]. The advantages of the direct manufacturing of the core were explicitly stated as:

> [0004] It is a further object of the present invention to provide a honeycomb core product which is easier and less costly to manufacture, eliminates expensive processing steps, eliminates foam splice lines, and delivers a consistent product which will reduce or eliminate post production testing (e.g. validation and verification testing).

From this statement, it can be seen AM could provide a solution to core splice lines discussed in Section 2.2.1, in addition to reducing testing requirements.

Other work has examined the manufacture of both the skins and the core through FFF, with Brischetto et al. [54] noting the flexural strength was greatest when the same material was used for both the core and the skin. This makes intuitive sense, as dissimilar polymers would not form as strong bonds, evidenced by their common use for support structures to allow easy removal during post-processing.

An alternative manufacturing method combined principles of the Sheet Lamination category of AM with the expansion method of honeycomb production to generate curved aerofoil sections, achieved through the cutting of paper cross sections before folding and glueing based on kirigami techniques [55]. This work showed the production of a double curvature aerofoil wing, vastly reducing the material waste as opposed to the machining from a conventional block, and highlighted its advantage to current fibre-reinforced tidal turbine blades.

2.3 POLYMER FFF

Polymer FFF is one of the most common forms of AM, and a subset of the Material Extrusion class presented in Table 2.1. Popularised by the open-source RepRap project [56], its flexibility, low cost, and simple construction has led to its extensive use in research. Three broad categories were identified to classify research of polymer-based FFF processes within this section; part properties, mechanical control, and thermal modelling.

2.3.1 Part properties

Parameters used during the manufacturing process affect the final properties of a component due to the concurrent shaping and bonding of the raw material, with key effects described in Table 2.2. As shown in Figure 2.1, there has been extensive academic research into AM, and a summary of some work identifying mechanical properties of components produced through FFF is shown in Table 2.3. Over these studies, a consistent factor is the anisotropy inherent in the layered manufacturing technique, as traditional three Degree of Freedom (3-DOF) systems produce “2.5D” components; this refers to the layers deposited in the xy plane of the print bed, and vertically stacked in the z direction. This process leaves parallel planes of lower strength bonds between each layer.
Table 2.2. Categorisation of process parameters and their effect on product quality adapted from [17, 59]

<table>
<thead>
<tr>
<th>Category</th>
<th>Parameter</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concept models</td>
<td>STL file</td>
<td>Warping, shrinkage, and meso-scale errors</td>
</tr>
<tr>
<td>Environmental factors</td>
<td>Temperature</td>
<td>Geometrical integrity, shrinkage, warping</td>
</tr>
<tr>
<td></td>
<td>Humidity</td>
<td></td>
</tr>
<tr>
<td>Unprocessed material</td>
<td>Density</td>
<td>Component mechanical integrity</td>
</tr>
<tr>
<td></td>
<td>Diameter</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Colour</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Melting temperature</td>
<td>Microstructure anisotropy</td>
</tr>
<tr>
<td></td>
<td>Viscosity</td>
<td>Start/Stop errors</td>
</tr>
<tr>
<td>Build orientation</td>
<td>Support structures</td>
<td>Surface finish, meso-scale errors</td>
</tr>
<tr>
<td></td>
<td>Layer orientation</td>
<td>Shear and tensile strength</td>
</tr>
<tr>
<td>FFF Machine</td>
<td>Model build temperature</td>
<td>Shear and tensile strength</td>
</tr>
<tr>
<td></td>
<td>Nozzle diameter</td>
<td>Tensile strength, surface finish</td>
</tr>
<tr>
<td></td>
<td>Envelope temperature</td>
<td>Shear and tensile strength</td>
</tr>
<tr>
<td></td>
<td>Machine calibration</td>
<td>Geometric errors</td>
</tr>
<tr>
<td>Working parameters</td>
<td>Air gap</td>
<td>Inter-road defects and overfilling</td>
</tr>
<tr>
<td></td>
<td>Raster angle</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Raster width</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Part interior style</td>
<td>Feature resolution</td>
</tr>
<tr>
<td></td>
<td>Layer thickness</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Part shrinkage factor</td>
<td>Accuracy of build, residual stress</td>
</tr>
<tr>
<td></td>
<td>Contour width</td>
<td>Subperimeter defects and voids</td>
</tr>
</tbody>
</table>

The University of Illinois conducted initial studies examining the properties of FFF components, noting the high levels of anisotropy due to inter-layer bonding. Bertoldi et al. [57] used analysis similar to that applied to composite materials to create a stiffness matrix, and link to the thermal expansion matrix. This was later expanded by Bellini and Güçeri [58], verifying results through use of FEA.

Inclusion of fibres into the filament has the potential to significantly improve part properties, as explored in a review by Brenken et al. [60]. However, with traditional FFF processes, the fibres are aligned and reinforce the print plane, with the lower inter-layer bond strength remaining to reduce the part strength in shear; Brenken et al. [60] notes there has been little conclusive research in the effect of fibre reinforcements on bond formation. Chopped fibres are most commonly used, with a fibre volume fraction of approximately 10% by weight, but continuous fibres can have a volume fraction of between 20-34.5% [60–62]. However, such continuous fibre systems have increased path planning difficulties, require the cutting of fibres, and provide an uneven distribution of fibres throughout the deposited road [61].

As can be seen from Table 2.3, numerous studies have modified the infill (raster) properties,
### Table 2.3. Literature summary of various papers investigating different aspects of part strength of FFF components.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Investigated property</th>
<th>Investigated parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>[63]</td>
<td>Tensile strength</td>
<td>Environment and nozzle temperatures, layer height, fibre width, layer build time</td>
</tr>
<tr>
<td>[64]</td>
<td>Surface roughness</td>
<td>Surface angle, layer height</td>
</tr>
<tr>
<td>[65]</td>
<td>Tensile strength, compressive strength</td>
<td>Raster orientation, air gap, bead width, colour, deposition temperature</td>
</tr>
<tr>
<td>[66]</td>
<td>Compressive strength</td>
<td>Build direction, machine type</td>
</tr>
<tr>
<td>[67]</td>
<td>Tensile strength, surface roughness</td>
<td>Environment and Nozzle temperatures, air gap</td>
</tr>
<tr>
<td>[68]</td>
<td>3-point bend</td>
<td>Location within build chamber</td>
</tr>
<tr>
<td>[69]</td>
<td>Dimensional accuracy</td>
<td>Layer thickness, contour width, raster density</td>
</tr>
<tr>
<td>[70]</td>
<td>DMA properties</td>
<td>Infill density</td>
</tr>
<tr>
<td>[71]</td>
<td>Compressive strength</td>
<td>Orientation, layer thickness, raster angle, raster width, air gap</td>
</tr>
<tr>
<td>[72]</td>
<td>Tensile strength</td>
<td>Layer thickness, raster angle, raster width, air gap</td>
</tr>
<tr>
<td>[73]</td>
<td>Tensile, flexural, and impact strength</td>
<td>raster gap, raster angle</td>
</tr>
<tr>
<td>[74]</td>
<td>Compressive strength, flexural strength</td>
<td>Unit cell volume fraction</td>
</tr>
<tr>
<td>[75]</td>
<td>Long-term compressive response</td>
<td>Comparison with traditional foam</td>
</tr>
<tr>
<td>[76]</td>
<td>Tensile strength</td>
<td>Build orientation</td>
</tr>
<tr>
<td>[77]</td>
<td>Tensile strength</td>
<td>Infill density and pattern</td>
</tr>
<tr>
<td>[78]</td>
<td>Tensile strength</td>
<td>Pre-heating substrate with laser</td>
</tr>
<tr>
<td>[79, 80]</td>
<td>Tear strength</td>
<td>Weld time</td>
</tr>
<tr>
<td>[81]</td>
<td>Tensile strength</td>
<td>Fibre-reinforcement</td>
</tr>
<tr>
<td>[82]</td>
<td>Impact strength</td>
<td>Build orientation</td>
</tr>
<tr>
<td>[83, 84]</td>
<td>Tensile strength</td>
<td>Bed and nozzle temperature, print speed, fibre width, layer height</td>
</tr>
<tr>
<td>[85]</td>
<td>Notched impact</td>
<td>Layer thickness, fill density, print speed, build orientation</td>
</tr>
<tr>
<td>[86]</td>
<td>Mode III peel</td>
<td>Nozzle temperature</td>
</tr>
<tr>
<td>[87]</td>
<td>Porosity</td>
<td>Nozzle temperature</td>
</tr>
</tbody>
</table>

25
with a higher part density tending towards that of an injection moulded component; a 100% infill density was within 1% of the injection moulded part strength [77]. However, this tensile test used force applied along the intra-plane x axis rather than applying loading over the inter-plane bonding, which would exhibit weaker properties. Methods to identify appropriate infill were explored by Li et al. [88], using a Finite Element Analysis (FEA) simulation to model load paths to reinforce areas of high stress.

### 2.3.1.1 Process optimisation

An increasing numbers of papers investigate the optimisation of process parameters to improve surface roughness, dimensional accuracy, material behaviour, build time, and mechanical properties. Mohamed et al. [17] conducted a thorough literature review of each topic, finding the Taguchi method, Response Surface Methods, Genetic Algorithms, and Artificial Neural Networks provided the best property predictions. While such modelling processes provide good estimation of part parameters, they require a significant number of samples, and the resulting model may not be optimal for a variety of components.

One seminal work in process parameter optimisation was conducted by Ahn et al. [65], examining the effects of raster orientation, air gap, bead width, colour, and model temperature on the tensile and compressive properties of ABS samples manufactured with FFF. Through a set of experiments, the authors determined the raster orientation and the air gap between the raster lines provided the most significant effects; this makes intuitive sense as this aligns the rasters with the loading direction and increases the density respectively. When compared to an injection moulded component of the same material, tensile specimens achieved 65-72% of the ultimate tensile failure stress, and 80-90% of the ultimate compressive failure stress. The authors then presented the following design rules for maximising part strength:

1. Build parts such that tensile loads will be carried axially along the fibers.
2. Be aware that stress concentrations occur at radiused corners. This is because the FFF roads exhibit discontinuities at such transitions.
3. Use a negative air gap to increase both strength and stiffness.
4. Consider the following issues on bead width.
   - Small bead width increases build time.
   - Small bead width increases surface quality.
   - Wall thickness of the part should be an integer multiple of the bead width.
5. Consider the effect of build orientation on part accuracy.
6. Be aware that tensile loaded area tends to fail easier than compression loaded area.

Recent attention has turned to lattice structures, where unit cells are repeated over the required volume. Beyer and Figueroa [74] compared a range of unit cells, noting the Additive
Manufacturing Format (AMF) would be a superior file format when compared to STL\textsuperscript{1} files, with inbuilt capability for lattice storage. This standard enhances the STL file through the use of curved triangles facets to better represent curved surfaces, the ability to use multiple and functionally graded materials, and embed tolerance and surface roughness requirements [89].

A limitation of the methods presented has been the use of commercial machines, subject to the supplied control architectures limiting the customisability of the input code, and the limited flexibility of slicing software for toolpath generation. Of the parameters optimised, infill consistently appears to affect the final build properties the most; while this vital for the integrity of most components manufactured through AM, it will not be explored in this work due to the use of thin-walled core structures for low density.

2.3.2 Mechanical control

Mechanical control of the printer can be separated into two parts; control of the filament feed rate into the extruder, and of the nozzle movement over the build area. A typical print path requires acceleration and deceleration around corner regions, causing under- and over-fill if not properly compensated. The importance of such control was highlighted by a patent from Stratasys entitled “Velocity profiling in an extrusion apparatus” [90].

As the nozzle approaches a corner, a “rounding off” is necessary to avoid coming to a complete stop; this is implemented in the Open-Source Marlin firmware, which forms the basis for numerous “hobbyist” category FFF printers, as a maximum “jerk” value [91]. An improvement in path planning for enhanced deposition properties was identified by Han et al. [92], with the development of a transfer function to map the required extrusion rate to the head speed. Jin et al. [93] mathematically described the deposition shape of the road, and looked at improvements to slicing algorithms to generate contoured infill to reduce the required sharp corners within the path. However, it was noted the generation procedure was computationally intensive, and the contoured infill caused an unevenly distributed voids within the component.

Camera measurements have been used to monitor the road deposition through a comparison with a parametric surface reconstruction, initially researched by Fang et al. [94] monitoring deposition and comparing a segmented image to identify regions of under and over-fill. A similar commercial product by MarkForged allows a user to perform a laser scan on specified layers and compare expected and actual deposition locations [95].

Hoelzle et al. [96] applied iterative learning control to optimise the flow control for a syringe-based extruder to improve corner consistency, through measurement of the deposited road thickness over five features of a print path; start, stop, corner, steady flow, and no flow. In a similar manner, Cheng and Jafari [97] used fuzzy classification to detect such defects and

\textsuperscript{1}STL files are commonly used represent the surface of a 3D object with tessellated triangles, each with a unit normal towards the exterior. Originally derived for the “STerioLithography” process by 3D Systems, other backronyms include “Standard Tessellation Language” and “Standard Triangle Language”.

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simulated the effects of a closed loop controller, using a parametric surface reconstruction method. However, camera-based methods are limited due to the physical size of the camera on the print head, with the aforementioned processes typically taking place off-line.

Improved nozzle movement control on low-cost printers was investigated by Weiss et al. [98], noting commercial accuracy ratings were based on theoretical calculations based on stepper resolution and gear ratios rather than the achievable dynamic resolution. Through implementation of feedback on the robot $xy$ axes, closed loop control halved the mean error at standard acceleration rates of $3000 \text{ mm s}^{-2}$. This was tested with a small ($5 \text{ mm} \times 5 \text{ mm}$) star-shaped extrusion profile; mean errors would be lower for shapes with straighter lines and smoother curves due to the increased time the nozzle would be moving at a steady state. A second observation of this research was the lower rigidity of low-cost printers undermined the advantage of closed-loop control due to vibration of the printer frame. It is expected this has been implemented on higher cost, closed source machines, and some low-cost machines such as the servo-actuated MOD-t printer by New Matter [99].

Compensation for mechanical error has also been applied to the input files to the slicing software. A series of papers by Tong et al. [100–102] measured a 2D profile produced with an vat polymerisation printer with a Coordinate Measurement Machine (CMM), correcting the input shape based on the recorded error. This was expanded to a 3D shape by a second paper [101], correcting the input STL file, and then adapted for FFF in 2008 [102]. The final paper showed a reduction in the average volumetric error by 30%.

Huang et al. [103] implemented a similar correction method, forming an equation characterising the error of a printed cylinder. The input was then modified to compensate for the expected error, and the final deviation was 10% of the previous value. This held for an untested cylinder size; however it was not clear if this process would be applicable to arbitrary geometries without a reformulation of the error function.

Relvas et al. [104] examined the effect of STL file accuracy over a variety of different machines. Using a benchmarking component containing geometries such as walls, cylinders, holes, and freeform shapes, slicing paths were generated from different resolution input STL files. The error of such components manufactured on different AM machines was calculated, identifying Powder Bed Fusion (PBF) had the highest geometric accuracy after CNC milling, but out-performed by FFF on both cost and dimensional accuracy. While this paper compared different printers, it should be noted only a single printer from each category was tested, so does not account for the variation in cost and quality between printers within or between each category. A rudimentary search of machine costs showed the CNC machine was available second-hand for approximately $6,600, while the same type of PBF machine was most likely the most expensive, with a second hand machine requiring a new component available for $75,000.
2.3.3 Thermal modelling

With material extrusion processes relying on the melting and subsequent solidification of polymers during the deposition process, control of the melt phase is vital for improved part properties. Figure 2.5 illustrates the expected effect of changes due to environmental ($T_e$) and extruded ($T_0$) temperatures [105]. As the material is deposited at a temperature above its melting point, deformation and bond formation are generally considered to occur during the cooling to the melting point, and internal stresses generated from further cooling [106].

Turner et al. [16] provided the seminal review into thermal modelling of a filament feed mechanism, liquifier dynamics, die swelling, deposited road shape, and inter-layer sintering. Yardimci et al. [107, 108] pioneered the analytical investigation into the modelling of the filament cooling and its effect on bonding. An initial paper noted the requirement for a cooling model for road interaction, and presented a method to extract the toolpath from a build file to virtually analyse the probable bonding over the component [107]; this was later implemented by Costa et al. [86]. A mathematical analysis of heat conduction within the nozzle was also presented, with detailed equations for modelling the melt front location and cooling [108]; the complexity of these equations limited their adoption in later literature.

Sintered bond formation was modelled by Bellehumeur et al. [68, 109] as dimensionless neck growth\(^2\); the sintering process is depicted in Figure 2.6, showing entanglement between adjacent roads. The equation examines the particle coalescence as a function of time, whilst accounting for the varying viscosity and surface tension with temperature. It assumes the deposited shape is cylindrical, where, due to the compression of the nozzle, it is more likely to be an elliptical shape [93] with a larger initial contact area.

Noting the difficulty in predicting bond strength due to the high number of process parameters, Yan et al. [63] introduced the concept of “bonding potential”. Through the discretisation of a 2D

\[^2\text{There is a typographical error in [68], omitting the “-” sign from the exponent } -2^g\]

Figure 2.5. Defects caused by changes in extruded and environment temperatures ($T_0$ and $T_e$ respectively) [105]. Image ©Scientific.Net.
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Figure 2.6. The formation of a sintered bond through the movement of the polymer chains, as presented in [109]. (a) shows the filament instantaneously after deposition, (b) shows the neck growth, and (c) the sintering effect due to the movement of polymer chains.

cross section along and between layers, cooling was predicted based on heat convection to adjacent segments, and relevant parameters calculated through regression from experimental results. Similar equations were presented by Gurrala and Regalla [110], with these noting incomplete neck growth between components.

Bond formation was also examined by Seppala et al. [79, 80], using an infrared camera to measure the temperature distribution during deposition and the time spent above the glass transition temperature ($T_g$); the layers below the uppermost layer did not reach $T_g$, so bonding would not be affected by the deposition of subsequent layers. It was also confirmed the weld time was sensitive to the print temperature, but not sensitive to print speed, where higher bond times provided a higher tear strength under Mode III shear. Similar observations with an IR camera were found by Wolszczak et al. [87], identifying extrusion at higher temperatures increased bond formation and associated part density. Creating a temperature map of the build zone was also shown to aid prediction of part properties [111]. With all thermal observations, a cyclic heating profile was observed, due to the nozzle passing nearby; this effect was reduced as successive layers were deposited, linking the part bonding and internal stresses to its thermal history [68, 79, 86, 87, 111].

Coogan and Kazmer [83, 84] used a similar method to Yan et al. [63] to estimate bond strength with tensile testing, presenting a model for bond strength as a function of raw material strength; this was the first paper to directly correlate bonding with material strength. This was achieved through the estimation of the diffusion of polymer chains across the wetted area formed between two adjacent filaments in a manner similar to [68, 109], and the results showed the model provided a good estimate of the predicted bond strength.

There has been less work investigating the dynamics of filament flow within the extruder due to the lack of observability. Initial work by Bellini et al. [112], collaborating with Güçeri, a co-author of the papers by Yardimci [107, 108], listed the following complications for modelling the liquifier dynamics:
2.4. QUALITY ASSURANCE AND CONTROL

- Fluid compressibility
- Slipping contact and stiction between molten flow and liquifier walls
- Slippage between extruder motor and filament
- Uneven heat flux across filament
- Change in physical state of filament

Equations for the internal pressures were derived, and the flow rate response to a step change in feed rate simulated and verified through measurement of the dimensions of an extruded road. This work did not account for the priming and retraction motions which occur at the start and end of an extrusion respectively.

Ramanath et al. [113] examined the melt front location through FEA for biopolymer fabrication; it was noted finer control is necessary for temperature-sensitive filaments. Industrial interest has been shown in the control of melt front through a patent filed by Stratasys in 2012, using a multi-zonal heater to more accurately control the melt location [114]. The patent discussed the advantage of moving the melt front further from the nozzle orifice would provide smoother extrusion at higher nozzle speeds, while closer to the nozzle orifice enables improved control for finer moves.

A finite element model of the nozzle, identical to that used in this thesis, was implemented in the FEA software COMSOL by Hofstaetter et al. [115], where a the slight asymmetry in heating across the filament due to the off-centre location of the heating element was identified.

An application of thermal modelling was explored by Du et al. [78], using a laser to heat the area directly under the deposited material, providing a 195% increase in tensile strength. The applied model showed good correlation between simulated temperatures and those recorded through an IR camera.

2.4 Quality assurance and control

In a discussion of the ISO 9000 family of quality management standards, David Hoyle emphasises the difference between process control and product control, with the former relying on controlling the driving variables during manufacturing and the latter relying on verification upon completion of the product. In order to fulfil the requirement for process control, “continuous monitoring and/or compliance with documented procedures” is required to ensure confidence in parts when it is unfeasible to test each individually [116, 117].

The “Generalised Design and Test” process is unsuited for AM, as the deposited material properties may not remain constant with increasing component size due to the strong relationship between the bonding and process [14]. Despite this, coupon tests are commonly used to provide an estimation of the effect of different print parameters on the final part properties. To utilise the full capability of customised AM components, it would be economically challenging to test each part produced, requiring in-process quality assurance to ensure the expected properties within
the qualified range of design parameters. The relationships between design space, QA methods, and part properties are further discussed in Section 2.6.

The following section introduces guidance produced by governing bodies and a selection of academic research not previously covered related to ensuring the quality of AM components. This is comprised of a brief overview quality control for metal-based AM, followed by the more applicable research for polymer FFF.

### 2.4.1 Government and Industry guidelines

Initial guidance documents produced by governments pertaining to the certification of AM components were produced for the medical industry, such as the Food and Drug Administration (USA) \[118\] and the Belgian Health Knowledge Centre \[119\]; both reports emphasise control and knowledge of the process as key for certification. Other reports released by governing bodies show the advantages of AM for the manufacturing industry, including by the European Union \[11\], the “America Makes” program \[33\], and the UK Additive Manufacturing Group \[30\]; the latter report also references equivalent works from China, Germany, Japan, and South Korea. A consistent trend across the reports is the need for improved process control, with the America Makes report stating the following as a medium priority gap, with a desired timeframe of 2-5 years:

**Gap PC4: Machine Qualification.** Current users may not have considered the influence of machine control on resulting product quality and material properties beyond form and fit, including machine-to-machine variation (even between machines of the same make and model). While guidelines for machine qualification can be developed, a broader view of part-specific, process-specific, and application-specific recommended practices is needed.

To address this, the ISO/ASTM committee 52903-2 is currently reviewing a standard for material extrusion based additive manufacturing of plastic devices, and a National Institute of Aviation Research (NIAR), at Wichita State University, are assisting SAE International in development of a new technical standard for polymer additive manufacturing \[120\].

The aerospace industry has significant quality requirements, and a workshop hosted by the FAA examined the current certification procedure for AM components to identify areas for improvement \[121\]. Consistent with the previous reports, it was noted “extreme diligence” would be required for certifying machine and process parameters. Manufacturing variation was a challenge, with two large companies stating a ~6 month qualification period for new machines. While the attendees of this workshop focused on metal alloy-based AM, the developed standards would be transferable to equivalents for plastic-based AM processes.
2.4. QUALITY ASSURANCE AND CONTROL

2.4.2 Metal-based AM

In a seminal review of metal-based AM in 2014, Frazier reviews a number of systems and the business case for their adoption to produce low-volume, high-value products, identifying the need for closed-loop and real-time control systems [122]. Various research efforts have investigated improved control for melt pool geometry [123], adaptive toolpath planning for turbine blade manufacture [124], and the implementation of PI + feed-forward controllers [125].

Frazier [122] addressed qualification of AM components with three basic questions, and an associated response as paraphrased below.

1. Has the materials technology been developed and standardised?
   → AM is a rapidly evolving technology with diverse units.
2. Has the materials technology been fully characterised (with a confidence level of 95%)?
   → Freezing the AM process, as required for standardisation, is antithetical to the flexibility afforded to AM.
3. Has the materials technology been demonstrated in a relevant operational environment?
   → Significant cost and time barriers exist in data acquisition.

Despite the significant costs involved in such part qualification, the aerospace industry has adopted metal-based AM in for at least two critical components within a jet engine; a fuel nozzle produced through PBF [13], and bosses on a fixture component manufactured through DED [14].

2.4.3 Polymer FFF

In a roadmap produced by Bourell et al. [21], process monitoring and control was highlighted as a key area for improvement, noting the requirement for a higher degree of sensing within the build area. Huang et al. [126] reviewed a number of aspects related to Engineering Process Control and Statistical Process Control for the FFF process, also concluding higher levels of sensing and data fusion are required to reliable produce high quality parts.

Simulations of the expected extruder vibrations were performed by Bukkapatnam and Clark [127], with an 80% correlation between simulated and measured frequency responses, and was capable of identifying under- and over-flow situations. Tlegenov et al. [128] implemented a similar system, modelling the force of the filament on the nozzle as a force on a pinned bar. Through comparing the dynamic response from an accelerometer with the simulated model, a nozzle clog could be identified as the system response resembled that of one with a reduced nozzle diameter. It was not clear if such accelerometer-based systems would be robust to the vibrations caused during the nozzle movement along an axis.

Application of extra sensing has also been used for in-process quality control, with Kim et al. [129] measuring the supplied current to the extruder to identify nozzle blockage; results showed a change, but its use for online control would be limited due to the low Signal to Noise Ratio.
Use of multiple sensors provided a more promising process monitoring method, as discussed by Yoon et al. [130], where piezoelectric sensors could identify a slight error in the belt drive. Rao et al. [59] implemented a full sensor array, with thermocouples, accelerometers, an IR sensor, and video to monitor the build process. A mixture model was trained on the system, with abnormal and failure sensor parameters identified, to allow for near real-time fault detection.

Similar to metal, AM components are currently have limited use with Aerospace operations, with the Stratasys Fortus 900 MC was qualified to produce aerospace interior components [19]. This was achieved through the “Aircraft Interior Certification Solution”, which includes design allowables dataset for a certified production of ULTEM 9085 material [18] and guidance on equivalency test design. To certify the materials, 4700 test coupons were manufactured over several machines in different locations, showing the large number of tests currently required to gain sufficient confidence in material properties [18].

2.5 Multi-Dimensional FFF

Traditional AM machines are actuated along three axes, limiting the specimens produced to vertically stacked 2D layers, commonly referred to as “2.5D” printing. Material Extrusion and Directed Energy Deposition are the most suitable processes for the manufacture of curved layers, depositing material from the extrusion head as opposed to requiring it to be placed onto the surface before fusion; a majority of research within this area has focused on ME methods, such as FFF, due to equipment availability and the low cost of components. This section begins with an overview of academic research of appropriate algorithms for complex path generation, followed by a summary of some academic and industrial implementations on parallel- and arm-based systems.

2.5.1 Algorithm development

The algorithms generating the print path increase in complexity as the system uses more degrees of freedom. In a broad paper, Brooks et al. [131] discussed the technologies necessary for increasing AM speed to enable machines to be commercially competitive with conventionally produced, medium volume, medium size components. This divided algorithms into three broad sections; adaptive slicing, Multi Directional Layered Deposition (MDLD), and curved layer slicing.

2.5.1.1 Adaptive Slicing

The stair-case effect of FFF is a result of the 2.5D layer-by-layer deposition, with the layer thickness causing a quantisation of a curved profile; shown in Figure 2.7(a); an early review of this area was undertaken by Pandey et al. [132].

Initial research into the area of adaptive slicing was pioneered by Sabourin et al. [133, 134], first presenting a recursive slicing procedure where thick slices are initially used, and refined in
areas with higher curvature, shown in Figure 2.7(b). A build time reduction of 52% was found using this algorithm over a uniformly thin slices [133]. The second algorithm separated the interior and exterior fill pattern generation, where thicker layers were used for the interior regions, whilst thinner exterior layers provided improved surface quality [134]; this reduced the need to deposit an interior layer for every exterior layer, reducing build time. A 50-80% reduction in build time was realised using this approach for the same exterior quality.

Later research optimised the layer thickness and part orientation within the build area to minimise the weighted sum of build time and part roughness [135]. The experiment used a Genetic Algorithm (GA), showing the result for varying the weight of the cost function components, but did not provide a conclusive recommendation for the balance between these contradictory parameters.

