UNIVERSITY OF THESSALY

SCHOOL OF ENGINEERING

DEPARTMENT OF MECHANICAL ENGINEERING

Additive manufacturing in the industrial sector: Fused Filament Fabrication of parts by Reverse Engineering

by

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Submitted in partial fulfillment of the requirements for the degree of Diploma in Mechanical Engineering at the University of Thessaly

Volos, 2025

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Date Approved: 03-10-2025

Additive manufacturing in the industrial sector: Fused Filament Fabrication of parts by Reverse Engineering

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Abstract

Additive manufacturing, also known as 3D printing, has revolutionized various industries by offering innovative methods for designing and manufacturing complex structures.

This thesis delves into the fundamental principles of additive manufacturing, its historical evolution, and its current applications in the industrial settings. An examination is presented of how this technology has evolved over the years from being an idea into a great prototyping tool and an essential component of modern manufacturing. Also a brief analysis of every additive manufacturing model is provided, exploring their capabilities, differences but also challenges and limitations, and how, in some cases, they are able to displace traditional manufacturing processes, through rapid prototyping and ready to use parts with just the push of a button and mechanically advanced machines. Furthermore, a deep dive into the manufacturing method of Fused Filament Fabrication or Fused Deposition Modeling is presented, featuring a comprehensive analysis of the machining used for the manufacturing process and the process of designing and producing parts successfully. Finally two case studies are presented featuring the design and manufacture of two complex, hard to acquire and costly to produce, parts, by reverse engineering. These components are used for a rebuilding project for military generators, testing their capabilities by quality control and real world testing as a traditionally manufacture part.

The purpose of this thesis is a complete understanding of the additive manufacturing process from the initial design of a part to the finished product, proving, according to the observations, results, testing and analysis, the potential of this manufacturing process in its everyday use.

Key words: Additive Manufacturing, Fused Filament Fabrication, unconventional manufacturing.

List of Contents

List of figures

Table of Abbreviations

SLA	Stereolithography
SLS	Selective Laser Sintering
DMLS	Direct Metal Laser Sintering
MJF	Multi Jet Fusion
FFF	Fused Filament Fabrication
CAD	Computer Aided Design
PLA	Polylactic Acid
ABS	Acrylonitrile Butadiene Styrene
PETG	Polyethylene Terephthalate Glycol
TPU	Thermoplastic Polyurethane
PC	Polycarbonate
ECU	Engine Control Unit

1. Introduction

1.1. Introduction and Historical Development of Additive Manufacturing

Additive Manufacturing, commonly known as 3D printing, is a process of creating three-dimensional objects by successively layering material in accordance to a digital design. Unlike traditional subtractive manufacturing methods, such us milling, grinding etc, which involve cutting away from a solid block of material, usually oversized, Additive Manufacturing builds objects precisely layer by layer, resulting in the manufacturing of parts with minimal material waste and a great enhanced design flexibility. Over the past few decades, Additive Manufacturing is involved in applications in numerous industries, including the aerospace, healthcare, automotive, and defense as well as the consumer goods industry.

The significance of Additive Manufacturing in mechanical engineering lies in its ability to produce complex geometries that are often impossible or cost-prohibitive with conventional machining processes (Fig 1.1). It enables a rapid prototyping model that facilitates custom parts manufacturing, and enhances sustainability by reducing material waste. As the technology continues to advance, Additive Manufacturing is becoming an integral part of industrial production and mechanical design, reshaping how engineers approach their everyday manufacturing challenges.

Figure 1.1. Parts produced with Additive Manufacturing techniques

The concept of Additive Manufacturing dates back to the early 1980s when Charles Hull introduced Stereolithography or SLA, a process that used ultraviolet lasers to cure liquid photopolymers into solid structures, that will be analyzed more further down the paper. Hull's invention paved the way for further developments in Additive Manufacturing. In the late 1980s, Scott Crump invented Fused Filament Fabrication or for short FFF, a method that extrudes thermoplastic materials layer by layer to create objects, which is the method that will be examined in depth in this thesis, as it is the most popular method around the world and has the easiest access. Selective laser sintering or SLS and electron beam melting or EBM were subsequently developed, expanding the range of printable materials to include metals and ceramics. A brief analysis of every method will be given in order to understand it’s capabilities and possibilities as well as their challenges in the manufacturing world.

Throughout the 1990s and early 2000s, advancements in computing, materials science, and laser technology led to significant improvements in Additive Manufacturing's accuracy and speed. By the 2010s, the affordability of desktop Additive Manufacturing machines or usually called 3D printers allowed hobbyists, researchers, and startup companies to explore Additive Manufacturing for a wide range of applications. Today, the industry continues to evolve with the integration of artificial intelligence (AI), automation, and advanced materials, further pushing the boundaries of what is possible with Additive Manufacturing. [1, 2, 3]

1.2. The Science Behind Additive Manufacturing

Additive Manufacturing, from an idea to a part, follows some core principles, those principles do not really vary from a small desktop 3D printer for a hobbyist to a large and sophisticated station used in a manufacturing facility. The Additive Manufacturing process typically follows the following essential steps.

Starting with a model design. A digital 3D model is created using computer-aided design or CAD software, for short. The model is designed to the specifications and needs for each instance and can be designed to be pretty intricate, because there are not a lot of limitations for the manufacturing process, as normally would via other traditional manufacturing methods. It is important to note that when designing a part that it is going to be manufactured via Additive Manufacturing the limitations of the machine and materials have to be considered as it will be demonstrated later down the paper. With Additive Manufacturing it seems like a parts are manufactured out of "thin air", but in order to make a successful part means more that it seems at the beginning as it also does with traditional manufacturing.

Step two is slicing. The model is divided into thin layers using a slicing software. This software, generally, is easy to use and must be suitable for the machine in use and also calibrated for each machine. Through this software the machine's settings and set up are controlled in order to make a controlled manufacture as the user believes is better for each case. The software will divide the part into slices to thickness of the users choosing, thinner slices means a lot more detail in the final part but also means a lot more manufacturing time and vice versa. In general you can expect slices from 0.05mm to 0.5mm. At last the software produces a program written in G-code that can be used from the machine as any CNC operated machine.

Step three, manufacturing or printing. The object is built layer by layer using the machine, a 3D printer, according to the material and designs specifications. As it will be demonstrated later every different method has its advantages and disadvantages and no method can be sufficient in every task that is needed in a manufacturing facility or even a prototype lab. It is of great importance to understand the limits of each method and design every part according to standards set for a usable part with regard to the equipment available because with Additive Manufacturing there is as much freedom as limitations and someone needs to be careful with designs and aspirations in order to succeed.

The final step is post-processing. Here additional finishing processes, such as polishing, curing, or painting, that are applied as necessary for every design and process, take place. As it will be made clear later down the paper every method has its own post processing process due to the nature of the method. Post processing for every method will be discussed in detail.(Fig.1.2) [1, 12]

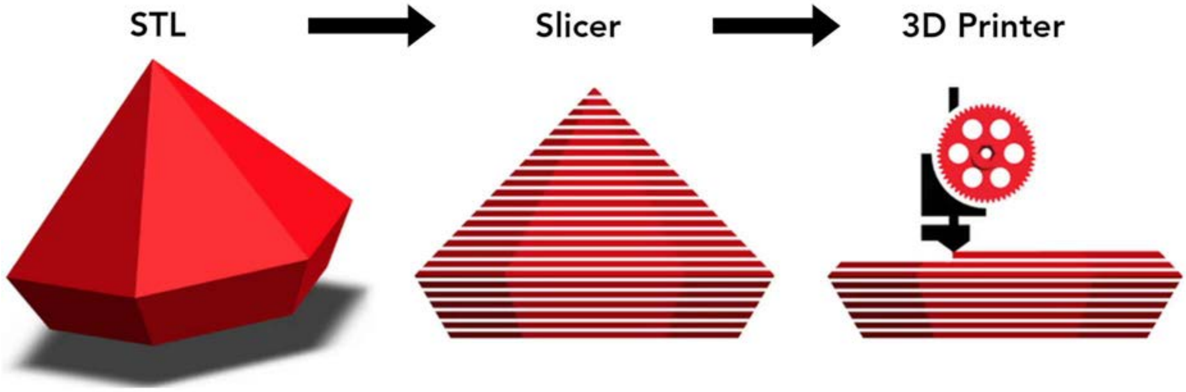


Figure 1.2. Flow diagram for the basic Additive Manufacturing methods

1.3. Industrial Applications of Additive Manufacturing

Additive Manufacturing throughout its evolvement has impacted many industries and has fount great use in factories and workspaces, as well as in an educational environment. Some key references will be stated below, in short, about some of the applications of Additive Manufacturing in some engineering industries. [3]

1.3.1. Aerospace industry

The aerospace sector was among the earliest adopters of Additive Manufacturing due to its demand for lightweight, complex, and high-performance components. Some of the applications include engine parts, for instance fuel nozzles for jet turbine engines where produced by GE Aviation using metal Additive Manufacturing techniques. Also structural brackets optimized with topology for weight reduction are always manufactured with Additive Manufacturing techniques as it is almost impossible with traditional manufacturing. Furthermore unmanned aerial vehicles, or UAV for short are manufactured as hole, easier than ever before and with no design prohibitions for the manufacturing process. Finally a lot of parts and satellite components are manufactured with Additive Manufacturing techniques nowadays and they are capable and optimized for weight reduction, structural integrity and faster manufacturing times.

