Periscope Network

Market Opportunity Report

Additive Manufacturing State-Of-The-Art Review and Roadmap

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This series of Market Opportunity Reports is provided to SMEs, knowledge institutions and other players in the innovation chain for concrete innovation actions and business development. Policy makers, authorities and business support organisations are also invited to use these reports as input to policies, strategies and conditions for Blue Growth.

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Periscope Market Opportunity Report

Additive Manufacturing State-Of-The-Art Review and Roadmap

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Contents

1 Introduction

1.1 General

This is a desktop-based benchmarking study which aims to provide a review of currently available literature in Additive Manufacturing (AM). This will be in the context of wind blades, tidal blades and vessels and is thus termed the 'blue economy'. The primary focus will be on 3d printing, and the scale of the print processes. A roundup of current large area additive manufacturing machines will be presented, along with a review of current materials suitable for large scale AM. This document presents a literature review of the current state-of-the-art and a technology development roadmap for AM in the blue economy.

1.2 Objectives

The first objective of the Periscope Network is to provide a deep-dive literature review on current additive manufacturing technologies. Potential applications will cover not only wind turbine blades, but also tidal blades, and marine vessels. This will result in a technology road map which will highlight further research questions beyond the current state-of-the-art. The literature review will provide required inputs for a SWOT analysis and a business case for AM technology. At present AM primarily excels in rapid prototyping, however it is highly desirable to move beyond rapid prototyping of designs towards manufacture of key load bearing structures. Currently the main barriers to this are the material mechanical properties such as strength and stiffness as well as maintaining optimal physical properties favourable for printing at high deposition rates.

2 Review: Current Lab-Scale AM Techniques

2.1 Introduction

Additive Manufacturing (AM, also known as 3D printing) can be defined as "the process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies" [1]. 3D printing has been at the forefront of materials and manufacturing research and development (R&D) in the last few decades and is emerging as a paradigm with a wide range of applications including medical, aerospace, automotive, and engineering industries. 3D printing allows more geometrically complex shapes to be produced with a degree of design freedom which is currently unachievable using current manufacturing methods. The medical industry has started to develop inroads towards the use of 3D printing for organs, tissues and other cellular biological structures [2, 3]. In the automotive industry, the lead times required for tooling is reduced through 3D printing, as well as the costs associated with manufacturing prototypes [4]. The aerospace industry has been one of the bigger beneficiaries of 3D printing, since it reduces material wastage in comparison to traditional manufacturing methods.

The materials used in AM include polymers, metals, ceramics, and composites. The material physical states vary between liquids, semi-liquids and powders depending on the exact AM process being used. Many different AM technologies have been developed since the 1980s beginning with stereolithography (SLA), selective laser sintering (SLS), solvent-cast direct writing, and Fused Filament Fabrication (FFF).

The review in this section will provide a basic overview and understanding of the various lab-scale AM techniques. However, more fundamentally for each AM process; the available materials, fabrication speed, and resolution of printing process generally needs consideration for each application. In general, AM is used for rapid prototyping of parts which are not necessarily intended for use in primary load bearing applications. The shift in research activities in AM will need to address this.

2.2 Fused Filament Fabrication (FFF)

Fused Filament Fabrication (FFF), was developed under the name of Fused Deposition Modelling (FDM) by Scott Crump, is a 3D printing technique which involves layer-by-layer build-up of a part by the deposition of a melted thermoplastic material through a heated extruder nozzle. The filament feedstock is fed through an electric motor controlled pinch roller system to a heat block which liquefies the filament, exiting the nozzle. The force from the solid filament entering the liquefier pushes the molten thermoplastic through the nozzle in a continuous bead. The viscous melt then solidifies onto the build plate allowing gradual build-up of the part layer-by-layer. In the case of desktop 3D printers the nozzle moves laterally in the x-y plane when depositing the material, and vertically in the z direction to build the layers upwards (figure 1). In other words, the print head assembly including the extruder moves through the build on a gantry using stepped motors. It is an example of a 2.5 axis CNC (Computer Numerical Control) system, however the various kinematic architectures available will be discussed in further detail in later chapters. The build plate can be heated to reduce the propensity of the structure to temperature gradients which can lead to print failure and peel-off at the base support. To produce a uniform surface, a contour or 'road' is printed around the part perimeter which forms a shell with the layers deposited at some fixed raster angle with the contours and bead width determining the dimensional accuracy and surface quality of the finished part. The dimensional accuracies are typically in the order of 100 µm.

The mechanical properties of thermoplastic materials are typically low in comparison to composites materials such as carbon or glass fibre reinforced plastics and other engineering materials. This is due to poor interfacial adhesion, typical low bond strengths in thermoplastic; the physical adhesion is driven only by the high viscosity of the melt which has low wettability. This is compounded by the rate and hence mass dependent shrinkage upon cooling.

FFF can be augmented to produce parts containing reinforcements and has been investigated in [5] as an alternative carbon fibre composites manufacturing method for low to medium production volumes with highly customisable parts containing complex geometries. Composites manufacturing typically involves several stages for example with Resin Transfer Moulding (RTM) the first step is the material layup, followed by infusion and then consolidation. Successful adaptation of 3D printing technologies to composite materials may enable a more simpler production method with reduced costs and a higher degree of automation.

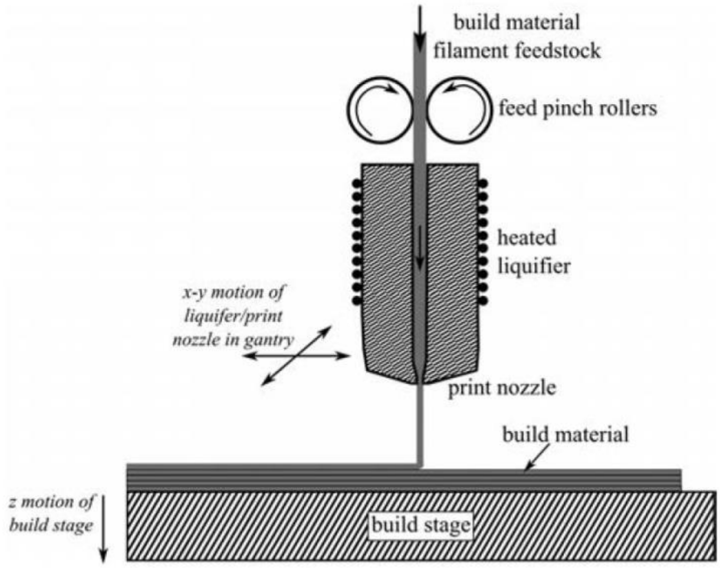


Figure 1: Schematic of the FFF Extrusion Process from [6]

To maximise the mechanical performance of parts printed using FFF, the key factors which affect the final print quality needs to be well understood. Turner et al. [6, 7] provides in-depth reviews of FFF in terms of process modelling. As the melted material is extruded, viscosity, temperature and surface energy are important in determining how the material flows through and exits the nozzle and secondly how the bonding process occurs between the beads as the material is deposited.

Since the material is deposited as continuous beads, the material characteristics of the printed part are highly dependent on the overall printing strategy as follows:

- *Raster angle* - Direction of continuous bead deposition.
- *Material* – Physical properties of the extruded material.
- *Geometry* - Accumulation of the continuous beads to give the 3D shape.
- *Accumulated strain* – Location of strains introduced throughout the process.
- *Inter filament bonding characteristics* – How well the continuous beads form together.

At the molecular level, the bonding between the polymer chains at the interfacial contact points of the continuous beads is a requirement for effective transfer of loads in the printed part. The process occurs via viscous flow and molecular diffusion of polymer chains across the interface between the continuous beads until randomisation occurs as shown in figure 2. The initial surface contact between beads, the heat distribution and viscosity play a part in neck formation. The neck formation slows down as the temperature decreases, causing a reduction in polymer diffusion and viscosity of the material. Therefore, the main factors in this process are temperature, viscosity (which is dependent on temperature), thermal conductivity, heat capacity, and cooling rate. High thermal conductivity also improves the heat distribution across the part. Secondly, the uniformity of cooling rate across the part may produce varying extents of neck formation leading to inconsistencies in the part quality. An optimal temperature would lead to good enough flow of the polymer beads, resulting in a sintering process which retains a good neck length between beads (2y), whilst maintaining dimensional accuracy of the part. Neck length 2y provides a measure of the quality of the bonding between the beads and layers. If the temperature is too high, then this may affect the final dimensional accuracy of the part due to excessive flow from reduced material viscosity and excessive molecular diffusion.

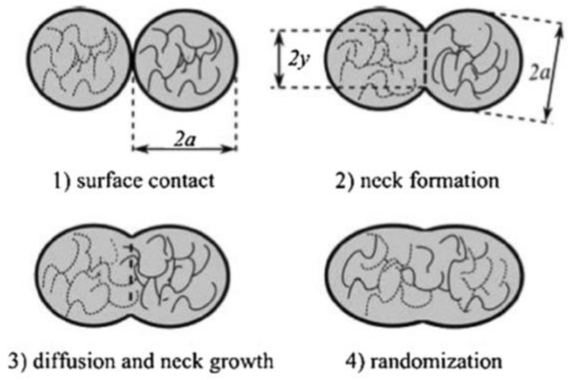


Figure 2: Schematic showing the polymer sintering effect [6]

Another significant process variable is the raster angle, defined as the directionality of the continuous beads. The properties will therefore be different in each of the different material directions. The tensile strength is thus significantly lower in the z and the x directions compared with the bulk material (up to ~50% depending on the material used) which reflects the typically weak bead-bead interfaces [8, 5].

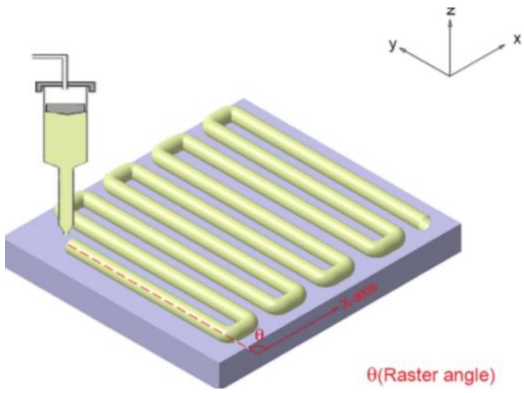


Figure 3 Schematic showing the raster angle definition [8].

Void content or air gaps which can run between each of the continuous printed beads can have a deleterious effect on the strength of the part. The printing pattern can be adjusted to maximise the contact between the beads therefore minimising the void formation. However, this is a simplistic scheme and, larger complex parts will have more complex path directions with a more complex distribution of voids and air entrapment. The void content has been studied by several authors by varying the gap size between the beads in a unidirectional configuration and determined that a small overlap between the beads produced optimal results with around 5% void content in the xz plane, and 27% in the yz plane [9]. Diamond shaped, and triangular shaped voids are found in the rectangular, and skewed configurations respectively as shown in the micrographs in figure 4.

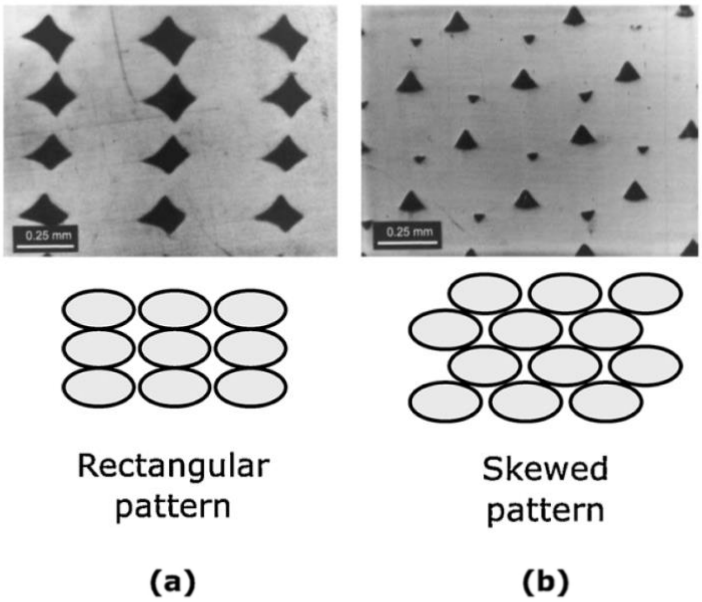


Figure 4 The two main path configurations in a unidirectional meso-structure [10].

After leaving the nozzle of the liquefier, the polymer bead will be deposited onto either the build plate or on a previously deposited bead. The bead (or road) once deposited will spread into an oval shape, with the spreading rate and final shape dependent on the viscosity of the molten bead and the surface at deposition. The nozzle tip interaction may also play a part in the evolution of the final shaped of the printed bead. As it spreads the bead is also cooling with viscosity increasing until it reaches an amorphous solid state. The temperature history of the cooling beads is also important, since layer by layer deposition of beads will result in thermal gradients in the structure. It has been shown that the thermal history of the bead is highly dependent on the convective air cooling around the build. The final bead width determines the resolution achieved in the process [6].

As the molten polymer goes through the nozzle it is under stress, with part of the deformation energy being stored elastically [11]. As the molten material exits the nozzle the stored elastic energy is released leading to radial expansion of the bead. This is referred to as die swelling and plays a part in determining the resolution of the extrusion-based AM part (figure 5).

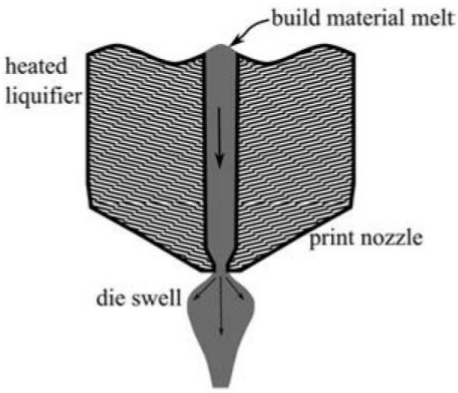


Figure 5. Die swelling phenomenon in the AM extrusion process [6]

2.3 Stereolithography (SLA)

Stereolithography was the first of the AM techniques patented and published in 1986 by Hull [12]. It was the first commercially deployed AM technique. A UV laser (or an electron beam) is focussed into a VAT of photopolymer resin. Each layer is constructed by the UV laser beam which scans in the x-y plane via the use of mirrors. As the laser traces the cross section on the surface of the resin, the liquid material is hardened on contact. Once a layer is complete, the build platform is indexed downwards to make space for the next layer. A re-coater blade moves across the surface depositing a thin new fresh layer of liquid resin which is uniformly spread. The laser continues to trace and form each of the layers atop each of the previous layers. The finished part is then removed from the resin and separated from the base fixture. The materials are typically acrylic, or epoxy based and undergo free radical polymerisation upon initiation by the UV light. Ceramic particles can be embedded into the monomers to give ceramic polymer composites [13]. SLA produces high quality parts with a fine resolution down to as low as 10 μm. However, it is slow, with a narrow range of materials available for printing due to their complex chemical reaction kinetics. The process is also relatively expensive in comparison to other techniques. The main factors controlling the layer thickness at each iteration is the energy of the light source and the exposure time [14, 15].

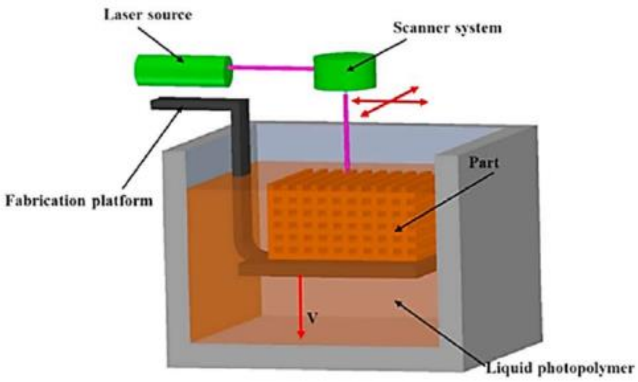


Figure 6. Scheme showing the SLA process [16]

2.4 Powder Bed Fusion (SLS, SLM, 3DP)

Powder bed fusion works in a similar manner to SLA, however instead of a liquid resin, a platform containing a very fine uniformly spread powder in which the closely packed particles are exposed to a laser beam or a binder. A binder is used if the powder doesn't have a low enough melting/sintering temperature for the laser. The subsequent layers of material are deposited over the previous layer after the platform is indexed downwards, this is repeated until the part is complete. The power and intensity of the laser along with the laser speed are major factors in this process. The excess powder is removed exposing the completed part. Further post-processing, such as painting, or coating as required. The distribution of particle size as well as particle packing which determine the density of the printed part are the primary factors in determining final part properties [17].

Selective Laser Sintering (SLS) can be used for various polymers, alloys and powdered metals, whilst Selective Laser Melting (SLM) can only be used for single metal powders such as aluminium and steel which have single melting points. The sintering process is different from the melting process as it only heats the powder to the point where the particles fuse together on a molecular basis. SLM uses the laser to fully melt the particles to form a homogenous part, therefore giving better mechanical properties, and hence fewer voids than for SLS [18].