Zhang and Liou [136] introduced curvature into a component through non-uniform layer thickness. The algorithm attempted to branch slicing directions to minimise the overhang, where supports would be necessary, and generated a transition zone with a non-uniform layer thickness to change layer orientation. Also noted was the increased likelihood of a collision with the previously deposited layers, requiring more thorough planning of travel movements.

### 2.5.1.2 Multi Directional Layered Deposition

Conventional FFF parts require support structures for overhanging parts, increasing material usage, build times, and post processing; higher DOF systems can alleviate this through changing the build direction as illustrated in Figure 2.8. Singh and Dutta [137] provided early investigation into algorithms to generate MDLD components through sectioning of the provided CAD model into viable build orientations to reduce support requirements. Later work by Qi et al. [124], with Singh as a final author, demonstrated the repair of a turbine aerofoil shape, shown in Figure 2.9.

Development of MDLD slicing continued, with Sundaram and Choi [140] applying a similar
algorithm to the vendor-neutral IGES CAD format, as opposed to a traditional STL file, to build a specimen with overhanging feature with a 6-axis DED system. With the application of adaptive slicing to each of the decomposed volumes, the number of printed layers was further reduced and build time shortened by 10%.

With a robotic arm, Kubalak et al. [141] produced tensile samples using FFF using a toolpath generated from a standard 2.5D slicing procedure. Upon completion, a number of additional roads were added to the surface to provide reinforcement in the loading direction; this achieving a 59% increase in yield modulus. The ability to print on existing surfaces was termed “Additive Finalisation” by Dröder et al. [142].

2.5.1.3 Curved Layer Slicing

Seminal research on the properties of curved layers was conducted by Singamneni et al. [143], comparing two bridge structures manufactured with flat and curved layers, as shown in Fig-
2.5. MULTI-DIMENSIONAL FFF

Figure 2.9. Use of Directed Energy Deposition for in-situ repair of a turbine blade by Qi et al. [124]. Image ©Springer.

Figure 2.10. Flat and curved layer bridge specimens used by Singamneni et al. [143]. Image ©ScienceDirect.

Under a 3-point bend test, curved layer specimens failed at approximately 320 N, and the flat layered specimens at 227 N, clearly showing the advantage of continuous layers.

Chakraborty et al. [144] analysed the contact between adjacent filaments in three dimensions, similar to that discussed by Han et al. [92] for two dimensional deposition. This method was applied to more complex shapes, noting the increase in extruded road length would provide improved mechanical properties, as observed by [143], due to the increased inter-layer contact area, however it noted the higher equipment complexity required would limit adoption.

A study of filament bonding in curved layers was conducted by Chen et al. [145], with the work later extended by Pan et al. [146], using a process based on Vat Polymerisation, where an optical fibre passed a UV light to cure resin within a vat. This required the generation of 3D tool paths, demonstrated in [145], and later investigated the use of this method to add features to an existing surface [146]. Using a variety of accumulation tools, different resolutions were achieved.
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FIGURE 2.11. Curved Layer FFF of a sandwich structure, showing the different components of the build. A shows a support structure, B the initial layer deposited to facilitate easy removal of the support. C-E shows the deposition of the bottom skin, core, and top skin respectively, and F a CAD render of the final component. Image from [147]. Image ©ScienceDirect.

and provided an improved surface finish over SLA produced at a 45° angle as the staircase effect was reduced due to the alignment of the print direction with the rod axis, no need for supporting structures and the associated residue on removal.

Some initial work on the manufacture of curved layer core components was conducted by Allen and Trask at the University of Bristol [147], and continued by Llewelyn and the same authors at the University of Bath [148]; this process can be referred to as Curved Layer Fused Filament Fabrication (CLFFF). A support component was a conventionally sliced and printed, and a bottom skin, core, and top skin printed with conforming curved layers; images of the process are shown in Figure 2.11. It was noted the delta printer structure was required for its increased $z$ axis speed, and collision between the nozzle and base component constrained the maximum achievable curvature.
2.5. MULTI-DIMENSIONAL FFF

2.5.1.4 Combination of slicing algorithms

Recent research has combined the aforementioned slicing techniques for the production of parts with increased complexity. The first combination is that of CLFFF with adaptive slicing, demonstrated by Huang et al. [149], under the supervision of Singamneni, in a process called Curved Layer Adaptive Slicing (CLAS). In this paper, a bridge specimen, similar to that previously investigated in [143], was produced with adaptive slicing to decrease the layer thickness around chamfered corners. Additionally, the required drop-off locations of the layers were investigated to maintain a continuous top layer.

CLFFF and MDLD have been combined to produce curved layers in multiple directions; the mathematics behind the segmentation of the model was presented by Wu et al. [150], and continued to include curved layer slicing by Dai et al. [151]. Such a process was also implemented with a robotic arm-mounted extruder by two separate groups in a more simplified manner through stacking layers with the same curvature; Zhao et al. [152] with an FFF system, and Ding et al. [153] with a DED system. Both used a propeller-shaped input, decomposing the volume into a curved central hub, with the blades deposited using curved layer AM systems. The results of both experiments are shown in Figure 2.12.

2.5.2 Implementation

While there has been significant developments in algorithms for toolpath generation, a limiting factor in implementation of the higher DOF is the increased hardware cost. Two structural layouts are suited to this DOF requirement; parallel and serial manipulators. A number of implementations of such systems are described. In general, the parallel systems mostly focused on low cost MDLD, while the serial manipulator research used industrial robotic arms.
2.5.2.1 Parallel FFF Systems

A variety of 3 DOF parallel systems are commercially available, such as the Rostock Max [154], commonly referred to as delta printers, as used by Allen, Trask and Llewelyn [147, 148] for their implementation of CLFFF. However, these systems do not allow for nozzle rotation relative to the build plate, limiting the maximum angle. Increasing the DOF of such systems has been achieved through a 2-DOF articulated build plate, or the addition of DOF to the parallel arms of a delta robot to create a Stewart Platform.

Singh et al. [155] presented a method for kinematic design of a printing system based on requirements for MDLD, where the extruder was mounted to a Cartesian gantry system, and the bed mounted to a reconfigurable platform. Through additional degrees of freedom to the bed, a printer can be optimised for a part. Realistically, this approach is unnecessary beyond a 3 DOF bed as a 6 DOF system should provide sufficient positioning capability. Any significant change to the design and layout would require generation and calibration of a new control system, reducing the rapid production changes advantageous to AM.

A different approach was taken by Bausch et al. [156], modifying a 3 DOF open-source RepRap style printer with a 2 DOF build plate. A toolpath was generated from the superimposition of a CAD feature onto a laser scan of the surface, implementing the “Additive Finalisation” proposed by Dröder et al. [142]. During this project, it was noted a difficulty in toolpath generation is that of avoiding the collision between the nozzle and the printed substrate.

In a similar manner, Shen et al. [157] used a 2 DOF print bed and a delta printer, identifying the nozzle dimensions as a limitation for the maximum bed orientation before a collision with the surface. A variety of components were produced, demonstrating adaptive slicing to transition between layer orientations (as described by Zhang and Liou [136]), a combination of plane orientations to reduce support material use, and the deposition onto a cylindrical surface. Additionally, it was identified an overhang angle of 51° was the transition point where 5-axis printing would be advantageous over 3-axis printing, as supports would then be necessary.

Peng et al. [158] used a 5-DOF printer, consisting of a 2-DOF print bed mounted onto a delta printer, for the “On-the-Fly Print” project, where virtual renders of a CAD file are physically prototyped during development. Attached to the printer nozzle was a mist spray to rapidly cool and solidify the extruded filament, allowing for a wire-frame construction of the CAD model currently under design. In the given example, the fuselage of an aeroplane was first designed and built, and then the wings deposited on the side. A cockpit was then added, where a heated cutting blade removed a segment of the fuselage to create a hole in the wire frame, which was reinforced by deposited filament, before a tail structure was finally added. This integration of computer design coupled with physical modelling allowed the user to test geometry and physical appearance more rapidly during the design process; while the model had low fidelity, this work demonstrated the uses of higher degrees of freedom for integrated additive and subtractive modelling.
An early application of a Stewart Platform, a 6 DOF parallel machine, was conducted by Song et al. [159], demonstrating the deposition on curved surfaces with the nozzle remaining perpendicular to the surface. The system was designed to be low cost, with the final system costing under $1500. A laser scanner allowed toolpath generation close to the surface to ensure adhesion when printing on unknown surfaces. It was noted the path planning problem possessed significant complexity for high-DOF systems requiring nozzle reorientation.

Also implemented on a Stewart platform, Dröder et al. [142] demonstrated “Additive Finalisation”, where features were added to an existing surface; although the demonstrated system had no sensors to observe the surface, as with [159], but the system was discussed in a more industrial context. The proposed application involved the printer sitting above a production line, customising mass produced base components with printed features; the target specimen was a part family produced in low- to mid-volumes, with small variations in the additively applied features.

Industrial milling tools have also been adapted for use in AM, with a seven axis machine used by Wulle et al. [160, 161], aiming to reduce support material use. Demonstrating the manufacture of a hemisphere with a thin exterior wall and no supports, this work showed the infeasibility of manufacture with a 3-axis system but success with the higher DOF system.

Systems based on 3-axis machines with a 2-DOF tool have been recently commercialised, with the 5AXISMAKER [162] and VSHAPER 5-AXIS MACHINE [163] both providing a combination of additive and subtractive manufacture; the company producing the former printer received funding from the European Commission Horizon 2020 program for “Directional Composites through Manufacturing Innovation” [164].

### 2.5.2.2 Arm-based FFF Systems

A number of arm-based systems have been implemented within academia, investigating combination of CLFFF, MDLD, and Adaptive Slicing; advantages of industrial arm use is the pre-existing control system. Table 2.4 summarises universities currently undertaking arm-based printing research, and the key research focuses of each system.

### 2.5.3 Industrial implementations

Arm-based AM has been implemented within industry for a variety of applications. Utilising the large workspace, Apis Cor and MX3D [173] have produced buildings and bridges respectively, with other companies, such as Aectual, producing elaborate floor designs [174]. Examples of MX3D and Aectual projects can be seen in Figure 2.13(a, c) respectively.

Interest has been shown by the aerospace and automotive community, with the Stratasys Infinite-Build demonstrator [175], in collaboration with Boeing, Ford, and Siemens, showed a robotic arm with changeable end effector capable of large object manufacture using FFF, as seen in Figure 2.13(b). The commercialised product similar to this system was the Stratasys H2000
### Table 2.4. Overview of existing research projects utilising arm-based printers in academia

<table>
<thead>
<tr>
<th>University</th>
<th>Year</th>
<th>Robot manufacturer</th>
<th>References</th>
<th>Research areas</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIT, USA</td>
<td>2013</td>
<td>Kuka</td>
<td>[165]</td>
<td>• Fixed FFF extruder and movable bed for CLFFF</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• Additive/Subtractive manufacture of a foam structure</td>
</tr>
<tr>
<td>Beihang University, China</td>
<td>2018</td>
<td>Kuka</td>
<td>[152, 166]</td>
<td>• Curved layer slicing and path generation</td>
</tr>
<tr>
<td>Virginia Tech, USA</td>
<td>2016</td>
<td>ABB</td>
<td>[76, 141]</td>
<td>• Surface reinforcement through out-of-plane deposition</td>
</tr>
<tr>
<td>Florida Institute of Technology,</td>
<td>2015</td>
<td>Motoman</td>
<td>[167–169]</td>
<td>• Multi-directional Layered Deposition</td>
</tr>
<tr>
<td>USA</td>
<td></td>
<td></td>
<td></td>
<td>• Lattice structures with use of vertical extrusion</td>
</tr>
<tr>
<td>Massey University, New Zealand</td>
<td>2016</td>
<td>ABB</td>
<td>[170]</td>
<td>• Curved layer toolpath generation</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• Fixed pellet extruder with movable curved workpiece</td>
</tr>
<tr>
<td>Southern Methodist University, USA</td>
<td>2017</td>
<td>Kuka</td>
<td>[153, 171]</td>
<td>• Metal deposition onto a rotating platform</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• CLFFF, MDLD</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• Infill generation for metal deposition</td>
</tr>
<tr>
<td>Ruhr Universität Bochum, Germany</td>
<td>2016</td>
<td>ABB</td>
<td>[139, 172]</td>
<td>• MDLD</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• Variation in print bed orientation</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• Improved metal forming through FFF of die supports</td>
</tr>
<tr>
<td>TU Delft, The Netherlands, and</td>
<td>2017</td>
<td>Universal Robots</td>
<td>[150, 151]</td>
<td>• CLFFF, MDLD</td>
</tr>
<tr>
<td>Tsinghua University, China</td>
<td></td>
<td></td>
<td></td>
<td>• Collision avoidance</td>
</tr>
</tbody>
</table>
A number of industrial arm-based printer systems. (a) shows a bridge designed and additively build by MX3D (Image ©MX3D), (b) the Stratasys infinite build demonstrator (Image ©Stratasys) [175], (c) the Aectual machine printing floor patterns (Image ©Aectual) [174], and (d) the Arevo robotic deposition system for continuous carbon fibres (Image ©Arevo) [176].

Arevo Labs is the current pioneer in 3D printing of reinforced fibres with a reinforced arm, receiving Series B funding of $12.5 million in May 2018 [176]. Using a robotic arm and specialised print head, continuous carbon fibres are deposited and reinforced with resin, allowing curved layers and out of plane deposition, with the stated aim of addressing manufacturing cost, scalability, and ease of use. While this appears to be the most advanced use of arm-based FFF to date, the demonstrations available still show the use of 2.5D layers reminiscent of the traditional process.

The commercial benefit of arm-based DED was demonstrated by GKN with the Additive Final-
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Figure 2.14. A Venn Diagram showing the research fields and overlaps for AM. The different sections are described in Table 2.5.

isation of a component for the Rolls Royce Trent XWB-97. With the base component manufactured through traditional forming processes, the bosses are applied through an arm-based DED process. While the details have not been fully disclosed, the process involved online simulation of the heat distribution to perform toolpath correction ensuring product quality [14].

2.6 Classification of current research

A Venn diagram has been constructed to demonstrate the placement of the different research topics presented, shown in Figure 2.14, and the relevant sections described in Table 2.5.

As shown in Table 2.5, there has not been significant research efforts into the optimal overlap region of Figure 2.14. Achievement of this region would enable the flexible manufacture of a component family, with both certified raw material and sufficient in-process monitoring (as described in Section 2.4.1) to minimise the post-production finishing and inspection. The closest identified example was the use of DED by GKN, described in Section 2.5.3, where toolpaths were constantly modified through in-process control to ensure a high quality finish, although it is not clear how adaptable this system would be for variants to the used components.
2.6. CLASSIFICATION OF CURRENT RESEARCH

TABLE 2.5. Relevant sections for each portion of the Venn Diagram shown in Figure 2.14.

<table>
<thead>
<tr>
<th>Venn Diagram region</th>
<th>Relevant section</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1: Design Space</td>
<td>2.2.2, 2.5.2</td>
<td>The flexibility of the system to produce a range of components, including slicing and support generation.</td>
</tr>
<tr>
<td>2: QA Methods</td>
<td>2.3.2</td>
<td>Reliability of components produced by the system, such as adherence to original design and avoidance of build failures.</td>
</tr>
<tr>
<td>3: Part Properties</td>
<td>2.3.1</td>
<td>Knowledge of the final mechanical properties of a manufactured component.</td>
</tr>
<tr>
<td>1-2: Quality Planning</td>
<td>2.3.3</td>
<td>Interaction between slicing pattern and final part properties, such as heat distribution during build.</td>
</tr>
<tr>
<td>1-3: Process Optimisation</td>
<td>2.3.1.1, 2.5.1</td>
<td>Adjustment of design and slicing methods to improve final part strength.</td>
</tr>
<tr>
<td>2-3: In-Process Monitoring</td>
<td>2.3.2, 2.4.3</td>
<td>“Right first time” production reliability and conformity between machines, environments, and design variants.</td>
</tr>
<tr>
<td>1-2-3: Optimal Region</td>
<td>N/A</td>
<td>Rapid manufacture of a component with suitable and optimised strength and cost to a high standard while minimising required prototypes.</td>
</tr>
</tbody>
</table>

2.6.1 Precursor project

A previous study at the University of Bristol by the author was based on the manufacture of cores for sandwich panel repair described in Section 2.2.2, by White et al. [46], and acted as a precursor to the research presented in this thesis [47]. This project investigated the use of a robotic arm to pick and place pieces of prepreg with a silicon pad for top and bottom skins, and additively manufacture a core in-situ; the proposed system is shown in Figure 2.15.

This system was designed to sit in the “Process Optimisation” region of the Venn diagram, shown in Figure 2.14, through streamlining the manufacture of sandwich panels through increased automation, while improving potential core geometry using the flexibility of AM. This thesis builds on the work through examination of core properties, and application of Quality Assurance methods to improve the manufacturing process.
CHAPTER 2. LITERATURE REVIEW

FIGURE 2.15. System described by Pollard et al. [47] for the automated manufacture of sandwich panels through pick and place of prepreg with a silicon pad, and in-situ core deposition.

2.7 Summary of Literature

This literature review has shown the potential of AM to aid the manufacturing industry in the adoption of Industrie 4.0 for the production of complex and multifunctional components. Qualification is one barrier to entry due to the strong material-process-property relationship and the reduced mechanical properties from the bulk material due to the inter-layer bonding. Prediction of exact properties is difficult based on the large number of affecting parameters, shown in Table 2.2. Both metal and polymer parts manufactured through AM have been approved for aerospace use, showing the willingness of the industry to adopt this technology given sufficient quality assurances and design methods.

Numerous academic works have studied properties of components produced through FFF, shown in Table 2.3 and discussed in Section 2.3, with the examination of process parameter optimisation, mechanical control, and thermal modelling. One missing area of research was the assumption the filament is extruded at a constant temperature, even during fluctuations in feed rate; a majority of hot-ends measure the filament temperature via a block-mounted thermistor, and IR sensing is physically difficult to observe more complex toolpaths.

Sandwich structures provide excellent mechanical properties at a low mass, but current manufacturing methods are both labour-intensive and costly. AM has been shown to be suited for core manufacture, but two gaps remain in the literature. The properties of the thin-walled FFF structures for core components should be further examined; a majority of previous research has examined the effects of infill which would not necessarily produce the lowest density component. The exploitation of a multi-DOF robotic system would allow for the production of large, curved layer core components in-situ.
2.7. SUMMARY OF LITERATURE

The links between the thesis objectives, presented in Section 1.3, relevant literature review sections, and chapters are summarised in Table 2.6.
Table 2.6. Links between objectives, literature review sections, location within the Venn diagram of Figure 2.14, and the associated thesis chapter.

<table>
<thead>
<tr>
<th>Objective</th>
<th>Literature review sections</th>
<th>Venn diagram location</th>
<th>Chapter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analyse the filament temperature during the extrusion process to identify and implement improved control strategies.</td>
<td>2.3.3, 2.4.1, 2.4.3</td>
<td>1-2</td>
<td>3, 4</td>
</tr>
<tr>
<td>Compare the performance of a core produced with AM to aerospace-grade Nomex honeycomb.</td>
<td>2.2.2, 2.3.1</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Analyse the effect of utilising the higher degrees of freedom of a robotic arm on mechanical properties of FFF components.</td>
<td>2.3.1, 2.5</td>
<td>1-3</td>
<td>6, 7</td>
</tr>
<tr>
<td>Demonstrate toolpath generation afforded to the high degree of freedom manufacturing systems.</td>
<td>2.3.2, 2.5</td>
<td>1-2-3</td>
<td>6, 8</td>
</tr>
</tbody>
</table>
2.8 Conclusion

The research question proposed in Section 1.3 was:

*How can the full design space of a robotic arm be used to create high quality FFF core components?*

During this literature review, it was identified the design space of robotic arms has been explored in both academic and industrial scenarios, but a majority of research has focused on path planning for CLFFF rather than the resulting part properties. Academic literature has examined part properties of components produced through 2.5D manufacture, but little work focuses on the thin-walled structures necessary for lightweight core components. While FFF print quality has been extensively discussed, there is a research gap within in-process thermal control, with a majority of papers using existing controllers. These conclusions justify the applicability of the proposed research question, research aim, and objectives to create a project of interest to both the academic and industrial communities.
Certification of a component requires accurate knowledge of the part properties and, as discussed in Chapter 2, numerous works have shown the strong relationship between the build process and final strength due to inter-layer bonding. This chapter investigates the fluctuations of the filament temperature during the extrusion process.

This work was presented at the 27th International Conference on Flexible Automation and Intelligent Manufacturing 2017. The author would like to thank the Society for the Advancement of Material and Process Engineering (SAMPE UK and Ireland Chapter) for a travel grant to aid the attendance of this conference. The peer-reviewed conference paper is available at:


3.1 Introduction

Thermal modelling is necessary for accurately predicting the final part properties of the FFF process due to the strong dependency on inter-layer bonding; initial research modelling melt flow within a liquefier was conducted by Yardicimi et al. [108]. The internal pressure within the liquefier was investigated by Bellini et al. [112], and the results expanded on by Ramanath et al. [113] to model the internal flow for bio-polymer printing. It was found that the melt front occurs far from the nozzle orifice, resulting in the filament at an elevated temperature for a longer duration.

The filament temperature and bonding has been investigated by Belleumeur et al. [68, 109], where an analytical model and experiments evaluated the effects of processing conditions on
CHAPTER 3. FILAMENT TEMPERATURE DYNAMICS

sintered bond formation while under steady state extrusion conditions. Accurate knowledge of the deposition temperature ensures material properties, and can be crucial to the formation of the correct crystalline structures in biopolymers [113].

This chapter examines the effect of the dynamic flow conditions of start, stop, and feed rate changes on filament temperature for ABS and PLA, two commonly used polymers representative of amorphous and semi-crystalline material classes respectively. Such data has not been previously reported in the literature. Temperatures were recorded using a thermistors embedded within both the block and nozzle, and a thermal camera. The sintered bond formation was then modelled to estimate the effect of the observed temperature fluctuations, and thin-walled FFF specimen profiles optically measured.

3.2 Filament temperature modelling

To measure the temperature throughout the extruder, an E3D 0.6 mm hotend had an additional thermistor embedded into a hole machined into the side of the nozzle. The 2.85 mm filament was actuated by a direct drive Bulldog XL extruder and controlled through a dSpace DS1103 rapid prototyping board with custom software written in MATLAB/SIMULINK and operated via ControlDesk. The controller was connected to a RAMPS 1.4 breakout board providing interfaces to the stepper drivers and temperature measurement, and the extruder was mounted onto a table, allowing the extruded filament to drop vertically down.

The step signal to drive the extruder stepper motor was produced using the DS1103’s inbuilt variable frequency square wave generator, and the heater cartridge controlled with the DS1103’s inbuilt PWM generator. Temperature was measured from the thermistors at a sampling rate of 1 kHz to monitor the of high frequency response. To investigate aspects of control, both the block and nozzle thermistor readings could be used as the input signal for the PI temperature controller, as it was hypothesized the nozzle would have an improved response time due to its lower thermal mass. Due to signal noise from the thermistors, a filter was applied to the block and nozzle thermistor readings as shown in Figure 3.1.

The extruded filament temperature, along with secondary measurements of block and nozzle temperatures, were monitored with a FLIR T650 thermal camera at frame rate of 30 Hz, and analysed using the accompanying ResearchIR software; good correlation between the temperatures measured by the thermistor and camera was found. Figure 3.2 shows the hotend, and a sample image obtained from the thermal camera highlighting the Regions Of Interest (ROI) around the block, nozzle, and filament during extrusion. The filament temperature was extracted from the maximum pixel value of the region.

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3.2. FILAMENT TEMPERATURE MODELLING

**Figure 3.1.** Design of filter and example application to recorded temperature results. *(a)* shows the low pass filter design, and *(b)* shows its application to temperature data from the block thermistor data.
CHAPTER 3. FILAMENT TEMPERATURE DYNAMICS

![Figure 3.2](image1.png)

**Figure 3.2.** Setup for measurement of thermistor thermal temperature. (a) shows the thermistors inserted into the block, and the flash tape used to enable IR temperature measurements through increasing the surface emissivity. (b) displays an image captured by the thermal camera with the regions of interest labelled.

<table>
<thead>
<tr>
<th>Table 3.1. Thermal response of filament, as recorded with a thermal camera, due to a step change in feed rate. Block / Nozzle denotes the location of the thermistor providing input to the PI temperature controller. These are depicted in Figure 3.3.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step</td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td>Low–High</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>High–Low</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

### 3.2.1 Filament temperature during step changes in feed rate

The first set of experiments recorded the filament temperature during a step change in feed rate with a constant temperature setpoint for ABS and PLA of 250 °C and 230 °C respectively. The low and high feed rates investigated were 0.5 and 2 mm s⁻¹, corresponding to flow rates of 3.19 and 12.76 mm³ s⁻¹. Table 3.1 shows the maximum overshoot, rise and settling times, and settled difference of the filament temperature due to the step change in feed rate, as measured by the thermal camera; example graphs of the low–high and high–low temperature data is shown in Figure 3.4, and representations of the responses in Figure 3.3.
Figure 3.3. An approximation of the filament temperature under block and nozzle control with a feed rate step changes at 0 s. (a) and (b) show the Low–High step response for ABS and PLA respectively, and (c) and (d) the High–Low steps for ABS and PLA respectively.
CHAPTER 3. FILAMENT TEMPERATURE DYNAMICS

Table 3.2. Effect of feed rate step change on steady state thermistor temperatures while under block-based control (°C).

<table>
<thead>
<tr>
<th>Step</th>
<th>Temperature change</th>
<th>ABS Block</th>
<th>ABS Nozzle</th>
<th>PLA Block</th>
<th>PLA Nozzle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low–High</td>
<td>-0.2</td>
<td>-3.1</td>
<td>-0.1</td>
<td>-2.4</td>
<td></td>
</tr>
<tr>
<td>High–Low</td>
<td>0.7</td>
<td>3.9</td>
<td>0.2</td>
<td>2.4</td>
<td></td>
</tr>
</tbody>
</table>

For the nozzle and block temperatures, a low–high step decreased the steady state temperatures after the initial overshoot due to the increased mass flow requiring increased heating for compensation. The opposite effect occurred for the filament temperature, with the high–low step causing an increase in filament temperature; this is depicted in Table 3.1.

Within the hotend, the expected temperature distribution is shown in Figure 3.5, with the highest temperature located near the heater cartridge, and the melt slightly cooling as it passes through the nozzle. It was hypothesised the overshoot was due to a feed rate increase forcing the higher temperature melt front closer to the cooler nozzle, providing the temperature overshoot, followed by a settling at a lower value; the increased mass flow rate would then require a higher heat input to maintain the same temperature. As the block temperature was maintained at the set point by the controller, the nozzle temperature changed dependent on the flow rate, evident from Table 3.2.

The ABS filament was found to have an overshoot larger than PLA, and a shorter rise time. A difference in absolute settled temperature differences after the step change in feed rate was also observed, with the effect of feed rate more pronounced for PLA than ABS. The use of the nozzle-based thermistor for control was shown to marginally shorten the rise time of the filament temperature, and decrease the total step size for the low–high step.

The comparison of settling times shows the nonlinear nature of the thermal controller, as heat can be actively applied to raise the block and nozzle temperatures for the low–high step. The high–low step relies on convective cooling, leading to a significant settling time increase. The difference between settling times between the block and the nozzle-based controllers for the PLA tests was larger than that for ABS, demonstrating the requirement for the controller to be tuned for the filament. While the same controller was used for both tests, feedback from a nozzle-based thermistor for PLA exhibited less effective temperature control, but ABS settled at a larger temperature difference. The decreased control effectiveness was evident in the increased steady state temperature difference from Table 3.1.

As the nozzle temperature responded significantly faster than the block temperature following a change in feed rate, a faster change in the heater PWM signal was expected. However, due to the less stable nozzle-based control, this effect was not observed. The increased distance between the heater location in the block and the nozzle thermistor caused an increased delay when compared...
3.2. FILAMENT TEMPERATURE MODELLING

**Figure 3.4.** Filament temperature for tests of ABS material during a test using the block thermistor for a feedback signal. (a) shows a low–high change of filament feed into the extruder, and (b) shows a high–low feed rate change.
CHAPTER 3. FILAMENT TEMPERATURE DYNAMICS

Fig. 3.5. Depiction of the expected temperature distribution within the hotend. Note the peak temperature is aligned with the heater element, with filament cooling slightly before exiting the nozzle.

to the block mounted thermistor. These fluctuations about the set point temperature for nozzle control will be further explored in Chapter 4, where improved controllers are implemented.