1.3.2. Healthcare and Medical Devices

Additive Manufacturing is revolutionizing personalized medicine and biomedical engineering. There are plenty of applications that Additive Manufacturing allows faster iteration and production of individualized devices, improving clinical outcomes and patient comfort, some of them include patient-specific implants and prosthetics, such as titanium cranial plates and custom surgical guides for more accurate procedures. Also orthodontic devices and hearing aids can be customized for every patient through Additive Manufacturing enabling better care for people with different needs. Every part can be customized for each patient and can be manufactured immediately with no further costs for tooling and manufacturing times, because of the ease of the Additive Manufacturing process to produce parts with slightly different designs every time.[4]

1.3.3. Automotive Industry

In the automotive industry Additive Manufacturing is used in both prototyping and end-use parts, but some of the most common applications are functional prototypes of components for design validation, ensuring better final designs through more model testing. Also Additive Manufacturing is a part of the production lines with the production of custom jigs and fixtures designed for every application and also with fully build lightweight performance parts that are used in motorsports or in the restoration of obsolete parts for vintage and specialty vehicles, that is almost financially impossible with one of components.

1.3.4. Architecture and Construction

Additive Manufacturing is beginning to impact construction and architectural design through large-scale Additive Manufactured concrete structures, crated with the use of concrete Additive Manufacturing machines that can precisely lay concrete layers one on top of the other, creating rapid housing solutions with the use of these automated extrusion systems. These methods can reduce waste and enable complex geometries in sustainable construction, when this technology is able to be adopted in a large scale.

1.3.5. Education and Research

Additive manufacturing is a key tool in education and academic research. Starting from teaching the basic engineering principles such as CAD design, and material science through rapid prototyping, robotics, fluid dynamics and test devices on-demand for projects in schools and universities. Additive Manufacturing has revolutionized the potential of educational facilities, because students are able to create their designs in real life and learn from their mistakes through model validation. Also with the use of Additive Manufacturing students can visualize their ideas and work with the creation of models especially created for each case, with ease and without a significant economic impact to the schools and universities.[5]

2. Additive Manufacturing Methods

Several Additive Manufacturing techniques are commonly used by hobbyist and industrial applications, all of them have in common the core principles of Additive Manufacturing as were stated above, a 3D model in CAD software is crated and then gets sliced in a slicing software, but there are many differences in the manufacturing process and post process of its method. Although every method has many differences a brief review of the most popular methods that are used today are going to be given stating their core manufacturing principles and explaining the process from start to the finished product. Furthermore, we will discuss their material capabilities and their advantages and disadvantages as a method of manufacturing components.

2.1 Stereolithography

Stereolithography or **SLA** is a method that utilizes ultraviolet lasers in order to solidify liquid resins.

Stereolithography is one of the earliest and most precise 3D printing technologies, and its known for its ability to produce high-resolution parts with smooth surface finishes. Utilizing a photopolymerization process, SLA has become a cornerstone in industries requiring detailed prototypes and complex geometries.

Figure 2.1. Example of a desktop and an industrial SLA machine

SLA operates by curing a liquid photopolymer resin using a light source, typically a laser or projector, in order to build objects layer by layer. The process involves directing the light source to trace each layer's cross-section, solidifying the resin in the targeted areas. After one layer is cured, the build platform adjusts to allow the next layer to be formed, repeating this cycle until the object is complete. (Fig2.2) [8, 13]

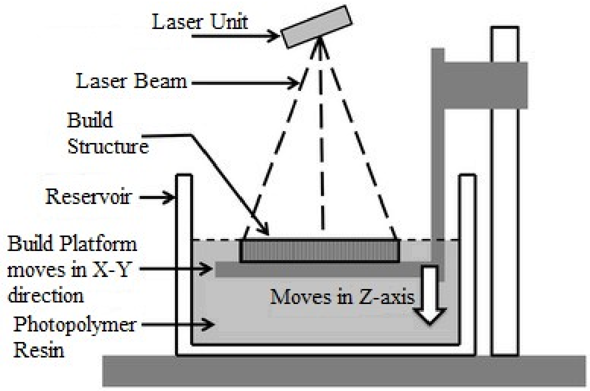


Figure 2.2. SLA manufacturing process in a machine

There are three main types of SLA Systems, starting with the Top-Down SLA, where in this configuration the build platform starts at the surface of the resin vat and moves downward as each layer is added. It is important to note that this method requires a significant amount of resin to keep the vat filled above the build platform at all times. Secondly the Bottom-Up SLA system, where the build platform begins just above a transparent window at the bottom of the resin vat. (Fig.2.3). After each layer is cured, the platform lifts to allow fresh resin to flow beneath the part. This approach uses less resin and is commonly used in desktop SLA machines. Lastly the Masked SLA system or mSLA, also known as LCD-based SLA, this method uses an LCD screen to act as a UV light source, that is used for curing entire layers simultaneously. (Fig.2.3). With mSLA someone can achieve faster print times and lower costs as there is no need for as much resin as the other methods, making it popular among hobbyists and professionals alike. SLA's precision and surface quality make it suitable for various applications across multiple industries such as creating detailed prototypes for design verification and testing, producing accurate anatomical models, surgical guides, and dental appliances, crafting intricate designs and patterns for the casting of jewelry and engineering components and parts that require tight tolerances and fine details.[15]

Figure 2.3. Examples of a bottom-up and a Masked SLA machine

As stated SLA utilizes photopolymer resins that solidify upon exposure to specific light wavelengths. These resins come in various formulations in order to meet different application needs (Fig.2.4). There are standard resins which are ideal for general-purpose parts and designs, that offer a balance between detail and strength. Also there are tough resins which are designed to withstand stress and strain and are suitable for functional prototypes and mechanical parts. Also, there are flexible resins that mimic rubber-like properties and allow for the creation of parts that require flexibility and elasticity. Also, castable resins, which burn out cleanly without residue, that are perfect for one off casting applications in jewelry and dentistry and finally there are high temperature resins that can withstand elevated temperatures and are used for applications like mold making and thermal testing. Selecting the appropriate resin depends on the desired mechanical properties, surface finish, and end-use requirements of the manufactured part, but through the years many resins, for almost every application, have being created and are currently used ensuring these methods continuous evolvement.[16]

Figure 2.4. Example of resins used in the SLA manufacturing process

The general process of creating a part is the same among the different types of Additive Manufacturing technologies, there has to be a CAD model of a part and a slicer program to create the G-code necessary for the motion system, but post-processing the manufactured part deferens. In SLA the user has to start from cleaning, the manufactured part has to be rinsed in a solvent, typically isopropyl alcohol, in order to remove uncured resin, then the removal of all the supports must take place, which are carefully detached in order to avoid damaging the part. And finally post-curing the part is necessary, by exposing it to additional UV light, in order to enhance its mechanical properties and stability. It is important to remember that proper post-processing is essential to achieve the desired strength, accuracy, and finish of a SLA-manufactured part.

There are a lot of advantages and disadvantages of SLA manufacturing with the main advantages being its high resolution and detail, SLA can produce parts with fine features and smooth surfaces (Fig.2.5), making it ideal for applications requiring intricate details as it is already stated. Due to the curing process, SLA parts exhibit uniform mechanical properties in all directions, which is beneficial especially for functional components. SLA manufactured parts are inherently water tight and that makes them suitable for fluidic devices and applications involving different liquids. Also a wide range of resins allows for great customization based on the specific application needs, from flexible to high-strength requirements, but at the same some SLA resins can be more brittle compared to other Additive Manufacturing materials, limiting their use in high-impact applications. Furthermore, SLA parts require thorough cleaning and curing after manufacturing, adding time and complexity to the workflow, in comparison to other Additive Manufacturing processes. Also resins can degrade over time when exposed to light and air, necessitating proper storage and handling. Desktop SLA machines often have smaller build volumes compared to other Additive Manufacturing technologies, restricting the size of components that can be produced via this method.[8, 14, 15]

Figure 2.5. Example of parts manufactured through the SLA method

2.2 Selective Laser Sintering

For the second method **Selective Laser Sintering** or **SLS** will be discussed, which uses lasers to fuse powdered materials into solid objects.

Selective Laser Sintering or commonly known as SLS is an Additive Manufacturing technology that uses a high-power laser to sinter small particles of polymer powder into a solid structure based on a 3D model. This process enables the creation of complex geometries without the need for support structures, making it ideal for rapid prototyping and finished functional parts.

Figure 2.6. Example of a desktop and an industrial SLS machine

SLS operates specifically by using a laser to selectively fuse powdered material layer by layer in order to manufacture a three-dimensional object. The process involves spreading a thin layer of powder across the build platform and then by the use of a powerful laser the powder is sintered in the desired pattern. After each layer is completed, the platform lowers, and a new layer of powder is applied. This cycle repeats until the entire object is formed (Fig. 2.7). One of the key advantages of SLS is that the unsintered powder supports the entire part during manufacturing, eliminating the need for additional support structures.[17]

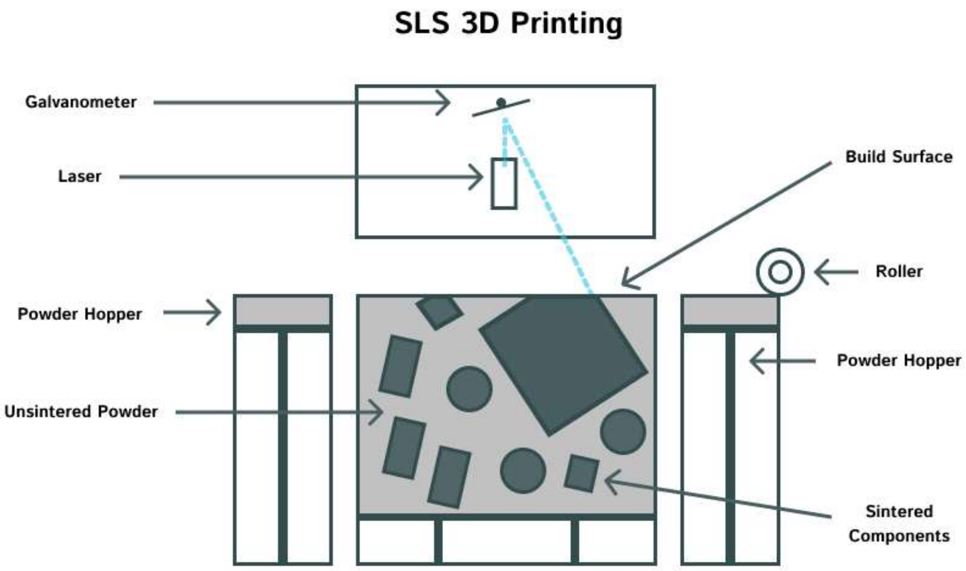


Figure 2.7. SLS manufacturing process in a machine

SLS primarily uses thermoplastic polymers in powder form (Fig 2.8). Common materials include Nylon or also known as PA 12, commonly used for its strength, flexibility, and durability, making it suitable for functional parts. Also glass-filled Nylon is used as a material that offers enhanced stiffness and thermal resistance as well as carbon-filled nylon that provides increased strength and rigidity. Lastly there is thermoplastic polyurethane or also known as TPU that is used for flexible and elastic parts. These materials are also chosen based on the specific requirements of each and every application that is needed, such as mechanical properties, thermal resistance, and flexibility.[19]