When using a liquid binder, the process is known as three-dimensional printing (3DP) where the binder is deposited by the print head instead of the laser. The properties of the binder along with the deposition speed of the binder and its interaction with the powdered particles play an important role in this process. The main limitations of 3DP is its high porosity content when compared to SLS and SLM [17]. Each of the powder bed fusion techniques results in the powder bed itself as support for the on part during its build. This allows more geometrically complex internal structures in comparison to methods such as FFF (FDM), which are constrained by having unsupported material to support.

More generally, powder bed fusion techniques produce high resolution and good print quality and can produce geometrically complex parts. Scaffolds for tissue engineering, and electronics are among many of the typical applications of powder bed fusion [15]. The major drawbacks are the printing speed, and high process costs.

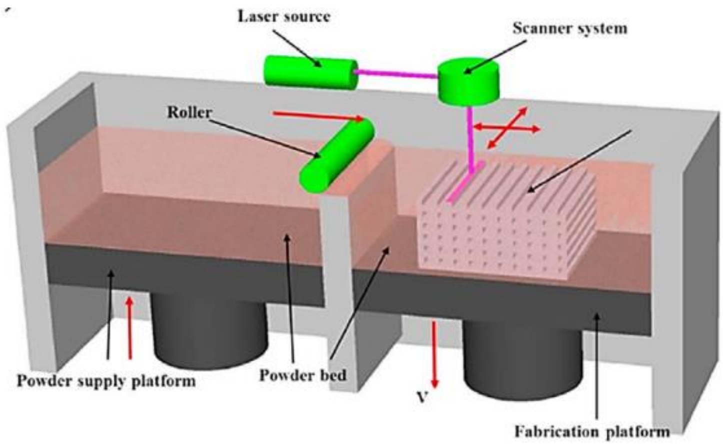


Figure 7. Schematic of the Powder bed fusion process [16].

2.5 Inkjet Printing

Inkjet printing is one of the main AM methods for production of advanced complex ceramic structures. Inkjet printing is a low temperature, low pressure process involving the deposition of liquid materials or solid suspensions via droplets through a small nozzle. As the print head raster scans the surface, each layer is built up over the preceding layer. It is adaptable to a wide range of materials including polymers, dielectric and conductive nanoparticles. The two main types of ceramic ink are either wax based or liquid suspensions. The wax-based inks are deposited and melted to solidify whereas the liquid suspensions are solidified through the process of evaporation. The droplets form a pattern on the substrate where they solidify to a sufficient strength prior to the application of the next layer. The printing resolution is important in any 3d printing process since this determines the smallest feature size and tolerance which can be printed. This method is fast and efficient and doesn't require any further post-processing. Typical applications include scaffolds for tissue engineering and printed circuit boards. The ceramic particle size distribution, viscosity of the ink, extrusion rate, nozzle size, size of the droplets, and printing speed are the major factors affecting part quality [19, 15].

2.6 Direct Energy Deposition

Direct energy deposition has been used for manufacture of high-performance superalloys. This method covers a range of terminology: laser engineered net shaping (LENS™), laser solid forming (LSF), directed light fabrication (DLF), direct metal deposition (DMD), electron beam AM (EBAM) and wire and Arc AM (WAAM). The difference between DED and SLM methods is that no powder bed is used in DED and the feedstock is melted before deposition in a layer-by-layer fashion similar to FDM but with a much higher amount of energy for melting metals [15]. DED is a more complex printing process commonly used to repair or add additional material to existing components, for filling cracks and retrofitting manufactured parts for which the application of the powder-bed method is limited. A typical DED machine consists of a nozzle mounted on a multi axis arm, which deposits melted material onto the specified surface, where it solidifies. The process is similar in principle to material extrusion, but the nozzle can move in multiple directions and is not fixed to a specific axis. The material, which can be deposited from any angle due to the use of multi-axis machines, is melted upon deposition with a laser or electron beam. The process can be used with polymers, ceramics but is typically used with metals, in the form of either powder or wire.

DED can be combined with conventional subtractive machining processes for post processing. This technique is commonly used with titanium, Inconel, stainless steel, aluminium and the related alloys for aerospace applications. Generally, DED is characterised by high deposition rates ranging from 0.5 kg/h for LENS [20] to 10 kg/h for WAAM [21]. There's potential for very large work envelopes up to 6 m×1.4 m x 1.4m for commercial printers [22]. The disadvantages include lower accuracy (0.25 mm) and lower surface quality. The parts are less complex compared with SLS or SLM [23]. DED is thus more commonly used for large components with lower complexity. It is also used for repairing larger components. DED can reduce the manufacturing time and cost, and provides excellent mechanical properties, controlled microstructure and accurate composition control. This method can be used for repairing turbine engines and other niche applications in various industries such automotive and aerospace [15].

2.7 Laminated Object Manufacturing

Laminated Object Manufacturing (LOM), was originally developed by Helisys Inc. A Continuous sheet of material is drawn across the build platform via rollers. Materials include metal, paper and plastic. Paper and plastic sheets are usually coated with an adhesive. A heated roller passes over the material melting the adhesive and consolidating the material on the platform. Layers of the build material for example, paper, plastic or metal are successively bonded together layer-by-layer. The desired pattern is cut precisely into each of the successive layers with a blade or a laser. The build platform then indexed downwards in preparation for the next layer. Another roller winds in the remaining material after cutting. The excess material after cutting is used as a support and after the process can be removed and recycled. The unused material is crosshatched for ease of removal upon completion. The process doesn't require the use of any specific chamber; however, some environmental conditions must be maintained for the layers to fuse properly. With adhesives being used for paper and plastic, metallic sheets tend to be welded together via thermal brazing or by ultrasonic means, however metals are more seldom used in LOM [24]. LOM has been used in paper manufacturing, foundry industries, electronics and smart structures. Advantages include the use of widely available materials which are well understood. LOM provides a wider temperature operating window although this depends somewhat on the resin/adhesive being used. The disadvantages of this processing method are the more limited geometries in comparison to other AM methods, poorer surface quality, and dimensional accuracy compared to powder bed methods, also removal of the excess laminate material is highly time consuming.

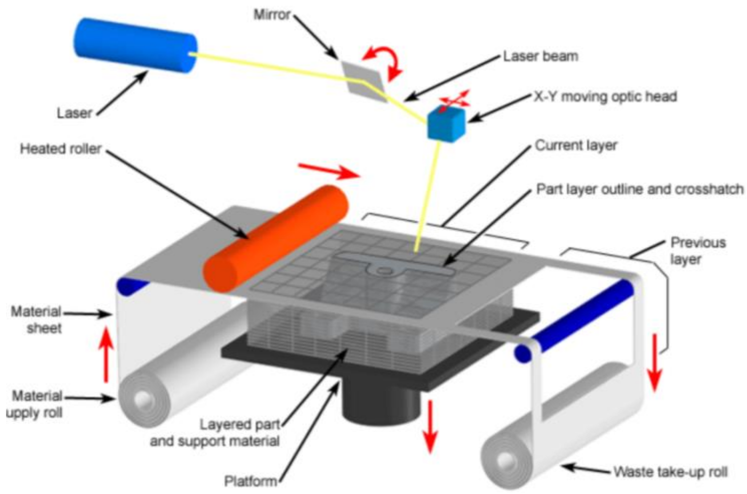


Figure 8. Laminated Object Manufacturing [25]

2.8 Concluding Remarks

Table 1 summarises each of the manufacturing processes and their advantages and disadvantages along with key parameters.

Table 1. Summary of each of the processing techniques.

Property Name	Fused Deposition Modelling/Fused Filament Fabrication	Stereolithography	Inkjet Printing	Powder Bed Fusion: Selective Laser Sintering, and Three-Dimensional Printing		Laminated Object Manufacturing
Abbreviation	FDM/FFF	SLA	MM, MJM	SLS	3DP	LOM
Material type	Solid (Filaments)	Liquid (Photopolymer)	Liquid	Powder (Polymer)	Powder	Solid (Sheets)
Materials	Continuous filaments of thermoplastics e.g. ABS, Polycarbonate, and Polyphenylsulfone; Elastomers	Resin with photoactive monomers, Thermoplastics (Elastomers)	Concentrated dispersion of particles in a liquid as an ink, thermoplastics such as Polyester	Thermoplastics such as Nylon, Polyamide, and Polystyrene; Elastomers; Composites	Ferrous metals such as Stainless steel; Non-ferrous metals such as Bronze; Elastomers; Composites; Ceramics	Thermoplastics such as PVC; Paper; Composites (Ferrous metals; Non-ferrous metals; Ceramics)
Max part size: in.(mm.)	36.00 x 24.00 x 36.00 (914 x 610 x 914)	59.00 x 29.50 x 19.70 (1500 x 750 x 500)	12.00 x 6.00 x 6.00 (300 x 150 x 300)	22.00 x 22.00 x 30.00 (560 x 560 x 760)	59.00 x 29.50 x 27.60 (1500 x 750 x 700)	32.00 x 22.00 x 20.00 (810 x 560 x 510
Resolution Range	50-200 μm	10 μm	5-200 μm	80-250 μm		Laminate layer thickness
Advantages	Low cost, high speed, simplicity.	Fine resolution, High quality	Ability to print large structures	Fine resolution, High quality		Good for large structures, reduced tooling and manufacturing time Low cost.
Disadvantages	Weak mechanical properties, Limited materials (thermoplastics only).	Very limited materials, Slow printing.	Maintaining workability, Coarser resolution	Expensive, slow printing		Rough surface quality, dimensional accuracy. Complex geometries difficult.
Min feature size (μm.)	130	100	130	130	200	200
Min layer thickness (μm.)	130	25	13	100	50	50
Tolerance (μm.)	±130	±130	±25	±250	±100	±200
Surface finish	Rough	Smooth	Very Smooth	Average	Rough	Rough
Build speed	Slow	Average	Slow	Fast	Very Fast	Fast
Applications	Advanced composite parts, Rapid prototyping, Form/fit testing, Functional testing, Rapid tooling patterns, Small detailed parts, Presentation models, Patient and food applications, High heat applications	Biomedical, Prototyping, Form/fit testing, Functional testing, Rapid tooling patterns, Snap fits, Very detailed parts, Presentation models, High heat applications	Form/fit testing, Very detailed parts, Rapid tooling patterns, Jewellery and fine items, Medical devices	Form/fit testing, Functional testing, Rapid tooling patterns, Less detailed parts, Parts with snap-fits & living hinges, High heat applications	Concept models, Limited functional testing, Architectural & landscape models, Colour industrial design models, Consumer goods & packaging	Form/fit testing, Less detailed parts, Rapid tooling patterns

3 Review: Large Area AM and Scalability

3.1 Introduction

Overall, AM is still an emerging technology with limited applications despite widespread expansion at rapid pace and adoption throughout various sectors. Material extrusion through Fused Filament Fabrication (FFF) is one of the common methods of Additive Manufacturing (AM) as discussed in section 2. However the use of filament as a feedstock limits the deposition rates making commercially available 3D printers unsuitable for parts with larger dimensions [26] [27]. The following subsections aims to give an overview of the current state-of-the-art in large scale FFF, followed by the main advantages and disadvantages, and a review of the major off-the-shelf materials in terms of their suitability, and finally some design considerations.

3.2 Overview of Current Approaches

Oak Ridge National Laboratory in collaboration with Cincinnati Incorporated (CI) have developed the Big Area Additive Manufacturing system (Figure 9). The BAAM system uses pellets as feedstock which allows much greater deposition rates and thus faster build times and larger parts [28]. With greater nozzle sizes come larger bead cross sections, enhancing the deposition rate. The largest BAAM system has a build volume of 6.1 m x 2.44 m x 1.83 m with build rates up to 45.4 kg/h.

Figure 9. CI BAAM at ORNL

As build rates increases, the propensity to achieve the desired geometry and surface resolution decreases. There is an opposing relationship with geometry/surface resolution with build/deposition rate. Part resolution is thus reduced with greater layer size, which also increases the size of defects. Defects are still very much present in standard desktop FFF 3d printed parts however the imperfections and defects are increased in scale and order of magnitude in BAAM. The size of the defects in Large Area Additive manufacturing could have a more notable effect on the intended function of the part. The post-processing in turn will also be more difficult, for example the surface finishing to lower surface resolution.

3.3 Standard and Quality of Parts

The very definition of part quality is vague and subjective and is dependent upon the application and the intended use of the part. A more objective definition of part 'quality' could be the degree of 'fitness for purpose'. Thus, for a printed part to be high quality it must be fit for the purpose and application it was intended for [29]. There are many things which will be required for the part to be fit for purpose, for example: Durability/weatherability, surface finish, to be within geometric tolerances, required strength and stiffnesses etc. The AM process thus needs to be robust and repeatable enough to achieve the requirements for a high-quality part.

3.4 Geometric Considerations

Geometric tolerancing and material properties are the two major factors in achieving part quality. The material considerations will be discussed later. BAAM has a very coarse resolution where the layer heights are typically within the region of ~4 mm. Furthermore, the issues regarding flow control of the extruder over varying nozzle tool path velocities makes it challenging to maintain consistent bead geometries thus causing other irregularities. Therefore often, CNC machining is required in a post-processing operation [30].

In all AM processes, the material is deposited layer-by-layer to reach the final build. The design of the part is defined by a Computer Aided Design (CAD) model and converted into a g-code which is required for any CNC machining or 3D printing operation. The AM printed part, will deviate from the original CAD model dimensions. The extent of this deviation must be within a certain acceptable range i.e. tolerance. Secondly the surface finishing requirements are also impacted by the geometric constraints due to the layer height and size of the bead [29].

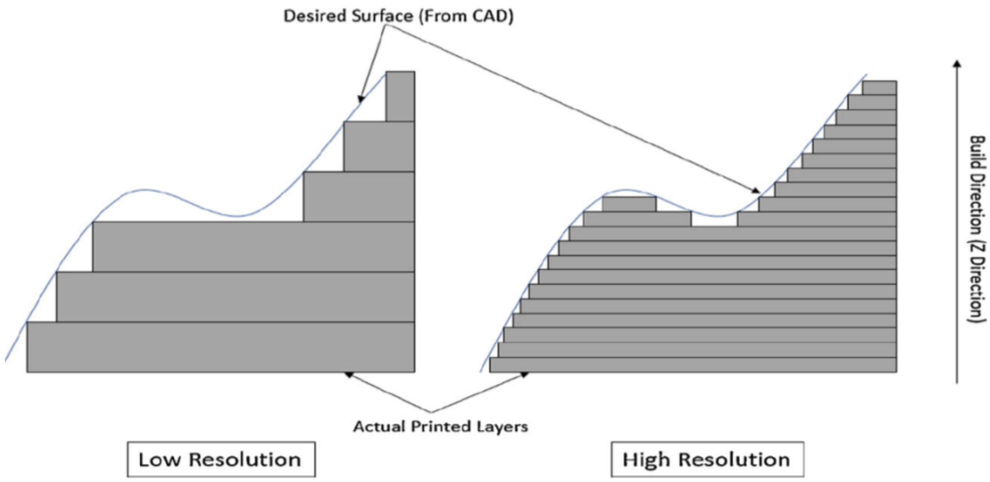


Figure 10. Layer height effect on resolution [29].

The primary issue affecting the geometric fidelity and surface finish of Large Area AM is the layer height (or resolution). The layering of the material throughout the build process introduces unavoidable deviations from the intended dimensions as defined in the CAD model (Figure 10).

Reducing the layer height by reducing nozzle size increases the resolution and the surface finish but it also reduces the deposition/build rate. When the layer height is decreased the total build/print time increases. This compromise between build resolution and build rate is a trade-off in many AM processes. The cost implications are also worth mentioning, lower resolution means greater throughput of parts due to shorter build times with higher cost efficiency and vice versa.

Calculations from [29] show that the deposition rate decreases with the square of the increase in the resolution, which presents a huge challenge if printing is to occur with both high resolutions and high deposition rates. However, the calculations assume that the nozzle velocity is constant with changes in the nozzle size. A possible solution is to increase the nozzle velocity whilst reducing the nozzle size to maintain increased deposition rates. In this case there are practical limits which include mechanical limits on the gantry system or robot system. Secondly there are limits on the mechanics of the extrusion process, with beads being either dragged or broken up. An increase in print speed is possible but with limitations. A third strategy is to have a hybrid approach in which both higher and lower resolutions are used within the same build. In this case quality critical regions of the part are produced using greater resolutions and smaller layer heights and vice versa. This involves changing the nozzle during the print. Most parts, for example moulds have some of the surfaces which required higher accuracy and tighter design tolerances, thus much of the part can be printed with low resolution except for the regions which require higher resolutions. This way high quality parts can be produced with higher throughput (Figure 11).