3.2.2 Filament temperature during retraction and priming motions

Start/stop tests then modified parameters related to the retraction and priming motions, and a pause between the stop and restart. Retraction and priming are common extruder functions within FFF systems; retraction to stop extrusion and avoid unwanted sprue formation during travel through movement of the melt front away from the nozzle orifice, and priming to return the melt front to initiate extrusion when required. The feed rate profile of retraction and priming are shown in Figure 3.6, where a negative feed rate indicates retraction of the filament, and positive feed rate priming for the next extrusion.

Two factorial investigations were conducted, with the factor levels shown in Table 3.3. The first experiment, with PLA, investigated the effect of different durations of retraction/priming, and the length of the pause between retraction and priming motions. The low values for the speed multiplier and feed rate were used. The second experiment, with ABS, investigated the effect of feed rate and the speed multiplier; a proportional change in duration and speed of the retraction/priming motions to maintain the same filament travel distance. The high level involved increasing the retraction/priming speed, whilst reducing the duration of the motion. Each factor
3.2. FILAMENT TEMPERATURE MODELLING

**Figure 3.6.** Filament feed rate into the extruder during high (dashed line) and low (solid line) retraction/priming motions. A positive feed rate denotes the filament was driven towards the nozzle orifice for extrusion. (a) shows the retraction profiles, used to stop extrusion, and (b) shows the priming profiles, used to restart extrusion.
combination was tested three times in a randomized order and the PI temperature controller used an input signal from the block-mounted thermistor throughout all tests.

It was found that the pause had no significant effect on the filament temperature response after the priming action; Figure 3.7 shows tests with both short and long pause durations. Further results depict the high pause time for clarity, with the first experiment with PLA shown in Figure 3.8, and the second with ABS in Figure 3.9. Values for overshoot and settling times of a selection of tests are presented in Table 3.4.

Figure 3.8(a, b) shows the temperature response for low and high retraction durations, with low prime values. No significant delay was observed in the temperature settling at a steady value where retract and prime values were equal, seen in Figure 3.8(a). A high retract coupled with a low prime, shown in Figure 3.8(b), had a delay before extrusion began, as expected, due to the increased distance from the melt front to the nozzle orifice due to the greater retract than prime filament travel.

Figure 3.8(c, d) depicts filament temperature responses for low and high retraction durations, with a high duration prime. There was no significant delay in either setting reaching the previous extrusion temperature, however there was a significant overshoot in Figure 3.8(c), where low retraction and high prime values were used; this effect was also observed in the ABS tests, shown in Figure 3.9(c). This was a similar effect to that observed in Section 3.2.1, where a low–high step caused an increase in filament temperature.

A comparison between Figure 3.8(a) and (d) shows the effects of modifying both retraction and priming durations. Both settings provided a fast temperature response with low overshoot, implying the priming and retraction motions should move the melt front an equal amount to ensure the filament temperature remains constant upon extrusion.

An increased temperature can be observed at approximately 16 s is present in Figure 3.8(a),

### Table 3.3. High and low factors investigated during testing of retraction/priming motions

<table>
<thead>
<tr>
<th>Factor</th>
<th>Low value</th>
<th>High value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Retract duration</td>
<td>0.05 s</td>
<td>0.5 s</td>
</tr>
<tr>
<td>Prime duration</td>
<td>0.05 s</td>
<td>0.5 s</td>
</tr>
<tr>
<td>Pause time</td>
<td>1 s</td>
<td>10 s</td>
</tr>
<tr>
<td>Speed multiplier</td>
<td>x1</td>
<td>x4</td>
</tr>
<tr>
<td>Feed rate</td>
<td>0.5 mm/s⁻¹</td>
<td>2 mm/s⁻¹</td>
</tr>
</tbody>
</table>

### Table 3.4. Overshoot (°C) and settling time (s) for selected temperature responses.

<table>
<thead>
<tr>
<th></th>
<th>Fig 3.8(c)</th>
<th>Fig 3.8(d)</th>
<th>Fig 3.9(a)</th>
<th>Fig 3.9(b)</th>
<th>Fig 3.9(c)</th>
<th>Fig 3.9(d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overshoot</td>
<td>10.1</td>
<td>2.4</td>
<td>12.9</td>
<td>8.1</td>
<td>15.1</td>
<td>18.5</td>
</tr>
<tr>
<td>Settling time</td>
<td>0.81</td>
<td>0.60</td>
<td>0.52</td>
<td>0.66</td>
<td>0.99</td>
<td>6.77</td>
</tr>
</tbody>
</table>
Figure 3.7. Effect of pause duration on filament temperature whilst using equal prime and retract parameters. (a) show a short pause duration, and (b) a long pause duration; the bottom of the temperature trace is truncated to improve readability, with the filament rapidly cooling towards room temperature.
and to a lesser extent in Figure 3.8(c) and Figure 3.9(c), potentially showing the effect of “ooze”; all of these tests used a short retraction distance. This effect would be due to the lower distance from the melt front to the nozzle orifice, leading to the flow of molten filament through the nozzle orifice. However, it was not clear why the effect was more consistent and pronounced in Figure 3.8(a) than the other experiments with low retraction values.

Through comparison of Figure 3.9(a) and (b), no major difference in temperature response time was observed when the speed multiplier was applied, supporting the previous observation of equal speed and duration between retraction and priming leading to a more consistent temperature profile. The higher speed multiplier setting reduced temperature fluctuations after the priming action occurred (between 20 and 25 s), but also increased the overshoot.

Figure 3.9(d) depicts the effect of an increased flow rate, with identical retraction, pause, and priming parameters to those used as Figure 3.9(b). An increased overshoot was observed for the higher flow rate, with a longer settling time.
Figure 3.8. Filament temperature response during retraction and priming tests for PLA. All plotted responses have a high pause time of 20 s. (a) shows responses for a low retract and low prime, (b) shows high retract and low prime, (c) shows low retract and high prime, (d) shows high retract and high prime.
Figure 3.9. Filament temperature response during retraction and priming tests for ABS. (a) shows high retraction and high prime, with a high level speed multiplier; the movement time was decreased and speed increased by a factor of 4. (b) shows high prime and retraction with no speed multiplier; analogous to Figure 3.8(d). (c) shows the combined effect of low retraction and high prime, analogous to Figure 3.8(c). (d) shows the effect of an increased feed rate of 2 mm s\(^{-1}\). Overshoot and settling times are shown in Table 3.4.
3.3 Measurement of bonding levels within thin walls

To estimate the effect of the recorded temperature fluctuations observed in Section 3.2, a numerical sintering model was applied to predict filament bonding. Thin walls were then manufactured using FFF, and the surface scanned with an optical coordinate measuring machine to identify if predicted changes in bond formation were visible.

3.3.1 Effect on sintered bonding

The bond formation caused by the polymer sintering effect was evaluated with a model presented by Bellehumeur et al. [68, 109]. Bond formation was represented by the dimensionless unit \( \frac{y}{a} \), the ratio of half the width of sintered bond \( y \) to the filament radius \( a \), as shown in Figure 2.6.

The model used for bond formation was in the form of a differential equation identifying the change in \( \theta = \arcsin \left( \frac{y}{a} \right) \). A nonlinear function predicted the neck growth \( \theta \) as a function of time \( t \), material viscosity \( \mu \), initial radii \( a_0 \), and polymer surface tension \( \Gamma \) (3.2); both viscosity and surface tension are functions of the material temperature \( T \), predicted by (3.3). The equation is shown in (3.1)\(^1\), and was solved using the ODE45 solver within MATLAB.

\[
\frac{d\theta}{dt} = \frac{\Gamma}{a_0 \mu} \frac{2 \mu^2 \cos \theta \sin \theta (2 - \cos \theta)^{\frac{1}{2}}}{(1 - \cos \theta)(1 + \cos \theta)^{\frac{1}{2}}}
\]

The cooling model, surface tension, and viscosity functions were derived within [109] for ABS P400, an ABS blend produced by Stratasys. While this was a different composition of ABS to that examined here, the rheological properties provide an approximation of bond formation over a range of temperatures. It was found the material parameters and initial temperature had the most significant effect on the anticipated bond formation in both the papers describing the model [68, 109].

Rheological properties were used from [68, 109], with key parameters described by the following equations; two equations for viscosity \( \mu \) were used, with the first, (3.4), provided by Bellehumeur et al. [109], and the second, (3.5), by Sun et al. [68]. A plot showing the difference between the functions is shown in Figure 3.10, and it can be seen (3.5) underestimated viscosity at lower temperatures. The parameter \( m \) was a nonlinear function relating further rheological properties. A comparison between simulations from [109] and the implemented model are shown in Figure 3.11; it can be seen a difference exists in the bonding evolution, but similar settled values were achieved.

\[
\Gamma = 0.029 - 0.00345(T - 240)
\]

\[
T = T_\infty + (T_0 - T_\infty) e^{-mx}
\]

\(^1\)Note: Sun et al. [68] had a typographic error in this equation, omitting the “−” sign from \( \frac{2}{\mu} \).
CHAPTER 3. FILAMENT TEMPERATURE DYNAMICS

(3.4) \[ \mu_1 = 1 \times 10^{33} e^{-12.31T} \]

(3.5) \[ \mu_2 = 5100 e^{-0.056(T-229.85)} \]

Through variation of steady state temperature based on the settled temperature and overshoot values from the step and dynamic tests, the expected level of sintered bond formation was calculated. Table 3.5 shows the resulting dimensionless bond size \( y/a \) within the range of observed temperature fluctuations, and the relative change based on the steady state temperature. There was a clear change in the estimated sintered bond formation within the temperature ranges shown to occur through dynamic filament movements, with both equations for \( \mu \) predicting a more significant change for a drop in temperature. It can be seen that the lower viscosity model increased the estimate for the dimension \( y/a \).

This model has underestimated the bond formation, as the assumed shape of the two filaments to be sintered was cylindrical, whereas the true extruded filament formed an oval-shaped deposited road [93]. This would be due to the mechanical compression of the nozzle, leading to an increased initial contact area than predicted.

### 3.3.2 Bond radii measurement

To measure the profile of the deposited road, FFF was used to produce thin walls 50 layers high (25 mm) and the thickness of a single extruded road. Specimens were printed along the \( x \) axis of
3.3. MEASUREMENT OF BONDING LEVELS WITHIN THIN WALLS

![Graphs showing temperature and dimensionless neck radius over time with different convection coefficients.](image)

**Figure 3.11.** A comparison of results from Bellehumeur et al. [109] (a, c) and that used in this section (b, d). The top row shows the cooling filament with different convection coefficients, and the bottom the corresponding sintering model.

**Table 3.5.** Variation of dimensionless sintered bond formation at an extruded temperature of 225 °C. The percentages show the effect of the variation on sintered bond formation based on the steady state deposition temperature expected after the feed rate changes.

<table>
<thead>
<tr>
<th>Temperature variation from 225 °C</th>
<th>-20</th>
<th>-10</th>
<th>0</th>
<th>+10</th>
<th>+20</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mu_1 ) y/a</td>
<td>0.089</td>
<td>0.109</td>
<td>0.129</td>
<td>0.148</td>
<td>0.160</td>
</tr>
<tr>
<td>Percentage change</td>
<td>-31.4%</td>
<td>-15.9%</td>
<td>0.0%</td>
<td>14.5%</td>
<td>23.9%</td>
</tr>
<tr>
<td>( \mu_2 ) y/a</td>
<td>0.132</td>
<td>0.154</td>
<td>0.178</td>
<td>0.201</td>
<td>0.216</td>
</tr>
<tr>
<td>Percentage change</td>
<td>-26.3%</td>
<td>-13.4%</td>
<td>0.0%</td>
<td>12.6%</td>
<td>21.1%</td>
</tr>
</tbody>
</table>
Table 3.6. Bond heights (µm) measured using an Alicona InfiniteFocus 3D for variations in extrusion speed. Step tests followed a Low–High speed change.

<table>
<thead>
<tr>
<th>Step Direction</th>
<th>Speed</th>
<th>Low speed</th>
<th>High speed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Std. Dev.</td>
<td>Mean</td>
</tr>
<tr>
<td>1 L/R Low-High</td>
<td>175.2</td>
<td>2.9</td>
<td>171.6</td>
</tr>
<tr>
<td>1 R/L Low-High</td>
<td>175.2</td>
<td>4.2</td>
<td>170.7</td>
</tr>
<tr>
<td>0 L/R Low</td>
<td>173.0</td>
<td>4.3</td>
<td>–</td>
</tr>
<tr>
<td>0 L/R High</td>
<td>–</td>
<td>–</td>
<td>165.0</td>
</tr>
<tr>
<td>0 R/L Low</td>
<td>174.3</td>
<td>3.5</td>
<td>–</td>
</tr>
<tr>
<td>0 R/L High</td>
<td>–</td>
<td>–</td>
<td>169.3</td>
</tr>
</tbody>
</table>

A Bits from Bytes RapMan 3.2 printer at a temperature of 225 °C in two directions, left to right and right to left, and at two speed levels; a low nozzle speed of 8.33 mm s⁻¹ with a feed rate of 0.5 mm s⁻¹, and at a high nozzle speed of 16.66 mm s⁻¹ with a feed rate of 1 mm s⁻¹. Additional specimens were produced with a step change in nozzle speed from low to high values at the center point of the wall, representing the step change investigated in Section 3.2.1. A pause was inserted between the layers on specimens printed with higher speeds to ensure a consistent print times of 14.5 s per layer.

Wall thickness was measured with a digital micrometer, and the surface profiles of the left and right sides of the specimens were measured using an Alicona InfiniteFocus 3D micro coordinate measurement machine, calibrated for a vertical resolution of 2.5 µm and a lateral resolution of 7.5 µm. Bond depth was measured from the resulting 3D model data with the Alicona IF MeasureSuite profile measurement tool, calculating the average height between the widest and narrowest points of the top ten layers of deposited filament; the lowest point measured was on the inter-layer bond line. Temperature was measured through the average step height of six lines containing a minimum of five peaks over a central 10 mm section on the left and right sides of the wall.

Table 3.6 shows the bond heights measured for the low and high speeds of each test. Three replicates were used, and the standard deviation presented was derived from the variation of the sample bond heights.

There was no statistically significant difference in wall thickness (0.91 mm) or measured bond height (174 µm) between the initial low speed sections of the step, and the specimens printed at a low and constant speed. A statistically significant difference was observed between the measured parameters of the post-step, high speed, specimens and the constant high speed specimens; an increase of 0.02 mm in thickness and 4 µm in bond height. However, as a proportion of thickness (<1%), the observed variation in bond height was not considered to be significant. Data thus far has shown no observable differences in the bond formation caused by variation in filament temperature due to step changes in flow rate; a finding supported by the consistency of bond depths from optical measurement. However, the effects of the inter-layer bonding due to polymer
entanglement would be in the centre of the bond, and unobservable with the equipment used.

3.4 Conclusions

This chapter has presented measurements of filament temperature fluctuations due to feed rate changes, and prime/retract motions used at the beginning and end of road deposition. It was found the ABS filament had higher temperature variations than PLA, showing the need for the controller tuning based on the filament used. In addition, a reduction in temperature overshoot and rise time was achieved through use of the nozzle-mounted thermistor for the temperature control feedback signal, as opposed to the traditional block-mounted thermistor. However, control instability due to the increased distance between the heater cartridge and the nozzle thermistor must be compensated for to reduce steady state errors.

There was no noticeable delay in steady state extrusion temperature achievement when identical priming and retraction settings were used. An increased feed rate before the retraction and priming motions amplified the overshoot from 12.9 to 18.5 °C, and, with a lower retraction than prime, the observed overshoot was similar to that of the low–high step test; this was hypothesised to be due to the melt front movement within the nozzle. All tests with a prime value equal to or greater than the retract value did not experience a temperature drop, providing confidence sufficient bonding would occur at the start of each road.

The application of a sintered bonding model provided an estimate of inter-layer bonding at different filament temperatures. The model predicted significant effects on sintered bond formation within the experimental temperature ranges, an effect with implications on bonding consistency. Results from optical measurement of the surface to identify variations in bond thickness due to speed changes were inconclusive, with observed variations small in comparison to the overall bond width. While the sintered bonding model underestimated the bond size observed in optical measurement, the true shape of extruded filament was not accounted for with deposited roads modelled as cylinders. The optical methods used could not identify the level of entanglement of polymer chains within the centre of the bond.

The following chapter models the block and nozzle thermal response to implement a more advanced control algorithm to reduce the temperature drop shown at increased feed rates and the fluctuation in nozzle temperature. Such methods would ease part certification, through an improved process knowledge and assurance of bond strength throughout the structure. The effect changes in extrusion temperature on bond formation is examined in Chapter 7, and discussed in Chapter 8.
The previous chapter has shown that the filament temperature has a complex dynamic relationship to the filament feed rate. The lowered stability caused by the larger delay when the a nozzle-based thermistor was used as a feedback signal was also noted, despite it providing a better reflection of the extruded filament temperature. This chapter implements advanced control methods to improve stability and temperature consistency.

Development of the model used in Section 4.5.2 and data collection for this chapter was aided by Jasper Kearney over his individual research project and a summer internship.

4.1 Introduction

Advanced control and monitoring has the potential to assist the quality control during the deposition process. Rao et al. [59] investigated real-time quality monitoring of FFF machines, with an array of sensors, including an IR camera and thermocouples to monitor the extruded temperature, capable of identifying drifts in surface roughness. Monitoring the temperature during deposition, Seppala and Migler used IR thermography to monitor the thermal effects of deposition on the surrounding area to monitor the temperature surrounding the deposition area, and related this to the tear energy [79, 80]. As with previous literature, parts produced with FFF did not achieve the properties of the bulk material.

Thermal control is typically performed using a PID controller due to the simplicity of manual tuning based on observation of the response, and ease of implementation. The commonly used PID controller within the Marlin firmware [91] on an Arduino provides adequate temperature control for a majority of applications. As shown in Chapter 3, significant fluctuations of filament temperature occur, and control of such may require higher performance control systems.
Stratasys highlighted the advantage of advanced thermal control in a patent filing for a multizonal extruder [114]. With zones at different temperatures, printed part quality was hypothesised to be improved by raising the melt front location for long extrusion moves and lowering around tight corners.

Commercially available hotends have a thermistor mounted in the heater block. By mounting a thermistor in the nozzle, closer to the point of extrusion, it was seen the nozzle temperature decreased at an increased flow rate, as shown in Figure 4.1(a). Using the nozzle thermistor for temperature control input relieved this problem, but increased the difficulty in tuning the controller; shown by the longer settling time in Figure 4.1(b).

This chapter explores advanced thermal controllers to maintain more consistent nozzle and filament temperature during the deposition process. A Laplace-domain model was constructed to represent the interaction of the heating element with the recorded temperature, aiding the development of a Smith Predictor controller; this was implemented on a high performance control prototyping system. Feed-forward controllers are then applied to compensate for changes in feed rate. The result of tests monitoring the block, nozzle, and filament temperatures under different feed rate profiles are shown and discussed, followed by an implementation on the Marlin firmware of the feed-forward controller, and the conclusions of this chapter.
4.2 Model identification

An empirical method was employed to identify a plant model to represent the thermal dynamics of the extruder system, based on work presented by Liu et al. [177]. Under open-loop control conditions, a constant PWM value of 40% was held until the temperature stabilised. 20 s after the measurement began, a 10 s pulse to a high PWM value (100%) or low PWM value (0%) was applied, and the response recorded for a total duration of 100 s. These tests were conducted at three constant feed rates of 0, 0.5, and 1 mm s\(^{-1}\); higher feed rates caused a blockage of the nozzle due to the temperature drop. Data was recorded by a MATLAB script connected to an Arduino Mega running a modified version of the open-source Marlin firmware [91]. The modification allowed direct PWM control of the heater, which was connected to the Arduino via a RAMPS 1.4 driver board to an E3D v6 hotend and a Bulldog XL extruder. The temperature was recorded at a rate of 2 Hz, suitable for the nozzle and block response time identified in Chapter 3.

A range of Laplace transfer functions, such as the one shown in Equation 4.1 were used as candidate models, all containing a time delay \( T \), followed by a rational transfer function. The time delay \( T \) was manually identified from the step tests, and the remaining factors identified through the minimisation of the RMS error between the model and test response, with use of the fmincon function from MATLAB. Figure 4.3 shows two verification tests for the optimised model, comprising of step PWM input repeated with constant feed rates. The model shown in Equation 4.1, tuned with the highest flow rate, had the lowest average RMS error over the test signals; it was noted the tuning with the higher flow rate performed best on all candidate models.

\[
\hat{G}_h(s) = e^{-Ts} \frac{As + B}{Cs^2 +Ds +E}
\]

A bode plot, shown in Figure 4.4, shows a significant decrease in phase at frequencies higher than 0.1 Hz due to the time delay present in the system caused by thermal inertia.

4.3 Control design

The model allowed for the simulation of the plant, enabling development of more advanced control structures. To ease testing and improve data collection, the extruder control system was implemented on a dSpace DS1103 rapid prototyping control system, and operated using the ControlDesk 6.1 software and MATLAB. Controllers were prototyped on Simulink and compiled to run on the DS1103 to enable direct testing with the hardware.

The DS1103 operated at frequency of 1 kHz, a significantly higher sample rate than the Arduino-based Marlin firmware. In order to better replicate the existing controller, the dSpace-based control systems were implemented at a sampling frequency of 5 Hz, and the output PWM signal quantised to 127 levels. A saturation limit of [0, 1] was imposed on the control PWM signal to remain within physical limitations of the signal type.
FIGURE 4.2. Example step tests used for the tuning of a model. (a) shows a high step to the maximum PWM value, whilst (b) depicts a step to a low PWM value.
Figure 4.3. Two verification tests showing the predicted and measured result to a varying PWM input. Solid line and dashed lines represent the measured and model response respectively. (a) shows a test conducted with no extrusion, and (b) shows a test conducted at the high feed rate of 1 mms$^{-1}$.
With the high measurement frequency of the DS1103, significant noise was present when recording temperature. Figure 4.5 shows the raw data, and the application of a mean filter, averaging over 164 samples, to ensure a smooth input to the temperature controller. It was observed there was an increase in the measured noise during application of the PWM signal, shown at the 30 s point as the temperature starts to increase; this was potentially due to electromagnetic interference within the RAMPS driver board.

4.3.1 Controller implementation

The Smith Predictor was developed to control systems with a large dead time using an estimate of the plants response [178]; the control loop structure is shown in Figure 4.6(b). Through use of the rational component of a plant model ($\hat{G}_h(z)$) excluding the time delay ($z^{-k}$), the controller estimates the system response excluding dead time. This ensures better tracking over more basic controllers, such as the PID controller implemented on Marlin [91] depicted in Figure 4.6(a). Meyer et al. [179] compared the theoretical performance of the Smith Predictor to existing controllers, identifying its suitability for processes with significant time delays with relatively fast load transfer function dynamics.

The use of the feed rate as a secondary control input to reduce the temperature drop experienced by the nozzle during a feed rate step change was also investigated. Under block control, the feed-forward (FF) controller ($G_f(z)$) consisted of a gain applied to the feed rate to adjust the temperature set point to increase the block temperature to compensate for the expected reduction...
in nozzle temperature, as shown in Figure 4.6(c).

When using the nozzle-based thermistor for the feedback signal, $G_f(z)$ consisted of a step followed by a constant gradient decay applied to the temperature set point, with the gain and decay time determined from the response time to stabilise the temperature after a flow rate change. The use of a gain plus decay of the control input ensured heating occurred on a change in feed rate, followed by a return to the initial temperature set point. A gain of $2 \, ^\circ C/(mm/s)$ with a decay time of 30 s was identified, and the response of these controllers to a step change in feed rate is shown in Figure 4.7.

For the Smith Predictor, the controller $G_c(z)$ was a PI controller, as the overshoot was compensated for by the predictor component. The feed-forward control implementation used a PID controller as $G_c(z)$, typical of the existing thermal controllers.

### 4.4 Results

Step tests within the typical temperature operating range were first conducted to tune and compare the Smith Predictor controllers, followed by three feed rate test signals to examine the disturbance rejection. During these tests, the filament temperature was observed with a FLIR T650 IR camera.
4.4.1 Temperature step tests

A step change in demand temperature from 250 °C to 255 °C at a time of 30 s was applied to tune the controllers $G_c(z)$ to ensure a stable response. Figure 4.8 shows the nozzle and block responses, and the corresponding PWM command signal. It was observed the Smith Predictor could be tuned with higher gains to provide a more aggressive control input with lower overshoot; this is especially clear in Figure 4.8(a) and (c), where the PID controller exhibited a slight overshoot. From observation of the PWM signal for Figure 4.8(b) and (d), the Smith Predictor showed a faster response, saturating the upper limit to provide rapid heating, with the predictive element compensating for the expected overshoot. For clarity, figures in Section 4.4.2 depict the PID controller used for the block, providing an insight into how this method could be applied to the existing firmware, and the Smith Predictor controller for the nozzle.

It was observed nozzle-based thermistor had significantly higher measurement noise than...
the block-based thermistor. This could be due to the attachment method; a hole was drilled into the edge of the nozzle, filled with heat sink paste, and the thermistor inserted in. While this provided a good measurement of nozzle temperature, it was more exposed to the atmosphere and would be more sensitive to disturbances than the block-based thermistor, which was more firmly embedded in the block.

### 4.4.2 Feed rate compensation

Three tests to evaluate the implemented controllers used a combination of a low feed rate (0.5 mms$^{-1}$), and a high feed rate (2 mms$^{-1}$); these were the same tests as used in Chapter 3. The first test comprised of a 120 s of high feed rate, Test 2 contained a feed rate of 60 s of low feed rate immediately followed by a 60 s of high feed rate, and Test 3 reversed the order of Test 2. These test profiles are depicted in Figure 4.9.

Figures 4.10, 4.11, and 4.12 show the resulting temperature profiles for the block and nozzle thermistors. In all of these figures, (a) and (b) show PID and PID + feed-forward control respectively, with the block thermistor as the feedback signal. (c) and (d) show the Smith Predictor and Smith Predictor + feed-forward control respectively, with the feedback provided by the nozzle-based thermistor.

Figures 4.10, 4.11, and 4.12 also show the filament temperature as recorded by a FLIR T650
Figure 4.8. Temperature response to a step change in demand temperature. (a) and (b) show the PID and Smith Predictor responses for block control respectively. (c) and (d) show the PID and Smith responses for the nozzle respectively.
4.4. RESULTS

**Figure 4.9.** Feed rate profiles of tests used to evaluate controllers. Tests 1, 2, and 3 correspond to plots a, b, c respectively.
IR camera, as used in Chapter 3. An image showing the observed IR image and ROI was included in Figure 3.2. During these tests, it was noted the filament temperature was significantly below that of the block and nozzle; this was due to the different emissivity of the ABS plastic used, and the maximum pixel extraction caused a high level of noise. While previous work using a thermal camera, such as that by Seppala and Migler [79], compensated for the emissivity through adjustment to the nozzle temperature, this was not implemented as the objective of the study was to observe the relative fluctuations and changes.

