# An investigation of cost-effective rapid tooling for fibre reinforced polymer parts using low-cost 3D printing

Darragh Mulkerrins

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# An Investigation of Cost-Effective Rapid Tooling for Fibre Reinforced Polymer Parts Using Low-Cost 3D Printing

Darragh Mulkerrins

School of Engineering

Faculty of Science & Engineering

University of Limerick

*Supervisor*

Dr Con Sheahan

*Submitted to the University of Limerick for the degree of*

*Master of Engineering (M. Eng.)*

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# Declaration

The substance of this thesis is the original work of the author and due reference, and acknowledgement has been made, where necessary, to the work of others. No part of this thesis has already been submitted for any degree and is not being concurrently submitted in candidate for any degree.

| Candidate: | Supervisor: |
|---|---|
| Mr Darragh Mulkerrins | Dr Con Sheahan |
| Date: | Date: |

# Abstract

This project investigates the use of low-cost additive manufacturing (AM) with a focus on the fused filament fabrication (FFF) technology to fabricate rapid tooling (RT) required to produce complex shaped fibre reinforced polymer (FRP) parts using liquid composite moulding (LCM) manufacturing techniques.

Advanced FRPs such as carbon fibre reinforced polymers (CFRP) offer very good strength to weight ratios, making them a superior material choice for many engineering challenges. Drawbacks to using these materials can be the low rate of production and the need for expensive tooling. The literature review shows that AM can be used to reduce tooling costs, however the use of AM is not commonplace in the composite industry yet, due to the financial barriers and use case uncertainty in adopting such a technology. Much of the literature surrounding the use of AM as a FRP manufacturing solution makes use of expensive AM machines. This work presents evidence that this does not need to be the case, and that less expensive AM machines can be used to allow composite manufacturers to get some of the advantages of AM for tooling without the risky investment in machinery.

This research documents the fabrication of mould tooling in three case studies that provide design guidelines and process chain. Each case study aims to provide an example of how FFF can be used to produce various forms of tooling in LCM applications. A directly printed tooling approach is adopted in the first case study for bespoke manufacturing, short series production or prototyping of composites. The second case study provides a method of fabricating a tooling plug from which a traditional composite mould is manufactured. A sacrificial tool is produced in case study three, this kind of tooling overcomes unique manufacturing challenges that are presented when producing complex shaped hollow composites.

The case studies provide design guidelines and practical tips from which conclusions are extracted. This work provides evidence that the FFF technology is a viable and cost-effective RT solution for LCM applications.

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# List of Abbreviations

| | |
|---|---|
| ABS | Acrylonitrile butadiene styrene |
| AM | Additive manufacturing |
| BAAM | Big area additive manufacturing |
| BJ | Binder jetting |
| CA | Cyanoacrylate |
| CAD | Computer aided design |
| CAM | Computer aided manufacturing |
| CFRP | Carbon fibre reinforced polymer |
| CNC | Computer numerical control |
| DfA | Design for assembly |
| DfAM | Design for additive manufacture |
| DfM | Design for manufacture |
| DMLS | Direct metal laser sintering |
| EBM | Electron beam melting |
| FDM | Fused deposition modelling |
| FFF | Fused filament fabrication |
| FRC | Fibre reinforced composite |
| FRP | Fibre reinforced polymer |
| IC | Investment casting |
| IPA | Isopropyl alcohol |
| LCM | Liquid composite moulding |
| MC | Mass customisation |
| ME | Material extrusion |

| | |
|---|---|
| MJ | Material jetting |
| NPD | New product development |
| PBF | Powder bed fusion |
| PETG | Polyethylene terephthalate glycol |
| PLA | Polylactic acid |
| PMC | Polymer-matrix composite |
| PVA | Polyvinyl alcohol |
| RIFT | Resin infusion under flexible tooling |
| RP | Rapid prototyping |
| RT | Rapid tooling |
| RTM | Resin transfer moulding |
| SCRIMP | Seeman’s composite resin infusion process |
| SLA | Stereolithography |
| SLM | Selective laser melting |
| SLS | Selective laser sintering |
| STL | Standard tessellation language |
| Tg | Glass transition temperature |
| TPU | Thermoplastic polyurethane |
| UM2+ | Ultimaker 2+ |
| UV | Ultraviolet |
| VARTM | Vacuum assisted resin transfer moulding |
| VOC | Volatile organic compound |

# Chapter 1: Introduction

The use of fibre reinforced polymer (FRP) composites in designs is ever growing for these materials and can offer better performance at reduced weight when compared to conventional metallic parts. FRPs are used in a wide range of applications from infrastructure, transportation, industrial to sporting goods. Rapid prototyping (RP) of cost-efficient composite parts are essential competitive business practices for success. Highly representative prototypes and moulds are required to reduce the design cycle and production times (Sudbury *et al.* 2017). Additive manufacturing (AM) has shown promise in the composite industry, being used for patterns and moulds (Stratasys 2017a), however, there are challenges associated with the adoption of AM, including the risk involved with adopting a technology where the gains may not be fully understood, and a lack of in-house expertise, as well as large investment required in machines and feedstock.

The focus of this work is to investigate how a low-cost 3d-printing technology such as fused filament fabrication (FFF) can assist in the design and manufacture of complex shaped FRP components through rapid tooling (RT). Example moulds are fabricated and presented in the form of case studies to investigate part quality, in terms of moulding challenges such as demoulding difficulty and surface defects.

For successful part fabrication, there are criteria that the mould tooling must adhere to, as this will affect the composite manufacturing process and types of parts produced. These criteria include tooling material and surface finish; machine fixed costs; tooling build time and running costs. These factors are worth considering when deciding if this methodology is suitable for a given use-case. In the manufacture of composites, it is essential that the tooling surface is completely sealed to prevent the resin matrix material from creating a mechanical lock between the FRP part and the mould tool. This sealed surface also determines the part surface finish. As AM builds parts in layers the tooling surface is inherently rough, and a coating must be applied to the tooling to seal and provide a smooth moulding surface to produce parts from. A mould sealing solution demonstrates that by adding a very thin layer on top of the tooling surface it that can be polished to provide a class 'A' surface finish, without the need for additional machinery such as computer numerical control (CNC) machines. The FFF technology makes use of thermoplastics, and for ease of printing, thermoplastics with relatively low glass transition (Tg) temperatures. As these polymer moulds have low softening temperatures, they are limited to composite manufacturing processes where the material is cured at low temperatures, therefore this RT methodology is best suited to FRP materials utilising room-temperature curing thermosetting resins. As the tooling is made from a soft material with a relatively low Tg, the methodology is not suitable for autoclave curing, as such equipment does not just create an extreme environment but also is very expensive to acquire and run. The size of the tooling should not be very large as the advantages of machining times may not be as noticeable, also, the amount of manual post processing may greatly increase. The tooling investigated in this research is limited to tooling that can be split into sub-components and be fabricated in a single print cycle.

From the findings obtained through these case studies, RT design guidelines for FRP processing are proposed for the chosen cost-effective AM technology. The case studies provide an insight into how a low-cost AM technology could be adopted in a composite manufacturing environment, while reducing the financial investment in terms of hardware costs, machining time and post processing. The methodologies presented in this work are aimed to provide a composite manufacturing solution for bespoke, short series and medium sized batch production in liquid composite moulding (LCM) applications.

In Chapter 1, the background to the study is outlined, prior to a more intensive investigation of the literature provided in Chapter 2. The information gathered from the literature review later influenced many of the decisions in the development of a low-cost RT solution suitable for use with cost effective composite processing techniques outlined in Chapter 3. The case studies outlined provide an in-depth description on fabricating the tooling as well as the preparation and post-processing steps of the composite parts produced to allow this RT technique to be easily replicated and implemented into current composite manufacturing workflows. Results referring to mould quality and mould fabrication are discussed afterwards. The results gathered were used in estimating the cost of these tools before the final conclusions and further recommendations of the low-cost tooling methods are presented.

Manufacturing methods in both additive and composite processing are rapidly advancing. The RT solutions presented in this work will be a valuable source of information for startups or composite manufacturers looking to make more effective product iterations with reduced lead-time and financial risk.

## 1.1 Background – Problem Statement

There are major drives in the manufacturing industry to compete effectively through the reduction of manufacturing times and cost while producing high quality products and services, a pressure resulting from international competition and market (Ma *et al.* 2007; Equbal *et al.* 2015). Efforts to reduce manufacturing lead times and cost create a greater need for new manufacturing processes that are flexible and aid in cost reduction to deal with small batch production of products (Ma *et al.* 2007).

Initially costs were one of the greatest barriers to AM, where machine costs ranged between 50%-75% of total production costs (Hopkinson *et al.* 2006). However, in recent years with the expiration of patents for the fused deposition modelling (FDM) AM process, there have been great developments in low-cost 3D printers, making this technology more accessible to individuals for both domestic and commercial use through material extrusion (ME) processes, the low-cost ME process are commonly referred to as FFF (Santana *et al.* 2017). FFF is an extrusion based AM process and has become the most common of the AM technologies, a result of the relatively low entry cost and ease of use (Tofail *et al.* 2018). However, FFF parts are typically used for producing visual aids, educational models, and form and fit models (Popescu *et al.* 2018).

Prototyping is an essential aspect of successful new product development (NPD) and innovation. However, the sunk cost associated with building prototypes presents a significant risk to startups constrained by time, money, and skill. Decision making is often affected by risk, resulting in some entrepreneurs to pass-up on risky decisions and opportunities (Nelson *et al.* 2019).  Up to 90% of startups fail, however there are factors that can help in succeeding, capital being one of these factors (Krishna *et al.* 2016). For startups and SME's, studies show prototyping best practices have a positive influence on the performance of the business. Having advanced prototypes has shown to secure more venture capital funding for startups than those that do not (Audretsch *et al.* 2012).

For many years now RP has proven to be effective in concept design verification (Ma *et al.* 2007; Kumbhar and Mulay 2018). However, some startups refer to limitations to 3D printing and available manufacturing methods as major difficulties in creating working prototypes (Nelson *et al.* 2019).

In recent years, FRP materials are becoming the material of choice for many engineering applications as parts can be stronger, lighter, and less-expensive than traditional materials (Nagavally 2017). In the FRPs industry, tooling used for short run production is often produced from soft materials such as tooling board, a high-density foam. The soft materials used are machined using CNC milling to produce complex geometries for either direct-to-mould tooling for temporary and limited-production tooling or as a tooling plug from which a production composite mould can be fabricated (Stewart 2010; Gebauer *et al.* 2017). In other cases, moulds are handmade by a composite technician, a process that can take weeks which increases the manufacturing costs of parts (Sudbury *et al.* 2017).

In attempt to overcome some of the expensive and time-consuming tooling challenges, AM can be used as a tooling solution suitable for low-volume product runs or for easily adaptable design iterations (Boparai *et al.* 2016). The use of AM in tooling fabrication is referred to as RT and it is expected that tools produced this way will have much shorter lead times, cost significantly less, have a considerably shorter tool life and have coarser tolerances than conventional tooling (Afonso *et al.* 2019). Stratasys, a manufacturer of expensive industrial FDM machines have released case studies of their technology being used for RT of high temperature lay-up tooling for FRPs (Stratasys 2017c), however, this AM technology is not accessible without significant financial investment in hardware, upwards of €100,000 (Tagliaferri *et al.* 2019).

The literature shows that low-cost FFF style 3D printing has become very accessible, if it is used as a RT solution it has potential to overcome some of the barriers associated with producing low-cost tooling for FRPs. The FFF technology was chosen for RT in this study in attempt to combine the benefits of both the composite material and the ability to produce complex geometries provided by AM, overcoming both composite tooling constraints and the 3D printing material limitations. Low-cost RT can allow for fast iterations and prototypes, without the large financial risk associated with prototyping due to equipment and tooling that may deter composite manufacturers and especially startups or financially constrained firms.

## 1.2 Research Objectives

The purpose of this research is to investigate the use of low-cost AM as an alternative processing technology in the fabrication of mould tooling used in LCM applications. An advantage of this AM approach is that the FFF machines used, are more accessible to a larger cohort of people due to their relatively low capital and running costs. The main applications for this RT methodology are in composites prototyping, customised composite parts, or for short production runs. The research objectives of this thesis are as follows:

1. To identify a rapid tooling solution for composite manufacturing organisations with additive manufacturing capabilities.
2. To develop a tooling solution for short batch production that is effective in terms of time and money.
3. To determine which composite processing techniques are most suitable with the FFF rapid tooling technology.
4. Determine the product categories that are suitable while using low-cost rapid tooling in terms of materials, processing conditions and surface finish.

# Chapter 2: Literature Review

## 2.1 Mass Customisation and New Product Development

The concept of mass customisation (MC) is to be able to produce products that best fit customer needs, while maintaining near mass production efficiency. Traditional mass production holds an advantage in high-volume production, the high volumes of products produced can offset the large, fixed costs associated with tooling, equipment, engineering and training. However, it can be difficult to cater to all customer needs with mass production, but low production-volumes cannot be justified using traditional manufacturing techniques because of the investment required to produce products (Jiao *et al.* 2003). Customers appear to have greater expectations than in the past, wanting products of the highest quality, high levels of customisation and with short lead times, however, are unwilling to adequately pay for these added features (Kumar 2007). MC points towards a change of the design and production model, from "made-to-stock" to "make-to-order". Adoption of new production processes to accommodate high product variation and low volume production, challenges conventional product development and supply chain management. To support the production model to be suitable for MC, the enterprise should reconsider their value chain to leverage on, lead time, product variety and economy of scale (Tseng and Hu 2014). Advanced manufacturing technologies have been identified as important facilitators to MC. Computer aided design (CAD) is heavily cited as a fundamental design tool for MC implementation, however research on other AMTs is less common in the MC literature. Much of the literature surrounding AMTs comes from the clothing, garment and shoes industry that focus on the integration of 3D scanning and CAD systems for virtual designs and fit testing (Fogliatto *et al.* 2012).

Product Configurators are identified through MC research to provide two main benefits to customers who experience customising products using them. These benefits of the MC experience are referred to as creative-achievement benefit and hedonic benefit. The creative-achievement benefit from the MC process gives the consumer a pride of authorship. In general, pride is a positive emotion and one an individual creates or has a sense of being the creator of an artefact or product. The hedonic benefit differs, as it refers to the enjoyment a customer experiences going through the MC process. This process of self-customising products with configurators in particular, can be rewarding because it can be entertaining like playing a game, or because of the visual feedback of configuration choices made by the potential consumer. The desire to have a positive experience is found to be an indication of a potential consumers willingness to engage in MC experiences (Trentin *et al.* 2014).

Some of the main roadblocks to MC is quality control, monitoring and reliability of MC products. Quality control practices are implemented for measuring the performance of processes and products. As MC systems will not have large batches to compare, traditional quality control systems will not easily be applied to these products. This only becomes more complex as a new set of quality characteristics must be defined with each customised product. Some of the most relevant quality characteristics may remain, but only for the basic operational functions of products. The probability that a component or system will perform as expected, for a specified duration under specified environmental conditions is its reliability. Empirical data is collected to measure a parts reliability and lifetime. Data is gathered from functional field-testing as well as laboratory testing where under normal environmental conditions parts are subjected to testing to accelerate failure. These kinds of testing methods are time consuming and often mandatory if the product or system must comply with international reliability standards. Reliability testing of MC products is very difficult as accelerated testing can be very costly and time consuming, adding more cost to the end product. This has affected the level of customisation offered to customers of MC products. For this reason, most manufactured MC products are configurations of pre-defined choices from a finite list of possibilities (Da Silveira *et al.* 2001).

NPD is a key success factor, as organisations are continuously re-engineering and developing new products to stay competitive (Bagalkot *et al.* 2019). One of the most difficult parts of NPD is the transition from the R&D stage to the prototyping stages and then onto the manufacturing stage, and it is common to see organisations of all sizes to have issues here (Brethauer 2002). From an engineering perspective, the NPD cycle can be looked at as a four-phase process as shown in Figure 2.1.

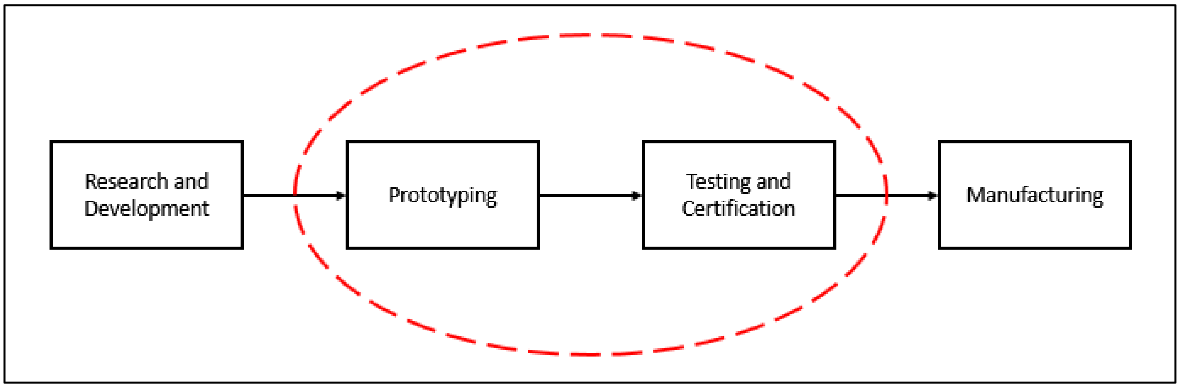


*Figure 2.1 Stages of NPD process from an engineering perspective, image redrawn from (Bagalkot et al. 2019)*

The centre portion of the NPD process highlighted in Figure 2.1 is generally the most challenging for organisations, a result of cost and time constraints, this is especially challenging for innovative start-ups and small companies (Otto 2003; Krishna *et al.* 2016). As these areas prove problematic it is important to be able to predict failures as early as possible in the NPD process. Studies of NPD have shown that late-stage issues can be over 100 times as costly as early stage ones (Barry 1981; Terwiesch *et al.* 2002). These costs can be several orders of magnitude higher in environments where large capital investments in production equipment is required. Thus, better testing strategies can be very beneficial in finding potential failures as early as possible in the NPD cycle. Often, testing is overlooked in many industries, where testing is done too little and too late, this is as it is often viewed as a verification step later in development rather than an opportunity to learn in earlier development (Loch and Kavadias 2008). To help increase the chances of new product success iterative development strategies are used by producing successive deliberate iterative steps. Products designed in this way are then presented to the customer for feedback, each iteration of the design consists of four key stages: build; test; feedback; revise. The build phase consists of either virtual or physical products being shown to the customer, where each iteration becomes closer to the end product. This allows the customer to test the product and provide feedback on that version of the design regarding what they like or do not like and the value they see in various product features. This valuable information is gathered and used to iterate the design and repeat the process. (Cooper 2014).

Product testing is a task that is used to resolve uncertainty in NPD, however there are different forms of uncertainty (technical, production, need and market). The use of solutions (e.g., materials) that have not been used before or are being used in a new way result in technical uncertainty. This kind of uncertainty is often connected to product functionality, thorough prototype testing can be a way to mitigate this kind of uncertainty. Upon overcoming technical uncertainties, the technical solution must work in the production environment it is meant for which results in production uncertainty. This exists when it is unknown if a technical solution that works well in prototypes can be produced cost-effectively, some manufacturing techniques work well in small quantities and are not suitable for mass production, and vice versa. The manufacturing process itself may need to be reconsidered to solve this problem. Rapidly changing customer requirements creates a need uncertainty, this exists as customers have difficulty specifying their needs because they face uncertainty themselves or are unable express their needs for products that do not yet exist. The fourth form of uncertainty is market uncertainty, arising about novel innovations, this kind of uncertainty can make firms reluctant to allocate sufficient resources to product development in these markets, as testing these markets is (Loch and Kavadias 2008).

These various forms of uncertainty pose many challenges for firms. The approach outlined by Cooper, 2014 to product development drives experimentation and encourages NPD teams to fail often, fast, and cheaply. Iterative design reduces market uncertainties but can also be used to solve technical uncertainties as technical solutions can be uncovered through this experimental, iterative method (Cooper 2014). These findings suggest that a cost-effective short run production and prototyping technique for NPD may improve a firms success rate.

This research investigates the use of cost-effective RT for FRCs, through the combination of AM with traditional composite manufacturing processes, to overcome some of the barriers to entry for NPD. As each aspect of this combination has many varieties, the options must first be explored to direct the research to a suitable method of fabricating cost-effective products and prototypes.

## 2.2 Additive Manufacturing Technologies

AM is a term that refers to a group of manufacturing processes that generate the physical part from digital data using an additive approach and a wide range of materials (Huang *et al.* 2015). The additive approach is inherently different to more traditional manufacturing processes, such as milling and turning where material removal is the method used to achieve part geometry, these methods are also referred to as subtractive manufacturing (Bhushan and Caspers 2017).

The term AM is often used interchangeably with terms such as 3D printing or RP. However, with recent advancements in the quality and output of this technology, these terms are now inadequate and do not effectively describe more recent applications of additive technologies. As per the ISO/ASTM 52900 standard that refers to AM principles and terminology, AM is now the term used to embody all processes that produce physical parts in an additive fashion. With AM there is often confusion around the terminology used. The definition for AM is;

> *"a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies".*

AM is a term used to cover a whole host of technologies that adopt this layer upon layer approach. AM technologies are constantly gaining popularity, as process developments and patent expiration have made AM more accessible to industry and educational facilities (Ngo *et al.* 2018).

These AM processes offer a clear technical advantage when it comes to producing highly complex shapes and customisation, factors that are impractical and sometimes impossible using traditional manufacturing techniques (Peng *et al.* 2018).

CAD software has developed rapidly as the requirement for designing complex geometry products has been heavily influenced by the aeronautic and automobile industries. These CAD systems give designers the potential to create products with very complex or organic geometries, which introduce machining problems when time and cost reductions are to be met. Computer aided manufacturing (CAM) systems are used to machine these kinds of geometries, however very skilled professionals are required, the success of milling processes depends strongly on the appropriate manipulation of the software (A.M. Ramos *et al.* 2003).

Traditional subtractive processes require a cautious and thorough analysis of the part geometry to determine toolpaths and the order in which different features can be fabricated, what tools and processes must be used and what supplementary fixtures may be needed to complete the part. In contrast, AM only needs some basic dimensional details and a modest understanding as to how the chosen AM technology works and the materials being used (Gibson 2010).

The AM process begins with a digital workflow to generate a set of instructions that allow the machine to commence a physical workflow where the AM machine transforms raw materials into physical 3D objects. The digital aspect can be broken into two stages, the first stage where a virtual 3D model of the initial product or part idea (which may be a set of 2D images or a physical 3D object such as a prototype or part) using CAD software is produced (Brown and Beer 2013; Thompson *et al.* 2016).

As AM builds physical parts in a layer-by-layer fashion, the digital CAD files must be sliced into these layers before the machine can process the file, this is done using a slicing software. Slicing is generally done uniformly throughout the object; thicker layers build objects faster but at a reduced resolution to those using finer layer heights (Ashley 1991; Rajaguru *et al.* 2020).

CAD files are converted into a readable file by the slicing software, the STL (standard tessellation language) file format is the most common for transferring 3D model data which is readable by most slicing software (Savio *et al.* 2019). For low-cost extrusion style printers Cura is one of the most used slicing software (Rajaguru *et al.* 2020), Slic3r and Blender are examples of other software packages used (Popescu *et al.* 2018; Rajaguru *et al.* 2020). With some AM machines and technologies proprietary slicing software is often used (Minetola *et al.* 2020)

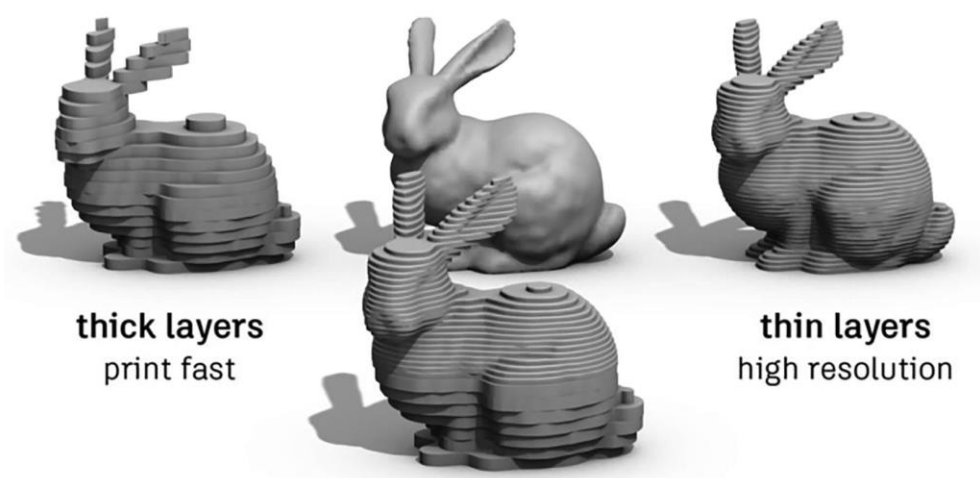


*Figure 2.2 Object slicing at various thicknesses, showing the effect it has on resolution and print duration (Rajaguru et al. 2020)*

It is here, in the slicing software where the process parameters are set, these parameters can be classified as slicing parameters, building orientation, and temperature conditions. Interactions between layer thickness (Figure 2.2), build orientation and infill percentages have a great effect on the mechanical properties of objects produced (Popescu *et al.* 2018).

The slicing software processes the STL file generating contour data (Rajaguru *et al.* 2020), from which the slicing software generates g-code, a set of commands used to run the 3D printer. This process is an essential aspect of the AM process and the STL file format is well researched as a suitable file format for both professional and non-professional AM use cases (Brown and Beer 2013).

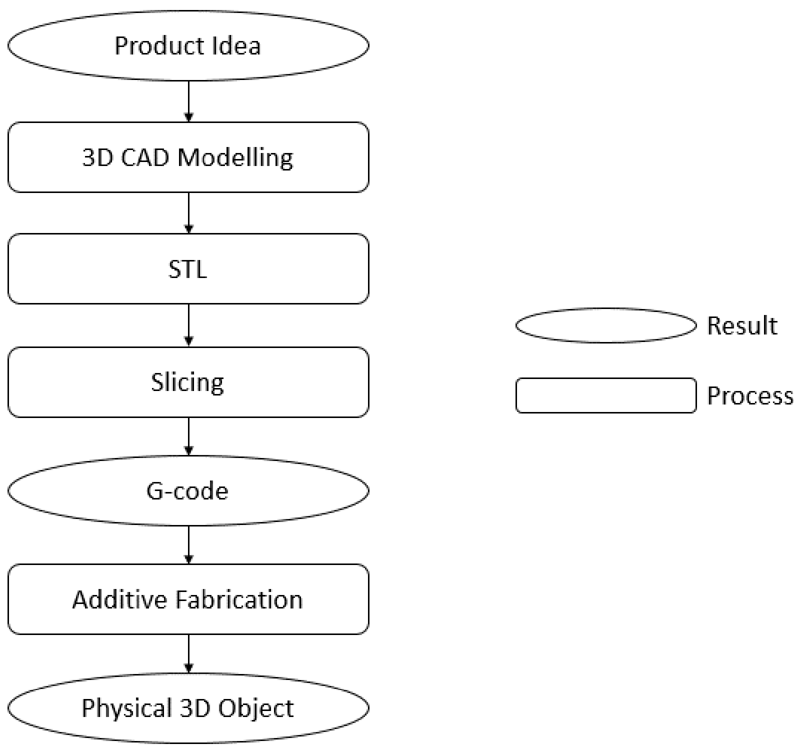


*Figure 2.3 Basic digital and physical AM workflow from idea creation to final physical component. Redrawn from (Thompson et al. 2016)*

The physical workflow follows as the sliced STL file is exported to the AM machine in the form of g-code (Figure 2.3), each AM technology has different operating principals, production characteristics, and material compatibilities. The cost, quality, size, and scale are characteristics that are determined by these traits. Process-specific characteristics must be considered throughout the design process and become even more important when producing functional parts (Thompson *et al.* 2016). The most common classifications of AM manufacturing systems include; extrusions, liquid and powder-based systems, each AM class has various technologies within it (Rajaguru *et al.* 2020).

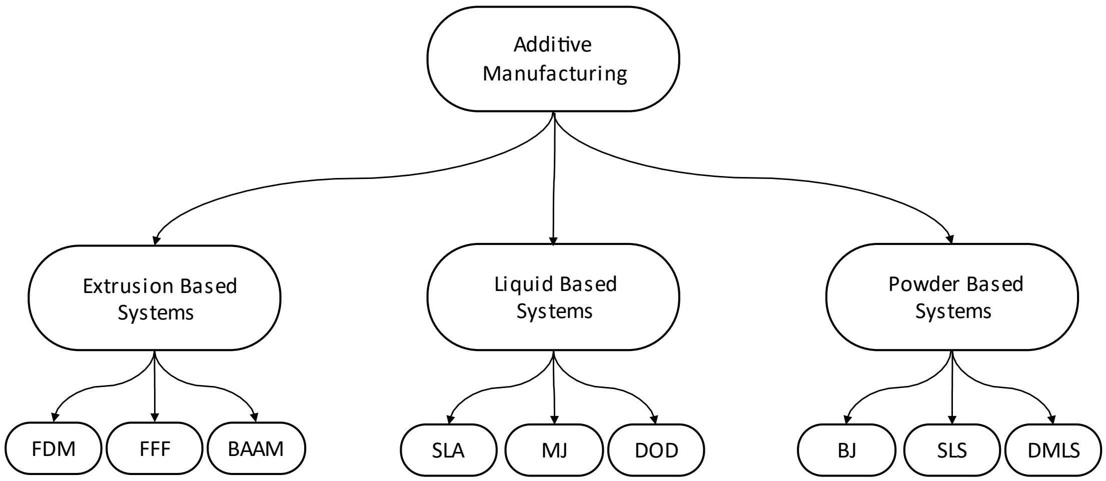


*Figure 2.4 AM process classifications, and their sub-processes. Redrawn from (Rajaguru et al. 2020).*

These various AM methods (Figure 2.4) will now be briefly described, as throughout the literature and the AM industry these process categories were not always clear (ASTM 2012).

### 2.2.1 Powder Based AM Technologies

Powder bed fusion (PBF) processes were some of the initial AM processes to be commercialised. The basics operating methods of these machines are very similar, containing a powder-based feed material, a powder levelling roller to spread material evenly across the build platform and a method of fusing the build material. Each PBF process modify this base approach in one or more ways to increase performance and/or to allow various material to be used (Gibson 2010).

PBF has multiple subsidiaries, the use of one or more thermal sources are used to fuse the powder particles, selective laser melting (SLM) and direct metal laser sintering (DMLS) are the most common (Gao *et al.* 2015), however other technologies include electron beam melting (EBM) and selective laser sintering (SLS). PBF is *“an additive manufacturing process in which thermal energy selectively fuses regions of a powder bed”(Iso/Astm 2015).*

Thermal energy is used to consolidate powder materials to form the 3D objects in PBF additive processes. DMLS, SLM and EBM are popular metal PBF technologies, these processes work off standard PBF operating principals whereby powder is rolled onto the build platform, where pre-alloyed, atomised powder materials such as 17-4 PH stainless steel, cobalt chromium and titanium Ti6-Al-4V are fused. Focused laser beams are used in SLM and DMLS while EBM utilises a scanned electron beam to fuse the powder. A vacuum or inert environment is required when using these technologies to prevent the powdered metals from oxidising (Gao *et al.* 2015). Plastics are also common in powder-based systems, SLS is the most common technology used in industry for the manufacturing of plastic parts (Baumers and Holweg 2019).

#### 2.2.1.1 Binder Jetting

Powder based polymers are not just processed using SLS but also through binder jetting (BJ). BJ is a process that requires two materials, a powder-based build material and a binder. By definition BJ is

*“an additive manufacturing process in which a liquid bonding agent is selectively deposited to join powder materials”(Iso/Astm 2015).*

Similarly, to other powder-based AM processes, the BJ process consists of very thin layers of very fine powders that are closely packed, spread across the build platform. This powder is joined using a liquid binder that is precisely dispensed using an inkjet style print head, subsequent layers of powder material is rolled on top of the previous layer (Figure 2.5) and the process of dispensing binder repeats until the final 3D object is complete (Ngo *et al.* 2018).

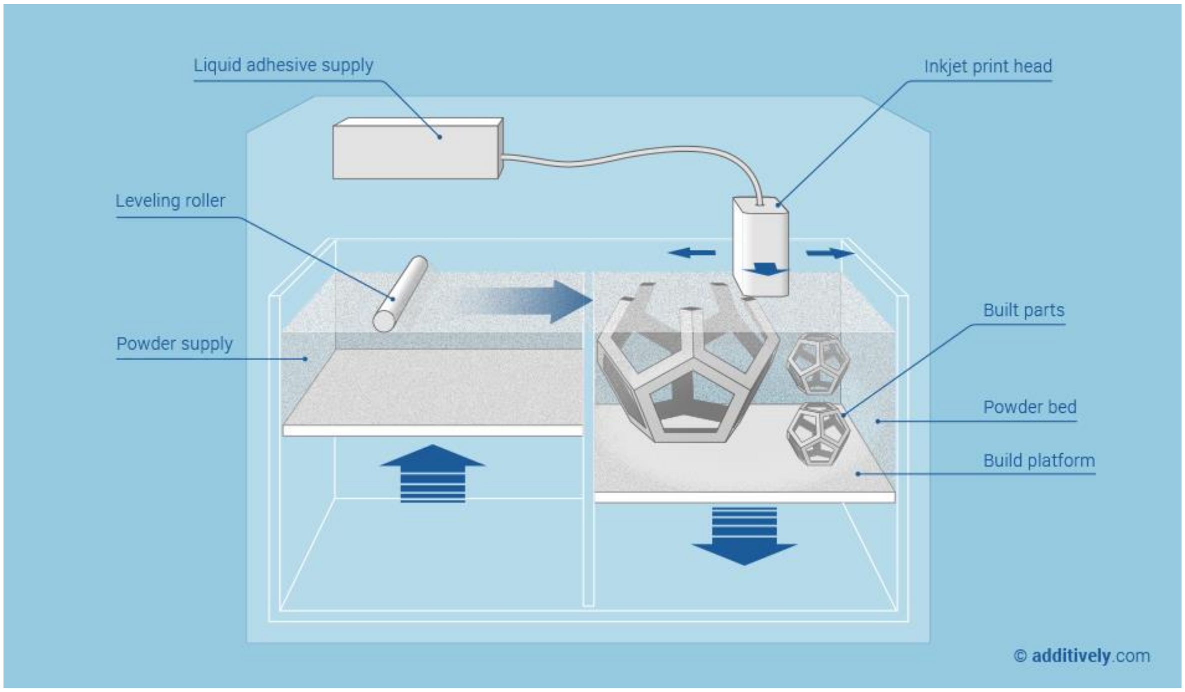


*Figure 2.5 BJ process – an inkjet head passes over a powder filled build bed, dispensing a binding agent to adhere build material, creating thin cross sections of physical parts. Image courtesy of (Additively 2018).*

In the BJ process, the part being manufactured is self-supported within the powder bed of build material (Bhushan and Caspers 2017). Once the part is finished, it is removed from the build platform and excess material is brushed away. Unused build material can be reused, for nylon polyamide a popular powdered material used for BJ, both particle size and molecular weight change during processing and screening of powders must be done in order to reuse them (Gibson 2010).

BJ for end use, functional components is most seen using polymer materials, multi jet fusion (MJF) from HP is a popular polymer BJ process. The high quality of parts and the high production rates make the MJF system as an AM production tool (Mele *et al.* 2020).

Most applications of BJ require post-processing, this includes powder removal, sintering and infiltration to improve part performance (Ziaee and Crane 2019).

#### 2.2.1.2 Powder Based AM Adoption Considerations

For many powder-based systems (excluding DMLS) the ability to produce multiple batches per batch is a major benefit to the systems as unused build material acts as support material parts can be stacked vertically throughout the build volume (Figure 2.6). Having the build volume utilized this way can help in reducing unit costs as fixed costs are spread across the number of parts being produced (Baumers and Holweg 2019).

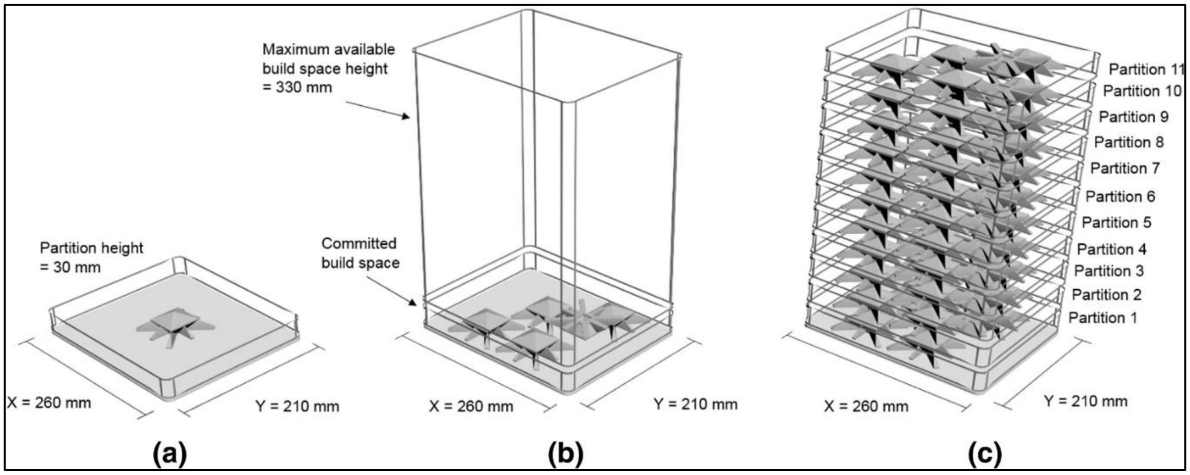


*Figure 2.6 Various powder build volume utilisation scenarios (a) Single part build (b) multiple parts on a single plane (c) multiple parts stacked on multiple planes in a single build. Source (Baumers and Holweg 2019)*

Over the years PBF processes have proven to be suitable for direct digital manufacturing as the material properties are comparable to many engineering grade polymers, metals and ceramics (Gibson 2010).

Some downsides to PBF processes are the technology adoption costs, in 2014 an estimated 543 metal-based AM machines were sold worldwide. Metal based systems sold by suppliers from the USA and Europe varied in cost from $700,000 to over $1,000,000 for build volumes of 1 cubic foot or larger (Vartanian and McDonald 2016).

The EOS P396, is an SLS machine significantly less expensive than metal based systems costing approximately €400,000, and MJF machines such as the JetFusion 3D 3200 and 4200 cost approximately half of this (~€200,000) (Tagliaferri *et al.* 2019).

## 2.2.2 Photopolymer Based AM Technologies

Liquid, radiation curable resins or photopolymers are used in photopolymerisation process as the primary build materials. Generally, radiation in the ultraviolet (UV) range of wavelengths is used to cure the materials used in these systems (Gibson 2010), the UV light directed across the surface of the resin or part, areas of resin exposed to the light are cured through cross-linking of the liquid material (Jacobs 1995).

Stereolithography (SLA) and material jetting (MJ) are two of the most common photopolymerisation technologies (Rajaguru *et al.* 2020). The high accuracy and smooth surface finishes are some off the advantages in parts produced using photopolymers (Gibson 2010; Bhushan and Caspers 2017; Mouzakis 2018).

These systems follow the same process steps as other AM technologies, where designed parts are imported into slicing software to set various process parameters and the appropriate support structures before they are sent to the machine for fabrication (Ruiz *et al.* 2015).

#### 2.2.2.1 Vat Photopolymerisation

Photopolymerisation processes are the oldest form of AM. Vat photopolymerisation (VP) is an

> *"additive process in which liquid photopolymer in a vat is selectively cured by light activated polymerisation (Iso/Astm 2015)."*

VP uses liquid, UV curable resins as their build materials, this technology is commonly known as SLA (Chartrain *et al.* 2018). These machines consist of a UV light source, a vat of liquid photopolymer and a build platform. To commence the process the build platform is submerged in the vat so that its surface is in the liquid resin, the UV light source scans the first layer of the object, solidifying or crosslinks the material, adhering the photopolymer liquid to the build platform. The build platform then moves up by the designated layer thickness and this process repeats itself layer by layer until the part is complete (Bhushan and Caspers 2017; Singh *et al.* 2017; Chartrain *et al.* 2018).

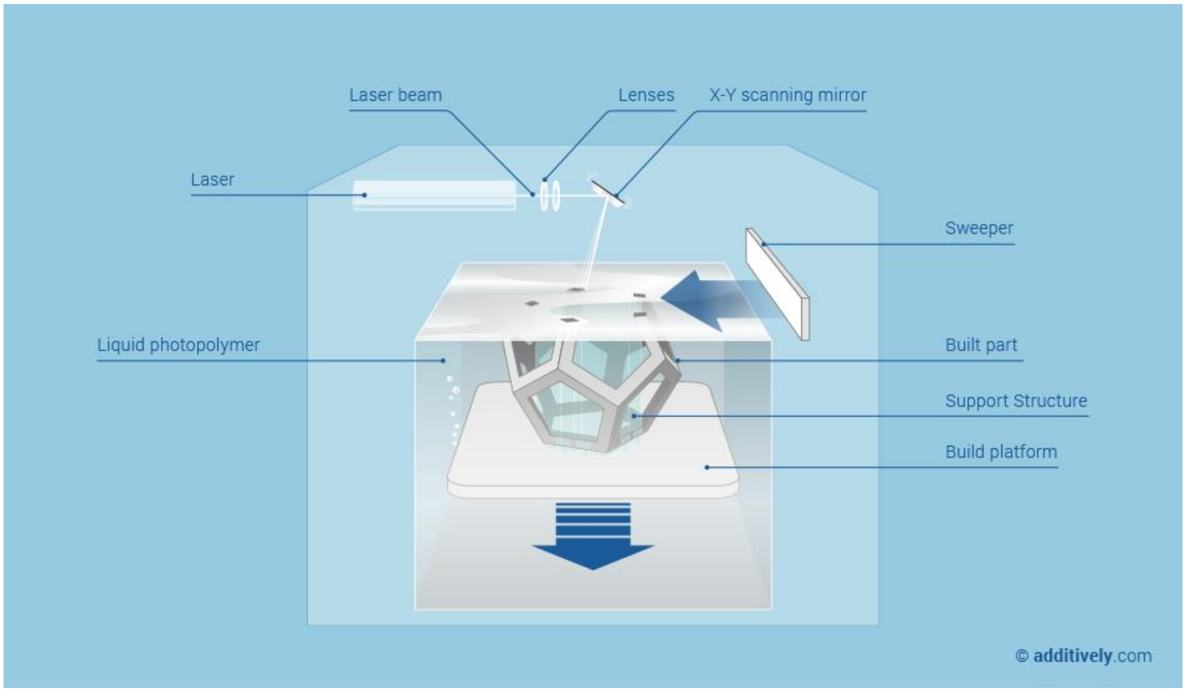


*Figure 2.7 SL process - showing a UV light source tracing out a layer of a 3D part. The part is built as after each layer the build platform leaves a thin film of photopolymer to be cured, adhering itself to previously cured material. Image courtesy of (Additively 2018)*

Finished parts from this process must undergo some post processing, they must be washed in a cleaning solution, often isopropyl alcohol (IPA) to remove excess uncured material, dried and then another curing process which will ensure the materials reach their full mechanical performance. Support structures must also be manually removed from finished parts (Gibson 2010; Ngo *et al.* 2018).

Due to the reliance on photopolymerisation to cure the build material, this process is inherently limited to photopolymers (Gao *et al.* 2015; Mouzakis 2018). SLA does produce highly accurate parts however some limitations of this technology are that it is relatively slow and have limited material options (Ngo *et al.* 2018), in recent years the SLA hardware costs have reduced and low-cost SLA printers are now available. The cost of SLA machines can range from €150 (Creality LD-002R) to in excess of €250,000 (Valentinčič *et al.* 2017).

The Form 1 machine from Formlabs was one of the earliest low-cost photopolymer-based desktop printers, that first shipped in My 2013 (Wohlers and Gornet 2014). Now on their 3$^{rd}$ generation of this machine, the Formlabs Form 3 printer when coupled with their wash and curing stations can be purchased for under €5,000. Materials for these machines are proprietary and cost ~€150/L (Chen *et al.* 2020), the relatively low costs Formlabs make this technology more accessible.