Figure 11 Hybrid resolution layers [29]

When printing using different resolutions, this will need to be considered in the printing process. This is feasible if the shorter layer heights are integer multiples of the larger layer heights. Multiple extruders with different nozzle diameters could be used however this adds considerable complexity to the system as the offset between the extruders must be known and the gantry system needs to be capable of moving the multi-extruder system. This could be resolved by having a single extruder with a nozzle where the diameter of the orifice can be adjusted, this was achieved by developing a nozzle with a poppet near the tip [29]. Figure 12 shows the poppet in grey in the up and down positions.

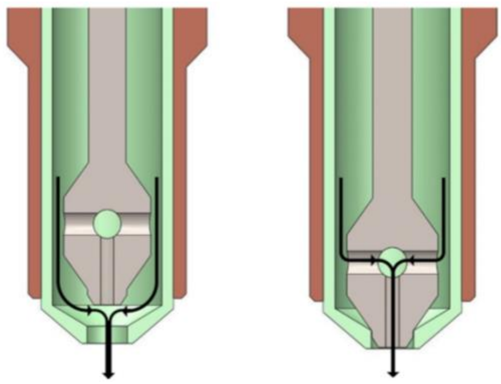


Figure 12 Dual port poppet orifice with material flow-path.

A hood mould for a Shelby Cobra car was produced with two distinct regions where the resolution in the finer portion was printed with a 2.5 mm nozzle, giving 1.3 mm layer heights and for the rest of the part, a coarser resolution with a 7.6 mm nozzle size was used giving a layer height of 3.8 mm. The post processing involved filling the roughness between the printed beads using a slurry of acetone and ABS. The surface was then hand sanded using an orbital sander to demonstrate the before and after finishing effect which showed that the roughness of the beads could be removed in their entirety without other subtractive processes.

3.5 Extruder Dynamics

When scaling up 3D printing from desktop to large area sizes, the transition from a filament fed extruder using a stepper motor to a pellet fed servo driven screw extruder increase the complexity of the system considerably. In the pellet fed system the polymer pellets are fed into a single screw extruder and is pushed through the heated barrel where it becomes molten, and the liquified feed is extruded. This results in considerable control issues since pellet flow is not nearly as consistent as filament feeding via feed pinch rollers. In addition, the behaviour of most polymer melts is highly non-linear and dependent on shear rate and temperature. The errors in print quality and geometric fidelity are further compounded in the dynamic regimes where the extruder flow starts and stops. With a stepper motor extruder, the flow out of the nozzle can be stopped by reversing the filament retracting the material back up the barrel. With a screw extruder the barrel is filled with molten polymer which exhibits non-Newtonian behaviour. Reversing the direction of rotation of the screw is not nearly as effective as retracting the filament as in the desktop system. Another issue will pellet extruders is that it is much more difficult to maintain a stable bead geometry, especially when the extruder nozzle accelerates and decelerates through the build. For example, when starting and stopping a print move or when printing around a corner or a radius.

The problem of transient extruder behaviour is a known issue in large-scale printing. The extruder flow starts and stops many times during a single print and even within a single layer. The nozzle velocity varies during the print, especially upon deposition round a radius. The deposition rate also must change to maintain the consistent bead geometry. As a result, a significant proportion of the printing takes place during some transient operation of the extruder.

It is a challenge to maintain a constant bead profile through the transient operation of the extruder due to non-linear effects of the extruder. There is no direct correlation between the pump speed and flow rate like there is in a positive displacement pump such as a piston. There are dynamic effects associated with the molten polymer interactions with the screw driving mechanism inside the extruder. Air entrapment in the system can also create a lag in the extrusion by creating compressibility in the flow behaviour. Furthermore, the material residence time whilst in the extruder can have an effect since the melt flow exhibits time dependent strain behaviour. Thus, if the extruder has remained idle for a period of time before commencing extrusion then the dynamics of the extruder will deviate [29].

3.6 Design Considerations

3.6.1 **CAD Design to Slice**

The first stage in the preparation for printing is to design the part, which is usually carried out in CAD (Computer Aided Design) software such as Solidworks or Fusion 360. However, it is important to understand the process by which the CAD model ultimately forms the G-Code. The software that carries out this function, known as slicing, has many capabilities but also limitations which ultimately affect the design considerations.

The CAD software will be used to design the part, and often any associated assemblies. The raw CAD file will contain any information about the part design for example arcs, splines, holes, and many other design details. The CAD file must then be exported as and STL (stereolithography) file, which uses a mesh of triangles to approximate the surfaces in the CAD design. The implications of this is that important data which includes curvatures is lost and replaced with planar triangles with straight lines.

Once the part has been designed and exported from the CAD software as an STL file, the file is loaded into the slicing software which creates the G-Code. G-Code is a programming language developed by MIT in the 1950s which effectively provides machine tools the information it requires to define the tool path. The slicing software divides the STL file data into layers, which is then uploaded to the printer. The printer now has the information required to build the part.

Slicing involves intersecting a horizontal plane through the STL file of the part and dividing the object into a stack of flat layers. Each time the plane intersects or finds the edge of a triangle in the STL file, a point in created where each of the points together form polygons which act as the boundaries for that layer. The slicer then fits toolpaths to each polygon which forms that layer. The size of the toolpath and how they get generated is determined by the user settings. Toolpaths are generated for each layer in the stack. Once all the paths have been generated it is then translated into a G-Code, which also includes machine commands such as machine speed, the positions for each axis, and the extruder speeds among others.

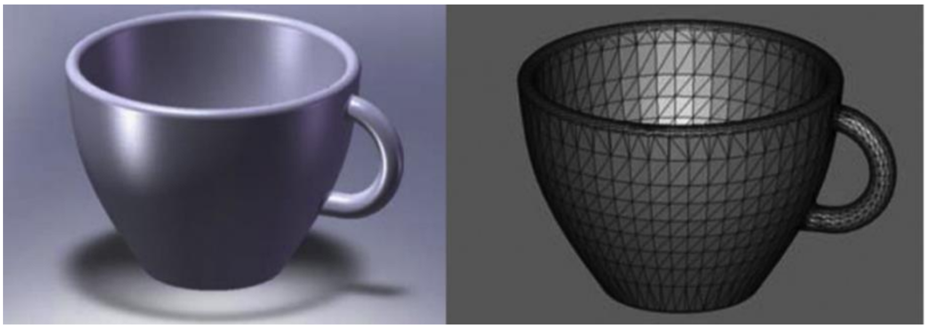


Figure 13. A mug from a CAD model (left), and its STL approximation (right) [31].

When designing parts in CAD software for large area additive manufacturing, it is important to bear in mind the desired bead geometry of the extruded material. For optimum results the CAD model mustn't contain features with less than two bead widths thick. As a rule of thumb, features narrower than 10 cm should be designed as exact multiples of the width of the bead.

3.6.2 General Design Guidelines for 3D Printing

Bridging

Bridging occurs when a horizontal overhang is formed between two towers or stacks. The size and magnitude of the gap under the bridge depends on the printer, material properties, and environmental factors. Smaller machines can print relatively larger gaps since the larger surface area to volume ratio results in a more rapid cooling rate. In the large area system, the surface area-to-volume ratio is substantially reduced resulting in much slower cooling rates. This can give rise to sagging and breakage due to increased weight and unfavourable material state. Hence a material which cools more quickly will be easier to bridge than one than doesn't.

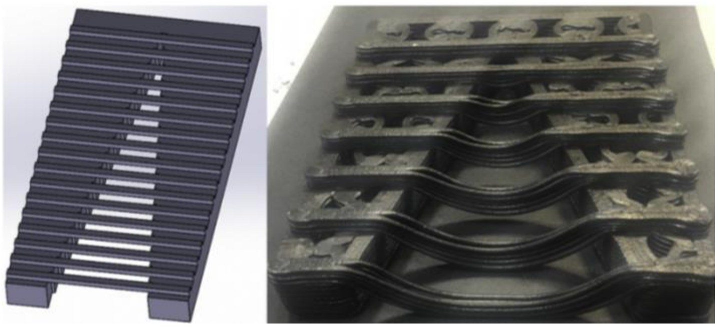


Figure 14. CAD model of part with bridging (left), and the resultant printed part (right) [31].

Cavities

A second design feature worth considering is cavities, which are hollow spaces within the body of the part. Cavities are possible using AM however whether they are feasible depends on the geometry and design. Ideally the geometry must be self-supporting to avoid using support structures. If the cavity is not self-supporting, then there must be a way of accessing the cavity via an opening in order to remove the supports. If the cavity is completely enclosed, then support material cannot be used.

Z-directional Strength, Delamination and Warping

There is a knockdown in strength in most of the AM processes in the Z-direction due to the lag between the layer deposition and the cooling as the part is built upwards. The quality of bonding that takes place between each layer in the z-direction is not as good since the molten polymer is being deposited onto a layer which is solidifying. The strength is highest along the direction of the printed bead, which can be further enhanced by adding fibre reinforcement to the material. When short fibres are used rather than continuous fibres, they may align upon extrusion and printing, dependent on the material, nozzle geometry, throughput, and other factors. Overall, however, the part must be designed in such a way that the loading is minimised in the weaker orientations.

Figure 15. Schematic showing strength knockdown perpendicular to the layers.

Delamination is the term given to the phenomenon where either the part separates from the substrate (build surface), or where the layers become separated from each other. Temperature effects are the root cause of these issues. Layer separation can be due to rapid cooling rates, and or thermal gradients arising from inconsistent cooling throughout the part. As a material cools it shrinks and vice versa, and this is a material property known as the thermal expansion coefficient. As the layers build up the layers lower down will be cooler and will contract and will be constrained by those layers further up, resulting in curling and warping. Put simply, if a hotter layer is placed onto a relatively colder layer so when thermal equilibrium is reached the most recent layer will contract relative to the least recent layers resulting in residual thermal stresses. If the thermal stresses exceed the strength of the build plate adhesion, then curling occurs. Generally, if the print cools down too rapidly, warping will be the most pronounced. Also, the stresses can be greater where two sides meet thus if the corners are rounded then this will alleviate the stresses and reduce curling. Some systems use a heated build plate to reduce these effects, whilst others use a tacky glue between the substrate and the part reducing the thermal expansion effects between substrate and part. The BAAM system used in [31] uses a heated build plate covered with a build sheet made from ABS which is held in place by a vacuum. Typically, at the end of the print, the part is left on the bed to cool as slowly and as uniformly as possible before removal, at this stage there is still a risk of warping. This depends on the geometry and temperature effects, where longer parts such as beams are more at risk of warping.

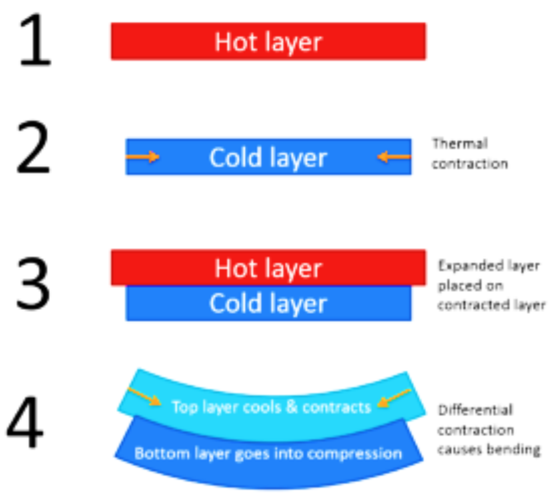


Figure 16. Schematic of thermal effects causing warping.

Surface Finish

Another design consideration is the quality of the surface desktop 3d printing with FFF. Desktop 3d printers typically produces smaller beads and greater resolution due to smaller nozzle size. However, for large area manufacturing systems like the BAAM Cincinnati, the bead sizes are larger, and the resolution of the layers is much lower. This generates a much more pronounced corduroy-like surface finish which can be post-processed to make the surface smooth using acetone, or by manual sanding or even by using a CNC router. For parts with large beads, the surface on the top of a part is usually smoother than that of the sides. The top of the part only shows variations where there is over or underfilling of the beads. Overfilling causes small ridges to appear whereas underfilling causes voids to appear.

Assemblies

Multiple components of a part can be additively manufactured where they are already mated together forming an assembly. Or they can be manufactured as separate parts. Small scale 3d printers produce parts with better resolution and can thus print complete assemblies with tighter tolerances. Large area additive manufacturing is designed to achieve higher deposition rates, albeit at the expense of resolution. This means that large area additive manufacturing is not suitable for tight design tolerances in assemblies, and this means that sections need to be produced separately before mating. When producing parts requiring assembly post fabrication via large area manufacturing, the design is typically rounded up by a dimension equivalent to the width of a bead. The parts for assembly are then machined down to the correct tolerances.

Overhang Angle

The overhang angle is the angle between the feature being printed and the horizontal plane of the build plate. Thus, the overhang angle of a side face of a cube will be 90°. Overhang angles less than 45 from the build surface plane results in inadequate support in the z-direction, with the layer being deposited not able to make the required contact for proper bonding. This means that there is a risk of unsupported material falling away or sagging, leading to build failure or loss of dimensional accuracy. In the BAAM system the polymer beads are wider, take longer to cool and remains prone to sagging or collapsing. Therefore, the layers must take time to cool and solidify prior to printing the next layer. A general rule of thumb is that overhang angles less than 45° from the plane of the build surface are not printable and should be avoided. However, in the case of desktop printing, supports can be used much more readily since it is easy to remove the excess material by using solvent or by breaking it off, thus angles less than

45° are achievable. Large area additive manufacturing doesn't allow for the use of supporting structures as the large extrusion bead size means that the surface area with which the part bonds to the supports would make the removal process difficult and could leave significant imperfections. Likewise, a solvent bath would be equally unobtainable due to the sheer volumes of solvent required. Therefore, in large area additive manufacturing, bridging gaps should be eliminated, or minimised, with overhang supports based on material capability. Holes generally should be left out due to unsupported cavities and drilled in a post-processing operation. Overhang angles should be increased to the point of not requiring supports or produced in a separate build and bonded in a separate step.

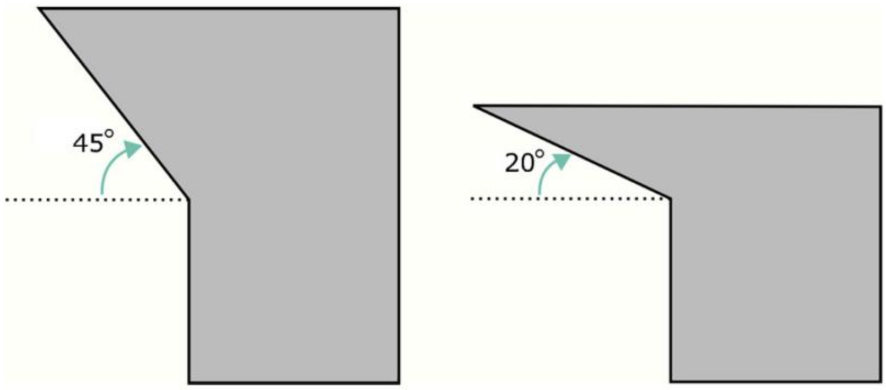


Figure 17. Schematic showing overhang angles of 45, and 20 from the horizontal plane [31].

Layer time limitations

There is both a maximum and a minimum layer time for optimal adhesion between deposited layers. Thus, to achieve good layer adhesion, the previous layer still needs to retain enough heat for the deposition of the next layer. On the corollary if the layer takes too long to print then the beads of that layer will have a poor interface with the subsequent deposited layer (maximum layer time). The maximum layer time is both geometry and material dependent. This is more complex than overheating since it depends on various features of a layer and how it cools as it is being printed. For example, a section with infill won't have issues with becoming too cool since it holds heat for longer. With large parts that have features with no infill, the time taken between each layer deposition will be too long giving a poor bond between layers. Beads which are grouped together will retain heat better than a single wall. Thus, thicker parts will also better retain heat and allow longer layer times. Also, parts made using ABS permit greater layer times than the high temperature materials such as PPS which have a much narrower window for application of the following layer. A solution is to print an additional part during the same build which will take more time, or it will slow down the speed of the printer giving each layer more cooling time.

If a printed layer is not given enough time to cool, then it won't be rigid enough to support the following layer. This is the minimum layer time. The molten polymer will deform and may be squeezed outwards resulting in loss of dimensional accuracy and potential failure of the part due to sagging and layers falling away. If sections of the parts therefore do not cool quickly enough, then likewise it can sag and or collapse due to the uneven thermal distribution. Therefore, the layer time limitations are dependent on the thermal properties of a material. To increase the layer time the print speed can be reduced or more parts can be printed at one time.