The SLS printing process involves the same several key steps again, with the addition of one more step before the post-processing, cooling after manufacturing, the build chamber is allowed to cool gradually in order to prevent warping or the distortion of the part due to the high temperatures that accumulate through the manufacturing process. For post-processing, the printed parts are removed from the powder bed, and excess powder is cleaned off. Additional finishing processes, such as polishing or dyeing, can be applied in order to achieve each design's specification.[17]

Figure 2.8. Example of the powder material used in the manufacturing process and manufactured parts in the machine after cooling

There are a lot of advantages with the SLS printing process, starting with the unsintered powder that acts as a support, allowing for complex geometries and overhangs to be achieved without the need of support structures making a complicated part a lot easier and faster to manufacture. Also SLS parts exhibit excellent mechanical properties, and are suitable both for functional testing and end-use applications because of their excellent material compatibility. Unused powder can often be recycled for future manufacturing, reducing the waste of material in each manufacturing cycle. As already stated SLS enables the production of intricate designs that would be challenging with traditional manufacturing methods, but the parts may have a rough surface texture and require post-processing for a smoother finish which adds for a longer and more challenging process. While SLS supports various materials, the range is narrower compared to other Additive Manufacturing technologies as it concentrates in mostly nylon based material which can be used in powder form. Also the high temperatures during the manufacturing process can lead to shrinkage and warping of a part if it's not properly managed, adding an extra layer of complexity to the process. Finally it is important to note that SLS machines are generally more expensive than other Additive Manufacturing machines, both for initial purchase and for use in manufacturing.[19]

Developing prototypes and end-use products with intricate designs is the basis of the SLS printing process but it's also widely used across various industries due to its versatility and ability to produce durable, complex and functional parts without the need for support structures or multiple machining processes, for example in the automotive industry creating prototypes, functional parts, and custom components is very common with SLS. In the aerospace industry you can expect manufacturing of lightweight and complex parts for aircrafts and spacecrafts and also in the medical industry the production of custom implants, prosthetics, and surgical tools is quite common.[17]

Figure 2.9. Example of parts manufactured through the SLS method

2.3 Direct Metal Laser Sintering

Direct Metal Laser Sintering or **DMLS**, is a method that enables the fabrication of metal parts using high-powered lasers.

Direct Metal Laser Sintering or DMLS is an advanced Additive Manufacturing technique that enables the production of complex metal parts directly from digital models. By utilizing a high-powered laser in order to fuse metal powders layer by layer, DMLS has revolutionized the manufacturing landscape, offering unparalleled design freedom and material efficiency. SLS and DMLS have a lot in common but at the same time they are two very different processes with different applications.

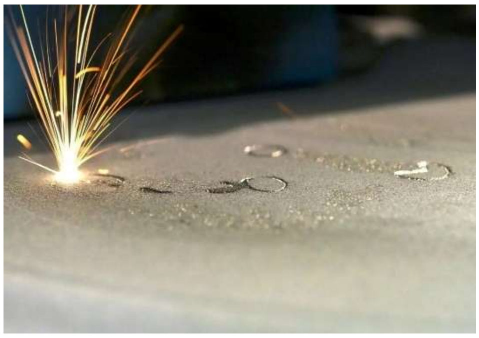


Figure 2.10. Example of a DMLS machine and process

DMLS operates on the principle of selectively fusing metal powder particles using a laser beam. The process again begins with a digital 3D model, which is sliced into thin layers. Each layer is then constructed by spreading a fine metal powder over the build platform (Fig2.14), and the laser selectively sinters the powder according to the design, then after each layer is completed, the platform lowers, and a new layer of powder is applied. This cycle continues until the entire part is formed. The unsintered powder acts as a support structure, eliminating the need of additional supports and allowing the creation of intricate geometries, as it is already discussed in SLS. (Fig. 2.12)[18]

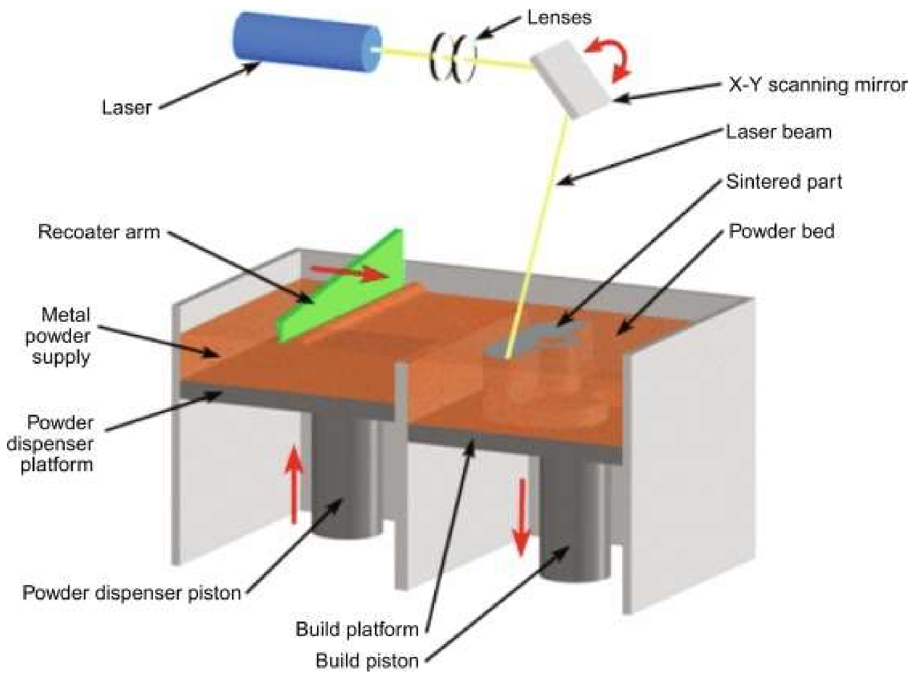


Figure 2.12. DMLS manufacturing process

The main difference of DMLS is its material capabilities, it supports a wide range of metallic materials opening a whole new world to the Additive Manufacture industry, some of these impressive materials include aluminum alloys which can create lightweight and corrosion-resistant parts, suitable for aerospace and automotive applications. Also it can manufacture parts from titanium alloys (Fig. 2.13) which is a material known for its high strength-to-weight ratio and biocompatibility, making it ideal for medical implants and aerospace components. Also stainless steel (Fig. 2.13) can be used and it offers excellent mechanical properties and corrosion resistance, and is used in various industrial applications. But the most impressive of them all are printable cobalt-chrome alloys with their high strength and wear resistance, they are commonly used in dental and orthopedic implants, as well as also nickel alloys, with the most common one being Inconel, which is a material that is known for its very high-temperature resistance, and is commonly used for turbine and engine components in the industrial sector, all of these materials pose difficulties in the traditional manufacturing processes but with DMLS they can be manufactured into parts with extreme capabilities. At the end of the day the choice of material depends on the specific requirements of the application, such as mechanical properties, thermal resistance, and biocompatibility but with this Additive Manufacturing process we have the choice of a full pallet of capable materials.[30]

Figure 2.13. Example of the powder material used in the manufacturing process (titanium and AISI 1060)

The DMLS process involves several key steps, as already discussed with the other methods above a 3D model is created using CAD software and converted into a format suitable for slicing. Then the model is sliced into thin layers, and the path for the laser is determined for each layer by the slicer software in code form suitable for the machine. After that is the manufacturing process, where the machine spreads a layer of metal powder, and the laser sinters the powder according to the G-code data. This process repeats for each layer forming the desired part. As SLS, after the manufacturing process cooling is required, so the build chamber is allowed to cool gradually in order to prevent warping or distortion of the manufactured part. Then for the post processing the manufactured parts are removed from the powder bed, and the excess powder is cleaned off. Latter additional finishing processes, such as heat treatment, machining, or polishing, can be applied in order to achieve the desired properties and surface finish, as now the part is made from metal.[30]