The fluctuations in nozzle and filament temperatures were calculated as the standard deviation over the central extrusion period, with results shown in Tables 4.1 and 4.2 respectively. For Test 1, this was measured from 75 s to 165 s, and Tests 2 and 3 from 50 s to 140 s, excluding the effect of the initial overshoot. The feed-forward element reduced the standard deviation of the nozzle temperature in all cases, but had a smaller effect on the filament temperature.
Figure 4.10. Test 1: Effect of high feed rate on block, nozzle, and filament temperatures during 120 s period of high flow rate, starting at 60 s. (a) shows conventional PID control based on the block thermistor reading, with (b) showing the controller with the feed-forward element. (c) shows the Smith Predictor controller using the nozzle thermistor as input, and (d) shows the same controller with feed-forward compensation.
FIGURE 4.11. Test 2: Effect of a step change in feed rate from low to high. (a) and (b) show the block-based PID and PID+FF controllers respectively, and (c) and (d) show the nozzle-based Smith Predictor and Smith Predictor+FF controllers respectively.
Figure 4.12. Test 3: Effect of a step change in feed rate from high to low. (a) and (b) show the block-based PID and PID+FF controllers respectively, and (c) and (d) show the nozzle-based Smith Predictor and Smith Predictor+FF controllers respectively.
CHAPTER 4. THERMAL CONTROL FOR IMPROVED QUALITY ASSURANCE

Table 4.1. Standard deviation (°C) of nozzle temperature over central period of test

<table>
<thead>
<tr>
<th>Test</th>
<th>Nozzle control</th>
<th>Block control</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PID</td>
<td>PID+FF</td>
</tr>
<tr>
<td>1</td>
<td>2.07</td>
<td>1.04</td>
</tr>
<tr>
<td>2</td>
<td>1.44</td>
<td>1.41</td>
</tr>
<tr>
<td>3</td>
<td>2.06</td>
<td>1.51</td>
</tr>
</tbody>
</table>

Table 4.2. Standard deviation (°C) of filament temperature over central period of test.

<table>
<thead>
<tr>
<th>Test</th>
<th>Nozzle control</th>
<th>Block control</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PID</td>
<td>PID+FF</td>
</tr>
<tr>
<td>1</td>
<td>1.67</td>
<td>1.80</td>
</tr>
<tr>
<td>2</td>
<td>9.23</td>
<td>5.80</td>
</tr>
<tr>
<td>3</td>
<td>6.79</td>
<td>5.82</td>
</tr>
</tbody>
</table>

4.5 Further demonstration

After the feed-forward controller was demonstrated with the dSpace system, two further advances were explored. Section 4.5.1 shows the application of the feed-forward element to the Marlin firmware supplementing existing PID controller. Improvements in the feed-forward element $G_f(z)$ by modelling the effect of feed rate on block temperature are discussed in Section 4.5.2.

4.5.1 Implementation on Marlin Firmware

The feed-forward controller using set point adjustment was coded into the Marlin firmware [91]. For implementation, feedback signal was taken using the block-based thermistor, with the output of the three feed rate tests previously described shown in Figure 4.13; (a, c, e) show the standard PID control, and (b, d, f) the PID+FF controller. Table 4.3 shows the deviation of nozzle temperatures during the high and low feed rate sections of the test.

Tuning of the feed-forward element was manually conducted using data shown in Figure 4.13(a). The temperature drop between the no extrusion and a high extrusion level was measured to be 3 °C at a feed rate of 2 mm/s⁻¹. This provided the gain of $G_f(z)$ to be 1.5 °C/(mm/s). This simple feed-forward compensator reduced the nozzle temperature fluctuation due to feed rate changes despite only using block-based control.

4.5.2 Model-based Feed-Forward Controller

With the improved response achieved through a simple feed-forward controller presented in Section 4.4.2, a model-based $G_f(z)$ was then implemented. The response of the block to changes in feed rate was modelled with a similar process to that described in Section 4.2. Application
4.5. FURTHER DEMONSTRATION

Figure 4.13. Nozzle and block temperatures of block-based PID controller with a feed-forward element implemented on the Marlin firmware. (a, c, e) show a PID controller, and (b, d, f) PID+FF controllers. Each row corresponds to the tests depicted in Figures 4.10, 4.11, and 4.12 respectively, with analysis of the nozzle temperature presented in Table 4.3.
### Table 4.3. Effect of feed rate changes on nozzle temperature (°C) when the Marlin PID is supplemented by the feed-forward element. The central section excludes first 15 s of the test to neglect the initial overshoot.

<table>
<thead>
<tr>
<th>Test</th>
<th>PID Mean</th>
<th>PID Std. Dev.</th>
<th>PID+FF Mean</th>
<th>PID+FF Std. Dev.</th>
<th>Central section Mean</th>
<th>Central section Std. Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test 1</td>
<td>242.5</td>
<td>1.09</td>
<td>–</td>
<td>–</td>
<td>242.4</td>
<td>0.96</td>
</tr>
<tr>
<td>Test 2</td>
<td>243.6</td>
<td>1.20</td>
<td>244.8</td>
<td>0.24</td>
<td>243.6</td>
<td>1.50</td>
</tr>
<tr>
<td>Test 3</td>
<td>243.7</td>
<td>1.48</td>
<td>245.5</td>
<td>0.63</td>
<td>243.7</td>
<td>1.47</td>
</tr>
</tbody>
</table>

**Figure 4.14.** System diagram of the model-based feed-forward controller to compensate for changes in feed rate.

... of this controller on the dSpace system allowed for improved pre-emptive compensation of the thermal response to a change in feed-rate, as shown in Figure 4.14.

Testing was conducted with a high feed rate, using the block-based thermistor for temperature measurement. A tuned PID controller provided the steady state temperature controller, with an additional control input to compensate for the predicted response of the block. This was implemented using the block-based thermistor, and Figure 4.15 shows the temperature consistency achieved when a step change in feed rate occurred at 30 s.

Further details on this implementation can be found in a research project report by Jasper Kearney [180].

### 4.6 Discussion

Figure 4.1 shows the decrease in nozzle temperature when under block-based control due to the higher flow rate, whilst the block remained at a constant temperature, implying the filament was...
Section 4.2 described a process to model the relationship between the input PWM signal and the temperature recorded by the block and nozzle thermistors, allowing the implementation of the Smith Predictor controller. The best-fitting model was generated using data from PWM step tests whilst at a high feed rate. The transfer functions evaluated were all linear, and thus were unable to fully capture the nonlinearities present in the heating dynamics of the block—whilst it is possible to heat the system, there is no mechanism for actively cooling, as evident in Figure 4.5 by the different gradients for cooling and heating. A possible reason for the improved fit of the thermal models tuned with higher flow rate data is the increased cooling effect of the filament flow linearising the plant.

The Smith Predictor and feed-forward controllers were then implemented using a rapid prototyping control system, with the former relying on the previously derived model to estimate
CHAPTER 4. THERMAL CONTROL FOR IMPROVED QUALITY ASSURANCE

the future system output negating the effect of time delay caused by thermal inertia. It was attempted to tune the models through simulation, but the gains obtained were too low to be of practical use. Figure 4.8 shows the performance of the Smith Predictor after manual tuning, and it was noted the Smith Predictor for the nozzle outperformed the conventional PID, whilst the block controllers provided similar performance. During the tuning process, it was identified the Smith Predictor could be tuned with a more aggressive response due to the overshoot compensation inherent in its structure.

Examination of the filament temperature in Figures 4.10, 4.11, and 4.12 show overshoots similar to those observed in Chapter 3. As there was no flow to ensure steady nozzle and block temperatures at the start of each test, this correlates well with the previously described concept of the melt front being maintained at a higher temperature. Additional support for this is shown in Figure 4.11, where the initial feed rate was relatively low, causing the temperature to remain higher for an extended period of time, whilst the melt front moves to its steady state equilibrium position.

Conversely, Figure 4.12 showed a drop in filament temperature during the change from high to low feed rate, also observed in Chapter 3. This is potentially due to the reduction in pressure on the melt front by the filament feed causing a short reduction in extrusion from the nozzle, although it is not clear why this occurred to a greater extent in Figures 4.12(c) and (d). This was reflected in the increased standard deviation of filament temperature identified in Table 4.2, and to a lesser extent in Table 4.1 for nozzle temperature deviation; in both cases, the feed-forward controller still provided an improvement in consistency.

The feed-forward element provided a significant reduction in nozzle and filament temperature variation for experiments involving a feed rate change. A key result was the feed-forward implementation when combined with the PID controller of the block provided similar performance to that of the nozzle-based control. While the explored implementation is suited for a constant temperature set point and step changes in feed rate, the controller derived in Section 4.5.2 could provide more flexibility for fluctuating temperature demands.

The result and implementation of the feed-forward controller onto the commonly used Marlin firmware showed a reduction in the standard deviation of nozzle temperature, as shown in Table 4.3; a similar reduction was achieved to those identified from the dSpace controller shown in Table 4.1. The required gain for the feed-forward element used in the Marlin implementation was manually identified from the temperature drop of the nozzle during extrusion. With the feedback signals taken as the block temperature and feed rate, the nozzle temperature could be stabilised, reducing the requirement for an additional thermistor.

During testing, it was noted the large size of the thermistor relative to the nozzle limited the achievable strength of the attachment. This hinders its use on a moving printer head, and would require a redesign of the nozzle to fully embed the thermistor.
4.7 Conclusions

Quality control is a vital process for qualifying components for the use in the Aerospace and medical industries; while FFF has a number of advantages in suitability to produce complex components, the layered manufacturing approach requires knowledge of the filament temperature to model bonding over the component. As Chapter 3 has shown, the filament temperature fluctuates during the printing process, and a thermistor based in the nozzle provided a more accurate representation of the filament temperature. However, due to the thermal mass of the block and nozzle, the higher frequency thermal dynamics of the filament during the start process were not be captured.

This chapter has modelled the relationship between the heating element and thermistors mounted in the block and nozzle for an FFF hotend, and improved control when using the nozzle-based thermistor. A Smith Predictor was found to have better performance for thermal control over conventional PID when using the nozzle thermistor measurement, and similar performances were achieved between PID and the Smith Predictor when using feedback from the block-based thermistor. A feed-forward controller was applied to adjust the temperature set point, compensating for the delay in a change in filament feed rate and its corresponding effect on the recorded temperature; results have shown this addition reduced the variation in nozzle temperatures during changes in feed rate. The open source Marlin thermal control was shown to improve extruded temperature consistency to a similar level as the dSpace system, identifying a significant improvement within the limitations of current FFF system hardware.

Thermal camera images captured filament temperature during the extrusion tests, identifying a highly nonlinear relationship between filament temperature, feed rate, and hotend temperature. The feed-forward element greatly reduced the fluctuation in nozzle temperature, especially when using the block-based thermistor as a control input. While the nozzle better reflects the exact filament temperature than the block, significant fluctuations were still present. An important finding was the errors observed were typically temperature overshoots, which would provide increased localised bonding, as identified in Table 3.5.

The implemented control algorithms have reduced the temperature fluctuation of the filament. As discussed in Chapter 3, bond formation is heavily dependent on temperature; this is further examined in Chapter 7, and discussed in Chapter 8.
Mechanical properties of thin-walled FFF components

Mechanical tests were conducted to compare the properties of FFF cores with existing materials. As discussed in Chapter 2, numerous works have identified optimal infill properties for components with internal volumes. However, for the lowest density, it is desirable to use thin walls in a tessellated structure printed in a single pass. This chapter examines the effect of wall thickness on the bond strength and stress-strain relationship.

Content from this chapter was initially presented at the 17th European Conference of Composite Materials, and later published as a journal paper with the assistance of Ed Cooper, who conducted further mechanical testing. This can be found in:


5.1 Introduction

For the increased adoption of sandwich panels within future Aerospace and automotive applications, improved manufacturing methods will be required to achieve the “Bigger, Faster, Cheaper” mantra [29]; one potential method is to print lightweight cores through FFF. Whilst previous work has provided an insight into the flexibility afforded to FFF cores [46–48, 53], there has been little characterisation of the thin wall mechanical strength or comparison of such cores to existing core materials. FFF components exhibit anisotropic behaviour despite comprising of homogeneous feed material due to the layer-based manufacturing process.

This chapter begins with an investigation into the effect of different wall thicknesses and print speeds on the inter-layer bond strength of ABS and PLA manufactured with a RapMan
CHAPTER 5. MECHANICAL PROPERTIES OF THIN-WALLED FFF COMPONENTS

Figure 5.1. Example cores produced through FFF [Images not to scale]. (a) shows a complex FFF core shape with top and bottom skins, (b) shows a core with ramped edges and top and bottom supports to prevent skin “telegraphing”. Images from [47].

3.2 printer\(^1\), a low-cost printer based on the RepRap project [56]. Such polymers are commonly used for FFF; ABS is considered more suited for load-bearing components and represents the amorphous class of polymers, while PLA is a commonly used semi-crystalline polymer to identify similar trends. Following these results, FFF cores were manufactured and tested to evaluate the effect of different build patterns. The results are discussed, presenting a theory regarding the cause of the observed failure profile, and succeeded by the conclusions.

5.2 Bond strength evaluation

Construction of walls through a single extruder pass allows for the lightest structures for core use; this research was conducted to understand the effects of print parameters on the thin wall strength. Tests were performed based on the ASTM D638 standard [181] to investigate the effects of varying build parameters on inter-layer bond strength of ABS and PLA polymers. A dominating factor in the mechanical strength of FFF components is the inter-layer bond strength [17, 68].

5.2.1 Manufacture of tensile specimens

Wall thickness and manufacturing speed variations were introduced through modification of the nozzle speed and the material flow rate. The printer was located in a research laboratory, with the build area at room temperature and normal humidity, and performed with ABS and PLA plastics. For ABS, three extruder flow rates were considered (4.08, 5.44, 6.80 mm\(^3\) s\(^{-1}\)), with nozzle speed settings to produce wall thicknesses (1.5, 2, 2.5 mm). Due to the lower viscosity of PLA, the same wall thicknesses were not achievable; two flow rates of 4.76 and 9.51 mm\(^3\) s\(^{-1}\)

\(^{1}\)Manufactured by Bits from Bytes, now part of 3D Systems.
were used to manufacture walls with thicknesses of approximately 0.9 and 1.7 mm. Additional PLA specimens were produced with a 13 s pause time to increase the total layer print time to 20 s to allow a longer cooling period.

After printing, the thin walls were machined into hourglass specimens using a laser-cut acrylic jig and Dremel. Specimens were 50 mm long, with a gauge length of $9 \pm 1$ mm and a width of $7.0 \pm 0.5$ mm. The specimens were orientated within tensile testing mounts to ensure the loading direction was perpendicular to the layer line. Figure 5.2(a) shows a test specimen mounted in position for a tensile testing, and (b) a typical failure observed during testing; a clean break between layers normal to the direction of applied force. This failure pattern was consistent with similar tests from the literature [63, 77, 83].

### 5.2.2 Tensile testing results

Testing was conducted at a rate of $2 \text{ mm min}^{-1}$ on a Shimadzu test machine with force measured using a 1 kN load cell sampled at 100 Hz. From the peak force before failure, the ultimate tensile stress for each wall thickness was calculated using measurements for sample width and thickness. The results are shown in Table 5.2 for ABS, and Table 5.3 for PLA. ANOVA analysis, shown in Table 5.1, identified no statistically significant difference in ultimate tensile stress for variations in extruder flow rate and a small change due to wall thickness; this is visible in the box and whisker plot of the ABS results in Figure 5.3. Of the 100 specimens produced, 14 failed during machining or outside of the gauge length during testing.

Figures 5.4 and 5.5 show the Stress-Strain curve for each specimen, with the yield points marked by black squares. The results of the longer pause duration are shown in Figure 5.6, with
CHAPTER 5. MECHANICAL PROPERTIES OF THIN-WALLED FFF COMPONENTS

Table 5.1. ANOVA analysis of effect of wall thickness and flow rate.

<table>
<thead>
<tr>
<th></th>
<th>df</th>
<th>Fcrit</th>
<th>Yield Stress</th>
<th>Ultimate Stress</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>F  P</td>
<td>F  P</td>
</tr>
<tr>
<td>Wall thickness</td>
<td>2</td>
<td>3.24</td>
<td>39.78 &lt; 0.01</td>
<td>4.13 0.02</td>
</tr>
<tr>
<td>Flow rate</td>
<td>2</td>
<td>3.24</td>
<td>0.88 0.42</td>
<td>0.06 0.94</td>
</tr>
<tr>
<td>Interaction</td>
<td>4</td>
<td>2.61</td>
<td>0.75 0.86</td>
<td>0.38 0.83</td>
</tr>
</tbody>
</table>

Table 5.2. Ultimate tensile stress (N mm$^{-2}$) for wall thickness and flow rate variations of ABS samples. These results are depicted in Figure 5.3

<table>
<thead>
<tr>
<th></th>
<th>Wall thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.5</td>
</tr>
<tr>
<td>Flow rate (mm$^3$s$^{-1}$)</td>
<td>4.08</td>
</tr>
<tr>
<td>4.08</td>
<td>24.2±1.3</td>
</tr>
<tr>
<td>5.44</td>
<td>25.2±3.8</td>
</tr>
<tr>
<td>6.80</td>
<td>24.7±3.9</td>
</tr>
</tbody>
</table>

Table 5.3. Ultimate tensile stress (N mm$^{-2}$) for wall thickness and flow rate variations of PLA samples. The sample group with a longer pause time is represented in italics.

<table>
<thead>
<tr>
<th></th>
<th>Wall thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.9</td>
</tr>
<tr>
<td>Flow rate (mm$^3$s$^{-1}$)</td>
<td>4.73</td>
</tr>
<tr>
<td>4.73</td>
<td>21.2±2.7</td>
</tr>
<tr>
<td>9.51</td>
<td>24.6±1.1</td>
</tr>
</tbody>
</table>

the plot of the same parameters excluding a pause, Figure 5.5(a), replicated for comparison.
5.2. BOND STRENGTH EVALUATION

**Figure 5.3.** Box plot of the yield and ultimate tensile stress of ABS. (a) shows the effect of wall thickness, and (b) the effect of flow rate (mm$^3$s$^{-1}$).
Figure 5.4. Stress-Strain curves for ABS tensile samples. The yield points for each specimen are identified by a black square; this point was determined through the decrease in gradient at the end of the region of linear deformation. The parameters used for each test are: (a) 1.5 mm wall, 4.08 mm$^3$s$^{-1}$ flow rate, (b) 2.5 mm wall, 4.08 mm$^3$s$^{-1}$ flow rate, (c) 1.5 mm wall, 6.80 mm$^3$s$^{-1}$ flow rate, (d) 2.5 mm wall, 6.80 mm$^3$s$^{-1}$ flow rate.
Figure 5.5. Stress-Strain curves for PLA tensile samples. The yield points for each specimen are identified by a black square; this point was determined through the decrease in gradient at the end of the region of linear deformation. The parameters used for each test are: (a) 0.9 mm wall, 4.73 mm$^3$s$^{-1}$ flow rate, (b) 1.7 mm wall, 4.73 mm$^3$s$^{-1}$ flow rate, (c) 0.9 mm wall, 9.51 mm$^3$s$^{-1}$ flow rate, (d) 1.7 mm wall, 9.51 mm$^3$s$^{-1}$ flow rate.
CHAPTER 5. MECHANICAL PROPERTIES OF THIN-WALLED FFF COMPONENTS

It can be seen the thinner-walled structures printed with ABS behaved in a more brittle manner than the thicker walled samples; exhibiting a shorter yield before failure; this is significantly more noticeable in the ABS samples than the PLA samples. It can be hypothesised from the higher amount of plastic deformation, identified on both Figures 5.4 and 5.5, the thicker specimens behaved closer to that expected for a conventionally manufactured plastic specimen; implying a higher level of inter-layer bonding than exhibited in the thinner-walled structures. The effect of fibre width on bond strength is consistent with existing literature investigating thin-walled structures [83].

Due to increased contact area between filaments in thicker walls from the wider roads deposited, a heat gradient during the bond-forming process would exist across the road width, with the edge section cooling at a higher rate due to convection, as noted in Chapter 3. As the entanglement between the polymer layers is related to the cooling profile, a higher level of entanglement would be exhibited in the center of the bond relative to the edge [68]. With the lower level of bonding at the edge, a peeling action may occur, causing the earlier yield point observed. The thinner walls would be expected to have a more uniform temperature along the filament bond, the yield point is reached closer to failure with minimal peeling between layers.

Comparing the graphs presented in Figure 5.4 and 5.5, the PLA specimens have a wider intersample variation than exhibited by ABS samples. This could be due to a number of factors; first, the materials have two different structures, with the semi-crystalline nature of PLA potentially more affected by environmental factors. Larger filament temperature fluctuations were also observed in Chapter 3 for PLA over ABS, which could affect the bond strength. Additionally, the manufacture and test of PLA specimens were completed at a different time of year by a separate experimenter, introducing a secondary cause of variation.

From the data presented in Figure 5.6, a statistically significant difference was observed in ultimate stress \((p=0.001)\) and the strain at failure \((p=0.003)\). This shows the duration between deposition of subsequent layers has an impact on the part properties and the strong process-property relationship inherent in FFF, with the increasing time between subsequent depositions representative of the manufacture of a larger component.

5.3 Compressive testing of cores

ABS cores were manufactured through FFF using various toolpaths, each resulting in a different wall thickness, and were compared PLA FFF cores and industry standard Nomex honeycomb. The honeycomb build pattern was selected, due to the efficiency of honeycomb as a filling pattern and the resemblance to Nomex honeycomb [40], and the test design was based on the ASTM D7336 standard [182].
5.3. COMPRESSIVE TESTING OF CORES

**Figure 5.6.** Stress-Strain curves for PLA tensile specimens printed with differing layer times. The black squares represent the yield points of the specimens, found through observation of the end of the elastic region of the stress-strain curve. (a) is the same data as presented in Figure 5.5(a) for comparison, while (b) had a 13 s pause applied.
CHAPTER 5. MECHANICAL PROPERTIES OF THIN-WALLED FFF COMPONENTS

Figure 5.7. A pictorial representation of the three toolpaths investigated, depicted for the construction of a single hexagon cell. The lines are offset to show each pass on for the edges of the honeycomb cell. Each line of continuous extrusion is represented by a different dash type.

5.3.1 Manufacture of the FFF cores

Custom code was created within MATLAB to output a GCode file suitable for the 3D printer, enabling control over the print toolpath, flow rate, and nozzle speed. Three different build profiles were investigated for the ABS specimens as depicted in Figure 5.7, and PLA cores were produced using toolpath 2. The physical properties of the manufactured cores are described in Table 5.4, with the wall thickness, normalised, and expected normalised thickness stated. The expected normalised thickness values were calculated from the number of repeated depositions over a hexagon wall, where 1 denotes the thickness of a single extruded road – a good correlation was identified between the expected and measured values. Toolpath 3 was identical to the output of the default slicing software provided with the printer (Axon 3), which would produce a toolpath assuming the two sides of the wall volume would be separated by a zero volume infill section.

Examples of the FFF and Nomex honeycomb cores used for this testing are shown in Figures 5.8(a, b). A 5 mm cell radius was used for the FFF core, and a 1.6 mm cell radius for Nomex honeycomb, which had a density of 48 kg m\(^{-3}\). FFF specimens were printed to a size of 50x50x14 ± 1 mm, and the Nomex honeycomb core cut with a bandsaw from a 14 mm depth sheet to 50x50 ± 2 mm. This specimen size was similar to those used by Zhang and Ashby when evaluating the theoretical compressive strength of Nomex honeycomb [28].

5.3.2 Compressive testing results

Testing was conducted with level plates mounted on a 50 kN Zwick test machine at a rate of 2 mm min\(^{-1}\), sampled at 10 Hz. The cores were preloaded to 50 N, and the plates checked to ensure the correct orientation. Force-Displacement curves for all tests are shown in Figure 5.9, and ultimate stresses in Tables 5.5 and 5.6.

Figure 5.10 shows Force-Displacement curves normalised by the ultimate failure load of
5.3. COMPRESSIVE TESTING OF CORES

Table 5.4: Core specimen build properties

<table>
<thead>
<tr>
<th>Wall type</th>
<th>Thickness (mm)</th>
<th>Normalised thickness</th>
<th>Expected normalised thickness</th>
<th>Build time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.56</td>
<td>1</td>
<td>1.00</td>
<td>41.0</td>
</tr>
<tr>
<td>2</td>
<td>0.79</td>
<td>1.42</td>
<td>1.33</td>
<td>47.8</td>
</tr>
<tr>
<td>3</td>
<td>1.11</td>
<td>1.98</td>
<td>2.00</td>
<td>69.8</td>
</tr>
<tr>
<td>PLA</td>
<td>0.85</td>
<td>1.35</td>
<td>1.33</td>
<td>47.9</td>
</tr>
<tr>
<td>Nomex</td>
<td>0.08</td>
<td>–</td>
<td>1.33</td>
<td>–</td>
</tr>
</tbody>
</table>

Figure 5.8. Cores used during testing. (a) shows an example core of ABS manufactured through FFF, as used within this paper. (b) shows a Nomex honeycomb core of the same size; the difference in cell size due to the dimensions of the FFF nozzle is clear.

the ABS and Nomex honeycomb cores to allow the comparison of failure profiles. Whilst the Nomex honeycomb followed the anticipated crushing behavior with a constant crush force [28], the FFF cores followed a more typical buckling behaviour for plastic structures, with a widened peak loading. The FFF cores withstood a significantly higher force before failure than Nomex honeycomb, with similar ultimate stresses experienced on the wall due to the increased wall thickness. The higher compressive strength of the PLA specimen over ABS corresponds to the findings of Tymrak et al. [183].

With a more brittle thin-walled structure, there was less deformation before buckling. This failure mode was exhibited through separation between layers, with the layers remaining relatively undistorted. The increased ductility of the inter-layer bond for thicker specimens, as discussed in Section 5.2, correlated to the more ductile core failure observed. With the increased contact area and ductile deformation, a significantly higher force was required to reach peak deformation. The post-failure behaviour, depicted by the force-displacement graphs in Figure 5.10,
shows the increased resistance to crushing after the initial failure with plastic behaviour similar to that presented in Section 5.2.2, where there was a larger deformation before yield.
Figure 5.9. Force-displacement curves for compressive testing of ABS cores produced through FFF. (a) was manufactured using toolpath 1, as described in Figure 5.7. (b) and (c) were manufacturing using toolpaths 2 and 3 respectively. (d) is a Nomex honeycomb core, commonly used within the aerospace industry.
Calculating the ultimate compressive stress per unit core area allowed a comparison with data provided by manufacturers, as shown in Table 5.5, demonstrating similar properties between the FFF cores and the thermoplastic and Nomex materials. Table 5.6 presents the yield force, yield and ultimate stress, and specific yield stress for each build pattern, calculated with the surface area of the walls. The specific yield stress was calculated by dividing the ultimate crush force by specimen mass. In a similar result to the tensile results presented in Section 5.2, thinner walled core behaved in a more brittle manner than the thick walled counterparts, with little plastic deformation occurring between yield and ultimate stresses.
5.4 Discussion

Section 5.2 presented inter-layer bond failure mechanisms for different wall thicknesses; the thicker walls behaved in a more ductile manner. In Section 5.3, it was observed that the FFF cores exhibited a higher compressive force, but a lower specific strength than the Nomex honeycomb. The cores manufactured through FFF had a higher compressive strength than stated strength of the thermoplastic polymer cores, and coupled with the increased density provided equivalent specific compressive strength. Wall thickness was found to be a contributing factor to the difference between the yield and ultimate displacements, providing the differing ductility during failure. However, with the increased crush force after failure of the plastic cores, there is potential for improved impact resistance [46]. Through correlation between Sections 5.2 and 5.3, it can be concluded that inter-layer bond strength is key in determining the failure properties and profile of the final core, influenced by the wall thickness.

Table 5.6 showed the yield and ultimate stress when calculated from the wall thickness. It can be observed the increasing wall thickness of the FFF core increases this ultimate stress, showing the failure is likely due to buckling; with the hexagon sides significantly longer than that of Nomex, they would be less supported. Analysis of the buckling of such structures was provided by Zhang et al. [28].

The deposition pattern also introduced anisotropic properties to the core, with a difference between bulk filament material and the final component due to the inter-layer bonding modelled in Section 3.3.1. As discussed in [41, 186], traditional Nomex honeycomb exhibits anisotropic properties due to the impregnated paper-based materials; there is very little lateral compressive stiffness. FFF exhibits anisotropic properties due to the layered manufacturing approach [17], but due to the higher stiffness of ABS compared to the paper-based Nomex honeycomb, there was no noticeable difference when handled in different orientations. This would be beneficial for ensuring geometric tolerances are maintained during layup of the upper skin of sandwich panels, discussed in Section 2.2.1.