3.6.3 Throughput

Throughput is the processing speed, or the deposition rate per hour of the build material (lb or kg per hour). The Cincinnati BAAM machine is capable of printing at rates of 100 lb/hr or ~45 kg/hr when printing using a 0.3" (7.6 mm) diameter nozzle with carbon fibre-reinforced ABS [31]. This is the most used material on this system. However, for an average part the processing speed is around half of the maximum capable printing rate due to the dynamic effects of the extruder accelerating and decelerating. The discrepancy between the maximum theoretical speed and the average processing speed is due to the geometry and the way that STL data sees curvature. For example, in order to make a circular shape, the printer head needs to make between the order of tens to hundreds of moves depending on the resolution. This is due to the triangles of the STL file causing more points created during slicing. In contrast a square can be printed in four moves. In order to maximise throughput curved edges ideally should be avoided however this is unlikely to be realistic if it is a requirement in a design, so curves should be minimised where possible in order to maximise throughput and minimise the numbers of points generated during slicing.

3.7 Advantages and Disadvantages of Large Area AM

AM has the potential to reduce the energy required for the manufacturing. An analysis carried out of large area additive manufacturing process showed that it is a very energy efficient process with production rates rivalling many conventional processes [32]. Large Area AM allowing larger part production at lower costs with greater throughput. At the present time, the primary applications of larger scale additive manufacturing are in the tooling industry such as moulds for the automotive and aerospace industries.

Some of the original barriers towards market penetration included speed, cost and size. Large area additive manufacturing can produce larger parts with higher deposition rates with relatively lower material costs, however this is dependent on material used. However, the major hurdles in large format additive manufacturing still yet to be overcome are part strength in the z-direction, material constraints (materials need to have optimal properties for extrusion AND retain desirable properties for the intended part), resolution/surface finishing and design tolerances, process control and the challenges in standardisation and certification of parts.

4 Review of Current Materials Suitable for Large Area AM

4.1 Introduction

Most commercial endeavours discussed in the previous sections of this work have focused on FFF for large scale AM implementation. As a result, material system development has been around the use of thermoplastic processable systems, which will be focussed upon here. If the 'performance tree' placing relative orders of merit is considered (REF) the bulk of those polymer families reside in the lower caste of the Engineering Resins section. Many so-called 'commodity resins' lack the required mechanical performance required of many large-scale applications. Conversely, many high performance, highly crystalline resins have both cost and processing disadvantages (figure 18). There is however a rich 'middle ground' of both native and copolymer systems which could find great utility as a base resin in and large-scale application. Many of these systems require the incorporation of 3rd phase fibre reinforcement to lend considerable advantage in semi/structural roles, to effectively form in-site random fibre composites from freely available (or appropriately modified) form of reinforced feedstock developed for current Injection Moulding application.

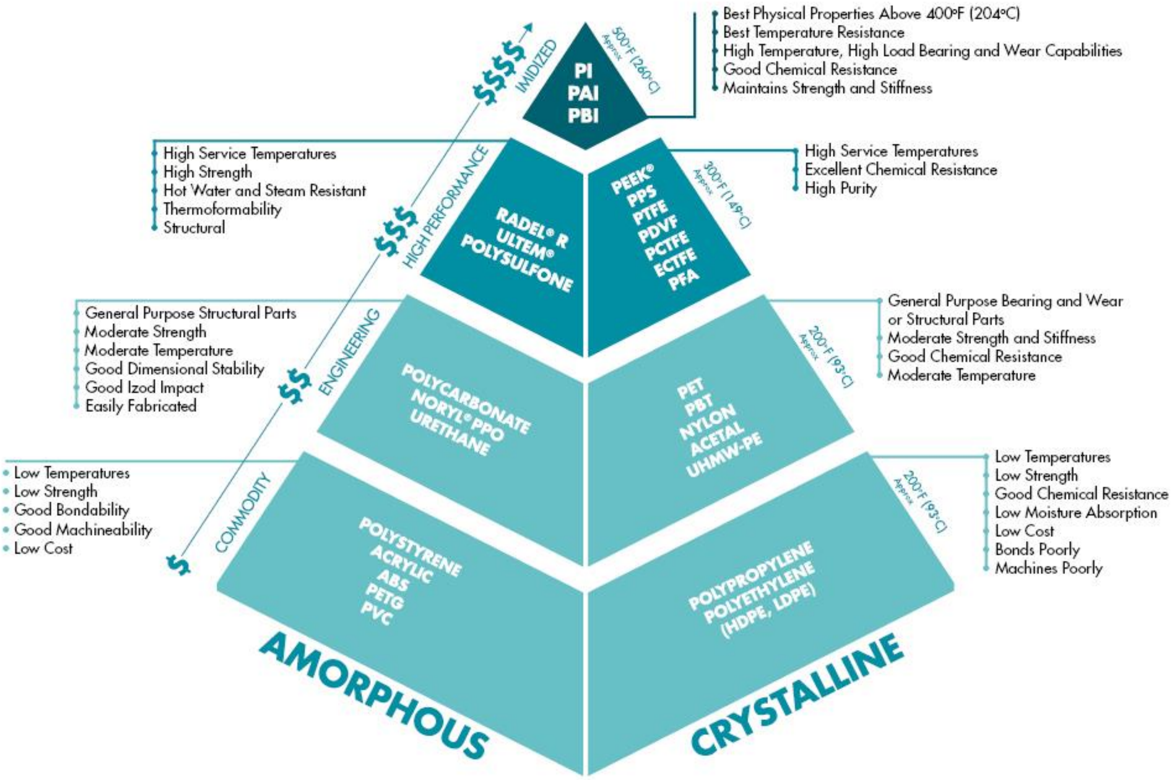


Figure 18. A schematic of the performance to cost for commercially available thermoplastics.

4.2 Large AM overall material requirements

4.2.1 Overview

When the thermoplastic polymer is extruded during deposition, the temperature of the molten polymer as it exits the nozzle must be greater than the melting temperature for semi-crystalline polymers, or greater than the glass transition temperature in the case of amorphous polymers. Once the molten polymer has exited the nozzle the temperature of the material decreases with viscosity increasing sharply enabling the bead to retain shape. In the case of large area additive manufacturing the beads are larger, retaining heat for longer and thus form an oval cross section. For the polymers to be printable via extrusion they need to be highly thixotropic and exhibit shear thinning material behaviour, they must have the appropriate viscosity in which the material can be extruded to form continuous beads resulting in geometric fidelity, the molten polymer must undergo a sharp increase in viscosity upon extrusion to retain shape, and finally the material must have the mechanical strength both to support the structure of the print and have the mechanical properties suitable for the use of the part.

Thermoplastic polymers are a class of materials which are governed by their thermal properties. Typically, the interactions consist of weak reversible intermolecular Van der Waals forces. These materials will soften upon heating where the intermolecular forces become rapidly more weaker exhibiting fluid-like behaviour. This is a completely reversible process and doesn't involve any breaking or forming of chemical bonds. This enables the polymers to be remoulded and reformed into any desired shape. Thermoplastics differ from thermosets which irreversibly react with a hardener to form strong chemical bonding upon curing, and thus do not melt upon heating. Thus, thermoplastic polymers are highly suitable for FFF. The viscosity reduces in the extruder barrel upon heating which facilitates extrusion through the nozzle. After extrusion the beads cool with increasing viscosity where the polymer solidifies and retains the final bead shape.

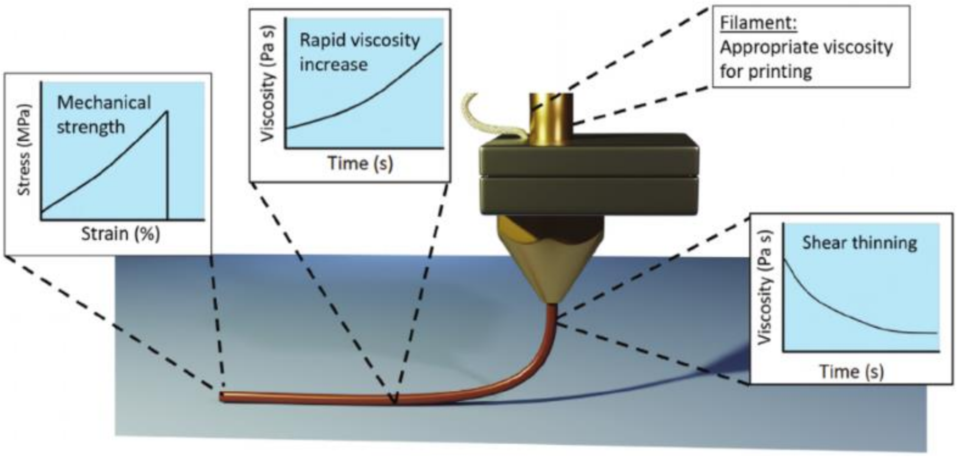


Figure 19. Schematic showing the key features required of the material [33].

4.2.2 Amorphous Thermoplastics

Some thermoplastics don't fully crystallise below their glass transition temperature and retain some or even all their amorphous characteristics. Amorphous thermoplastics have a randomly ordered molecular structure and lack a sharp definitive melting point. These polymers will thus soften and become more like a viscous fluid on heating above their glass transition temperatures (Tg). Amorphous and semi-amorphous thermoplastics tend to be less resistant to chemical attack and environmental degradation due to their lack of a crystalline structure. Typical amorphous thermo plastic polymers include: Acrylonitrile Butadiene Styrene (ABS), Polymethylmethacrylate (PMMA), Polycarbonate (PC), Polysulfone (PS), and Acrylonitrile Styrene Acrylate (ASA). Typical characteristics of amorphous polymers include softening over a broad range of temperatures, easy to thermoform, good bonding characteristics with adhesives, prone to stress cracking, poor resistance to fatigue loading, and applications limited to structural thus not suitable for bearing/wear applications.

4.2.3 Semi-Crystalline Thermoplastics

Semi-crystalline polymers have structure containing both amorphous and crystalline components which are highly ordered. When crystalline materials are cooled below their melting point the molecules in the crystalline phase begin to arrange in a more orderly fashion, and thus take up lower volume than for an amorphous material cooling below its melting temperature. The shrinkage rate for of semi-crystalline polymers is greater than for amorphous polymers. Typical shrinkage rates for amorphous materials are in the region of 0.4-0.7%, whereas for semi-crystalline materials they're in the region of 1-3%. Semi-crystalline thermoplastics have a true definitive melting temperature (Tm) where on heating the crystalline domains break up and become more disordered and the polymer rapidly enters a fluid phase. The melting temperature is generally above the upper range of that of the amorphous thermoplastics. Typical semi-crystalline thermoplastic polymers include: Polybutylene terephthalate (PBT), polyethylene terephthalate (PET), Typical key characteristics of semi-crystalline thermoplastics are: sharp defined melting point, difficulty of thermoforming, relatively difficult to bond using adhesives and solvents, good resistance to fatigue loading, good for bearing, wear and structural applications. The major drawbacks for some of these polymers systems such as the high temperature high strength thermoplastic PPS is the requirement for a secondary annealing step. Annealing is the process where a material undergoes heat treatment to just below the glass transition temperature in order to relieve the part of internal stresses introduced during fabrication. This can in turn provide better mechanicals. However, despite the excellent performance which can be afforded from these higher temperature thermoplastics the annealing step requires a fully enclosed heated chamber and therefore incurs substantial costs and time associated with this extra step.

4.2.4 General Effects of Fillers

Fillers can be added to modify the polymer properties for example, conductive fillers can build in electromagnetic shielding properties into the polymer. Also coupling agents such as silanes can be added to improve the interactions between glass fibres with the surrounding polymer matrix material. Other additives include flame retardants, lubricants to lower viscosity, and plasticisers to increase the flexibility.

Low Asp*ect Filler*

Fillers tend to modify the polymer properties of the extruded polymer to enhance characteristics or to reduce the negative characteristics of the polymer. Low aspect fillers will improve basic properties however not as much as with high aspect ratio fillers. Shrinkage will be reduced, thermal resistance may be improved, compressive strength will be improved, although impact resistance will be lower than for unfilled polymer, and solvent resistance can be improved. The addition of fillers will also increase the melt viscosity, thus other additives such as surfactants and plasticisers may be required. The addition of fillers causes agglomeration, nozzle and print head blockages, and improper adhesion between beads [34].

High Aspect Fillers: Fibres

If fillers such as carbon or glass fibres are used, then this results in significant deviation of the properties of the polymer to which it is added. With the assumption of good interfacial bonding between fibre and the surrounding polymer, the strength along the direction of the fibres will be substantially increased. Therefore, higher strengths are to be expected along the directions of the printed beads. Also, the elastic modulus along the fibre directions will be improved but the modulus perpendicular to the fibre direction will be close to that of the unfilled polymer. Likewise, the thermal shrinkage will be substantially reduced along the direction of the fibres, compared with the shrinkage perpendicular to the fibre direction. It has been shown that this effect can be in the order of magnitude of 5-10 times the strength in the z-direction across deposited layers for ABS with 20% carbon fibre filler [35]. The general comparative qualities that distinguish both glass and carbon fibres are summarised in table 2.

Table 2. The properties which carbon or glass fibres can add as material fillers.

Property Requirement	Filler
Affordability	Glass
Tensile	Carbon
Stiffness	Carbon
Durability	Glass
Polymer Bonding Interaction	Carbon
Flexibility	Glass
Low Weight	Carbon
Heat Resistance	Both
UV Light Resistance	Both
Fatigue Resistance	Carbon

The addition of carbon fibres (CF) to the feedstock ABS material for example, has a big impact on CTE. Love et al. measured the CTE of samples in both parallel and perpendicular directions to the deposition direction in accordance to ASTM E228 using a TA TMA Q400 system *[36]* (table 3). The extrusion results in the fibres shear aligning to the primary direction of extruded beads, thereby changing the CTE by orders of magnitude, however in the perpendicular direction the CTE along with thermal conductivity remains similar to the unreinforced ABS. This reduction in CTE and enhanced thermal conductivity has a profound impact on geometric accuracy. The motivation is thus to reduce thermal gradients which can result in warping or curling of the part. By increasing the thermal conductivity of the CF reinforced material, the thermal gradients are minimised throughout the part. Hence also reducing the CTE minimising the strains due to the part cooling down to ambient temperature, the combined effect of these two factors significantly reduces the part distortion through the manufacturing process.

Table 3. Effect of CTE on thermal conductivity and CTE for ABS with and without CF filler [36].

	CTE (µm/m°C)	Thermal Conductivity (W/m K)
ABS	87.32 ± 6.17	0.177
ABS/CF 13% parallel to deposition	9.85 ± 0.84	0.397
ABS/CF 13% perpendicular to deposition	106.3	0.156

4.2.5 Mechanicals

Compared with the neat polymer materials, fibre reinforcement typically increases the strength of parts by orders of magnitude. The materials will need to withstand the design loads of components. If they don't have the required material strengths and stiffnesses, then they will be unsuitable for use in load bearing parts. However, the addition of short fibres into a 3d printing filament for example, increases the stiffness, but the strength increase can be more limited if the fibres pull out before fibre breakage [5]. So, the fibre length which gives the most beneficial strength enhancement needs to be fully understood and is given the term critical fibre length. Critical fibre length is the point where the tensile strength reaches the fibre limit stress in which rupture occurs. Thus, the embedded length in which the fibre fails is the critical length. For fibres which are shorter than the critical length complete interfacial debonding occurs whereas if the fibre length is greater than that of its critical length then fibre failure occurs without interfacial debonding [37]. In general, it is unlikely that 3d printed thermoplastic materials will find immediate uses in highly load bearing structures e.g. in the case of spar caps of wind turbine blades or the stringers, spars and skins of wing structures. However, they must retain sufficient mechanical properties to be able to compete with existing materials for example in sandwich cores which carry moderate loading but are not the main load bearing component like spar caps. If the strength to weight ratio is not either as good as, or better than conventional composite materials or sandwich core materials than they are rendered unsuitable for these applications.

4.2.6 Cost

Given the large volume of material represented by the focus area of Wind & Tidal Blades and Marine Vessels, cost is a dominant consideration for the use of any proposed AM material. The straight Bill of Material (BOM) Line-cost however should not be the governing metric, rather the Total Life Cycle cost should be considered, inclusive of repair, recycling and end-of-life costs. However there needs to be a balance between processing costs and material costs with the application of the material, for example in primary load bearing structures a high strength material would be an essential requirement.

4.2.7 Continuous Use Temperature

Use temperature requirements must not only consider the direct environmental temperatures encountered, but also use cases include potential exposure to hot water, steam and transient machine heat/hydraulic/lubricating fluids.

4.2.8 Chemical Exposure

Apart from the obvious exposure case of the saltwater environment, prospective AM materials must be able to resist commonly encountered chemicals during manufacture, operation and maintenance of Wind & Tidal Blades and Marine Vessels.

4.2.9 Recyclability

In order to produce the next generation of parts by large area additive manufacturing through FFF, there are strong drivers towards using materials which show the ability to be recycled. Especially in the wind industry. Recyclability is made more challenging with the addition of fillers in terms of being able to separate the constituents and extract and reclaim the fibres. Hence materials would ideally need to show some potential for both thermal and chemical routes to recycling.