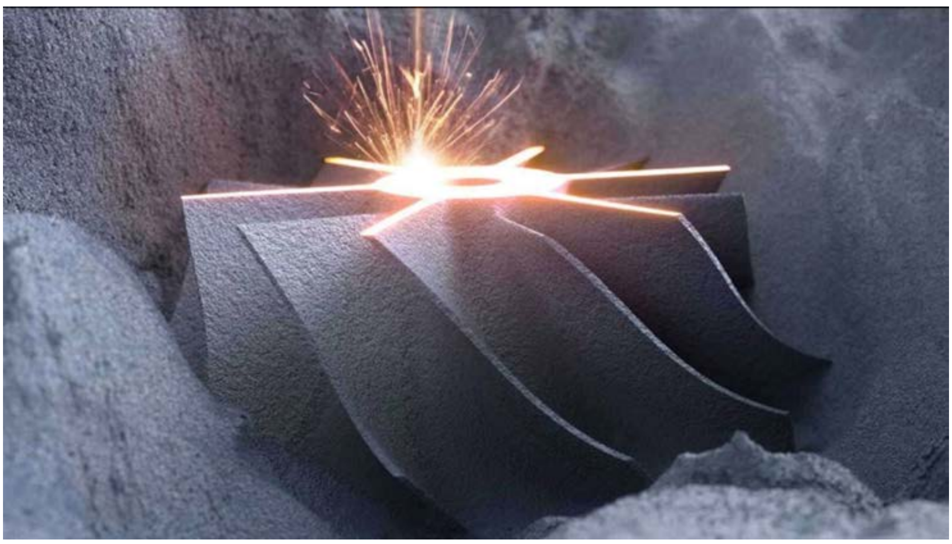


Figure 2.14. Manufacturing of a turbine wheel with DMLS

There are a lot of advantages with the DMLS method, for start it allows the creation of intricate designs that would be challenging or impossible with traditional manufacturing methods without material limitations, as its able to incorporate materials able to withstand any design characteristics. Also the unused powder can often be recycled for future prints, reducing waste and cost, in conjunction with most manufacturing processes that remove material in a way that is no longer usable. Finally this method produces fully functional metal parts with mechanical properties comparable to those made by conventional methods and also enables mass customization, that allows the production of tailored parts without additional tooling or manufacturing time. At the same time this method has its limitations, DMLS has problems with surface finish, as parts may have a rough surface texture and can require post-processing if a smoother finish is required. Also while DMLS supports various materials, this range is narrower in comparison with other Additive Manufacturing technologies as is with the SLS method. Finally, between the high temperatures during the manufacturing process that can lead to part shrinkage and warping, if the temperatures are not properly managed, and the equipment cost that is considerably more than any other Additive Manufacturing machining, DMLS is a challenging manufacturing process to get started.[29]

DMLS is widely used across various industries due to its versatility and ability to produce functional parts without the compromise of plastic materials, for instance in the Aerospace industry it is used for the creation of lightweight, complex components that can withstand high temperatures and stresses and are almost impossible to produce by traditional manufacturing processes. Also the production of custom implants and prosthetics tailored to individual patients via the DMLS method is more common in the medical industry today, and in the automotive industry is often used for the development of high performance parts with optimized geometries for weight reduction and strength in tailored applications, such as exhaust manifolds and intake systems for custom race cars, and the manufacturing of specialized tooling and molds with conformal cooling channels for improved performance.[29]

Figure 2.15. Example of parts manufactured through the DMLS method

2.4 Multi-Jet Fusion

Multi Jet Fusion or **MJF** is an advanced Additive Manufacturing technology developed by Hewlett-Packard or commonly known as HP that has revolutionized the production of functional prototypes and end-use parts.

Unlike traditional Additive Manufacturing methods, MJF offers high-speed production, excellent mechanical properties, and the ability to produce complex geometries without the use of any support structures.

Figure 2.16. Example of a desktop and an industrial MJF machine

MJF operates on the principle of selectively fusing powdered material using a combination of fusing and detailing agents, followed by the application of heat. The process begins with the deposition of a thin layer of powder material, typically nylon, on the build platform. An inkjet array then selectively applies fusing and detailing agents to the powder bed. The fusing agent promotes the absorption of infrared energy, while the detailing agent inhibits fusion and enhances the part's resolution. Subsequently, an infrared lamp passes over the bed, causing the areas with the fusing agent to solidify. This sequence repeats layer by layer until the final part is formed. (Fig. 2.17) [6]

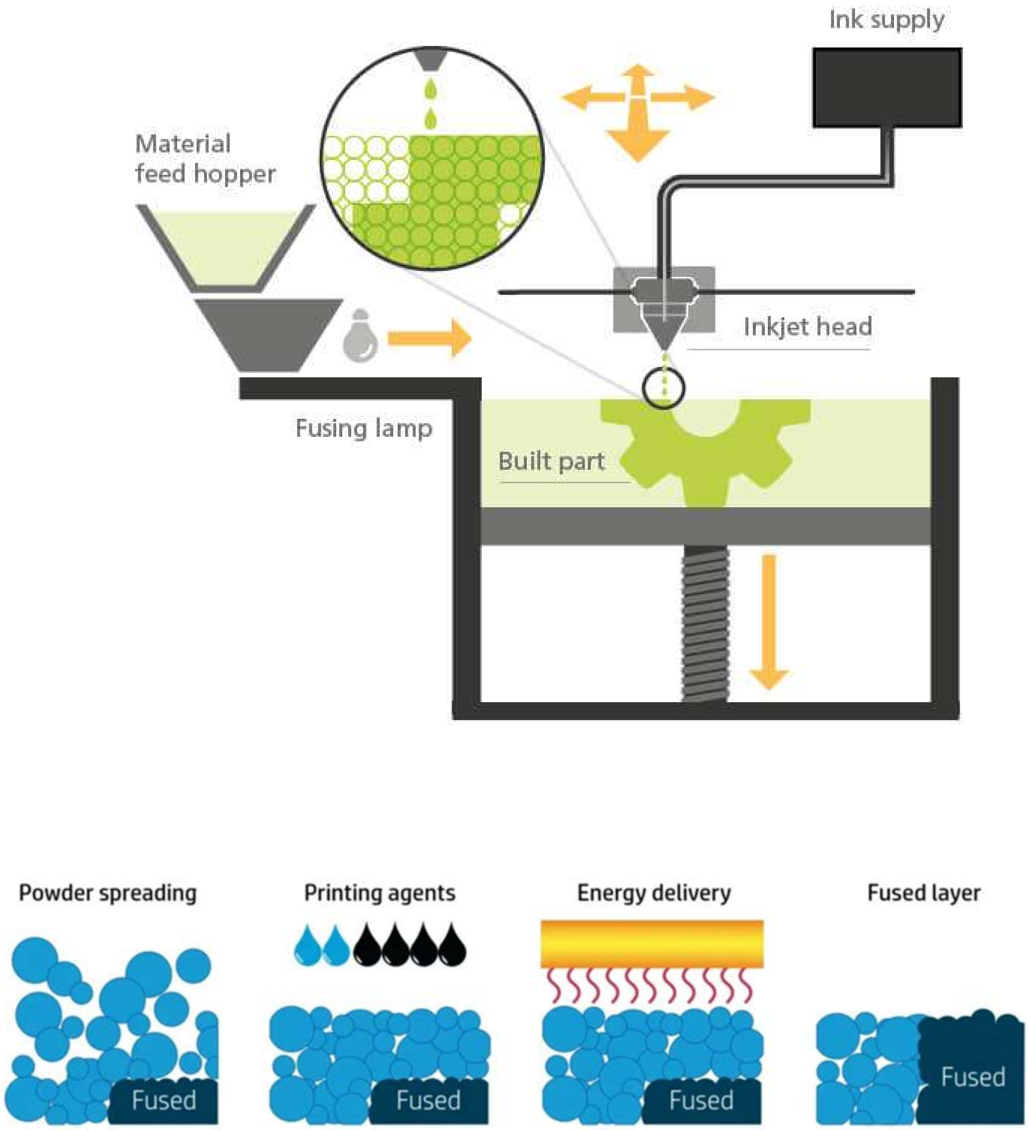


Figure 2.17. MJF manufacturing process and process diagram

MJF primarily utilizes thermoplastic polymers in powder form. Common materials include Nylon PA 1 known for its strength, stiffness, and chemical resistance, making it suitable for functional parts and Nylon PA 11 that offers higher ductility and impact resistance, ideal for parts requiring flexibility. Also Polypropylene or PP that provides excellent chemical resistance and low moisture absorption and Thermoplastic Polyurethane or TPU that is used for flexible and elastic parts. These materials are chosen based on the specific requirements of the application, such as mechanical properties, thermal resistance, and flexibility as all it is stated for every method.[7]

The MJF manufacturing process once again involves the main key steps as all Additive Manufacturing processes do, a 3D model is created using CAD software and converted into a format suitable for slicing, then the model is sliced into thin layers, and the path for the inkjet array is determined for each layer, and then the machine spreads a layer of powder, and the inkjet array applies fusing and detailing agents according to the G-code data. An infrared lamp then passes over the bed to solidify the fused areas. This process repeats for each layer in order to produce the desired part. Again after manufacturing, the build chamber is allowed to cool gradually in order to prevent part warping or distortion. And for the post-processing the manufactured parts are removed from the powder bed, and excess powder is cleaned off. Additional finishing processes, such as dyeing or polishing, can be applied in order to achieve the desired properties and surface finish per the design requirements.[6]

The MJF method is known for its high speed and efficiency it can produce parts faster than many other Additive Manufacturing technologies, making it suitable for both prototyping and production. Parts produced with MJF have smooth surfaces and fine details, reducing the need for post-processing and the unsintered powder acts as a support, allowing for complex geometries and overhangs to be produced without the need of further structures and inconsistencies. Also unused powder can often be recycled for future prints, reducing waste and cost and the most important advantage of this method is that it produces fully functional parts with mechanical properties comparable to those made by conventional methods. But while MJF supports various materials, the range is narrower compared to other 3D printing technologies as it supports Nylon derivatives and some thermoplastic materials only. Also this method requires good thermal management because of the high manufacturing temperatures and is also a quite expensive method to get started. Despite its disadvantages the ability to produce durable and complex parts without the need for support structures makes MJF a valuable tool in many sectors. MJF is widely used across various industries, in the automotive industry it is used for creating prototypes, functional parts, and custom components and in the aerospace industry the manufacturing lightweight and complex parts for aircrafts and spacecrafts is quite common and in the medical the production of custom implants, prosthetics, and surgical tools has started to develop.

Figure 2.18. Example of parts manufactured through the MJF method

2.5 Fused Filament Fabrication

2.5.1. Introduction

Fused Filament Fabrication or **FFF** is a method which employs a heated nozzle in order to extrude thermoplastic filaments.