### 2.2.2.2 Material Jetting

Two-dimensional inkjet printing processes have been in existence for many years (Gibson 2010), the MJ process works in a similar fashion where ink is replaced with wax or photopolymer build materials that are directly deposited onto a substrate (Gao *et al.* 2015). For this reason, MJ is often referred to as inkjet printing (Bhushan and Caspers 2017; Ngo *et al.* 2018; Rajaguru *et al.* 2020). MJ is described as an

> *"additive manufacturing process in which droplets of build material are selectively deposited (Iso/Astm 2015)".*

Acrylate photopolymers are the main material used in this process, the material is jetted from nozzles that move horizontally across the build platform, this is then followed by a curing stage where a head containing a UV light source passes above the deposited material, curing it (Gibson 2010).

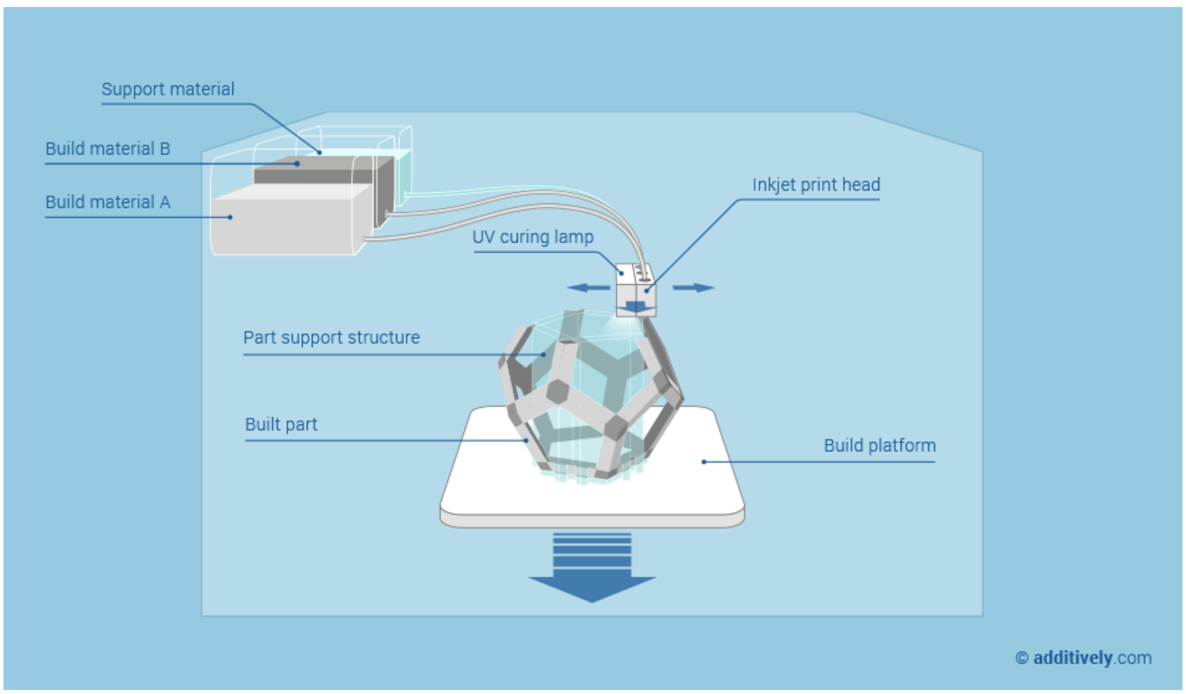


*Figure 2.8 MJ process - as the inkjet head passes over the build platform an array of nozzles jet photopolymer build material to the build platform in a predefined pattern. The liquid photopolymer is quickly cured using UV light, forming a cross sectional layer of the final part. Image courtesy of (Additively 2018)*

The Stratasys PolyJet line of AM machines are a popular range MJ machines. This technology offers full-colour multi-material printing with good dimensional resolution and part quality, in comparison with full colour BJ. However, this technology is very expensive due to the system complexity, materials and PolyJet patent protection (Cheng *et al.* 2020). The Stratasys J750 is a PolyJet style printer that costs $300,000 (USD), with expensive materials of approximately €400/kg (Chen *et al.* 2020).

### 2.2.3 Material Extrusion

ME also known as FFF or 3D printing is an

> *"additive manufacturing process in which material is selectively dispensed through a nozzle or orifice"(Iso/Astm 2015).*

Thermoplastic polymers are typically used in ME applications, prior to extrusion the materials are heated above their melting points so that they can be forced through a fine orifice or nozzle by the solid material upstream (Stansbury and Idacavage 2016). The thermoplastic polymers used in ME typically come in a filament form. The primary components of typical ME machines (Figure 2.9) are a heated hot end or liquefier, a filament extruding system and a build platform (Carneiro *et al.* 2015).

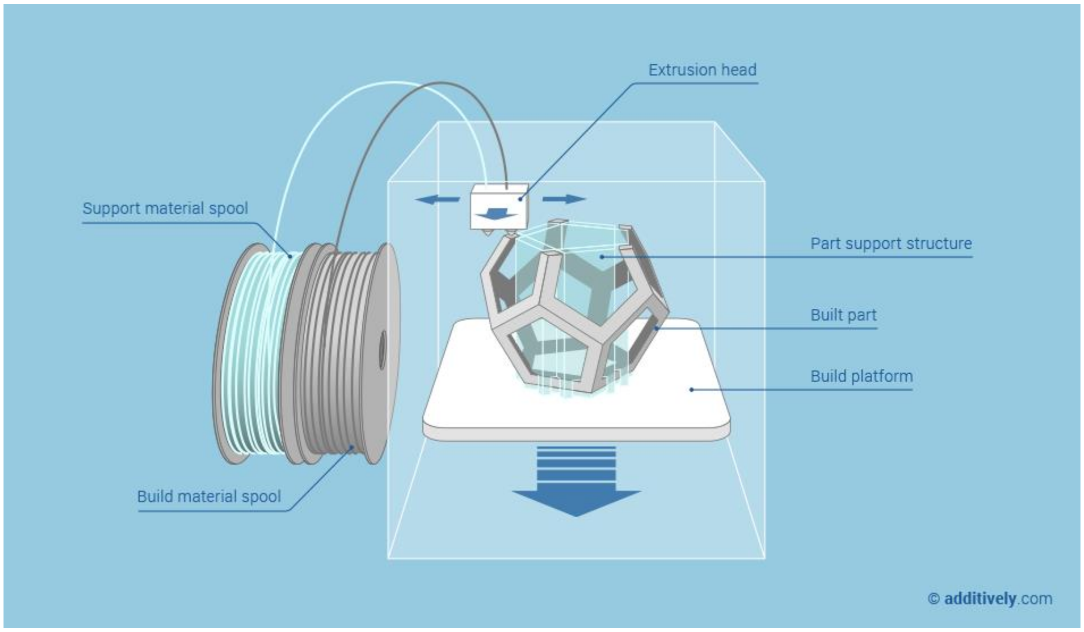


*Figure 2.9 ME process - where a spool of polymer filament is fed through a heated extruder nozzle. The nozzle positions the molten polymer as per the part cross section that is predefined in the slicing software. Image courtesy of (Additively 2018).*

Semi-molten polymers are deposited along the build platform one slice at a time as per the slicer process parameters. The build platform lowers to allow subsequent layers to be deposited on top of previous layers. The thermoplastic nature of the materials used in ME is an essential property for this method, allowing layers of filament to fuse together during printing (Ngo *et al.* 2018). The nozzle moves on a horizontal plane and is capable of starting and stopping material flow as need be as material is deposited. This approach is similar to traditional polymer extrusion processes but the extruder is mounted vertically on a plotting system rather than fixed horizontally (Gibson 2010).

Parts and products fabricated using this technology typically comprise of a solid outer shell and a sparse inside. The amount of plastic used in the inner portion of the print is determined by infill density, higher infill densities inside of the print result in heavier and stronger parts (Yadlapati 2018). Many different infill patterns are widely available, which effect the strength of a FFF product. Concentric style infill patterns can give the greatest ultimate tensile strength and yield strength, this is dependent on the loading direction and build orientation, an area where further study is recommended (Pandzic *et al.* 2019). However, gyroid patterns which are lattice structures, when used as infill patterns in ME based additive processes they show nearly isotropic properties, making this pattern suitable for applications where parts are subjected to multiple loading directions (Parab and Zaveri 2020).

Overhanging features are a challenge in ME processes, to enable such features a support structure is require. In single material machines, the build material is used to support these overhanging features and is broken away during the post-processing of the parts. Some machines are capable of printing multiple materials and use soluble materials as the support material which can be removed leaving a better surface finish (Carneiro *et al.* 2015).

Machines using this technology can be purchased for under €2000 (Alsoufi and Elsayed 2018), however high temperature printers have come down in price some can be purchased for approximately €30,000, yet industrial machines often cost upwards of €100,000 (Zawaski and Williams 2020).

Polymer material feedstock are the most common for ME based AM machines however, aggregate-based materials such as concrete, and fibre-filled filaments are also becoming available (Paolini *et al.* 2019).

#### 2.2.3.1 Fused deposition modelling

FDM is a common ME process, which is a trademark technology owned by Stratasys. The term FDM is often used to describe all ME processes (Chen *et al.* 2020; Rajaguru *et al.* 2020), however, for this study FDM will be used only to describe ME machines from this company.

The FDM technology is used in the Fortus line of Stratasys machines, directed at professional users (Stoklasek *et al.* 2018). These printers can cost upwards of €120,000 (Fortus 450mc) (Tagliaferri *et al.* 2019). These printers are often used to produce manufacturing aids, prototypes and for short-run digital manufacturing. This is made possible by the larger build volume (36”x24”x36”, Fortus 900mc that costs ~€350,000) and material compatibility, Common engineering thermoplastics such as ABS, PC, Nylon and ULTEM (Crean 2017; Stoklasek *et al.* 2018; Tagliaferri *et al.* 2019), can be used with Stratasys FDM technology.

#### 2.2.3.2 Fused Filament Fabrication

In recent years, the popularity of desktop ME 3D printers has grown drastically. Desktop, low-cost and personal are terms often used to describe printers under €5,000, FFF machines are the most common low-cost AM machine (Li *et al.* 2017; Wholers *et al.* 2017).

With the expiration of Stratasys’ FDM process patents, major developments have been made in making the technology accessible to a wider audience, and enabling the emergence of low-cost FFF machines (Santana *et al.* 2017).

As the quality and reliability of desktop 3D printers have increased, so has the demand making FFF is the most popular AM technology that can be adopted for both industrial and home/hobbyist use (Ngo *et al.* 2018).

Often overlooked in the literature are the benefits of desktop AM machines as teaching and research tools, they are extremely useful in facilitating new design developments in the engineering field (Justino Netto and Silveira 2018), these benefits may explain why the second largest market for desktop AM machines are educational institutions (Wholers *et al.* 2017; Justino Netto *et al.* 2019).

Thermoplastic polymers in filament form are the material source for this technology, polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS) are the most common build materials used with FFF machines as they are relatively easily processable (Bourell *et al.* 2017). New materials are constantly being developed such as polyethylene terephthalate glycol (PETG), thermoplastic polyurethane (TPU), polyvinyl alcohol (PVA), and a variety of composite filaments (Ning *et al.* 2015; Zawaski and Williams 2020).

The development of low-cost FFF printers came about through the RepRap open-source project that commenced in 2005, designing printers in the form of kits and fully assembled machines (Wohlers and Gornet 2014). Based on the RepRap printers, many other companies began to develop their own machines such as MakerBot and Ultimaker. Along with open-source hardware, came open-source software, unlike commercial AM machines a range of slicing software can be used with low-cost FFF printers. However, not all slicing software can achieve satisfactory results, even when the same process parameters have been set in the slicing software as can be seen in a study by Šljivic et al. (2019) who compared three of the most common slicing packages for FFF. Cura, Slic3r, and Simplify3D were compared for two case studies using the same printer (Infiltary M508) and processing conditions to determine the impact the slicing software has on the accuracy of parts. This study suggests that parts produced using Slic3r were inferior, while Cura achieved good results and Simplify3D achieved the best results. Both Cura and Slicer3D were recommended as suitable for not only low-cost but also semi-professional and professional desktop printers (Šljivic *et al.* 2019).

These machines offer the ability to adjust many printing parameters including nozzle orifice diameter and melt temperature, with experience modifications like these can result in faster printing times, better surface finishes or part accuracy. In contrast most industrial machines do not offer this level of freedom, these industrial systems rely on proprietary materials and pre-defined process parameters with little room for modification to assure system accuracy and repeatability. That said with experience and carefully selected print parameters FFF machines such as the Ultimaker 2 (using Cura slicing software) have been shown to produce parts with tighter tolerances than industrial EOS Formiga (SLS) and Arburg Freeformer machines, when configured correctly (Minetola *et al.* 2020).

### 2.2.3.3 Big Area Additive Manufacturing

Big Area Additive Manufacturing (BAAM) is a large-scale, 3D printing technology developed by Oak Ridge National Laboratory's Manufacturing Demonstration Facility and Cincinnati, Inc. (Post *et al.* 2019). BAAM was developed to overcome some of the limited performance metrics many AM processes have, for example small build volumes, low production rates and relatively expensive feedstocks when compared to traditional mass manufacturing processes. BAAM is an extrusion process that uses traditional pelletised injection moulding feedstock, rather than a filament style polymer used in FDM and FFF machines. Utilizing pellets and a single screw extruder significantly increases deposition speed and lowers material cost by utilizing low-cost injection moulding feedstock a wide range of common thermoplastic materials can be used (Holshouser *et al.* 2013; Post *et al.* 2016)

These systems can deliver build material at high rates, using larger nozzles (typically 2.5mm-7.6mm) than those found on small scale FFF printers (0.25mm-0.8mm). BAAM is designed to print large parts quickly, in doing so print resolution is sacrificed. The low-resolution of parts produces near net-shape components, when making parts that must be assembled post-fabrication machining is required to achieve tolerances required for assembly (Roschli *et al.* 2019). The BAAM platform can accommodate parts up to 6m in length, 2.4m wide and 1.8m tall, approximately 10x larger than most commercial systems (Duty *et al.* 2017). Machines of this scale require significant space and capital (hundreds of thousands of euros), making them suitable for large-scale industries such as automotive and aircraft manufacturing. To bridge the gap between desktop FFF machines and BAAM, a class of large scale FFF machines are emerging, with build volumes of approximately 1 cubic meter, such as the BigRep ONE, the Delta WASP 3MT and the Tractus3D T3500, such machines cost tens of thousands of euro making them more accessible than BAAM (Novak and O'Neill 2019).

*Material Extrusion Conclusions*

Although there have been great advancements in recent years to AM technologies, parts produced using many AM processes lack acceptable mechanical properties due to the anisotropic nature embedded in parts due to build orientation. Particularly in polymer-based AM the anisotropy of mechanical properties is dependent on the build orientation of a specimen. It is widely known that vertically orientated (ZXY) specimens suffer from decreased tensile strength when compared to horizontally orientated (XYZ) parts (Bellini and Güçeri 2003; Shaffer *et al.* 2014; Torrado and Roberson 2016).

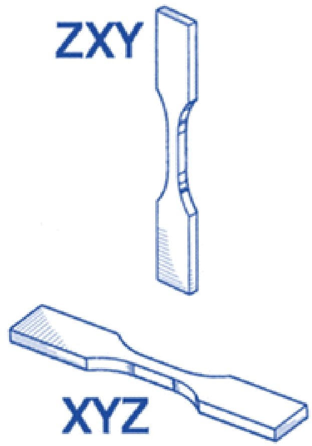


*Figure 2.10 Graphical representation of tensile test specimens printed in the horizontal XYZ and vertical ZXY build orientations (Torrado and Roberson 2016)*

Understanding AM technologies, their advantages, and limitations aid in the process of selecting the most appropriate technology for a given use case. As parts often show anisotropic material properties it is essential to design for additive manufacturing (DfAM) to produce 3D printed parts with greater functionality.

### 2.2.4 Design for Additive Manufacturing

In order to take full advantage of AM CAD packages, structured design tools and procedures are required (Friesike *et al.* 2018). Designing products for AM require a different approach to traditional manufacturing techniques, for effective and efficient designing it is important that designers are educated to understand AM and take full advantage of the benefits it can offer. Therefore for current designers working in industry who are familiar with traditional manufacturing techniques such as injection moulding, casting and machining, should be rethought the methods and skills required for AM (Ituarte *et al.* 2016).

Design for manufacture (DfM) traditionally is the term given by designers to ensure their design ideas do not contain features that the intended manufacturing process will have difficulties with, this is done to minimise the cost and time to produce parts (Rosen 2007). In In AM, it is recommended that designers ignore traditional DfM limitations (Campbell *et al.* 2012), and familiarise themselves with DfAM as the limitations are different to traditional manufacturing techniques (Chaudhuri *et al.* 2019).

Design for AM (DfAM) is a sub-category within DfM, an area where interest is growing as AM matures into a potential manufacturing solution (Schmidt *et al.* 2017). With the rapidly improving technology that is AM, many of the existing design constraints are mitigated. Due to the nature of AM, parts can now be manufactured as one-off components or even as 10’s or 100’s of units. As more complex parts can be produced AM can be used to create single components out of what was previously sub-assemblies using traditional manufacturing methods, part reductions like this are a great way of reducing assembly complexity. Generally, AM is considered as an enabler for customisation, product performance improvements, multi-functionality and manufacturing cost reduction, primarily down to AM’s ability to produce complex shapes with ease (Rosen 2007).

Specific DfAM must be considered to get the most out of any AM technology. Therefore, the decision to use AM technologies should be made early in the product development process when part and assembly design is not yet fixed. There are varying operating principals, processing characteristics and compatible material types with each different AM technology, all of which influence the cost of AM parts. The ability to estimate the costs of AM parts based on a few parameters early in the design process is essential in making the decision to use AM for a part or assembly (Baldinger *et al.* 2016).

In a study conducted by Chaudhuri et al, (2019) case studies describing how companies benefited from DfAM, based off data published by AM service providers, equipment manufacturers and specialised trade journals. Of the 65 case studies which were reviewed, 32 of these cases specifically included DfAM aspects. These case studies related to a variety of different industries including automotive, aerospace, industrial, consumer product, sporting goods and telecommunication, 7 of the 32 cases were for production jigs, fixtures or grippers while the other cases referred to parts or components for end use products. Findings from this study show that the primary motivations for companies to implement DfAM were,

1. weight reduction
2. development and production of complex parts
3. product customisation
4. reduction of development and go-to-market times

Some similarities existed between the various companies' motivations, competencies and performances, for companies or designers with similar motivations, developing the required DfAM competencies could yield better results (Chaudhuri *et al.* 2019). Design rules are guidelines that provide an essential insight into manufacturability during design and process planning, guidelines that allow designers to make useful changes to part geometries without compromising manufacturability. As there is such a wide range of additive technologies available process related design parameters, material parameters, and the individual machine parameters all influence the success of an AM part. Examples of these parameters are as follows (Mani *et al.* 2017);

- Process design parameters: feature size, angles, accuracy, surface roughness, wall thickness, etc.
- Material parameters: size, distribution, flowability, etc.
- Machine parameters: laser powder, scan speed, layer thickness, etc.

Understanding parameters such as build orientation or angle can have an effect on many aspects of the AM part including, surface quality, build duration, support structure complexity, and the overall layer count. The height and surface quality requirements are often determining factors for build orientation (Brown and Beer 2013; Hinchy 2019). In extrusion-based printing, the stair-stepping effect becomes more evident as the build orientation angle increases, resulting in greater surface discrepancies (Buj-Corral *et al.* 2019). Shell thicknesses in FDM printing can provide strength to functional parts (Jesse Hanssen 2009).

### 2.2.5 AM Summary

AM technologies are inherently less wasteful than traditional subtractive manufacturing techniques, creating opportunities to reduce the environmental impact of business activities. (Ford and Despeisse 2016).

Some researchers such as Huang et al. go as far to say that 3D printing is evolving from RP into a rapid manufacturing process, allowing manufacturing near finished products, enabling on-demand manufacturing while greatly reducing inventories and product lead times (Huang *et al.* 2015).

AM technologies allow for more complex and optimised components to be designed due to greater freedoms in shape and geometry, as well as the development of simpler assemblies comprising fewer parts and fewer different materials. Examples of product improvements include greater operational efficiency, functionality and durability, and ease of manufacturing and maintenance (Despeisse and Ford 2015).

However, AM technologies still face many challenges, limitations and uncertainty with regards to the performance of these technologies, slow manufacturing times, certification of parts, and educating manufacturers of the potential use cases and benefits of adopting AM technologies (Ford and Despeisse 2016; Ngo *et al.* 2018).

### 2.2.6 Alternative AM Use Case - Rapid Tooling

Industries often turn to AM to stay competitive by reducing waste of raw materials, shorter product lead times and eliminating the need for expensive tooling (Wagner and Walton 2016). Investment casting (IC), injection moulding and resin transfer moulding (RTM) are traditional manufacturing techniques for producing metal, polymer, and composite parts respectively. Such technologies require tooling components such as moulds and inserts to be developed specifically for a new part or product. The time and cost required to develop these tools due to machining and treatment sometimes invalidate low volume production cycles and limit the introduction, in a market of niche products (Afonso *et al.* 2019).

AM has some major benefits in producing prototypes, a result of its speed to fabricate relatively low costs parts for bespoke applications and small batches. Sometimes these parts can be used in production however, there are still many drawbacks that include lack of material availability, non-isotropic material properties, poor surface finish and often relatively low strength make these parts unusable for end use production (Ong *et al.* 2002; Bagalkot *et al.* 2019).

This leaves a void between prototyping and production where RT can be adopted to bridge in some situations (Bagalkot *et al.* 2019). For this reason low-cost RT is sometimes referred to as bridge tooling, for its ability to be used for producing functional prototypes or for early production samples and for small volume production (Equbal *et al.* 2015; Afonso *et al.* 2019).

RT is the term given to the production of tooling for a variety of manufacturing processes directly from CAD models. This manufacturing technique evolved from RP, for there was a need to evaluate prototype models in terms of their performance. To assess such performance, it is essential that the prototypes are produced in the same material and by the production processes that are intended to be used in the final production part (Rosochowski and Matuszak 2000).

Through assessments of such prototypes in early stages of product development ensures that any adjustments required for either the part or tool design can be made, minimising the risk of late modifications of the final production tools (A. Ramos *et al.* 2003; Bassoli *et al.* 2007).

RT methods provide an efficient way of producing one-off parts, small batches or new product trial manufacturing (Chua *et al.* 2005), by combining additive techniques with conventional tooling practices, reduced time to market and lower costs of producing functional models is a primary aim (Achillas *et al.* 2015). Traditional tooling is generally categorised as either hard or soft tooling, this relates to the materials they are constructed from, RT by AM typically falls under the soft tooling umbrella as the materials used in these methods are relatively soft (Rosochowski and Matuszak 2000). Soft tooling is associated with lower costs, used for lower volume production cycles, and uses materials that have relatively low hardness levels such as silicones, epoxies, low-melting point alloys (Yarlagadda and Wee 2006)

For high volumes of production, cycles of thousands of parts, hard tooling is required which can include tooling produced via DMLS and incremental sheet metal forming, but typically hard tooling refers to moulds manufactured from hardened tool steel. Most conventional steel tooling is manufactured using traditional metal cutting processes or by electric-discharge machining, adding to tooling lead times and cost of mould manufacture (Yarlagadda and Wee 2006; Equbal *et al.* 2015; Afonso *et al.* 2019).

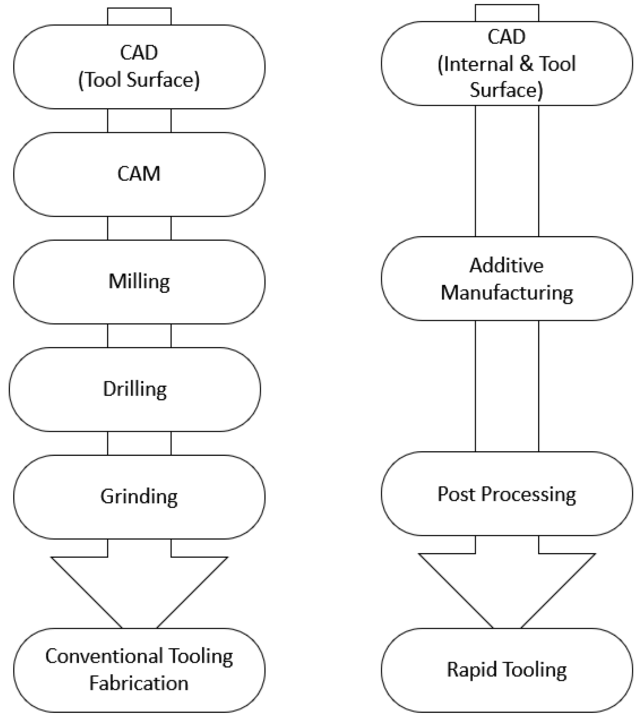


*Figure 2.11 Conventional Mould Manufacturing and RT process comparisons. Redrawn from (Junk and Tränkle 2011)*

The term RT is used to describe moulds or mould tooling components fabricated at reduced lead times to tooling fabricated using traditional techniques, either through direct or indirect processes. A vast array of technologies or techniques can be used, however, RT is mainly associated with AM processes (Afonso *et al.* 2019). AM provides several economic advantages over conventional manufacturing technologies for tool making. The primary factor is the reduction of lead-times through the removal of time consuming conventional steps such as CAM (Figure 2.11), an essential machining phase where the cutting tool paths are programmed (Junk and Tränkle 2011).

As RT becomes more popular, it is important to classify the various techniques into different categories (Figure 2.12), where soft tooling is compared to hard tooling, direct tooling and indirect tooling as well as prototype and short run production tooling (Rosochowski and Matuszak 2000; Matta *et al.* 2015)

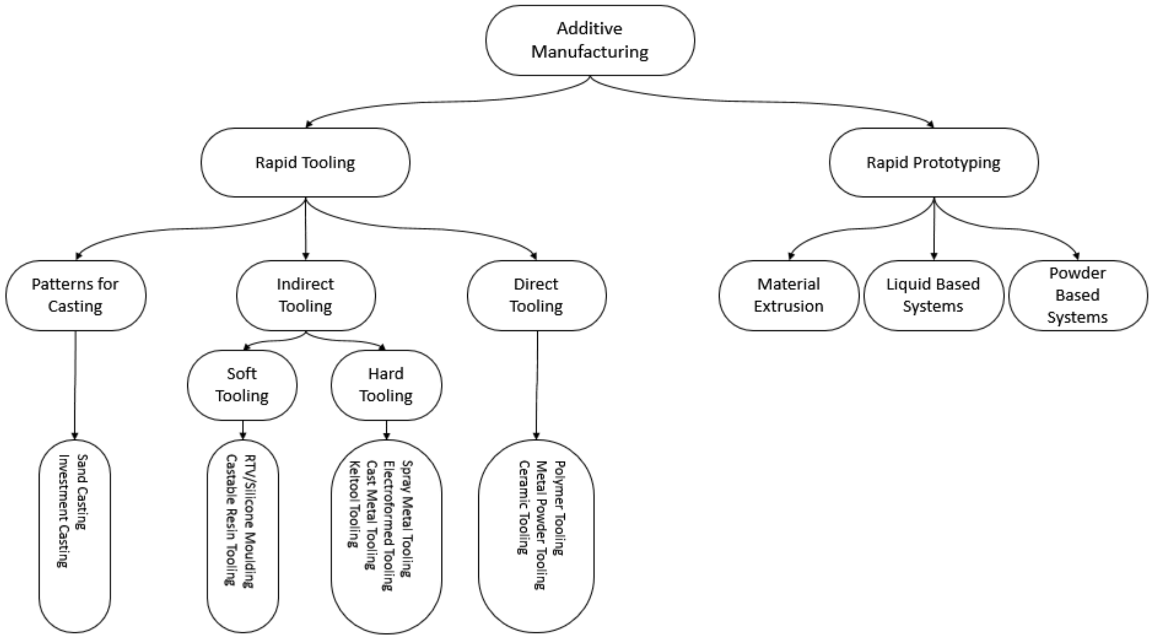


*Figure 2.12 Classifications of AM and RT (Rosochowski and Matuszak 2000; Achillas et al. 2015; Equbal et al. 2015; Afonso et al. 2019)*

IC was one of the earliest examples of RT using AM-fabricated patterns in 1989 (Greenbaum and Khan 1993), since then RP techniques have become increasingly popular in IC for tooling and manufacturing applications. In rapid IC scenarios there are three approaches; using RP to fabricate sacrificial IC patterns; using RP to fabricate tooling for wax injection; using RP to directly fabricate ceramic IC shells (Chhabra and Singh 2011). Examples of AM technologies suitable for IC applications include SLS, FFF and SLA, all of which can produce wax patterns (first approach) similar to that used in foundries that can be used directly in IC (Blake *et al.* ; Prioleau 1991; Greenbaum and Khan 1993; Dickens *et al.* 1995; Sundaram 1996; Cooper and Williams 2000; Bassoli *et al.* 2007).

With direct RT, moulds and inserts are made directly with AM processes. The direct RT does not require as many steps as indirect RT and has the potential to preserve overall part features and accuracy (Siemer 2007; Najmon *et al.* 2019). Typically, direct RT are classified as soft due to the soft materials generally used in AM processes. As thermal and mechanical properties of soft tooling is significantly different to conventional tooling techniques, the longevity of these tools are unpredictable, for this reason suited to short manufacturing runs (Equbal *et al.* 2015; Mendible *et al.* 2017). Indirect tooling however refers to tooling fabricated using multiple processes or technologies, where a pattern is created first before the final tooling is produced from this pattern (Hilton and Jacobs 2000; Vasconcelos *et al.* 2002; Wohlers and Gornet 2014).

The combination of SLA master patterns and Room temperature vulcanization silicone is a common method of indirect RT that can be adopted to produce soft tooling for low volume production of approximately 50 units (Afonso *et al.* 2019).

A sampling phase is common in conventional tooling, whereby the steel is machined to the inside tolerance dimension giving some room for modifications after mould production or during this sampling phase, this is generally not the case when it comes to RT. As RT solutions are often produced in one shot from a master, modifications may require the tooling to be re-fabricated. For these reasons choosing the correct RT technique is essential to suit the process materials, process requirements as well as the moulding results (Afonso *et al.* 2019).

The limitation in additive fabrication of tooling tends to be the required post processing to achieve the required surface finish. Beyond metal tooling, plastic (or resin) rapid prototype moulds are also frequently produced for a variety of purposes like casting urethanes and silicones (Siemer 2007).

Because of RP shortcomings, RT processes must be developed to aid the NPD cycle, RT processes compliment and take advantage of the RP options by providing higher quality models in the desired final material. Traditional prototyping techniques result in fewer design iterations being made, thus greater risks are taken with regards to expensive design changes being required in later stages of the NPD cycle. RT is a way of verifying component performance, however it is also essential in rapid product development. RT can help in eliminating some of the time consuming and expensive high skill requirements used in the traditional methods of prototype production.

FFF has been proven as a commercially viable RT process in various rapid casting applications (sand, vacuum and IC) (Pal and Ravi 2007). The fixed costs involved in the design and manufacturing of metal tooling for wax injection moulding can be overcome through AM to fabricate sacrificial patterns for IC, which has been shown to reduce the lead time in the production of prototype casting with very high quality results (Chhabra and Singh 2011).

Composite manufacturing is an industry where RT has gained some interest primarily with industrial AM technologies such as FDM, BAAM and powder-based technologies. The popular FFF technology has not received much attention and is often overlooked as a prototyping tool. Understanding the various composite manufacturing techniques and processing requirements is needed to gain insight into why the FFF technology is less popular as a RT solution in this industry. A section outlining traditional composite manufacturing processes will follow to determine whether this low-cost AM technology has a place in RT for composite prototyping.

## 2.3 Composite Manufacturing, Processes & Materials

FRPs are gaining popularity in many structural applications since the late 1960s, this is due to demand for structural components with high specific strength and stiffness. In the U.S. alone, the composite end-products market was valued at $26.7billion in 2019 and it is forecasted that these figures will continue to rise to $33.4billion by 2025 (Sanjay Mazumdar 2020) and to $114.7 billion globally (Markets 2019; Ngo 2020). The popularity of composite materials in high performance applications (due to weight savings) has been one of the main driving forces in this growth. However, the adoption of composites across a wide range of markets such as infrastructure (buildings, bridges, roads and railways), industrial (pipes, tanks and grating), transportation (automotive, marine and aerospace) and sporting goods (from bikes, skis and snowboards to hockey sticks) that has also contributed to the drastic growth in the composite industry.

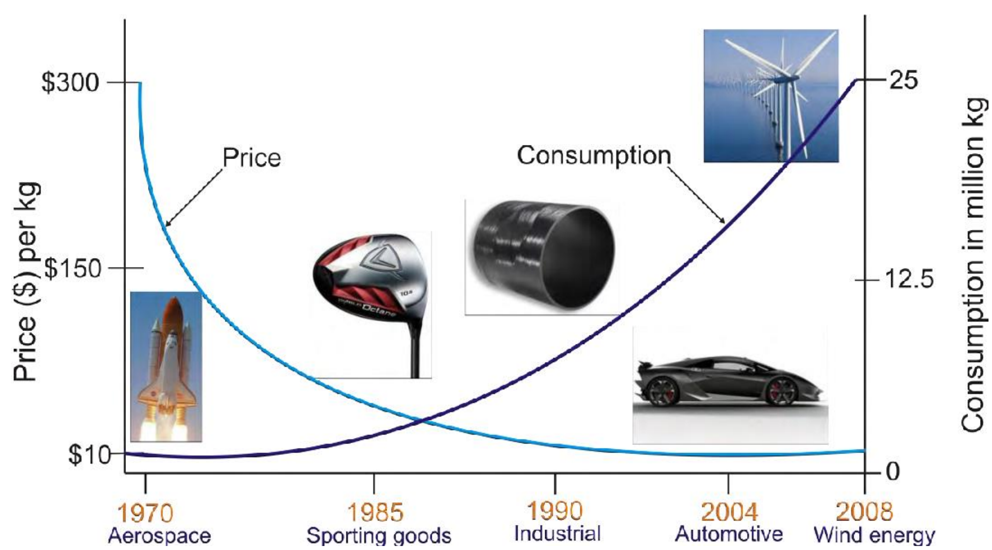


*Figure 2.13 Image of the increase in CFRP consumption versus the reduction of cost of composite production from 1970 to 2008 (Nash 2016)*

CFRPs are composite materials with high strength and stiffness properties at low weight, making them a very interesting material for the development of high-performance lightweight structures. CFRP consumption and range of applications has improved as CFRP processing costs have reduced, making it a viable material for a broader range of industries, especially where a high strength-to-weight ratio is required such as in aerospace, sporting goods, automotive and in robotics applications (Türk *et al.* 2015; Nash 2016).

Composite materials are either engineered or naturally occurring materials, consisting of two or more principal materials with differing mechanical, physical or chemical properties that stay separate in the finished structure (Ngo 2020).

Composite materials are most commonly composed of a reinforcement (fibres, particles, flakes, fillers) embedded in a matrix (polymers, metals, ceramics). FRPs, also known as fibre-reinforced plastics are a set of composite materials consisting of fibres embedded in a polymer matrix. The reinforcing fibres are the primary load carrying members, while the matrix is responsible for maintaining fibre location and orientation, acting as a load transfer medium between fibres, while protecting them from the surroundings (Nagavally 2017). In combination, both fibres and matrix retain their physical and chemical properties, properties neither material can achieve acting alone (Masuelli 2013).

In structural applications the most common way of using FRPs is as a laminate, which are created by stacking thin layers (plies) of fibres and consolidating them in the matrix to the desired thickness. Physical and mechanical properties of laminates are controlled by the stacking sequence and orientation of the fibres in each ply, a wide range of physical and mechanical properties of the composite laminate can be controlled this way (Figure 2.14). Often FRP materials offer comparable strength and modulus to traditional structural metallic materials, however FRPs are far less dense, because of this the strength-weight and modulus-weight ratios are far superior. Many composite laminates also have great resistance to fatigue, for these reasons composites are used and being considered as substitutes for many weight critical components in a range of industries (Mallick 2007; Masuelli 2013).

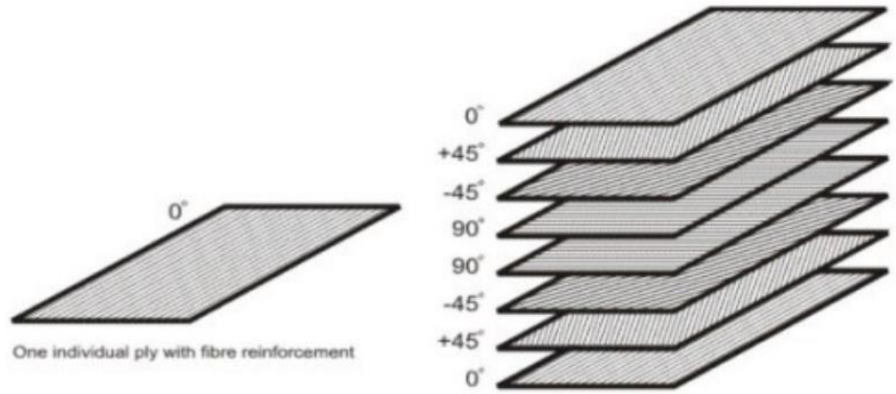


*Figure 2.14 Illustration of a composite laminate, a stack of individual plies orientated to enhance part performance (Lombard 2014).*

### 2.3.1 The Reinforcement

Long fibre composite manufacturing begins with a large number of fibres combined into a thin layer of matrix to form a lamina, a ply or a preform. Laminas used in FRP can come in a range of thicknesses, varying from 0.1-1 mm. Each form of fibre can be incorporated into a matrix either as continuous (long) or discontinuous (short) lengths. Individual fibres, generally have a round cross section, have very small diameters and are difficult to handle and process, for this reason many continuous fibres are bunched together to form a strand or end when referring to glass or Kevlar fibres and a tow for carbon fibres (Mallick 2007; Masuelli 2013).

Fibre plies are often manufactured in sheets, continuous mats, or as continuous filaments for spray applications. Long continuous fibres are commonly used in the production of a lamina, generally these fibres are either unidirectional (all fibres orientated in the same direction), bidirectional (fibres in two directions, generally perpendicular to each other) or multidirectional (fibres orientated in more than two directions). The most common manufacturing techniques of the fibre preform come from the textiles industry, these processes include weaving, knitting, braiding and stitching. Weaving processes are used to produce bi- or multidirectional fibres in the form of fabrics (Figure 2.15). Fibres are weaved into fabrics to maximise the performance of a composite, as fibres have their greatest strength and modulus in the orientation of the fibre. Therefore, unidirectional fibres have good mechanical properties in the longitudinal direction of the fibres, however in the transverse direction these properties are very poor. By incorporating a weaved ply the fibres can also run in this transverse direction, balancing the strength and modulus properties of the ply, in these given directions (Mallick 2007; Masuelli 2013).

Discontinuous or short fibres are an alternative for use in lamina, these can be unidirectional however they generally tend to be in random orientation. Random orientated fibres have isotropic mechanical and physical properties, meaning the properties are equal in the plane of the lamina. Although properties are equal in each direction they are also lower than that of those obtainable using continuous fibres (Mallick 2007).

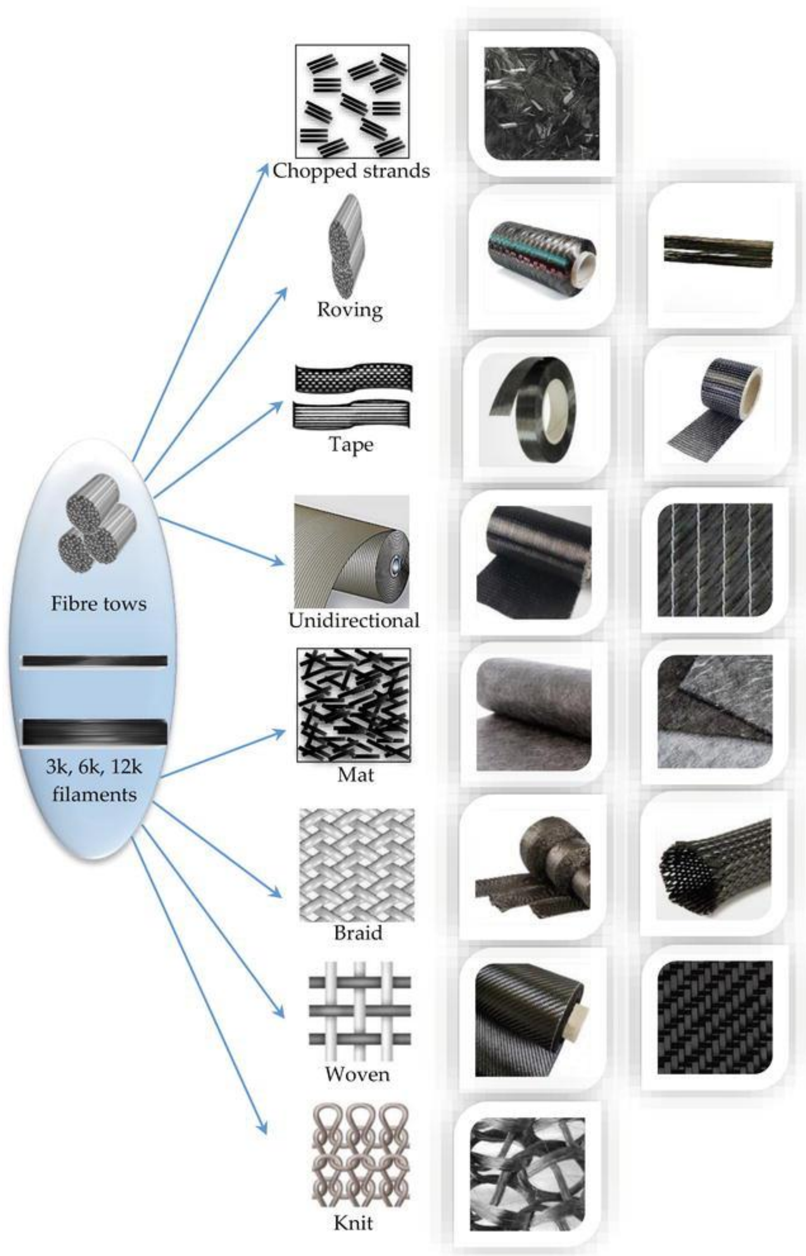


*Figure 2.15 Various forms in which fibre reinforcement is processed for various use cases (Ngo 2020).*

As the popularity and use cases of composites are increasing, they are used in structures subjected to a wide variety of loading conditions, including low/high-velocity impacts, during their lifetime, to replace traditional materials including metals and light-weight alloys. Depending upon the ingredients used in production of composite materials, they can fall into a wide range of categories (Figure 2.16) (Priyanka *et al.* 2017).

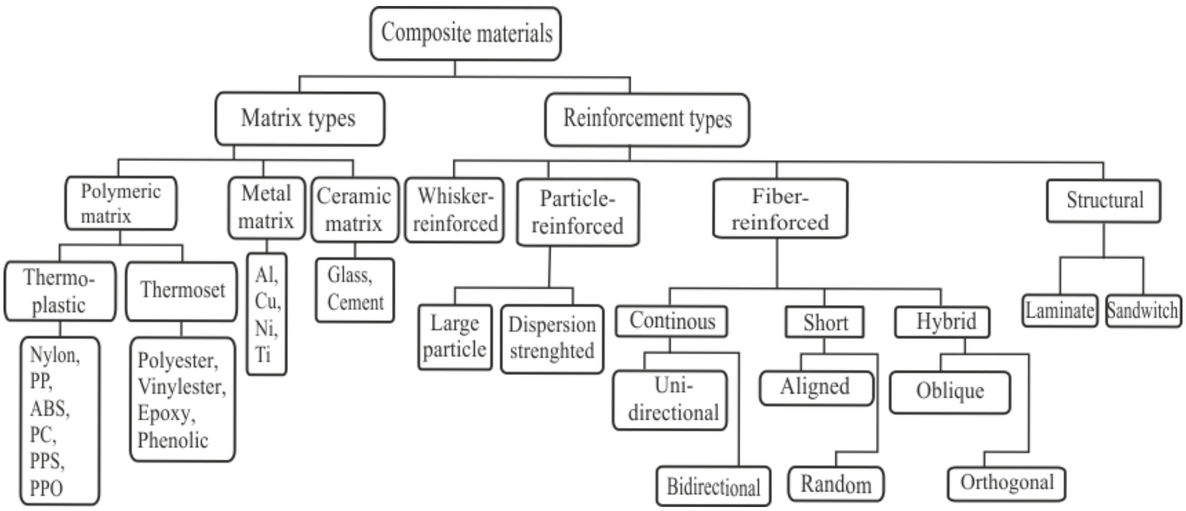


*Figure 2.16 Composite material classifications based on reinforcement and matrix types (Priyanka et al. 2017)*

In designing FRP many factors must be considered, fibre material, reinforcement architecture, weaving pattern, fibre orientation, stacking sequence, and number of fabric layers all affect the final composite part performance. Multiple plies are stacked in specified sequences to obtain the desired performance of a composite material, this adds thickness and reinforces the composite part to support a given load or maintain given deflections. The stack that is created is consolidated to form a laminate (Mallick 2007).