A number of quality control issues were identified during the specimen manufacture and

<table>
<thead>
<tr>
<th>Wall type</th>
<th>Yield Force (kN)</th>
<th>Yield stress (Nmm⁻²)</th>
<th>Ultimate Stress (Nmm⁻²)</th>
<th>Specific Yield Stress (Nmm⁻²g⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9.1±0.3</td>
<td>18.9±1.1</td>
<td>21.6±1.5</td>
<td>4.0±0.2</td>
</tr>
<tr>
<td>2</td>
<td>20.1±0.7</td>
<td>29.6±2.8</td>
<td>35.2±2.4</td>
<td>4.8±0.4</td>
</tr>
<tr>
<td>3</td>
<td>33.2±0.4</td>
<td>34.5±1.0</td>
<td>40.0±1.1</td>
<td>3.7±0.1</td>
</tr>
<tr>
<td>PLA</td>
<td>32.8±1.2</td>
<td>42.9±2.6</td>
<td>51.1±3.2</td>
<td>5.0±0.2</td>
</tr>
<tr>
<td>Nomex</td>
<td>5.4±0.1</td>
<td>36.6±1.0</td>
<td>41.2±0.7</td>
<td>19.1±0.5</td>
</tr>
</tbody>
</table>

Table 5.6. Force and stress of compressive testing of different deposition patterns for FFF and Nomex honeycomb cores. The area used was the estimated surface area of the wall in the xy plane.
data acquisition. One observation of this chapter was the increased variation in yield point for FFF parts produced with thicker walls, and their susceptibility to errors during manufacture; with higher flow rates potentially causing nozzle blockages. It was observed the print quality was dependent on the initial layer height; while a constant layer height was used, having the initial layer deposited too low could cause “ripples” throughout the component due to uneven flow conditions. This effect caused such specimens to be discarded before machining. Only a single, hobbyist type printer was used, with the associated low-cost materials. Use of more advanced materials, or a different printer, may reduce these effects, but it is expected the relationship between failure profiles and wall thickness to remain.

There was a difference of an order of magnitude between the cell sizes and wall thickness of the FFF and Nomex honeycomb cores, necessitated by the nozzle diameter of the extruder. The larger cell size of the FFF cores presented a risk of “telegraphing”; where the top skin vertically deforms into the cell. This could be countered through printing a shell structure over the top, such solutions were described by Riss et al. [48]. This solution may require additional supports inside the cell dependent on the consolidation pressure to be applied to the top skin during curing. However, this would change the cell geometry and performance, increasing design complexity and requiring post-processing.

5.5 Conclusions

This chapter presented the results of testing filament bond strength of thin-walled honeycomb cores produced with two common FFF materials (ABS and PLA). Tensile testing was conducted to evaluate bond strength with samples machined from FFF thin walls, and results have shown thicker walls are more susceptible to plastic deformation, with a lower yield stress than thinner walls whilst maintaining a relatively constant ultimate tensile stress. Compressive testing of the FFF cores has demonstrated the thicker walled specimens behaved in a more ductile way, consistent with the tensile testing; the maximum crush force of the FFF cores was significantly greater than Nomex honeycomb. When considering the specific compressive stress per unit core area, the FFF cores were comparable to Nomex and Polycarbonate cores.

Chapter 7 continues testing bond strength of thin walls through a series of tensile tests at a range of bed and nozzle orientations, achieved through implementation using the 8-DOF robotic cell detailed in the following chapter. Chapter 8 includes a cost comparison between FFF and Nomex core structures.
IMPLEMENTATION OF FFF USING A ROBOTIC ARM

The previous chapter has investigated the mechanical properties of FFF components manufactured using a traditional gantry-style FFF system, and it was noted these have a high weight when compared to Nomex, but similar ultimate compressive stress. An advantage of AM cores is the suitability for in-situ manufacture and the capability to produce complex components, including on curved substrates, which could provide improved mechanical properties and surface finish, as discussed in Chapter 2.

This chapter presents a comparison of structural layouts of FFF machines, assessing their accuracy, followed by an overview of the implemented 8-DOF system. The chapter then details operation of the system to produce toolpaths for the deposition on a cylinder, using an external axis for rotation, and three curved layer components.

The content of the first half of this chapter detailing the implementation was presented at the IC4M conference in Barcelona on the 24th February 2018, and subsequently published in the MATEC Web of Conferences:


The second half of this chapter, detailing toolpath generation, was presented at the 18th European Conference of Composite Materials, held in Athens, Greece in June 2018. The author would like to acknowledge the Alumni Foundation of the University of Bristol for a travel grant to aid the attendance of this conference. The conference paper is available at:

CHAPTER 6. IMPLEMENTATION OF FFF USING A ROBOTIC ARM

6.1 Introduction

A majority of AM processes, including FFF, are based on a slicing procedure to generate a component; a CAD format file is provided, “sliced” into a stack of 2D layers, and a toolpath for the required material deposition is generated for each layer. The effect of layered manufacturing requires support structures for overhanging sections, and the “staircase effect”, where the layer thickness causes an uneven surface on sloping sections; this effect is visible in FFF where layer heights are typically greater than 0.1 mm [187]. Additionally, the part orientation greatly affects the final properties, as numerous studies have found the bonding between surfaces is significantly weaker than the material properties in the plane of the layer [9, 187].

Previous research efforts have investigated various algorithms for generating multi-directional and curved toolpaths, as introduced in Section 2.5.1. Singamneni et al. [143] evaluated curved layer deposition, with an investigation into toolpath generation for curved layers, and demonstrated improved surface quality and mechanical properties of a curved beam; the compressive load of the curved part under 3-point bending increased by 40% over the traditional 2.5D layered design. Multi-Directional Layered Deposition (MDLD) was explored by Singh et al. [138, 155], where overhangs, which typically require support structures, were eliminated through changing the angle of the slicing plane relative to the build surface. This process allows for the division of a CAD model into supported and unsupported sections and, through varying the slicing orientation between sections, eliminated the requirement for printing of supports for overhanging sections. Such works demonstrate the advantages of printing in multiple dimensions, but limitations imposed by traditional gantry-style mechanisms limit the use of these systems.

This chapter details an approach to the adaptation of an industrial robotic arm for use in FFF research to explore aspects of in-situ manufacture. This chapter begins with a comparison of structural layouts of existing FFF machines to identify the use cases for an arm-based FFF system, and an overview of the current implementation at the University of Bristol. Descriptions of the process to generate print paths for the localisation and manufacture of a structure on a rotating cylinder, and deposition onto a curved substrate are then presented, and followed by a demonstration of manufacture of an aerofoil-shaped core structures with curved layers.

6.2 Comparison of 3D printing system structures

To identify the merits of robotic arm-based printing, an accuracy comparison was performed between three structural layouts, as presented in Table 1. The Ultimaker 3 [188] and the Rostock Max V3 [154] were used as representative machines of the gantry and delta classes respectively, and compared to the 6 DOF ABB IRB140 [189], used for the remainder of this thesis; examples of the machines studied are shown in Figure 6.1. As the Stewart Platform-based printers have only been discussed in the literature, sufficient data was not available and so are qualitatively discussed below for comparison.
6.2. COMPARISON OF 3D PRINTING SYSTEM STRUCTURES

Figure 6.1. Printers compared within this study. (a) and (b) show gantry and delta style printers respectively (photos courtesy of Ultimaker and SeeMeCNC) [154, 188], (c) shows a Stewart Platform printer used by Song et al. [159] (Image ©ASME), and (d) shows the ABB IRB140 arm printing onto a bed supported by the ABB IRBP A250 workpiece positioner.

Table 6.1. Comparison of structural layouts between common FFF machines.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Positioning Accuracy (µm)</td>
<td>125</td>
<td>(variable)</td>
<td>30</td>
</tr>
<tr>
<td>Max. speed (XY, mm/s)</td>
<td>300</td>
<td>300</td>
<td>1000+</td>
</tr>
<tr>
<td>Max. speed (Z, mm/s)</td>
<td>5</td>
<td>300</td>
<td>1000+</td>
</tr>
<tr>
<td>Build Area / printer footprint</td>
<td>0.356</td>
<td>0.336</td>
<td>22.2</td>
</tr>
</tbody>
</table>
CHAPTER 6. IMPLEMENTATION OF FFF USING A ROBOTIC ARM

There are no standardised methods for assessing the accuracy of FFF machines. A common method of stating accuracy for hobbyist-type machines is based upon the stepper motor resolution and associated gearing, with the gantry layout achieving 12.5 µm accuracy in the $xy$, and 2.5 µm in $z$, as described by the manufacturers [188]. Upon examination of such a printer, Weiss et al. [98] identified a mean error during a trajectory to be 400 µm at a speed of 90 mm s$^{-1}$. No data could be found for the accuracy of the delta printer, but as the gearing used is similar to that of the $xy$ stage of the gantry printer, the accuracy was expected to be similar [190].

The Stewart Platform system, used by Song et al. [159], had a stated accuracy of <500 µm, and Dröder et al. [142] note the accuracy of their implemented Stewart Platform-based printer remained slightly lower than a comparable 3D printer; this may be partially due to the difficulties of inverse kinematics implementation for high DOF parallel system [190]. In contrast, the robot arm has a significantly higher achievable accuracy, due to its development for industrial applications and higher component cost. However, the stated accuracy when following a path is significantly lower, at 670 µm, with the impact of this discussed in Section 6.7.

Table 6.1 shows a key difference between the gantry and delta printers is the capability of fast movement in the $z$ axis. As the former has a single stepper motor for each axis, the $xy$ positioning is controlled by a belt drive, and the $z$ through a lead screw, increasing the accuracy but decreasing the maximum speed. At typical print speeds, the slower $z$ axis speed of the gantry inhibits the printing of curved layers at typical print speeds; at a print speed of 50 mm s$^{-1}$, the maximum gradient would be 5.7°. It was for this reason Allen et al. to use a delta printer during their investigations into curved layer deposition [147]. Similar to a delta printer, the robot arm is capable of rapid movements throughout its workspace, as an FFF nozzle would typically be within the payload limitations of the arm.

Finally, the ratio of build area to the printer footprint is relatively low for both the gantry and delta robot. The calculation in Table 6.1 for the robot arm was performed with the $xy$ plane intersecting the base of the robot, as the reachable workspace varies with $z$, as shown in Figure 6.2. While the delta robot is capable of rapid movement in the $z$ direction required for printing curved layers, the inability to position the nozzle normal to the substrate constrains the maximum printed gradient to be dependent on the nozzle geometry and the potential for impact with the deposited curved layers. The Stewart Platforms proposed in [142, 159] allow for repositioning for the nozzle to remain normal to the surface, but exhibit a strong positional and orientation coupling [190].

Through the comparison of the four structural layouts for FFF, use cases for arm-based FFF can be identified as increased manufacturing speed of larger components through utilisation of higher achievable speeds over the workspace – this would require larger diameter nozzles, reducing achievable quality but increasing deposition rates. “Additive Finalisation” would be a second use case, presented by Dröder et al. [142], where the base component could be placed on a conveyor belt adjacent to the robot arm, allowing the arm to locate and print on the
6.3. System design

The robotic system at the University of Bristol was implemented on a 6 DOF ABB IRB 140 robotic arm, which has a 6 kg payload capability, 0.8 m reach, and a pose repeatability of 0.03 mm. The robot cell also contained a 2 DOF IRBP A250 workpiece positioner with the print bed mounted on, partially shown in the left of Figure 6.1(d), and was controlled through an ABB IRC5 controller running RobotWare 5.15. The relevant options enabled on the robot are the 616-1 PC Interface, and a DSQC 652 digital I/O module. Additionally, the “Absolute Accuracy” calibration option was enabled, ensuring true accuracy in relation to the base coordinate system. An Arduino, connected to a RAMPS 1.4 breakout board, was used to control the extruder temperature and a stepper motor for filament feed. This was connected to the DSQC I/O module via a potential divider, reducing the voltage from the 24 V signal to 4.8 V suitable for the Arduino. The extruder is comprised of a BondTech dual drive extruder, directly mounted to an E3D V6 hotend with a 0.6 mm nozzle; this was selected to enable higher speed printing whilst maintaining sufficient accuracy. Figure 6.3 shows the system architecture, detailing the key operational functions.

OpenABB [191] was a software package developed by Michael Dawson-Haggerty for controlling ABB robots through Python, C++, or ROS (Robotic Operating System), and released under the MIT License. The package was composed of two parts; a server module written in RAPID,
the native language implemented within the IRC5 controller, and a Python class implemented on the controlling PC to send commands via an Ethernet connection. The OpenABB software was adapted to send print commands in a buffer, providing the IRC5 with the coordinates for the execution of a full path to avoid pauses whilst awaiting further position data. As similar paths are often repeated for successive layers in FFF, functions were implemented to save, load, and offset the buffer to reduce time spent communicating coordinates.

The extruder activation signal was supplied by the IRC5 robot controller to ensure synchronisation with the robot motion. To adjust the feed rate for the current path speed, a signal was passed to the extruder controller through a Group Output; a collection of eight digital signals to representing an 8-bit unsigned integer in the range \([0, 255]\). The Arduino controlling the extruder was connected to the operator’s PC to allow monitoring of extrusion temperature, and adjustment of extrusion settings; this would allow the testing of different thermal control systems, as discussed in Chapter 4.

### 6.4 Robot Operation

Using a Python script running on a laptop vastly improved the flexibility afforded to the industrial robot arm operation. Typical operation requires intensive programming to move the robot to the required positions; while this process is suited for manufacturing environments, AM applications involve numerous different toolpaths making this approach unreasonable. This process does not bypass the inbuilt safety mechanisms of the robot controller, and provides a low-cost solution to generating and running complex operations.

To operate the robot, the relationship between the tip of the nozzle and the print surface must first be defined. This was conducted using the inbuilt functions of the teach pendant, with
transformation from the robot Tool Centre Point (TCP) to the nozzle tip calculated from four positions with different orientations where the tip is contacting a specific point. Work object coordinates were calculated in a similar manner from three locations, identifying an origin, a point along the $x$ axis, and a point along the $y$ axis. Results from the coordinate definitions were input to a configuration file.

Initialisation of the robot required the passing of the saved parameters, conducted as shown below:

```python
import abb
from Robot_Config import robot_config as rc

R = abb.Robot("192.168.125.1")
R.reset_position(1)
R.set_joints(rc.get_initJoint(0))
R.set_workobject(rc.get_wobj(0))
R.set_tool(rc.get_tool(0))
```

Operation of the robot typically involves passing a range of $xyz$ coordinates with associated quaternions; the generation of these are further discussed in Section 6.6.1; initial tests used a quaternion value of $[0, 0, 1, 0]$ to rotate $180^\circ$ about the $y$ axis of the work object coordinate frame. With a list of $xyz$ coordinates stored in $xyz\_coord$ and their associated quaternion orientation in $q\_coord$, a series of poses are constructed, and sent to the operating buffer. Upon execution, the robot follows this path, and the argument 1 enables the extruder.

```python
pose_list = [[xyz, q] for xyz, q in zip(xyz_coord, q_coord)]
R.buffer_set(pose_list)
R.buffer_execute(1)
```

As this code was developed for the research project, no GUI was implemented. The typical screen layout, shown in Figure 6.4, had the currently executing program on the right side of the screen, and command prompts on the left showing the current operating state of the robot and extruder on the top and bottom respectively.

### 6.4.1 Initial demonstration

Figure 6.5 shows two objects produced through the robotic arm FFF process; a rectangular section (a), and a repair patch (b) for a composite panel printed within a confined space on an angled surface. During printing, the average time to send a movement within a buffer was 0.08 s – this was the delay used in the OpenABB code to ensure reliable communications. A key issue found was the accuracy during the start and stop of the extrusion process, due to the over-extrusion during the IRC5 processing time. These errors were minimised with the addition of a vertical movement at the end of an extrusion process.
CHAPTER 6. IMPLEMENTATION OF FFF USING A ROBOTIC ARM

**Figure 6.4.** Typical screen layout for robot operation, showing the command prompt for robot control, Arduino IDE serial connection for monitoring temperature, and operating code.

**Figure 6.5.** Two examples of FFF using the ABB IRB140 arm and IRBP A250 positioner system. *(a)* shows the manufacture of a specimen as used for Chapter 7, and *(b)* shows the in-situ deposition of a repair patch for a composite sandwich panel.
6.5 Cylindrical deposition

The first demonstration mapped and printed a 2D toolpath onto a cylinder positioned arbitrarily on the workpiece positioner; such a process is similar to that used during filament winding for conventional automated composite manufacture. This section introduces the localisation solution and the toolpath transformation.

A video showing the robot depositing onto a cylinder is available at https://www.youtube.com/watch?v=v36t1wzLFEM.

6.5.1 Cylinder localisation

As there were no sensors fitted to the robot arm to track the location of the cylinder, the kinematics between the base coordinate frame of the robot \((c_0 = xyz_0)\) and the position on the cylinder surface during a rotational movement must be identified for open-loop control. This was comprised of the transformation from \(c_0\) to the centre of rotation \((c_1 = xyz_1)\), the rotation about the \(z\) axis of \(c_1\) to a rotated coordinate frame \((c_2 = xyz_2)\), and the location \((x_{cyl}, y_{cyl})\) of the cylinder within \(c_2\); as depicted in Figure 6.6, with the associated kinematics in (6.1a). As all \(z\) axes were aligned, the problem was reduced to 2 dimensions, and the \(z\) transformation from \(c_0\) to \(c_1\) identified through measurement.

Four 2D linear translation parameters were required for the kinematic equation (6.1a); from \(c_0\) to \(c_1\) \((x_1, y_1)\), and the cylinder location \((x_{cyl}, y_{cyl})\) within \(c_2\). This provided an estimate of
CHAPTER 6. IMPLEMENTATION OF FFF USING A ROBOTIC ARM

Figure 6.7. Estimated accuracy of localisation procedure for random errors applied to the measured points.

the cylinder position \((x_{est}, y_{est})\) in the robot base coordinate frame for a given rotation \(\theta\). For parameter identification, the nozzle was positioned on the cylinder’s circumference at \(n\) different rotations, providing three measured coordinates \((x_{n,meas}, y_{n,meas}, \theta_{n,meas})\). An optimisation routine minimised the cost function of (6.1b) through variation of the linear translation parameters in (6.1a), comparing the difference between estimated and measured coordinates for each rotation angle \(\theta_{n,meas}\).

\[
\begin{align*}
\begin{bmatrix}
  x_{n,est} \\
  y_{n,est}
\end{bmatrix}
&= \begin{bmatrix}
  x_1 \\
  y_1
\end{bmatrix}
+ \begin{bmatrix}
  \cos \theta_n & -\sin \theta_n \\
  \sin \theta_n & \cos \theta_n
\end{bmatrix}
\begin{bmatrix}
  x_{cyl} \\
  y_{cyl}
\end{bmatrix}
- \begin{bmatrix}
  r_{cyl} \\
  r_{cyl}
\end{bmatrix}
\begin{bmatrix}
  \cos \theta_n \\
  \sin \theta_n
\end{bmatrix}
\end{align*}
\]

\[
\text{cost} = \frac{1}{2n} \sum_n \left| x_{n,est} - x_{n,meas} \right| + \left| y_{n,est} - y_{n,meas} \right|
\]

To evaluate the accuracy of the localisation procedure, values were set for the system geometry \((x_1, y_1, x_{cyl}, y_{cyl})\), and the corresponding measured points at rotation angles of 45° increments were calculated using (6.1a). Error terms following a standard deviation of up to 2 mm were added to each of the measured coordinates, and passed through the optimisation process to estimate the geometric offsets. The average absolute mean error in system geometry from 100 runs using a varied number of measurements is shown in Figure 6.7.

It can be seen there was little reduction in the error with greater than four measurements, and further tests to identify the effect of the \(\theta\) angle range had no effect on accuracy. Upon implementation, it was found four measurements provided a good first estimate, but manual adjustment was required to reduce the error sufficiently for printing. With a layer height of 0.5 mm, the positioning error should be less than 0.25 mm to ensure first layer placement, and
6.5. CYLINDRICAL DEPOSITION

Figure 6.8. Generated toolpath (a) and deposition (b) of the University of Bristol logo onto a cylinder.

This would require the measurement point accuracy to be 0.5 mm; the physical size of the nozzle prevented the achievement of this due to its blunt shape.

6.5.2 Generation of cylindrical toolpath

A planar 2D toolpath was generated, consisting of multiple points along each path \((x_i, y_i)\), to be “wrapped” around the cylinder surface. \(x_{\text{path}}\) was mapped to the cylinder rotation angle \(\theta\) based on the arc length around the circumference, shown in (6.2a), and \(y_{\text{path}}\) was mapped directly to the nozzle \(z\) height, shown in (6.2b).

The cylinder offset from the centre of rotation caused a displacement in the \(xy\) plane of \(c_1\) upon rotation; (6.2c) provided the required offset for the nozzle in the coordinate frame \(c_1\) to track the cylinder surface. The full coordinates required for the robot to print on the cylindrical surface were the rotation of the cylinder on the positioner \(\theta_i\), the nozzle position \((x_i, y_i, z_i)\) in the coordinate system \(c_1\), and the nozzle orientation, held constant at normal to the cylinder surface, depicted in Figure 6.8(b).

\[
\theta_i = \frac{x_{i,\text{path}}}{r_{\text{cyl}}}
\]

\[
z_i = y_{i,\text{path}}
\]

\[
\begin{bmatrix}
x_i \\
y_i
\end{bmatrix}_{c_1} =
\begin{bmatrix}
\cos \theta_i & -\sin \theta_i \\
\sin \theta_i & \cos \theta_i
\end{bmatrix}
\begin{bmatrix}
x_{\text{cyl}} \\
y_{\text{cyl}}
\end{bmatrix}_{c_2}
\]

To demonstrate this process, the 2D toolpath was extracted from the Scalable Vector Graphics (SVG) file of the University of Bristol logo, and a corresponding print path calculated. The result from a visualisation of the toolpath and the deposition is shown in Figure 6.8.
6.6 Curved layer deposition

Using the full 6-DOF afforded to the robotic arm allows the nozzle to remain normal to the substrate when printing curved layers. Three types of curved print were explored, produced using a projection of a 2D toolpath onto a curved surface. The first example shows the deposition onto a curved surface, with variable z print direction remaining normal to the surface. Curved aerofoil-shaped core components were then produced, examining a method of generating the toolpath for curved layers on both the top and bottom surface; such paths would be beneficial for both eliminating the staircase effect and to improve mechanical properties.

The robot performing the described curved layer deposition procedure is shown in https://www.youtube.com/watch?v=v36t1wzLFEM.

6.6.1 Printing onto a curved surface

To generate the toolpath for deposition onto a curved surface, an STL input file was used to describe the substrate; this is a standard CAD export format used within FFF slicing programs. An STL file describes a 3D model as a series of tessellated triangles, with each facet containing three coordinates and a surface normal away from its surface. An additional benefit was the ability to directly manufacture the substrate with a traditional FFF printer.

The STL file was imported using the Python STL library, and rotated, translated, and trimmed to contain only facets from the top surface. A vertical projection of the 2D toolpath provided the required z coordinate for each point, and the surface normal for each point was assumed to be equal to the surface normal of the enclosing facet. For deposition of successive layers, the point was offset in the direction of this normal, described below, or in the z direction, demonstrated in Section 6.6.2. Collisions with the prebuilt surface during travel moves were avoided by execution of a circular path between two print lines. An example deposition using this process is shown in Figure 6.9, where the logo print path used in Section 6.5.2 was deposited directly onto a hemispherical shape.

The quaternion required to maintain the correct nozzle orientation, $q_{\text{nozzle}}$, relative to the work object coordinate system $c_1$, was generated based on the surface normal, $n = (n_x, n_y, n_z)$ and its angle to the x and y axis vectors, $x = (1,0,0)$ and $y = (0,1,0)$ respectively. The calculation is shown in (6.3). An addition of $\pi$ to the rotation angle around the x axis provided the $180^\circ$ rotation to orient the z axis of the TCP to the opposing direction to $n_z$.

\[
q_x = \left[ \frac{\theta_x}{2}, 0, \sin \frac{\theta_x}{2}, 0 \right] \quad \text{where} \quad \theta_x = \arcsin \frac{x \cdot (n_x, 0, n_z)}{|(n_x, 0, n_z)|} + \pi \\
q_y = \left[ \frac{\theta_y}{2}, \sin \frac{\theta_y}{2}, 0, 0 \right] \quad \text{where} \quad \theta_y = \arcsin \frac{y \cdot (0, n_y, n_z)}{|(0, n_y, n_z)|} \\
q_{\text{nozzle}} = q_x \times q_y
\]

120
6.6. CURVED LAYER DEPOSITION

Figure 6.9. Generated toolpath (a) and deposition (b) of the University of Bristol logo onto a hemisphere.

Figure 6.10. Generated toolpath (a) and deposition (b) of a straight aerofoil shape with curved top and bottom layers.

6.6.2 Manufacture of a curved layer component

Two aerofoil cores were manufactured to demonstrate applicability to the Aerospace industry; a straight, untwisted aerofoil, and a tapered, twisted aerofoil. The bottom surface of each specimen was described by an STL file, and a 2D hexagonal toolpath generated to cover the aerofoil surface, with the conforming layer generated as in Section 6.6.1. Successive layers were generated through application of an offset along the \( z \) axis, with points higher than the centre line truncated. The resulting toolpaths were then reflected to produce the upper half, curved in the opposing direction, depicted in Figure 6.10, with (a) showing the top and bottom toolpaths generated, and (b) manufacture of the final component.

Further expansion of the software allowed for a variable \( z \) height along the path layer, calculated from the vertical intersection with a second STL file denoting the top surface. Two STL files were created to define the shape with the first defining the centre plane, and the second using a “loft” feature to create an aerofoil shape cutout along this plane; the latter file was printed.
as a mould for the printed component. This allowed the manufacture of a curved and tapered aerofoil shape, showcasing the high levels of complexity achievable with a robotic arm, depicted in Figure 6.11, where a twisted and curved aerofoil was printed.

6.7 Discussion

As discussed in Section 6.2, the stated accuracy of the ABB IRB 140 arm for linear path following is 670 µm, with a pose accuracy of 30 µm [189]. This reduces the theoretical accuracy, but it should be noted that the linear path following accuracy was tested under ISO 9283, where the error was measured and averaged over a range of tool speeds – previous research has shown a relationship in trajectory following error with speed due to the inertia of the serial mechanism [192]. Upon implementation, there was no noticeable error along layer lines when printing typical 2.5D specimens due to the relatively low speeds used during the printing process, as opposed to the maximum speeds used during the manufacturers tests, allowing for improved trajectory following. An increase in nozzle positioning error was identified in Section 6.6.1, where high joint speeds were required for nozzle reorientation to maintain the nozzle orientation normal to the surface. The limiting factor on maximum print speed was the inter-layer adhesion, with the deposited material peeling from the substrate.

Sections 6.5.2, 6.6.1, and 6.6.2 introduced methods of mapping a 2D toolpath to a 3D surface. One key result was the generation of a toolpath for curved layers to be situated on the top and bottom surface of the aerofoil shape. This has two advantages, with the first being elimination of the staircase effect on the outer surface, and the second the improvement in mechanical properties expected. However, the slicing methodology does not interlink the curved layers, producing a single plane where the curvature changes between halves.
6.7. DISCUSSION

<table>
<thead>
<tr>
<th>Error</th>
<th>Magnitude</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arm positioning</td>
<td>30-670 µm</td>
<td>Robotic arm accuracy, but operation was conducted at low velocities, so will be at the lower range.</td>
</tr>
<tr>
<td>Localisation error</td>
<td>0.6 mm</td>
<td>Affects printing on a rotating cylinder, as it relates to the external axis.</td>
</tr>
<tr>
<td>TCP to nozzle tip</td>
<td>0.1 mm</td>
<td>Inbuilt ABB function.</td>
</tr>
<tr>
<td>Workobject definition</td>
<td>0.1 mm</td>
<td>Inbuilt ABB function.</td>
</tr>
</tbody>
</table>

### 6.7.1 Sources of error

The largest observed error was the variation in extruded wall thickness, especially at the beginning and end of an extruded road, or points with high reorientation requirements. This was due to the lack of communication of TCP speed between the IRC5 motion controller and the Arduino extruder controller, with the group output speed request only sent before the extrusion of a line.

This effect was clear during the production of specimens, most notable on the hemisphere in Figure 6.9. The frequent reorientation required to maintain a normal angle between the nozzle and substrate led to large movements of the joints; it is these higher speed motions which cause deceleration of the TCP and higher degrees of positioning error.