As already stated above with this method we will go in great depth to a proper understanding of its fundamentals because later in the paper this method is used in order to produce some hard to acquire parts for a military diesel power generator unit.

Figure 2.19. Desktop and industrial FFF machine examples

Fused Filament Fabrication or FFF, also known as Fused Deposition Modeling or FDM, is one of the most widely used Additive Manufacturing technologies. Its accessibility, affordability, and versatility have made it the most popular choice for both hobbyists and professionals. At its core, FFF is a material extrusion process where a thermoplastic filament is heated to its melting point and deposited layer by layer in order to build a three-dimensional object. The process involves several key components in order to have a manufacturing machine capable of producing a part. First of all we need the material, the material comes in filament form, in different sizes, different machines require different thicknesses of material, and it's also measured by weight. The material is holed in a spool and it constantly feeds the printer while it unwinds. The material enters the printer from the extruder. The extruder is usually a device powered by a stepper motor that can precisely feed the machine with the exact necessary amount of material in order to manufacture a layer and also then retract the filament when it's necessary to proceed in a different spot or change layer. The filament is pushed from the extruder to the hot end assembly where it's heated to the necessary melting temperature of the material that is used, and then it gets pushed out of a nozzle with a precise point to the build platform. The build platform is an essential part of the machine. It has to be perfectly level and most of the time heated in order to have the best results possible. The machine has a motion system that is designed for the capability of precise movements in order to create a part. The motion system controls the movement of the extruder and the build platform along all axes XY and Z usually with the help of stepper motors and encoders. Every part of the machine will be analyzed in great detail further down the paper as well as the thermoplastic materials in filament form that are used today.[10]

FFF is by far the most successful and most used Additive Manufacturing method in the world because it offers several benefits, first of all its cost effectiveness. Generally speaking the machines for FFF manufacturing have a lower initial investment and a lot lower operational costs than other machines for different Additive Manufacturing models. FFF manufacturing machines are easier to set up and a lot simpler to use from everyone, they allow for a user friendly environment easy for a start in Additive Manufacturing immediately without the need off furthermore equipment or training. FFF has a huge material variety and they are cost effective in comparison with other models that we have discussed already, and there is almost no waste of material during manufacturing, despite the support structures needed in some cases. All of those advances allow the user to be able to develop prototypes or even finished parts faster than any other manufacturing process that we know today.[31]

Despite its advantages, FFF has certain limitations starting with the surface finish. When you are printing something layer by layer the layer lines are very visible and additional processing may be required in order to achieve a smooth finish, although it's not very necessary it all depends on the finished product’s design. A lot of materials tend to wrap or shrink after the manufacturing process because of the temperature difference during manufacturing, the material is going from its melting point to a rapid cooling from the machines fans. Every overhang on parts requires support and the supports add material usage and also manufacturing time and at the same time it’s something that needs to be removed in the post processing, increasing manufacturing time again and user error at the same time. Finally the most important disadvantage of FFF Additive Manufacturing are its mechanical properties along the manufactured Z axis, the Z axis is there a weaker link of a FFF manufactured part, because it exhibits far lower mechanical properties due to layer adhesion. The multiple layers that are adhered one to the other may have a failure if the manufacturing environment is not perfect, a very important aspect to acknowledge when designing and slicing a part.[31]

FFF is utilized across various industries creating functional prototypes in order to validate designs, produce jigs, fixtures and tooling components that can be useful during projects with other manufacturing processes. Also the manufacturing of low volume custom parts for final use is common due to the technological advancements for this method specifically as well as the continuous material development. Also FFF is utilized in education, because of its cost effectiveness it is a great teaching tool for design, engineering and manufacturing concepts among students all around the world.

Figure 2.20. Parts manufactured with the FFF method

2.5.2. Hardware Analysis of a FFF Machine

2.5.2.1. Hot End Assembly

Starting the analysis by the Hot End Assembly (Fig. 2.21), it serves as the thermal processing unit, as it was stated above, that melts polymer filament and extrudes it through a nozzle in order to create the multiple layers of an object. The performance of the hot end directly impacts the manufacturing resolution, mechanical strength, and the overall reliability of the Additive Manufacturing process. Understanding its components and operation is essential for optimizing manufacturing quality and expanding the machine’s capabilities.

Figure 2.21. Hot end assembly example

Starting with a typical Hot End Assembly, it consists of the following key components (Fig. 2.22), first of all is the heater block, it is a metal block, usually made from aluminum, that houses a resistive heating element and a thermistor that are used to distribute heat to the nozzle and melt zone. The Heating Element is a resistive cartridge heater that provides the thermal energy needed to raise the temperature of the filament to its melting point, typically ranging from 180°C to 300°C depending on the material used in each case, while the Thermistor or Thermocouple is a temperature sensor that monitors the Hot End Assembly’s temperature, allowing precise thermal control via feedback loops from the machine's firmware. Further, at the lowest point there is the nozzle, which is a precision-machined brass or hardened steel tip that shapes the molten filament into a fine stream. Nozzle diameters typically range from 0.2 mm to 1.0 mm and are chosen based on the circumstance, necessary quality and material specifications. Above the heater block is located a heat break and a heat sink for temperature control, the heat break is a narrow section that reduces thermal conduction upward from the heater block, while the heat sink, often finned and actively cooled, via fans, dissipates heat in order to prevent the filament from softening in the upper cold zone and cause clogs and material overflow.

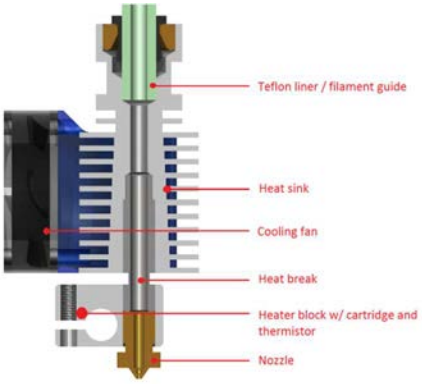


Figure 2.22. Hot End Assembly diagram analysis

It is of great importance to analyze the thermodynamics and heat transfer within the Hot End Assembly, as its efficiency depends heavily on thermal management. Heat must be rapidly conducted to the filament in the melt zone while being effectively isolated from the cold end. This is achieved through conduction, the heat transfer from the heating element to the nozzle and filament is maximized through materials with high thermal conductivity, such as copper or aluminum alloys. Convection via active cooling with fans prevents heat creep, because unwanted conduction of heat upwards can cause filament jams and multiple other problems to the Hot End Assembly. Lastly control systems with Proportional-Integral-Derivative or commonly known as PID control algorithms in order to regulate the heater, based on real-time temperature readings from the thermistor, ensuring stability within ±1°C, which is essential for the manufacturing quality without defects and other hardware problems.

Furthermore, there are different types of Hot End Assemblies, all for different material capabilities, because not all materials can be printed through the same nozzle for instance, brass nozzles are suitable for more standard filaments like PLA, ABS, and PETG due to good thermal conductivity but at the same time they lack wear resistance, where hardened steel or ruby-tipped nozzles are designed for abrasive filaments such as carbon fiber-reinforced and metal reinforced polymers, or other harsh, or mechanically advanced materials. Lastly there are all-metal Hot End Assemblies, required for high-temperature filaments like polycarbonate, Nylon, and PEEK, as they avoid the use of internal PTFE linings that can degrade at high manufacturing temperatures.

The Hot End Assembly affects several critical aspects of the FFF manufacturing quality (Fig. 2.23), such as extrusion consistency through stable temperature and a uniform melt flow that ensures the reduction of under-extrusion and stringing. Also through the Hot End Assembly improvements of the part’s resolution are possible, as smaller nozzles enable finer detail but at the same time require precise temperature and flow control as well as manufacturing time. Finally and most importantly, through the Hot End Assembly, the retraction performance of the machine is controlled, because with efficient thermal transitions material “oozing” is minimized during travel moves, which directly improves the manufacturing quality and minimizes the post-process needed for a completed manufactured part.[9]

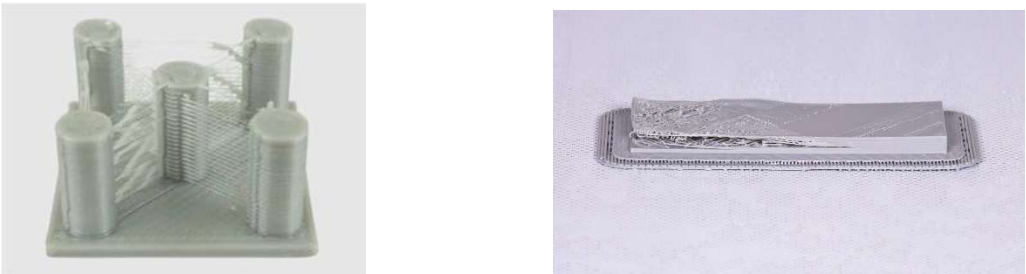


Figure 2.23. Manufacturing defects due to Hot End Assembly dysfunction and poor retraction

Through the success of FFF manufacturing new innovations for next generation Hot End Assemblies are flooding the market. The most impressive of these recent developments include high-flow Hot End Assemblies that enable larger melt zones and enhanced heat transfer, making them the perfect solution for faster manufacturing without the compromising of quality. The modular designs (Fig. 2.24) of the newer Hot End Assemblies allow quick swapping of nozzles or heater blocks entirely, for different materials and resolutions, faster and effortless than ever before and with the integration of advanced sensors for filament presence, clog detection, and flow rate feedback, they give the user enhanced automation and reliability for every part manufactured, in comparison with older styles, where someone had to disassemble most of the machine it shelf in order to change your Hot End Assembly’s capabilities and also monitor every print, real time, in order to be able to stop the manufacturing process if proper flow was not occurring.