When clear loading conditions of laminates is unknown, a quasi-isotropic layup can be used. This layup is used to mimic normal isotropic material behaviour, where properties are equal in all directions. There are two common layup stacking methods to obtain such behaviour, a $[0/45/-45/90]_s$ or $[0/60/-60]_s$ are suitable (Lombard 2014). The notation used to describe such a layup indicates to the orientation of individual plies in a preform, in the $[0/45/-45/90]_s$ quasi-isotropic example, “0” refers to the first ply where the fibres are running parallel to the length of the component, the following ply is then placed with the fibres running 45° to the first layer and so on. The subscript “s” indicates that the laminate is symmetric, meaning this is an eight-lamina composite where the second four plies are a mirror image of the first four (Chung 2010).

Laminates can contain various fibre types and orientations, combining different forms of fibres results in an interply or an intraply hybrid laminate. These hybrid laminates differ as an interply is a laminate consisting of various kinds of laminates in comparison to the intraply, which consists of different types of fibres within a single lamina. For the best interlaminar bonding results the same matrix is typically used throughout the laminate (Mallick 2007; Priyanka *et al.* 2017).

The principal fibres in commercial use are usually variations of glass, carbon and aramid, often known as Kevlar (Masuelli 2013; Ngo 2020). However, these are not the only available fibres for manufacture, *Amiri et al. 2017* adopted a hybrid manufacturing approach using 70% flax fibre (a natural fibre) in combination with 30% CF and a bio-based epoxy resin to build a composite bicycle frame. The aim of this hybridized structure was to avail of the advantages of one type of fibre and overcome the disadvantages of the other fibre. In this study the author tries to balance the cost, performance, and sustainability of the structure with the high-performance characteristics of carbon fibre and the low-cost and renewability of flax fibre (Amiri *et al.* 2017).

Fibres composite reinforcement fabrics are distributed in two common ways, dry or pre-impregnated with a matrix (prepreg). Composite moulding with prepreg materials uses heat and/or pressure in various ways to shape the composite to tooling surfaces. Dry fibres however are utilised in wet moulding techniques where the matrix and reinforcement are combined during the moulding process (Masuelli 2013).

### 2.3.2 The Matrix

In terms of FRCs, the vast majority of matrix materials are polymer based, these materials are known as polymer-matrix composites (PMC). There are several different polymers used in the industry, PMCs are classified by the matrix material as either thermoset or thermoplastic. Most commonly thermosetting polymers are used (Figure 2.16) however, thermoplastics are gaining popularity. Both thermoset and thermoplastic have their place as matrix materials in composite manufacturing with benefits and limitations to both. Thermosets have been traditionally used and are well-established, often they have lower raw material costs and allow for easier wetting of reinforcing fibres making them more easily processed than thermoplastics. In contrast thermoplastics tend to be less-brittle than thermosets and do not need refrigeration like uncured thermosetting prepregs (Chung 2010; Ngo 2020).

*Basic Matrix Properties*

Thermosetting polymers are an excellent substitute for most of the conventional materials. The principal commercial groups of thermosetting resins are phenolic resins, epoxy, unsaturated polyester, and vinyl ester. Typically, these resins are sold in a liquid form and through chemical reactions or applying heat these materials are crosslinked or cured, solidifying them. These materials will degrade rather than melt, the temperature resistance or glass transition temperature of these materials varies and is often dependant on the maximum temperature experienced during curing (Summerscales et al. 2018).

Epoxy resins are one of the extensively used thermosetting resins. Often used in engineering applications in the form of coatings and structural adhesives, however, in FRP applications is stands out due to its superior thermal and mechanical properties, excellent corrosion and chemical resistance (Shivamurthy et al. 2013; Abdurohman et al. 2018).

The properties associated with common polymer matrices are listed (Table 2.1 Comparison of typical polymer matrix properties (Mallick 2007; Chung 2010)), epoxies are often stronger, stiffer and more brittle than most thermoplastic polymers. Another major difference between thermoplastics and epoxies is the higher processing temperatures of thermoplastics (300–400°C) (Chung 2010).

*Table 2.1 Comparison of typical polymer matrix properties (Mallick 2007; Chung 2010)*

| | Common Thermoplastics | | | | Low Temperature Cure Epoxy |
|---|---|---|---|---|---|
| | PES | PEEK | PEI | PPS | Epoxy |
| Processing Temperature (°C) | 350 | 380 | 350 | 316 | 23 |
| Tensile Strength (MPa) | 84 | 70 | 105 | 66 | 55-130 |
| Tensile Modulus (GPa)) | 2.4 | 3.8 | 3.0 | 3.3 | 2.75-4.10 |
| Density (g/cm3) | 1.37 | 1.31 | 1.27 | 1.3 | 1.2-1.3 |

With regards to epoxies and thermosetting resins the pot life (or cure time) and temperature are necessary aspects to complete the polymerization reaction which are reliant on the type and amount of curing agent used. the reaction initiates and proceeds at room temperature with some curing agents, however, others require elevated temperatures to cure. Epoxies as a matrix group have multiple advantages over other thermoset matrices including (Mallick 2007):

1. A wide variety of properties, as a variety of starting materials, curing agents, and modifiers are available
2. An absence of volatile maters during cure
3. Low shrinkage during cure
4. A strong resistance to chemicals and solvents
5. Having excellent bonding and adhesion properties with a wide variety of fillers, fibres, and other substrates.

In many industries there is a growing demand for high performance end-use components such as automotive components, chemical and water tanks which are expected to build on the global market for thermoset PMC over the next 6 years. Thermosetting polymers have proven to withstand harsh conditions (a result of the many advantages thermosetting materials possess as outlined above from Mallick 2007), through 30-40 years of use in aerospace applications. For example, the fuselage of the Boeing 787, which uses an epoxy-based PMC (Ngo 2020).

Considering the many advantages of thermosetting PMC, from this point onwards of this study only these materials will be considered. For the aim of this study is to minimise the barriers to entry of prototyping of FRP through low-cost tooling. To keep the fabrication costs low, relatively inexpensive fabrics, and matrix materials will be used with processing techniques that allow for bespoke or short series manufacturing to be conducted with inexpensive tooling.

### 2.3.3 FRP Processing Techniques

There is a wide variety of composite manufacturing processes, these processes are continuously advancing to meet specific manufacturing challenges making it difficult to recommend any one given process. Part design, choice of feedstock and the choice of processes are co-dependent; any change to one of these attributes will lead to changes in one or both of the others. Factors that typically determine the final manufacturing process are the component geometry, size, the required mechanical performance and the predicted scale of production (M.G. Bader 2002). Common composite manufacturing techniques such as

- Open contact moulding
- Resin transfer moulding
- Compression moulding
- Pultrusion
- Filament winding
- Autoclave moulding

will be described in this section. The purpose of describing these is to provide an overview of the available processes, to allow for an informed decision to be made with regards to the suitability of these techniques for the manufacture of low-cost composite parts via RT.

### 2.3.3.1 Open Contact Moulding

Hand lay-up is one of the oldest and simplest techniques for fabricating composite parts. Operators manually place dry reinforcement onto a single sided mould and resins are then poured and spared over the fibres. Operators then take brushes and/or rollers to force resin into the fibres and to remove air pockets that may get trapped between plies of reinforcement (Figure 2.17). For thick or large parts, this process can be done over multiple stages where a few layers of fibres are wetted and let cure in standard atmospheric conditions prior to adding more reinforcement (Strong 2008; Vogt 2011; Nagavally 2017; Abdurohman *et al.* 2018; Ngo 2020).

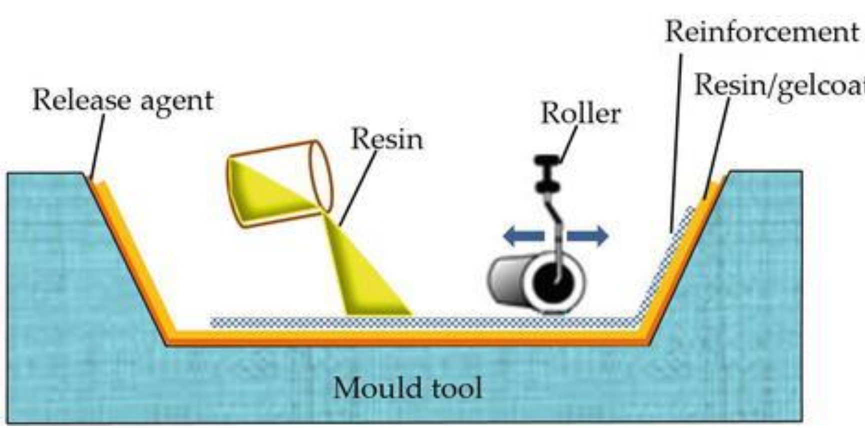


*Figure 2.17 An illustration of the hand lay-up process (Ngo 2020)*

Spray up moulding, similar to hand lay-up is an open moulding process that is generally used when parts size increases and designs are simple. This is a semi-automated process allowing operators spray short fibres and resin onto the tooling surface simultaneously. Once the mould is sprayed up operators roll the laminate to compact the fibres and reduce void content (Figure 2.18). This technique is not used for small complex parts, but typically used in the construction of boat hulls, baths and shower trays. Limitations of this method in contrast to the hand layup process are the equipment required for spraying, more limited resin selection, random orientation of fibres and the need of higher skilled operators (Strong 2008; Vogt 2011; Ngo 2020).

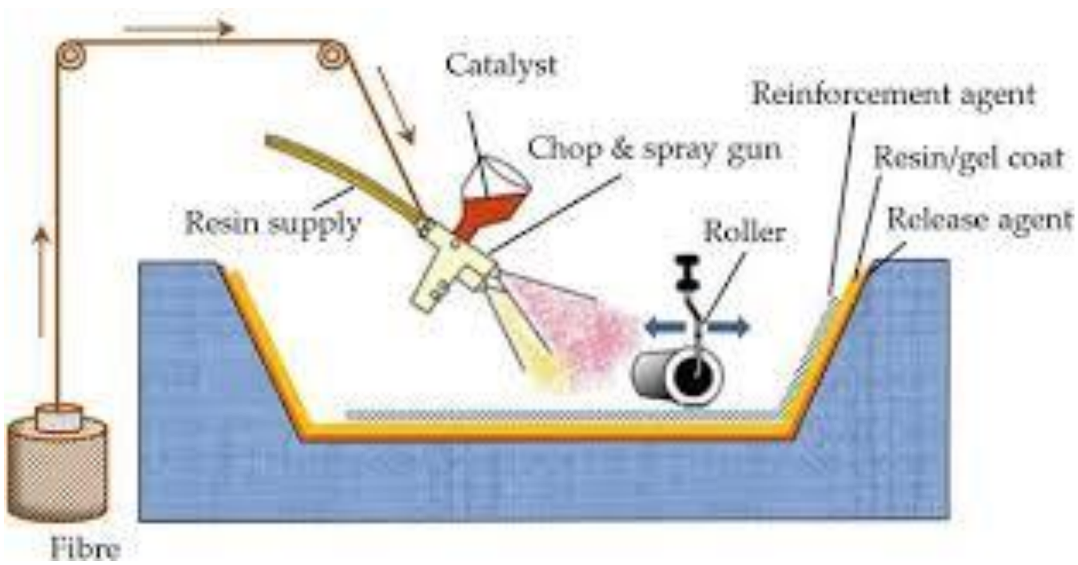


*Figure 2.18 An illustration of the spray-up process (Ngo 2020)*

These open moulding processes are often used in tandem to reduce labour costs, however, operator experience can be a limiting factor in the repeatability and quality of the parts (Vogt 2011; Nagavally 2017; Ngo 2020).

### 2.3.3.2 Resin transfer moulding

As demand for faster production rates continues, alternative fabrication techniques have been required to replace open contact moulding processes with semi-automated processes where possible. RTM is often considered the most appropriate route to mass production for small to medium sized composite components. This is a closed mould process where dry fibre preforms are placed between two mould halves that have had mould release pre-applied, the mould halves are then clamped together and heated to a set temperature (Figure 2.19). A low-viscosity thermosetting resin and catalyst are then dispensed, mixed and injected into the mould under pressure to wet out the fibre preform quickly before the resin begins to gel and cure, and to remove air from the mould (Khan and Mehmood 2016; Ngo 2020).

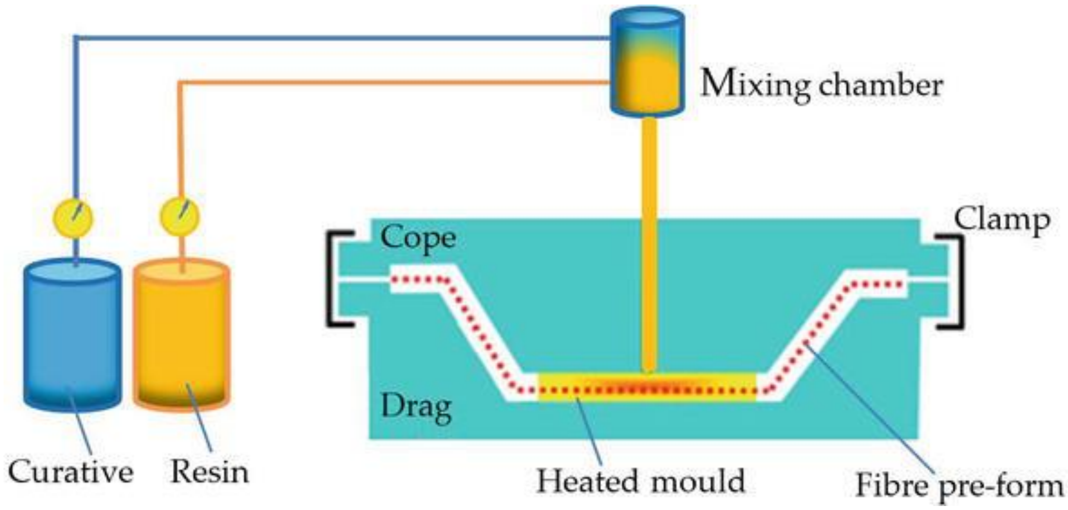


*Figure 2.19 An illustration of the resin transfer moulding process (Ngo 2020)*

Relatively low capital and operating costs, good dimensional accuracy, good surface finish on both sides, high fibre volume fraction and low emissions are some of the main benefits associated with RTM. However, limitations arise with tooling design, where it can be difficult to produce complex parts that require trial and error experiments or flow modelling to be conducted (Mazumdar 2001; Khan and Mehmood 2016). RTM has been heavily adopted by various automotive manufacturers, McLaren used the process in producing components for the Mercedes SLR and BMW have used RTM in manufacturing CFRP roofs and other components for their M3 and M6 models (Jacob 2010). In a study conducted by (Khan and Mehmood 2016) to identify cost-effective composite manufacturing processes, many more developments and successful RTM applications are presented with an emphasis on the automotive sector.

*<u>Vacuum Assisted Resin Infusion</u>*

The RTM process is suitable for relatively small components, however as parts size increases, the forces of the closing mould halves become too great. These moulding forces and the ever-increasing pressure from the aerospace and wind energy industries for lower costs has driven process innovation for more cost-effective manufacturing processes. Many researchers and companies have been focused on vacuum infusion understanding and improvement. As a result of all this innovation there are many resin infusion methods and procedures mentioned throughout the literature that represent a subgroup of the LCM group (Advani *et al.* 2003).

These resin infusion processes use vacuum pressure to wet-out fibre preforms rather than injection pressure that is used in RTM. A primary difference between infusion and RTM is mould design. Rigid matched mould halves are required for RTM to withstand injection pressure. Flexible films over single sided tooling replace a matched pair of moulds in infusion processes, reducing the cost of manufacture even further when compared to the traditional RTM process (Mallick 2007; Khan and Mehmood 2016). It is a common misconception that resin is sucked into the cavity (mould) during resin infusion processes. However, the pressure difference between the resin supply and the mould, driving resin to flow through the fibre stack (Hindersmann 2019).

### *Resin Infusion Under Flexible Tooling*

These cost-effective infusion techniques can achieve the required laminate quality while reducing the consumption of auxiliary materials and resin. Much research has been published focusing on the understanding and the enhancement of vacuum infusion. Therefore, a large number of infusion techniques, all contained within the liquid composite moulding group have been developed (Advani et al. 2003). This development of technologies has led to some confusion and an acronym jungle as described by (Beckwith and Hyland 1998), since resin infusion under flexible tooling (RIFT) has been used as a collective term for these processes (Summerscales and Searle 2005; Hindersmann 2019).

### *Vacuum Assisted Resin Transfer Moulding*

Vacuum assisted resin transfer moulding (VARTM) is the most basic form of RIFT where no distribution of flow media is used to air fibre wet out. First used in the 1950s, that other infusion variations and methodologies evolved from (Muskat 1950). The structure of the VARTM process from bottom to top consists of a mould surface, a ply stack, a release fabric and a vacuum bag sealed to the mould using a thick sealant tape to produce an airtight seal. Resin inlets and vacuum outlets are positioned in the mould to best promote resin flow (van Oosterom *et al.* 2019).

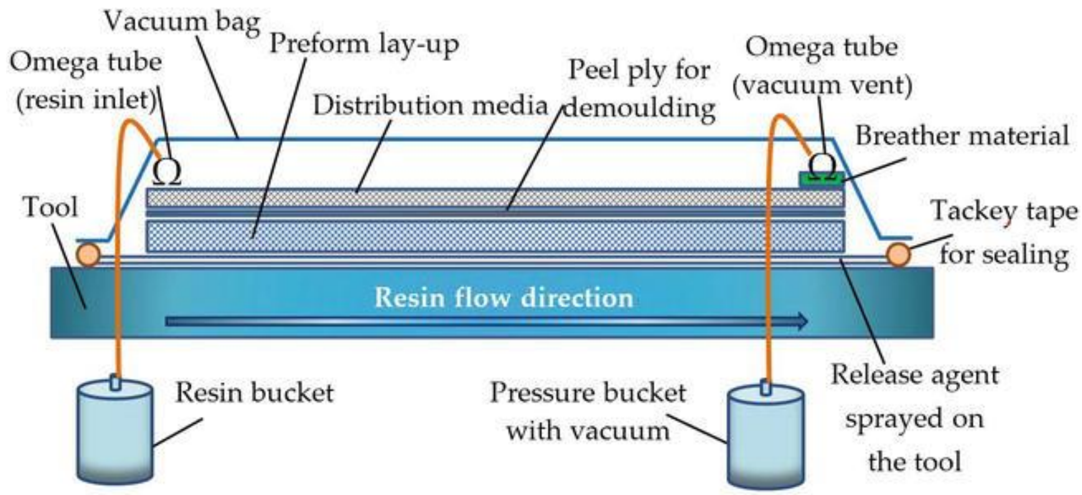


*Figure 2.20 An illustration of SCRIMP, similar to VARTM but with an added distribution media to aid resin flow (Ngo 2020)*

*<u>Seeman's Composite Resin Infusion Process</u>*

Seeman's composite resin infusion process (SCRIMP) is the most widely used form of resin infusion, patented by Seemann Composites Inc. in 1990. SCRIMP consists of a similar set up to the traditional VARTM, but with the addition of a consumable distribution media and/or flow channels that are designed to assist the flow of resin across the surface of the part, reducing the time required to wet out the preform. Flow channels are generally used within foam cores, that are used in sandwich structures. The distribution media can be positioned below, above or within a reinforcement stack. This allows for drastically faster infusion speeds using the same resins and fibre reinforcement stacks when compared to VARTM (Seemann III 1990; van Oosterom *et al.* 2019).

Using resin infusion techniques, high fibre volumes of up to 70% can be achieved, the semi-automated process ensures low void content and consistent preform reproduction. RIFT processes have been significant in boatbuilding, they have also been adopted by The Boeing Co. (Chicago, IL, USA) and NASA, as well as small fabricating firms, to produce aerospace-quality laminates without an autoclave (Ngo 2020).

### 2.3.3.3 Bag Moulding Process for Prepreg Materials/ Autoclave material processing

The bag-moulding process is most used in the aerospace industry where having high production rates is not an important consideration (Mallick 2007; Thorvaldsen 2012). High-performance composites, such as aerospace components, are manufactured by vacuum bagging of prepreg with autoclave cure (Rogers *et al.* 2014). The autoclave bag moulding process is the state-of-the-art manufacturing technique for high performance applications, as high-performance thermoset parts require heat and high consolidation pressure to cure, conditions that are achieved using an autoclave (Türk *et al.* 2016; Nagavally 2017). An autoclave is an expense for the company, both the acquisition and to run the autoclave (Thorvaldsen 2012). Manufacturers that are equipped with autoclaves usually cure several parts simultaneously (Nagavally 2017).

The method of layup is either manual hand layup of prepreg materials or by numerically controlled automated tape layup machines (Mallick 2007; Thorvaldsen 2012). Typically autoclave cure prepreg materials are used where individual sheets of prepreg material are cut and laid down in the desired fibre orientation in an open mould. The material is covered with release film, bleeder/breather material and a vacuum bag. A vacuum is pulled on part and the entire mould is placed into the autoclave, where predefined temperatures ranging up to 180°C and pressures up to 10 bar are applied for curing and consolidation of the part. This is a very common process in the aerospace industry because it affords precise control over the moulding process due to a long slow cure cycle that can run for multiple hours. This precise control creates the exact laminate geometric forms needed to ensure strength and safety in the aerospace industry, but it is also slow and labour intensive, meaning costs often confine it to the aerospace industry (Masuelli 2013; Türk *et al.* 2016).

#### 2.3.3.4 High Volume Moulding Techniques

*Compression Moulding*

Compression moulding is a closed mould process, which is suitable for processing both thermosetting and thermoplastic materials. The moulding compound, that can be thermosetting prepregs, fibre-reinforced thermoplastic, moulding compounds such as sheet moulding compound, bulk moulding compounds, or chopped thermoplastic tapes, is placed in a heated metal mould either manually or robotically. A matched metal mould half is then closed using screws or hydraulic presses to apply pressure to maximise the compaction of the composite material. Cycle times are depending on the part size and thickness in compression moulding and typically complex parts with high strength can be produced with thicknesses ranging from 1 mm to over 50 mm (Khan and Mehmood 2016; Ngo 2020).

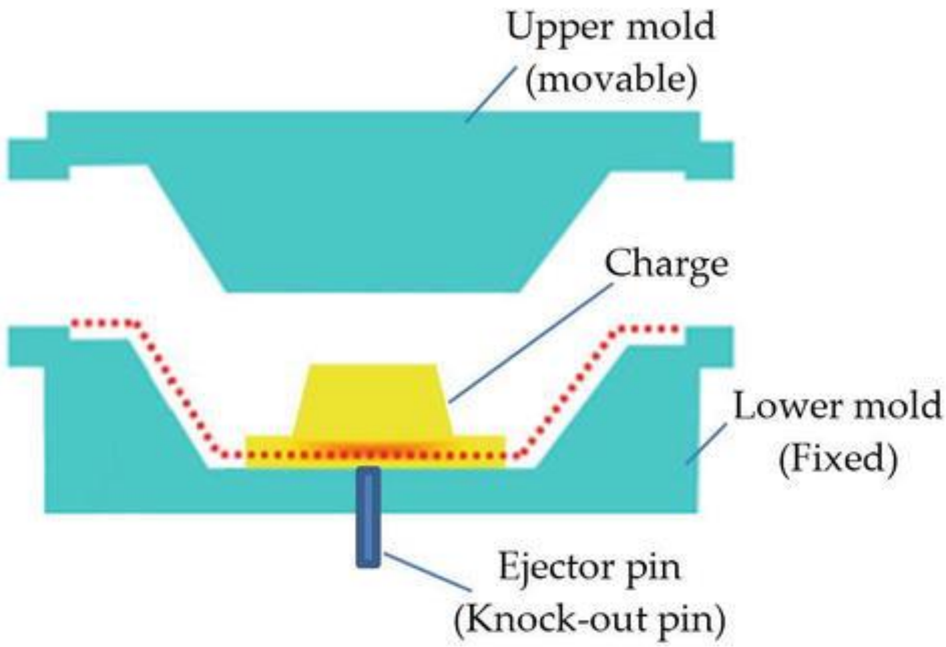


*Figure 2.21 An illustration of the compression moulding process (Ngo 2020)*

This process allows for non-uniform thickness, ribs, bosses, flanges, and holes to be incorporated into the finished part, eliminating a number of secondary finishing operations, such as drilling, forming, and welding. The entire compression moulding process can be automated, making it very suitable for mass production of composite parts. It is considered the primary method of manufacturing for many structural automotive components, including road wheels, bumpers, and leaf springs (Mallick 2007; Howell and Fukumoto 2014).

*Filament Winding*

Filament winding is a continuous fabrication method that can be highly automated and repeatable, with relatively low material costs. A long, cylindrical tool called a mandrel is suspended horizontally between end supports. Dry fibres are run through a bath of resin to be wetted. After impregnation, they move back and forth by means of the guide, while the mandrel rotates at a specified speed, placing fibre onto the tool in a predetermined configuration. Computer-controlled filament-winding machines are used to control the motion of the guide and the mandrel. Filament winding results in parts with exceptional circumferential or "hoop" strength. The process can be automated for making high-volume parts in a cost-effective manner, the single highest-volume application of filament winding is in the production of golf club shafts, other major applications include fishing rods, pipe, pressure vessels and other cylindrical parts (Khan and Mehmood 2016; Nagavally 2017; Ngo 2020).

*Pultrusion*

Composite pultrusion is a processing method for producing continuous lengths of fibre-reinforced polymer structural shapes with constant cross-sections. In this relatively simple continuous process, the reinforcing fibre is typically pulled through a heated resin resin-wetting station or bath and then formed into specific shapes as it passes through one or more forming guides or bushings. The wetted material is then pulled through heated dies, where it takes its net shape, and the final composite profile is then left to cure. After curing, the resulting profile is cut to desired length. Pultrusion yields smooth finished parts that typically do not require post-processing. A wide range of continuous parts of both solid and hollow profiles are pultruded, such as I-beams, T-beams, or frame sections and ladder rails, the process can be custom-tailored to fit specific applications. Pultrusion is a low-cost, high-volume manufacturing process and therefore the major reasons for the growth of the pultrusion market (Mazumdar 2001; Khan and Mehmood 2016; Nagavally 2017; Ngo 2020).

This research will focus on low-pressure liquid composite moulding techniques for parts produced through these processes can be of great quality as previously discussed. Operator skill and judgment is used in infusion circumstances to determine the resin inlets and outlets. Although simulation software is sometimes used when there is a need to determine the flow of resin during RTM or vacuum assisted processes. Such software that is used is RTM-Worx by Polyworx, this package uses a generalised version of Darcy’s Law and Continuity equation to develop a model for flow through a porous media. A combination of finite elements and constant velocity methods are used in these packages to solve the flow problem. Software packages like this can be used to improve locations for resin inlet and vacuum outlet ports ensuring full wet-out of fibres and an indication of resin filling times (Dippenaar and Schreve 2012). For this research, such software was not used as it is outside the scope of this work as the focus is on a low-cost solution to produce direct and indirect tooling through AM techniques rather than the composite processing technique adopted.

## 2.4 Composite Part and Tooling Guidelines

Regardless of the manufacturing process the moulds are not just the definer of part shape, but also are the provider of a surface where composite materials are laid before they are cured (Strong 2008). Moulds or tooling for composite parts can be manufactured from a wide range of materials. For small batch production of parts that can be cured at ambient or low temperatures or for prototype parts where there is a lesser requirement for high dimensional accuracy, fiberglass, high density foams, machinable epoxy boards or wood can be suitable tooling materials. AM polymer tools are also becoming increasingly popular for both prototype and production parts. However, as part dimensional accuracy, surface finish and unit requirements increase so does tooling costs and complexity (CompositesWorld 2016).

The choice of which tooling material is used depends on multiple factors including mould wear, cure temperature, moulding pressure, thermal expansion and cost will determine the appropriate tooling solution. Metal tooling such as aluminium, steel or Invar (nickel-steel alloy) are generally superior when it comes to wear, temperature resistance and moulding pressures. Invar has been the tooling material of choice for many years, as it is a durable material that performs excellently with a similar coefficient of thermal expansion to that of composite materials used in them to make parts (CompositesWorld 2016). Although expensive to fabricate the investment of the tooling is recovered through mass production of components. However, over time as requirements for larger composite parts have risen, metal tooling has become impractical due to cost of machining invar and excessive weight of the tools. To overcome these challenges presented by metal tooling, the go-to process for many manufacturers has been to indirectly build composite tooling. The indirect mould making process has been proven as a viable tooling solution especially when using carbon fibre and epoxy for increased dimensional accuracy and mould stability rather than more traditional glass and polyester resins. Epoxies increase mould performance as they are more robust at elevated temperatures making them a more suitable tooling material (Stewart 2010).

The manufacture of indirect composite moulds is a two-step process. The first step is to produce a part known as a master model, also known as a pattern or a plug, which is a positive form of the finished component, which is used to produce the negative mould (Post *et al.* 2019). The plug takes the exact same shape as the finished part and is generally produced using traditional cutting processes. Once the 3D geometry of the part is finalised, scaling or sectioning of the part into distinct segments that will later be merged or bonded may be required depending on the size of the machine being used (Trivković *et al.* 2017). The plug is machined from foam (Kennedy 2018), MDF (Broad 2012) or wood (Amiri *et al.* 2017; Trivković *et al.* 2017), various surface coatings are applied that can be sanded and buffed to give a very smooth surface to build the final mould (Amiri *et al.* 2017).

Adhesion between part and mould surfaces, friction due to the absence of air between surfaces and some shrinkage of parts during the curing process can cause demoulding difficulties. Through the use of a suitable mould release system adequate draft angles adhesion can be mitigated. Draft angles must be incorporated into the master pattern design to ensure parts do not become trapped within the mould, a minimum draft angle of 3° should be used for shallow parts and at least 5° for deeper parts (Veldsman 1995; Dippenaar 2010).

When the master model has met the part finish and tolerances, it is prepared with a mould release. This mould release is applied to the surface of the pattern to ensure the composite mould will release post cure. The lay-up technique used when fabricating indirect moulds is similar to that of FRP products using open contact moulding techniques, first a specific tooling gelcoat is applied to the plug surface, before the fibre reinforcement and resin is applied until the desired mould thickness is achieved (Figure 2.22).

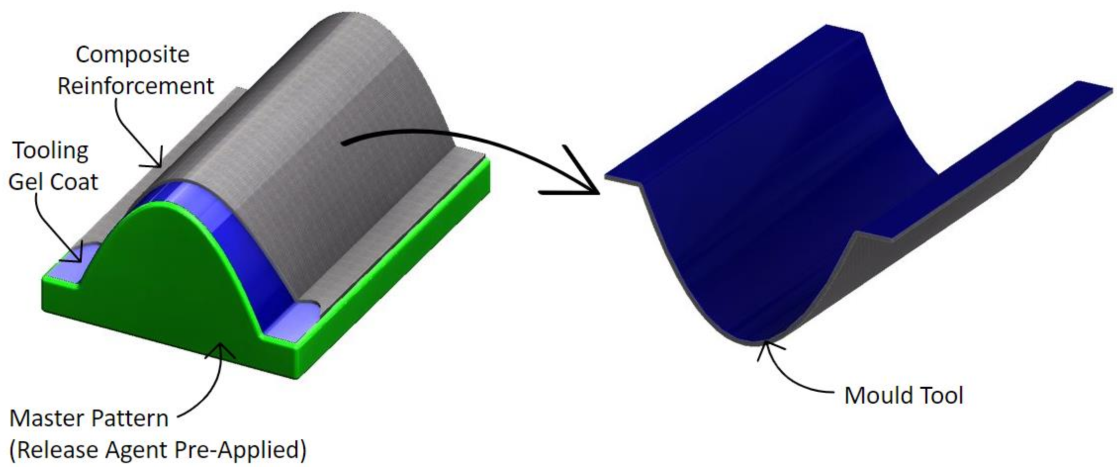


*Figure 2.22 Master model with tooling gelcoat (blue) and fibre reinforcement applied*

There are four steps in the mould building process (Figure 2.22), the order of events are as follows (Strong 2008):

1. Release agent
2. Gelcoat
3. Fibre layup & wet-out
4. Plug and Part Removal

*Release Agent*

Part removal is an essential stage of part production, tooling preparation through the application of mould release to master models and to moulds is an essential part of the composite moulding process and allow for the successful production of high quality FRP components (Thorvaldsen 2012). Regardless of tooling material, the importance of mould release agents cannot be over-emphasized. Release agents form a barrier between the mould and part, preventing part or mould adhesion and facilitating part removal (CompositesWorld 2016). Release agent selection is influenced by various factors such as mould size and complexity, moulding numbers and surface finish requirements. Applying an appropriate release agent is very important in ensuring quality and consistency in the finished product (S. Bader 2002). For open moulding, most releases are either wax or polymer chemistry based, polymer mould release systems are often semi-permanent, allowing multiple parts to be moulded and released between applications, in contrast to paste waxes, which need to be reapplied for each part. Semi-permanent releases, are preferred for better control over volatile organic compound (VOC) emissions, these are formulated specifically to meet the needs of RTM and other closed mould processes (CompositesWorld 2016). The most common types of release agent are described in this section.

Polyvinyl alcohol (PVA) is a film forming release agent often applied to the tooling surface that can be easily washed off of parts when they are cured, as PVA dissolves in water (Strong 2008; Chung 2010). PVA is available in concentrated form, or as a solution in water or solvent. It is commonly applied to plug/mould surfaces by cloth, sponge or spray. PVA release agents are generally used for small mouldings with a simple shape, or as a secondary release agent and are suitable for use on metal and FRP composite moulds. Care should be taken when using PVA-based release agents in vertical sections, as it tends to run down and accumulate in corners where it may take a long time to dry. If a moulding is laid up before any such areas are dry, the release agent will not be effective and result in adhesion, causing damage to the mould (S. Bader 2002).

Wax was first used as a release agent in the composites industry in the 1950’s. Carnauba wax-based products are the most suitable for use with composite materials and these are widely used, particularly in open contact moulding applications. Wax release agents are available in several forms but those most commonly used are pastes or liquids. Among the advantages of wax release agents are their ease of use, convenience and low-cost. Waxes are mostly used in low volume open contact moulding applications, as the need for regular re-application can be time consuming on larger moulds. There is also the potential for problems, created by wax build-up and transfer (S. Bader 2002).

Semi-permanent mould release systems such as Loctite Frekote and Easy-Lease provide good sealing properties with very low build up suitable for a wide range of tooling surfaces (EasyComposites 2017). Semi-permanent systems allow for multiple releases from moulds, making them the release agent of choice in some medium to high volume production. When using such systems it is essential that mould surfaces have been thoroughly cleaned to allow a good film to form on the surface (S. Bader 2002).

Both Loctite Frekote 770-NC and Meguiar's Mirror Glaze 87 are examples of effective release systems. A study from (Lombard 2014) shows the size of pinholes created by these systems are smaller and that the number of pinholes created by the other release agents were greater, when testing for a class "A" finish of in-mould gelcoated parts. Lombard found Loctite Frekote 770-NC release system and Meguiar's Mirror Glaze 87 Wax to demoulded easily, without any damage to either of the tooling surfaces tested (2K paint and gelcoat tooling surfaces were used) (Lombard 2014).

*Gelcoat*

The use of a gelcoat helps in achieving a better outer surface, this is a special layer of resin that is applied to the inner mould surface before the fibres are placed. The gelcoat becomes the outer surface of the composite part or tooling when it has been demoulded, as the gelcoat releases from the mould or plug it precisely replicates the moulding surface, therefore preparation is essential to achieving a clean surface free from any cosmetic defects. Gelcoat covered parts can then be used as end use parts or as a low-cost tooling solution. Gelcoats are sprayed or applied by brush to the plug or mould surface as per the manufacturer's specification, usually 0.46 mm ± 0.05 mm is the most suitable thickness for gelcoat applications, coatings that are too thin may not cure correctly and if they are too thick there is a risk of cracking the gelcoat. The gelcoat is applied to the tooling surface prior to the composite part lamination, as a decorative surface while providing a protective finish to the composite part beneath (Strong 2008; Witik *et al.* 2012). The gelcoats used as tooling surfaces differ from part surface layers, specially formulated tooling gelcoats are used as they provide a high gloss surface finish with good impact and chemical resistance (Reinforced_plastics 2004). When applying tooling gelcoats with a brush, long even strokes and firm bristles should be used, trimming the bristles can increase the stiffness of the brush. Stiffer bristles aid in preventing void formation in the coating, applying heat during gelcoat application is another common method of releasing surface voids (Lombard 2014).

*Mould Finishing*

In the automotive industry, having acceptable surface roughness for exterior car body panels is referred to as Class A surface finish. Surface finishing can be divided into three classes denoted A, B and C. These classes are dependent on the location of the part and are described in (Table 2.2) (Lombard 2014; Upmold 2017; Varotsis 2020).

*Table 2.2 Summary of mould surface finishing characteristics (Upmold 2017; Varotsis 2020)*

| Class | Surface location | Comparative metal mould finish | Part Finish Characteristics |
|---|---|---|---|
| A1 | Any surface that the customer sees, for example exterior panels of doors, wings etc., plastic mirrors, optical plastic goods. | grade #3 diamond buff | - High-gloss finishes<br>- No mould parting marks or tool or machining marks |
| A2 | | grade #6 diamond buff | |
| A3 | | grade #15 diamond buff | |
| B1 | Any surfaces that are not always visible, but could be seen if exterior panels are, for instance, bent down. | 600 grit paper | - Semi-gloss with some sheen<br>- No mould parting marks, or tool or machining marks |
| B2 | | 400 grit paper | |
| B3 | | 320 grit paper | |
| C1 | Surfaces which are situated at the underside of a part which is permanently installed or covered by another part. | 600 stone | - Matt finish<br>- No mould parting marks, or machining marks |
| C2 | | 400 stone | |
| C3 | | 320 stone | |

Class A finishes are high-gloss surface finishes with no mould parting lines or machine marks. To achieve Class A finishes using sandpaper, higher grits than P600 must be used. This is suitable for composite soft tooling as gelcoats or painted surface can be sanded using P1500 paper (Aiken and Aiken 2010).

Sandpapers are inexpensive and effective for achieving the required surface quality for composite tooling. With this knowledge, sandpapers will be used to obtain high quality surface finishes in this project, to keep the investment costs at a minimum surface roughness measuring systems will not be used.

*Mould Maintenance*

Much care must be given throughout the mould making process to build a high quality mould, this care must continue throughout the life of the mould to ensure durability (Strong 2008). In a publication by (Stewart 2010), Bob Lacovara a principal consultant at Convergent Composites speaks to correct mould maintenance programmes, which must be put in place to ensure that moulds will be sufficiently durable and provide a good return on investment. Lacovara highlights that mould maintenance is often overlooked and becomes a mould repair situation as the moulds are often abused, only being treated when there are clear defects (Figure 2.23) such as chips or cracks at the trim edge or on the mould surface.

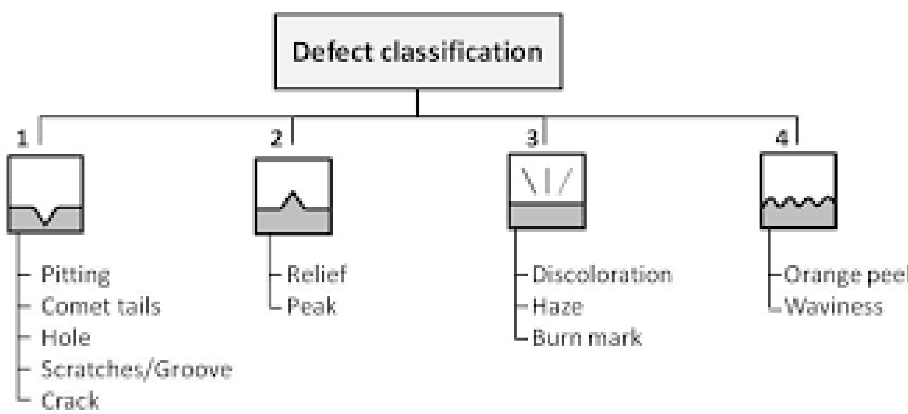


*Figure 2.23 Schematic of defect classifications to be avoided through effective mould maintenance programs (Rebeggiani et al. 2011).*

By stripping the mould surface periodically, polishing the tool and correct mould release application are essential processes in mould maintenance and can significantly increase mould life. A common tooling mistake he observes is inappropriate support structures behind the tool, tools with better designed support structures have proven to last longer than those supported by a lightweight structure (Stewart 2010).

*Tooling Design*

Soft composite moulds are often open moulds that can be either female or male moulds (Figure 2.24), the dimensional accuracy of a surface and the finish required will determine which mould type is used. The use of a matched mould can be beneficial in thickness control and creating parts with a smooth finish on both sides however, greatly increases the tooling costs (Niu 1992).

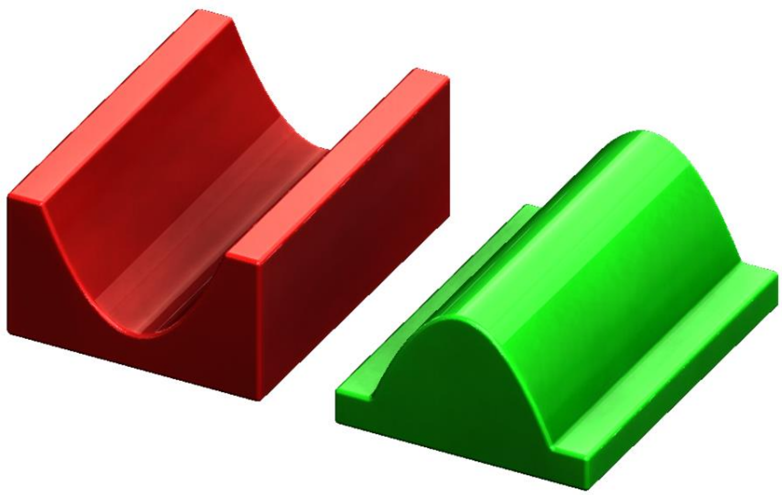

*Figure 2.24 A negative female mould (red) compared to a positive male mould (green)*

It is possible to CNC machine low-cost moulds directly, however this can result in some complications, firstly a reverse image of the final part must be machined as the mould and part will be reflections of each other. When designing the tooling this requires reverse thinking, doing so tends to be a common area where mistakes are made in the mould making process. The costs associated with machining is another area which can add significant cost to tooling whether directly machining a mould or a plug, as the machines used can be extremely expensive. Mould wear is the third complication that arises from directly machined soft tooling. For these reasons an indirect moulding solution is most commonly adopted to produce more robust production composite tools (Strong 2008). Direct tooling is generally only used for one-off projects where surface finish requirements are not a priority, it is advised to go the indirect route when batch sizes exceed 20. However, these guidelines are dependent on the parts that are to be produced from such moulds (Stewart 2010).