Various errors and their magnitudes within this system are described in Table 6.2; these errors were “tuned” out of the robot during operation by manual adjustment. Errors due to the inbuilt ABB functions are caused by difficulty in accurately aligning the blunt nozzle tip with a specific point. Other errors were considered of a negligible magnitude when compared to those presented include variations in filament diameter, vibration of the attachment point to the TCP, and change in the extruded distance per revolution due to the tightness of the extruder motor wheel on the filament.

### 6.7.2 Alleviation of TCP error

The effect of TCP speed variation was reduced by proportionally lowering the maximum linear speed and extruder flow rate to reduce the overextrusion during slight pauses in the motion during reorientation. TCP speed during extrusion for the hemisphere specimen was 20 mm s⁻¹, and for the curved aerofoil layers an increased 30 mm s⁻¹ due to the more linear nature of the toolpath. For the printed structures used in Chapter 7, this limitation did not reduce quality as the toolpath consisted of relatively long straight lines.

During development, an attempt to alleviate the TCP error implemented “Trap” interrupt routines in the RAPID module. These providing the current TCP speed as a group output, scaled in the range [0, 255] relative to the maximum requested movement speed. However, this method was unsuccessful as the maximum update rate for this routine was 10 Hz, and at a low print
speed of 50 mm s\(^{-1}\), this could be up to a 5 mm movement at an incorrect extrusion rate.

Two other options were identified, requiring additional hardware or software for the IRC5 respectively. The first is the use of an Analog I/O card, which when combined with “Trigger” movements in the RAPID code, outputs a signal scaled between −20 V and 20 V in proportion to the TCP speed; this is commonly used for control of glue application. The “Multi-Threading” option would also provide a solution, and was implemented in the OpenABB code [191] allowing monitoring of the current TCP speed. By running in a separate thread to the robot operating code, this solution would output the TCP speed directly to the extruder controller via the Group Output, or relay commands via the host PC.

6.8 Conclusions

This work has examined the different structural layouts used for FFF (gantry, delta, Stewart Platform, and industrial robotic arm), finding the gantry platform had more consistent printing accuracy over the build area, and the delta platform had improved z axis speed, at the cost of a decreased build area ratio and increased vertical size. The Stewart Platform allowed for multi-DOF printing, but with a reduced workspace, and the industrial robotic arm was capable of rapid movements, higher manipulability, and a workspace significantly larger than its footprint, a factor not exhibited by other structural layouts for FFF. Drawbacks of the arm-based FFF system include the decreased accuracy at higher speeds, inherent in the arm dynamics, and the lack of fine extruder control, inherent in the current implementation due to machine constraints. Both of these factors could be mitigated through design of toolpaths involving relatively long, straight paths, with few rapid joint motions for nozzle re-orientation. Based on these criteria, it was concluded arm-based FFF printers are suited for higher speed manufacturing of larger components, and “Additive Finalisation”.

An implementation of FFF on a 6 DOF robotic arm, in this case an ABB IRB 140, was then presented, describing the hardware setup and a summary of the software communication protocol. Examples of the robot operation were presented, and its flexibility to print on slanted surfaces shown. The control software, based on the OpenABB architecture, used to operate this robot was released under the MIT license, and is available at:

https://github.com/davepollard/CurvedLayer_FDM

Additionally, a video was produced showing the robot operation during the deposition onto a cylinder, and hemisphere, and the manufacture of the aerofoil core shapes. This was released as part of the paper presented at the 18th European Conference on Composite Materials, and is available on YouTube at:

Curved Layer FDM with a robotic arm, by David Pollard:
https://www.youtube.com/watch?v=v36t1wzLFEM
An additional video depicting the application of the repair of a composite sandwich panel is also shown in:

Arm-based 3D printing for composite repair, by David Pollard:
https://www.youtube.com/watch?v=mI93TwYS0So

The described system was used in Chapter 7 to investigate the effects of different build and nozzle orientations, and a TRL assessment of this system and its capabilities is presented in Chapter 8.
Effects of multi-dimensional Additive Manufacture

With an industrial robot arm adapted and demonstrated as an FFF printer in Chapter 6, the number of accessible degrees of freedom for the printing process increases. However, any changes in the inter-layer bond strength over this wider design space must be identified. This chapter assesses this effect on the bond strength at different bed orientations, with different build directions relative to the gravity vector, and nozzle orientations relative to the print bed.

7.1 Introduction

Thin walls are desirable to minimise the mass of a core structure, a requirement for the weight-sensitive Aerospace sector; previous work has shown the wall thickness can be optimised for specific loading conditions [48] and provide differing failure characteristics, as discussed in Chapter 5. Application of FFF to the manufacture of larger components is of industrial interest, with patents filed by Boeing for producing shaped aerofoil cores [53]. Descriptions of other arm-based AM systems were provided in Section 2.5; a majority examined methods of Additive Finalisation or curved layer toolpath generation.

A robot arm has been shown to be suitable for printing thin-walled structures at variable orientations by Rieger et al. [139]. Tensile specimens were produced by Kubalak et al. [76] at different orientations relative to the print bed, but the print bed remained in a normal orientation; their results were consistent with numerous previous studies showing the layer line was the weakest point in the structure.

The exploration of non-normal orientation printing in the hobbyist community has included
the Upside-Down Inside-Out (UDIO) printer\textsuperscript{1}, and with a standard gantry-style printer in various orientations\textsuperscript{2}. To the best of the authors knowledge, there has been no study on the effect of using extra degrees of freedom afforded to a robotic arm on bond strength.

This chapter aims to fill this knowledge gap by investigating the inter-layer bond strength of thin-walled structures manufactured with a robotic arm. Two sets of tensile tests were performed on specimens manufactured at varied bed orientations relative to the ground, and nozzle orientations relative to the bed. Samples were produced at two temperature levels to identify if an interaction effect between the lower viscosity due to a higher temperature and print orientation existed. Changes in surface quality caused by the nozzle orientation were then further quantified using an optical coordinate measurement machine, and the results then discussed.

7.2 Methodology

This section introduces the specimen preparation and the testing process, based on the ASTM D882 standard \cite{193}. The use of this standard is different to ASTM D638 \cite{181}, used in Chapter 5, to reduce the specimen machining requirements, with ASTM D882 derived for testing thin-walled sheets using rectangular samples.

7.2.1 Specimen manufacture

Thin-walled cuboid structures were printed under atmospheric conditions in an open laboratory, with base dimensions of 70 mm × 70 mm, and a height of 110 mm. All specimens were manufactured from 3 mm ABS filament from 3DFilaPrint, at two extrusion temperatures of 240 °C and 260 °C, with the filament stored in a sealed bag with a silica gel desiccant between use. The layer height was set to 0.5 mm, a feed rate of 2 mm s\textsuperscript{-1}, and a nozzle speed of 50 mm s\textsuperscript{-1}; the resulting walls were 0.80 ± 0.02 mm thick. The four walls of the printed cuboid were printed as separate lines, with the nozzle moving away from the print and stopping extrusion to re-orient; this was necessary to avoid over-extrusion as discussed in Section 6.7.2. Rectangular samples were cut using a PCB guillotine to a width of approximately 10 mm, and tested with a method based on the ASTM D882 standard, derived for the tensile properties of thin plastic sheets (<1 mm thickness) \cite{193}.

Two phases of testing were conducted, with the first investigating the effect of bed orientation and temperature on the tensile strength of the inter-layer bond. Bed orientations of 0° (equivalent to standard printers), 45°, 90°, 135°, and 180° (a completely inverted print) were examined. The second phase investigated four nozzle orientations. These were the standard orientation normal to the print bed, perpendicular to the direction of travel, and two orientated inline with the

\textsuperscript{1}UDIO 3D Printer (Upside-Down, Inside-Out) by Jeff Kerr: https://www.youtube.com/watch?v=hdju_6XEHZ4
\textsuperscript{2}The Upside-down 3D Printer Experiment - 2015 by Maker’s Muse: https://www.youtube.com/watch?v=bTHIoYxZad4
7.2. METHODOLOGY

Figure 7.1. Four different nozzle orientations examined, with the arrow depicting the direction of nozzle travel. (a) shows a standard orientation, where the nozzle is orientated normal to the print bed. (b) shows a 30° rotation perpendicular to the direction of travel. (c) and (d) are two inline orientations investigated with the extruded filament turning through angles of 120° and 60° respectively.

direction of travel, as depicted in Figure 7.1. During the inline print, two walls were printed with the extruded filament rotating through 120° upon deposition, as in Figure 7.1(c), and two rotated through a smaller angle of 60°, as in Figure 7.1(d). A video showing specimen manufacture is available on YouTube\textsuperscript{3}.

To test, specimens were placed in the tensile grips at a gauge length of 50 mm on a Shimadzu

\textsuperscript{3}“Robotic FDM Orientation Tests” by David Pollard: https://youtu.be/pU6NZ0nInyk

NB: This is currently an unlisted video as a paper discussing these results was awaiting submission, so the URL is required to access.
CHAPTER 7. EFFECTS OF MULTI-DIMENSIONAL ADDITIVE MANUFACTURE

7.2 Figure 7.2. Histogram of break location distance from the gauge length centre line.

A test machine, with the layer lines used as a reference to ensure alignment. The force was measured with a 1 kN load cell, and the test proceeded with a crosshead displacement rate of 1 mm/min. The ultimate tensile force was taken from the peak force achieved before failure, and the elastic modulus calculated from the gradient between 10% and 90% of this value. The bond height of surplus samples from the nozzle orientation tests were measured using an Alicona InfiniteFocus optical measurement system, as used in Chapter 3.

7.3 Results

A total of 357 specimens were considered during the analysis; 209 from the bed orientation test, and 148 from the nozzle orientation tests. An additional 27 specimens were produced to identify causes of variation between the two groups due to a new filament roll and time gap in testing; these were produced using the filament from the first test, and immediately prior to the production of the second test. A histogram showing the break location in relation to the centre of the gauge length is shown in Figure 7.2, and the average break point on the specimens was 46 ± 17 mm from the top of the print, with the error to one standard deviation, and a majority of specimens failed within the gauge length. No significant difference was found in the ultimate tensile stress or elastic modulus due to the specimen distance along the wall from the start of extrusion. As with Chapter 5, failures occurred on the inter-layer line to provide a clean break across the specimen with little plastic deformation observed before failure.
7.3. RESULTS

<table>
<thead>
<tr>
<th></th>
<th>df</th>
<th>(F_{\text{crit}})</th>
<th>(F)</th>
<th>(P)</th>
<th>(F)</th>
<th>(P)</th>
</tr>
</thead>
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<td>Orientation</td>
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<td>3.48</td>
<td>1.88</td>
<td>0.19</td>
<td>1.61</td>
<td>0.25</td>
</tr>
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<td>Temperature</td>
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<td>0.98</td>
<td>0.35</td>
<td>3.98</td>
<td>0.07</td>
</tr>
<tr>
<td>Interaction</td>
<td>4</td>
<td>3.48</td>
<td>0.32</td>
<td>0.86</td>
<td>0.11</td>
<td>0.98</td>
</tr>
</tbody>
</table>

Table 7.1. ANOVA analysis of effect of temperature and bed orientation.

![Graph](image)

Figure 7.3. Ultimate stress and strain of all samples from the bed orientation tests.

7.3.1 Print bed orientation

214 specimens were produced for the print bed orientation tests, with five eliminated based on non-conformity to the majority of results on the stress/strain curve, shown in Figure 7.3. The specimens were extracted from 20 printed cuboids, with two replicates for each combination of bed orientation and temperature. Statistical analysis was performed using the averaged values for each cuboid. During the printing process, there was no visible difference between the different orientations or temperature.

A line of best fit on Figure 7.3 estimated an elastic modulus of 985 N mm\(^{-2}\), with \(R^2 = 0.96\). The distribution of break locations fell along this line, and the elastic modulus did not show a significant difference despite variations with temperature and orientation, shown in Figure 7.4. ANOVA analysis, shown in Table 7.1, was performed using results for each cuboid print, and confirmed there was no correlation between elastic modulus and orientation or temperature.

Higher standard deviations in ultimate tensile stress were observed from samples in non-vertical build directions, as shown in Figure 7.5. No statistically significant difference was
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FIGURE 7.4. Variation of sample elastic modulus with print bed orientation.

identified for the bed orientation change, as shown in Table 7.1; it was expected the temperature would have an effect on ultimate tensile strength, as previously reported in the literature, but this effect was masked by the high degree of variation. Individual T-Tests conducted between specimens of different temperature at each orientations identified statistical difference between results for temperatures over all orientations \((p < 0.05)\); with the exception of the 90° orientation test, where there was significant variation within both the 240°C and 260°C samples; this difference is clearly visible in Figure 7.5.

7.3.2 Consistency test

To identify if differences in environmental conditions or a change in filament rolls (both purchased at the same time from 3DFilaPrint) would cause a change in mechanical properties, an intermediate test was conducted through printing of two cuboid samples at 260 °C with a 0° print bed angle and a normal extruder orientation, yielding 27 specimens. This intermediate test run was conducted five weeks after the bed orientation test, and immediately prior to the nozzle orientation test, and used the filament from the same roll as the bed orientation tests.

Figure 7.6 shows the resulting failure locations of the tensile specimens on a stress-strain plot, with all specimens falling within a region similar to that of Figure 7.3; for the purposes of this investigation, the samples circled were eliminated from further analysis. T-Tests identified statistic similarity between both the ultimate stress and elastic modulus between the consistency and nozzle orientation tests, while statistically significant differences were identified between these tests and the bed orientation tests. This shows the inter-test variation was due to differing
7.3. RESULTS

If the outliers were considered, the statistical difference remained for the elastic modulus, but there was no statistical difference between the ultimate stress of the three comparable tests.

7.3.3 Nozzle orientation

12 cuboids were printed for the nozzle tests, with two replicates for each combination of nozzle orientation and temperature. An additional two cuboids were printed using the inline nozzle angles at both temperatures to raise the number of specimens available for this analysis due to an inline orientation print containing two walls at 120° and two at 60°.

Visual examination of the specimens showed those printed with the nozzle angled at 60° to the travel direction, as depicted in Figure 7.1(d), had a high variation in surface width. Force per unit wall length (Nmm$^{-1}$) was used to classify the difference between inline specimens to neglect the specimen thickness; the results from all tests are shown in Figure 7.7. A significant difference was found between inline orientation specimens, with those printed at a nozzle angle of 60° failed at a mean of 3.06 ± 0.91 Nmm$^{-1}$, while those from the 120° orientation failed at 7.05 ± 2.12 Nmm$^{-1}$. These specimens were eliminated from the remainder of the analysis, with Figure 7.7 showing a comparison to other specimens, and the differences between surface profiles discussed in Section 7.3.4.

The elastic modulus derived by a line of best fit to the failure locations on the stress/strain plot of the included specimens printed with a normal nozzle angle was calculated to be 942 Nmm$^{-2}$, with $R^2 = 0.97$, lower than that identified in Section 7.3.1.
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**Figure 7.6.** Consistency check between test groups using walls printed using 260 °C temperature, with a normally orientated nozzle and print bed. Specimens enclosed within a dashed circle were eliminated from this analysis.

**Figure 7.7.** Identification of excluded samples of nozzle orientation tests due to high surface roughness. Excluded specimens were those produced with the 60° nozzle orientation.
7.3. RESULTS

**Table 7.2. ANOVA analysis of effect of nozzle orientation.**

<table>
<thead>
<tr>
<th></th>
<th>df</th>
<th>( F_{crit} )</th>
<th>( F )</th>
<th>( P )</th>
<th>( F )</th>
<th>( P )</th>
</tr>
</thead>
<tbody>
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<td>Orientation</td>
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<td>5.14</td>
<td>34.48</td>
<td>&lt;0.01</td>
<td>37.62</td>
<td>&lt;0.01</td>
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<td>0.07</td>
<td>0.80</td>
<td>17.91</td>
<td>0.01</td>
</tr>
<tr>
<td>Interaction</td>
<td>2</td>
<td>5.14</td>
<td>0.41</td>
<td>0.68</td>
<td>6.20</td>
<td>0.03</td>
</tr>
</tbody>
</table>

**Figure 7.8.** Mean elastic modulus for various nozzle orientations relative to the travel direction.

Figure 7.8 presents the elastic modulus for the different settings, with evaluation through ANOVA analysis identifying no significant effect of temperature or interaction, but a significant effect from orientation, as shown in Table 7.2. ANOVA analysis yielded significant effects from both orientation and temperature on the ultimate tensile stress, shown in Figure 7.9, and a significant interaction effect. This could represent the effect of viscosity on the bond formation, with higher temperatures lowering viscosity to enable improved bond formation due to the force exerted by the nozzle.

When the E3D v6 hotend was inclined at 30°, the outer edge of the nozzle is 0.375 mm lower than the centre of the orifice, resulting in no interference to the extruded filament when printing perpendicular or angled at 60° to the travel direction. However, this interference would cause significant compression of the deposited filament when angled at 120° to the travel direction.
Figure 7.9. Mean ultimate stress values for various nozzle orientations relative to the travel direction.

Figure 7.10. Example surface profile captured by the Alicona microscope showing the clear layer lines of the FFF process.

### 7.3.4 Surface profile measurement

An Alicona InfiniteFocus optical measurement system, as used in Chapter 3, was used to extract surface profiles from both sides of four specimens printed with various nozzle angles at 260 °C. Figure 7.10 shows an example of the profile; a strip of at least 5 mm on either side of the specimen was scanned with a vertical and horizontal resolutions of 1.67 µm and 7.82 µm respectively.

Table 7.3 presents the average step height of the trough to peak of the bond, measured using the HeightStep tool in the Alicona software, showing the similarity between the measured normal and perpendicular orientations bond heights. No significant difference was identified between
TABLE 7.3. Average step heights (µm) of the FFF part surface as measured with the Alicona HeightStep function.

<table>
<thead>
<tr>
<th>Nozzle orientation</th>
<th>Bond height</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>124</td>
</tr>
<tr>
<td>Perpendicular</td>
<td>117</td>
</tr>
<tr>
<td>Inline 60°</td>
<td>220</td>
</tr>
<tr>
<td>Inline 120°</td>
<td>328</td>
</tr>
</tbody>
</table>

Figure 7.11. Surface profile measurement for various nozzle orientations. Due to the similarity between the surface profiles of the nozzle orientated perpendicular to the travel direction to the normal orientation only the latter is shown for clarity.

either side of the wall when the nozzle was orientated perpendicular to the travel direction. The 120° angled nozzle produced a consistent surface profile, with the bond height alternating between a low and high bond height, depicted in Figure 7.11. It was observed the specimen with the nozzle at an angle of 60° had a lower profile consistency, not retaining a clearly repeating pattern. The width of the smaller peaks of the 120° specimen is approximately 0.32 mm, similar to the displacement of the trailing edge of the nozzle from the centre.

7.4 Discussion

Over the course of two phases of testing, inter-layer bonding within thin-walled structures manufactured through FFF was investigated using a tensile testing method requiring rectangular specimens [193], as opposed to alternative methods requiring samples to be machined into a
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traditional dogbone shape. This method provided a good distribution of break points along the gauge length, depicted in Figure 7.2, and specimens typically failing at a point above the centerline, consistent with the findings Coogan and Kazmer [83]. The specimens from 23% of the manufactured walls failed at a similar vertical displacement from the print bed, and the break point varied between the different walls of a sample cuboid, showing the fault intolerance of the deposition of single thickness walls. This was also noted in previous research on thin-walled components by Coogan and Kazmer [83].

Consistent with the findings of Chapter 5, the thin walls failed in a brittle manner with low yield. As the method discussed in Chapter 5 required machining, the applied heat could increase the sintered bond formation, potentially contributing to the higher ultimate tensile stress recorded in Chapter 5 than in Section 7.3. However, other confounding effects include the different filament rolls, a different type of hotend, or environmental conditions.

The environmental conditions of the laboratory contributed to the distribution of failure points, emphasised by the consistency test, where a significant difference was found between runs with the same filament. Parts comprising of a single thickness wall would be subjected to both a faster cooling and lower reheating cycle than a typical component where adjacent walls and infill would be required, as discussed in Chapter 5. This effect was highlighted in a previous study by Sun et al. where components in the centre of a build area exhibited stronger tensile properties due to the higher average temperature [68]. This shows a clear advantage to improved knowledge and control of the thermal process, as explored in Chapters 3 and 4.

The elastic modulus remained constant with variations in temperature or bed orientation, highlighted by the tight grouping along the diagonal line on Figures 7.3 and 7.7; examination of all specimens from the bed orientation tests and the comparable specimens from the nozzle orientation tests yielded high $R^2$ factors of 0.96 and 0.97 respectively. This provides reassurance that the part should behave as expected within the elastic deformation range irregardless of the bed angle, and shows the robot arm-based FFF is directly applicable to the manufacture of large components where high degrees of curvature are required, such as depositing stiffening features on a fuselage skin [194].

It was identified rotations of the nozzle inline to the direction of travel cause a significantly greater reduction in ultimate tensile stress than those perpendicular to the travel direction. When the nozzle was inclined at 120° to the direction of travel, the molten filament was mechanically compressed by the outer edge of the nozzle upon extrusion due to its vertical displacement of 0.375 mm, causing the alternating high/low step height observed in Section 7.3.4. In the case of the 60° orientation to the travel direction, the deposited layer was not compressed by the trailing edge of the nozzle, with the leading edge of the nozzle remaining above the previous layer. The reduction in compressive force was manifested as an inconsistency in bond heights, observed Figure 7.11. This was quantified through visual quality inspection using an optical microscope to view the bonding, showing its potential as a form of Non-Destructive Evaluation.
Such techniques would be especially applicable to thin-walled components, such as the cores produced in Chapters 5 and 6, as both sides of the wall could be profiled.

A nozzle orientation of $30^\circ$ would allow deposition 2.5 mm closer to a wall than a conventional orientation when printing within a confined space for composite repair, as discussed within Section 2.2.2. If achieved through an orientation perpendicular to the travel direction, this would maximise the filled space and minimise the decrease in mechanical properties.

7.5 Conclusions

This chapter has used tensile testing to investigate bond strength of FFF components manufactured with a robot arm over a variety of bed and nozzle orientations, providing an insight into requirements for quality assurance when printing large structures; the results are applicable to large curved structures where multiple build orientations will be used. The angle of the print direction was not found to affect the elastic modulus or ultimate tensile strength, justifying the use of FFF for the additive finalisation of large, non-planar components.

The nozzle orientation typically used in FFF, normal to the surface, provided similar mechanical properties to a rotation perpendicular to the print direction. A significantly decrease was observed when angled inline to the print direction due to the mechanical interference of the nozzle with the deposited road. Requiring the nozzle to be orientated normal to large curved surfaces necessitates the use of a robotic arm, as lower degree of freedom systems are unable to maintain the correct nozzle orientation angle, and other high-DOF systems may not have the required workspace; this has been explored in Chapter 6.

The findings identified in this chapter are significant for the generation of toolpaths for curved layers and within a constrained environment where varied nozzle orientation could increase the build area. A demonstration composite repair scenario, available on YouTube⁴, shows the in-situ manufacture of a core patch on an angled panel. The results presented in this chapter imply it would have similar mechanical properties to a normally printed patch. For this situation, improved toolpath planning would maximise the internal build volume to ensure the nozzle remains perpendicular to the travel direction when angled close to the wall. A further discussion of the cost and advantages of using a robotic arm-based FFF system for aerofoil core manufacture is presented in Chapter 8.

⁴“Arm-based 3D Printing for composite repair” by David Pollard: https://www.youtube.com/watch?v=mI93TeYS08o
This chapter summarises the results presented over the course of the thesis, covering the testing and control of thermal dynamics, mechanical properties, and robotic implementation. The cost differences of manufacturing an aerofoil-shaped core between the developed system, a more traditional AM system, and machined from Nomex honeycomb is then presented. An assessment of the Technology Readiness Level (TRL) of the developed system was conducted, and its application to other composite manufacturing processes discussed.

8.1 Thermal control

The thermal dynamics and control of the FFF extrusion process were discussed in Chapters 3 and 4 respectively; to the best of the authors’ knowledge, this has not been previously explored in the literature. As shown in Chapter 7, and by Coogan and Kazmer [83, 84], the deposition temperature has an effect on part strength. Initial observations identified a step increase in filament feed rate caused an overshoot in extruded filament temperature, with the magnitude of the response dependent on the material. The pause between the stop and start of extrusion, representative of increased travel times, did not lead to an appreciable difference in thermal response. With equal retract and prime parameters, minimal temperature overshoot was observed upon the commencement of extrusion, and a lower retract than prime distance caused an overshoot similar to the step change in feed rate.

The effects of the initial temperature overshoot were also observed in the extrusion tests with an updated controller in Section 4.4, and most visible in Figure 4.10, where a high extrusion level commenced after a long pause. These results support the hypothesis of the melt front moving away from the nozzle orifice before extrusion, as the block maintained a higher temperature than
the nozzle. This temperature differential was shown by Hofstaetter et al. [115] in a COMSOL model of a similar E3D hotend, although their modelling did not account for the dynamics of filament flow.

Practically, this dynamic temperature overshoot does not present a significant issue as an increased temperature would cause improved bond formation. The 10 °C temperature overshoot observed would provide an estimated increase in sintered bond formation of over 10%, as described in Table 3.5. While the application of a bonding model from Bellehumeur et al. [68, 109] did not predict the actual bond shape due to the mechanical compression of the extruded filament, this estimate shows an expected increase in part strength.

It was observed the nozzle temperature was more sensitive to feed rate variations than the block temperature due to its lower thermal mass. A typical hotend controller uses feedback from a block-based thermistor, allowing a reduction in nozzle temperature during an increase in feed rate whilst the block is maintained at a constant temperature.

The Smith Predictor and feed-forward controllers were applied to greatly improve the nozzle temperature consistency, and reduce the deviation in filament temperature. This ensured a more consistent temperature output, potentially leading to improved part properties and consistency. A key difference between the Smith Predictor and conventional PID was the more aggressive response to a change in the temperature set point; the compensation for the time delay allowed for saturation of the heater input PWM whilst avoiding temperature overshoot. However, typical printing applications require a constant hotend temperature, reducing the advantage of the improved Smith Predictor response.

The performance in steady state was similar to that achieved with a conventional PID controller with a feed-forward element, when integrated with the existing Marlin firmware, provided a substantial improvement in reducing nozzle temperature fluctuations. Additionally, results were similar between block- and nozzle-based feedback, and the Arduino- and dSpace-based controllers. This key finding shows an improved thermal controller can be implemented on existing hobbyist-level hardware.

Bellini et al. [112] presented a number of factors affecting liquifier dynamics, described in Section 2.3.3, and the findings from this thesis shows the recent time history of the feed rate should also be taken into consideration. This would have an impact on path planning, especially with adaptive slicing, where variable thickness layers would require different flow rates requiring compensation for the extruded temperature differences to maintain sufficient bonding levels.

### 8.2 Part properties

The properties of thin-walled FFF components have not been widely explored in the literature, and results of this research were consistent with those of previous studies. The tested specimens were the thickness of a single deposited road, as such parts would provide the low-density cores
suited for the proposed Aerospace core application. At the time of writing, there is no specified or recommended test method for FFF components due to the strong interaction between build path and bond strength [14].

Two methods of specimen manufacturing for tensile tests were used, the first, ASTM D638 [181] in Chapter 5, requiring dogbone-shaped samples, and the second, ASTM D6882 [193] in Chapter 7, rectangular specimens. A Dremel was used to machine dogbone shaped specimens, with the aid of a laser-cut jig, and the second cut with a PCB guillotine. Tensile testing identified the inter-layer bond strength by applying force normal to the bond line; as expected, all tensile specimens failed across this region.

The differences in the ultimate tensile stress of thin ABS walls between Chapters 5 and 7 (24.6 N mm$^{-2}$ and 14.7 N mm$^{-2}$ for normally orientated specimens respectively) could be due to the machining method required for each test method. The Dremel would have heated the material during the cutting process causing an increase in bond formation. Conversely, the guillotine may have caused small and unobservable defects along the layer line during the cutting of samples. It was not possible to quantify these effects due to other confounding factors such as a different printer and hotend, environmental conditions, and filament batch. It should be noted Coogan and Kazmer [83, 84] compared laser cut with machined specimens, and did not find any statistically significant differences in ultimate tensile stress, however both of these methods also involved heating the specimen. Their work identified an ultimate tensile stress of approximately 24 N mm$^{-2}$, similar to that achieved in Chapter 5 with a Dremel-based machining.