Figure 2.24. Modular hot end assembly example by Ultimaker

2.5.2.2. Print Bed

Following the analysis there is the Print Bed (Fig. 2.25), it is the surface upon which all layers of an Additive Manufactured object are built. Its primary functions include securing the initial layer, ensuring thermal consistency, and supporting the weight of the manufactured part throughout fabrication without chatter or compliance, in order to maintain accuracy and the best results possible. Print Bed design influences ultimately, the success rate of the parts manufactured via the machine. Its interaction with the heated and mechanical subsystems requires a multidisciplinary understanding of materials science, thermodynamics, and mechanical engineering.

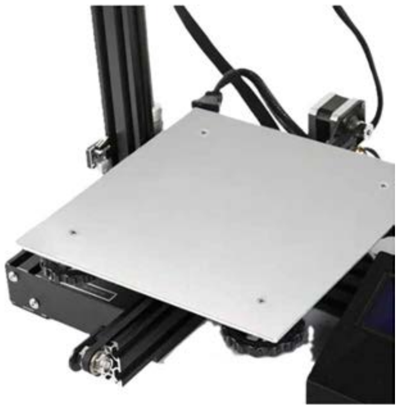


Figure 2.25. Print Bed example on a desktop FFF machine

The Print Bed of a FFF machine typically consists of several integrated components. Starting with the build surface (Fig. 2.26), which constructs the outermost layer, which directly contacts the manufactured part. It is commonly built by materials such as polyetherimide (PEI), glass, textured steel, or BuildTak sheets. It is often removable or replaceable as a piece of maintenance and also for ease of cleaning or even as a material requirement because surface adhesion is one of the most critical aspects of a successful FFF manufactured part. Surface treatments or coatings that can enhance adhesion are used based on material compatibility, for instance PEI sheets offer excellent adhesion for materials like PLA, PETG, and ABS without additional adhesives, where glass is preferred for smooth bottom layer finishes but often requires adhesives, like glue sticks or specialized liquid glues, for certain types of thermoplastics. Last but not least textured surfaces, like powder-coated steel can be used as the build surface, or even double sided sticky paper tape in order to improve grip for materials prone to warping, such as ABS or Nylon. In conclusion surface roughness and cleanliness are all variables that affect the bonding of the molten filament to the Print Bed, adding a very important variable for a manufacturing set up.[24]

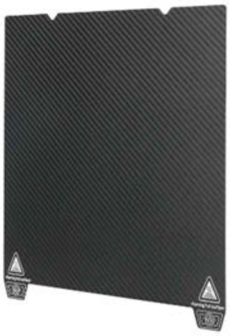


Figure 2.26. PEI build surface and glass build surface with the use of glue

Then there is the heating element, a resistive heater that is used to elevate and maintain the bed temperature in order to achieve optimal material adhesion. It is often PCB-based or a silicon pad and it can maintain temperatures over 100 degrees Celsius. As it is already stated, temperature regulation is crucial in order to reduce warping (Fig. 2.27) and at the same time improve the first-layer's adhesion on the Print Bed. The Print Bed's temperature must be carefully tuned to match the glass transition temperature of the material in use, for example the temperature zones for the most commonly used materials are, for PLA it is aimed for 50–60°C, for PETG it is aimed for 70–90°C , for ABS it is aimed for 90–110°C, and for Nylon and Polycarbonate it is aimed for 90–120°C. Some key thermal considerations are important to state because uneven heat distribution can cause parts to warp or lift from one side, and that leads to an unsuccessful manufacturing of a part. Starting with thermal inertia, thick glass or metal plates have higher thermal mass and can maintain more stable temperatures, but at the same time that is also a drawback because they are heating slower and can put a lot of strain on the machine, the perfect middle ground has to be used in order to have successful results with minimum machine fatigue, with conjunction of the control systems. Thermistors or thermocouples are embedded in the bed surface in order to provide the real-time temperature data needed for on the fly temperature management and are typically managed by a PID controller on the machines motherboard.

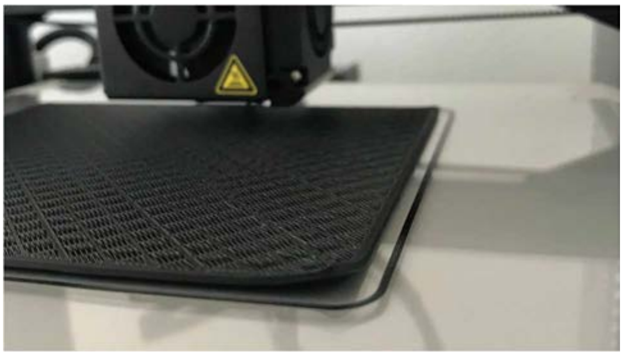


Figure 2.27. Material wrapping through insufficient thermal control

The next part of the Print Bed is the base plate. It is usually made of aluminum, in order to achieve even heat distribution across its surface while providing sufficient structural integrity. This plate provides the rigid foundation that is needed for the build surface and heater to perform at the best of their capabilities. Finally, an insulation layer is in place in order to reduce heat loss and improve the machine's thermal efficiency by isolating the heated bed from the printer's lower frame or external environment. As already described the machine's Print Bed needs to be mechanically and structurally designed to achieve perfect flatness and rigidity under thermal expansion and mechanical loads, in order to avoid shifting between the multiple layers of a part or even losses of the Print Bed's leveling during manufacturing. It is important to remember that precise adjustment of the initial nozzle height relative to the Print Bed is crucial for consistent first layers and layers in general (Fig. 2.28), that is achieved by a comprehensive mounting system typically on spring loaded or kinematically constrained platforms allowing for manual or automated leveling before each and every manufacturing attempt, whereas advanced machines usually use automated print bed leveling or even mesh Print Bed leveling that is performed right after the successful heat up of the machine, in order to ensure a perfect calibration of the Z axis.[26]

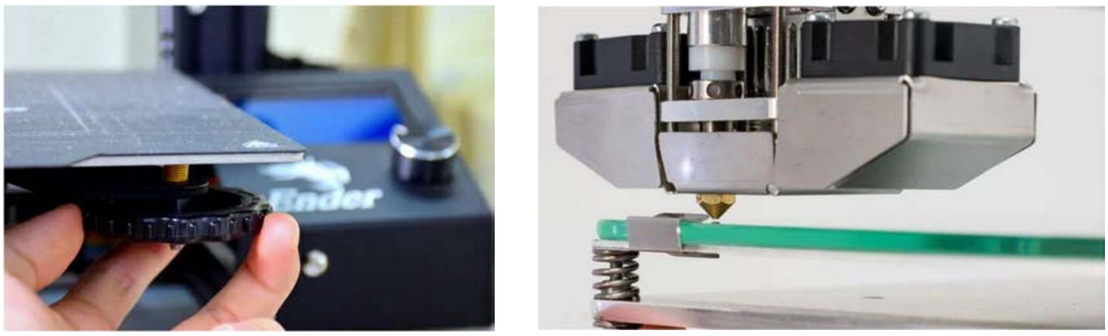


Figure 2.28. Examples of manual and automated Print Bed leveling

As the Hot End Assembly, the Print Bed for the FFF machines continues to develop and here are again some of the most impressive developments, starting with the magnetic flexible build plates. With the use of these build plates the user can remove the manufactured part from the build plate with ease and at the same time swap between surface types quickly without the need of tooling and other accessories. Also most machines at the market today come with inductive and capacitive bed sensors that enable them to automatically compensate for bed tilt or surface variation ensuring less failed manufacturing attempts and create a machine that is more user friendly and easy to use.

2.5.2.3. Extruder

Furthermore, there is the extruder, it is a fundamental component in FFF Additive Manufacturing, as it facilitates the movement and control of the thermoplastic filament. It ensures a consistent flow of material into the Hot End Assembly, where the filament is melted and extruded through a nozzle as already analyzed. Extruders must operate with high precision and reliability, as inconsistencies can cause under-extrusion, clogging, or layer delamination. Extruders are generally classified into two main types, the Direct Drive Extruder or DDE (Fig. 2.30), where the extruder is mounted directly above the Hot End Assembly(Fig. 2.29). With this design a shorter filament path is present that improves the retraction control and the responsiveness of the material insertion. It makes it an ideal solution for flexible filaments like TPU and TPE, but at the same time it adds weight to the print head, which can reduce the machine's maximum manufacturing speed. Then there is the Bowden Extruder (Fig. 2.30), where the extruder is mounted remotely, and the filament is pushed through a PTFE tube into the Hot End Assembly(Fig. 2.29). With this design the moving mass on the print head is considerably reduced, allowing faster manufacturing speeds and better accuracy on larger machines, but it can also struggle with flexible or soft filaments due to the friction created in the tube. Extruder design impacts the machine's ability to process different filaments, for instance high-torque extruders are required for high-friction or composite filaments such as carbon-fiber-reinforced PLA, where dual-gear systems are essential when there is a need to improve grip and extrusion accuracy, which is especially beneficial for flexible or inconsistent-diameter filaments. Also for manufacturing at higher temperatures (≥250°C) all-metal-path extruders are essential in order to avoid PTFE degradation and filament jams.[36]