### 2.4.1 RT for Composite Manufacturing

Even with all the advancements made in composite material science and production methods in the past thirty years, the production of complex composite parts has proven to be a challenging and long process (Stratasys 2017c). Turk et al. have published multiple papers in the combination of AM with CFRP, one of the first was in combining the two to produce highly integrated structures, the case study used was the development of a Hydraulically actuated Quadruped robot leg. As tooling for complex composite structures is expensive and laborious, AM was adopted to produce the inner tooling for the complex shaped composite components. There are two major areas where CFRP can provide considerable weight savings, these include;

- Load introductions into composites
- Production of complex shapes currently limited by tooling

Removing the need to join composites in post-production was one of the driving forces to the original work conducted by (Türk *et al.* 2015). Joining of composites is a challenging process in load bearing areas as the laminates strength and stiffness characteristics cannot be fully transferred through the joint without a significant weight penalty. Generally, composites are joined using rivets (mechanical), bonding (adhesive) or both. Drilling holes through the reinforcing fibres of a laminate is required for mechanical fastening, creating stress concentrations in the laminate and reducing fibre length resulting in reduced load bearing capabilities of the material (Godwin and Matthews 1980). A common approach to overcoming these disadvantages in the joining areas is to locally thicken the laminate for reduced bearing and net section stresses (Parkes *et al.* 2014), this technique however greatly increases the weight of the joint area. The second common joining technique is adhesive bonding, this technique allows lightweight and complex structures to be created with an almost negligible increase in weight. Resulting in designs that avoids critical shear stresses being surpassed is essential for good adhesive bonding (Pethrick 2012).

Turk (2015) suggest that load introductions and inner tooling are the two main design potentials when combining AM with CFRP manufacturing technologies as tooling strongly influences component shape and thus loading transmission. Strength issues often arise in critical component areas such as joints and cut-outs, these critical points interrupt the primary load distribution by geometrical or material discontinuities leading to stress concentrations reducing the life of dynamically loaded structures (Wiedemann 2007). Quasi-isotropic layup is a design measure used to reduce stress concentrations in these areas when multiple loading cases are present (Schürmann 2005). Using quasi-isotropic laminates requires more material to be used in the area to attain the desired stiffness and often induces a weight penalty, reducing the weight advantage of using CFRP compared to lightweight alloy materials. Design optimisation is another design measure which can be used to reduce stress concentrations of a structure, this often requires highly complex geometries that can be extremely challenging to produce using traditional CFRP manufacturing methods. As previously discussed, (Section 2.2) AM is a technology which allows for highly complex designs to be manufactured. The production of such complex structures allows for components to be designed in a manner that reduces stress concentrations within a part. The combination of CFRP and AM can be used to produce hybrid materials, which can be used to manufacture components containing the required specific properties provided by the CFRP and overcome the geometrical complexity challenge faced through AM (Figure 2.25) (Türk *et al.* 2015).

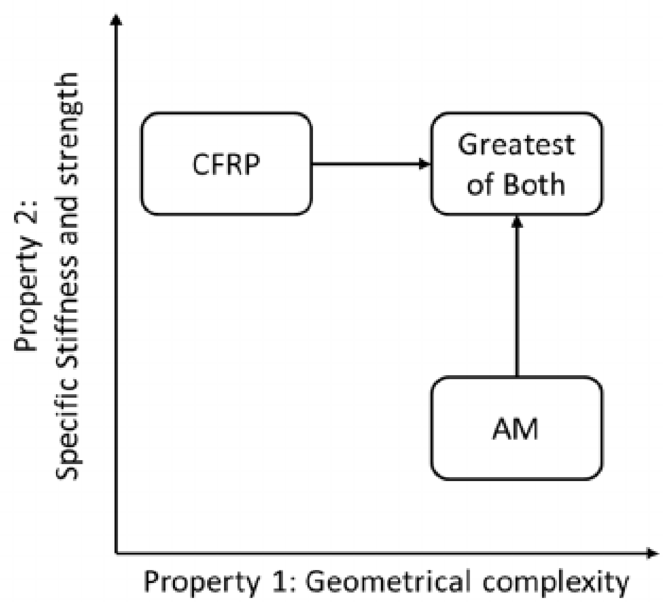


*Figure 2.25 The benefits which can be achieved through the hybridization of CFRP and AM according to Ashby (2011) (Türk et al. 2015)*

Stratasys a major producer of AM machines and technologies recognised through industry partners the benefits that can be realised through this combination of AM for composite tooling. One of these case studies describe how SSL a designer, manufacturer, and integrator of satellite systems in California takes advantage of FDM for rapid response, customised, high temperature lay-up tooling. SSL for many years had used FDM as a method for prototyping and even producing some production parts, however FDM proved more beneficial for SSL to produce this high temperature tooling when very short lead times were required for custom and complex geometries. In partnership with Stratasys SSL were able to produce the required tooling in under two days a 50% reduction in lead time that was essential for the project. SSL found themselves in a case where high costs and long lead times associated with tool production could be eliminated. With such large cuts in lead-times SSL gained much flexibility as it allowed them to meet increasing demands and also gave them more design freedom with the ability to run more product iteration cycles, resulting in superior final parts with increased levels of performance and functionality (Stratasys 2017c).

Another case study published by Stratasys is an overview of how Spring SRL an Italian concept development and prototyping firm found FDM a viable method for producing tooling for composite motorcycle fenders. The Italian company incorporated ten FDM printers from Stratasys into their concept development process, in doing so they were able to meet customer demands for larger quantities and with shorter turnarounds. Spring SRL found that 3D printing helped them in breaking down the barriers of traditional manufacturing for low-volume production. The use of Stratasys ST-130 soluble support material gave Spring SRL great design freedom, as they could now lay-up the composite material on the mould which would be later washed away, leaving a final composite component. Using FDM printed tooling allowed them to reduce their lead times for the fender project by 75%, with a 50% reduction in tool fabrication time when compared to traditional methods. Tool weight reductions is an area in which Spring SRL valued the example given in this case study is of a CNC machined aluminium kitchen part that was replaced by an FDM printed polycarbonate one that was 59% lighter than the equivalent metal part. This part was produced 36% faster than using traditional methods while maintaining the required mechanical performance characteristics (Stratasys 2017b).

In 2015, Stratasys released a technical application guide for FDM sacrificial cores and mandrels for composite layups. This guide describes the difficulty in producing cavities that trap mandrels when the composite part has cured. Sacrificial cores have traditionally been made of eutectic salts, ceramic, urethane or memory bladders, these solutions present several challenges that include handling difficulty due to fragile materials, additional tooling being required and geometric limitations due to production or removal methods. Multi-piece extractable cores are also considered however, they are said to greatly limit final part geometry. To combat the shortcomings of traditional sacrificial tooling methods Stratasys have developed soluble materials for their FDM machines. The process of using FDM to fabricate complex sacrificial tooling is said to be a more cost effective and efficient approach to producing seamless composite parts with high-quality internal surface finishes. The technique proposed by Stratasys involves wrapping composite materials around the sacrificial core and once the resin has cured, the core is dissolved. Stratasys say that wrapping composites around a core is a simpler process than pressing it into a cavity as it is less labour intensive and eliminates the need for hard tooling (Stratasys 2015b; Ross Jones 2017). One of the early partners with Stratasys using this technology is Champion Motorsport, who develop aftermarket components to improve the performance of Porsche cars. They design inlet ducts to provide more power to the engine through better airflow, from carbon fibre for strength and weight purposes as well as its ability to be moulded into complex geometries. Traditional manufacturing techniques forced Champion Motorsport to sacrifice either airflow or part aesthetics as moulds for complex hollow composites is difficult to achieve. Traditionally to produce parts with smooth inner and outer walls components were moulded in two parts and bonded in a secondary process, resulting in hollow composite parts that would be weaker than ones made from a single piece. Champion experimented with sacrificial sand cores but had difficulty producing these consistently. Taking CAD files and directly printing the moulds proved very beneficial as a technique for producing their internal cores, with better internal and external surface finish. The design iteration and prototype building phase were very important for Champion as they often go through up to eight prototypes before producing a part that works as intended. With FDM and soluble cores the required man hours to produce tooling is greatly reduced as the machines can be left unattended building these parts itself while the operator can now be doing another task. Louis Malone, the Technical Director at Champion Motorsport praises the FDM process as it saves "time and money" while opening up new design possibilities (Wyman 2015).

Although there are many examples of AM being used in the composite industry, the technology is not yet widespread due to the associated risks of adopting such a technology. Much of the associated risks associated can be mitigated if low-cost AM techniques such as FFF are adopted. Evidence presented by Antin and Parnanen (2017) suggests that this technology can be used to make inexpensive tooling that is more cost effective in prototyping of FRP products. This study is brief and little information is provided with regards to the fabrication of the low cost tooling (Antin and Pärnänen 2017).

## 2.5 Literature Review Concluding Remarks

The tooling used in composite manufacturing can be categorised as either direct or indirect tooling. Traditionally, direct tooling has been produced by CNC machining from a solid block of material, different materials can be used depending on the tooling use case. Metals are generally used for high volume and high-pressure applications and foam/polymer tooling (soft) is often used in low volume scenarios. Direct soft tooling is generally only used for one-off projects where surface finish requirements are not a priority, it is advised to go the indirect route when batch sizes exceed 20. However, these guidelines are dependent on the parts that are to be produced from such moulds (Stewart 2010).

Indirect tooling is used to make traditional composite moulds, this is a two-step process where firstly a positive master model or plug is fabricated from which a mould can be manufactured. Composite parts are created from the mould and the mould itself is created from a plug. Typically, the plug is CNC machined from a block of soft material (high-density foam or MDF) where the surface layers and their finishing are the most crucial elements of the plug, as these will determine the surface finish of the end product (Wanberg 2009; Lombard 2014).

Researchers have investigated the use of various types of AM to produce RT for use in composite fabrication. Stratasys FDM (Lušić *et al.* 2016), BAAM (Sudbury *et al.* 2017; Post *et al.* 2019), BJ (Türk *et al.* 2016; Maravola *et al.* 2019) are examples of AM technologies that have been investigated in producing tooling for composite manufacturing. Another area of composite manufacture that proves challenging is the production of complex (not straight tubes) hollow composites, the composite materials are generally laid onto two mould halves and an inflatable bladder is used to consolidate the composite materials. For custom hollow composites this method is very expensive, therefore AM has been investigated as a solution to this challenge using FDM and Stratasys proprietary materials (ST-130) (Türk *et al.* 2018)

In terms of AM technologies, The FFF technology has the largest market share of all AM technologies (Wohlers *et al.* 2019), with both a small footprint and a modest entry price these systems make AM accessible to more businesses and makers by providing the technology with a low financial barrier to entry (Zawaski and Williams 2020). The FFF technology is mainly used for fast prototyping as the mechanical properties and quality of printed parts are lower when compared to powder or resin-based systems (Ngo *et al.* 2018). AM for RT limitations with regards to material properties have been addressed by some companies, through the development of proprietary high-performance printing materials (ULTEM 9085/1010, ST130) for FDM, these materials are capable of being subjected to autoclave temperatures and pressures (Stratasys 2017a).

There are quite a few examples of the combination of AM and CFRP throughout the literature. Of these publications Stratasys FDM (Li *et al.* 2015; Lušić *et al.* 2016; Türk *et al.* 2018), BJ (Dippenaar and Schreve 2012; Türk *et al.* 2015; Türk *et al.* 2016; Maravola *et al.* 2019), and BAAM (Kunc *et al.* 2016; Post *et al.* 2016; Sudbury *et al.* 2017; Post *et al.* 2019) are the most common technologies for RT for composites. The technologies used are not the most accessible forms of AM, yes, it is true that tooling produced using these machines is less expensive than traditional hard tooling but the entry cost into the AM via these techniques is significant. Another significant factor to note about these studies is that the tooling in question was designed for autoclave curing conditions, which is known for being an expensive process to run. FDM is the technology that Stratasys recommend for tooling in their design guide “FDM for Composite Tooling 2.0”, this guide includes many essential topics such as tool design, construction, and post-processing. However, the materials outlined in this guide are only suitable for use with expensive industrial FDM machines, thus making the RT process for composites less accessible at low costs.

As FDM and FFF are both ME processes with similar build characteristics such as the stair casing effect, the design and finishing techniques outlined by Stratasys will be adopted throughout this work. The materials must change for this to be done, as low-cost FFF machines cannot process materials such as ULTEM that the Fortus machines can. For this reason, PLA will be used for its ease of use and availability, as the primary focus of this work is to try reducing the cost of prototyping composite parts. As the tooling materials adopted are soft with relatively low softening temperatures, less demanding composite processing techniques will also need to be adopted.

This research study aims to investigate how FFF (low-cost AM) can be adopted in a composite manufacturing environment either directly or indirectly for bespoke, short series and small-medium batch production.

# Chapter 3: Materials and Methods

The literature review provides evidence that there is a need for RP of functional parts. AM has gained much attention in NPD, however for testing purposes, prototypes should be fabricated using the same material as the intended end-use product. RT has been used to overcome this challenge, but the technologies typically used to manufacture such tooling are expensive, costing 10-100's of thousands of euros. This research focuses on the use of the FFF technology as a method to produce prototype and soft tooling for cost-effective composite parts quickly. While using such an accessible technology may offer many advantages relating to the investment cost and costs of consumables, it comes with some limitations, some of the major considerations to overcome include material physical properties, surface finish, maximum part size or print volume.

As highlighted through the literature review not all composite applications require autoclave curing, often thermosetting resins are curable at room temperature with or without vacuum consolidation are suitable. For room-temperature curing processes, mould materials need not be highly temperature resistant, it is important to note that these resins do generate heat through the chemical reaction taking place between the resin and hardener. Although autoclave parts are typically of higher quality, the use of such equipment poses significant expense, which is outside the scope of this study.

Surface finish is a common limitation for printed parts produced on both low-cost and industrial level ME machines where the staircase effect is present. The porous nature of parts fabricated this way is another aspect that needs to be addressed for tooling purposes. Through effective DfAM and post processing of parts using sealing and sanding techniques, the surface finish and porosity limitations associated with the FFF process are addressed in this chapter.

Thirdly, the small build volume of many low-cost additive technologies is a drawback restricting part size. Build volume limitations are overcome using sectioning in the design phase and bonding of the finished parts prior to post processing. This allows designers to think outside of the build volume and fabricate larger parts or moulds.

Presented (Figure 3.1) is a process flow diagram, outlining the manufacturing stages followed for the manufacture of cost-effective RT for low volume composite products. The proposed process flow is divided into two main sections, a virtual manufacturing stage and a physical manufacturing stage. Both manufacturing stages are described in this chapter and case study products will be built as per process flow. These case studies were conducted using the FFF technology and presented as a guide for producing cost-effective for composite products using FFF.

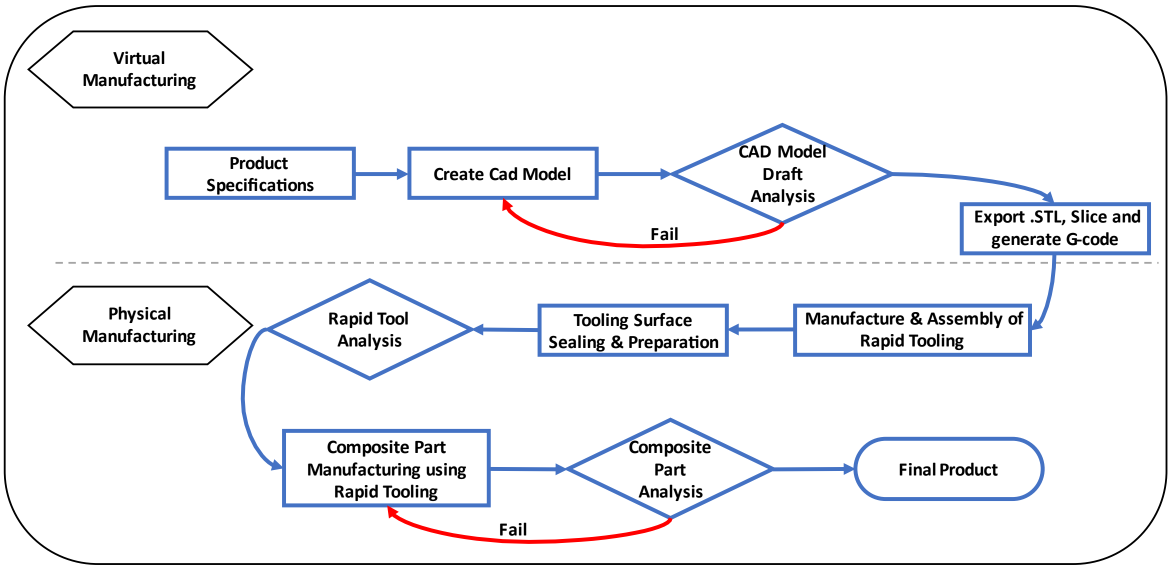


*Figure 3.1 Proposed process flow for producing composite parts using FFF.*

## 3.1 Equipment

The virtual prototyping requires both hardware (workstation computer) and software (CAD, slicing application). The hardware requirements for the virtual manufacturing phase are dependent on the CAD software used. Solidworks 2019 was the program of choice for this study. It is recommended to have a dedicated CAD workstation that are often specified with a multicore CPU with a high single core clock speed, as only one core is typically utilised in part modelling environments, large amounts of computer memory/RAM (16Gb or greater) and a certified professional graphics card are other key components for an effective CAD workstation.

From the CAD 3D modelling program individual part files are exported to the .STL file format that is commonplace in AM. The slicing software used to process the .STL files is Cura (version 4.5.0), this software is free to download and developed by Ultimaker, the manufacturer of the FFF machine used in this investigation. However, the Cura software is also compatible with a wide range of desktop FFF machines from third party manufacturers, with custom printer profiles available to download.

The physical manufacturing phase of this study was conducted using a FFF style 3D-printer, both desktop prosumer and consumer grade printers were used. The primary machine used in this study was the UM2+ (<€2,500 printer). The UM2+ is a single extruder machine that has similar properties to other low-cost AM machines with regards to resolution, material capabilities and relatively small print volume (223 x 223 x 205 mm). Hence, the Cura slicing software was chosen for its popularity and as it is the native software for this machine. A Creality CR-10S was also used (~€500 printer) for its significantly larger build volume (300 x 300 x 400 mm), see Appendix A.

Both printers used are FFF style 3D-printers, with open filament access meaning third party materials can be used. PLA material was chosen as this is the most popular material for these machines and is known for its ease of printing. RS PRO 2.85 mm Black PLA (batch: 16497102, tolerance ±0.1 mm, roundness ≥ 95%) was used in case in the direct and indirect RT case studies and water-soluble support material (Ultimaker PVA) in the soluble core case study. The UM2+ is a good representative of a standard single nozzle desktop FFF machine. The chosen machine has similar specifications to other low cost FFF machines with default layer heights of 0.04 mm - 0.15 mm and interchangeable nozzles (0.4 mm diameter default). For faster printing or for larger models, greater layer heights and nozzle diameters can be used. It is important to understand the relationship between layer height and nozzle size with print time. Also, larger layer heights and nozzles result in a more noticeable stair stepping effect on the final part which may add to the post processing and surface treatment times of the RT.

It is typical with composite processes that there are some consumable items used. Vacuum consolidated layup and infusion consumables such as vacuum bagging film, release film, peel ply, infusion mesh, breather cloth and tacky tapes were used where appropriate. A vacuum pump (EC4 Compact Composites Vacuum Pump) and resin catch pot (CP1 Resin Infusion Catch-Pot 1.2L) are required, all composite manufacturing equipment and materials were purchased through Easy Composites. With regards to the reinforcing fibres parts were fabricated from glass and carbon fibres accompanied with epoxy resins as the matrix material for its low VOC emissions, low levels of shrinkage and high-performance properties.

## 3.2 Virtual Manufacturing of RT

There are some important DfAM considerations that should be implemented into the CAD model of the RT. These DfAM considerations are very important for the successful production of parts using the RT method. Tool design does not only require DfAM, but also for successful production of composite parts, where mould and product designs are critical. Especially on a soft tool, more moulding design features must be considered to allow for success. Primary guidelines that should be considered in mould design for RT include;

- Implementing large positive draft angles in moulds to aid the demoulding process.
- Maintaining relatively simple mould designs, avoiding unnecessary geometrical features.
- Adding fillet radii and chamfers, avoiding sharp corners, which run the risk of race tracking.
- Designing tooling for net shape manufacturing to reduce on post processing operations.
- Design strong moulds with moulding forces in mind.
- Consider sealing solutions.
- Consider resin inlets and outlets to promote mould filling (for infusion).

These guidelines should be implemented from the beginning of the virtual manufacturing stage. The final product was first designed, from this the tooling surface that was generated using CAD. Depending on the type of part being fabricated the processing technique and consolidation methods may vary. There are three main vacuum bagging consolidation methods to consider a surface bag, a tabletop bag or an envelope bag. The choice of vacuum bag is determined on the style of tooling used. The two styles of tooling are block and shell tools (Figure 3.2).

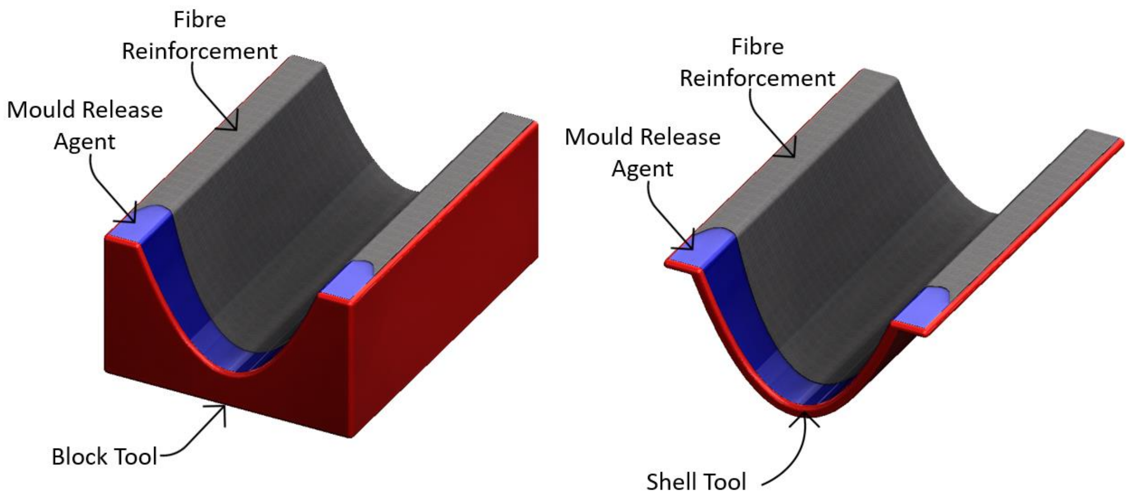


*Figure 3.2 Block Tool compared to a Shell Tool*

Block tooling is compatible with any of the aforementioned bagging types, however, for surface bagging the tool surface must be completely sealed to hold vacuum pressures. The surface must also be very smooth, like glass, so that the tacky tape used to seal the bag can adhere with an airtight seal, for this reason glass sheets are commonly used in infusion processes where constant vacuum pressure is required. The block tool uses more build material, resulting in longer tool fabrication times and greater expense. The shell tool is smaller resulting in a mould that requires less material and can more easily fit the build volume of AM machines. Envelope bagging is recommended for this kind of tooling. The envelope bags should be sufficiently large to reduce the risk of the bag bridging and negatively effecting the consolidation of the composite or damaging the printed tool. This bagging technique is often easier to set up as little to no pleats are required, as the FFF tooling is much lighter they can be moved easily into envelope bags (Schniepp 2017).

### 3.2.1 CAD Model Creation and Analysis

The tooling style is decided depending on the part design or process the composite product is fabricated from, regardless a tooling analysis is conducted. Draft angles are checked using the CAD software, this is one of the design considerations that must be checked during the virtual manufacturing phase. Minimum angles of 3-5° are recommended and a colour scale can be used to represent this visually (Figure 3.3). The virtual tooling was then inspected for sharp corners, edges and areas that may be difficult to print or cause moulding difficulties.

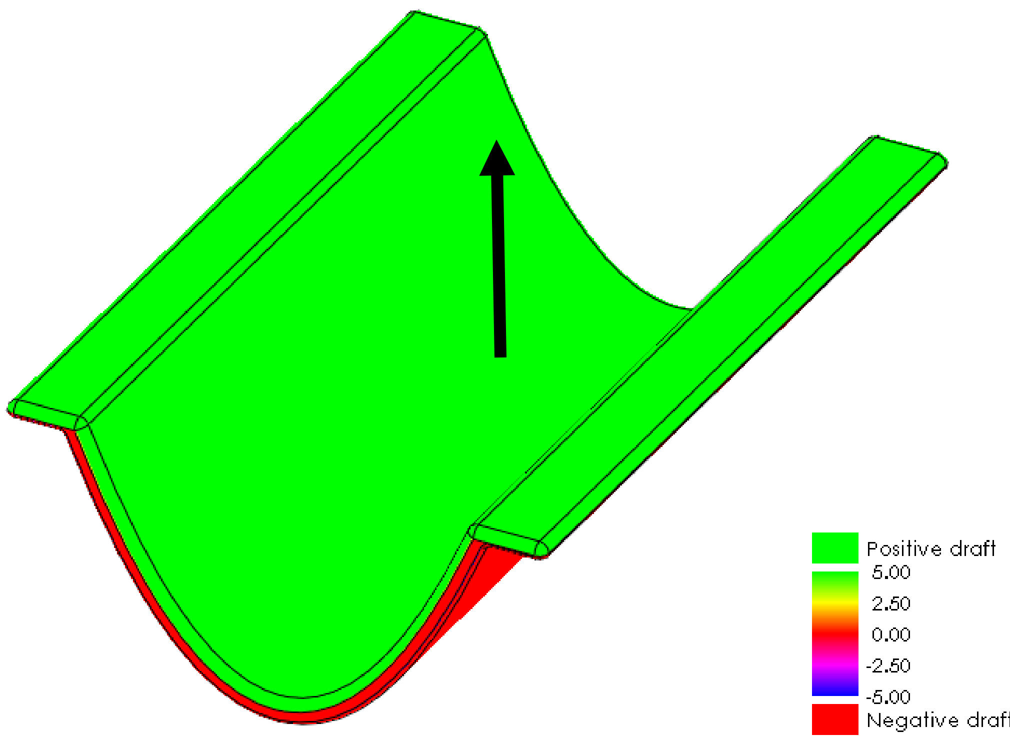


*Figure 3.3 Example of a draft analysis with a minimum positive draft angle of 5° in the direction of pull/demould highlighted in green.*

### 3.2.2 Design for Assembly

Once satisfied with the draft analysis and tooling considerations the part file was split (if required) to fit the build volume in the desired orientation. It is preferable to print the tooling as a single part if possible. If larger or modular tooling is required, where parts exceed the build volume of the AM machine, it is possible to design the tooling in multiple parts which are to be later assembled. Joint features are advised to ensure proper fit and alignment of segmented tooling. Mechanical joint features such as tongue and grove, dovetails and butterfly locks are appropriate, when designed large enough they add to the structural integrity of the joint as well as aiding in assembly and alignment. Butt joints should be avoided where possible, as these do not offer reliable mechanical strength or alignment that is required (Stratasys 2017a).

When working with PLA, cyanoacrylate (CA glue) is a common adhesive used when joining AM parts, however this can also be done with epoxy. Epoxies will provide a better bond than with conventional adhesives, with the added benefit that they will fill in the small gaps present between bonding surfaces (Formlabs 2016). An additional advantage of using epoxies is that they are also suitable to be used on the surface of the tooling to remove layer lines and stair stepping that may be present from the printing process. As an alternative to adhesives, thermal welding methods can be used. This technique involves fusing components making use of melting thermoplastic material. If welding is performed with build material this can result in a joint that preforms in a similar fashion to the surrounding structure both mechanically and thermally. There is a range of thermal welders available, such as extrusion welders that feed a bead of material into the joint interface and hot air welders that require material to be fed manually (Stratasys 2015a). The bonding methods and finishing techniques should all be predetermined to ensure all design features required for the techniques are considered prior to manufacture, allowing the design to be modified in CAD.

### 3.2.3 Exporting CAD Files for Slicing

DfAM and design for assembly concepts must be applied prior to exporting the .STL file, for successful tooling fabrication. Each individual solid body was exported from the CAD software as a .STL file, suitable for AM slicing packages. When exporting files to this format the quality was increased to generate files with a higher resolution.

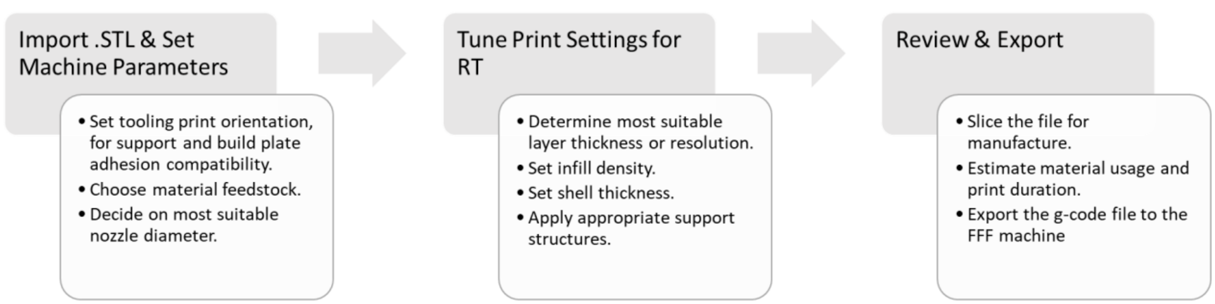


*Figure 3.4 Slicer workflow for RT using FFF.*

The workflow (Figure 3.4) for processing files in the slicing software is used to ensure a systematic approach. The .STL files were imported into the slicing software (Cura) to prepare for printing. In the slicing software, the print properties were modified from default settings to make parts suitable for use as composite tooling, especially if they are to be used as a direct tooling solution. Following the workflow in Figure 3.4 the tooling was processed in the Cura slicing software. On importing the .STL file of the tooling positioning and orientation within the build volume of the FFF machine are first addressed. Assess the tooling model and position it on the print bed with post processing and moulding in mind.

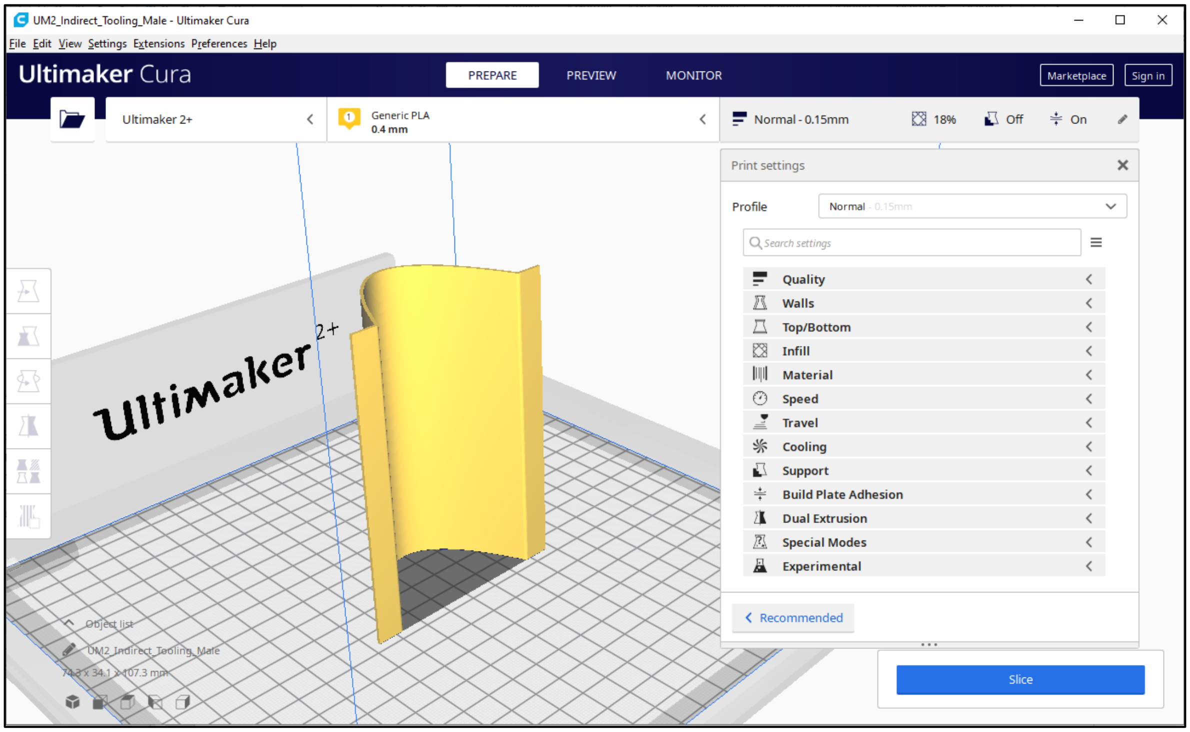


*Figure 3.5 The Cura "Prepare" screen with the STL file of the tooling imported, the "print settings" menu was used to tailor the material usage, tool strength and build time.*

The appropriate feedstock and nozzle diameter were chosen, the slicing software preconfigures the print profile for the selected inputs, this print profile determines settings such as extrusion temperature and print speeds. The preconfigured profiles were modified for RT purposes, to add material to the tooling surface to provide strength. In Cura the print properties are available on the right-hand side of the screen (Figure 3.5). The most influential FFF properties that were modified for RT were;

1. Build plate adhesion
2. Layer height
3. Shell thickness
4. Infill density & pattern

1. Build plate adhesion becomes an important factor depending on the contact area between the part and the build platform. Applying build plate adhesion features such as a brim will create a larger surface area for the tooling to adhere to the print bed, this is a single layer printed during the first layer of a print around the perimeter of the object to be printed. The other main advantage of this setting is that it will reduce the chances of the tooling warping at the edges during manufacture. A 5 mm brim was used in each case study, and support material was applied where overhanging features were present. An

upright or vertical print orientation of the tooling surface is most desirable, this is not always possible due to build volume limitations. If the model cannot be orientated with a tooling surface perpendicular to the build plate, orientate the model in such a way that the tooling surface is least affected by stair stepping, avoid the use of support material in contact with the tooling surface as this will result in surface imperfections that are difficult to remove when post-processing the RT.

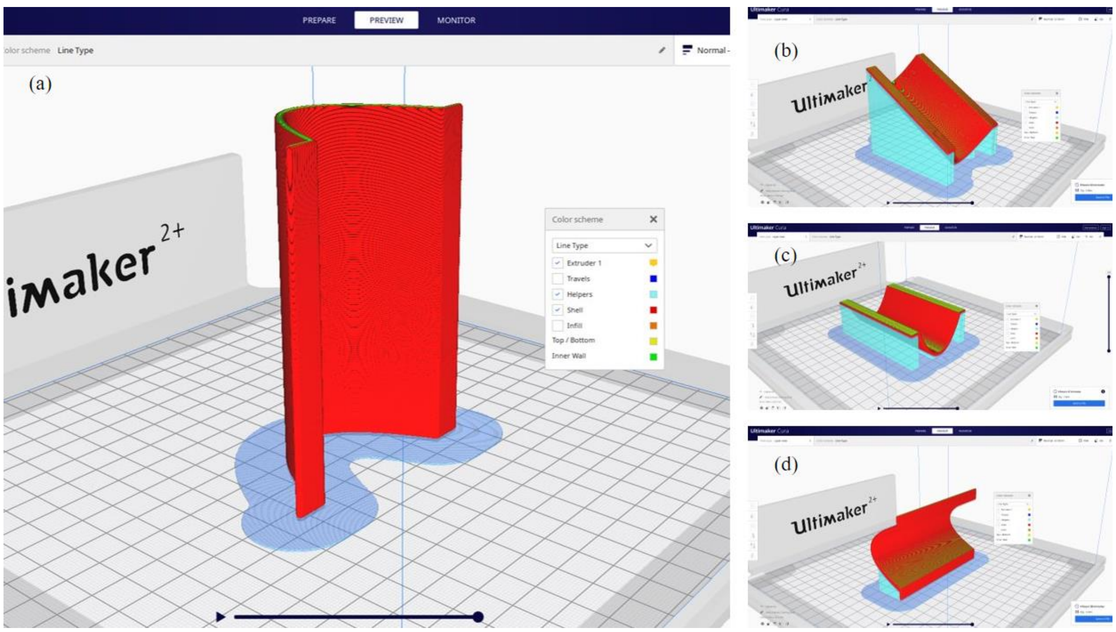


*Figure 3.6 Print orientation variations for RT: (a) Vertical orientation, ideal with direction of pull perpendicular to the z-axis. (b-d) various sub-optimal slicer angles resulting in greater staircase effect, longer build durations and greater material usage due to support requirements.*

2. A layer height 0.15 mm was selected for the RT in this study, this layer height was selected as it is relatively accurate when compared to other ME machines such as FDM with ULTEM which is printed between 0.254 - 0.33 mm (Stratasys 2020). Although the printer is capable of printing at higher resolutions, and some stair stepping is expected at 0.15 mm the build times were relatively short.
3. The wall and top thickness are important factors in maintaining a strong mould surface that can withstand the demoulding process, these settings determine the thickness of the skin or outer shell of the tooling. A minimum shell thickness of 1.3 mm was used for the RT case studies, as outlined in the literature this thickness aids is resisting adhesion and shearing forces (Jesse Hanssen 2009).
4. As there is a thick outer shell, the tooling infill does not need to be too dense, its purpose will be to provide rigidity to the tooling surface. Infill densities of 10% were used in this

research to reduce build time. Some infill patterns are more suitable than others, in attempt to increase the compressive strength of the tooling, a lattice infill pattern known as gyroid was selected. These patterns are generally used for their compressive benefits, which is important during the vacuum bagging procedure as pressure is applied from many different angles.

## 3.3 Physical Manufacturing of RT

The printer was prepared for tooling fabrication prior to each print job. The heated glass build plate was levelled, and a door was installed on the front of the machine to further enclose the printer. These preparation measures were taken to improve the consistency of the printed parts. Throughout the print cycle the progress was checked periodically to ensure there were no failed prints. The exported files were fabricated by the FFF machine, and the print bed was left to cool, this allowed for easy removal of the parts from the print bed, which was followed by post processing of the parts. The removed printed parts were inspected for defects. Once inspected the support brim material was removed by breaking it away. Poor surface finish was noticed in areas where support material was removed from the parts , these areas were then sanded to remove any support material remains, this was done by hand with a low grit (P120) sandpaper. This need to remove the support material manually highlights the reasons why supports were avoided on joining and tooling surfaces. The tooling was lightly sanded (P120) by hand all over, not to remove material but to roughen the surface of the parts for later adhesion with sealers.

*Joining*

The parts were then assembled, they were bonded using a CA adhesive which bonded each section together quickly. CA adhesive was used throughout this work for its ability to join tooling sections quickly and effectively.

*Sealing*

Due to the porous nature of FFF parts a sealing step must be included to improve surface finish and vacuum integrity especially if surface bagging. If not sealed effectively, the matrix resin used may penetrate the outer layer of the tooling making it difficult or impossible to demould. Epoxy sealers are the most versatile sealing solution as they can be used to accommodate tools of all shapes.


*Figure 3.7 XTC-3D epoxy sealer from Smooth-On, designed for sealing and filling 3D-printed parts.*

Epoxy sealers such as Smooth-On XTC-3D (Figure 3.7) can be applied using a brush, this specially formulated epoxy for 3D-printed parts has self-levelling properties and it is advised that a thin layer is applied and continuously worked until the resin begins to set up to avoid dripping or running. For complicated or large prints this process can be completed processing one section at a time, as the epoxy will bond to layers previous applied. Similarly, to applying gelcoats to composite tooling, the epoxy sealer should be left cure until it becomes tacky prior to the application of subsequent coats. If correctly applied each layer of XTC-3D should be very thin, approximately 0.4 mm. The sealer was left to cure tack-free; this should take two hours at room temperature however, this process can be accelerated to approximately fifteen minutes when cured at 60°C.

The sealed tooling received a final sanding and polishing using fine grit wet and dry sandpaper of at least 800 grit to achieve a Class A surface finish on the mould. The tooling must be cleaned to remove any dust particles and treated with a mould release system to finish the mould making process. A visual inspection takes place prior to composite part production to ensure there are no moulding defects.

## 3.4 Composite Part Manufacture

For wet layup processes, place the fibre reinforcement onto the tooling and brush or roll each layer with a laminating epoxy resin throughout the process. Upon completion of the layup process, the composite must be consolidated and set aside to cure. The consolidation technique can vary depending on the shape of the part. Often regular envelope bagging is best suited however sometimes shrink tape may be a more suitable option when dealing with internal tooling where traditional bagging may not provide the desired surface finish.

Other benefits of using shrink tape include ease of removal as it is coated in a release agent, fewer consumables and it leaves better cosmetic surface finish on the part. Using a heat gun to consolidate the shrink tape is common however, an oven might provide more consistent results as care must be taken with the heat gun not to exceed the low glass transition temperature of the FFF tooling material, that may cause distortion. If overheating of the core is a concern traditional vacuum bagging may be better suited, leaving a peel-ply finish, which may be a desirable feature for later bonding.

When using FFF tooling fabricated from PLA that has a low Tg of 60°C, room temperature curing resins are used, as curing at elevated temperatures will likely distort the mould. Allow the composite to cure at low or room temperatures. If higher cure temperatures are required, adopt a two-stage approach whereby the initial cure is conducted at room temperature and then post cure the parts separate from the mould.

The wetting-out of fibres during the wet layup process conducted in this research was done prior to layup. This is done by placing pre-cut dry reinforcement on a transparent plastic film, the resin is mixed and degassed before it is poured over the fabric. Another layer of plastic film is placed on top this will maintain a clean workspace. Using a resin mixing stick the resin is pushed to wet out the fabric and to remove excess resin, this ensures the fabric is saturated. The individual plies are cut out around the plastic film and are ready to be placed into the mould, this should be done soon after this process before the resin begins to gel. It is essential that all plastic film is removed from a ply before it is placed in the mould as this will stop the plies from conforming to the contours of the mould and will inhibit bonding between plies, resulting in a defective laminate. Depending on the mould type this composite can be cured in an open mould or consolidated using an envelope or tabletop vacuum bag. Standard wet layup consumables such as peel ply, release film and breather cloth are used in vacuum bagging situations to improve part quality.

In the case where soluble core materials are used the resin is applied to the reinforcement as it is in place on the core as braided fabrics are used. If braided fabrics are wetted out prior to layup, it would become more difficult to apply these layers.

*Resin Infusion*

A sealant tape is then applied around the perimeter of the mould and the dry fibre reinforced stack is laid onto the tooling surface in the predetermined orientation. The fabric in the mould is then covered in a layer of peel ply, a fabric that helps distribute vacuum pressure and creates a bondable surface on the cured composite part. A flow media is added next, this polymer mesh promotes resin flow over the mould under the vacuum, ensuring fibre wet-out. Vacuum inlet and outlet tubing are then placed, at least one of each are required to draw a vacuum on one side of the mould and to infuse resin on the other, these tubes are carefully placed and wrapped in sealant tape to ensure an air-tight seal with the bagging. A vacuum bag is cut oversized, and the edges are sealed with the previously placed sealant tape, additional strips of tacky tape called pleats are used to seal the remainder of the bag. Once sealed the resin inlet is clamped off and a vacuum is drawn to remove all air from the bag. Once a full vacuum is drawn a vacuum drop test is conducted, where the bag is sealed off and let sit for at least fifteen minutes to ensure the bag is completely sealed. When the bag is completely sealed, the resin is thoroughly mixed in the ratios stated by the manufacturer and the inlet clamp is released allowing resin to be drawn into the bag, care should be taken not to introduce air into the bag during this process. The rate at which resin is drawn through the fibre reinforced fabric is determined by the thickness of the laminate, the viscosity of the resin and the vacuum pressure placed on the part. Once resin begins to flow through the outlet hose and/or into the resin catch pot the lines are clamped, stopping the flow of resin. With room temperature curing resins, the part is left to sit to cure. Once the part is fully cured the vacuum bagging, lines and peel ply are removed and discarded, the part is then removed from the mould surface and inspected, this is the end of the infusion process, and the part is ready for post processing. Further details of the resin infusion process used are available in Appendix B.

*Part Removal and Demoulding*

Part removal and demoulding is the next phase of the physical manufacturing process of composite parts from low-cost RT. For single sided tooling parts are removed by prying the part from the mould surface this is done using plastic wedges. Care should be taken not to damage the mould or part surface when demoulding. With sufficient mould release and draft parts should be easily removable.