The tests in Chapter 5 identified a statistically significant change in ultimate tensile stress due to different wall thicknesses. Coogan and Kazmer [83] also found a significant effect, but with a relationship of $\sigma \propto 26.5t$ for walls of 0.4-0.8 mm thick. This ratio did not hold for the tested wall thicknesses of between 1.5-2.5 mm, with a significantly lower change in ultimate tensile stress observed, as shown in Figure 5.3(a). This supports the hypothesis of higher heat retention within the thicker walls increasing the interior sintered bond formation. Such heat retention could also be a potential cause for the difference in observed ultimate tensile stress between Chapters 5 and 7.

The effect of temperature on bond strength was investigated in Chapter 7, aiming to identify if an interaction effect existed between the bed or nozzle orientation and the change in filament viscosity due to increased temperature. Consistent with previous work on thin-walled parts, the temperature affected the overall bond strength [83]. No interaction between bed/nozzle orientation and temperature was observed, although a small effect would have been overshadowed by the result deviation.

In contrast, Ahn et al. [65] found nozzle temperature did not affect bond strength for tensile properties. However, this paper used a 10°C temperature differential, which would reduce the impact on UTS. The temperature differential was also compared to raster orientation, the change would be relatively minor, and the samples were produced flat on the bed, with the tensile
strength tested the adjacent roads rather than vertically stacked layers. Coogan and Kazmer [83] used a temperature range of 50 °C within their tests.

A high degree of variability was exhibited within the sample groups of both Chapters 5 and 7, with standard deviations of ultimate tensile stress typically greater than 2 N mm\(^{-2}\); this was found with both the commercial RapMan printer, and the developed arm-based printer. With the walls comprised of a single deposited road, there was little tolerance for minor deposition errors, highlighted by the consistency of failure locations of samples, as discussed in Section 7.4. Such errors could include a minor change in filament diameter or small environmental fluctuations; Table 5.6 shows the Nomex core had a lower variation in ultimate compressive stress than the FFF cores. This shows the need for improved control methods, such as those discussed in Chapter 4, to improve part consistency and compensate for environmental changes.

As discussed in Section 2.3.1, a majority of existing studies on mechanical properties have been conducted using specimens manufactured with 3-DOF printers. This literature uses the term “build orientation” to describe the slicing angle of a component, selected to allow faster printing, lower support material use, or improved properties during use [17, 65, 66]. Using the robotic arm-based printer, it was possible to change the build direction relative to the gravity vector, and it was found there was little effect on ultimate tensile stress or elastic modulus. This supports the use of the full workspace afforded to a robotic arm-based printer.

All surveyed research has assumed the nozzle should remain normal to the substrate during printing. This limitation is violated when using 3-DOF printers for the manufacture of curved layer specimens, as introduced in Section 2.5.1, but, to the best of the authors knowledge, no mechanical tests have been previously conducted to evaluate the resulting properties. The findings of Chapter 7 showed the existing assumption of maintaining the nozzle orientation to be well-founded, although there was only a minor difference when the nozzle was orientated perpendicular to the print path.

Knowledge of the effect of nozzle orientation on part strength is key to path planning for operations such as composite repair, as discussed in Chapter 6. As the hotend used was asymmetrical, rotation about the vertical axis would be required to maximise the filling of a cavity machined for a sandwich panel repair; such work was recently examined by an undergraduate project at the University of Bristol [195]. Additional reorientation perpendicular to the direction of travel would further increase the build area, ensuring maximal space filling; a nozzle orientation of 30° would be capable of depositing filament 2.5 mm closer to the wall than a normally-orientated nozzle for the E3D hotend used.

Core samples for compressive testing were manufactured using three different toolpaths, each providing a different wall thickness, and manufactured with a commercial 3-DOF RapMan printer. Standard slicing software produced double-thickness walls, as the software assumed the STL file contained a volume, thus requiring two outer walls and an interior. Custom software generated the required thin walls, and failure properties were consistent with the results of
tensile testing; thicker walls yielded significantly more before failure showing increased energy absorption. This is clear when observing the results normalised to the failure force in Figure 5.10; the thin-walled specimen more closely resembled the Nomex failure.

FFF cores had a significantly greater ultimate compressive force than Nomex, similar performance for specific ultimate compressive stress, and were comparable to industrial thermoplastic cores. Examining the stress over the wall area, rather than the total area, the toolpath 2 core had an ultimate stress of \(35.2 \text{ Nmm}^{-2}\). This was similar to values identified in the literature for the compressive stress of FFF cylinders of \(37 \text{ Nmm}^{-2}\) by Lee et al. [66], and \(32 \text{ Nmm}^{-2}\) by Ahn et al. [65]; both of these tests from the literature were conducted on FFF ABS cylinders with a 100% infill density.

It can be seen the the stair-case effect was eliminated on the outer surface of curved layer cores presented in Chapter 6. Printing with carbon-reinforced filament has been shown to provide significant mechanical advantages [81], and curved layers to have improved strength over conventionally sliced components [143]; cores produced combining the curved layers and carbon reinforcements are postulated to have superior properties. The current slicing strategies involved reflection of the print path, causing a single plane at the centre of the structure which would reduce the effectiveness of the curved layers. Such a fault could be eliminated through a more curved interior plane, or adoption of an adaptive transition region as explored by Huang and Singamneni [149].

### 8.3 Robotic implementation

The implementation of FFF using an industrial robotic arm was described in Chapter 6. This examined the advantages of a robot arm, identifying a significantly greater printable area when compared to the floor footprint than conventional printers, in addition to the higher DOF available for nozzle positioning, as shown to be advantageous for curved layer printing in Chapter 7. Numerous examples of such systems exist in both the academic and industrial spheres, described in Section 2.5.2.

The toolpath generation software was written in Python, and based on existing open source software [191]. This is a high-level and portable language suitable for running on all operating systems, with significant potential for further expansion. This offers a lower cost, and more reconfigurable, alternative to programming via the Teach Pendant or Portable Logic Controllers (PLCs). Other potential applications of the developed software are introduced in Appendix C.

By printing on cylindrical and hemispherical substrates, this system has been shown to be suitable for the “Additive Finalisation” process proposed by Dröder et al. [142]. This would increase the throughput of the system by not relying on the 3D printing of an entire component, merely the addition of customised features.

The ability to rotate the nozzle about the vertical axis opens two advantages for monitoring
and improving the print quality. As noted in Chapter 7, the surface quality could be monitored by an end-effector mounted sensor to ensure print quality; this is especially applicable for thin-walled structures as both sides of the wall could be imaged. Rotation of the nozzle would ensure cameras mounted on the end effector are viewing the previously deposited road, providing a view “along” the printed wall; such movement would not be possible for existing 3- or 5-DOF systems. Work exploring toolpath generation for a rotating asymmetric nozzle to print a core repair was undertaken by an undergraduate project [195].

Similarly, lasers to pre-heat the substrate have been shown to improve bond strength by Du et al. [78]. In a similar fashion, the lasers could be mounted on the end-effector and rotated to ensure they are consistently directed at the substrate in front of the nozzle. This would not be possible on other FFF structural layouts, as they do not possess sufficient manipulability to rotate the nozzle about its extrusion axis.

A constraint of the implemented system was the missing connection between the TCP speed and the extruder flow rate; an important consideration as discussed by Han et al. [92]. Two solutions were proposed in Section 6.7.2, requiring either a hardware upgrade to include an Analog I/O board, or an IRC5 software upgrade to enable multithreading. The effect of this was alleviated by reducing both the requested TCP speed and feed rate around areas with high reorientation requirements.

During FFF operation, the accuracy at the operating speeds was sufficient for high quality prints, despite the lower path following accuracy of the robotic arm (670 µm) stated in the data sheet. This lower accuracy would be caused by inertia, an inherent feature of serial manipulators, of the arm whilst moving, especially at high speeds or with large reorientation requirements. Other larger-scale systems would have similar issues with increasing inertia at increasing sizes, whilst also requiring a larger floor footprint, as shown in Table 6.1.

## 8.4 Cost comparison

A seminal cost comparison between a traditional and additively manufactured component was performed by Atzeni and Salmi [10], investigating the difference between high-pressure die-casting and metal powder bed fusion production of an aircraft landing strut. This identified a cost crossover point of 42 components, shown in Figure 1.2, and noted the increased design space afforded to AM would enable further structural optimisation for more economical AM production. This section begins with a brief cost comparison for core panels, and then the manufacture of an aerofoil-shaped core.

Within the journal paper accompanying Chapter 5, a cost comparison estimated the material price difference between ABS printed cores and an aerospace grade Nomex honeycomb core. It was found a sheet of Nomex core (121.9x243.8x2.5 mm) costs between $927 and $2663 [196]. Printing the same volume of core using toolpath 2, shown in Figure 5.7(b), as the Nomex honeycomb would
8.4. COST COMPARISON

Figure 8.1. Visualisation of the example aerofoil used for a cost comparison between manufacturing methods.

weigh 13.44 kg, costing $403.22 using the filament purchased from 3DFilaprint [197]; a factor of between 2 and 7 lower than Nomex. This analysis did not take into account the personnel or machining costs for producing more complex geometries; an aspect where the FFF process would have reduced waste and a higher degree of automation.

An aerofoil core measuring 300x180x50 mm was designed for estimating the cost difference for a finished component, as shown in Figure 8.1. This was analysed for manufacture using three different machines. First, a quote was obtained for the manufacture from Nomex honeycomb from Upland Fab, specialists in composites and plastics machining\(^1\). This quote included the machine setup costs, and the cost for producing batches of 10 and 100. A second estimate for traditional AM printing was calculated using the slicing software Cura, by Ultimaker, which provided print time and material estimates for the designed STL file. Finally, the software developed in Section 6.6.2 was used to estimate the material use and manufacturing time for the robotic arm-based FFF system.

The AM costs were evaluated using Ultimaker PVA soluble support material ($113.31 per kilogram) [198] for the traditional AM support, and ABS ($30.00 per kilogram) [197] for the mould required for robotic AM. ULTEM 9085 ($275.00 per kilogram) [199] was used for the component material as it is a high-performance resin similar to that used within the Stratasys certified systems; the price difference between the certified and non-certified material could not be identified.

8.4.1 Traditional AM cost breakdown

To estimate the required build time and cost using a traditional AM printer, the Cura software package, by Ultimaker, was used for slicing the CAD model. The software was configured for a custom printer to possess a build volume sufficient for slicing the aerofoil shape, using a

\(^1\)Upland Fab, 1445 West Brooks St, Unit L, Ontario CA, 91762.
Figure 8.2. The expected build of an aerofoil shape from a traditional printer. The darker colour shows the required support structure.

nozzle speed during extrusion of 50 mm s\(^{-1}\) and a layer height of 0.5 mm. The core structure was generated using automated infill generation for a square grid, with no outer shells. The infill density used was 18.3%, calculated from the ratio of the total wall thickness of hexagonal walls to the wing area of the robotic slicing process. Figure 8.2 shows the sliced CAD model, including the additional support material required for the overhang of the leading and trailing edges.

### 8.4.2 Robotic AM cost breakdown

The toolpath for robotic AM of the aerofoil core structure was generated using the same software introduced in Section 6.6.2. A 0.5 mm layer height was used, with a 50 mm s\(^{-1}\) extrude speed in conjunction with a 2 mm s\(^{-1}\) feed rate, as used in Chapter 7. The mould required to support the curved outer layers, was sliced with Cura, as used in Section 8.4.1, with the build profile set for a fine print quality with a 0.1 mm layer height, 20% infill; ABS was selected for its good material properties. The mould is shown in Figure 8.3(a), and the toolpath for the component in (b).

### 8.4.3 Results

The approximation of manufacturing cost for the aerofoil component from the three methods is shown in Table 8.1. It can be seen both AM processes are significantly cheaper than the commercial machining process, with a small difference in price between the AM methods. A significant cost reduction was evident for the Nomex core with increasing purchase volumes, with an effective component price of $1426.11 to $835.56 for batch sizes of 10 and 100 respectively; while this shows the suitability for higher production levels, this higher setup time and cost would hinder initial development. The cost of both support material and structure for the traditional
8.4. COST COMPARISON

and robotic AM methods is small relative to the non-recurring setup charge, clearly showing the increased flexibility afforded to the AM process; such cost differences between AM and traditional manufacture would be emphasised during design changes. This difference in the significantly higher setup cost for a machining than an AM process is similar to that shown in Figure 1.2.

The manufacture of both the traditional and robotic AM components would be significantly faster than the 12 week lead time required from Upland Fab. As printing of the support structure for each component was not necessary for the robotic AM, the manufacturing time per component is lower than that of the traditional AM process. The long build time of the mould required for robotic AM would limit its suitability for rapid design iterations of the external shape, but enable faster iterations of the internal shape where no mould re-print would be necessary, as would be required for each print of conventional 2.5D AM.

8.4.4 Limitations of cost analysis

This brief analysis has omitted the initial and operational cost of the manufacturing system due to the unknown cost of the Nomex machining system, and the hypothetical printer used as the traditional AM system. It should be noted that ULTEM 9085 requires a heated build volume to maximise the mechanical properties, adding additional cost and complexity to the system.

As the Nomex honeycomb was produced by a third party company, it was not clear how much the cost would be reduced by in-house manufacturing; assuming a typical 30% cost of production, the estimated manufacturing cost of the Nomex would be between $245.03 and $371.49, similar to the figure estimated for FFF production.

The selected aerofoil design does not fully encompass the potential of AM design, despite the geometry which is difficult to machine from Nomex due to its double curvature. Additional functionality, such as fasteners, wiring, and multiple materials, could be incorporated within the AM structure to enable further cost reductions through reduced assembly time or increased

\[ \text{Figure 8.3. (a) the mould for producing the aerofoil shape in the Cura slicer. (b) the toolpath generated for FFF of the aerofoil-shaped core.} \]
Table 8.1. Cost estimation of aerofoil core for Nomex, a standard 3D printer, and an arm-based 3D printer.

<table>
<thead>
<tr>
<th>Process</th>
<th>Cost Component</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machined Nomex</td>
<td>Non-recurring setup</td>
<td>$1,875.00</td>
</tr>
<tr>
<td></td>
<td>Per component (batch size 10)</td>
<td>$1,238.31</td>
</tr>
<tr>
<td></td>
<td>Per component (batch size 100)</td>
<td>$816.78</td>
</tr>
<tr>
<td></td>
<td>Lead time</td>
<td>12 weeks</td>
</tr>
<tr>
<td>Traditional AM</td>
<td>Support material</td>
<td>$14.35</td>
</tr>
<tr>
<td></td>
<td>Aerofoil (ULTEM 9085)</td>
<td>$112.75</td>
</tr>
<tr>
<td></td>
<td>Manufacturing time per component</td>
<td>8.47 hours</td>
</tr>
<tr>
<td>Robotic AM</td>
<td>Support structure</td>
<td>$17.55</td>
</tr>
<tr>
<td></td>
<td>Support manufacturing time</td>
<td>53.05 hours</td>
</tr>
<tr>
<td></td>
<td>Aerofoil (ULTEM 9085)</td>
<td>$104.27</td>
</tr>
<tr>
<td></td>
<td>Manufacturing time per component</td>
<td>5.74 hours</td>
</tr>
</tbody>
</table>

system performance. Other materials could be used, such as curved layer reinforced filaments in loading directions, and structural optimisation would also be beneficial, as both of the proposed AM designs used a constant core density throughout the structure.

8.5 TRL Assessment

Technology Readiness Levels (TRLs) were first implemented by NASA to measure technology maturity level on a scale of 0-9 [200]; the definition of each level is presented in Table 8.2. This classification system was developed in response to cost and schedule over-runs due to integration issues of new technologies, and aims to improve the risk management of projects. In a general context, university research focuses on TRLs 1-3, and industry levels 7-9. The central region is considered the “Valley of Death”, where new technologies may be too costly or difficult to integrate into viable commercial products [201].

After an assessment of the project outcomes according to the TRL definitions in Table 8.2, a TRL level of 4 has been achieved over the course of this thesis. The manufacture of curved layer structures in a laboratory environment was demonstrated in Chapter 6, with assessment of the material properties in Chapters 5 and 7. Additionally, a better understanding of the controller was achieved, with a breadboard evaluation through the implementation of the feed-forward control element on the Marlin firmware presented in Chapter 4. As this was conducted in a laboratory environment, it has not been subjected to the required testing and usage to count as a “relevant environment” for TRL 5; although it should be noted such a system would likely operate in a clean room, as with standard composite production techniques [45, Chapter 7]. This would have more consistent temperature and humidity than the laboratory environment the robot was
8.6 Conclusions

This chapter has summarised the key findings of the three thesis themes of thermal modelling and control, mechanical properties, and the implementation of a multi-dimensional robotic FFF system. It was then found the cost for manufacturing an aerofoil core, excluding the initial setup, was comparable to a conventional AM printer and to the estimated machining costs for industrial grade Nomex. It was identified a TRL of 3 was achieved for the robotic AM system, and this evaluation method provided guidance for future project development. The main limitation of TRL advancement was the requirement for programmatic rigidity and the prediction of final part properties; while this has been completed at small scale, it was not expanded to a component level.

\[\begin{array}{|c|c|}
\hline
TRL Level & Description \\
\hline
TRL 1 & Basic principles observed and reported \\
TRL 2 & Technology concept and/or application formulated \\
TRL 3 & Analytical and experimental critical function and/or characteristic proof of concept \\
TRL 4 & Component and/or breadboard validation in laboratory environment \\
TRL 5 & Component and/or breadboard validation in relevant environment \\
TRL 6 & System/subsystem model or prototype demonstrated in relevant environment \\
TRL 7 & System prototype demonstration in operational environment \\
TRL 8 & Actual system completed and qualified through test and demonstration \\
TRL 9 & Actual system proven through successful mission operations \\
\hline
\end{array}\]

To reduce the assessment objectivity and to provide guidance on areas of improvement, Nolte et al. [202] created a check-list breakdown of aspects of the TRL levels. This was implemented on a Microsoft Excel spreadsheet\(^2\) and allows evaluation of the TRL, Manufacturing Readiness Level (MRL), and Program Readiness Level (PRL). The latter two criteria refer to the complexity of hardware production and program management respectively. Classifications were further subdivided into “Green”, “Yellow”, and “Red” denoting completion (all criteria fulfilled), sufficient criteria fulfilled to claim achievement (67%), and unachieved respectively. Table 8.3 denotes the achieved levels estimated by this method, and a brief description of the results. Appendix B shows the criteria for this evaluation method, providing guidance on future steps to improve technological maturity.

\(^2\)The document is available at: http://aries.ucsd.edu/ARIES/MEETINGS/0712/Waganer/TRL%20Calc%20Ver%202.xls

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**Table 8.3. Achieved technology levels within this project.**

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Section</th>
<th>Level</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRL</td>
<td>Green</td>
<td>1</td>
<td>Initial proof of concept demonstrated, scientific feasibility published in literature, and potential customers have been identified.</td>
</tr>
<tr>
<td></td>
<td>Yellow</td>
<td>3</td>
<td>Lacks extensive prediction of properties.</td>
</tr>
<tr>
<td>MRL</td>
<td>Green</td>
<td>3</td>
<td>Breadboard components have been produced and operational, with feasible manufacturing concepts.</td>
</tr>
<tr>
<td></td>
<td>Yellow</td>
<td>3</td>
<td>Lack of formal inspection of designs or scalability.</td>
</tr>
<tr>
<td>PRL</td>
<td>Green</td>
<td>1</td>
<td>Potential customers identified and have shown an interest in the technology. Rudimentary cost and risk management implemented.</td>
</tr>
<tr>
<td></td>
<td>Yellow</td>
<td>2</td>
<td>No formal customer requirement documents, Systems Engineering Master Plan, or system performance metrics.</td>
</tr>
</tbody>
</table>

The following chapter relates the discussed findings to the initial aim and objectives. It then advises of some limitations of this study, and identifies future avenues of research.
Over the course of this thesis, the application of multi-dimensional FFF to manufacture composite sandwich cores has been examined. The research has been grouped into three themes of improving thermal control of the extruder, exploring the mechanical properties, and implementing robotic control for a multi-DOF FFF system. This chapter reviews the placement of AM for manufacturing on the hype cycle, relates the identified results to the aim and objectives introduced in Chapter 1, discusses its research impact, limitations, and introduces potential further work.

### 9.1 Current state of AM for manufacture

Chapter 1 introduced the location of various AM technologies on the Gartner Hype Cycle, reproduced in Figure 9.1. Based on the findings of Chapter 2 and the research presented in this thesis AM for manufacturing is believed to be entering the *Slope of Enlightenment*. An indication AM is gaining traction in the manufacturing industry is shown by the industrial application of advanced, multi-dimensional AM systems, discussed in Section 2.5.3, and an increased academic interest in AM, clearly shown in Figure 2.1.

The research presented in this thesis aids the advancement of AM for manufacturing, contributing the open-source and flexible robotic controller presented in Chapter 6. The demonstration of improved, in-process thermal control with existing hardware and thin-walled part properties when printed with a higher-DOF system could help process understanding and inform component design. Finally, the compressive tests shown in Chapter 5 and the cost comparison presented in Section 8.4 shows FFF has the potential to be competitive with traditional manufacturing technologies.
Based on the literature review and previous discussion, the author suggests the current position of AM in manufacturing operations to be within at the beginning of the Slope of Enlightenment. Image source: Gartner Hype Cycle for 3D Printing, 2018, Pete Basiliere, Michael Shanler, 13 July 2018.

9.2 Relation of key findings to aim and objectives

With the key findings discussed in detail within each chapter, and summarised in Chapter 8, this section relates findings to the project aim and objectives introduced in Chapter 1.

**Aim:** To investigate thermal control of the FFF process and evaluate mechanical properties of thin-walled FFF components.

A literature review, presented in Chapter 2, provided a review of the current state of the art for FFF research and the implemented multi-dimensional FFF systems. Figure 2.14 shows a division of the research into key overlapping regions of design space, quality assurance, and part properties, assisting the derivation of the following objectives.

**Objective 1:** Analyse the filament temperature during the extrusion process to identify and implement improved control strategies.
It was found the high speed thermal dynamics of filament temperature during feed rate changes are more accurately reflected by a nozzle-based thermistor, and a typical error during the start/stop process was a filament temperature overshoot; this would cause a localised increase in bond formation. An improved robustness of nozzle and filament temperatures to feed rate changes was achieved by the application of feed-forward control, and this can be effectively applied using existing low-cost hardware.

**Objective 2:** Compare the performance of a core produced with AM to aerospace-grade Nomex honeycomb.

Cores manufactured through FFF had superior compressive strength than existing Nomex cores, comparable specific strengths, and can be produced at a lower cost. The failure profile was dependent on wall thickness, with thicker walls behaving in a more ductile manner reminiscent of typical bulk plastic properties. Improved control and process planning are required to reduce the variability of thin-walled specimens due to minor extrusion errors.

**Objective 3:** Analyse the effect of utilising the higher degrees of freedom of a robotic arm on mechanical properties of FFF components.

The angle of the nozzle relative to the print direction had a significant impact on component strength due to the interaction of the nozzle with the extruded filament. The inter-layer bond strength did not significantly change with print angle relative to the gravity vector, showing suitability for utilising the full workspace of a robot arm for large-scale curved layer FFF.

**Objective 4:** Demonstrate toolpath generation afforded to the high degree of freedom manufacturing systems.

The flexibility of an industrial robotic arm-based FFF system, the deposition onto cylindrical, hemispherical, and curved surfaces was demonstrated, showing the manufacture of a tapered and twisted aerofoil core. It was shown a multi-DOF system is necessary to ensure the nozzle remained orientated normal to the substrate surface for high print quality during curved layer FFF.

### 9.3 Contribution to Knowledge

The contribution of this thesis can be classified in three fields; process, properties, and application. Results were disclosed over the duration of this project in the form of journal papers and presented at academic conferences; these are listed in Table 1.1. Videos of the robot operation were used to further demonstrate the system, and such systems are presented in Table 1.2. Finally, the software to control the robot was released as open-source under the MIT license, available at:

https://github.com/davepollard/CurvedLayer_FDM
CHAPTER 9. CONCLUSIONS AND FURTHER WORK

Key academic contributions to FFF mechanical properties and process are discussed, followed the contributions to the application of the research conducted.

9.3.1 Properties

Chapter 5, based on a published journal article, demonstrated the change in mechanical properties based on the wall thickness. A key contribution of this chapter was the similar specific strength achievable between a traditional Aramid-fibre Nomex core and the low-cost FFF core.

As shown in Table 2.4, numerous research institutions have created arm-based FFF systems, and most research has focused on toolpath generation. This thesis has explored the mechanical properties of thin-walled structures printed using different nozzle and bed orientations; to the best of the authors knowledge, this was the first academic work examining such properties. It was found there was no significant change in bond strength for different bed orientations, demonstrating the potential to in-situ manufacturing of components on large and curved surfaces.

9.3.2 Process

High-speed thermal dynamics of the FFF process had not been previously covered within academic literature, despite the filament temperature having a significant impact on inter-layer bonding. The fluctuations were shown to reduce through the use of a feed-forward control element, potentially increasing process stability. It was also observed that the temperature controller should be adapted based on the filament type used, with different responses observed for ABS and PLA.

A derived process requirement based on Chapter 7 was the nozzle would ideally remain normal to the surface during the print to minimise adverse interaction between the nozzle and the deposited filament. As such orientations are unachievable with traditional 3-DOF systems, this strengthens the case for adopting arm-based FFF systems for large and curved structures.

9.3.3 Application

Typical FFF printers use a PID temperature controller; while this is stable and easily tuned, this thesis has shown the addition of a simple feed-forward element can compensate for feed rate and reduce the variability of filament temperature. This would allow exploration of a wider variety of engineering materials which have a narrower processing window.

A number of observations have been made regarding the mechanical properties of thin-walled FFF structures. Tensile testing exhibited a high degree of variability between specimens, showing the fault-intolerant nature inherent in relying on a single deposited road. This can be alleviated in core structures through both improved process control, such as that explored in Chapters 3 and 4, and the redundancy inherent in creating a structure of multiple passes; this would be designed into a structure as a safety factor.
This thesis has also informed on the generation of toolpaths for curved surfaces, where it has noted the nozzle should not be angled inline with the print direction. However, it was shown the nozzle could be angled perpendicular to the travel direction, leading to maximisation of build space for internal geometries, or reducing the reorientation requirements when printing over larger surfaces.

The software used to control the robot arm, based on an existing open-source project, has been released under the MIT license. This will enable the implementation and advanced development of robotic arm-based FFF systems within other research institutions and companies; interest has already been shown by a leading research and technology organisation.

Other applications of the robotic control system have been found within the composite manufacturing region; these are discussed in Appendix C. These demonstrate the flexibility afforded to the PC-based controller, lowering the accessibility barrier to other research groups.

9.4 Limitations of current work

A key limitation of this project was the concurrent nature of the research, resulting in the advanced thermal controller not being integrated onto the robotic arm. Research identifying and designing the controllers, in Chapters 3 and 4, took place alongside the implementation of the robotic arm controller and specimen manufacture, in Chapters 6 and 7. The work conducted in Chapter 5 used a commercially available printer, and the firmware did not allow for controller modification.

A second was the variability exhibited by the thin-walled specimens during tensile testing, highlighting the need for more consistent environmental conditions within the robot workcell. This reduced the ability to implement Design of Experiments techniques to investigate more factors, as a high number of samples were needed to obtain good estimates for part properties.

A final limitation to the exploration of the design space was the lack of connection between the robot TCP speed and the extruder feed rate, discussed in Section 6.7.2. With the additional constraint of constant supervision required for the risk assessment, this limited the robot’s operational time.

9.5 Conclusions

The research question underpinning this thesis was:

How can the mechanical quality of FFF components be improved through thermal- and multi-DOF- control for the manufacture of sandwich cores?

Inter-layer bonding of the process drives the mechanical quality of FFF components, and the level of bonding is reliant on deposition temperature. Chapter 3 explored the dynamic filament temperature response during common FFF actions, and it was identified the filament temperature
response to a step increase in feed rate is an up to \(10^\circ\text{C}\), and a lower steady state temperature. It was noted that ABS and PLA, amorphous and semi-crystalline polymers respectively, had very different responses, highlighting the requirement for improved tuning based on the filament type. Chapter 4 aimed to reduce this steady state difference through a feed-forward controller, and demonstrated successfully when implemented on the widely used open source firmware.