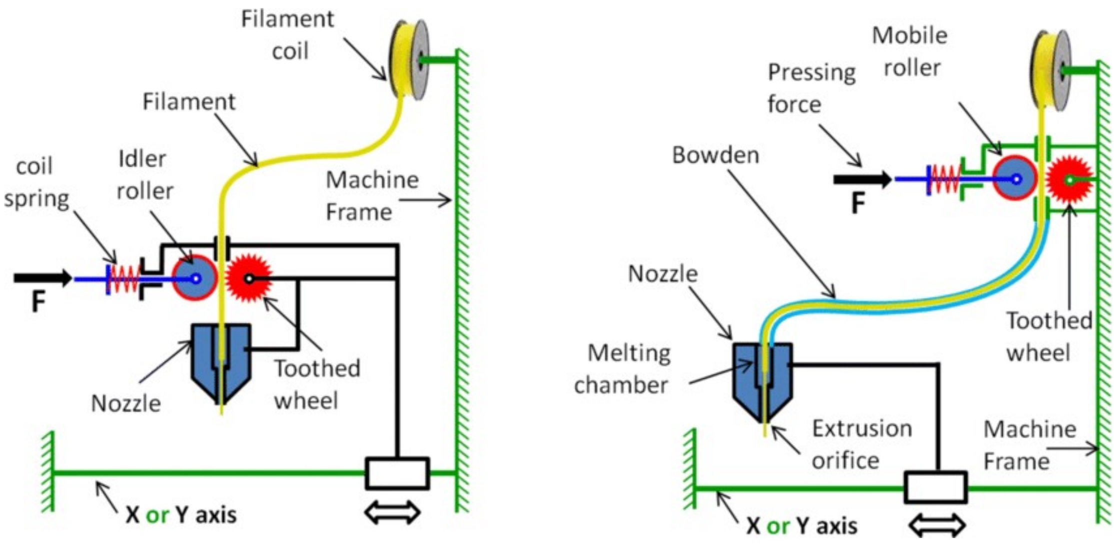


Figure 2.29. Direct and Bowden extruder design examples

The extruder system in a FFF machine consists of several key components, starting with the drive gear, a toothed gear that grips and pushes the filament forward and backwards for feeding and retraction, which helps reduce stringing and oozing during non-print moves. It is driven by a stepper motor, a precise motor that controls filament movement based on the digital instructions provided by the G-code program, and provides the necessary mechanical force for extrusion, while maintaining precision in every move. Then there is the idler, a spring-loaded bearing or wheel that presses the filament against the drive gear, ensuring consistent grip with the drive gear. And finally there is the guide, just a simple channel that ensures that the filament travels smoothly into the Hot End Assembly, it is often lined with polytetrafluoroethylene (PTFE) in non-all-metal systems. Extrusion is precisely coordinated with the printer’s motion system via the firmware using e-step calibration, that ensures the correct amount of filament is extruded per motor rotation and linear advance or pressure advance algorithms compensate for pressure buildup and lag in the extruder system, also filament sensors can detect filament runout or clogging and pause the manufacturing process in order to prevent failure. The PID-controlled heaters in the Hot End Assembly complement the extruder by ensuring that the filament is at the proper temperature when it reaches the nozzle.

Although the extruder itself does not melt the filament, its performance significantly affects thermal control in the overall system. The extruder must generate enough pressure to overcome resistance in the melt zone without skipping steps through the torque of the stepper motor, and overcame the thermal expansion without sudden extrusion or retraction that can introduce pressure fluctuations and affect flow consistency. Also it is important to remember that prolonged operation at high torque may heat the motor, influencing nearby components and potentially softening filament before it enters the melt zone which can cause problems during the manufacturing process, so proper extruder design is important for each application in order to achieve successful FFF manufacturing.[35]

Again as stated above there are advancements in extruder technology with the most impressive ones include, integrated extruder and hot end assemblies that combine precision feeding with modular Hot End Assemblies, creating a manufacturing process as easy as possible and a machine set up change quicker and strait forward and with the addition of multiple sensors such as torque feedback, clog detection, and flow sensors they ensure the best possible real-time manufacturing quality assurance.

Figure 2.30. Bowden and direct extruder examples

2.5.2.4. Motion System

Finally the most important section of a FFF machine is the motion system, it is responsible for accurately positioning the Hot End Assembly and Print Bed in the three-dimensional space during the manufacturing process. With the use of mechanical structures, motors, belts, rails, and control electronics a motion system that ensures the quality, speed, and precision of every manufactured part is created. Generally speaking in FFF, the controlled deposition of molten thermoplastic is achieved through coordinated movement of the Hot End Assembly or Print Head and the Print Bed or Build Platform. The motion system translates digital models into physical motion with the use of G-code written by the slicing software. Accurate motion is critical for ensuring proper layer alignment, surface quality, and dimensional accuracy. Poorly calibrated or unstable motion systems lead to failures such as layer shifting, ghosting, and inaccurate geometries.

Starting with the stepper motors, most FFF machines use stepper motors for motion control due to their high torque and positional accuracy. They move in discrete steps, typically 1.8° per step, which correlates to about 200 steps per revolution, and are controlled by pulse signals from a microcontroller linked to the machine’s motherboard. The stepper motors move every axis usually by two different methods, with belts and pulleys or lead screws and ball screws. Belt and pulley systems are commonly used in the X and Y axes due to their low backlash and smooth movement, utilizing GT2 timing belts and toothed pulleys in order to ensure synchronized motion with minimal slippage, with the use of linear rails and bearings in order to guide the motion along rods, rails, or V-slot aluminum extrusions, while high-end systems may use MGN linear rails for reduced play and increased stiffness. Lead screws and ball screws are typically used primarily for Z-axis motion due to their high precision and resistance to back-driving. Lead screws convert rotational motion into linear displacement, providing stability for vertical positioning and ensuring perfect layer height with every motion (Fig. 2.31).[38]

Figure 2.31. Example of a stepper motor, a belt and pulley system and a lead screw motion system

With the success of FFF manufacturing there are a lot of different motion architectures implementing different machines with several mechanical configurations. The most commonly used system is the cartesian system (Fig. 2.32). It is the most common architecture found on FFF machines, where each axis moves independently in straight lines (X, Y, Z). It has the advantages of being a really simple design capable of implementing accurate movement while being easy to calibrate. But at the same time it carries speed limitations due to the enormous moving mass, especially if the bed moves in the Y direction. Furthermore there are the core-XY and H-Bot systems (Fig. 2.33), where in these systems, two motors simultaneously control movement in the X and Y axes using a belt-driven parallelogram mechanism, which reduces the moving mass and allows for higher manufacturing speed and better inertia distribution. It requires a complex belt tensioning procedure and added synchronization procedures in order to achieve successful results. Following there is the delta system (Fig. 2.34), a system that utilizes three vertical towers with arms that control a central effector platform, housing the Hot End Assembly. The movement is calculated via inverse kinematics and the three arms move correspondingly to perform the necessary motions. Via this motion system we can achieve higher speeds and smoother motions while it's ideal for the manufacturing of tall parts, but it requires a really complex calibration while having less intuitive kinematics. Last but not least, there are SCARA and polar systems that are usually used in custom or tailored applications where non-linear arm configurations are needed. They provide a wide, arc-based movement and are dependent on the application.

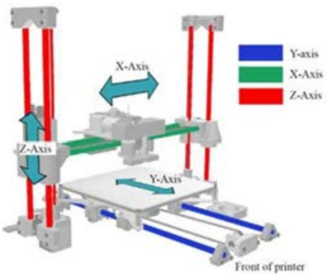


Figure 2.32. Cartesian

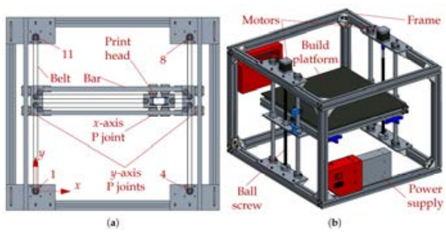


Figure 2.33. core XY / H- bot

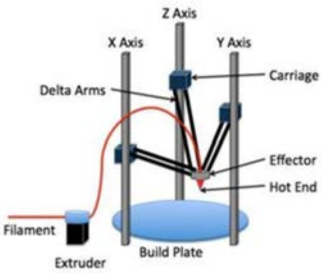


Figure 2.34. Delta motion system

All the above motion systems are controlled by motion planning algorithms embedded in the corresponding firmware used by the machine, with the most common ones being Marlin or Klipper. We will go through the basic principles that control the motion precision, starting with the G-code interpretation which, as already stated, converts 3D models into movement commands. It is written by the corresponding slicer software tailored for every machine. Via this G-code and the machines embedded jerk and acceleration control, which smooths out sudden changes in direction to prevent ringing or ghosting, and linear advance for the synchronization of the extrusion pressure with the corresponding movements, it ensures better corner sharpness and flow consistency. Also via microstepping, the process of dividing motor steps into finer increments in order to improve the resolution, the best possible result is achieved for all of manufactured parts. Also with further PID tuning, stepper current limits, and motion smoothing filters every user can further enhance every machine’s motion control precision. Terms such as accuracy, repeatability, and manufacturing quality are commonly referred to as the “path to success” with FFF manufacturing, because positional accuracy determines how closely the print head reaches its intended location, which is crucial for determining our part’s dimensions. Repeatability measures the consistency of reaching a location over multiple passes in order to ensure that every layer is exactly on top of the other without inconsistent layers of walls. All of the above make the manufacturing quality. To ensure the best possible manufacturing quality, not only a perfect G-code for the machine is needed, but the machine itself must be in the best shape possible. Mechanical problems will lower the manufacturing quality of the machine, problems such as backlash, or commonly known mechanical slack in the belts or lead screws used, introduces errors during direction changes and compromises the targeted dimensions. Also severe vibrations and resonance, commonly induced at high manufacturing speeds, can create surface artifacts and layer misalignment making a part unusable. High-precision machines mitigate these effects with rigid frames, tensioned belts, and dynamic acceleration algorithms, in order to reduce speed before the target spot, ensuring better results and lower manufacturing times. [39]

Again with the motion system there are constant innovations in order to provide better results with modern FFF machines, increasingly incorporated features such as sensorless homing which detects axis limits using stepper motor feedback and without the use of limiting switches, that can cause a malfunction. Also input shaping in order to reduce mechanical resonance by compensating for known vibration frequencies. And closed-loop stepper control, provides real-time position feedback using encoders, improving the accuracy under load make some of the best innovations today.