4.2.10 Shrinkage, Geometric Tolerances and Thermal Expansion

The coefficient of linear thermal expansion (CTE) influences the part shrinkage and describes the expansion of the material relative to its original dimensions when heated with units of $°C^{-1}$. Thermoplastics that require a higher print temperature are more at risk of thermal shrinkage. Also, polymer type, influences shrinkage. The FDM process is more suited for printing amorphous thermoplastics since they solidify more quickly with less thermal shrinkage. The solidification of semi crystalline polymers takes a greater amount of time depending on the extent the crystallinity and the cooling rate. The crystallinity also causes higher degree of thermal shrinkage and potential for part distortion. Also as previously discussed, using ABS with 20% carbon fibres, filler type and morphology also play a big part in thermal shrinkage.

4.2.11 Weatherability

A prime consideration given the enhanced UV and salinity environments. This weatherability requirement will clearly be less important in those components which can be shielded from direct exposure, but secondary exposures must still be considered to achieve maximal service lifetimes.

4.2.12 Water Uptake

A driving factor given the operational environment, those systems which display lower overall water uptake will suffer less from dimensional changes and the induced stress entailed.

4.3 Initial Material System Candidates

Acrylonitrile Butadiene Styrene (ABS) is an amorphous commodity thermoplastic which is cheap, however has low strength, and is potentially hazardous when under polymer processing conditions due to decomposition into its constituents and dispersion of ultrafine particles when exposure during printing. The impact resistance and toughness of ABS is notable and can be improved by increasing the proportion of polybutadiene to styrene and acrylonitrile however this will affect other properties. Glass reinforced ABS has improved properties (strength rigidity, and dimensional stability) compared with unreinforced polymer. The strength of ABS is improved to 103 MPa from 38 MPa in the unreinforced polymer when using 40% glass fibre filler. However, it is attacked by some solvents such as Methyl Ethyl Ketone (MEK) among others, which means solvent bonding is a useful method of assembly and mating parts. However long-term exposure to ketones and esters should be avoided. Other issues with ABS are the requirement for a heated bed, ABS also don't adhere well with the bare build plate which for desktop printers is usually borosilicate glass. Topical build plate application of removable adhesive layer (e.g. PVP) or semi-permanent film release layer (e.g. polyetherimide) aid adhesion of the critical first print layer.

4.3.1 Co-polyesters PET/PETG/PBT

Polyethylene terephthalate (PET), and Polybutylene terephthalate (PBT) are semi-crystalline engineering thermoplastics. These can be used for general structures and for general bearing and wear structures. PBT is closely related to PET, high resistance to solvents, low thermal shrinkage during forming, with moderate strength and mechanical properties, heat resistant up to 150°C. However thermal resistance is raised when included with GFRP reinforcements. In general, when compounded with fillers and reinforcements the strength, rigidity, and heat resistance is dramatically enhanced. However, compared with PET, PBT has slightly lower strength and rigidity, with marginally improved impact resistance, and lower glass transition temperature. Owing to good chemical resistance, both PET and PBT are difficult to bond. The glycol modified analogue of PET, PETG is a clear, amorphous commodity thermoplastic, and is tougher, and stiffer than PET with a greater elongation at yield and at failure. PETG is well suited for 3d printing due to good chemical resistance, formability and durability.

4.3.2 Polycarbonate PC

Polycarbonates (PC) are a group of amorphous engineering thermoplastic polymers which have high impact strength, moderate cost and temperature resistance, and high toughness. PC is also durable and has high impact resistance but low scratch resistance. PC can also undergo large plastic deformations without cracks or damage and can thus be formed at room temperature using traditional sheet metal techniques. The toughest grades of PC use higher molecular mass but are more difficult to process. The dimensional stability can be further improved by reinforcement with glass fibre. Furthermore, reinforcement with glass fibres reduces the thermal expansion coefficient to 1.8 µm/mm/°C, resulting in notable implications for warping and shrinkage. Standard PC materials are not suitable for long term exposure to UV radiation and require UV stabilisers. At elevated temperatures PC will hydrolyse to form Bis-phenol A, thus when incinerated BPA crystals can form and pose an environmental hazard. BPA can also leach out at ambient temperatures and can thus be persistent in landfills. The main advantages of PC are creep resistance, toughness, and dimensional stability. Major limitations include poor chemical resistance, difficulty in processing, and low fatigue endurance.CF and GF reinforced

4.3.3 ASA

ASA is an amorphous thermoplastic developed as an alternative to ABS but with much improved weatherability. The weatherability ensures that it retains gloss, colour, mechanical properties, chemical and heat resistance. It is also structurally like ABS and has good UV resistance and mechanical properties. ASA is mildly hygroscopic, hence absorbs moisture over time and has low thermal moulding shrinkage. ASA parts can be welded together via ultrasonic welding techniques. In comparison to polycarbonate PC, ASA has greater resistance to environmental stress fracture.

4.3.4 PES/PSU

Polysulfone (PSU), and Polyether sulfone (PES) are amorphous high-performance thermoplastics, which come at a higher cost. They have a high service temperature and are thus highly temperature resistant, they have high flexural and tensile strength, good stiffness, and excellent chemical/solvent resistance. The strength and stiffness of polysulfones is retained between -100°C and 150°C. The glass transition temperature of polysulfones is between 190-230°C. The dimensional stability is generally very high. PES has relatively high-water absorption, but outstanding toughness. PES tends to be used in the aerospace and automotive industries where superior thermal and mechanical properties are required. However, PES in its unfilled form is not suitable for outdoor use due to poor weathering, ozone and UV resistance. This weathering can be offset or negated with the addition of other materials. A comparative table of material properties is shown in table 4.

Table 4. Properties for some common material systems.

Material System	Density at RT (g/cm3)	Glass Transition Temperature (°C)	Melting Temperature Range (°C)	CTE (µm/mm °C)	Thermal Conductivity (W/m K)	Ultimate Tensile Strength (MPa)	Elastic Modulus (GPa)	Moisture Absorption at Equilibrium (%)	Elongation at Failure (%)	Elongation at Yield (%)	Raw Cost ($/kg)
PC	1.2	145	250-343	65.9	0.196	68	2.2	0.151	100	10.3	1.2-1.3
PBT	1.32	66	250-260	85.9	0.245	57.6	2.53	0.133	95.4	3.75	1.1-2.6
PET	1.28	73.5	120-295	70.5	0.204	42.5	3.1	0.32	74.4	5.51	0.65-0.8
ABS	1.08	108	177-320	80.7	0.172	38	2.06	0.18	53.6	5.56	1.8-3
ASA	1.07	100	180-280	95.8	0.17	44.7	2.1	0.35	37.1	5.01	2-3.8
PC (20% CF)	1.29	148	135-332	22.1	n/a	123	11.8	0.145	4.11	3.45	n/a
PC (20% GF)	1.34	n/a	221-343	29.8	0.233	92.7	5.59	0.139	4.35	n/a	9.9
PET (50% GF)	1.73	n/a	255-300	20.3	n/a	175	16.6	0.157	2.33	n/a	n/a
PET (40% GF)	1.63	n/a	257-300	25.1	0.764	170	13	0.183	2.28	n/a	n/a
PES	1.49	221	288-399	38.3	0.473	114	7.46	0.539	6.15	2.75	28-30
PSU	1.35	214	260-410	47.2	0.266	86.4	5.2	0.284	18.2	3.63	20-30
PETG	1.26	80.9	180-293	63.3	0.2	42	2.65	0.146	124	52.7	1.56

5 Review: Robotics and Automation

5.1 Overview of Current Robot Solutions

An industrial robot is a robot system used for the purpose of manufacturing, and are automated, programmable and have 3 or more axes of movement [38]. Typical applications include painting, palletising, welding and machining. The most common robot types include SCARA (Selective Compliance Articulated Robot Arm) robots, Parallel robots, Cartesian (Gantry) robots, and articulated robots. Robots generally exhibit varying degrees of autonomy. SCARA robots are useful for small assembly operations and have good speed and accuracy on pick and place tasks. They are compliant in the horizontal X-Y direction but fixed/rigid in the Z direction and are relatively small with 4 degree of freedom and are generally unsuitable for more complex operations. Other robots include parallel manipulators that uses several computer-controlled serial chains supporting a single platform which acts as the end-effector. A typical example of this type is in flight simulators where six linear actuators support a movable platform. Cartesian/Gantry robots typically use three or more standard linear actuators with mounting brackets, positioned above the working area, the custom design of these robots typically makes the programming and design challenging for smaller manufacturers, however the main disadvantage is the lack of reach around more complex artefacts. Articulated robots are those which contain several axes of rotation (usually between 4 and 7) with the most common being the 6-axis robot. These are more notable for their ability to navigate more complex geometries as well as better quality, consistency and better safety for repetitive pick and place tasks, and reduced labour costs. Sealed joints and protective sleeves also allow for use in both clean and dirty environments. However articulated robots are perhaps less suited for very high-speed movements due to more complex kinematics and mass, and the level of sophistication that comes with these machines means that the initial cost is relatively high in comparison to the other types.

Using additive manufacturing, it is possible to produce parts without the need for tooling [39]. Parts with complex geometries can be made in one single process step in theory, eliminating some of the productions steps and reducing the time to market [40]. AM also reduces material wastage, and reduces the time required for design and prototyping. So, AM has been used in a wide variety of sectors from medical, aerospace and construction. Developments during the last decade have shown an increased use of AM systems for larger structures, however most systems tend towards cartesian coordinate gantry systems such as in [32]. Current commercial FDM printing systems are usually 3 axis machines in that the fixed building direction is in the z-axis. The main drawbacks of having 3 axis machines with a single fixed building direction is the lack of strength requiring support structures and more notably the stair-step effect [40]. The stair step effect is the result when the curves and gradients of a part vary causing an offset in the printed layers. The resolution and the stair-step effect are issues when building layer by layer in the z-direction and is increased with layer thickness and shallower gradients in the build direction [41]. However, in more recent times, there has been greater effort in the use of articulated multi axis robots in the field of AM processing in order to reduce the supports needed and to allow for more complex geometric features.

5.1.1 Definition of Key Parameters

- *Number of Axes (Degrees of Freedom):* Two axes are required to reach any point on a plane. Three axes are required to reach any point in space, however in order to fully control the wrist or end-effector, additional axes are required. These are yaw, pitch and roll.
- *Working Envelope:* The region in space where the robot end (wrist) is able to reach.
- *Kinematics:* This describes the arrangement of rigid members and joints in the robot and hence the configuration that describes the motion of the robot. For example, SCARA, Gantry etc.

- *Payload:* This describes the maximum weight that can be carried at the end of the robot (wrist), also known as an end-effector.
- *Speed:* The velocity of the end of the robot arm, either as the angular or linear of each of the axes, or the overall speed of the arm at the tool end.
- *Acceleration:* How rapidly an axis can accelerate can be a limiting factor in whether or not the robot can navigate shorter distances or more complex tool paths requiring complex directional changes.
- *Accuracy:* The difference between the robot's commanded position and its actual position. Accuracy can vary with the speed and position of the working envelope and also the payload of the end-effector.
- *Repeatability:* This is defined as the degree of agreement between each of the positions reached by the robot end-effector for the same controlled programmed position when repeated several times under the same conditions [42]. Thus, it is important not to confuse repeatability with accuracy (Figure 19). Repeatability can also differ in different parts of the working envelope and also can vary with speed and payload of the end-effector.
- *Compliance:* This is the inverse of the stiffness and is thus the flexibility of the system when a force in applied, in this case through the end-effector. Hence when a robot reaches a specified position with maximum payload it will occupy a position which is slightly beneath the position when carrying no payload.
- *Motion Control:* This is a subdivision in automation responsible for moving the robot parts in a controlled fashion. Controlled orientation and velocities are important for more sophisticated applications such as welding and finishing which require continuous control of force and movement in the operating envelope.
- *Drive:* In jointed robots, some electric motors are connected via gears, other electric motors are directly connected to the joints without gears (also known as direct drive). With geared joints backlash can be a problem. Backlash or play is the clearance or lost motion due to gaps between the moving parts (gears).
- *Work Envelope:* A 3D field in in which the boundaries of the robot manipulator is able to reach, also known as the reach envelope.

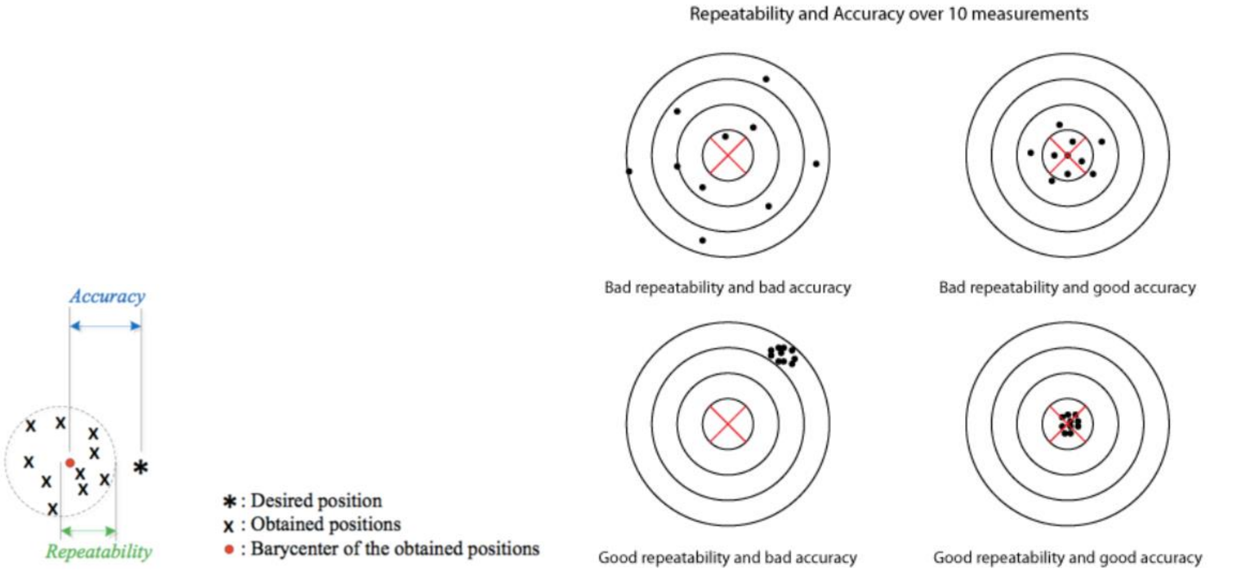


Figure 20. Schematic of a 2D Geometric Definition of Accuracy and Repeatability [42].

5.2 Multi-axis Articulated Arm Systems

The combination of multi-axis articulated robot systems with an extruder which can perform FFF offers the possibility of producing parts of greater geometric complexity. However, the development of multi-axis FFF systems require innovations in hardware and software components. New algorithms are required for freeform trajectory planning of the end effector [40]. Trajectory planning is defined as the movement from point A to point B whilst avoiding any collisions over time and is a major subdivision of robotics. In the context of FFF the robot and its printing head cannot collide with the object it is printing in 3d space during the build process. This involves new approaches to hardware and software design. For further details on trajectory planning approaches for optimising accuracy, quality and build time in FFF the reader is directed to [43]. There are several companies which now sell fully integrated solutions for FFF using multi-axis robots however they are still in their relative infancy as it is still an emergent ongoing multidisciplinary research area. These will be discussed in further detail in section 8. This section aims to collate general examples of articulated arm robots in the context of AM.

Zhang et al. [44] produced parts fabricated from ABS filament using an ABB robot to validate process simulation towards design optimisation. They used a computational platform developed by ABB to carry out the process simulation using a 6-DOF robot arm with a printing head end-effector. In a similar fashion Wu et al. [45] used a Universal Robots UR3 with 6-DOF to build PLA parts from their filament form to demonstrate part build with a reduction in supports structures. A research team from the University of Michigan [46] used a 7-axis KUKA robot to produce a monolithic elastic net using a thermoplastic elastomer. They used a screw extruder with the pellet form of the material. Their project aims were to produce lightweight kinetic surfaces to give reconfigurable spatial enclosures with the minimum amount of material, for example cable nets and tensile surface control. Using a 7-axis robot affords a high degree of freedom which enables printing of complex architectures without supports, minimises post processing steps, minimises the material usage and waste, and improving accuracy. Another example is the use of an ABB 2400 L articulated robot arm to produce parts using a thermosetting polymer consisting of two reactive material components which when mixed react irreversibly in the mixing part of the nozzle where the viscosity increases in printing. They describe a novel method of additive manufacturing which enables the creation of 3d objects on any given working surface regardless of its inclination and smoothness [47]. Robot assisted extrusion technologies have been applied to architectural building elements. Felbrich et al. [48] devised a rapid additive manufacturing concept for the continuous extrusion of thin free-form composite thermoplastic shells inspired by the snail shell formation using 6-DOF robots. Gosselin et al. [49] developed an extrusion-based robotics methodology for large scale printing of ultra-high-performance concrete for architects and builders. They produced structures without temporary supports and with geometric complexity enabling multifunctionality. A research group from the Tongji University in China [50] developed a strategy based on a combination of primary curved structures with auxiliary curve structures in contact with the primary ones. A 6-axis (DOF) KUKA robot was used with one principal and three secondary nozzles in order to simultaneously print the primary structures with the auxiliary structures. The extruder system was designed to be used with ABS.