Core removal is more labour intensive than demoulding using open moulding or resin infusion. The core is sacrificial and must be destroyed to leave the hollow composite part. Breaking open the ends of the core exposes the sparse gyroid infill pattern that will allow for better water flow through the core especially if there are bends present. These ends can be opened using a large diameter drill bit or a rotary tool. PVA dissolves in warm water, place the cured composite part in a water bath and allow the core to dissolve and soften. Good circulation through the core will aid in accelerating this process, this is achieved by attaching a hose to a warm water source and washing water through the core. As the PVA dissolves it become waxy and manual removal of the softened core using a nylon pipe cleaning brush can help reduce the time required for the core removal process.

*Part Inspection and Finishing*

As raw material is processed at the same time as the composite component there is many aspects of the part that require validation to ensure high quality of finished parts. Visual, non-destructive testing will be done to determine whether or not parts and moulds are successful. The visual inspection conducted will be used to identify failures such as delamination, fibre orientation, resin rich areas, dry fibres, porosity, tooling marks as well as other surface defects that can be observed through visual examination. A tap test can be conducted to determine if there are major voids or defects within the laminate. Using a hard object such as a coin, tap the surface of the part, listening for a change in pitch or volume of the noise produced. The advantages of these inspection techniques are little to no added cost of equipment or materials to run such tests and they are quick tests to perform.

The composite part is ready for any post processing that may be required once demoulded. This can include sanding, bonding, painting and trimming etc., for some of these processes, jigs and fixtures are required. FFF is used to produce these jigs and fixtures to keep costs low by reducing lead-time through in-house fabrication.

## 3.5 Case Study 1– Direct Single Sided Tooling Approach

This case study follows the manufacture of the top shell of a bicycle saddle, a complex curvature part, with curvature in multiple planes. This product was chosen as it takes advantage of AM and its ability to produce complex contours. This product is also an ideal size (265 mm x 160 mm x 45 mm) for the printer only needing to be split into two parts, therefore it makes sense to produce the saddle instead of a scaled down version of another product that is also manufactured using LCM processes.

### 3.5.1 Virtual Prototyping of the Composite Saddle Top Shell

Defining the product specifications is the beginning of the virtual prototyping stage. These product specifications are defined within the CAD model, the shape and dimensional data are details expressed by the customer or designer. Throughout this stage, DfM must always be considered to save time making revisions at a later stage, some of the main concerns with tooling are insufficient draft angles and design features that cannot be moulded.

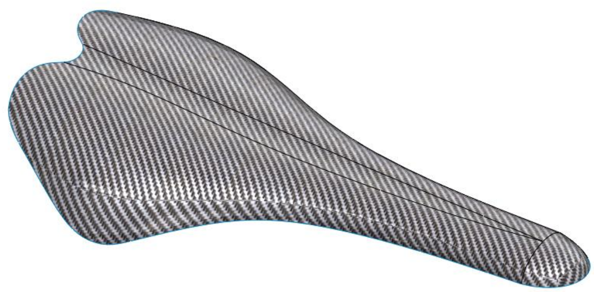

*Figure 3.8 Thickened surface model from which the mould shape is generated.*

The part is designed as a surface model using SolidWorks, and it was decided that this part would be moulded using a wet layup. The decision to use a wet layup process influences the type of tooling used, this process is suitable for envelope bagging that doesn't require the tooling to be as large as surface or tabletop bagging solutions. Smaller tooling here will need less build materials, smaller flanges and therefore faster build rates. For an example of a resin infused version of this composite part, see Appendix A.

First a flange area was added to the outside of the part surface at an angle (65°) tapered to the part (Figure 3.9 (a)), this will not just provide an area for excess material to be placed but also as a part trim line. Thickness is added to the surface model (10 mm) in the opposite direction to the tooling surface (Figure 3.9 (b)), as this surface contains the dimensional data required for this part. It is essential before proceeding to ensure that the part will pass the draft analysis prior to investing more time into the tool design (Figure 3.9 (c)). On successful completion of the draft analysis, the part length and width are measured in CAD to determine how best the tool can be split to fit the build platform. A single cutting surface is sufficient, and a butterfly lock was designed to fit the back of the tool to lock both sections of this single sided tooling together (Figure 3.9 (d)).

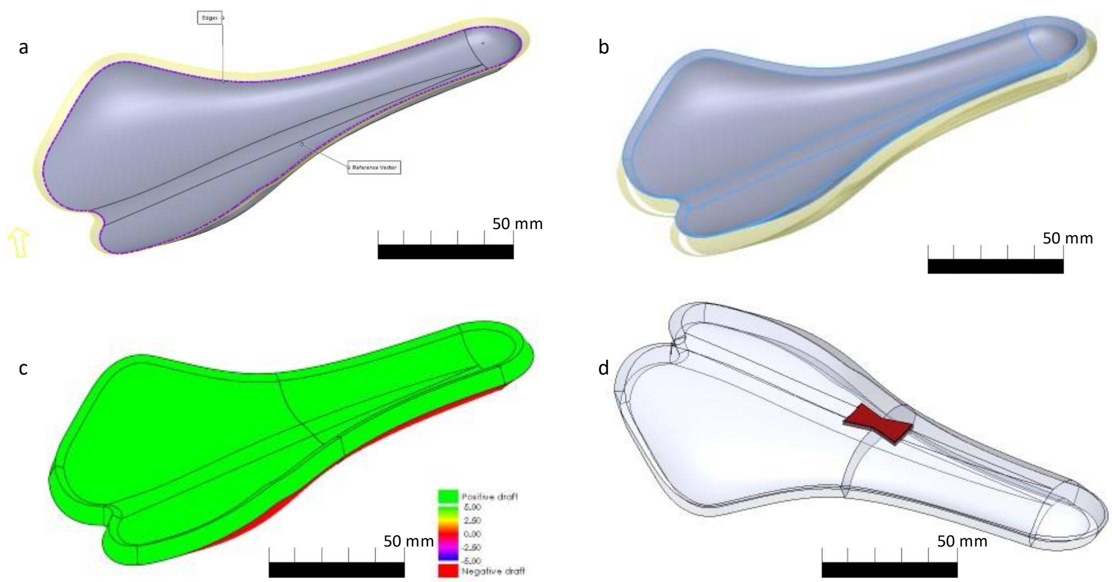


*Figure 3.9 The virtual manufacturing process steps. (a) A 5 mm flange was added around the border of the tooling surface. (b) The tooling surface was thickened to 10mm. (c) A draft analysis was conducted in the direction of pull, with green showing areas with draft ≥5°. (d) The reverse side of the tooling showing the mould split line a butterfly alignment tab.*

The setup on the build platform in the slicer is essential to remove unwanted post-processing with regards to stair-stepping, this calls for a vertical orientated part. A vertical orientation will yield the best tooling surface, however the end in contact with the build platform could result in different levels of accuracy in the post processing phase. Having a flat joining surface, it may seem logical to have this surface on the build plate as it ensures the faces will be flat as they are joined, however, this is not always the case as defects can present themselves where parts contact the build platform. Warping is a common defect at the first layer interface, so having the joining surface and tooling surface printed away from the build platform may prove beneficial if possible (Figure 3.10 (b)). This is a guideline, not a definitive rule as AM parts have so much design freedom the setup for each part and machine must be considered independently.

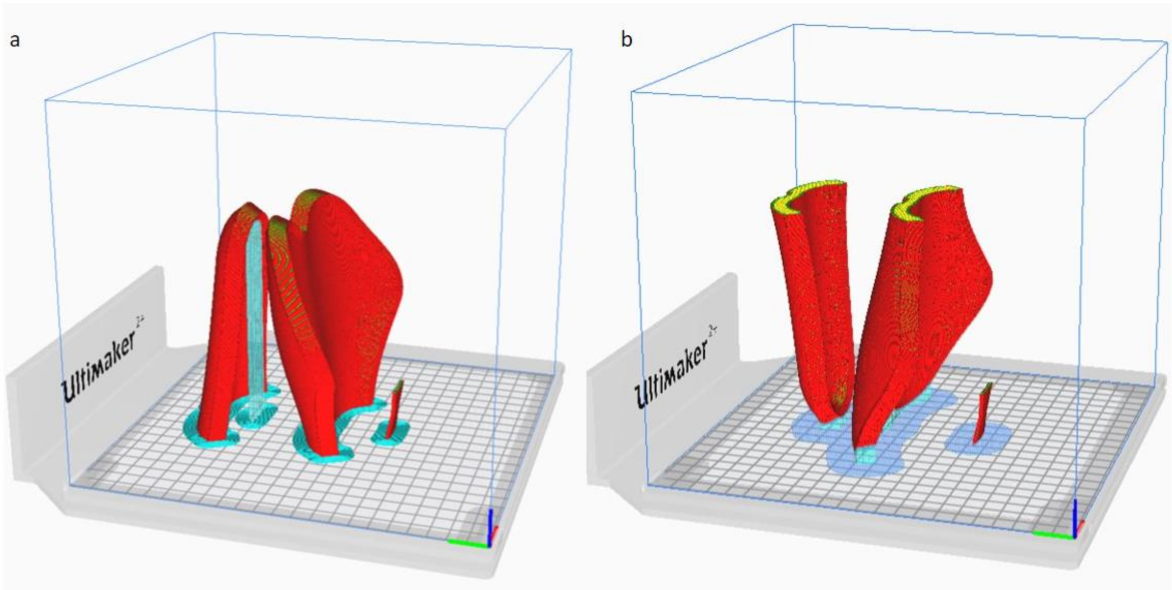


*Figure 3.10 Split shell tooling vertically orientated on the build plate (a) the joining surface that is flat is in contact (b) the parts are rotated 180°, the joining surface is away from the build plate.*

Having the mating surfaces pointing upwards is the chosen build orientation, this print setup requires supports and a raft to be printed to increase the contact between the tool and the print platform for good adhesion.

### 3.5.2 Physical Manufacturing of Shell Tooling

Support removal and part sanding are the initial steps post-printing. The sanding is done with P120 grit sanding paper, the aim of this process is not to remove layer lines, but to key the surface so that the mechanical lock between the epoxy sealer and PLA tool is improved. IPA is used to clean any dust from sanding or oils from the operator's hands, and CA adhesive is used to bond the segmented tool together, this fast-acting adhesive provides a strong bond between the parts and cures rapidly. Once joined the tool receives its first sealing layer of epoxy. This not just seals the tool but also fills in layer lines for an improved smooth tooling surface. This epoxy sealing process is repeated while the first layer is partially cured so coats adhere to each other well, building a thicker tooling surface that is sanded to at least P800 for an even Class A surface finish.

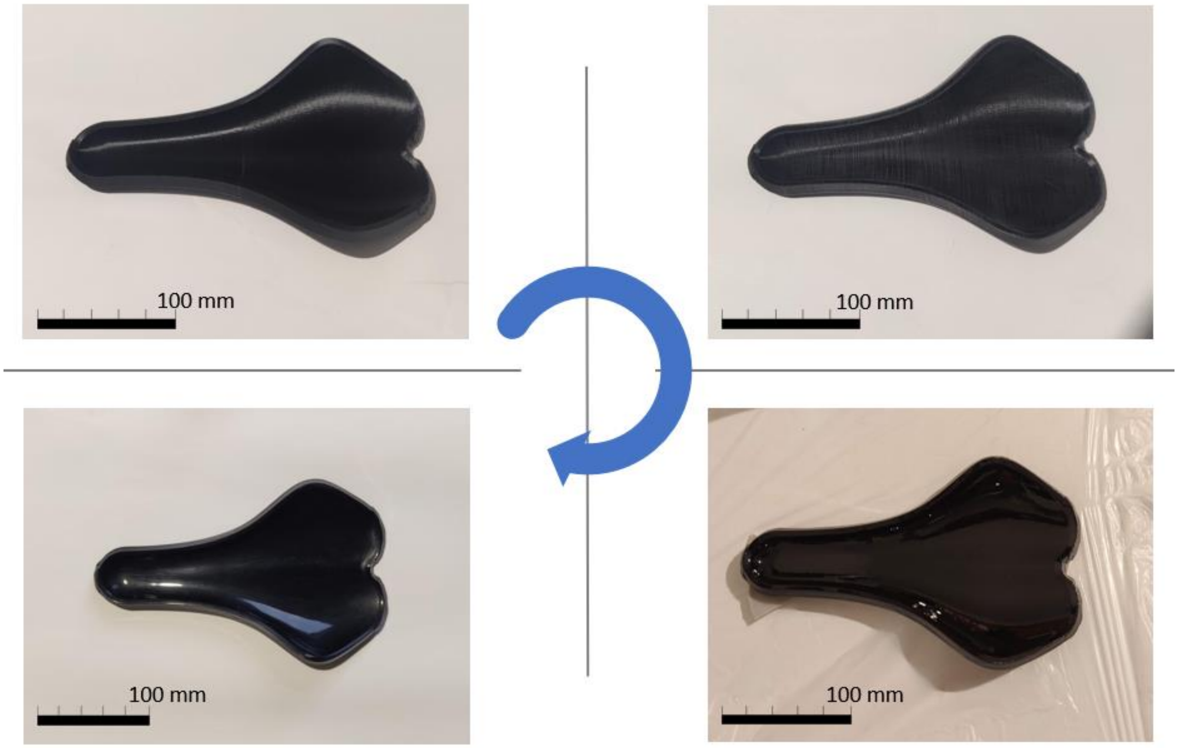


*Figure 3.11 Mould preparation phase, showing tool assembly, pre-sanding, sealing and polishing.*

Six applications of a chemical release agent (EasyLease Chemical Release Agent) were applied to the sealed mould, as recommended by the manufacturer for new moulds. Each coat of the release system was applied using a lint-free cloth and excess was wiped away, leaving a thin film on the surface. Between each application, the release agent was let cure for fifteen minutes, and one hour after the final coat prior to using the plug. A chemical film-forming system was selected for its semi-permanent protective barrier to make the tool suitable for short series production.

### *Composite part manufacture*

All the materials required for the composite part manufacture were pre-cut prior to mixing the epoxy resin. The prepared mould was set aside while the dry composite fibre was wetted out with pre-mixed epoxy (100 EL-2 : 30 AT-30 Fast) resin between two sheets of polymer film (vacuum bagging material). The EL2 Epoxy Laminating Resin with the Slow AT30 hardener can also be used to give a longer working time of 95-115 minutes.

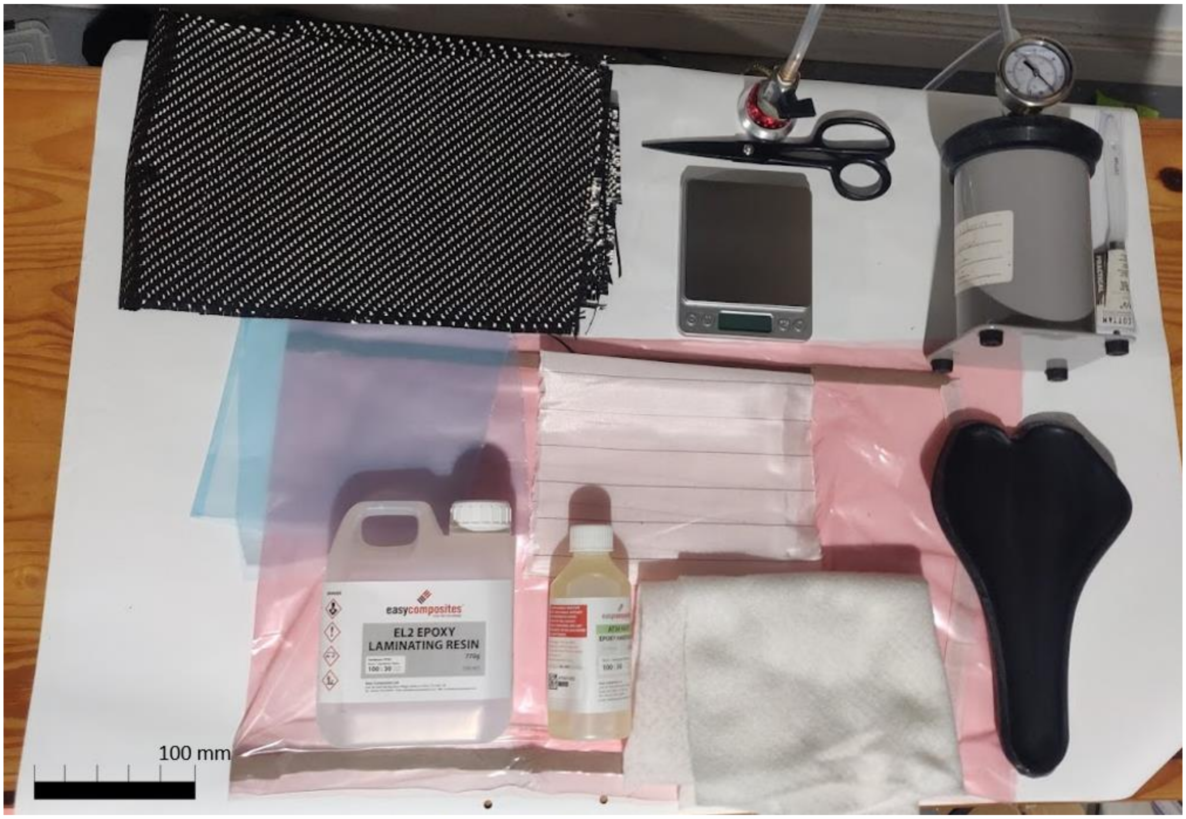


*Figure 3.12 Materials pre-cut and organised prior to wet layup process*

The wetted-out fibre laminates were placed into the mould and gently pushed into the tooling surface using a brush. Excess fibre preform that was overhanging excessively beyond the product surface was cut off using a composite shears. The back of the composite part was then covered with peel-ply, perforated release film and breather fabric before placing all within an envelope bag for consolidation. The composite part was left to cure as per the resin manufactures instructions prior to the demoulding process. Both the part and mould were inspected after demoulding for defects and tool wear. A coat of the release system was reapplied prior to fabricating more composite parts.

The cured composite part was trimmed to its final shape by cutting along the trim lines using a tungsten carbide abrasive cutting wheel. A cutting tool was 3D printed and used to mark the composite where it was less clear where the cutting lines were. This cutting tool was printed using PLA and was placed on the composite part, using a fine tipped pen the cut line was marked, and the part was trimmed (Figure 3.13).

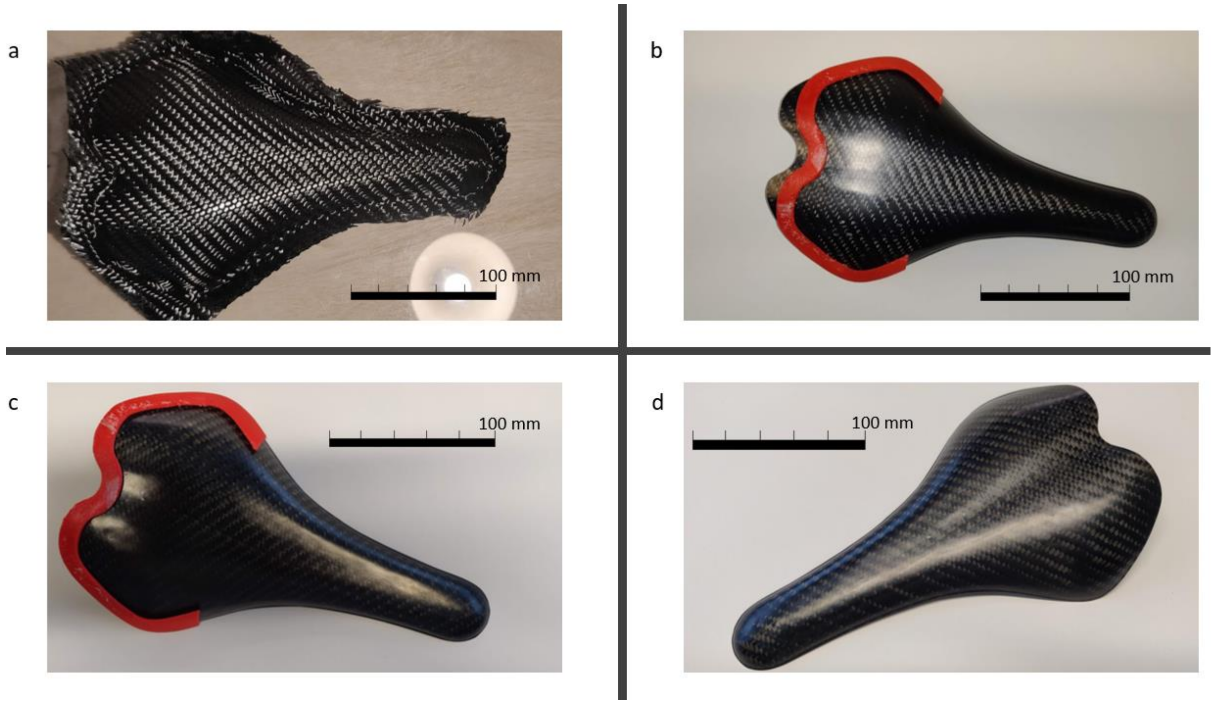


*Figure 3.13 Composite trimming process using a FFF cutting tool.*

## 3.6 Case Study 2 – Indirect Tooling via FFF

A custom camera face shield was designed for a local R&D company, who provided the product specifications (Figure 3.14). The purpose of this part was to support a camera in an outdoor environment. Initial prototypes were made using the FFF technology to finalise part geometry. Through RT composite products were fabricated from FRP for prototyping purposes. This case study is used to show how to indirectly fabricate composite tooling quickly and cost-effectively using a FFF style plug.

### 3.6.1 Virtual Prototyping of the Tooling Plug

*Product Specification*

Parts were printed from PLA to produce initial prototypes from which the design was revised and finalised. This iterative design phase is where the product specifications were determined prior to tool building, as per the RT process flow (Figure 3.1).

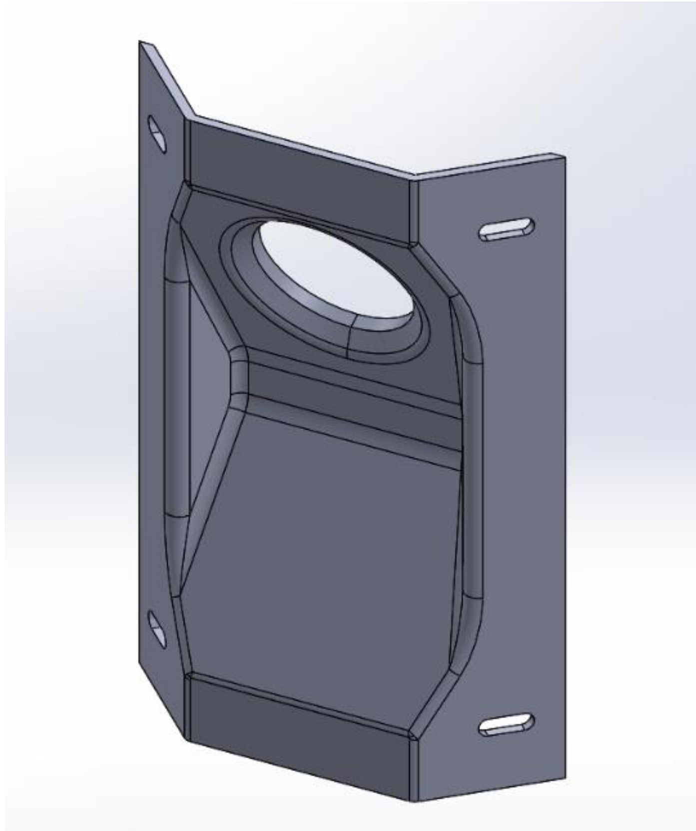

*Figure 3.14 Part design for the camera faceplate used to design a plug.*

DfM was considered from the beginning of the design cycle and potential moulding challenges were highlighted as this may influence the design. The part was imported into the CAD software to allow plug design to begin. Plug design must abide by the same design rules followed in the direct tooling example. Firstly, a single sided female mould was decided on. The plug was designed so that it would be mounted to a smooth flat sheet to provide an area for mould flanges to be formed, for later vacuum bagging purposes. A transition feature must also be considered to allow the plug to be demoulded easily.

### *CAD Model Creation & Analysis*

The tooling surface was defined, from which the plug body was be designed. The open holes were shut off, large draft angles were applied for a smooth transition of fibres and reduced risk of voids at sharp corners. A small flange area and a transition to the glass sheet with a generous draft angle were implemented for easy removal of the plug from the composite tooling (Figure 3.15).

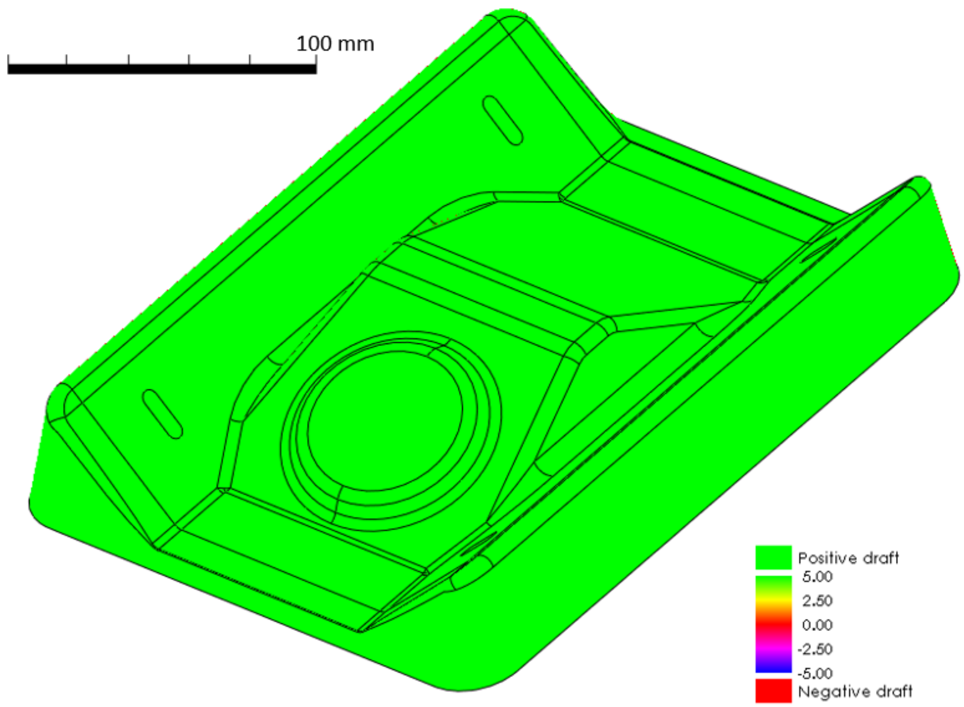


*Figure 3.15 Draft analysis of tooling plug, after open surfaces are patched and flanges are added.*

Splitting surfaces for FFF and assembly were positioned to allow the print orientation to be perpendicular to the demoulding direction. Two of these cuts are positioned at the upper and lower flange transition areas, the third is along the tool centre axis (Figure 3.16 (a)). As the tooling surface is split an added lip and groove feature (Figure 3.16 (b)) can be added to aid with alignment during post-processing. For a better mating surface, this feature should be facing upwards from the build plate, mitigating the need for support material.

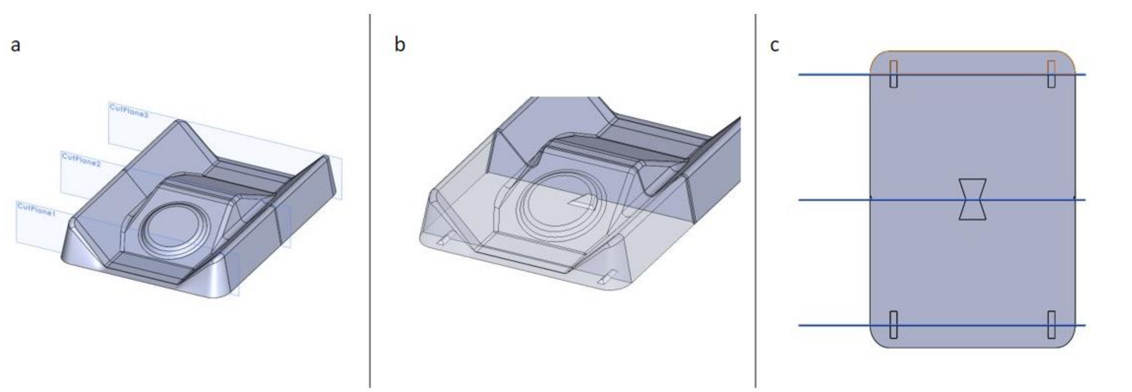


*Figure 3.16 (a) Plug splitting surfaces. (b) A lip and groove feature added to the split in the centre of the tooling surface, to ensure accurate alignment of the surfaces. (c) Alignment pins and butterfly lock on the underside of the plug.*

For alignment purposes of the split flange areas, small 2 mm deep locating pins are incorporated into the plug design (Figure 3.16 (c)). These pins are used instead of the butterfly lock or the lip and groove feature as this area of the plug was very thin.

*Slicer Settings*

Each part was imported into the slicing software and the parts were manipulated on the build plate in the orientation that positions the demoulding direction perpendicular to the z-axis of the machine. Parts are rotated and organised on the build plate so that each component was fabricated in a single print job, while minimising unnecessary print head travels (Figure 3.17 (a)). A gyroid infill pattern was selected at a layer height of 0.15 mm using a 0.4 mm nozzle (Figure 3.17 (b)).

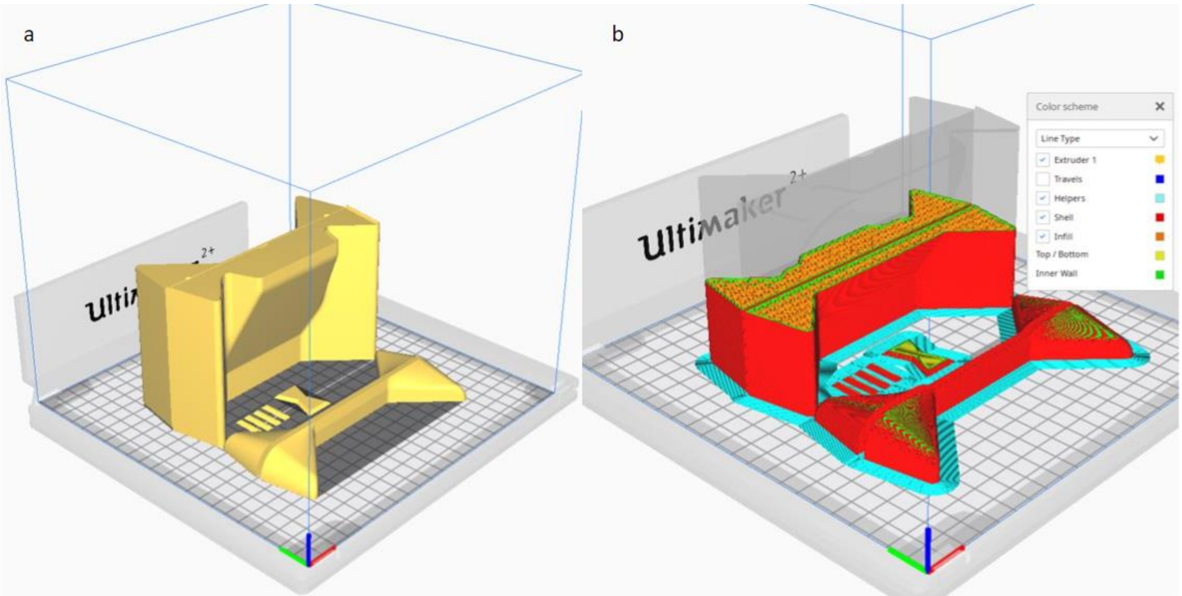


*Figure 3.17 (a) Print job arranged to fit the build plate while reducing the distance between travels for shorter more efficient travel of the print head between parts. (b) The sliced tooling plug showing the various line types of the tooling.*

### 3.6.2 Physical Manufacturing of the Tooling Plug

*Plug Preparation*

The printed plug sub-assembly was removed from the printer and supporting brim material was removed. The plug joining surfaces were sanded and the plug was assembled using a CA adhesive. As there were multiple parts to be assembled the main tooling surface was first assembled, followed by the two end flanges. The assembled plug was set aside to allow the adhesive to cure before sanding the PLA plug with a coarse sandpaper (P120) for a good bonding surface with the epoxy sealer (XTC-3D). A thin film of epoxy sealer is applied to the cleaned tool, this is applied by brush. The sealer is applied and worked into the tooling surface and left to partially cure to a tacky hard state (ninety minutes), at this point a second thin coating of epoxy is applied and set aside to cure (four hours).

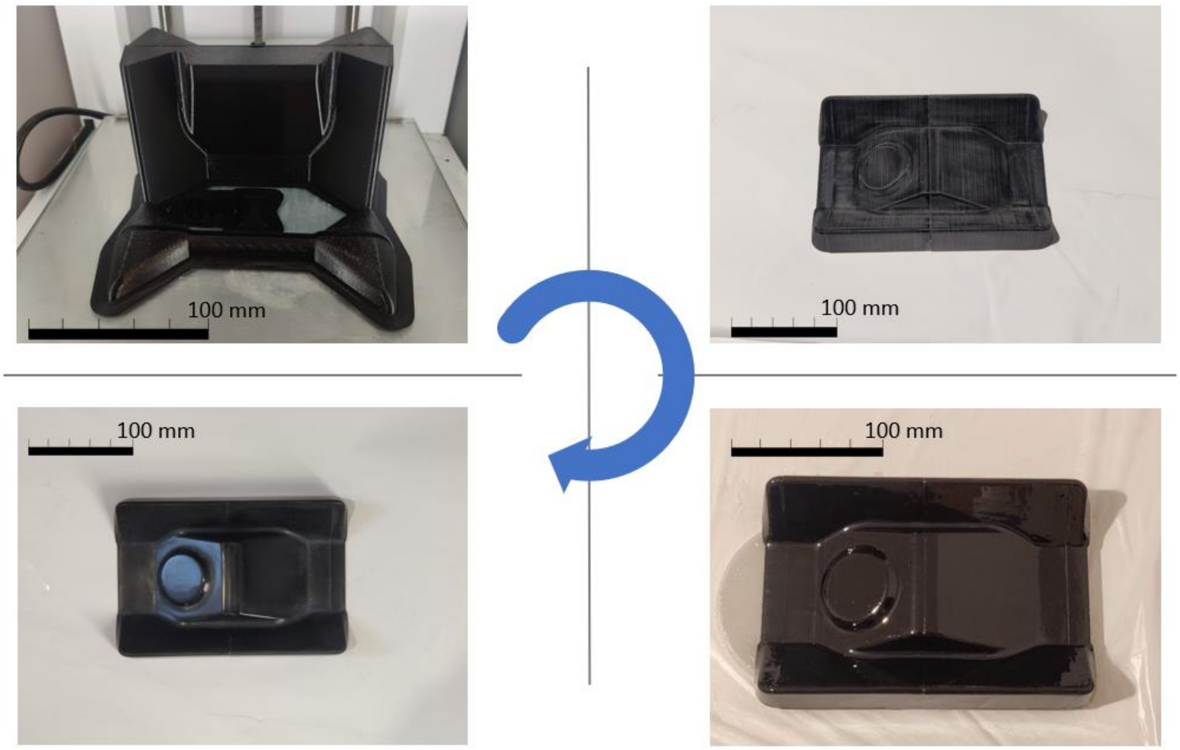


*Figure 3.18 Plug preparation phase, image shows process steps from print removal to tool assembly, sanding, sealing and polishing.*

The sealed plug was inspected for defects and was hand sanded to remove any high spots on the plug surface. A medium density foam sanding block was wrapped with the abrasive paper to allow the paper to follow the contours of the tool. Starting with P120 dry abrasive paper, this was followed with P240, P400 then a final wet and dry manual sanding phases with P800 and P1500 abrasive papers. The tooling received final polishing with a sponge pad and NW1-Premium abrasive paste to achieve a Class A surface finish.

The sealed mould was prepared with a wax-based release agent (Meguiar's M-08). A small amount of wax is applied to the sealed mould surface with a lint-free cloth in circular motions. The wax was left to dry for fifteen minutes, and then using a clean cloth lightly wiped away until the tool looks swirl free and glossy. This process was repeated three more times, as per the manufacturer's guidelines, for a greater barrier between the tool and composite mould. The wax release was chosen for its ease of application and reliability, as this is an indirect moulding example a semi-permanent release system was not required.

*Composite Tooling Fabrication*

The prepared plug was mounted to a glass sheet, secured using hot melt glue to prevent movement during the composite layup process. A filleting wax was applied around the edges of the plug where it contacted the glass so that no undercuts are created during the mould making process, creating a smooth seam line between the plug and the glass plate. As this tool is intended to be used for vacuum bagging and/or resin infusion, a flange area was added to allow for a surface bag to be set up. A flange area of 100 mm was marked from the edges of the plug using a flash release tape and three coats of EasyLease chemical release agent was applied to the glass (Figure 3.19).

The tooling gelcoat (EG60 Epoxy Tooling Gelcoat) was then prepared by measuring and thoroughly mixing the EG60 epoxy with the hardener catalyst. A thin layer of gelcoat was applied to the plug and surrounding flange area marked out on the glass sheet and was left to cure to a tacky state (2-3 hours @ 20°C) before a second coat of the gelcoat was applied. The gelcoat was applied using a brush, thin coats were applied at a thickness of approximately 0.5 mm. The second gelcoat application is set aside to cure to a tacky state before laminating glass fibres as tool backing plies (2x100 g chopped strand mat and 2x290 g plain weave 0/90) with an epoxy laminating resin (EL2 with the AT30 Fast hardener).

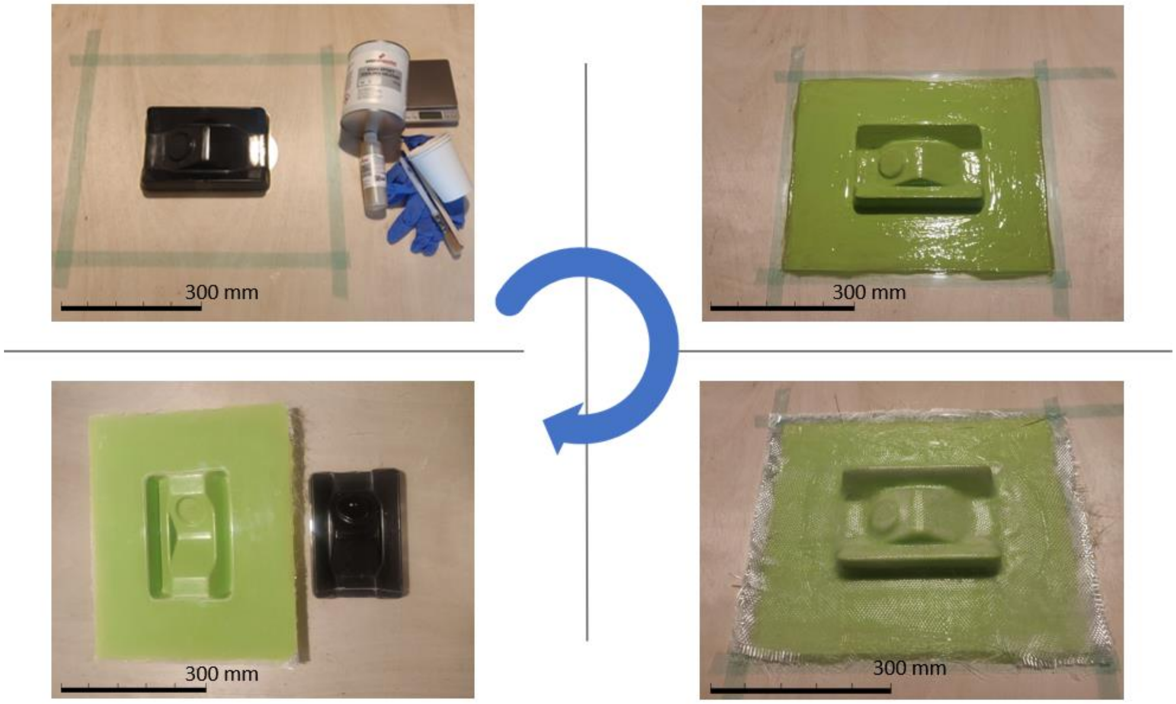


*Figure 3.19 FFF tooling plug mounted on a glass sheet with a flange area, followed by the gelcoat and glass backing application, prior to demoulding.*

The plug and newly fabricated composite mould were demoulded after the epoxy and gelcoat had fully cured, as per the resin manufacturers guidelines. Inspect both the plug and composite tool for defects, to determine if the mould is acceptable, or if some repairs are needed. The composite mould was cleaned (acetone) and prepared with a semipermanent release system for the composite manufacturing process to follow. CFRP products were then laminated and consolidated under vacuum pressure (Figure 3.20).

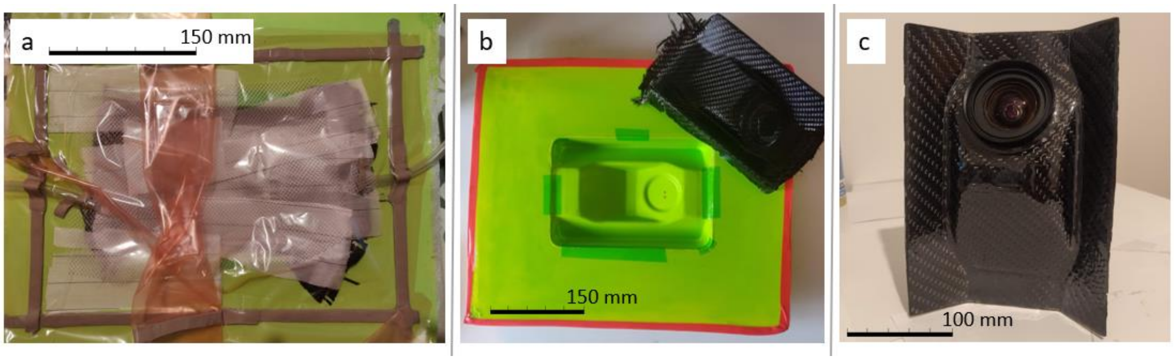


*Figure 3.20 Consolidation (a) through to assembled product of the CFRP camera mounting plate (c).*

Wet layup with vacuum bagging was used in this case study, this tooling may also be suitable for vacuum infusion similar to that used with the direct block tooling example in Appendix A. See Appendix B for the University standard operating procedure for resin infusion.

## 3.7 Case Study 3 – FFF Sacrificial Tooling for Hollow Composites

This section outlines a low-cost process of fabricating sacrificial tooling from dissolvable PVA produced on the UM2+ machine. This approach was applied to road bicycle clip-on aero handlebars which are commonplace in cycling to achieve a more aerodynamic position, reducing aerodynamic drag. This example was chosen in this project as it is an easily customisable component and is not excessively large for the build volume of the FFF machine. As this part has a curve in it, traditional roll wrapping is not suitable, and matched tooling with an inflatable bladder was avoided due to the difficulty of fabricating such parts using wet layup of infusion. The consolidation method used will largely affect the cosmetic finish of the part produced and depending on complexity care should be taken to successfully produce parts (Appendix C). The goal of this section is to outline the process steps followed for bespoke and short series production for hollow parts using sacrificial tooling.

### 3.7.1 Virtual Prototyping of Hollow Composites

When designing composite parts with internal tooling the thickness of the laminate must be accounted for before the tooling can be produced, it is important to note that the tooling determines the internal dimensions of the composite. When using Solidworks 3D modelling software, surface modelling was used as it is an effective modelling technique in producing parts containing complex contours, however surface models have no thickness associated with them. To determine the shape of the soluble core, thickness must be added to the surface model part, the internal structure of the composite can now be identified. If designing an open-ended composite, the core should be extended beyond the opening, to provide an area that can be trimmed during the post-processing phase to provide a clean edge to the finished part (Figure 3.21).

*Figure 3.21 Variable diameter curved tube mandrel design showing core and composite in CAD.*

Often it is the case that the tooling will be too large or cannot fit the build volume in the desired tool orientation (as identified in the previous case studies sections 3.5 and 3.6). Again, the tooling was split in a way that it can be accurately assembled post fabrication. As this component has a round cross section, simply cutting and adding a lip and grove feature would not suffice. A splitting surface was designed in such a way so that the parts could only mate in a specific orientation (Figure 3.22). This was implemented by adding a flat edge to a circular protrusion, and by adding a draft angle with a small gap (e.g. 0.1 mm) between the mating faces of the printed tooling parts. This slight gap designed into the CAD file provided a void for adhesive to fill during assembly and sufficient clearance for a good fit during assembly.