The mechanical properties of sandwich cores in relation to component wall thickness was evaluated in Chapter 5, finding an increased wall thickness increased the energy absorption before failure. A key observation from this research was the similarity of specific strengths between commonly used Nomex and FFF core components of 1.21 and 1.46 N mm\(^{-2}\) g\(^{-1}\) respectively. Chapter 6 described the implementation of an 8-DOF robotic cell for FFF, demonstrating the manufacture of curved layer core components, which could have superior properties due to the continuous layer on the outer surface.

Further mechanical properties were then explored in Chapter 7, with use of the robotic cell presented in Chapter 6, and investigating the difference between two deposition temperatures. Tensile testing identified no significant difference in bond strength between deposition over a variety of print bed angles, but the interaction of the nozzle with the extruded road was identified to have an impact on mechanical quality. This can inform toolpath generation to ensure the nozzle is ideally orientated normal to the surface, or angled perpendicular to the direction of travel to maintain mechanical properties; this requires higher-DOF systems than a majority of existing FFF machines.

### 9.6 Further work

Over the course of this thesis, numerous avenues of further work have been identified; these will be introduced in the thematic sections related to the thermal properties, mechanical properties, and robotic implementation, and followed by a roadmap for future development.

The thermal controller has been shown to reduce the variability of the filament and nozzle temperature, but it remains to be shown if this has a significant impact on the mechanical strength. A model-based feed-forward controller between feed rate and filament temperature should be further explored, in addition to an improved hotend design to enable faster heating and active cooling for control over the dynamic temperature response.

Mechanical properties of FFF components require further examination to improve the prediction of part properties. Such work could examine curved layer cores, the effect of layer height, and the properties of different filament types. Advanced work would use the generated data to improve the prediction of core properties and allow for structural optimisation.

A key upgrade for the FFF application would be the use of an Analog I/O card or multithreading to enable feed rate adjustment based on the current TCP speed. The controller could also be applied to larger ABB robots to demonstrate the manufacture of significantly larger cores, and to
explore other advantages of arm-based FFF, as discussed in Appendix C.

A roadmap defining the future work from this project can be based on Appendix B, which highlights a link with potential users would be key to aid the definition of system requirements. A reduction in part variability would begin with the implementation of a model-based feed-forward controller to effectively compensate for feed rate fluctuations during specimen manufacture. The further examination of bulk and extruded material properties throughout the workspace would enable better selection and design for part strength. Investigations into qualified engineering materials, such as the aerospace-grade Ultem 9085, would be of great industrial interest. This would allow the integration of aspects presented in this thesis to reach the optimal region of the Venn diagram, shown in Figure 2.14, between the Design Space, provided by the robotic arm, QA Methods, assuring the correct deposition temperature, and Part Properties, identified through mechanical testing.


US Patent 6,054,077.


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This appendix depicts the seven different AM processes as classified by ISO 52900 [1], and described in Table 2.1. All images in this appendix are from, or based on, images available on the Wikimedia Commons by Scopigno et al. [2].

**Figure A.1.** Schematic of a typical FFF printer. (a) shows the filament supply, being drawn into the movable hotend by the extruder motor, (b), where it is melted and pushed through the nozzle (c). Deposited on a build platform, (e), movable in the z direction, the final part can be built up (f). To support the overhang between layers, support structures are necessary (d). Image from [2].
**Figure A.2.** Schematic of a typical Powder Bed Fusion printer. A movable head (a) uses a laser, or other energy source, to fuse regions of the uppermost powder layer. Upon the completion of a layer, the base (f) moves vertically down, with a new layer of powder pushed from a storage area (c) to the print area by a blade (b) to ensure an even surface. The part (d) is produced through successive layers, with the unsintered powder (e) suitable for recycling. Image based on those from [2].

**Figure A.3.** Schematic of a typical Vat Polymerisation printer. A light pattern is projected from source (a) through a tank of photo-polymerising resin (c) through a transparent panel (b), causing solidification on a vertically moving surface (e) to produce component (d). Image from [2].
Figure A.4. Schematic of a typical Material Jetting printer. Material is fed into inkjet-style heads (a), which is moved to deposit droplets to form a layer of the component (b) on a vertically moving print bed (d); overhangs are supported by a second material (c). Image based on those from [2].

Figure A.5. Schematic of a typical Binder Jet printer. A binder (a) is deposited onto the top powder layer of the build chamber (e) on a descending bed (f) to produce the component (d). Successive layers of powder are transferred by a blade (b) from storage area (c) to ensure a smooth surface. Image from [2].
Figure A.6. Schematic of a typical Sheet Lamination printer. A movable head \( (a) \) cuts and deposits a binder onto the top sheet, and the platform \( (e) \) descends. Successive layers are added by transferring sheets \( (c) \) via a roller \( (b) \). Image based on those from [2].

Figure A.7. Schematic of a typical Directed Energy Deposition printer. A part \( (c) \) is constructed through a movable head \( (a) \) sintering filament or powder stream using an energy source \( (b) \) on a vertically moving platform \( (d) \). Image based on those from [2].
The Technology Readiness Level (TRL) was assessed based on the AFRL Transition Readiness Level Calculator [202]. This provides a list of statements to standardise TRL assessment, categorised into Hardware/Software/Both (H/S/B) and the associated Technology/Programmatic/Manufacturing (T/P/M) Readiness Level. Tables B.1-B.5 show which criteria the implemented system meets, as discussed in Section 8.5 for TRLs 1–5; higher TRLs are presented within the spreadsheet but no aspects were met within the scope of this thesis.

All table entries are quoted directly from the TRL assessment spreadsheet described by Nolte et al. [202], and available at:
http://aries.ucsd.edu/ARIES/MEETINGS/0712/Waganer/TRL%20Calc%20Ver%202.xls
### Table B.1. Assessment criteria for TRL 1.

<table>
<thead>
<tr>
<th>Category</th>
<th>Component</th>
<th>Completed</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>T</td>
<td>Y</td>
<td>“Back of envelope” environment</td>
</tr>
<tr>
<td>B</td>
<td>T</td>
<td>Y</td>
<td>Physical laws and assumptions used in new technologies defined</td>
</tr>
<tr>
<td>S</td>
<td>T</td>
<td>Y</td>
<td>Have some concept in mind that may be realizable in software</td>
</tr>
<tr>
<td>S</td>
<td>T</td>
<td>Y</td>
<td>Know what software needs to do in general terms</td>
</tr>
<tr>
<td>B</td>
<td>T</td>
<td>Y</td>
<td>Paper studies confirm basic principles</td>
</tr>
<tr>
<td>S</td>
<td>T</td>
<td>Y</td>
<td>Mathematical formulations of concepts that might be realizable in software</td>
</tr>
<tr>
<td>S</td>
<td>T</td>
<td>Y</td>
<td>Have an idea that captures the basic principles of a possible algorithm</td>
</tr>
<tr>
<td>B</td>
<td>P</td>
<td>Y</td>
<td>Initial scientific observations reported in journals/conference proceedings/technical reports</td>
</tr>
<tr>
<td>B</td>
<td>T</td>
<td>Y</td>
<td>Basic scientific principles observed</td>
</tr>
<tr>
<td>B</td>
<td>P</td>
<td>Y</td>
<td>Know who cares about technology, e.g., sponsor, money source</td>
</tr>
<tr>
<td>B</td>
<td>T</td>
<td>Y</td>
<td>Research hypothesis formulated</td>
</tr>
<tr>
<td>B</td>
<td>P</td>
<td>Y</td>
<td>Know who will perform research and where it will be done</td>
</tr>
<tr>
<td>Category</td>
<td>Component</td>
<td>Completed</td>
<td>Criteria</td>
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</tr>
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<td>P</td>
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<td>Customer identified</td>
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<tr>
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<td>Y</td>
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<td>Y</td>
<td>Paper studies show that application is feasible</td>
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<td>P</td>
<td>Y</td>
<td>Know what program the technology will support</td>
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<td>T</td>
<td>Y</td>
<td>An apparent theoretical or empirical design solution identified</td>
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<td>H</td>
<td>T</td>
<td>Y</td>
<td>Basic elements of technology have been identified</td>
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<td>Y</td>
<td>Desktop environment</td>
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<tr>
<td>H</td>
<td>T</td>
<td>Y</td>
<td>Components of technology have been partially characterized</td>
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<td>T</td>
<td>Y</td>
<td>Performance predictions made for each element</td>
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<td>P</td>
<td>Y</td>
<td>Customer expresses interest in application</td>
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<td>S</td>
<td>T</td>
<td>Y</td>
<td>Some coding to confirm basic principles</td>
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<td>T</td>
<td>Y</td>
<td>Initial analysis shows what major functions need to be done</td>
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<td>N</td>
<td>Modeling &amp; Simulation only used to verify physical principles</td>
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<td>P</td>
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<td>System architecture defined in terms of major functions to be performed</td>
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<td>Y</td>
<td>Experiments performed with synthetic data</td>
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<td>P</td>
<td>N</td>
<td>Requirement tracking system defined to manage requirements creep</td>
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<td>Rigorous analytical studies confirm basic principles</td>
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<td>P</td>
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<td>T</td>
<td>Y</td>
<td>Know what output devices are available</td>
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<td>Know capabilities and limitations of researchers and research facilities</td>
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<td>T</td>
<td>Y</td>
<td>Know what experiments you need to do (research approach)</td>
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<td>N</td>
<td>Predictions of elements of technology capability validated by Analytical Studies</td>
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<td>T</td>
<td>N</td>
<td>Analytical studies verify predictions, produce algorithms</td>
</tr>
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<td>Science known to extent that mathematical and/or computer models and simulations are possible</td>
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<td>Y</td>
<td>Laboratory experiments verify feasibility of application</td>
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<td>Predictions of elements of technology capability validated by Laboratory Experiments</td>
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<td>Customer representative identified to work with development team</td>
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<td>P</td>
<td>N</td>
<td>Customer participates in requirements generation</td>
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<td>Cross technology effects (if any) have begun to be identified</td>
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<td>Y</td>
<td>Design techniques have been identified/developed</td>
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<td>Y</td>
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<td>Scaling studies have been started</td>
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<td>Algorithms run on surrogate processor in a laboratory environment</td>
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<td>Know what software is presently available that does similar task</td>
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<td>T</td>
<td>Y</td>
<td>Existing software examined for possible reuse</td>
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<td>M</td>
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<td>Producibility needs for key breadboard components identified</td>
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<td>S</td>
<td>T</td>
<td>Y</td>
<td>Know limitations of presently available software (Analysis of current software completed)</td>
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<td>Y</td>
<td>Scientific feasibility fully demonstrated</td>
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<td>Y</td>
<td>Analysis of present state of the art shows that technology fills a need</td>
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<td>Y</td>
<td>Risk areas identified in general terms</td>
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<td>P</td>
<td>N</td>
<td>Risk mitigation strategies identified</td>
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<td>P</td>
<td>Y</td>
<td>Rudimentary best value analysis performed, not including cost factors</td>
</tr>
<tr>
<td>Category</td>
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<td>Criteria</td>
</tr>
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</tr>
<tr>
<td>B</td>
<td>T</td>
<td>Y</td>
<td>Cross technology issues (if any) have been fully identified</td>
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<td>H</td>
<td>M</td>
<td>Y</td>
<td>Ad hoc and available laboratory components are surrogates for system components</td>
</tr>
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<td>H</td>
<td>T</td>
<td>Y</td>
<td>Individual components tested in laboratory/by supplier (contractor’s component acceptance testing)</td>
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<tr>
<td>H</td>
<td>M</td>
<td>Y</td>
<td>Piece parts and components in a pre-production form exist</td>
</tr>
<tr>
<td>H</td>
<td>T</td>
<td>N</td>
<td>M&amp;S used to simulate some components and interfaces between components</td>
</tr>
<tr>
<td>S</td>
<td>T</td>
<td>N</td>
<td>Formal system architecture development begins</td>
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<td>Customer publishes requirements document</td>
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<td>Overall system requirements for end user’s application are known</td>
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<td>B</td>
<td>P</td>
<td>N</td>
<td>System performance metrics have been established</td>
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<td>S</td>
<td>T</td>
<td>N</td>
<td>Analysis provides detailed knowledge of specific functions software needs to perform</td>
</tr>
<tr>
<td>B</td>
<td>P</td>
<td>N</td>
<td>Laboratory requirements derived from system requirements are established</td>
</tr>
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<td>H</td>
<td>M</td>
<td>N</td>
<td>Available components assembled into system breadboard</td>
</tr>
<tr>
<td>H</td>
<td>T</td>
<td>Y</td>
<td>Laboratory experiments with available components show that they work together (lab kludge)</td>
</tr>
<tr>
<td>S</td>
<td>T</td>
<td>N</td>
<td>Requirements for each function established</td>
</tr>
<tr>
<td>S</td>
<td>T</td>
<td>Y</td>
<td>Algorithms converted to pseudocode</td>
</tr>
<tr>
<td>S</td>
<td>T</td>
<td>N</td>
<td>Analysis of data requirements and formats completed</td>
</tr>
<tr>
<td>S</td>
<td>T</td>
<td>Y</td>
<td>Stand-alone modules follow preliminary system architecture plan</td>
</tr>
<tr>
<td>H</td>
<td>T</td>
<td>Y</td>
<td>Hardware in the loop/computer in the loop tools to establish component compatibility</td>
</tr>
<tr>
<td>S</td>
<td>M</td>
<td>N</td>
<td>Designs verified through formal inspection process</td>
</tr>
<tr>
<td>B</td>
<td>P</td>
<td>N</td>
<td>S&amp;T exit criteria established</td>
</tr>
<tr>
<td>B</td>
<td>T</td>
<td>Y</td>
<td>Technology demonstrates basic functionality in simplified environment</td>
</tr>
<tr>
<td>S</td>
<td>P</td>
<td>N</td>
<td>Able to estimate software program size in lines of code and/or function points</td>
</tr>
<tr>
<td>H</td>
<td>M</td>
<td>N</td>
<td>Scalable technology prototypes have been produced</td>
</tr>
<tr>
<td>B</td>
<td>P</td>
<td>N</td>
<td>Draft conceptual designs have been documented</td>
</tr>
<tr>
<td>H</td>
<td>M</td>
<td>N</td>
<td>Design techniques identified/defined to where small applications may be analyzed/simulated</td>
</tr>
<tr>
<td>B</td>
<td>T</td>
<td>Y</td>
<td>Controlled laboratory environment</td>
</tr>
<tr>
<td>B</td>
<td>P</td>
<td>Y</td>
<td>Initial cost drivers identified</td>
</tr>
<tr>
<td>S</td>
<td>T</td>
<td>N</td>
<td>Experiments with full scale problems and representative data sets</td>
</tr>
<tr>
<td>Category</td>
<td>Component</td>
<td>Completed</td>
<td>Criteria</td>
</tr>
<tr>
<td>----------</td>
<td>-----------</td>
<td>-----------</td>
<td>----------</td>
</tr>
<tr>
<td>B</td>
<td>M</td>
<td>Y</td>
<td>Integration studies have been started</td>
</tr>
<tr>
<td>B</td>
<td>P</td>
<td>N</td>
<td>CAIV targets set</td>
</tr>
<tr>
<td>S</td>
<td>T</td>
<td>Y</td>
<td>Individual functions or modules demonstrated in a laboratory environment</td>
</tr>
<tr>
<td>H</td>
<td>M</td>
<td>Y</td>
<td>Key manufacturing processes identified</td>
</tr>
<tr>
<td>B</td>
<td>P</td>
<td>N</td>
<td>Scaling documents and diagrams of technology have been completed</td>
</tr>
<tr>
<td>S</td>
<td>T</td>
<td>Y</td>
<td>Some ad hoc integration of functions or modules demonstrates that they will work together</td>
</tr>
<tr>
<td>H</td>
<td>M</td>
<td>N</td>
<td>Key manufacturing processes assessed in laboratory</td>
</tr>
<tr>
<td>B</td>
<td>P</td>
<td>N</td>
<td>Draft Systems Engineering Master Plan (SEMP)</td>
</tr>
<tr>
<td>B</td>
<td>T</td>
<td>Y</td>
<td>Low fidelity technology “system” integration and engineering completed in a lab environment</td>
</tr>
<tr>
<td>H</td>
<td>M</td>
<td>N</td>
<td>Mitigation strategies identified to address manufacturability/produciability shortfalls</td>
</tr>
<tr>
<td>B</td>
<td>P</td>
<td>N</td>
<td>Customer commits to transition through ATD commissioning and/or MOU</td>
</tr>
<tr>
<td>B</td>
<td>T</td>
<td>N</td>
<td>Functional work breakdown structure developed</td>
</tr>
<tr>
<td>B</td>
<td>P</td>
<td>N</td>
<td>Integrated Product Team (IPT) formally established with charter</td>
</tr>
<tr>
<td>B</td>
<td>P</td>
<td>N</td>
<td>Customer representative is member of IPT</td>
</tr>
<tr>
<td>B</td>
<td>P</td>
<td>N</td>
<td>Formal risk management program initiated</td>
</tr>
<tr>
<td>B</td>
<td>P</td>
<td>N</td>
<td>Preliminary Failure Mode and Effects Analysis (FMEA) or Risk Waterfall analysis performed</td>
</tr>
<tr>
<td>B</td>
<td>P</td>
<td>N</td>
<td>Technology availability dates established</td>
</tr>
</tbody>
</table>
### Table B.5. Assessment criteria for TRL 5.

<table>
<thead>
<tr>
<th>Category</th>
<th>Component</th>
<th>Completed</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>T</td>
<td>Y</td>
<td>Cross technology effects (if any) identified and established through analysis</td>
</tr>
<tr>
<td>H</td>
<td>M</td>
<td>N</td>
<td>Pre-production hardware available</td>
</tr>
<tr>
<td>B</td>
<td>T</td>
<td>Y</td>
<td>System interface requirements known</td>
</tr>
<tr>
<td>B</td>
<td>P</td>
<td>N</td>
<td>System requirements flow down through work breakdown structure (systems engineering begins)</td>
</tr>
<tr>
<td>S</td>
<td>T</td>
<td>Y</td>
<td>System software architecture established</td>
</tr>
<tr>
<td>H</td>
<td>M</td>
<td>N</td>
<td>Targets for improved yield established</td>
</tr>
<tr>
<td>S</td>
<td>T</td>
<td>N</td>
<td>External interfaces described as to source, format, structure, content, and method of support</td>
</tr>
<tr>
<td>S</td>
<td>T</td>
<td>N</td>
<td>Analysis of internal interface requirements completed</td>
</tr>
<tr>
<td>H</td>
<td>M</td>
<td>N</td>
<td>Trade studies and lab experiments define key manufacturing processes</td>
</tr>
<tr>
<td>B</td>
<td>T</td>
<td>N</td>
<td>Interfaces between components/subsystems are realistic (Breadboard with realistic interfaces)</td>
</tr>
<tr>
<td>H</td>
<td>M</td>
<td>N</td>
<td>Significant engineering and design changes</td>
</tr>
<tr>
<td>S</td>
<td>T</td>
<td>Y</td>
<td>Coding of individual functions/modules completed</td>
</tr>
<tr>
<td>H</td>
<td>M</td>
<td>Y</td>
<td>Prototypes have been created</td>
</tr>
<tr>
<td>H</td>
<td>M</td>
<td>Y</td>
<td>Tooling and machines demonstrated in lab</td>
</tr>
<tr>
<td>B</td>
<td>T</td>
<td>N</td>
<td>High fidelity lab integration of system completed, ready for test in realistic/simulated environments</td>
</tr>
<tr>
<td>H</td>
<td>M</td>
<td>Y</td>
<td>Design techniques have been defined to the point where largest problems defined</td>
</tr>
<tr>
<td>H</td>
<td>P</td>
<td>N</td>
<td>Form, fit, and function for application addressed in conjunction with end user development staff</td>
</tr>
<tr>
<td>H</td>
<td>T</td>
<td>N</td>
<td>Fidelity of system mock-up improves from breadboard to brassboard</td>
</tr>
<tr>
<td>B</td>
<td>M</td>
<td>N</td>
<td>Quality and reliability considered, but target levels not yet established</td>
</tr>
<tr>
<td>H</td>
<td>M</td>
<td>N</td>
<td>Some special purpose components combined with available laboratory components</td>
</tr>
<tr>
<td>H</td>
<td>P</td>
<td>N</td>
<td>Three view drawings and wiring diagrams have been submitted</td>
</tr>
<tr>
<td>B</td>
<td>T</td>
<td>N</td>
<td>Laboratory environment modified to approximate operational environment</td>
</tr>
<tr>
<td>H</td>
<td>M</td>
<td>N</td>
<td>Initial assessment of assembly needs performed</td>
</tr>
<tr>
<td>H</td>
<td>P</td>
<td>N</td>
<td>Detailed design drawings have been completed</td>
</tr>
<tr>
<td>H</td>
<td>M</td>
<td>N</td>
<td>Sigma levels needed to satisfy CAIV targets defined</td>
</tr>
<tr>
<td>B</td>
<td>P</td>
<td>N</td>
<td>Draft SEMP addresses integration</td>
</tr>
<tr>
<td>B</td>
<td>P</td>
<td>N</td>
<td>Draft SEMP addresses test and evaluation</td>
</tr>
<tr>
<td>B</td>
<td>P</td>
<td>N</td>
<td>Draft SEMP addresses mechanical and electrical interfaces</td>
</tr>
<tr>
<td>H</td>
<td>M</td>
<td>N</td>
<td>Production processes have been reviewed with Manufacturing and Productibility office(s)</td>
</tr>
<tr>
<td>Category</td>
<td>Component</td>
<td>Completed</td>
<td>Criteria</td>
</tr>
<tr>
<td>----------</td>
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<td>-----------</td>
<td>----------</td>
</tr>
<tr>
<td>B</td>
<td>P</td>
<td>N</td>
<td>Draft SEMP addresses performance; translate measured to expected final performance</td>
</tr>
<tr>
<td>B</td>
<td>P</td>
<td>N</td>
<td>Risk management plan documented</td>
</tr>
<tr>
<td>S</td>
<td>T</td>
<td>Y</td>
<td>Functions integrated into modules</td>
</tr>
<tr>
<td>B</td>
<td>P</td>
<td>N</td>
<td>Configuration management plan in place</td>
</tr>
<tr>
<td>S</td>
<td>T</td>
<td>Y</td>
<td>Individual functions tested to verify that they work</td>
</tr>
<tr>
<td>S</td>
<td>T</td>
<td>Y</td>
<td>Individual modules and functions tested for bugs</td>
</tr>
<tr>
<td>S</td>
<td>T</td>
<td>Y</td>
<td>Integration of modules/functions demonstrated in a laboratory environment</td>
</tr>
<tr>
<td>S</td>
<td>P</td>
<td>N</td>
<td>Formal inspection of all modules/components completed as part of configuration management</td>
</tr>
<tr>
<td>B</td>
<td>P</td>
<td>N</td>
<td>Configuration management plan documented</td>
</tr>
<tr>
<td>B</td>
<td>P</td>
<td>N</td>
<td>Draft Test &amp; Evaluation Master Plan (TEMP)</td>
</tr>
<tr>
<td>S</td>
<td>T</td>
<td>N</td>
<td>Algorithms run on processor with characteristics representative of target environment</td>
</tr>
<tr>
<td>H</td>
<td>P</td>
<td>N</td>
<td>Preliminary hardware technology “system” engineering report (Draft SEMP) completed</td>
</tr>
<tr>
<td>B</td>
<td>P</td>
<td>N</td>
<td>Customer commits to transition via POM process</td>
</tr>
<tr>
<td>B</td>
<td>P</td>
<td>N</td>
<td>Draft Transition Plan with Business Case</td>
</tr>
<tr>
<td>H</td>
<td>P</td>
<td>N</td>
<td>Failure Mode and Effects Analysis (FMEA) performed</td>
</tr>
<tr>
<td>B</td>
<td>P</td>
<td>N</td>
<td>Value analysis includes analysis of multiple technology and non-material alternatives</td>
</tr>
<tr>
<td>B</td>
<td>T</td>
<td>N</td>
<td>IPT develops requirements matrix with thresholds and objectives</td>
</tr>
<tr>
<td>B</td>
<td>T</td>
<td>N</td>
<td>Physical work breakdown structure available</td>
</tr>
<tr>
<td>B</td>
<td>P</td>
<td>N</td>
<td>Value analysis includes life-cycle cost analysis</td>
</tr>
</tbody>
</table>

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Appendix C - Further Application to Composite Manufacture

This thesis has covered the improved thermal control and an arm-based implementation of FFF in relation to the manufacture of sandwich core components. However, the developed knowledge could have applications across a multitude of composite manufacturing processes; two examples of complex panel manufacture and drape are discussed below.

C.1 Automated Fibre Placement

Automated Fibre Placement (AFP) is an automated additive composite manufacturing process used to make large components with relatively low curvatures, depositing thin strips (tows) of prepreg from a robotic head onto a mould [24, Chapter 17]. It has been noted modern AFP machines have been developed by industrial robotic companies with limited exposure to the composites industry, a disparity which causes difficulties with optimising component design [26, 203]. The toolpath planning methods have been derived from the manual layup process leading to unnecessary constraints, and the control problems are similar to those tackled within Chapter 6. Through the application of the developed AM planning techniques to AFP applications, the barrier to entry of composite manufacture could be reduced [62].

As discussed in Section 2.3.1, fibre reinforcements have been shown to significantly improve the mechanical properties of AM components, and have been compared to AFP by Frketic et al. [62]. This study identified material extrusion processes were only able to achieve 20-75% of the tensile strength of typical chopped glass or carbon fibre composite components; this would be expected to be lower if tested out of the fibre direction due to the weaker inter-layer bonding of FFF. It should also be noted existing AFP parts require consolidation and curing under pressure;
such post-processing techniques have the potential to reduce the weakness of inter-layer bonding with AM.

Brenken et al. [60] reviewed the literature regarding fibre reinforced parts, noting the FFF process is still empirically calibrated, and three major research areas exist for modelling part properties; the interaction between material flow and fibre orientation, bond formation between layers, and the solidification and subsequent internal stress formation.

The formability difficulties of continuous fibre FFF components was documented by Blok et al. [61], similar to, but less extreme than, the issues posed by AFP [26, 203]; continuous fibres provide significant performance enhancements over more conventional short fibre reinforcement [61]. The issues arose due to the higher stiffness of the fibres than the encompassing matrix, causing wrinkling of AFP tows, or lack of fibre wetting in FFF, around tight radii; FFF was capable of achieving significantly higher curvatures then AFP.

A potential solution from AM path planning research was presented by Jin et al. [93] during their examination on reducing under/overfill within interior sections; a numerical optimisation process maximised the corner radii of infill sections. An alternative solution would be the use of highly aligned short fibres, above the critical length of 0.5 mm, which balances the processability of the shorter, randomly aligned fibres with the performance of the continuous fibres [61, 204].

A final application of this research to panels manufactured with AFP is the improved thermal control strategies presented in Chapter 4. A disadvantage of the traditional thermoplastic materials for FFF is the low glass transition temperature; a proposed solution is to develop solutions employing thermoset materials [62]. Such control methods could be applied to both AM manufacture, as thermoset resins are more sensitive to heat, and to AFP, where material tack must be accurately controlled [26, 203].

C.2 Drape

Drape is the action taken to deform a prepreg sheet over a surface and is typically a manual process due to the complexity, as discussed within Section 2.2.1. Elkington et al. [38] described the different motions used to manipulate the fabric for better placement, and implemented a robotic system to drape a pre-deformed prepreg sheet to a complex surface [205]. It was noted the layup of a tool can be achieved through a variety of drape patterns, a cause of inter-component variability when manufactured by different operators [34].

An application of the developed robotic control system is for the layup of the pre-deformed prepreg using the silicon rollers developed by Elkington et al. [205]. Toolpath generation could be informed by software modelling of the fabric response with tools, such as Virtual Fabric Placement (VFP), developed by the University of Bristol [206, 207]. When combined with the AM end effector, this system would be capable of manufacturing a complete sandwich panel through the subsequent in-situ deposition of an AM core, before drape of the top skin.