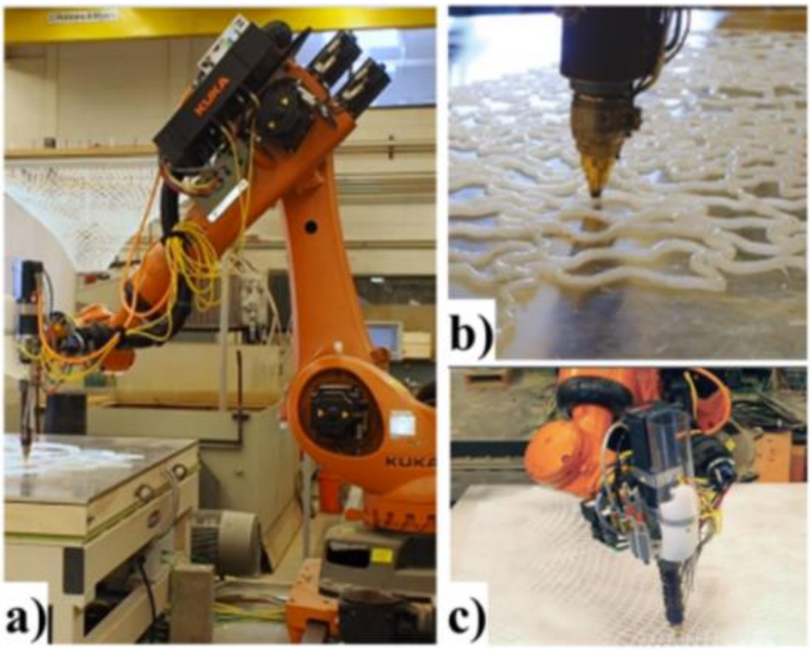


Figure 21. Extrusion system with a 7-axis KUKA articulated robot, (b) FFF printing head, (c) Material deposition [46].

Also there have equally been similar research efforts undertaken in the metal AM process (Direct Energy Deposition) regarding 6-axis robots. The process requires accurate adjustment of laser power/intensity, carrier gas flow, powder feed rate, working distance, cooling intervals among many others [40]. Commonly used materials for powder-based systems include Inconel 625, Ti6Al4V, nitinol, stainless steel, aluminium and tool steel [51]. DED can have limitations in producing complex shapes with efficient powder delivery and material property control. Several research centres are developing DED systems [52, 53] for example at Cranfield University they have explored deposition rates with a focus on cost reduction using a 7-axis KUKA robot for wire and plasma arc additive manufacturing large 1.2 m Ti6AlV4 structures [54]. At the Oak Ridge National Laboratory, Bandari et al. are investigating laser wire DED for applications in the aerospace industry [55].

5.3 Gantry Systems

In early 2014, Oak Ridge National Laboratory (ORNL) entered a collaboration with Cincinnati Inc which is a custom builder of machine tools to focus on large scale additive manufacturing using polymers. Initial work was first undertaken under an ORNL led laboratory directed R&D program. The overall goals were to show feasibility of out-of-oven manufacturing processes with a size of greater than 2m, and with deposition rates greater than 50 cm^3. It was at least an order of magnitude improvement on the then current state of the art. The initial feasibility project then resulted in a deeper collaborative agreement in order to mature and upscale the technology and was supported by the US Department of Energy (DOE) Advanced Manufacturing Office at the ORNL Manufacturing Demonstration Facility. The resulting Big Area Additive Manufacturing (BAAM) system they developed is designed to use polymer pellets as opposed to drawing a filament. Thereby substantially reducing the cost per kg of the feedstock material from $50-100/kg to $1-2/kg [32].

Cincinnati Inc. whose product lines include high speed gantry systems for laser cutting which have powerful high speed linear electric motors with high acceleration. The payloads on their gantry systems can also able to withstand 45 kg making it ideally suited for the end-effector equipment required for carrying out BAAM activities. In this second phase of maturing and upscaling, the BAAM technology was transitioned using CI's existing high-speed linear gantry system which at the time was used on their laser cutting system. The collaboration in the maturation phase focussed on heated platform development, software integration, preliminary processing parameters, and material properties. By the end of the maturation phase of the project, ORNL and CI had successfully transitioned the technology to a point which led to a commercial sale of their first complete BAAM system at the International Manufacturing Trade Show [32]. Whilst ORNL were able to prove the initial feasibility of the technology in the laboratory, their partnership with CI enabled them to mature the technology from the lab scale to the commercial market. Further refinement and development continue.

In other applications as well as 6-axis robot systems, Gantry systems have likewise been used in the construction of large architectural-scale structures with the deposition of concrete from an extruder [56], however the one of the major disadvantages of using a gantry system is that the required scale for the frame which must be larger than the structure to be built. This means that the initial setup costs are high. The gantry system is only capable of movement in the x, y, and z directions and hence can only extrude simple 2D layers so is unable to produce parts with greater geometric complexity as with multi-axial articulated robot arms.

6 Potential Applications

6.1 Overview

This section aims to bring together various current applications of Additive Manufacturing in the context of industrial applications with more commercial relevance. AM has been around since the 1980s however it wasn't until 2009 when the last major patent for FDM extrusion expired that 3d printers could be produced more cheaply without intellectual property infringement. This led to an increase in commercial interest and investment in FDM technologies. Despite widespread adoption of AM technologies, the industry is young and more novel applications of AM are still under development. At the time of writing it could still be many years before AM begins to compete with conventional manufacturing processes and truly revolutionises manufacturing by replacing conventional industrial manufacturing processes [57]. For 3D printing and AM to become a more functional means of production, the technology needs to move beyond rapid prototyping and conceptualisation. The processes must become faster, easier and more reliable. The speed of printing is an important performance factor and in some cases one of the main challenges inhibiting it from becoming a practical way of manufacturing. Also, part size presents another challenge, larger objects means more material to print, and hence features such as larger nozzle sizes, and greater deposition rates are being considered. Unless the deposition rates and production times can be substantially improved to be able to demand higher quantities of material for larger parts, conventional manufacturing will remain the preferred option. However, AM offers new potential opportunities for manufacturing in terms of reduced lead times, easier part reworking, shorter time to market, with commercial demands being met more quickly. Further research efforts are still required in order to overcome the implementation challenges.

6.2 Wind Turbine Blades

The blades are some of the most critical components of the turbine – not only are they key to improving energy production, but catastrophic failure of a blade can lead to failure of other parts of the turbine structure and so it is to be avoided at all costs. Extreme wind or operational loads can cause sudden damage, whilst regular loads over their service life can cause material degradation and fatigue, which can limit their effectiveness and safety.

The blade structure and materials define the types of manufacturing processes which can be used, so they are summarised here. The primary function of a wind turbine blade is to capture the wind and transfer the load to the shaft, which creates a bending moment on the root bearing, and a torque on the main shaft. A blade is a large cantilever beam, which is primarily loaded in two ways. Flapwise, or out-of-plane, bending loads arise from aerodynamic forces and edgewise, or in-plane, bending arises from the blade self-weight.

The blade structure is designed to resist these loads whilst having a form which is as close as possible to the optimal aerodynamic shape. The suction side and pressure side shells are large aerodynamic panels designed to "catch the wind" and transfer the loads to the spar caps. They are comprised of a lightweight core material sandwiched between triaxial fabric.

They are typically moulded in two "blade shell" tools, and adhesively bonded to each other along their leading and trailing edge, and to the spar caps in the middle. Shell skins are lightweight triaxial glass fibre skins, of low thickness; they therefore need to be stabilised using a lightweight core (typically made from balsa wood or PVC foam) to prevent buckling. The shells are bonded together at the leading and trailing edges.

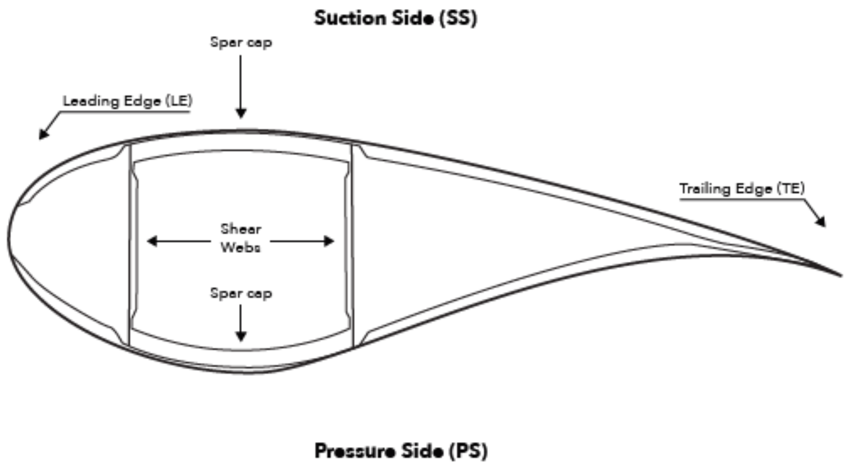


Figure 22. Terminology and parts of a wind turbine blade

The spar caps are generally made of uniaxial material (often carbon fibre instead of glass for modern offshore blades) placed at the thickest part of the section to maximise their contribution to the bending stiffness. The shear webs transfer the forces between the spar caps and are typically made of biaxial glass fabric with a core material (again made from balsa wood or PVC foam).

The entire exterior of the blade is coated in a general coating to protect the composite structure from the environmental conditions of UV degradation and moisture ingress and provide an aerodynamic surface. This general coating is typically a gelcoat applied in mould but can also be a filler and topcoat. Additionally, on the leading edge close to the tip a rain erosion resistant material is applied. This blade manufacturing process is shown in figure 23 (a).

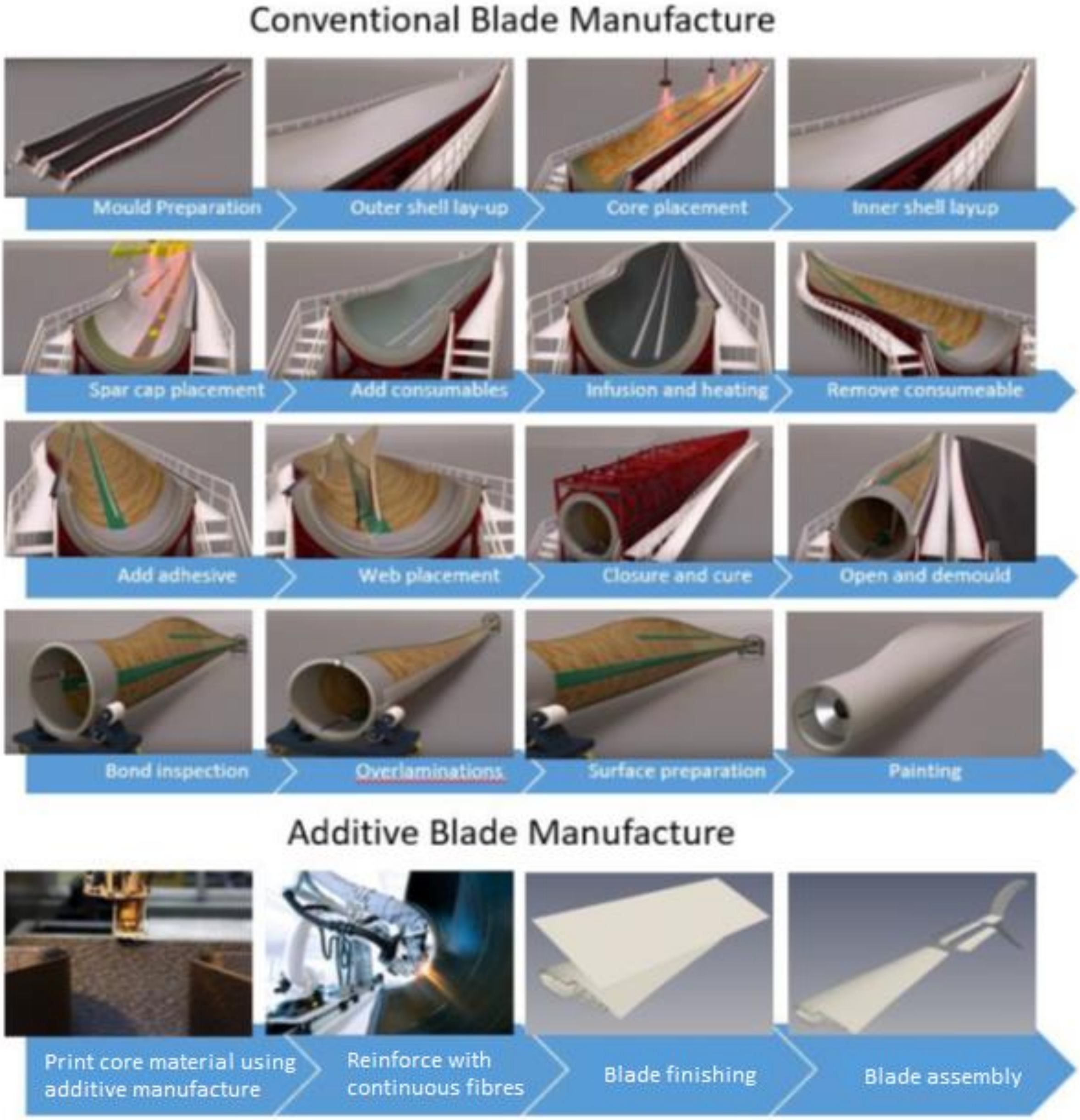


Figure 23 - Conventional blade manufacturing process comparison (a) with additive manufacture (b)

In the context of additive manufacturing, the properties of additive materials (even with reinforcement fillers) prevent their use for the primary structural elements of the blade. These would still need to be added using continuous fibre reinforced plastics, using techniques such as automated fibre placement (AFP), automatic tape laying (ATL) or using pultruded battens bonded into slots in the structure.

This means that the main use case for additive manufactured components in wind turbine blades is replacing the core materials, creating a framework which can then be reinforced using the methods described previously, as shown in figure 23 (b).

There are several levels of intervention of additive manufacturing which could be conceived:

1. The blade manufacturing process could be kept the same, with only the core materials replaced with equivalents created using AM. This could still have advantages over the conventional blade manufacturing process, as conventional core materials suck up resin during the infusion process,

leading to an increase in their density. They are also scored with a grid pattern to allow them to conform with the shape of the mould, and these slots tend to act as initiation points for blade damage in the field, eventually leading to delamination of the skins from the core material. The AM manufactured cores could be watertight and could be pre-shaped to the mould, so they would not need to be scored.

2. The mould tool could be eliminated for the individual components of the blade, using a core material which is offset inwards by the thickness of the surface laminates. The AM core material itself is then used as a male mould to apply reinforcement fibres to, using techniques such as AFP or ATL. The individual components could then be assembled, either by bonding the parts together as in current practice or by exploiting the properties of thermoplastics and using techniques such as thermal or solvent welding. Conventional design and analysis techniques can be readily transferred to this approach. This approach is shown in figure 24 (a).

3. The greatest use of AM could occur with a structure where the entire blade cross section is printed in a single pass, and material placement is optimised using techniques such as topology optimisation. In this approach intra-modular joints are eliminated entirely, which is a major advantage when we consider that joints frequently act as failure points in the field. In this case, conventional analysis methods from current practice in wind turbine blade design cannot be applied, so new techniques would need to be developed and agreed with certification bodies. A conceptual image of this approach is shown in figure 24 (b).

The design freedom which additive manufacture affords would allow site specific tailoring of blade design, and short turn-arounds for new blade designs. Developing mould and tool-less manufacturing will significantly reduce capex investment for new blade designs and will allow the exploitation of digital and automated manufacturing processes.

Material selection and formulation could also improve recyclability, recovery, repair and re-use of wind turbine blades. This is currently a major problem for the industry as the thermoset matrix materials currently used are very difficult to recycle.