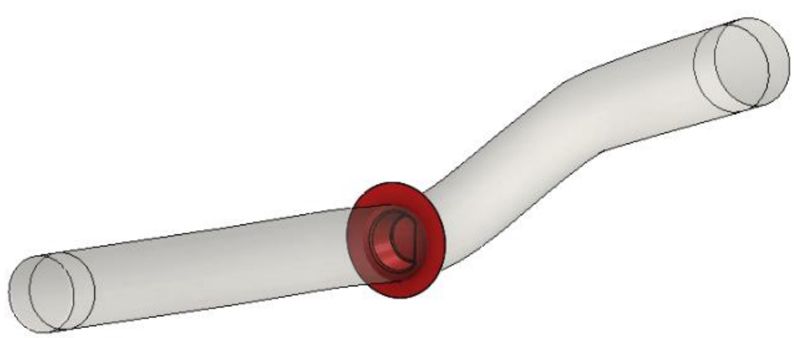

*Figure 3.22 Splitting surface (red) designed to ensure correct alignment in post-processing.*

Once the core was split into sub-components to fit the build platform, .STL files are generated and imported into Cura. The parts were orientated with the joining surface facing upwards and the custom PVA print profile for the UM2+ was applied (Table 3.1).

*Table 3.1 PVA print profile used for sacrificial tooling.*

| Print Setting | |
|---|---|
| Infill Pattern | Gyroid |
| Infill Density | 15% |
| Nozzle Diameter | 0.4 mm |
| Slice Height | 0.15 mm |
| Print Temperature | 230°C |
| Infill Speed | 38 mm/s |
| Infill Overlap | 50% |
| Wall Line Count | 2 |

The soluble core print file was subsequently sliced in the slicing software and the g-code file generated was exported to the printer, for the physical manufacturing phase to take place (Figure 3.23).

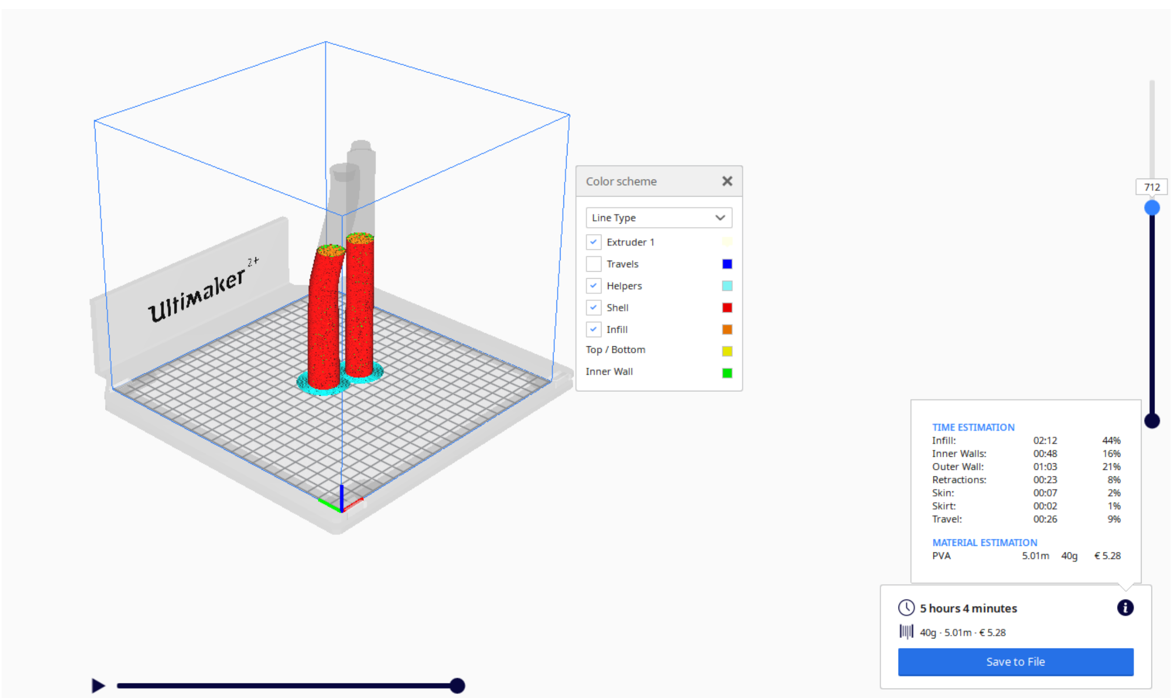


*Figure 3.23 The sliced file of the soluble core.*

## 3.7.2 Physical Manufacturing of the Soluble Core

The printed soluble core was inspected for surface defects prior to the part being assembled and sealed. The part was bonded using a CA adhesive and was lightly sanded using P120 sandpaper to remove any surface imperfections and to prepare it for the epoxy sealing layer. As the PVA core is water soluble take care in cleaning sanding dust from this part not to damage the core, a dry lint free cloth was used to remove the heavy dust particles. A vacuum cleaner with a bristle brush head was then used to remove any remaining particles from the sanding process. The sacrificial tooling was next sealed with a coat of XTC 3D epoxy, only one coat was applied as this is a single-use tool. A single-coat PVA release system was applied using a lint-free cloth, the cloth was liberally wetted using PVA release agent and wiped over the mould. The PVA release system's dark blue die was used as an indicator that the mould surface was entirely covered. The tooling was then set aside for 15 minutes to allow the release agent to dry.

*Composite Tube Lamination*

While the tooling was set aside to cure the materials for composite layup were organised. These materials included: 20 mm EasyComposites braided CF sleeve; IN2 epoxy infusion resin and AT30 slow hardener; composites high-shrink tape and envelope bag.

The 20 mm CF braid was cut longer than the mandrel it was applied to, this allowed braid to conform to the tooling shape and maintain an edge with good fibre alignment where it would later be cut in post-production. Two layers of the braided CF were carefully fed over the mandrel (Figure 3.24).

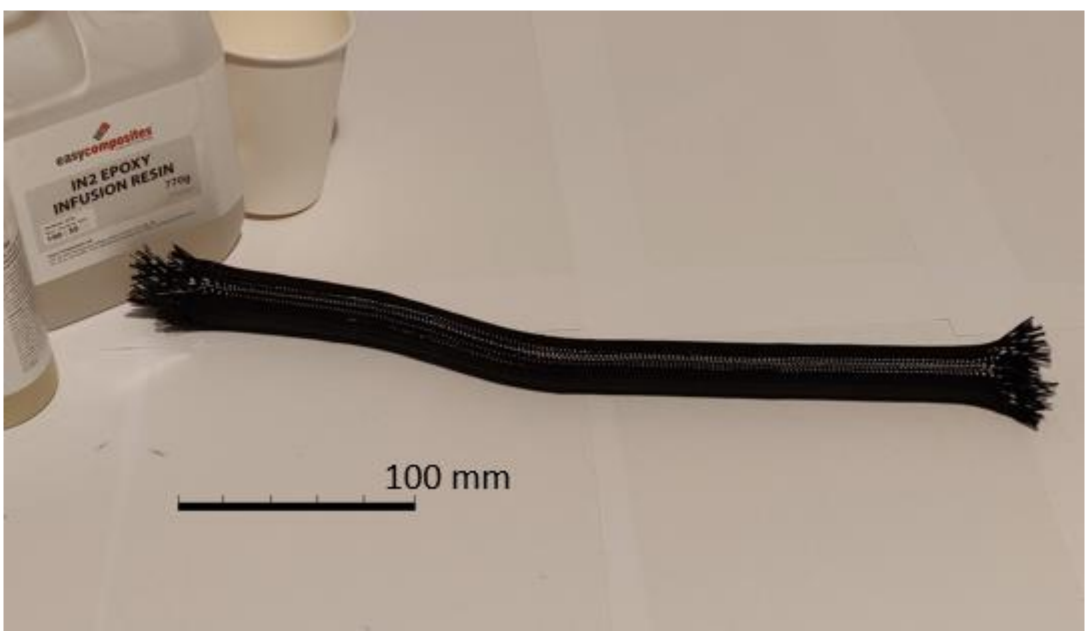


*Figure 3.24 CF braided sleeve over PVA sacrificial mandrel.*

The epoxy resin was mixed and brushed into the braided fibres, working from the centre of the mandrel outwards towards the open ends so that the braided sleeves would tighten over the tooling and to prevent the ends from fraying.

*Sacrificial Tooling Consolidation and Core Removal*

Three different consolidation methods were used, firstly a typical envelope bagging technique. The laminated composite and tooling received further application of vacuum consumable material including a peel ply layer followed by a perforated release film and finished with a breather cloth. This uncured part was then placed inside the envelope bag that was sealed using tacky tape and subjected to vacuum pressures.

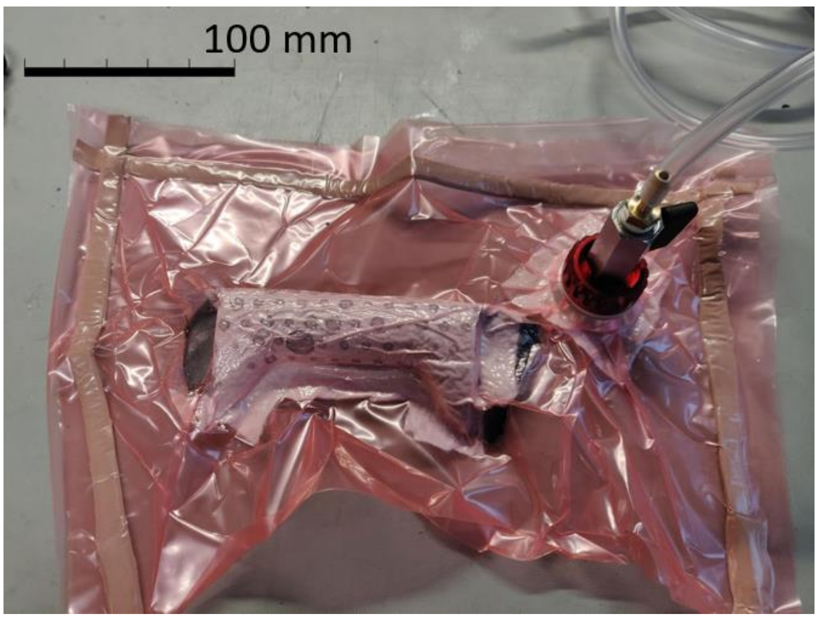


*Figure 3.25 Envelope bagging consolidation of CFRP product and sacrificial internal tooling produced using FFF.*

Secondly a flexible silicone outer tooling was designed for more control over the external surface finish. The master for the silicone tooling was printed using PLA and received the same post-processing as the direct and indirect PLA tooling used previously. This master model for the silicone was designed with an offset to account for the thickness of the CFRP product. The CS25 condensation cure silicone rubber was mixed and degassed to remove air voids. This silicone was poured into the mould and set aside to cure before pouring the second half of the mould. Prior to pouring the second half of the mould "Smooth-On Universal Mould Release" was sprayed over the silicone to ensure the two halves would separate (Figure 3.26 (a)).

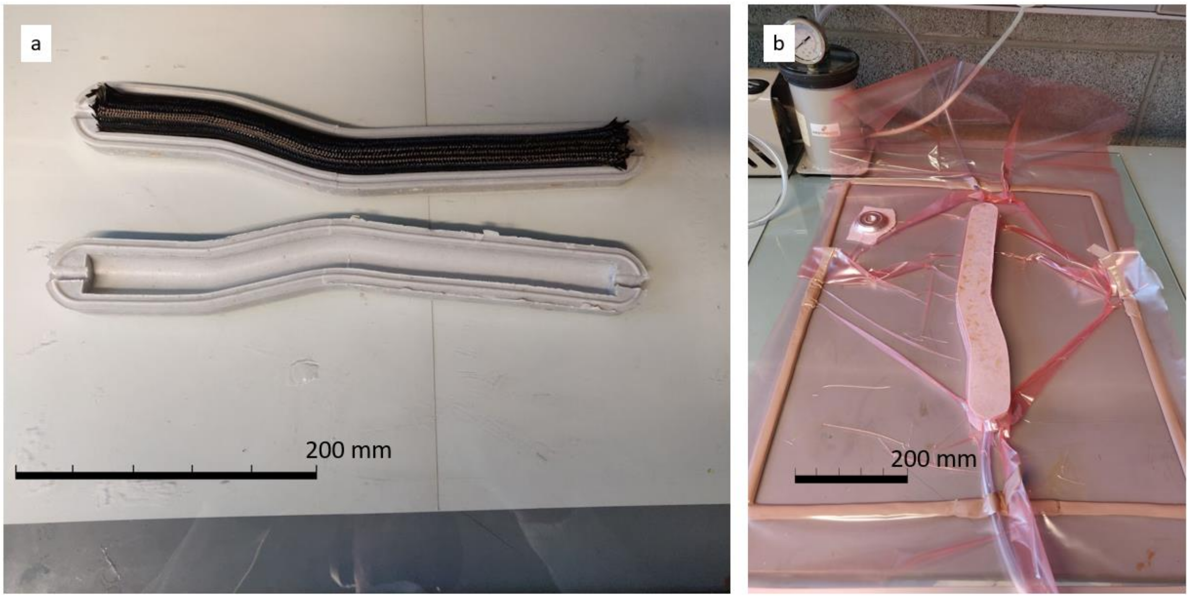


*Figure 3.26 (a) Flexible silicone tooling used for greater control over the external surface finish of the CFRP product. (b) Tabletop bagging used for the silicone mould*

The CFRP laminated sacrificial tooling was placed into the silicone rubber mould and then inside a tabletop vacuum bag for consolidation of the composite material (Figure 3.26 (b)). The final consolidation technique used was with composites shrink tape which was tightly wrapped around the mandrel overlapping the tape between one third and half the width of the tape, before it was gently heated with a heat gun to consolidate the CFRP about the tooling. The CFRP products were set aside to cure for 24 hours prior to demoulding.

Once demoulded and all consolidation materials were appropriately discarded of the external surface finish was examined. The sacrificial core was then next to be demoulded, first the cores were exposed using a Perma-Grit 32 mm cutting disc and a rotary tool the excess ends of the CFRP and tooling core are trimmed to the desired length (Figure 3.27).

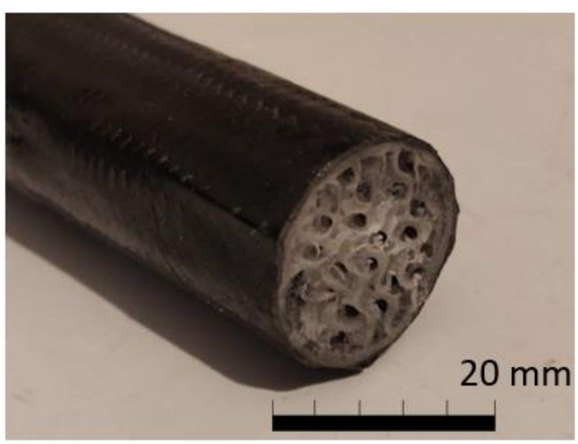


*Figure 3.27 Cut the ends of the cured CFRP product to expose the soluble mandrel.*

The composite product and tooling were then submerged in warm water (35°C) for one hour to soften the soluble core. Any remaining soluble material was then removed manually using a nylon bristle pipe cleaning brush. Once the core was removed, the part was dried and inspected.

# Chapter 4: Results & Discussion

Sample tooling for use in LCM applications were created using the FFF AM technology to provide evidence that RT is not limited to high-end industrial printers. PLA was the material of choice for the direct and indirect tooling approaches as this is the most popular FFF material as it is a reliable and inexpensive printing material. Although there are many material options available for the Ultimaker 2+ such as ABS, PC and Nylon to name a few, these materials are not as commonly used across FFF machines as some require heated beds and higher printing temperatures that can cause issues with warping. PVA water soluble support material was used in the sacrificial tooling example, this material is more expensive than PLA, however it is only a fraction of the cost of industrial FDM materials such as ST130 used in some additive sacrificial mandrel making. Each of the case studies are examples of how a FFF machine could be used for NPD of composite products from bespoke to short series production runs in a cost-effective manner. In doing so the versatility of such a machine is portrayed from a composite manufacturing perspective, as the investment in a FFF machine is not limited to building 3D representative models of new designs, but fully functional parts fabricated using their intended materials and processes.

## 4.1 Case Study 1 – Direct Single Sided Tooling

### 4.1.1 Direct Tooling Results

Splitting the tooling to fit the build volume of the UM2+ allowed for a vertical build direction, that was perpendicular to the demoulding direction. This build orientation resulted in a tool that had minimal staircasing effect. The butterfly locking feature ensured alignment of the tooling components while the CA adhesive cured, fixing the halves in place. The seam line between these two components matched up accurately and this joint remained effective throughout the duration of the testing. The print breakdown is available in (Table 4.1).

*Table 4.1Table 4.1 Shell tooling print breakdown.*

| Setting | Value |
|---|---|
| Material | PLA |
| Material Usage | 153 g |
| Material Cost | €5.34* |
| Print Time | 16 hours |
| Print Quality | 0.15 mm |
| Infill Density | 10% |
| Shell Thickness | 5 Lines / 2 mm |

**Price for RS PRO PLA, 2.85 mm diameter 2300g spool (€80.26 exc. VAT).*

Sealing of the part with the epoxy provided a durable tooling surface to the PLA mould that was sanded using wet and dry abrasive paper (up to P1500) then polished using an abrasive paste to develop a glossy “Class A” surface. Any imperfections from the joining of the untreated PLA components were also filled and were indistinguishable when polished. When sealing the mould some minor imperfections were induced from dust or small runs of resin, these were easily removed during the sanding process. Post processing of the printed tool is a labour-intensive stage as a manual approach was adopted to minimise financial investment (Table 4.2).

*Table 4.2 The time spent on each process in preparing the shell tooling for a wet-lay process.*

| Process | Operator Time (HH:MM) |
|---|---|
| Support Removal & Assembly | 00:05 |
| Sanding | 00:15 |
| Sealing (mixing & application) | 01:00 |
| Polishing & Mould Release | 02:00 |
| Curing Time | 06:30 |
| Total Time | 09:50 |

The epoxy sealer created a thin barrier between the tooling surface and FRP part that was compatible with the mould release system used. EasyLease, a chemical film-forming system was selected for its semi-permanent protective barrier properties, no adverse effects to the tooling or tooling surface were observed while using this release system with the direct FFF tooling. The material costs during the post processing stage were very low. Only a small amount of epoxy sealer was used, the other consumables such as release agent, laminating brushes, mixing cups, sandpaper, and lint free cloths were also relatively inexpensive (Table 4.3).

*Table 4.3 Raw Materials used in the production of directly fabricated tooling.*

| Item | Qty. | Cost (€) |
|---|---|---|
| PLA | 153 g | 5.34 |
| XTC-3D Epoxy Sealer | 20 g | ~1 |
| NW1 Polishing compound | 25 g | ~1 |
| Mixing cups, stick & brushes | - | ~2.50 |
| Wet/Dry Abrasive Paper P120-P1500 | 6 | ~2.50 |
| Total Material Costs of Direct Tooling | | <15 |

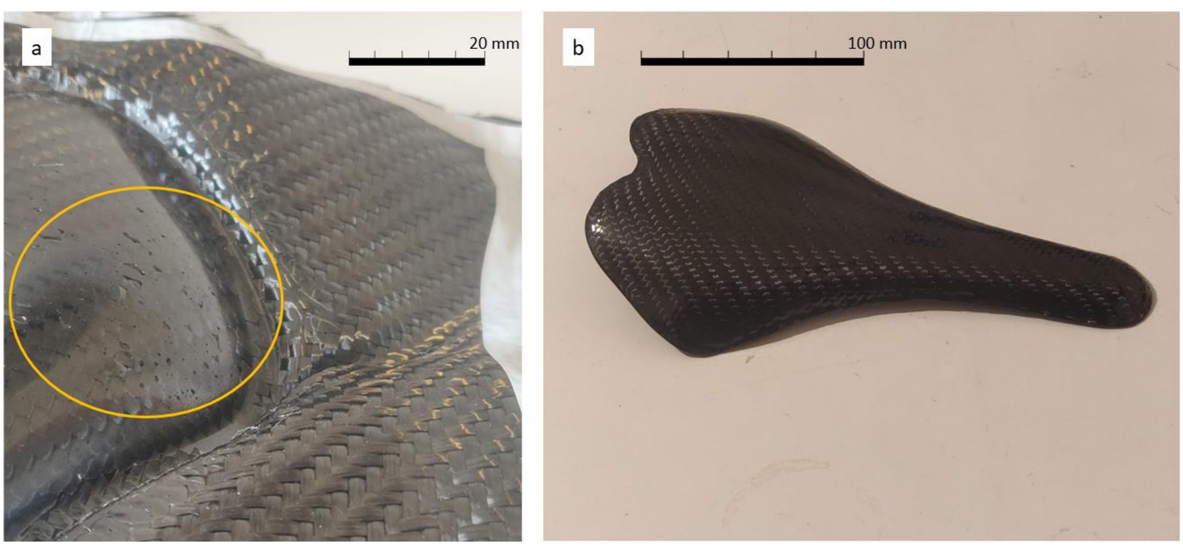


*Figure 4.1 Surface pinholes (a) resolved by applying a topcoat of epoxy laminating resin (b) o the cured CFRP product from the direct FFF tooling.*

Minor product surface imperfections (pinholes) were observed on some of the parts extracted, these issues were resolved in an additional processing step where a thin layer of epoxy resin was applied to the surface (Figure 4.1).

The tooling surface, after five demoulded parts showed no sign of wear, maintaining its polished finish. One coat of the chemical release agent was applied between moulding cycles as per the manufacturer's recommendation for new moulds. No demoulding issues were experienced throughout the production of FRP (both carbon and glass) parts from this tool. The XTC-3D sealer and EasyLease mould release system provided a durable surface for short series production using direct tooling, this combination successfully produced five components with no damage observed to the printed mould (Figure 4.2).

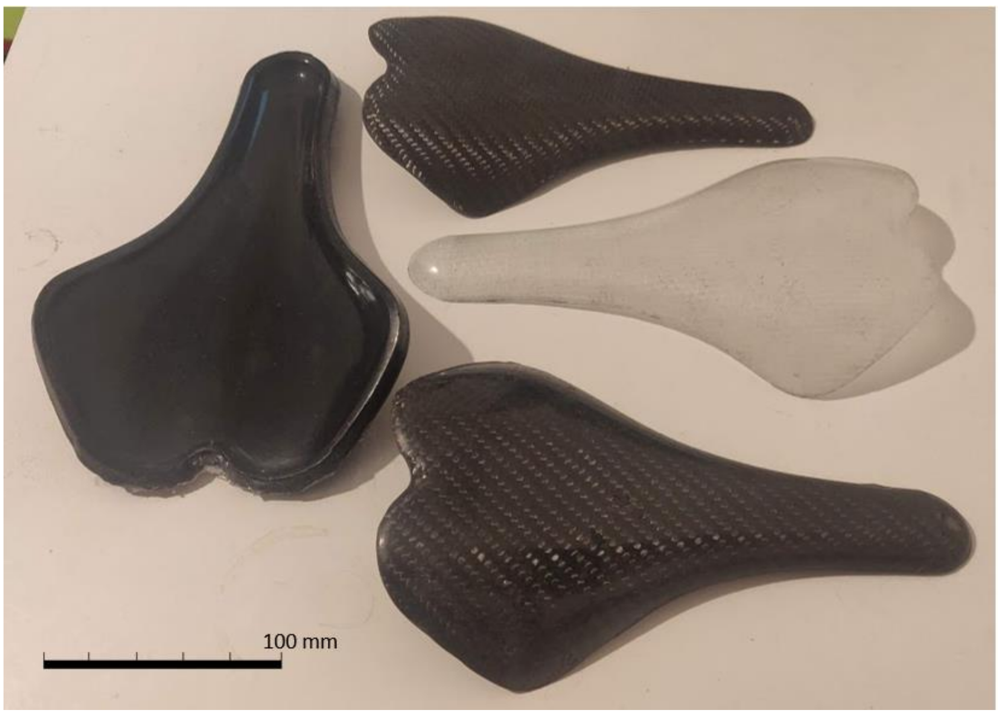


*Figure 4.2 The direct mould and FRP products that were demoulded.*

The cost of the direct tooling solution is approximately €220 (Figure 4.3) if the mould fabrication was conducted externally in a FabLab, these services charge by the number of printing hours (~€10 p/h) in addition to the feedstock costs, the electrical costs for running the machine, although minimal are also considered. Under four hours of manual post processing were required to seal and polish the tooling surface. This process cost ~ €50 at the minimum wage per hour of labour.

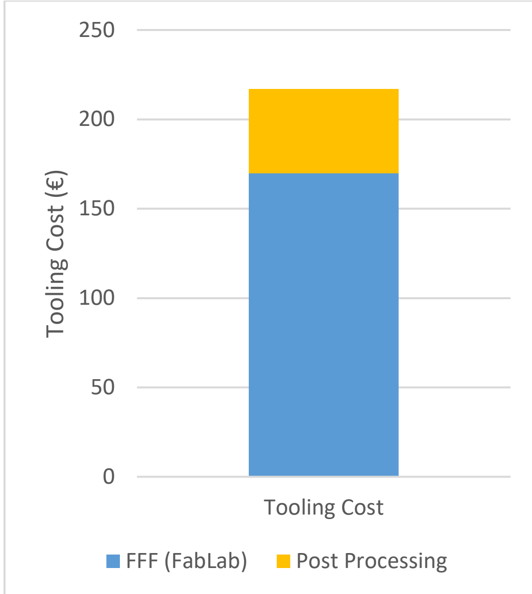


*Figure 4.3 Tooling cost breakdown for AM and post-processing of the direct FFF tooling.*

When comparing the cost of producing a direct FFF mould to a traditionally fabricated CNC metal mould, the RT costs only a fraction (< 25%) of the traditional tooling. There is also a clear advantage with regards to tooling lead times where the traditional tool could be manufactured over a nine day period, the RT however was ready to be used in just three days (Figure 4.4). The tooling cost and lead times for the CNC aluminium tooling are quotation values from Protolabs, a company who offer provide rapid manufacturing solutions for custom and low volume production of parts.

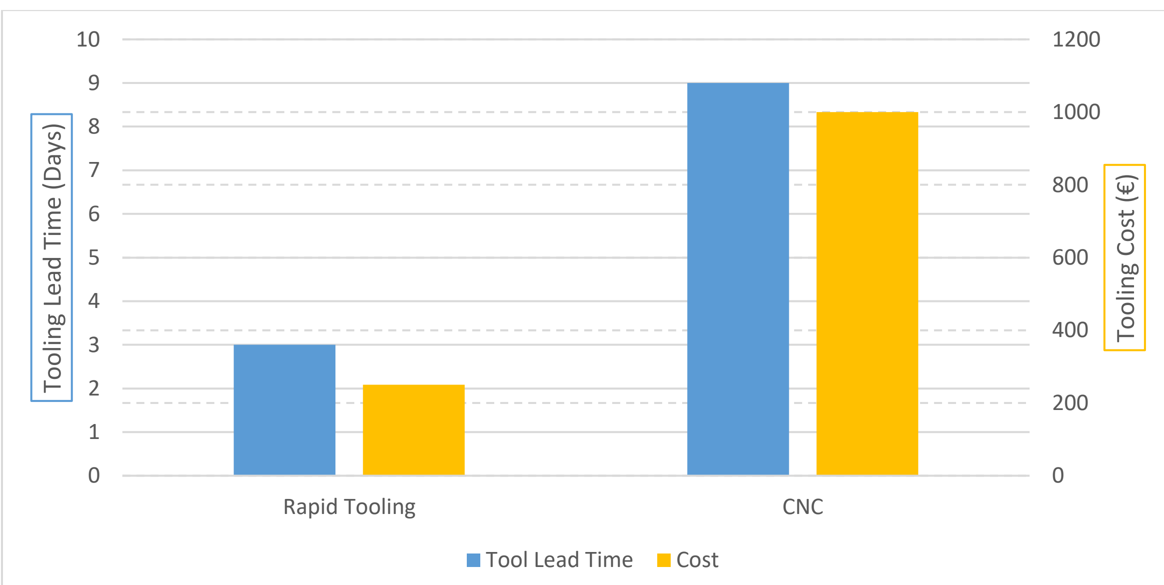


*Figure 4.4 FFF Tooling vs CNC Aluminium Tooling in terms of tooling lead time and manufacturing cost (RT tolerance of ±0.15 mm and CNC manufactured at a tolerance of ±0.1 mm).*

Although multiple products were successfully demoulded from this RT it is unknown as to how many parts this kind of tooling is suitable for, there are many factors that may influence the mould life. These findings naturally lead on to using the FFF technology to fabricate more durable moulds, this was done indirectly to fabricate traditional composite moulds for larger production runs. This concept is discussed in section 4.2 of this work.

### 4.1.2 Direct Tooling Discussion

DfAM and tool preparation were essential factors to the success of this case study. The tooling was split into two parts for assembly, as the mould was too large to print as a single component, splitting the tooling allowed the mould to be fabricated in a single print job. Understanding both the additive and the composite layup processes influenced the orientation of the split mould on the build plate. The vertical orientation of the parts during manufacture added resistance to shearing forces due to demoulding and increased the accuracy of the tool by minimising the stair casing effect inherent to ME based additive technologies. By keeping joining surfaces parallel to the build plate and using a brim for better adhesion to the print bed the risk of warping and misalignment of the joint is minimised.

The print settings used for the direct tooling included a thickened shell, as recommended by Hanssen (2009), this resulted in a strong mould where no issues were observed with regards delamination or deformation to the tooling during or after parts being fabricated. Two factors that are suspected to have been critical in the successful fabrication of this RT are the print settings used for the PLA mould and the post-processing conducted. By sealing the FFF part, no composite matrix material penetrated or came in contact with the surface of the PLA. This epoxy barrier provided an ideal tooling surface, especially after sanding and polishing. Unlike Post *et al.* (2019), there was no need to skim the tooling surface using a CNC machine as the nozzles and layer heights provide a finer resolution when compared to tools manufactured using BAAM. Post sanding the sealed mould gave control over the surface finish removed any imperfections that were present. This step could be omitted from the process as the epoxy used provided a high-gloss finish, however not conducting this step would lead to more surface imperfection on the tool and subsequently on the FRP product. The chemical release system chosen was another contributing factor to the success of this tool, although many applications of this system were needed prior to first use, the system was effective in allowing the product to be easily demoulded with little to no force required. Being a semi-permanent barrier also aided in maintaining the tooling surface finish even after multiple pulls, as the release system was easily added to between uses, with one additional coat. From observation of this mould over multiple uses it is apparent that a combination of these factors, the FFF configuration, the PLA post processing and the tool maintenance that are responsible for the success of this tooling, making it suitable for short series production.

Sample parts manufactured using the single sided tooling resulted in varying levels of success. The procedure for each manufacturing run remained the same to the best of the operator’s ability throughout the production of parts. From the observational analysis of FRP products post demoulding, surface defects such as pinholes were present on some samples where others yielded glossy surface finishes. In each of the examples where defects were present, there was insufficient vacuum pressure due to leaks in the envelope bagging. The defects observed are common in open moulded FRCs or when there is insufficient consolidation from the vacuum bag. Surface defects such as those observed can easily be fixed through post processing to achieve the desired surface finish. The successful composite parts were produced when the envelope bagging was successfully sealed, and full vacuum pressure remained in the bagging for the curing cycle to finish. From these observations it is evident that operator experience affects the quality of the finished composite product, however the focus of this study is on the tooling and not operator experience. By pre-saturating the fibres between the polymer film, there were no dry spots in the composite products, this technique also aided in maintaining good fibre alignment which can be disrupted when applying the resin to dry fibres placed in the mould. The application of the resin in this manner proved beneficial to the wetting out of the fibres and may result in a more consistent method of resin application particularly in small composite parts, in larger applications this may not be as easily done as it could potentially be difficult to place the preform into the tooling. Great care should be taken when sealing the vacuum bagging, reusable vacuum bags may be beneficial to reduce the risk of vacuum bagging leaks and the time spent preparing the envelope bags, this is more concerning if using fast acting resin hardeners as good consolidation is desired before the resin begins to cure.

Directly fabricated PLA moulds for composites were used in this study to tackle the challenge associated with bespoke and short series production. This case study has shown that this cost-effective process (Table 4.3) is viable for manufacturing FRP parts with a high-quality surface finish for small batches or NPD prototyping purposes. Benefits of direct FFF tooling in terms of cost and tooling lead time are presented in Figure 4.4, where the FFF tooling is compared to CNC Aluminium tooling. Great reductions in both tooling/product lead time and cost are presented for Case Study 1 of the bicycle saddle tooling example, when compared to outsourcing the tool manufacturing to a RP firm. This 66% reduction in tooling lead time and 75% reduction in tooling costs, make in-house RT via FFF a viable solution for short series manufacturing or for functional prototyping.

The rapid trim tool for finishing the composite product was an effective, inexpensive tool that was fabricated very quickly on the FFF machine. This trim tool aided in the marking for removal of excess, unwanted composite material with greater repeatability than doing so by eye. This tool shows another use case for the low-cost FFF technology in this RT process, this additional tooling capability helps in the justification for investing in FFF, demonstrating further the versatility that the technology can provide in NPD of composite products.

## 4.2 Case Study 2 – Indirect Rapid Tooling Using FFF

### 4.2.1 Indirect Tooling Results

The time spent in the virtual manufacturing phase for the indirect tooling is shown to be very quick (Figure 4.5), this process is dependent on plug geometry and complexity. This phase of the plug design was completed in under four hours, from CAD through to slicing and exporting the g-code file. This is an example of how effective the FFF technology is for setting up of manufacturing, by removing the need for CAM, many hours of experienced toolmakers can be saved by adopting this approach.

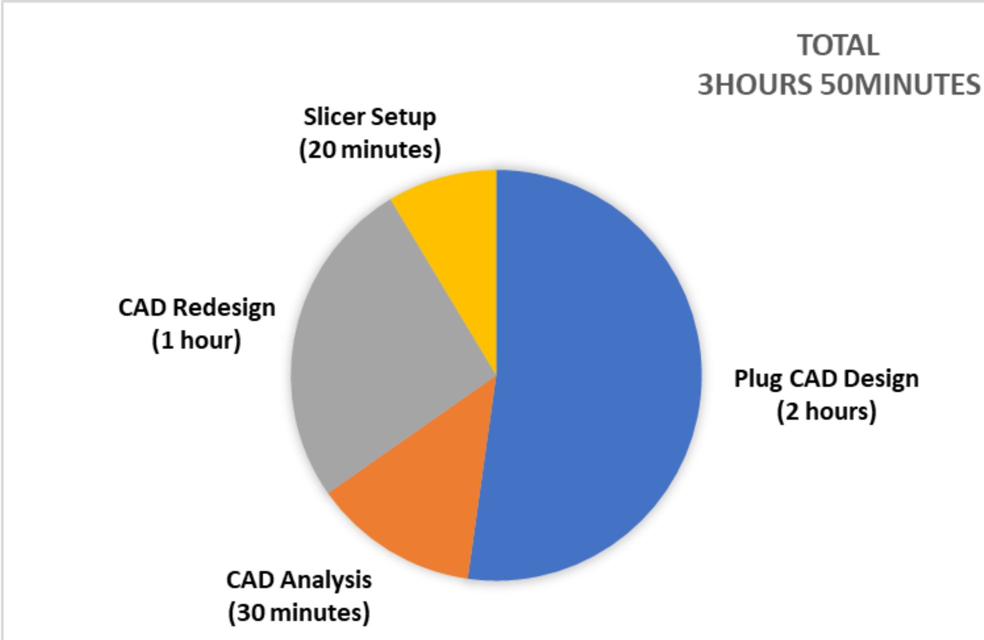


*Figure 4.5 Virtual manufacturing of tooling plug time breakdown.*

The printing of this tool was completed in one print job, achievable through the splitting of the tooling to fit the build volume while not creating the need for support materials. This tooling was fabricated quickly (<1 day) using inexpensive PLA material, the plug was fabricated for approximately €10 including both material and running costs, for the 200 W UM2+ FFF machine. The cost of energy consumption was estimated off of the average price (€0.1326 per kWh) of electricity for businesses in Ireland for the second half of 2020 (Statista 2021).

*Table 4.4 Time and costs of producing the indirect tooling plug.*

| | |
|---|---|
| Material | RS PRO - PLA |
| Nozzle Diameter | 0.4 mm |
| Layer Height | 0.15 mm |
| Wall Line Count | 4 |
| Shell Thickness | 0.16 mm |
| Print Duration (HH/MM) | 23:36 |
| Material Usage | 242 g |
| Material Cost | €8.44 |
| Electricity Costs | €0.63 |

Post assembly, the seam line was evident along the centre of the tooling where a lip and groove feature was implemented. This slight gap was effectively filled using the resin sealer. The first application of the XTC-3D sealer was so thin that the layer lines from the additive process were still present on the tooling surface, the build-up of epoxy from the second application was sufficient to provide a quality finish with no layer lines apparent. The breakdown of the time spent during each plug preparation process is presented in Table 4.5

*Table 4.5 Plug preparation times for each process.*

| Process | Operator Time (HH:MM) |
|---|---|
| Support Removal & Assembly | 00:25 |
| Sanding (Surface preparation) | 00:25 |
| Sealing (2 coats) | 01:00 |
| Polishing (P1500) & Mould Release | 02:00 |
| Curing Time | 07:00 |
| **Total Time** | **10:50** |

This tooling surface was buffed to a "Class-A" finish that made it easy to apply the wax-based release system. The application of the wax was visible and left a slight swirl pattern on the tooling surface (Figure 4.6).


*Figure 4.6 Swirling pattern from the application of Meguiar's M-08 wax on the plug tooling surface.*

The manual composite tooling fabrication process was labour intensive. Starting the process at the beginning of a working day, the layup was complete 4-5 hours later. The epoxy and gelcoat require a further 8 and 12 hours respectively to cure to a de-mouldable state at room temperature (25°C). The nature of this process resulted in a composite tool that required one working day to manufacture.

Demoulding of the plug was challenging, the interface between the tooling gelcoat and the plug was ground back using a rotary tool to allow demoulding wedges to be inserted between the plug and composite tool. As the part began to release from the tooling surface it remained bonded in one corner, the forces used during removal resulted in the plug being destroyed during the removal process however, the composite mould was saved. The plug fractured at the interface between an end section and the main body of the plug (Figure 4.7). This section was then removed without causing damage to the tooling gelcoat surface.

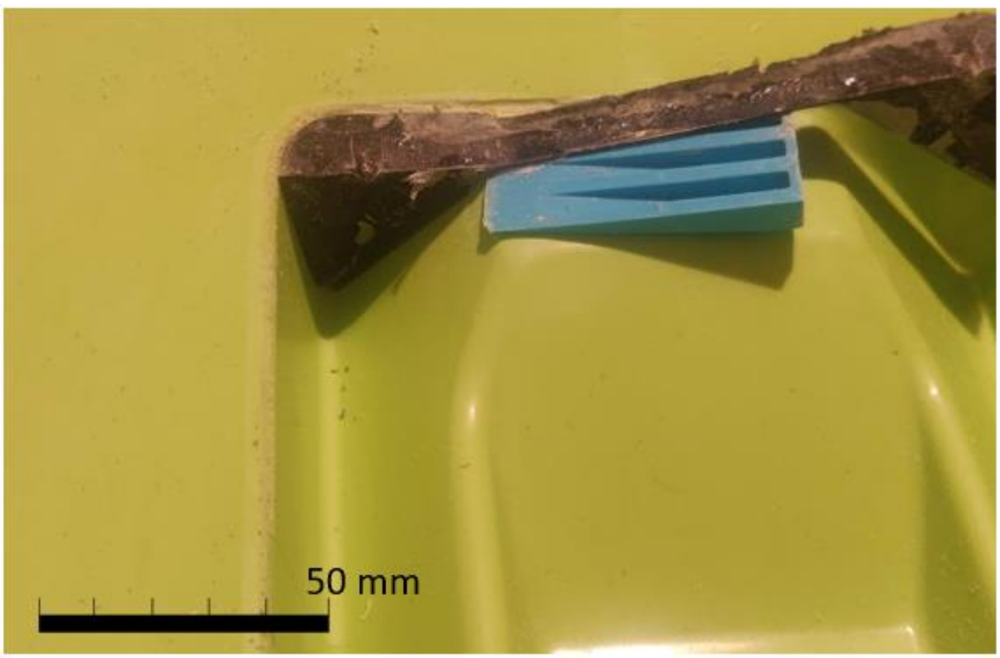


*Figure 4.7 Composite tool with part of the fractured tooling plug adhered and edges ground.*

Some minor repairs were performed on the tooling gelcoat to salvage the mould. These repairs consisted of mixing a small batch of gelcoat and applying it to the damaged areas of the mould. Flash release tape and filleting wax were used to localise the repair to the damaged areas (Figure 4.8).

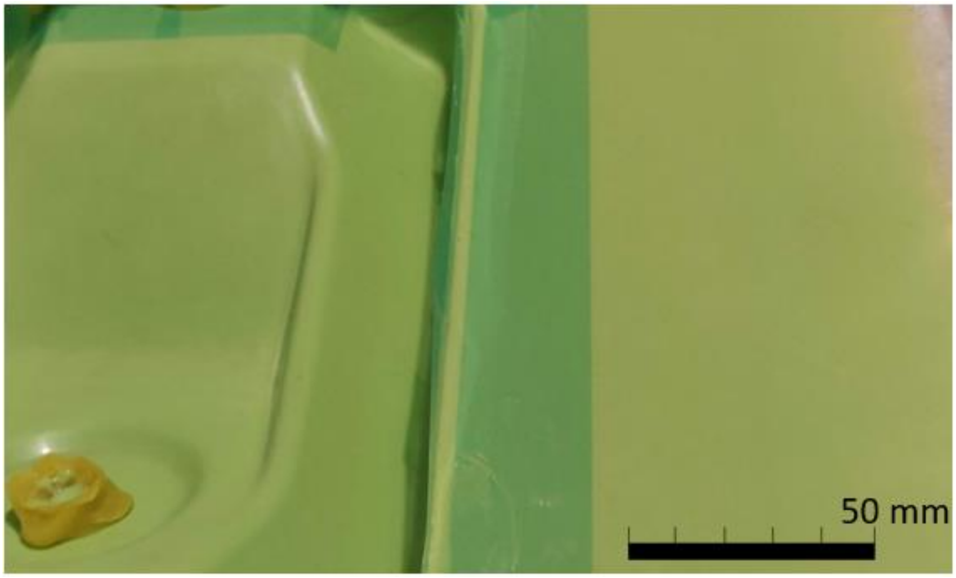


*Figure 4.8 High quality surface finish and repairing the indirect tooling gelcoat.*

Beyond the repaired areas, a high-quality finish was achieved across the tooling gel surface where there was no visible evidence of layer or seam lines from the plug fabrication and preparation stages. On removal of the wax and tape used in the repair, this area was hand sanded using P120, followed by P240, P400 and P800 for a smooth finish. The mould repair process added one day to the tooling lead time, this tooling fabrication process was concluded after four days (Table 4.6).

*Table 4.6 Indirect tooling lead time*

| Process | Time (HH:MM) | | Working Day |
|---|---|---|---|
| | Total | Hands On | |
| Virtual Manufacturing | 03:50 | 03:50 | 0-0.5 |
| Plug Fabrication | 24:00 | 00:25 | 0.5-1.5 |
| Plug Preparation | 10:50 | 03:50 | 1.5-2 |
| Mould Manufacture | 17:00 | 04:00 | 2-3 |
| Mould Repair | 13:00 | 01:00 | 3-4 |
| **Total Time** | **68:40** | **13:05** | **4 days** |

### 4.2.2 Indirect Tooling Discussion

This section discusses the second case study conducted where a traditional composite mould was produced indirectly via the FFF technology. This case study follows the same process flow as the direct tooling example, beginning with defining the product specification and creating a CAD model of the proposed tooling. A traditional composite tool of fibreglass and epoxy laminating resin, with a hardwearing tooling gelcoat as the mould surface was manufactured over the PLA plug. The intended use for this tool is in LCM applications with surface bagging, the design was for a female tool with a large flange area for adhering the vacuum bagging consumables. Generous draft angles (>5°) were incorporated into the design of the plug that was manufactured from PLA using FFF. The intention of the large draft angles was to hopefully aid in the demoulding process of both the plug and FRP parts that would be manufactured later.