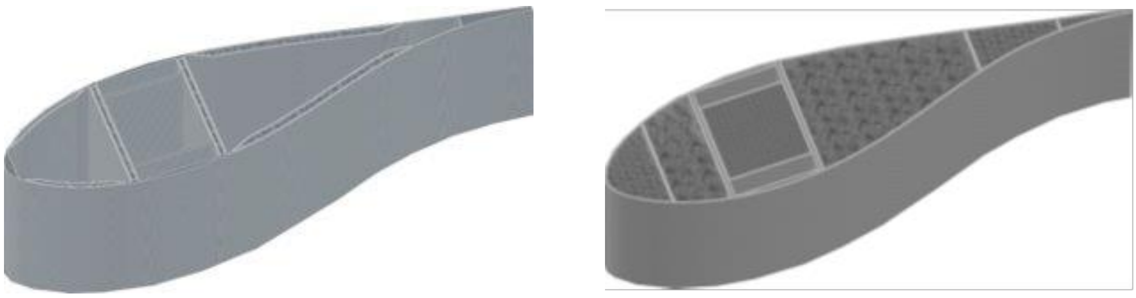


Figure 24 - Blade using AM with separate parts (a) and fully exploiting AM (b)

In order to verify that additive manufacture could positively impact the blade manufacturing process some cost modelling work has been undertaken. The NREL detailed cost model [58] has been implemented for the DTU 10MW reference blade [59] to provide a comparator. The cost which is predicted for this model is found to be in line with current cost expectations for a blade of this size (86m), and the cost breakdown per blade is shown in figure 25.

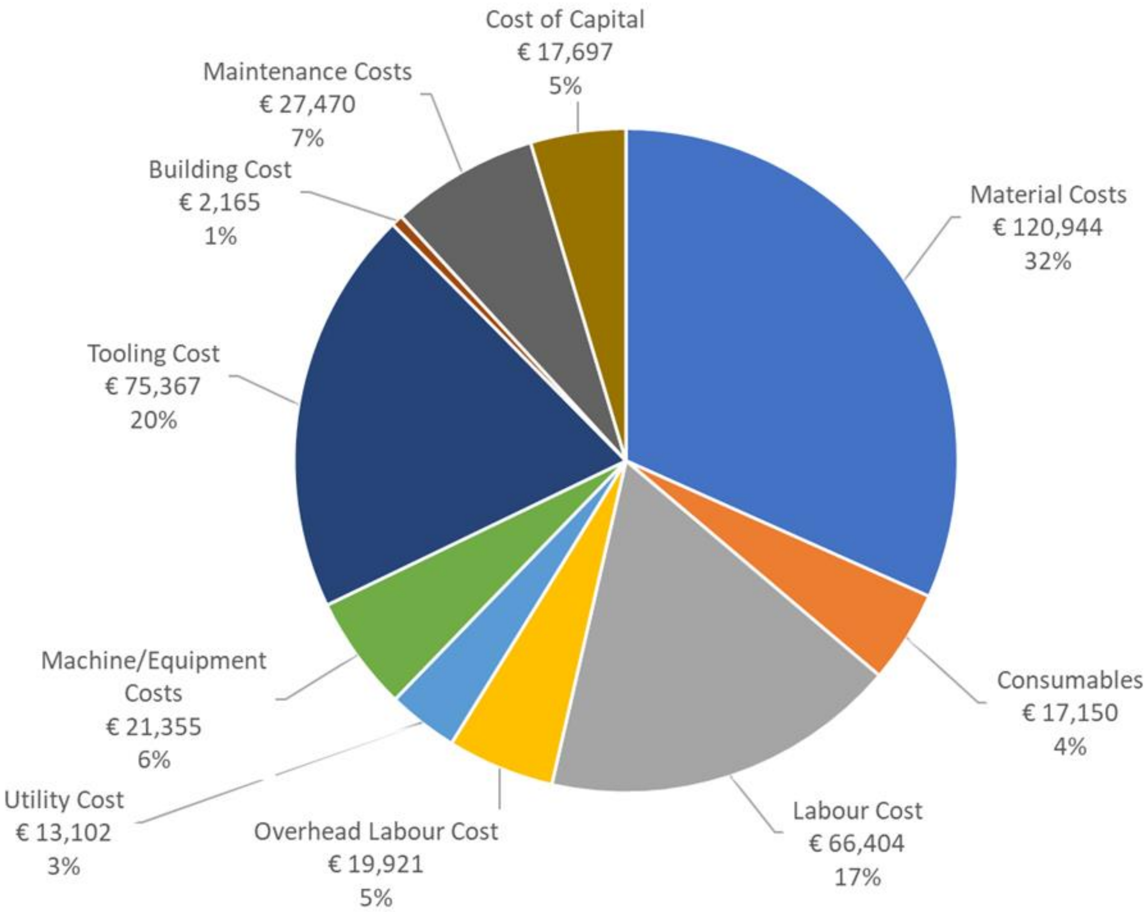
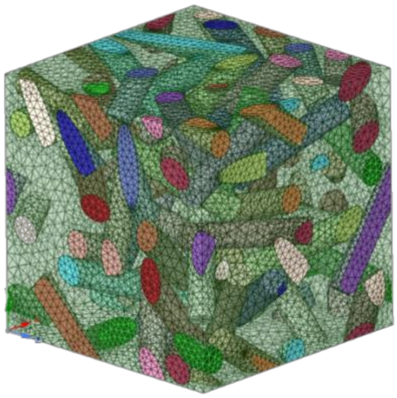


Figure 25 - Cost breakdown for conventional manufacture of the DTU 10MW reference blade (total €381k)

For the additive manufacture case, the second option described above has been chosen so that as many existing analysis methods can be used as possible. This option eliminates the amortised cost of the tool and the cost of consumables. A key input of the costing for the wind turbine blade case is the material properties which can be achieved with the printed material. These have been estimated using a representative volume element (RVE) generated in ANSYS as shown in figure 26(a), with the calculated material properties shown in figure 26(b).



Property	E-Glass	Carbon
E (MPa)	5708	6445
v	0.31	0.31
P (kg/m^3	1444	1345

Figure 26 - Representative volume element (a) and material properties for carbon and glass filler (b)

Once the material properties are known, it is then necessary to calculate the properties of the printed structure. These will vary depending on the cell size of the voxel and the wall thickness of the printed material, so in order to assess how these parameters effect the achieved properties another RVE model was created using a gyroid structure as the infill pattern. Many different infill patterns are possible, and they will have different structural properties. Gyroids are thought to have the advantage of reducing the accelerations of the print head and providing a quasi-isotropic behaviour (meaning they have the same properties in every direction).

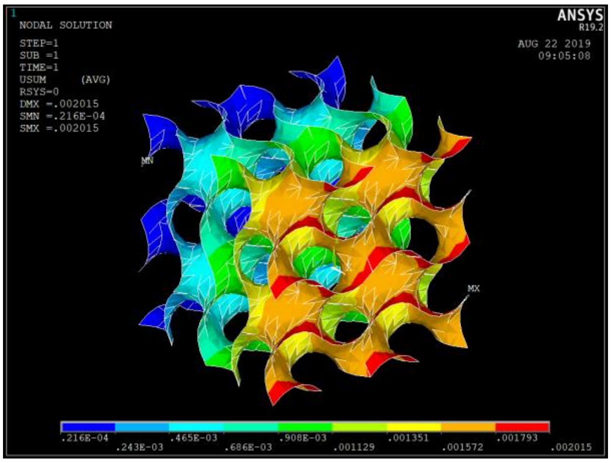


Figure 27 - Representative volume element of gyroid structure

The model can be tuned to vary the cell size and wall thickness, and output the Young's modulus, density and Poisson's ratio of the structure. Wall thicknesses of 1mm, 3mm and 5mm were studied, and cell sizes from 5cm up to 25cm were considered.

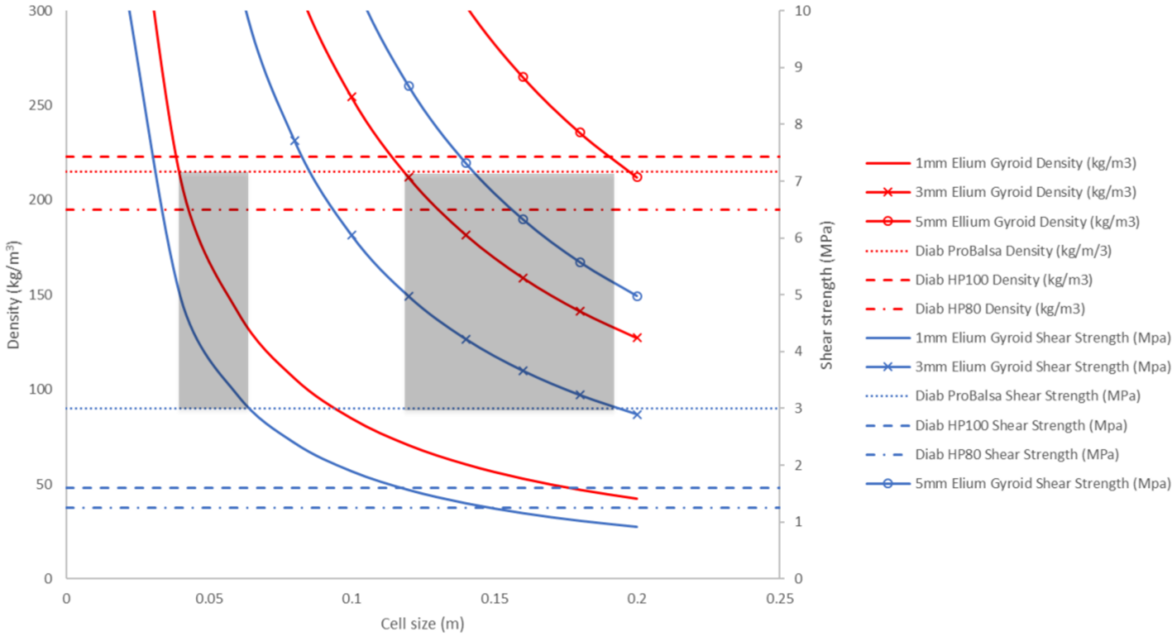
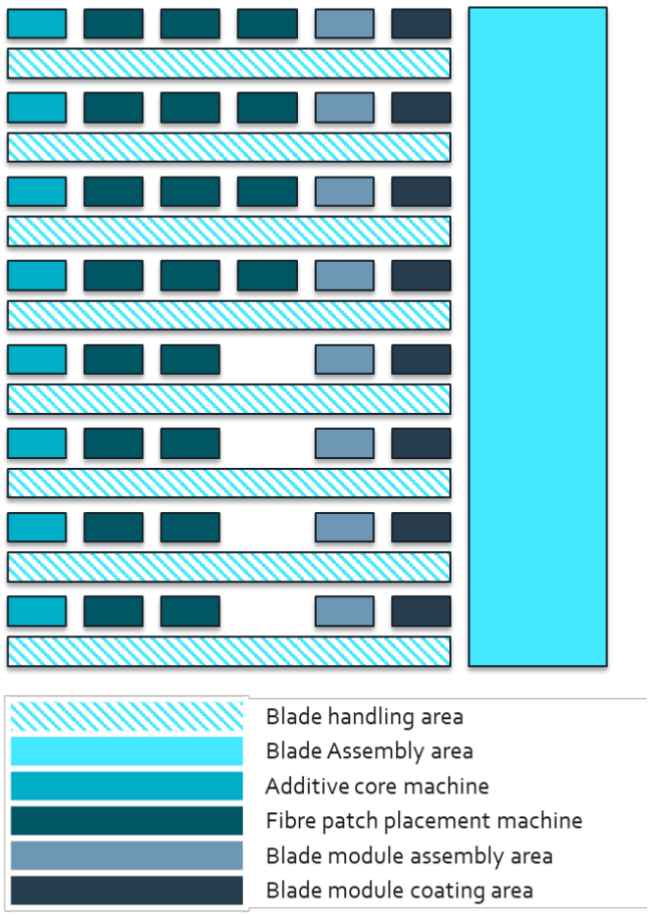


Figure 28 - Comparison of properties for AM gyroids of different wall thickness and cell size with conventional core materials

Figure 28 shows how the properties of the gyroid structure change with cell size – the horizontal lines show the properties of some conventional core materials. The grey areas are the regions in which the gyroid outperforms (has higher shear strength whilst having lower density) the best performing conventional core material (balsa) for a 1mm and 3mm wall thickness. Whilst these results are preliminary, they are very encouraging as they demonstrate a considerable margin over balsa, the best performing conventional material (the density could be reduced by 40% whilst maintaining the same shear strength). Some of this margin will be removed when we account for the fact that the material must have face skin, however.

Once the quantity of material has been calculated, it can be used in a cost model of the additive blade. Where possible, elements of the NREL detailed cost model have been used in the same way in the additive manufacturing cost model. Costs, energy consumption and deposition rate for large scale additive manufacturing have been taken from [32] and costs for AFP/ ATL have been estimated based on the size of the machine and the quoted deposition rates.



- *One blade every 21 hours*
- *The factory assumes 8 modules of roughly equal mass*
- *8 additive manufacture machines feed 20 AFP machines*
  - *Simplified factory assumes that all shell fibre is put down by AFP*
  - *Spar is formed from pultrusions*
- *ATL would have lower cost and higher deposition rate but would probably not be able to traverse all of the required geometry*
- *Cell-centric machines are utilised for 21 hours per day with 3 shifts*
- *Expensive AFP machines are utilised for nearly 100% of the time (unlike conventional mould-centric case)*

Figure 29 - AM blade manufacturing facility layout and cost model assumptions

The cost model was found to be insensitive to the cost of the machines and the number of machines (essentially a proxy for throughput, as more machines will be required if throughput is lower). For example, using a throughput rate of 20kg/hr instead of 40kg/hr for the AM machines would mean that the factory would need twice as many machines, which would increase the cost of the blade from €207k to €251k.

The cost model is currently focussed on the blade manufacture and lacks detail around the blade assembly and finishing steps. However, the margin in terms of material properties and cost that the blade manufactured with additive processes has over the conventional blade manufacturing process is extremely substantial, so even once more detail is added into both the engineering and cost models it is clear that additive manufacturing will be a very attractive option for blade manufacture. Figure 30 shows a cost breakdown for the additive manufactured blade with the baseline assumptions.

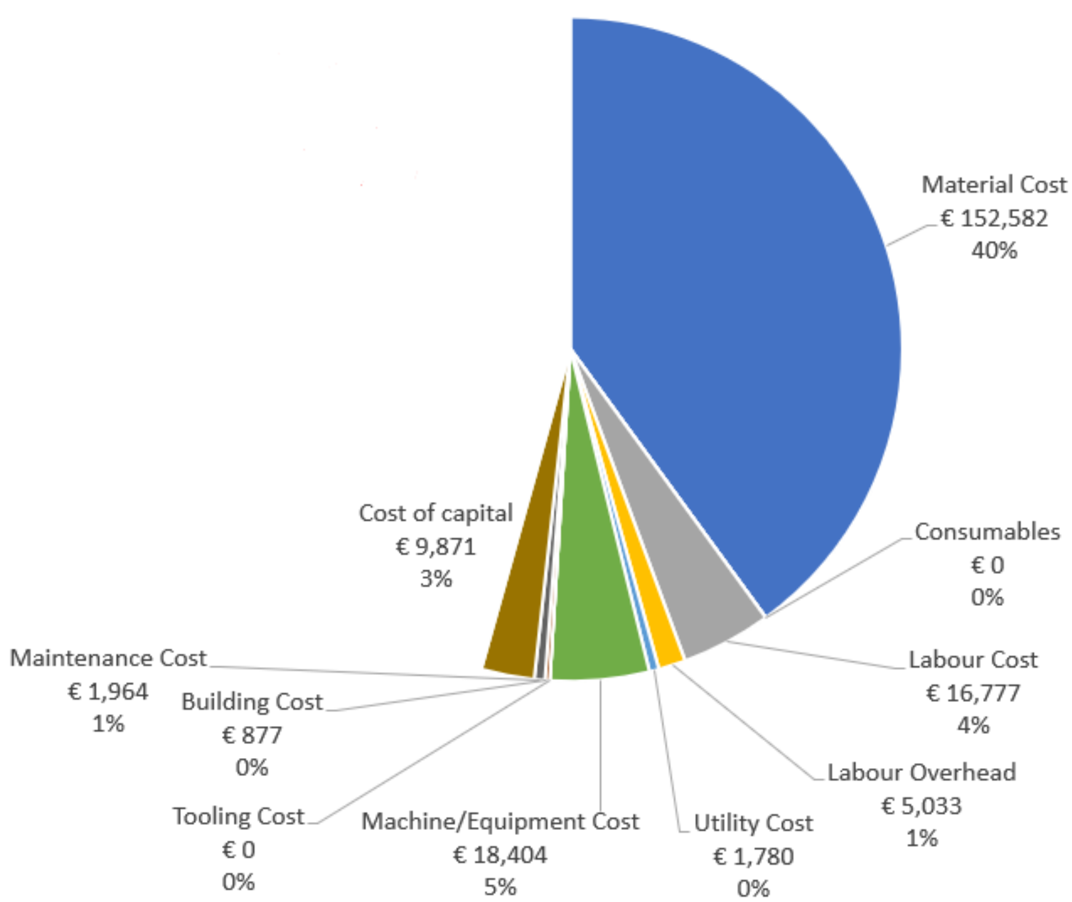


Figure 30 - Cost breakdown for additive manufactured blade

Initially, these manufacturing methods would be unlikely to be applied to the whole blade, with a more likely scenario involving adoption for individual blade parts, such as a modular tip which could be adapted to suit different sites and which has complex annual energy production (AEP) enhancing features such as a winglet.

Alternatively, the mould tool could be made using AM. The most detailed study to date [60] has revealed that mould production is a viable means of using AM in blade manufacture. Conventional blade manufacture involves creating a plug (the male mould from which the female mould is then made) manufactured by subtractive machining of foam and tooling resin, which may take around 12 weeks for a 50m blade. The plug is then inspected for dimensional accuracy, which may take around 3 weeks, before a fibreglass shell is laid over it and it is put into a steel truss structure to keep it rigid, which could take a further 6 weeks. Finally, a further 6 weeks of work is required to create electrical connections for the mould heating and prepare the mould for shipping. The mould will therefore take around 27 weeks to manufacture. The main plugs will be reliable for the creation of 6 to 10 moulds, and each mould would be expected to produce 1000 blades (albeit with many repairs during this lifetime).

In contrast, an additive manufactured mould could be created in only 20 weeks – 12 weeks to print the mould sections, 4 weeks to layup fibreglass over the mould shell and then machine it back to the correct geometry, before polishing the surface. The steel frame is still required, and it is connected at this stage, but resistive heating of the structure is not used in this case. Instead, air channels enabled by additive manufacture run around the back surface of the mould and it is heated using hot air. The plugs are not necessary in this case – only CAD geometry of the mould.

The NREL detailed cost model uses a cost of \$5000/m^2 for the cost of the blade moulds. The surface area of the mould for a 50m blade would be approximately 450m^2, meaning that the cost of the moulds would be \$2.25M [58] – this cost estimate is in the range of what is given in [61] (the cost of blade moulds is not routinely published). In contrast to this cost, it was estimated that mould tools created using AM could be created for as little as \$650k [60], with the potential for further reductions below \$300k if much larger machines were utilised.

6.3 Tidal Blades

In order to produce tidal turbine blades, the structure must be capable of withstanding the increased density, pressure, temperature, and the environment of an underwater location. In comparison to wind energy the greater density of water is expected to generate higher power outputs for blades with comparable dimensions to that of wind turbine blades with comparable fluid flow velocities [62]. One of the main current barriers of tidal energy is the reliability of materials used which can incrase the operational and maintenance costs, hence the drive towards cheaper materials which retain reliability. The design solution to tidal blades generally is that the blade is shorter wth a relatively higher thickness than for wind turbine blades, and has a much more aggressive transition from the root outwards towards the hydrodynamic parts of the blade. The more agressive this transition the more difficult it is to minimmise any stress concentrations. When the composite structure in a tidal blade needs to be fully operational whilst submerged in a highly corrosive saltwater environment it must be capable of much greater strength and durability than for wind turbine blades. Secondly the presence of marine life and biofouling of the blades can affect the drag of the structure significantly. Composite materials used in tidal blades have a tendency to absorb water which can impact the strength over time, thus these blades will need to be designed to accommodate this strength reduction. ANDRITZ HYDRO Hammerfest (figure 31 had designed built and tested a small HS300 (300kW) tidal blade but were looking to scale up in order to progress towards a 10MW tidal farm in the Sound of Islay in Scotland. They approached the resin manufacturer Gurit in order to develop composite blades for the new blade the HS1000 which would generate 1000W and act as a commercial demonstrator for tesing and certification. Tidal blades are expected to function for 25 years with minimal maintenance. These blades were produced with Glass and carbon fibre preimpregnated with resin and oven cured.

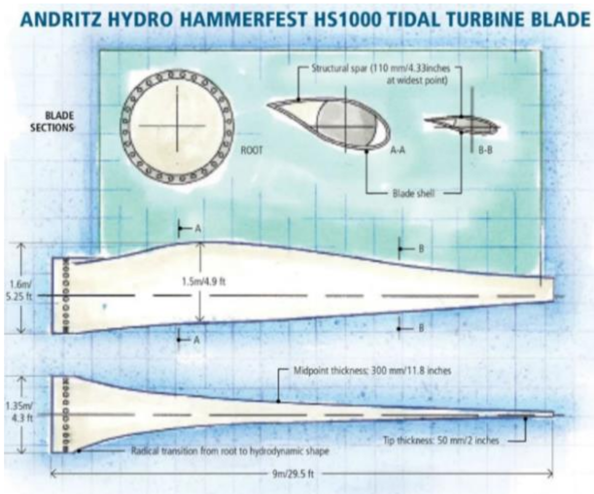


Figure 31. ANDRITZ HYDRO Hammerfest HS1000 Tidal Blade Schematic [62].

6.4 Marine Vessels

In the maritime industry typically the AM process is more focused around Wire Arc Additive Manufacturing (WAAM) which is a variation of Direct Energy Deposition and uses arc welding to 3D print metal parts. Instead of using the more common metal powder AM processes WAAM works by melting metal wire with an electric arc to heat the material. Like in the thermoplastic processes the process can be controlled by an articulated robot arm. The part is built on a substrate material and cut from it once the process has finished. Any metal which can be welded essentially can be used in WAAM. WAAM can produce larger scale parts in contrast to powder bed fusion which produces smaller parts with higher resolution. The welding wire also is cheaper than the powdered metals used for PBF since WAAM is based on welding which is already a well-established technology. The port of Rotterdam's AM facility known as RAMLAB, is using this process to speed up the production of spare parts for marine applications and produced a full-scale prototype in 2017 of the world's first class approved ship propeller. The 'WAAMpeller' was fabricated from a layers of nickel aluminium bronze alloy weighing 400 kg. The part took seven months to complete and demonstrated the potential of WAAM for further optimisation of production of future marine vessel components [63]. In 2018, RAMLAB in collaboration with Huisman Equipment commenced a project to additively manufacture a large offshore crane hook which weighed almost 1000 kg. Huisman furthermore went on to produce a 36 metric ton hook via WAAM, certified it, and then installed it for use in offshore lifting operations.

Figure 32. A ship propeller formed from WAAM.

7 Large-Scale AM Equipment Providers

7.1 Overview

This section aims to introduce a selection of current commercial vendors for direct processing of structures for using in secondary load bearing applications. Some of which are configured as multi-axis articulated robot arms and with others using a gantry robot system. The primary goals of most of these commercial vendors is to produce turnkey machines which enable the shortening of lead times, reduce manufacturing costs with fast prototyping of provisional tools of pre-production runs.

7.2 Review of Commercial and Developmental Systems

In order to produce parts with reliable strength often they need to have some form of fibre reinforcement material to afford the most strength in the printed bead direction. As the number of companies which are taking an interest in the commercialisation of continuous fibre 3D printing increases, there is a trend for increasing build volumes, numbers of applications, and widening the spectrum of available materials. Most commercial vendors of AM cells can also produce parts containing continuous fibre reinforcement which can be more relevant to primary load bearing structures and hence future endeavours however the main focus is on capability to produce parts which have secondary structural applications. There are also upcoming systems which are, at the time of writing at a conceptual stage such as the Stratasys Infinite build platform which aims to remove the limitation of build height, however this is beyond the scope of this section since the focus is on current commercially available AM systems.

7.2.1 CEAD

CEAD is a supplier of large-scale 3D printing equipment based in Delft in the Netherlands. The company produces a fully enclosed gantry based CFAM (Continuous Fibre Additive Manufacturing) cell which is also dedicated to discontinuous thermoplastic fibre reinforced pellet extrusion. The maximum build volume is 4 m x 2m x 1.5 m in the CFAM model with an average output of 15 kg/hr whilst using a wide variety of thermoplastics. CEAD also offers the AM Flexbot which is a robot arm-based system with additional optional capability to combine 3D printing with subtractive processes such as milling in one automated process making it suitable for tooling applications that require high surface finish tolerances. Both systems that the company offer can combine 3D printing with additional AFP (Automated Fibre Placement) tapes.

7.2.2 Electroimpact

Electroimpact is a provider of factory automation and tooling solutions which began operations near Boeing's Everett plant as a machine tooling supplier to Boeing. However, they have expanded significantly and have multiple sites globally acting as major suppliers to other aerospace companies such as Airbus and have become one of the largest integrators of aerospace assembly lines. The company have introduced a multifunctional unified Scaleable Composite Robotic Additive Manufacturing system (SCRAM). SCRAM uses a 6-axis articulated robot arm with an advanced FFF 3D printing head and an integrated AFP system (figure 33). This system also allows for manufacturing of aerospace grade integrated composite structures, using high performance thermoplastics. SCRAM cells are fitted with a nozzle optimised for deposition of thermoplastic materials reinforced with short fibres. This system has the capability to 3D print variable density cores with complex geometries with the option of producing skins made from continuous AFP tapes. The Electroimpact system also uses a proprietary laser heating system to aid the interlayer bond strength of the 3D printer part. A wide range of thermoplastics are applicable, typical material systems include the high strength thermoplastics such as PEEK, and also low temperature thermoplastic such as PA12 and ABS. Optional extras include subtractive machining end effectors and a high throughput pellet extrusion end effector for greater deposition rates and higher part throughput.

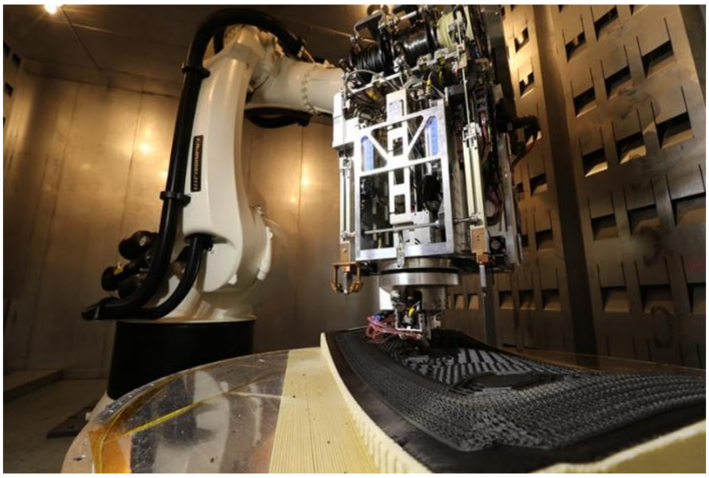


Figure 33. Electroimpact SCRAM.

7.2.3 Ingersoll

Ingersoll are a turnkey machine tool supplier based in Rockford Illinois and is responsible for the manufacture of moulds for the wings of the Boeing 787. However, Ingersoll's involvement in the wind industry revolves around metal cutting and in particular, finishing hubs for large wind turbine generators. In the field of polymer-based AM, they offer the Masterprint (figure 34), which is a gantry driven extrusion machine with a build volume of 6m (x) x 4m (y) x 2m (z). The 5-axis milling head enables subtractive processes post extrusion and can switch to this configuration automatically. Also, under the same gantry system, multiple modules are available to also include fibre/placement/tape laying inspectional and trimming. They also offer a 5-axis version of this gantry driven system under the name Masterprint 5X which allows for more geometrically complex curved features to be printed. Ingersoll also offer a 3-axis articulated multifunctional robot variant (Masterprint Robotic) with a 3 m reach and a maximum build volume of 3m (x) x 1.2m (y) x 1.5m (z). Their major applications are in aerospace, and in the naval industries. Their continuous fibre AM turnkey solution is a continuous filament applicator on a 6-axis articulated arm robot with a rotary table as a 7^{th} axis under the name of MasterPrint Continuous Filament. Each turnkey solution is supplied with CAD/CAM programming, simulation and diagnostic proprietary software.

Figure 34. Ingersoll Masterprint

7.2.4 Orbital Composites

Orbital Composites have a commercially available large-scale AM system which can use both thermoplastic (PEEK, PA, PEI, and PS) and thermoset materials reinforced with carbon and glass fibres. Several systems for larger parts are also under development. Their Orb1 (figure 35) will be the first member of a family of industrial systems. It is based on a 6-axis KUKA KR10 with a maximum reach of 1.1m which is frame mounted with a high throughput thermoplastic nozzle. The build surface consists of a 1m x 1m platform. The maximum temperature of the nozzle is 600°C, and the nozzle is capable of resolutions of 0.5 mm, 1 mm and 2 mm. Like many other turnkey solutions, they supply proprietary software for controlling the robot movements. The thermoplastic extrusion is with 1.75 and 2.85 mm filaments. Suitable materials include PLA, nylon, and CF reinforced nylon with the intention of introducing further suitable materials over time.

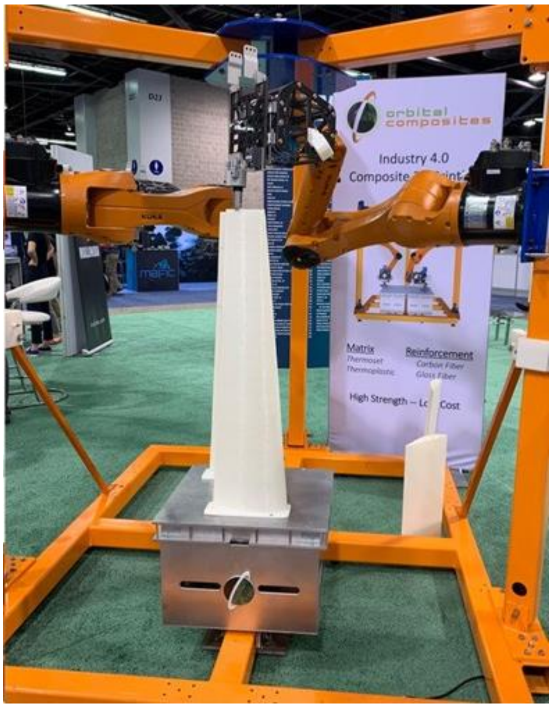


Figure 35. Orbital Composites ORB1

Table 5.Table of Vendors with Main Features

System Model	Max Build Volume	Deposition Rate (kg/hr)	Thermoplastic Material Type	Configuration
CEAD AM Flexbot	3m x 1.2m x 1.7m	12.5	Unreinforced/Short fibre/ Pellets	6-axis Robot Arm
CEAD CFAM	4 m x 2m x 1.5 m	15	Unreinforced/Short fibre Pellets/Continuous	Gantry Robot

Electroimpact SCRAM	1.2m x 1.2m x 1.8m	-	1, 3.5 and 6.5mm filaments, optional pellet extruder.	6-axis Robot Arm
Ingersoll Masterprint	6m x 4m x 2m	68	Pellets	Gantry Robot
Ingersoll Masterprint Robotic	3m x 1.2m x 1.5m	68	Pellet	3-axis Robot Arm
Orbital Composites ORB1	1m x 1m platform	-	1.75- and 2.85-mm filaments	6-axis Robot Arm

7.3 Future Work

Future efforts will be more concentrated around producing parts which have greater strength via the use of continuous fibre reinforcement. The end-goal is to migrate from secondary AM structures towards using AM to fabricate primary load bearing structures. There are current efforts in producing novel machines such as the Stratasys infinite build, which is designed to manufacture parts so that part height is less of a restriction.

There are several potential implications over conventional manufacturing of these novel methods in the context of the wind turbine blade factory setting using the machines discussed. The first scenario involves indirect manufacture around the production of cheaper AM moulds which would be easier to manufacture and repair than replace.

Direct manufacturing approaches include the 3D printing of short fibre reinforced thermoplastic secondary core structures with continuous fibre reinforcement formed over it, which is the type of capability offered by the various turnkey solutions. Several upper-level approaches to wind blade manufacture in the context of AM have been presented in 6.2.

The first approach is to simply replace traditional core materials with AM thermoplastic materials and keeping the traditional manufacturing mould approach. The presence of large volumes of porous core material plays an important role in large scale commercial resin infusion processing. For example, a critical vacuum level is required prior to introducing resin flow and the time required for complete evacuation of air in a complex stack of dry material can take longer than the infusion process. A porous core can act as a sink or a source for entrapped air. A likely project would involve the investigation of resin flow fronts with comparisons made with a standard balsa wood as used in conventional core blade manufacturing with moulds. The flow front within skin laminate and core is highly complex, with significant void formation in cores which have low permeability. AM cores could be tailored with an optimal permeability which keeps void formation between skin and core at a minimum reducing the propensity for delamination.

The second approach involves the elimination of the mould tooling altogether whereby the AM core acts as the adherend for the applied prepreg tows via an automated fibre deposition system. Projects which could emanate from this include skin-to-core bond performance of continuous skin reinforcement with various additively manufactured cores. Other project outlines could be on increasing the strength in the z-direction of 3D printed parts such as investigating the effects of through thickness reinforcements on AM materials (analogous to z-pinning in traditional carbon fibre reinforced laminates).

No matter the approach(es) taken, there must be continuous cost-tracking of alternate AM technologies via detailed cost modelling to enable the rapid assessment and uptake of solutions into the commercial realm, be it wind/tidal blades or marine vessels.

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