Similarly, to Case Study 1 the part was sectioned so that it could be orientated vertically on the print bed. The vertical orientation is implemented for reduced stair stepping on the tooling surface and increased delamination resistance to demoulding forces perpendicular to the direction of pull. Various design for assembly features were implemented to ensure accurate alignment of the tool. A lip and groove feature was applied to the centre sections of the plug which is also to be the midpoint of the final part, making this a crucial area to mate well for an accurate tooling surface. The butterfly lock was used again as an added feature for alignment of these sections that was used to help pull these sections together along with clamps during the bonding process. A flat face was created in the tool where it would come in contact with the print bed for good adhesion, this required two more splitting surfaces to be implemented that would simply be reassembled using CA adhesive during post processing.

The plug was printed using the same print profile as the direct tooling solution in the first case study. Prior to printing the plug, a comparison between nozzle diameter and layer height was completed and their effect on print duration. In attempt to reduce the print-time, a larger diameter nozzle and coarser layer height were compared with the default nozzle and slice height (Table 4.7).

*Table 4.7 Comparison of nozzle diameter on plug fabrication time.*

| | 0.4 mm Standard Nozzle | 0.8 mm Large Nozzle |
|---|---|---|
| Print Duration (HH/MM) | 23:36 | 13:22 |
| Layer Height (mm) | 0.15 | 0.2 |
| Wall Line Count | 4 | 2 |
| Material Usage (g) | 242 | 259 |
| Material Cost (€) | 8.44 | 9.04 |

The coarser, and quicker print was not chosen as this print would still require more than 1 working day (8 hours), therefore could not be post processed until the following work day regardless. The longer build time using the standard 0.4 mm nozzle, adds quality to the printed plug, and as these machines run unmonitored, it does not add to any operator labour time. The higher resolution helped in fabricating a more accurate plug, a feature that will aid in the assembly of the tool so that split surfaces transition smoothly. A smooth transition is especially desirable in this indirect tooling example, as the indirect composite tool from the plug is one that is suitable for use in short to medium batch manufacturing.

The comparison in print profile (Table 4.7) shows how print accuracy and duration can be tailored to meet certain needs. The difference in print time would increase in larger, longer prints, in these scenarios the choice to move to a larger nozzle and layer height would make lots of sense, where days could be saved by selecting a coarser print profile. In this case study the 0.4 mm standard nozzle was selected as it would produce a more accurate part in a relatively short amount of time. The coarser print profile may be a better choice in larger prints or in direct prototype tooling examples where shorter lead times are required and tooling accuracy may potentially be less important.

The printed plug was assembled and bonded using a CA adhesive for its rapid curing properties and its proven effectiveness as an adhesive for printed parts throughout the literature and in the prior case study. Once assembled the PLA tooling surface was lightly sanded (P120) to key the surface for the epoxy sealer. The application of the sealer is unchanged from the direct tooling example, two coats were used and sanded smooth (P120-P1500) and polished with the NW1 polishing compound on a soft sponge polishing pad. The sealed and polished surface was then treated with a release agent. A wax release system was chosen for its ease of application and reliability.

As an indirect mould is being fabricated, it was decided that the plug did not require a semi-permanent release system, such as the chemical release system used in the prior case study. The guide for the wax release system (Meguiar's M-08) was followed, applying four coats with fifteen minute intervals, this is two coats less than the EasyLease chemical release system used in the direct tooling example and does not require a one hour wait after the final application. The composite tool was set aside to cure as per the recommendations of the manufacturer however, it is during the plug removal process where plug extraction challenges arose. The following reasons were identified as potential causes for the adhesive failure:

- Insufficient draft angles.
- Improper application of release barrier.
- Undercuts present due to insufficient filleting wax along the plug/flange interface.

Each of the causes could have influenced the plug removal process, as no cohesive failure occurs in the main portion of the plug, the wax release interface between the tooling gelcoat and the epoxy sealed plug is a compatible system, as three of the four corners of the plug demoulded with relative ease. Insufficient draft is unlikely the reason for this failure identified during demoulding, although a greater draft angle would appear to aid in plug removal, the angles used (minimum of 5°) proved successful but for one corner, that had the same angle as the other corners of the plug. Improper application of the release barrier appears to be the most likely cause of adhesion, as the adhesion is localised to one corner of the plug/mould. The edges of the gelcoat were ground back slightly to remove any slight overhang, locking the plug into the composite tooling. The grinding bit used was small cone shaped tungsten carbide abrasive, being small allowed for accuracy when removing gelcoat material. To mitigate the need for such grinding a more gradual transition between the plug and the glass sheet that it was mounted to may have helped, this could have been accomplished by using more fileting wax during the set-up phase of the plug.

It was decided that with some minor repairs to the gelcoat where it was ground down, that the tooling was suitable for use as the critical surfaces were undamaged and that the demoulding issue was less of a concern given sufficient release was used. The repair of the tool called for a small batch of gelcoat to be mixed and applied to the damaged areas. The gelcoat repair was left to cure and sanded to provide a smooth rounded edge prior to the application of the chemical release agent (EasyLease). The rework required to repair the composite tool added one day to the completion of this tooling example, where if the tool were scrapped the time and materials to this point would have been wasted as the plug would have needed to be fabricated once again adding up to four days to the process. This rework was justified by saving three days of a labour-intensive process.

Through the adoption of the FFF process, short lead times (less than five days) were attained in the fabrication of a traditional composite mould using an indirect tooling approach (Table 4.6). This is an example of how AM can be used as a tooling method appropriate for short series manufacturing runs or for cost-effective prototyping purposes, Boparai *et al.* (2016) suggest this is an effective method of overcoming some of the lead time and cost challenges associated with traditional tooling techniques. Depending on part complexity and shape mould fabrication times will vary, however this case study provides evidence that a plug fabricated using the low-cost FFF technology and PLA build material can be a viable indirect tooling technique for fabricating traditional composite style moulds. This study only investigated the use of PLA as this material is the most common FFF material for its ease of printing on even the most basic FFF machines.

## 4.3 Case Study 3 – FFF Sacrificial Tooling for Hollow Composites

The fabrication of hollow composites poses manufacturing challenges when it is not a part with a straight-wall cavity. Part configurations that trap mandrels within require an alternative solution. Solutions to such a challenge include extractable cores, soluble cores, two-piece layups, and clamshell moulds with inflatable bladders for consolidation. Sacrificial tooling with eutectic salts, ceramic, urethane, or memory bladders all requires additional tooling which increases time and cost. Stratasys are an example of an AM company who offer an FDM solution for producing sacrificial tooling, but this material is only compatible with their expensive industrial AM machines. Using the FFF technology, a water-soluble material was adopted to provide a low-cost alternative for the fabrication of sacrificial tooling for composites. This approach was adopted in attempt to reduce product lead time, and cost for bespoke tubes by wrapping the composite material around cost-effective sacrificial tooling, in contrast to pressing it into a cavity. This technology makes the process easier and less labour intensive, while eliminating the need for additional external tooling.

### 4.3.1 Sacrificial Tooling Results

The guidelines for using PVA as a support material suggest printing temperatures of 215-225°C, and a build plate temperature of 60°C. Through observation of printing various PVA samples with differing print settings the material profile was tuned to settings that printed reliably using the UM2+ FFF machine (Figure 4.9(a)).

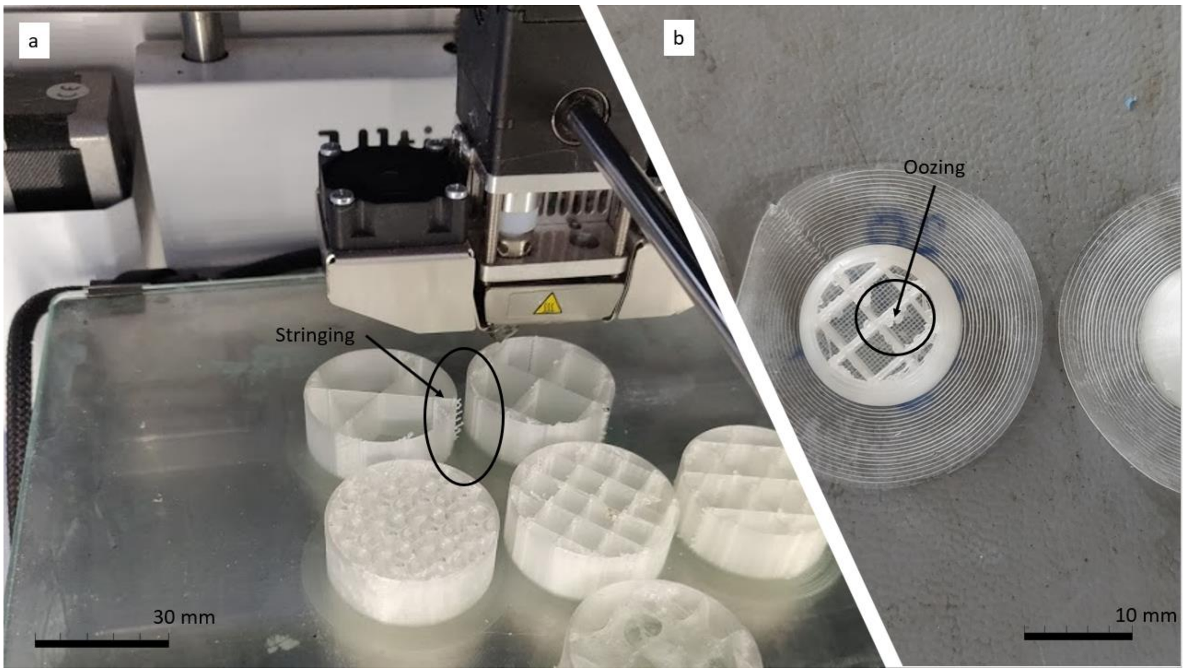


*Figure 4.9 (a) PVA material profile testing using different infill patterns. (b) Close up image of excess infill material accumulation.*

Print issues such as stringing (Figure 4.9 (a)), oozing (Figure 4.9(b)) and blocked nozzles were experienced, increasing the temperature to 230°C reduced the frequency of blocked nozzles. Higher temperatures of 235-245° were tested but led to discolouration of the material and a structure that appeared more brittle (the print brim no longer peeled away from the part, but instead broke away in shards). Slower infill print speeds and an increase in the infill overlap were applied, as the infill in early testing did not adhere to the print walls effectively resulting in strong intra-layer adhesion (Table 4.8).

*Table 4.8 Soluble PVA print profile adjustments from the baseline predefined generic PLA profile.*

| Print Setting | PVA | PLA (Generic Default) |
|---|---|---|
| Infill Pattern | Gyroid | Grid |
| Infill Density | 15% | 18% |
| Nozzle Diameter | 0.4 mm | 0.4 mm |
| Slice Height | 0.15 mm | 0.15 mm |
| Print Temperature | 230°C | 220°C |
| Infill Speed | 38 mm/s | 60 mm/s |
| Infill Overlap | 50% | 10% |

A range of infill patterns were compared, and each printed with similar levels of success (Figure 4.9 (a)). As this part was sacrificial and to be removed using warm water during post processing, a gyroid infill pattern was selected. This lattice structure is advantageous as water can flow freely through the internal structure of the parts unimpeded, unlike a traditional pattern such as a grid where the grid walls would obstruct the flow of a liquid as the profile of the sacrificial core changes direction, for example as the tube bends in this case study.

The tooling with this print profile withstood the pressures of the various consolidation methods. Each method resulted in a different product surface finish. The traditional vacuum bagged sample left a peel ply finish, a smooth matte finish on the sample consolidated using a tabletop bag and flexible silicone outer tooling, and the heat shrink consolidated sample had an inconsistent glossy finish with a spiral effect where the tape was overlapping.


*Figure 4.10 Cut away of composite shrink tape consolidated CFRP tube after the core was dissolved.*

Of the three consolidation methods the heat shrink composite tape was the quickest and easiest method for consolidating the parts. The envelope bagging gave good consolidation but was difficult to size correctly (Appendix C) and it was the most labour-intensive process due to the application of the additional consumable materials. The external silicone tooling provided the most consistent results, but it was the most expensive and time-consuming method of consolidation, the external tooling added four working days. The silicone outer tooling however was reusable. The core was effectively dissolved in all samples using warm water for sixty minutes. After this time the core was fully softened and extracted using a long-nosed pliers and a nylon bristle brush, it is clear from the cut-away view presented in Figure 4.10 that no part of the tooling remains adhered internally. Submerging the core in warm water after just twenty-four hours resulted in the resin used in the composite to soften, making the part less stiff to handle, but stiff enough to hold its shape.

### 4.3.2 Sacrificial Tooling Discussion

As seen in the literature review Stratasys have proprietary FDM materials (ST130) for soluble tooling applications, a material used by Turk *et al.* (2018) in the manufacturing of complex hollow CFRP. however, the use of desktop AM machines is a concept that would greatly reduce the cost of fabricating such tooling, making internal sacrificial tooling accessible to a wider audience. PVA is a water-soluble material available for the FFF technology, this material is used as a soluble support material for multi-headed machines. At the time of writing this report no print profiles were available for single-extrusion printers since this material (Ultimaker PVA) is primarily used as a support material for dual-extrusion prints. For this reason, a custom print profile was developed for all parts fabricated using this material throughout this study.

The tooling printed reliably using the settings outlined in this document, given that the material has been stored as per the manufacturer's recommendations. The PVA material is sensitive to moisture in humid environments, this moisture can be absorbed by the material, and it begins to boil once the material reaches the machines hot nozzle, causing bubbles to form in the material and audible popping as air escapes the material. When printing PVA in this state, more failed prints are observed and when successful the prints tend to break more easily. If this occurs, follow the manufacturers guidelines for drying of the filament. When using dry material strong parts are produced that are only further strengthened by the sealing process. The XTC-3D sealer was applied to the PVA core the same way it was applied to PLA in the previous case studies, with no added difficulties. The epoxy used does not appear to have a negative effect on the PVA tooling, this coating helped in strengthening the core and provided a barrier between the lightweight core and the CFRP that was later applied. If the sealer was not applied, the resin used during manufacturing would soak into the core due to the porous nature of FFF and potentially make the removal process very difficult.

The sealed core received a single coat of the liquid PVA release barrier. Unlike the wax-based release or chemical release agents used in the previous case studies, PVA cannot be polished to leave a mirror finish on parts, but it is a reliable release for difficult to demould parts. PVA is also only ever applied in a single coat, as attempting to apply a second coat will remove the first resulting in an uneven surface. A single coat application was better suited for this product and application as the tooling used was sacrificial, it was only to be used once. The single application of the release system saves on labour time and is a suitable technique for this application as the additional time in applying semi-permanent barriers will be lost as this tooling is washed away.

The core was wrapped in a 20 mm braided CF sleeve for its easy in application and improved performance, a result of having no seam lines and longer fibre strands. The braided CF sleeve from EasyComposites also accommodates for change in diameter, from 6mm to 26mm, making this sleeve very easy to apply on to the mandrel. A slow curing epoxy hardener was chosen to extend the working time of this composite, so that the operator did not need to rush the application or consolidation of the fabric. The consolidation of the part is applied with a release coated shrink tape for a good external finish.

Cutting the ends of the composite and the soluble mandrel exposes the gyroid infill of the core, allowing water to infiltrate the part and soften the entire core for removal. This lattice structure allowed for the fluid to pass through the entire infill pattern unlike a grid pattern would for example. Allowing water flow through the entire core assisted in dissolution of the core, a shell of two wall lines (0.8 mm) was also used for core removal purposes, thicker walls also add to print time, material usage and therefore the cost of the core. The part dissolved efficiently however, the composite part needs to be cured sufficiently prior to washing away the core, submerging the core in warm water resulted in the resin softening even though the stated time for full cure had passed. This is a concern for it makes it more difficult to suggest an accurate product lead time as it can take up to 14 days to obtain the full mechanical properties of the epoxy resin used. A post-curing cycle may prove very beneficial with this kind of composite, this can be done by heating the part in an oven from 40°C to 60°C in 10°C increments every two hours, after the initial 24-hour curing cycle. A post-curing cycle like this one would reduce the cycle time by up to 14 days and will result in a higher performing composite product, this method should be used if the facilities to do so are available. The temperatures used in such a post-curing process are low and should not have any adverse effect on the PVA mould that may lead to distortion of the product.

The consolidation techniques used have various benefits and drawbacks, this makes it difficult to recommend one over another. These external surface finish results make the decision product orientated. In cases where a peel ply finish is required the envelope bagging technique is most suitable. For a high gloss finish the composite shrink tape is a suitable alternative but it required more skill in wrapping the CFRP product to avoid any wrinkles forming. This method might be best suited for bespoke products with geometries that can be easily wrapped. Using the silicone mould to control the external surface finish is a suitable solution for short series production as the mould is reusable and should provide greater reliability and repeatability due to the closed nature of the tooling.

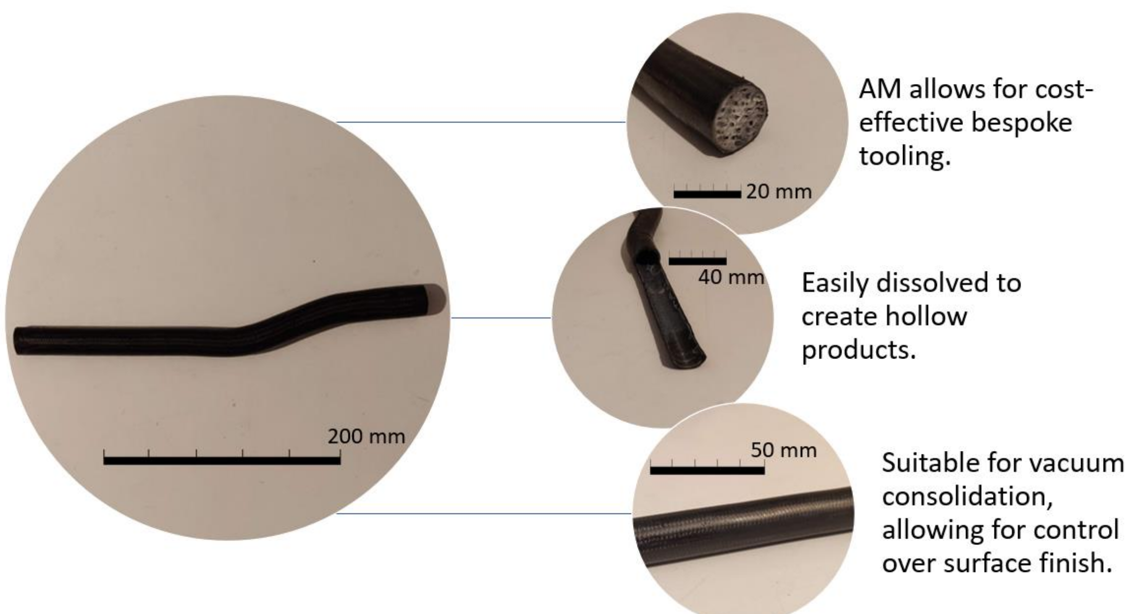


*Figure 4.11 Advantages of using FFF for bespoke complex hollow composites.*

Although a single consolidation method cannot be recommended for all circumstances, multiple solutions were outlined depending on the product use case. The internal tooling for each consolidation technique remained the same for each consolidation technique. This case study provides evidence that bespoke manufacturing of complex hollow composites, is possible using the combination of FFF and PVA water soluble material (Figure 4.11). Similarly to the saving of time and money experienced by Champion Motorsport (Wyman 2015), using the FFF technology offers many of the benefits of FDM at a lower price point making the technology more accessible. Nelson *et al.* (2019) identified the risk associated with adopting a new technology can result is some companies passing up on new opportunities. The cost of industrial FDM machines and materials may deter companies from adopting the FDM technology, however the use of FFF provides a low-cost alternative that is suitable for LCM applications.

## 4.4 Short Series Production Tooling – Criteria for Success

This technology using FFF manufacturing machines offers many benefits over traditional mould manufacturing methods for one-off or short series manufacturing runs. Table 4.9 outlines the criteria that is used to assess what technologies are best suited to cost effective short series production, this table compares low-cost additive technologies to CNC of both hard and soft materials and to traditional composite tooling fabrication methods. The symbols used below are to aid in identifying the strengths and weaknesses of each tooling technology with regards to the criteria identified for cost-effective tooling for FRP composite manufacturing.

The criteria outlined in Table 4.9 show how FFF can be used as a cost-effective RT solution accessible to organisations with minimal resources. The criteria are used to identify the abilities of FFF as a tooling method, while Table 4.10 presents the composite manufacturing technologies that FFF tooling may be suitable for.

*Table 4.9 Criteria of success for cost effective RT for FRP manufacture*

| Criteria | Traditional CNC Hard Tool | Traditional Composite Tool | Traditional CNC Soft Tooling | FFF Direct Tooling | FFF Indirect Tooling |
|---|---|---|---|---|---|
| Tool Fixed Costs | High fixed costs associated with CNC machining of metals. | Fixed costs from CNC machining of soft materials and in the labour-intensive task of building a composite tool. Typically, less expensive than metal moulds. | Can be an inexpensive tool, due to relatively low feedstock costs. However, NC programming phase may be time consuming and expensive. | Inexpensive mould making process where most of the costs lie in the mould post-processing. Feedstock and machine running are relatively inexpensive. | Relatively inexpensive when compared to traditional CNC methods as the cost of using the FFF process is low when compared to CNC. |
| Associated Risk (Tool Costs) | If there is a lack of demand for products from this tooling, the investment in the tooling may be difficult to recover. | This tooling is relatively expensive to produce, therefore care must be taken when designing moulds and a market gap should be identified prior to fabrication to ensure the tooling costs are recovered. | The cost of such tooling increases the unit cost of parts produced to a price that consumers are unwillling to pay for such item. | By using FFF the risk associated with NPD is greatly reduced as the cost of prototyping is minimal in comparison to traditional methods. | Low risk when using such a method, due to relatively short lead times and tooling costs. When used in conjunction with direct tooling via FFF this can be used as low-cost bridge tooling between short series manufacturing and mass production. |
| Testing Product Market Potential | Not suitable for market testing as fixed costs are high. | Due to the cost of such tooling confidence in market uptake of the product is required to succeed with such a tool. | Tooling is primarily used for high value added bespoke components and prototyping as these moulds are only suitable for short series production. | Rapid tooling excels at meeting new emerging market demands through short series production. This can be used to accelerate the NPD cycle through functional prototyping. | Indirect rapid tooling can be used to get new innovative products to market faster with a production-ready tool fabricated from a traditional material. |

| Criteria | Traditional CNC Hard Tool | Traditional Composite Tool | Traditional CNC Soft Tooling | FFF Direct Tooling | FFF Indirect Tooling |
|---|---|---|---|---|---|
| Resource Barriers to cost effective tool making. | CNC machining of tooling is complex as toolmakers must generate reliable NC programs to cut blocks of material accurately and reliably while reducing machining hours. This requires high-skilled toolmakers. | CNC machining of tooling is complex as toolmakers must generate reliable NC programs to cut blocks of material accurately and reliably while reducing machining hours that require high-skilled toolmakers. This process adds a second level of complexity in fabricating the composite tool which also should be performed by trained personnel. | CNC machining of tooling is complex as toolmakers must generate reliable NC programs to cut blocks of material accurately and reliably while reducing machining hours. This requires high-skilled toolmakers. | The tool paths for FFF parts are easily generated using slicing software. With some modifications to the printing parameters an effective low-cost tool can be easily fabricated with minimal post-processing. | The tool paths for FFF parts are easily generated using slicing software. With some modifications to the printing parameters an effective low-cost tool can be easily fabricated with minimal post-processing. This process adds a second level of complexity in fabricating the composite tool which also should be performed by trained personnel. |
| Tool Variable Cost (number of products per mould) | Suitable for mass production, to offset the cost of tooling. | Composite tooling is suitable for medium sized production runs. With good mould maintenance, composite tools may be used for 100s of cycles. | Suitable for bespoke to short series manufacture (<20 units). | Suitable for bespoke to short series manufacture (<20 units). | Composite tooling is suitable for medium sized production runs. With good mould maintenance, composite tools may be used for 100s of cycles. |

| Criteria | Traditional CNC Hard Tool | Traditional Composite Tool | Traditional CNC Soft Tooling | FFF Direct Tooling | FFF Indirect Tooling |
|---|---|---|---|---|---|
| Cost of Product Iteration | Due to the high cost of machining hard tooling, often many weeks are spent in the design of the tooling to ensure it does not require expensive and time-consuming rework or additional iterations. | The CNC master or plug is typically no more expensive than a directly manufactured tool. Much of the costs associated with this tooling is due to labour of laminating the composite tool. | The least expensive CNC tooling to iterate due to its soft nature it can be machined faster | The cost of iteration is far less using FFF direct tooling as tooling re-work costs are high compared to printing another piece of tooling using FFF. | The FFF master or plug is inexpensive. Much of the costs associated with this tooling is due to labour of laminating the composite tool. |
| Time for Product Iteration | As a result of high costs and need for careful NC programming, many weeks may pass between product iterations. | Moderate to long product iteration times, as a master model must first be created fabricated, prior to composite tooling lamination. Multiple weeks between product iterations are typical for this kind of mould. | Short lead times (1+ weeks) between product iterations. This can vary depending on mould complexity, as this may add to the NC programming and machining times. | Very short product iteration times for small tooling. Typically, tools can be fabricated, assembled, and receive appropriate surface sealing in >1week. | Short/medium product iteration times 1-2weeks, due to the additional process steps when compared to direct FFF tooling. |
| NPD Tooling Scalability (Rapid ramp) | Very high tooling cost may limit the number of tools that can be fabricated and used in parallel. | One master model can be used in the fabrication of multiple composite moulds that can be used in parallel. | Many soft moulds could be used in parallel, but each mould is limited to relatively short production runs. | Direct FFF tooling can be used in parallel, but each mould is limited to relatively short production runs. | One master model can be used in the fabrication of multiple composite moulds that can be used in parallel. |

| Criteria | Traditional CNC Hard Tool | Traditional Composite Tool | Traditional CNC Soft Tooling | FFF Direct Tooling | FFF Indirect Tooling |
|---|---|---|---|---|---|
| Product manufacture cycle time | Elevated temperatures can be used to reduce cycle times (cycle times and temperatures are resin specific). | Elevated temperatures can be used to reduce cycle times (cycle times and temperatures are resin specific). | Elevated temperatures can be used to reduce cycle times (cycle times and temperatures are resin specific). | Cycle times are limited to room temperature curing cycle times. | Elevated temperatures can be used to reduce cycle times (cycle times and temperatures are resin specific). |
| Product Time to Market | Due to the high cost of hard tooling, often many weeks are spent in the design of the tooling to ensure it does not require expensive and time-consuming rework or additional iterations. These materials are much slower to machine also. | Moderate to long lead times as master model must first be fabricated, prior to composite tooling lamination. Multiple weeks lead time should be expected for this kind of mould. | Short lead times (1+ weeks). This can vary depending on mould complexity as it may add to the NC programming and machining times. | Very short lead times for small tooling. Typically, tools can be fabricated, assembled, and receive appropriate surface sealing in >1week. | Short/medium lead time 1-2weeks, due to the additional process steps. |
| Organisation Financial Barriers to Tool Making | High capital cost of machines and high NC programming costs. Machines typically are large and have a large footprint that require dedicated laboratory space. | High capital cost of machines and high NC programming costs. Machines typically are large and have a large footprint that require dedicated laboratory space. Soft tooling is less expensive and easier to machine than tool steels. | High capital cost of machines and high NC programming costs. Machines typically are large and have a large footprint that require dedicated laboratory space. Soft tooling is less expensive and easier to machine than tool steels. | Desktop FFF machines are relatively inexpensive (<€5000), combined with free slicing software and negligible set up times. | Desktop FFF machines are relatively inexpensive (<€5000), combined with free slicing software and negligible set up times. No expensive equipment is required to building a composite tool. |

| Criteria | Traditional CNC Hard Tool | Traditional Composite Tool | Traditional CNC Soft Tooling | FFF Direct Tooling | FFF Indirect Tooling |
|---|---|---|---|---|---|
| Tool/Product Dimensional accuracy | ✓ One of the greatest strengths of CNC machining is its ability to achieve very tight tolerances. | ✓ One of CNC machining's greatest strengths is its ability to achieve very tight tolerances. | ✓ One of CNC machining's greatest strengths is its ability to achieve very tight tolerances. | ⚠ FFF can produce parts to ±0.1mm, or greater depending on the slice height used. The sealer used should be applied in very thin layers approximately 0.04mm thick. This further reduces the accuracy of the tooling. | ⚠ FFF can produce parts to ±0.1mm, or greater depending on the slice height used. Note indirect tools are mirror images of the FFF master model. |
| Tool/Product Surface finish | ✓ CNC can produce high quality surface finish, without the need for post-processing. | ✓ Post-processing required, sanding to above P800 is typically acceptable for a class 'A' surface finish. | ✓ Post-processing required, sanding to above P800 is typically acceptable for a class 'A' surface finish. | ✓ Post-processing required, sanding to above P800 is typically acceptable for a class 'A' surface finish. | ✓ Post-processing required, sanding to above P800 is typically acceptable for a class 'A' surface finish. |
| Composite Cure Temperature Range | ✓ Suitable for most composite processing methods. For applications under high temperature that require very tight tolerances, metal tooling is not always suitable due to the differing coefficient of thermal expansion between the tool and laminate. | ✓ Suitable for LCM and prepreg laminate use, and stable trough a wide range of temperatures. | ✓ Some specilist epoxy tooling boards are available that can be autoclaved at temperaures up to 130°C. | ⚠ Suitable for low temperature OOA (out-of-autoclave) applications. Open moulding or under vacuum for consolidation. FFF can also be used to produce sacrificial soluble tooling that can be used to produce bespoke hollow composits. | ✓ Suitable for LCM and prepreg laminate use, and stable trough a wide range of temperatures. |

*Table 4.10 Composite Manufacturing Process Applicability for different tooling types*

| Process | Traditional CNC Hard Tool | Traditional Composite Tool | Traditional CNC Soft Tooling | FFF Direct Tooling | FFF Indirect Tooling |
|---|---|---|---|---|---|
| **Liquid Composite Moulding** | | | | | |
| Open Contact Moulding | ✓ | ✓ | ✓ | ✓ | ✓ |
| Resin Transfer Moulding | ✓ | ✓ | ✓ | ✓ | ✓ |
| Vacuum Assisted Resin Infusion | ✓ | ✓ | ✓ | ✓ | ✓ |
| **Prepreg Moulding** | | | | | |
| Autoclave material processing | ✓ | ✓ | ⚠ Some specilist epoxy tooling boards are available that can be autoclaved at temperaures up to 130°C. | ⊘ Many FFF materials have low glass transition (Tg) temperatures making them unsuitable for elevated curing. Softening temperature: PLA ~60°C & ABS ~95°C) | ✓ |
| Out-of-Autoclave processing (elevated temperatures) | ✓ | ✓ | ⚠ Some specilist epoxy tooling boards are available that can be processed at temperaures up to 130°C. | ⊘ Many FFF materials have low glass transition (Tg) temperatures making them unsuitable for elevated curing. Softening temperature: PLA ~60°C & ABS ~95°C) | ✓ |

## 4.5 Benefits Statement

A review of the current state of additive and composite manufacturing techniques were reviewed throughout the duration of this work. The use of AM in RT for composites has been a recurring theme in both the literature and from large AM machine producers alike in recent years. Much of the research conducted focuses on the fabrication of moulds for complex fibre composite parts while reducing the cost of production when compared with traditional subtractive manufacturing techniques. The conclusions made by many of these researchers show that AM is a viable RT technique for producing, yet the AM machines used and suggested are typically industrial level machines that are expensive to buy and run. It is also common to see whitepapers published by the large AM technology providers on the use of their technology in toolmaking, these technologies are expensive and not available to financially constrained organisations. However, most AM machines sold are FFF machines, their low cost and ease of use are major strong points of this technology this technology when compared with industrial FDM and SLS technologies. FFF machines are often overlooked for RT applications, however they can produce complex geometries like other, more expensive, ME technologies and are available in many sizes at more affordable price points, for these reasons this technology was adopted in this RT study. The effects of adopting this technology, in terms of its benefits to an organisation will now be discussed.

### 4.5.1 Financial Benefits to FFF Tooling

The financial benefits are some of the most compelling reasons for adopting the technology outlined in this study. The fixed cost of tooling is drastically reduced by adopting this technology, the FFF tooling costs are presented and cost reductions of 75% can be seen when comparing the direct RT of Case Study 1 to the equivalent CNC machined aluminium tool. Unlike traditional manufacturing techniques the associated risk of tooling is greatly reduced. The reduction in risk is not limited to tooling cost reductions but also tooling lead times, where tools are ready to use within a matter of days in both direct and indirect tooling solutions. Traditionally design iterations are time consuming and expensive to implement and reworking of metal tooling is common in attempt to reduce costs. It is suspected that the cost and lead time factors associated with tooling via the FFF technology will promote product iterations and testing throughout the NPD cycle. The tool life is unpredictable and may be influenced by many factors such as tooling complexity, surface finish and mould preparation, for this reason the tooling variable cost or the number of products that can be produced by a single mould is unclear, especially in the direct tooling approach. This lack of clarity in tool variable cost makes it difficult to predict the unit cost of parts fabricated via this tooling approach, therefore the direct tooling technique may be best suited to NPD prototypes and/or to very short batch production of high added value components. The low-cost and short lead times of the direct tooling however do offer an additional layer of scalability to production as for example in case study 1, four tools could be fabricated for the same cost as one aluminium tool, making it an ideal solution to implement rapid ramp as multiple products can then be made in parallel.

The costs referred to in this study for the direct FFF tooling include a flat rate of €10/hr which is typical of the cost to rent a FFF machine in a FabLab, this charge however does not apply to organisation who own such machines. Desktop FFF machines as the machine used in this study are relatively inexpensive hen compared to CNC machines. These machines also do not require highly skilled operators to run or manage, require little maintenance and are suitable for lights out manufacturing, allowing them to run unattended often overnight. These features make FFF very versatile throughout the NPD process, and in the fabrication of functional prototypes using cost-effective RT.

Indirect RT (Case Study 2) presents a technique for the production of traditional composite tooling, albeit through non-traditional plug fabrication means, allows organisations bring their designs from prototype all the way through to production using the FFF technology to assist. These moulds are typically suited for medium batch production runs, this offers the organisation a route to fabricate cost-effective production tooling.

### 4.5.2 Product Quality

Dimensional accuracy, surface finish and material used are aspects of the AM technology which influence the limitations of this methodology. AM machines are often used in fabricating complex shapes, due to the additive nature of this set of manufacturing technologies this is possible (Hinchy 2019). However, there is a direct relationship between layer height (dimensional accuracy) and print time (tooling lead time), as a result the two should be balanced in a way to suit the product requirements. Where more dimensional accuracy is required smaller nozzle diameters (<0.4 mm) and small layer heights (0.1 mm) can be used. By selecting an appropriate nozzle diameter and layer height for the product accuracy are important, but DfAM also plays an important role in producing dimensionally accurate products. Following the design for AM guidelines in this report will aid in the fabrication of better-quality tooling being fabricated, by minimising the stair-casing effect that is present in additively manufactured parts. This report also provides guidelines for making stronger tooling by adjusting the tooling shell thickness, without adding unnecessary material that adds to build time and costs. However, regardless of the hardware or software variables changed, the parts must be sealed. The epoxy coating applied in each case study is used to both sealed the moulds which are porous by nature, and to provide a smooth tooling surface. The application of this epoxy sealer is very thin (0.04 mm recommended per layer) which will have little effect on the end accuracy of these parts. This epoxy sealer can be used directly as a tooling surface with no post processing, as it has self-levelling properties it leaves a good finish however, the moulds were sanded and polished after sealing to provide more control over the surface finish, to produce a product with a Class A surface finish (>P800). PLA is one of the most popular FFF filaments to use for its relatively low-cost and ease of printing, but it also has a low softening temperature that limits the RT to low temperature curing composite manufacturing processes. Room temperature curing resins are widely available which are well suited to the direct tooling approach, for applications that require higher operating temperatures a composite tool is typical, this study shows how FFF can be implemented indirectly to fabricate such tooling. The indirect RT method adds a process step when compared to the direct technique, but it results in a superior tool that will last hundreds of production runs while retaining dimensional accuracy as the mould and product expand and contract at the same rate.

The indirect RT overcomes the temperature limitations that are associated with many FFF materials such as PLA, making them a more versatile mould. This low-cost method of fabricating composite tooling can assist in bridging the gap between prototyping and production, this is an area where a need has been identified in recent years by researchers such as Afonso *et al*. (2019) and Equbal *et al.* (2015). As this technique provides a cost effective and rapid solution to FRP manufacturing it encourages NPD teams to solve technical uncertainties associated with a product through design iterations, a technique that Cooper (2014) advises to improve the quality and probability of product success.

### 4.5.3 Manufacturing Process Compatibility

Tooling materials should be selected on the manufacturing processes that will be used and the conditions that they are subjected to. Temperature as mentioned above can play a big role in the curing of composite products however, elevated temperatures are not always necessary, as shown in this study where room temperature was sufficient for curing. The direct PLA/PVA tooling are not recommended where elevated temperatures are required, this limits the manufacturing processes in which they are applicable, in contrast to traditional metal or composite tools. Therefore, the direct tooling methods used in this study should be suitable for liquid composite moulding application, using room temperature curing resins. This study shows however that organisations who have adopted FFF technologies can fabricate traditional composite tooling indirectly from a PLA plug. This gives these organisations the ability to produce higher performing composites both autoclave and out of autoclave prepreg processing methods.

# Chapter 5: Concluding Remarks

In this research, a low-cost alternative for producing RT for FRC manufacturing is presented, using FFF for both direct and indirect tooling solutions. The aim of this research was to explore the use of the low-cost FFF technology to fabricate tooling for liquid composite moulding techniques. Along with using a low-cost AM technology, the composite processes selected were also chosen for their low financial barrier to entry.

LCM techniques were adopted, as these processes allow for room temperature processing using vacuum pressures making them ideal for quick prototyping, bespoke products and for short production runs. The techniques described in this study provide thorough process descriptions of the methods and materials used to allow someone start manufacturing FRP parts, with relatively short lead times and relatively low entry costs. The case studies result in a cost-effective guide being presented for the fabrication of a range FRP parts.

## 5.1 Conclusions

*Objective 1: To identify a rapid tooling solution for composite manufacturing organisations with additive manufacturing capabilities.*

FFF was shown to be a viable tooling fabrication process for organisations which do not have in-house toolmakers or CNC machines at their disposal for mould tooling construction. FFF machines are shown to be versatile machines that have a place in the NPD cycle of FRPs for making prototype parts, cost-effective RT and custom trim tools.

*Objective 2: To develop a tooling solution for short batch production that is effective in terms of time and money.*

The use of FFF tooling throughout the Case Studies provide evidence to how the NPD cycle for FRP parts can be reduced. A reduction in lead time of 66% is seen for the tooling in case study 1, when comparing the proposed FFF direct tooling to an outsourced CNC machined aluminium mould. The use of the FFF tool also provides a 75% reduction in tooling costs. These reductions in tooling lead times and costs aid in the NPD cycle as they allow organisations iterate on designs more effectively, allowing them to reduce the time to market, while providing high quality products. Such tooling is a viable solution for short batch production of FRPs, multiple tools can be manufactured and used in parallel, providing a route to the rapid production of FRPs for the organisation.

*Objective 3: To determine which composite processing techniques are most suitable with the FFF rapid tooling technology.*

Liquid composite moulding processes with room temperature curable resins are suitable for moulds manufactured using this technology. These kinds of processes are well suited to composite manufacturing organisations who wish to produce small volumes or bespoke items cost effectively as buying the raw fabric materials dry is less expensive that prepregs. Using the direct FFF tooling technology outlined in this work the organisation is limited to liquid composite moulding processes at low temperatures (> 60°C) as PLA, the thermoplastic material used to manufacture the moulds begins to soften beyond this temperature.

An indirect tooling approach is outlined to provide a cost-effective method of producing composite moulds, which are more durable and suitable to be used at higher temperatures. Using the indirect tooling approach, the organisation can quickly produce master models or tooling plugs, using FFF as in the direct tooling technology, from which the composite mould is fabricated.

The third case study outlines a unique use for PVA a water-soluble FFF material, where it is used as sacrificial mandrel for complex hollow composites. This technology allows for bespoke hollow products to be produced in a short timeframe, without the need for additional tooling. This method is a direct tooling approach which also is limited to room-temperature curing processes.

*Objective 4: Determine the product categories that are suitable while using low-cost rapid tooling in terms of materials, processing conditions and surface finish.*

Common composite fibre materials such as carbon and glass were used in this research as examples of fibre fabrics that are suitable for cost-effective liquid composite moulding. The products produced were chosen due to their complex contour designs, a challenge that the FFF technology is well-suited for overcoming. Best practices for design for AM and mould building are outlined to minimise post-processing to the RT, while maintaining the strength required to survive vacuum bagging consolidation. Epoxy resin is used to effectively seal the mould and was easily polished to a class A surface finish that holds up against multiple manufacturing runs.

## 5.2 Limitations of the Proposed Technology

There are limitations to the direct RT technology, the inability to process at elevated temperatures may limit the applications where the end composite product can be used however, the indirect tooling approach is a potential solution to overcome this shortcoming. This reduced processing temperature may also result in longer cycle times depending on the resin used, the EL2 Laminating Resin used in this work however has not got recommended elevated temperature cure cycle to accelerate cycle times.

The durability of the tooling has not been tested in this work, however five parts were extracted from the direct mould used in case study 1 without any signs of deterioration to the moulding surface. Directly fabricated FFF tooling is not as forgiving as a hard tool and the application of the appropriate release system is essential for success, otherwise cohesive failure may be experienced where the tooling surface adheres to the composite part resulting in failure.

Tooling size is also limited by the build volume of typical low-cost FFF machines. Methods of overcoming this limitation are presented, by splitting the tool into multiple sub-components, a larger tool is later assembled making it possible to produce tooling that extends beyond the limitations of the 3D-printer build chamber. For a printer as small as the UM2+ the most practical application of the RT technology is in relatively small complex components. Larger FFF printers are available, however these machines are typically more expensive (>€5,000) and were not tested or investigated as part of this work.

Results of this study should help give confidence to composite manufacturing organisations in implementing FFF as not just a prototyping technique but as a solution for RT in the composite manufacturing field.

## 5.3 Recommendations and Future Work

Development of a cost model for RT for each composite process to make more accurate cost estimations.

This research does not test the direct FFF mould to failure, it would be beneficial to estimating the unit cost of a composite part via this technology it the average tool life of FFF rapid tools was known. It is expected that moulds with deep cavities and less draft applied to the cavity walls will reduce the tool life. A study such as this would be helpful in identifying the limit of what product feature are feasible with this technology.

PLA material was used in the fabrication of tooling in this research, it would be worthwhile investigating the use of other FFF materials such as polycarbonate (PC), nylon (PA) and co-polyester (CPE+) as tooling materials as alternative materials as these may perform better in terms of higher service temperatures and resistance to wear. These materials were not chosen in this study as PLA is less expensive and widely accepted as one of the easiest materials to print with across all levels of FFF printers.

The FFF technology was adopted in this study for its low equipment/material costs, its ease of use and for its speed. Other AM avenues should be explored further and compared, to aid in the AM technology selection, as some technologies may overcome the short comings of the direct FFF tooling shown in this study. A balance between cost, tooling lead-time and durability would help in finding the most appropriate additive technology to adopt.

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# Appendix A Saddle Direct Manufactured Tooling for Resin Infusion

## *Virtual Prototyping of Tooling*

Early infused composite parts were competed using a direct block style mould for the designed bicycle saddle. This tool set was designed to reduce post processing of the tooling as much as possible, to do so thermoforming was used to create the top surface of the tooling. This both protected the mould from wear and produced a smooth tooling surface. The thickness of the thermoformed skin was offset from the tooling surface to maintain part accuracy.

To produce the block tooling a flange was added around the outer surface of the mould, giving a clean and accurate cutting line for the complex shaped composite being produced. Thickness is then added to the to the tooling to create a solid body designed for infusion, the tooling requires a flat base so that it can be positioned on the glass sheet where tabletop bagging will be placed. A draft analysis was conducted to ensure that the demoulding of the final part would be possible (Figure A.1).

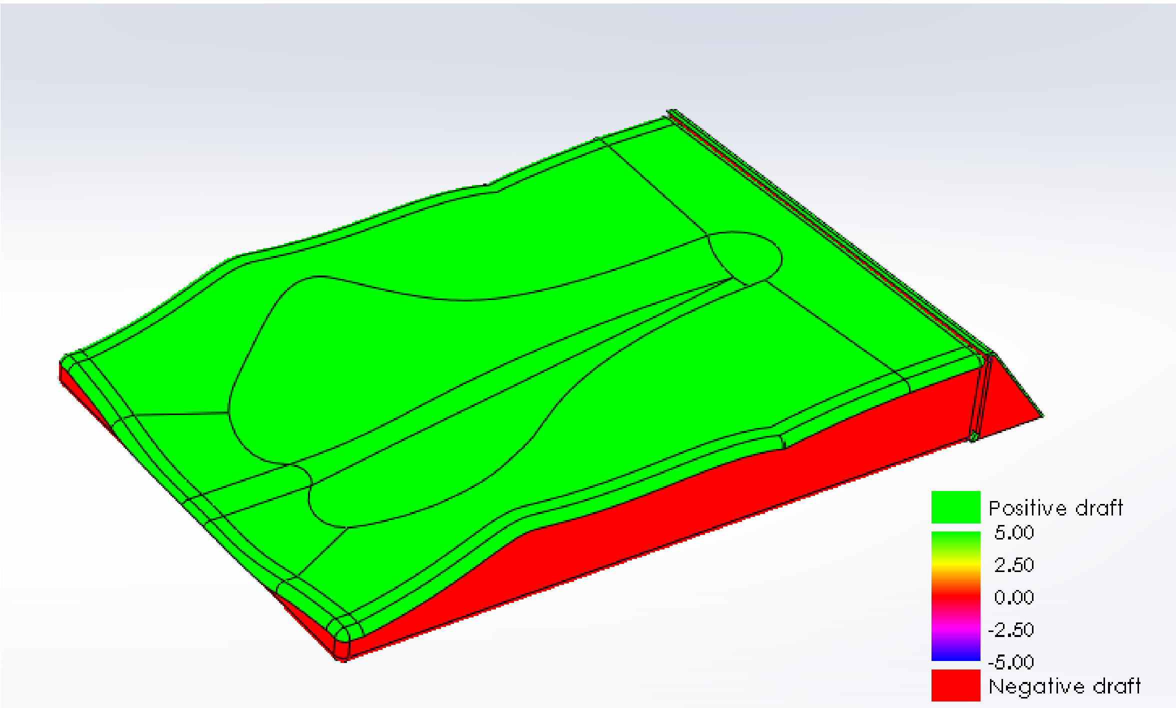


*Figure A.1 Draft analysis of female saddle mould*

From the draft analysis, it is evident that the tooling surface has sufficient draft and that the mould sides do not, composite materials should not be laid over these edges as the tooling may become difficult to remove during the demoulding process.

This part has an added flange area of the back of the tooling to make it easier to include infusion lines and maintain a gradual transition from the mould surface to the tabletop. This part was designed with no splitting surfaces, thus had to be printed horizontally. As this was an early tooling case study, the importance of printing the tooling surface vertically was underestimated. This part exceeded the print volume of the UM2+ with a length of 220mm, therefore this part was printed on a less expensive FFF machine (Creality CR10S4, approximately $600).

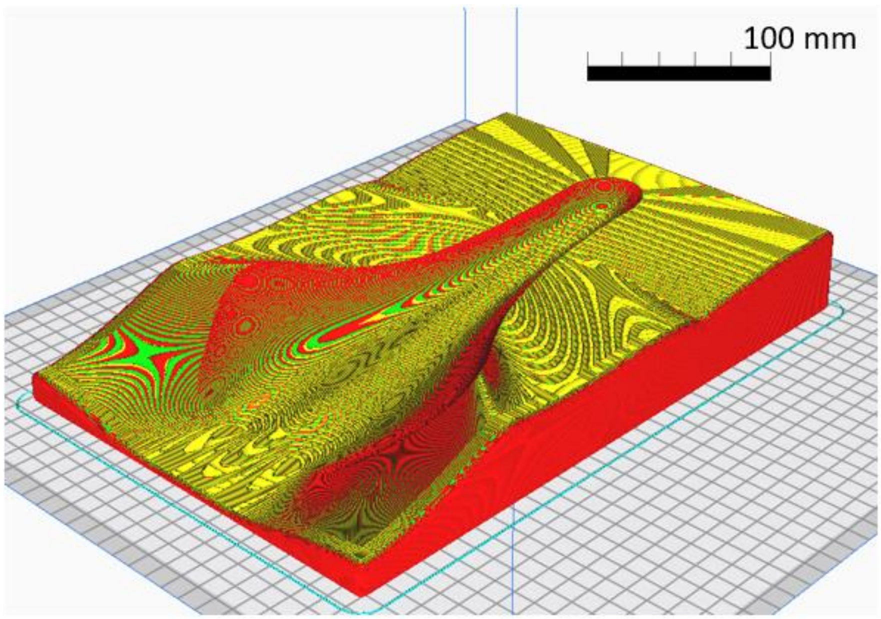


*Figure A.2 The sliced block tool for the saddle, showing the stair stepping effect clearly due to the horizontal build orientation.*

As this was a large block tool and printed with relatively default settings (infill pattern was changed to gyroid) the print time was very long. This print lasted over two and a half days at the default layer height of 0.2mm. The slicer settings used to prepare this model are found in Table A.1.

*Table A.1 Print properties for block style infusion tooling.*

| | 0.4mm Standard Nozzle |
|---|---|
| Print Duration (DD/HH/MM) | 02:14:07 |
| Layer Height (mm) | 0.2 |
| Top Layers Count | 4 |
| Material Usage (g) | 607 |
| Material Cost (€) | 22.05 |

## *Physical Prototyping of Direct Tooling*

The printed part is built, and post-processing commences. This printed tooling has pronounced stair-casing effect (Figure A.3 (a)), a result of the horizontal build orientation. Sanding of the tooling surface with 120grit sandpaper was done for better adhesion between the tool and the epoxy sealer.

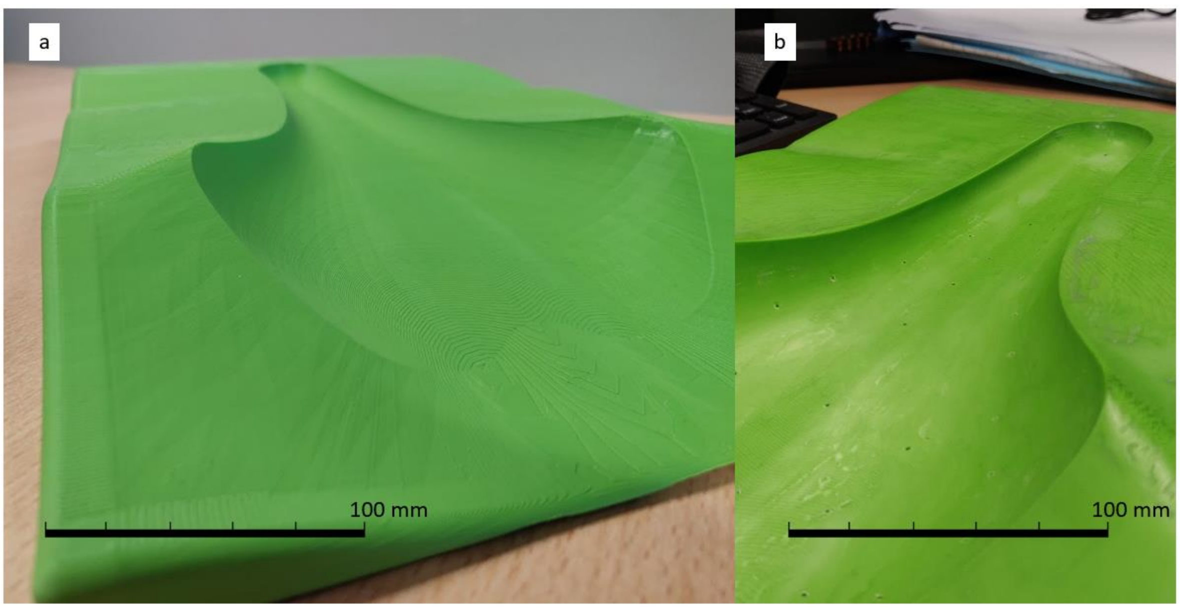


*Figure A.3 (a) Block Tool for infusion directly off the printer. (b) Block tool after receiving epoxy sealer and drilled with 1mm diameter holes for thermoforming.*

The sealed mould received further sanding (800grit) before the surface was deemed acceptable for thermoforming. The sealing process effectively filled layer lines, however a second coating may have resulted in a more consistent surface. Blemishes are visible in Figure A.3 (b), as another surface layer was yet to be added these blemishes were accepted to save time applying, curing and post processing a further layer of epoxy. A series of small 1mm holes were drilled across the tooling surface, as well as larger holes in the base of the tool to assist in the thermoforming process. As a gyroid infill pattern was chosen air can travel throughout the tooling uninterrupted by walls of infill material, as would be the case if a standard grid pattern were used. A thin styrene sheet (0.6mm thick) was used in the thermoforming process. The mould was placed in the thermoforming machine and heated until the material became pliable, at this point the tooling was raised and a vacuum was pulled, drawing the plastic over the printed mould.


*Figure A.4 Thermoformed covers of the bicycle saddle infusion tooling. Gloss (left) and matte (right).*

The styrene sheet had one gloss surface and one matte surface, covers were formed with both to compare the visual results obtained from each mould type and demoulding differences. This is the final stage of the tooling manufacture. Next parts will be fabricated using the resin infusion process.

### *Composite Part Manufacture from Direct Rapid Tooling*

The mould and glass sheet were first cleaned to with IPA. The RT was next coated in Frekote release system five times with 15-minute intervals between coats. Two plies of 200 g/m2 2x2 twill weave 3K carbon fibre is cut to size to cover the tooling surface (290x200mm plies), this laminate was laid in a [0/90,0/90] orientation. The set up for this part (Figure A.5 (a)) is as per university guidelines available in Appendix B, the standard operating procedure for liquid resin infusion.

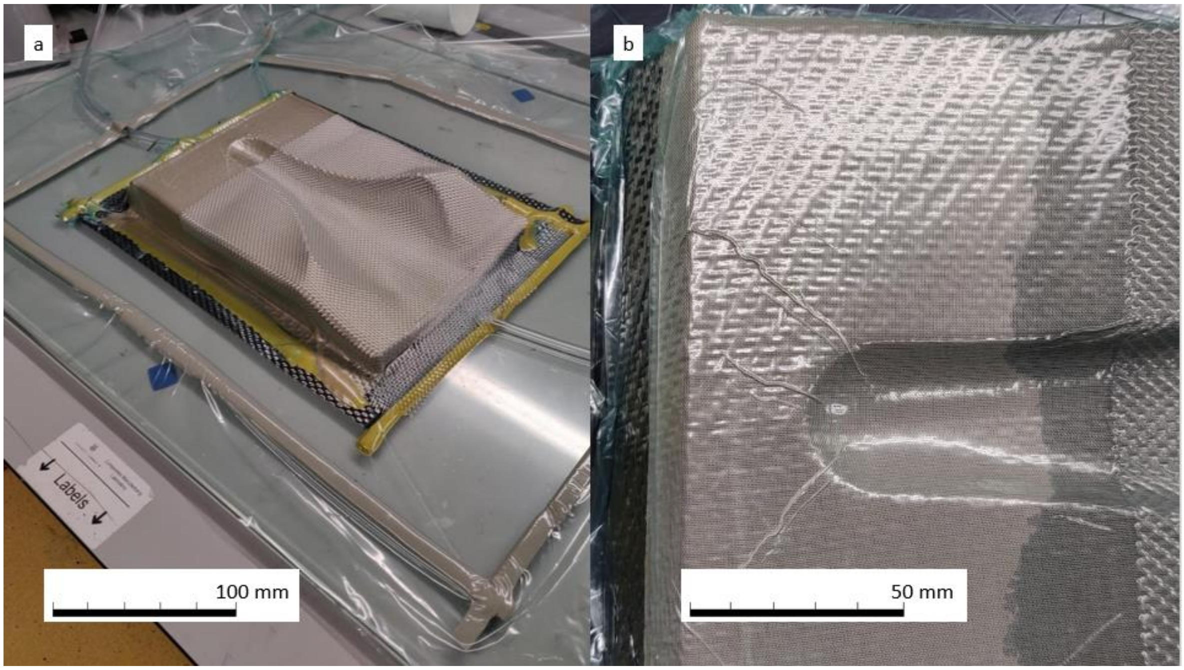


*Figure A.5 (a) Resin infusion set up, prior to infusion and post 15-minute vacuum drop test. (b) The resin flow front during infusion, towards the nose of the saddle.*

The parts were infused (Figure A.5 (b)) and once resin was drawn into the outlet pipe, it was clamped and left to cure. EasyComposites IN2 Epoxy Infusion Resin was used for these parts, with the AT30 fast hardener. Part demoulding commenced once parts were cured (6-8 hours), at this point, the vacuum bagging consumables and peel-ply layers are removed and the part was removed from the mould.

Separate thermoformed sheets were used for each infusion and visual results from both the matte and glossy moulds are compared. Although both parts produced resulted in composite parts with a high-quality surface finish, there is a noticeable difference in the appearance. The part on the right (Figure A.6) has a more reflective surface, however, the surface produced from the matte-side-up thermoformed sheet is also glossy but produces less reflections. It is suspected that the Frekote release system used enhanced the surface finish by reducing surface roughness, as the thin film formed with this release agent is designed to do.

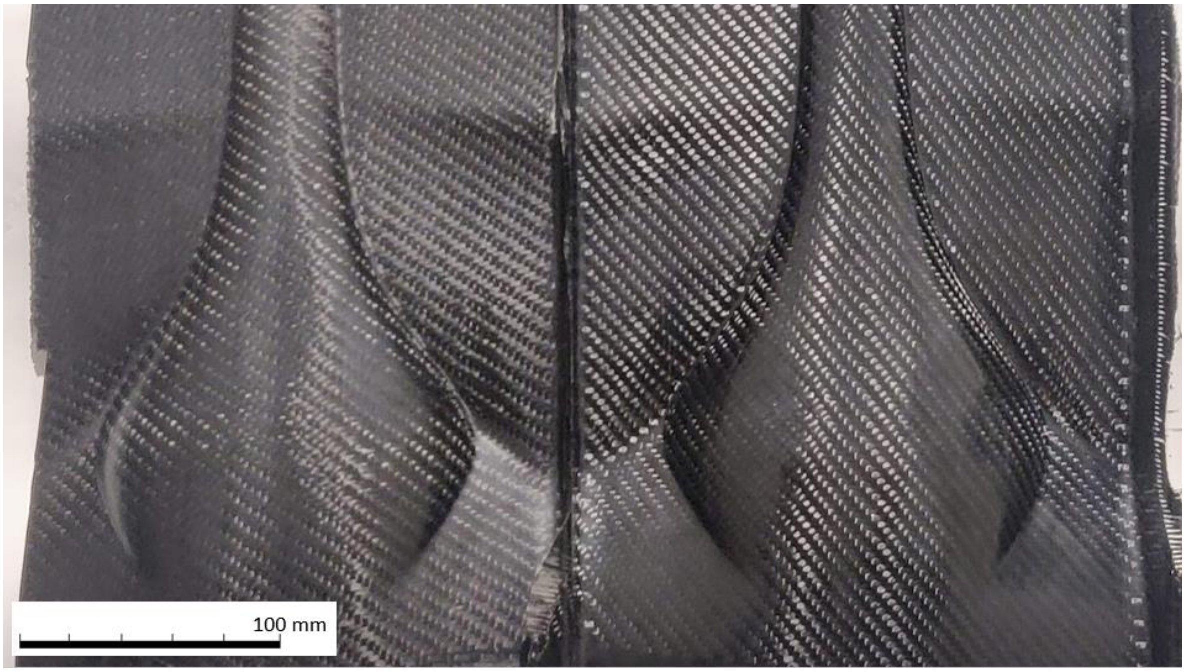


*Figure A.6 A side-by-side comparison of CFRP infused parts from the matte (left) and gloss (right) thermoformed tooling.*

### *Part trimming & trim tool fabrication*

To finish these parts, the final step of the process is to trim the composite to size. In this example the trim line is obvious for the most part however, towards the back, wider end, of the bicycle saddle this trim line becomes much more difficult to detect. A trim tool was required to accurately mark out the trim line for this area of the part. The trim tool is another area where the FFF technology was adopted to quickly produce a guide to mark the composite edge (Figure A.7 (a)). From the part design a lightweight tool is designed that can be quickly printed (2hours 10minutes) from PLA, weighing only 17g which is approximately €0.60. The default nozzle and layer heights of 0.4mm and 0.15mm respectively were used with the part inverted so that the rough surface produced by the support interface is not in contact with the glossy finish of the infused composite. A raft was also used to increase the surface area in contact with the build plate (Figure A.7 (b)).

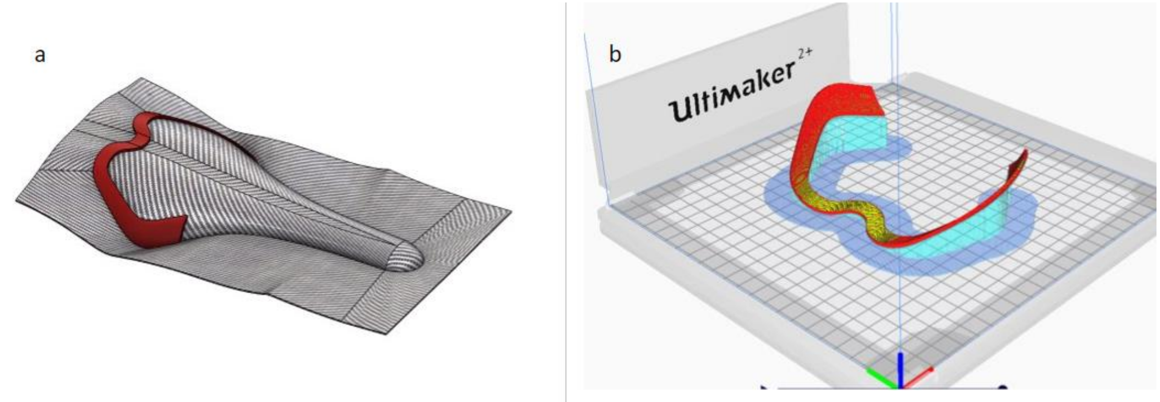


*Figure A.7 (a) Trim tooling design in CAD for infused saddle. (b) Trim tool slicer set-up in Cura.*

The composite part is cut near net shape by eye using a handheld rotary tool with a carbide abrasive cutting disk. The newly fabricated trim tool is mounted to the composite part and a trim line is scribed into the surface of the epoxy. The trim tool is removed once again, and the cutting process is continued. Cutting with such a disk can be done close to this trim line but other rotary grinding tools and hand finishing techniques should be used to obtain the final shape (Figure A.8).

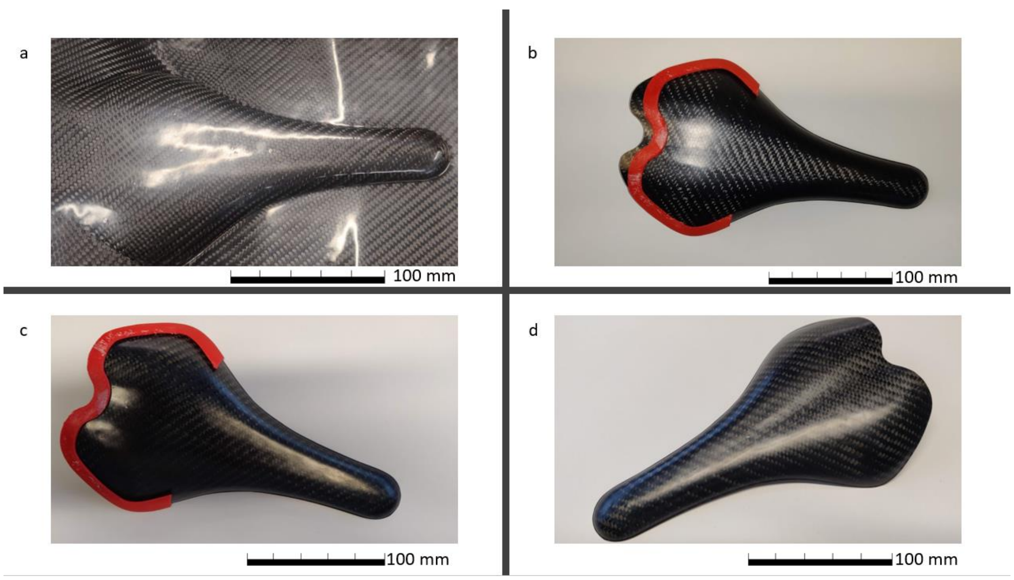


*Figure A.8 Trim tool process for the resin infused saddle mould.*

This system although cost-effective, it requires more equipment and financial investment to get set up, for this reason it was omitted from the main body of the report. This example shows how a direct tooling approach could be adopted for higher volumes as the tooling surface is easily replaced with a new vacuum formed cover. The thickness of the vacuum forming sheet must also be considered for the highest level of accuracy from this tooling solution.

# Appendix B University SOP for Resin Infusion

**BI-T-001/SOE-T-001** – Standard Operating Procedure – Liquid Resin Infusion
Composite Manufacturing Suite | Owner: Composites Technical Officer

School of Engineering/Bernal Institute

University of Limerick

Standard Operating Procedure

Liquid Resin Infusion

| | |
|---|---|
| Code: | BI-T-001/SOE-T-001 – Standard Operating Procedure – Liquid Resin Infusion |
| Version: | 0.1 |
| Created by: | Niamh Nash |
| Approved by: | Anthony O'Carroll |
| Date of version | 17 SEP 2018 |
| Signature | |
| Revision Due | 17 SEP 2019 |

## Title

Standard Operating Procedure – Liquid Resin Infusion

## Purpose

This document describes the safe operating procedure for liquid resin infusion in the Composites Manufacturing Laboratory. Liquid resin infusion is the process of infusing a polymer resin, which will harden/cure into plastic, into a pre-prepared fabric preform. The users range from FYP students to post-doctoral researcher.

## Scope

The scope of this document is to describe the step-by-step process of liquid resin infusion.

## Responsibility (or Rights & Responsibilities)

The Technical Officer is responsible for the upkeep and safe operation of the equipment. Each user is responsible for the safe operation of the equipment, ensuring that it does not become damaged. If the equipment does become damaged, the user must notify the Technical Officer.

## Records

The most up to date copy will be kept on the SharePoint with a signed hard copy stored in the laboratory lobby.

## Process Verification

This process is to be reviewed yearly.

## Revision History

| Revision Number | Date | Approved by: | Details of Change | Process Owner |
|---|---|---|---|---|
| 0 | 17/9/2018 | Anthony O'Carroll | Initial Release | Niamh Nash |

## Referencing Documents / Appendix

n/a

## Procedure

The following PPE should be used when performing this task.

Safety Glasses Latex Gloves Lab Coat

Before using this equipment ensure that:

- You have completed training on this machine and have permission to use it
- You have read this manual and are familiar with the operational steps
- You have booked time using Outlook (i.e. send a meeting request to Composites.VartmRT1@ul.ie) for the entire time that you will need the plate (tool/mould) and various equipment
- Students Only - You have requested an infusion slot with the Technical Officer or a competent lab user
- You know the correct mixing ratios for your resin and curing agent(s)
- You know the safety procedure to follow if an exotherm occurs

Please ensure you show up on time for your booking slot and cancel any appointments you cannot make. If you are more than 10 minutes late the booking slot will be made available to other users. Please complete the logbook once you are finished.

1. Record the mass of the dry fabric (i.e. preform). Tare the balance and record the mass of the fabric in your lab journal. Cover the fabric in a protective film until it is ready to be laid up on the tool.
2. Ensure the extraction is on over the infusion tool plate with the handle in the position shown in Fig 1. Check that air is flowing. Clean the tool surface with acetone and a paper towel (Fig 2). *Remainder: safety glasses and gloves are required.*

Fig 1

Fig 2

3. Stick the sealant tape onto the tool. Ensure that there is at least a 2 inch gap between the side of the preform and the sealant tape. The paper backing should be left on the tape until the vacuum bag is ready to be secured. In this example, the inlet is on the left and outlet on the right.
4. Using a paper towel, apply the release agent (follow the recommendations in the manufacturer's guidelines) to the tool surface within the confines of the sealant tape.

Fig 3

Fig 4

**5.** (a) For large resin trap:
Open the resin trap by loosening the wing nuts and removing the lid. Place a 5 litre pail in the resin trap (Fig 5a) and line it with PTFE film (Fig 5b). This will allow for easy disposal of any resin in the resin trap.


Fig 5a


Fig 5b

(b) For small resin trap:
Remove the lid and place a paper cup inside the resin trap (Fig 6). Replace the lid.


Fig 6

6. Lay-up the preform on the released tool surface ensuring correct alignment of the fibres and that there is little or no stray fibres on the edge of the stack. Ensure that the stacking sequence is checked on your lab journal as each ply is laid down (Fig 7).
7. Lay the peel ply over the preform. The peel ply should be cut such that the width is just wider than the preform and the length should be about 2 inches longer on either end of the preform. It is important that when this step is complete the fabric is no longer visible (Fig 8).
8. Dam tape is now used at both ends of the peel ply and **directly** in contact with the sides of the preform (Fig 9); this will aid/contain the resin flow. **The dam tape will prevent race-tracking of resin along the sides of the preform, so it is important that there is no gap between the dam tape and the sides of the preform.** At the inlet and outlet, ensure there is enough space before and after the preform so that the resin can spread and flow.


Fig 7


Fig 8

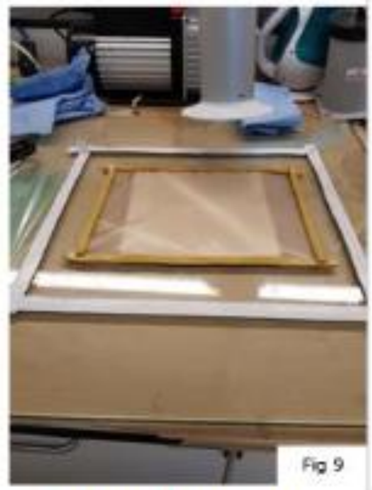
Fig 9

9. Lay the distribution medium over the peel ply (Fig 10). The distribution medium should be cut such that the width is just narrower than the preform to prevent race-tracking, and the length should be about 1 inch short of the total length of the fabric on the outlet side to facilitate full wet-out of the fabric. The distribution medium and peel ply are aligned at the inlet side. Ensure that the distribution medium stays inside the perimeter formed by the dam tape.

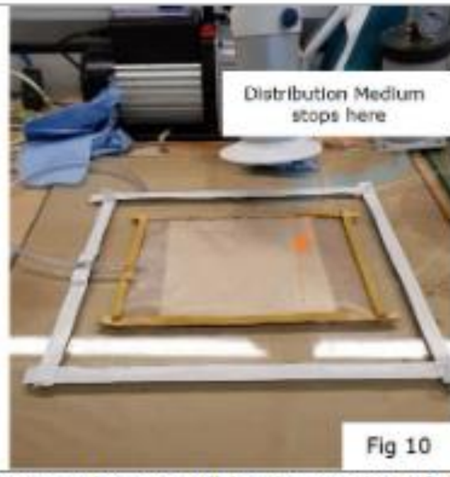


Fig 10

**10.** Place the resin container where it will be during the infusion. Measure a length of tube that is long enough to easily reach from the base of the resin container to the inlet side of the bag. Cut the inlet tube.

**11.** Tear the paper at the centre of the sealant and dam tapes on the inlet side. Place the tube across the tapes at this point and cover with a 2" piece of the appropriate tape on the top (Fig 11).

**12.** Repeat Step 11 at the outlet, ensuring that the tube can easily reach the resin trap. Cover the preform ends of both tubes with distribution medium (Fig 12).

**13.** Stick the vacuum bag onto the sealant tape ensuring that there are no creases or folds. Work the bag into the tape to ensure good adhesion.

**14.** Clamp the inlet tube. The clamping pressure can be adjusted with the screw at the end of the handle. The clamping pressure should be high enough to ensure no air is pulled through the inlet, but not so high that it is difficult to close the clamp as this could cut the tube.

**Important** – Ensure that there is enough tube length below the clamp for the level of resin in the resin container.

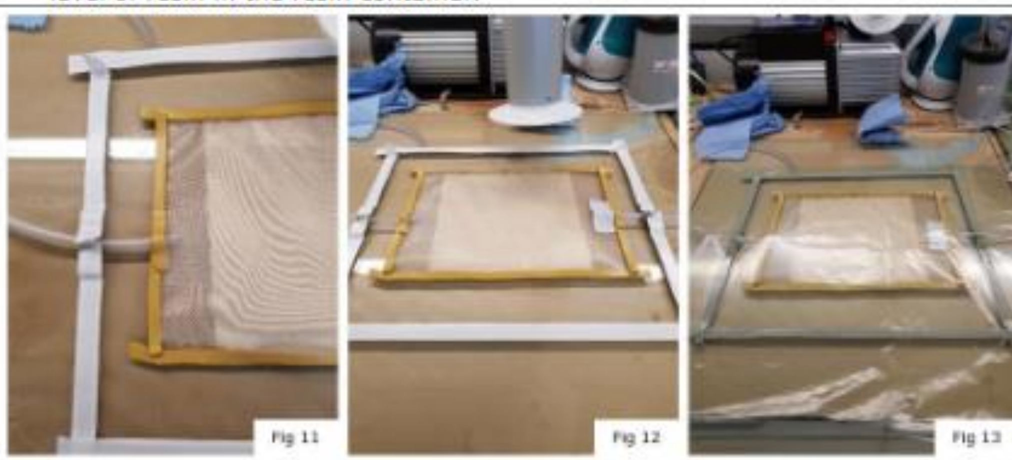

Fig 11 Fig 12 Fig 13

15. Connect the outlet tube to the resin trap and place some sealant tape around the point of entry (Large resin trap only) to ensure an airtight seal (Fig 14). On the small resin trap place the black collar around the outlet tube (Fig 15a) and then connect to the resin trap ensuring that the black collar is tight (Fig 15b). DO NOT put sealant tape on the small resin traps.


Fig 14

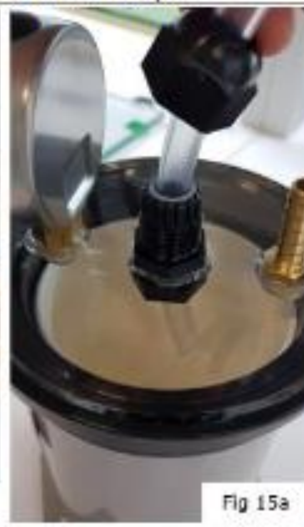
Fig 15a


Fig 15b

16. Connect the vacuum pump to the resin trap and switch it on. While the vacuum is being pulled, work on ensuring that there is no air being pulled into the vacuum bag through any gaps between the bagging film and the sealant tape. Ensure the wingnuts/black collar on the large/small resin trap are tight (Fig 16).
17. Once the needle on the resin trap gauge has reached the highest point, disconnect the vacuum pump from the resin trap and leave for 15 minutes. The needle should not drop in this time. If it does, there is a leak in the system. This must be fixed and the leak test performed again until the vacuum level holds for 15mins.
*Note: the leak may be in the resin trap itself also, you may need to isolate this to double check.*

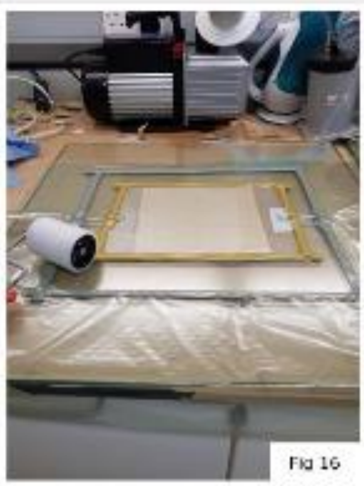
Fig 16

**From this point forward, supervision of a competent lab user is required.**

**18.** Prepare the resin according to the manufacturer's guidelines. Ensure you have the correct mixing ratios recorded in the lab journal and you are aware of the safety procedures (Fig 17). Before mixing, place a sticker on your resin container with your name, the name of the resin system and when it will be fully cured and ready to be disposed of (cooled to room temperature).

**Caution: most resin system will exotherm (give off heat) as they cure. If there is too much resin left in the mixing pot or if the incorrect mixing ratio is used then a large exotherm may occur. A large exotherm may cause the mixing pot to become compromised, and/or give off significant amounts of smoke. This should be avoided, familiarise yourself with the safety procedure should it happen (Fig 17).**

**What to do in Case of Exotherm**

My resin container is heating up

Immediately:

1. STOP INFUSION - Clamp inlet tube
2. Put resin container in steel container with water
3. Move extraction arm over the resin container
4. Make sure extraction arm is on
5. Inform the Technical Officer/Post-doc/RA

DO NOT CONTINUE INFUSING UNDER ANY CIRCUMSTANCES

Fig 17

**19.** Connect the vacuum pump to the resin trap and turn on the vacuum. Place the inlet tube in the resin container and, when everything is ready for infusion (e.g. setting a timer to record infusion time), unclamp the inlet tube while it is fully immersed in resin. Depending on the panel size, the infusion time will vary. It may be of interest to mark the resin front gently after every 60s with a marker.

**20.** When bubble free resin appears in the outlet tube, clamp the inlet and outlet tubes. Disconnect the vacuum pump from the resin trap and switch off the pump. Remove the outlet tube from the resin trap. Cover the ends of both pipes.

FYI - At this point, the part is fully infused.

**21.** Place the resin pot (containing excess resin) in the fume cupboard to complete curing. If the pot is sufficiently hot, place it in a larger bucket with water in the base. This can be disposed of when it is cold.

**22.** Remove the cup/bucket from the resin trap and ensure it is clean. **Replace with a new cup/bucket with PTFE for the next user.**

**23.** Please ensure all areas are clean. Return once the part is completely cured to demould.

**24.** Certain parts require post-curing. Please follow the standard operating procedure for heat blankets. Ensure that an unattended experiment form is completed.

# Appendix C Configurable Soluble Core Example

The handlebar was chosen as the example part here as the use of composites in the sporting goods industry is ever growing and they are a highly customisable part that will demonstrate the benefits of this manufacturing technique with regards to product lead times and ability to make functional prototypes of design iterations.

## *Virtual Prototyping of Composite Aerobars (tubes with bends)*

Using the method outlined above the handlebars were designed using SolidWorks. The model was designed in such a way that any of the important metrics could be changed at any given time using SolidWorks Global Variables, allowing the model dimensions to be fully tuned for each printed set of handlebars (Figure C.1).

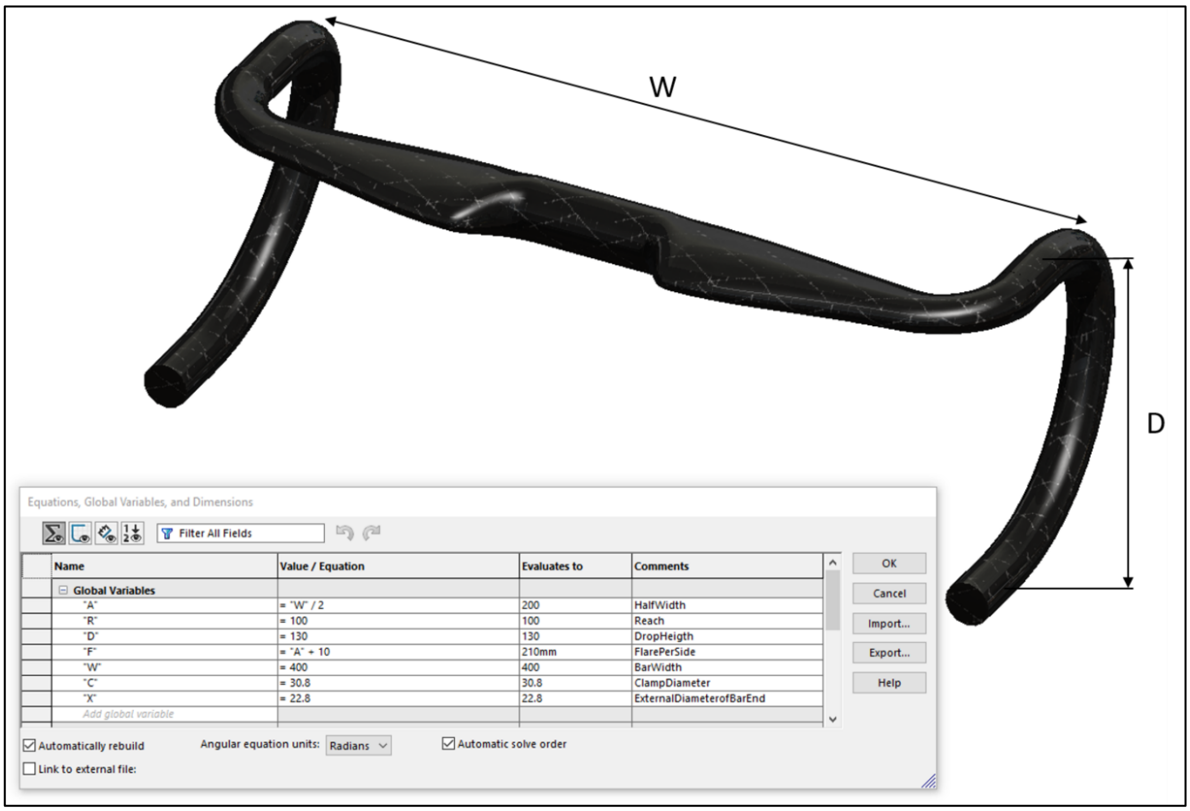


*Figure C.1 Parametric driven CAD model of road bike handlebars using global variables to customise final dimensions.*

Due to the shape of this tube and the build volume restrictions of the UM2+ desktop 3D printer, the CAD file of the core tooling must be split into multiple sub-components, for assembly post printing. The core is split into 5 separate parts using splitting surfaces, these parts include the centre portion, left and right tops and left and right drops sections. The splitting surfaces were designed using a registration key to ensure accurate alignment of the soluble core during assembly (Figure C.2).

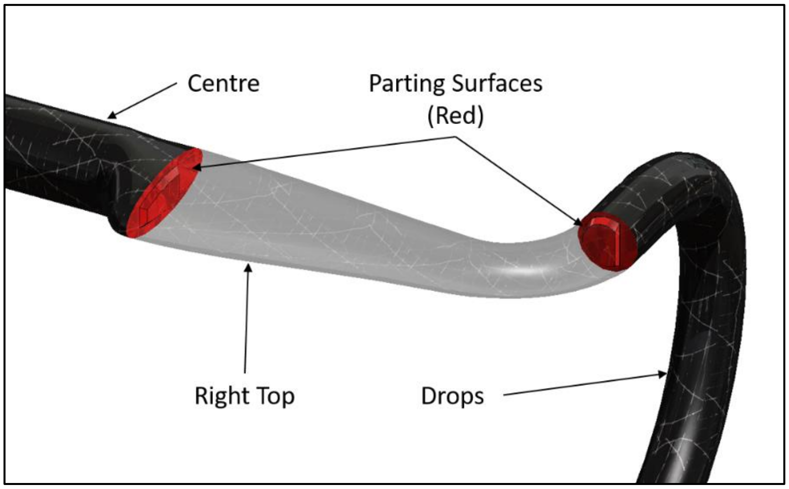


*Figure C.2 Splitting surfaces (red) between each section of the handlebars to ensure correct alignment*

Each part body was then exported from SolidWorks and imported into the printers slicing software (Cura) as a .STL file, the parts were then orientated to fit the build platform and reduce support material required (Figure C.3).

The infill pattern used was a gyroid pattern as this infill provides more uniform strength to AM parts in multiple directions when compared to standard infill patterns.

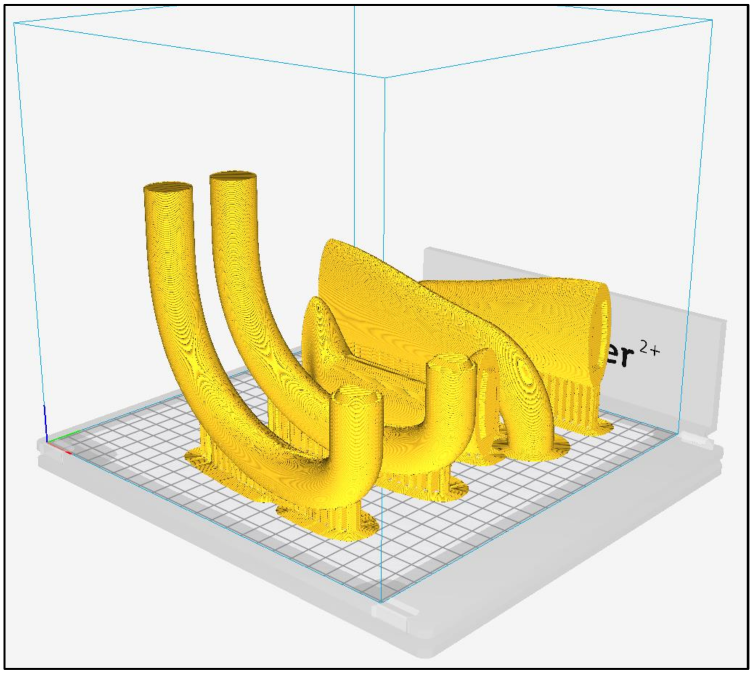

*Figure C.3 Core split up into multiple sub-components and orientated to fit the build volume.*

Other settings which were changed from standard include the extrusion temperature which was increased to 230°C and the infill print speed which was greatly reduced to ensure there was good adhesion between the layers, faster print speeds resulted in the infill parting from the outer shell of the model resulting in a failed print. A standard layer height (0.15mm) was chosen as it provided a balance between good resolution and print times (approx. 24 hours). At this point the virtual prototyping phase is complete parts are sliced and are ready for manufacture.

*Physical prototyping of Soluble Cores*

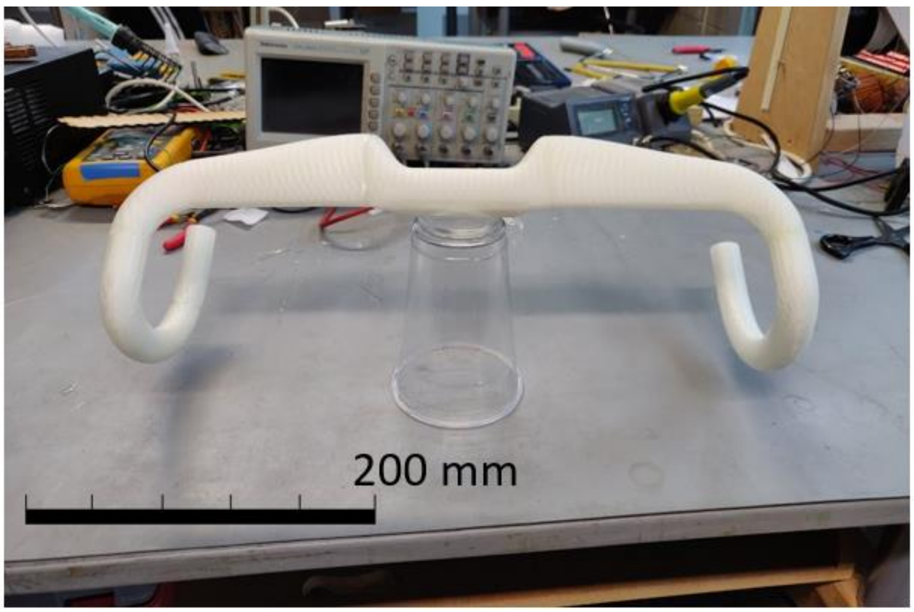


*Figure C.4 Soluble mandrel assembled and sanded.*

This tooling example shows how the FFF technology can be adopted for configuring bespoke hollow composite parts. A tool with such complex geometry may be difficult to laminate and consolidate. The use of braided fibre sleeves and shrink tape would likely be the easiest method of laminating and consolidating this kind of tool as envelope bagging is likely to bridge and damage the soluble core. As this product would be fabricated with little consolidation pressure it would be difficult to produce a product that would be safe for use where loading conditions are complex. This tooling solution requires further investigation to test the quality of the composite products, however this technology might provide a cost-effective technique in the fabrication of demonstration models or non-safety critical products.