2.5.3. Manufacturing Parameters

Now that the machine is fully analyzed, the manufacturing procedure can be examined. The process begins again with a digital 3D model, which is sliced into layers using slicing software, an example and further analysis will be stated below in order for better understanding of the slicer software. The machine then follows the toolpath generated by the slicer to deposit material layer by layer, gradually building the final object. There are several parameters that influence the quality and properties linked to the software and our G-code program.

Through the slicing software control over all the manufacturing settings can be achieved. The most important ones that serve the biggest role in the manufacturing process of a part, will be stated. First of all the layer height of the part has to be determined. The layer height is one of the most important parameters to choose in the slicing software. It determines the thickness of each layer that will create the part, thinner layers improve surface quality increasing manufacturing times and mechanical properties, and thicker layer heights translate to poor surface quality but a lot faster prints.

Secondly the manufacturing speed, or print speed has to be considered. The manufacturing speed is the maximum speed that the axis will move in the machine, also tuning of the speed while manufacturing is possible as well as a speed table for every aspect of the manufacturing process, for instance if lower speed of the first layer for better layer adhesion to the bed is needed the user can slow it down and then going to speed up the manufacturing process in the next layers for faster manufacturing time. Generally speaking higher speeds reduce manufacturing time but may compromise layer adhesion and surface quality and also can cause failed manufacturing attempts. Choosing the manufacturing speed is not only a correlation of a design but also a correlation of the machine itself because every machine has a top speed that it can produce parts without problems but also someone has to be mindful of the results he expects from each process.

Another very important parameter is the extrusion temperature. The temperature is set in correlation with the material we are going to be using for the manufacturing procedure. Different materials require different extrusion temperatures because of their different melting temperatures, it must be optimized for the specific material in order to ensure proper melting and flow. For choosing the extrusion temperature, always check the material data from the material manufacturing company, always in every material someone can find the appropriate extrusion temperature range as well as the appropriate bed temperature range in which the best results possible can be achieved. Through that range, with testing, the temperatures for the specific equipment can be fine-tuned ensuring the best possible result with both the extruder as well as the Print Bed of the machine.

Last but not least one of the most important aspects of an Additive Manufactured part is the infill. A Additive Manufactured part with the FFF method is a shell constructed by layers of material with a patterned core, that core is called infill. The infill’s density and pattern can be tuned in order to produce a part that is best for the application needed. The infill density is measured by a percentage of the core that is made out of the material and the other percentage is empty, as far as the pattern goes there are many patterns that someone can choose from, depending on the slicer software, and the choice is made depending on the situation. A higher infill density increases the weight of the part, influences the strength and also uses more material. More infinite density doesn't mean more strength because layer separations can always occur, it's very important to choose an infill density and an infill pattern that can distribute the load of a part better than a solid piece of plastic.

2.5.4. Materials for FFF Additive Manufacturing

Fused Filament Fabrication Additive Manufacturing relies on thermoplastic filaments (Fig. 2.35) to build objects layer by layer. These materials vary in strength, flexibility, heat resistance, and cost, making them suitable for different applications. There are also specialty materials such as Carbon Fiber Reinforced Filaments with increased stiffness and strength for specialty or industrial applications, Wood-Filled Filaments, Metal-Filled Filaments and Conductive Filaments, but for this thesis only the most common materials are further analyzed. As stated above the filament is material in filament form, it varies in thickness, length and weight with the most common being 1,85mm in thickness and 1kg in weight, although some manufacturers produce filaments on their specification as it will be determined later by the case studies. There are a lot of materials available for FFF manufacturing starting with:[11]

Figure 2.35.. Examples of material in filament form for a FFF machine

2.5.4.1. PLA

Polylactic Acid or commonly known as PLA has become one of the most popular materials in FFF manufacturing, especially among hobbyists, educators, and the prototype industry. Derived from lactic acid through fermentation of biomass, PLA is classified as a biopolymer with thermoplastic behavior. Unlike petroleum-based polymers such as ABS or PETG, PLA offers a significantly lower environmental footprint, which also aligns with the growing interest in green technologies and circular manufacturing.

PLA is an aliphatic polyester and is synthesized through the polymerization of lactic acid monomers obtained from carbohydrate-rich crops. There are two approaches for the formation of PLA, the direct polycondensation of Lactic Acid and the ring opening Polymerization or ROP of Lactide, which is usually preferred, because it creates higher molecular weights. PLA can exist in various stereochemical forms, mainly PLLA or poly-L-lactide, PDLA or poly-D-lactide, and a racemic mixture called PDLLA. The crystallinity and thermal properties depend on the ratio and arrangement of these isomers.

PLA is well-suited for FFF Manufacturing due to its relatively low thermal requirements, which are shown below. Unlike semi-crystalline polymers such as Nylon, PLA exhibits more amorphous behavior in standard manufacturing conditions, which simplifies deposition and cooling.

- Glass Transition Temperature: 60–65 °C
- Melting Point: 150–180 °C
- Manufacturing Temperature: 190–220 °C
- Heat Deflection Temperature: 55 °C

PLA also offers some mechanical strength, although it is brittle compared to other thermoplastics, the mechanical properties of PLA are shown below. These properties are suitable for static and generally non-load-bearing parts. However, PLA's brittleness and low impact resistance limit its use in dynamic applications or structural components.

- Tensile Strength: 50–70 MPa
- Young's Modulus: 3.5 GPa
- Elongation at Break: 4–10%

As it already stated PLA is the most commonly used material in FFF manufacturing, and it is for plenty of reasons, some of them are its minimal shrinkage upon cooling, which allows for manufacturing without a heated bed, although a bed temperature between 50–60 °C greatly improves adhesion. Also PLA is odor-free during manufacturing unlike other materials like ABS, which can emit unpleasant fumes. Furthermore PLA parts are known for their sharp details and smooth surfaces, which reduces the post-processing needs for the user and with its ability to facilitate a strong inter-layer bonding under the right temperature and speed settings PLA's ease of use makes it the ideal material for beginners and rapid prototyping. PLA is used in various applications such as educational tools, models, architectural prototypes, decorative items and consumer products, biodegradable packaging and disposable items, however, due to its poor thermal and mechanical endurance, PLA is not preferred for high-stress engineered parts or outdoor parts.[20, 21]

2.5.4.2. ABS

Acrylonitrile Butadiene Styrene, or ABS, is a versatile engineering thermoplastic commonly found in consumer goods, automotive parts, and electronic housings. In FFF Manufacturing, ABS is favored for its robustness and ability to withstand mechanical stress and elevated temperatures. However, its processing requires careful thermal control and often the use of enclosed manufacturing environments, which limits its use to more advanced printers and experienced users.

ABS is a terpolymer composed of three monomers, Acrylonitrile, that provides chemical resistance and rigidity, Butadiene, that contributes to toughness and impact resistance and Styrene, for enhanced processability and surface quality. These monomers are combined in varying ratios through emulsion or mass polymerization, resulting in an amorphous polymer that balances stiffness and ductility, making it ideal for structural applications.

ABS has a higher processing temperature compared to PLA and no distinct melting temperature which makes it suitable for components exposed to mechanical loads or moderate heat, but for manufacturing it requires a controlled thermal environment in order to prevent warping or other manufacturing errors. The thermal properties of ABS are,

- Glass Transition Temperature: 105 °C
- No distinct melting point due to its amorphous nature
- Manufacturing temperature: 220–250 °C
- Bed manufacturing temperature: 90–110 °C
- Heat deflection temperature : 95–100 °C

ABS is known for its good balance of strength and toughness, characteristics that allow ABS parts to endure mechanical stresses and dynamic loads, making it suitable for functional prototypes and end-use parts compared to PLA, as you can see from its mechanical properties below.

- Tensile Strength: 40–50 MPa
- Young's Modulus: 2.0 GPa
- Elongation at Break: 10–50%
- Impact Resistance: High, especially compared to PLA

ABS is a challenging material in FFF manufacturing, despite its mechanical properties as ABS cools, it shrinks significantly, causing layers to peel or crack, stating a part unusable. For that reason heated beds and enclosed chambers are used in order to maintain ambient temperature and minimize thermal gradients. Also ABS emits volatile organic compounds, or VOCs, including styrene gas, which can be unpleasant or even harmful if not properly ventilated. Furthermore ABS tends to detach from the print bed if not properly adhered, usually methods such as ABS slurry, PEI sheets, or specialized adhesives are needed in order to ensure proper adhesion during manufacturing. Despite its challenges ABS is widely used in the Automotive and aerospace industry for many components, tooling, jigs, and fixtures. ABS's impact resistance and post-processing capabilities further expand its industrial use and ability for FFF manufactured parts in industrial applications, and in order to enhance its properties or ease of processing, ABS is often blended or compounded with additives in order to create modified grades that broaden ABS's utility. Some of them modified grades are briefly stated below,[22]

- ABS+ , an improved formulation for better printability and reduced warping.
- Glass-Fiber-Reinforced ABS, an improved formulation for increased strength and stiffness.
- Carbon-Fiber ABS , an improved formulation for rigidity with reduced weight.
- ESD-safe ABS, an improved formulation for use in electronics manufacturing.
- Flame-retardant ABS, an improved formulation for applications with fire safety standards.

2.5.4.3. PETG

Polyethylene Terephthalate Glycol or PETG is a thermoplastic polyester widely used in packaging, medical devices, and nowadays Additive Manufacturing. Derived from Polyethylene Terephthalate or PET through the addition of glycol modifiers, PETG avoids the brittleness and crystallinity, which is typically associated with PET, while offering a middle ground between the rigidity of ABS and the printability of PLA. It's an ideal material for Additive Manufacturing users that seek performance and ease of use in one material.

PETG is synthesized by adding cyclohexanedimethanol or ethylene glycol to the PET polymer backbone. This modification disrupts crystallinity, causing the material to be in an amorphous state, which reduces brittleness, improves impact resistance and enhances thermal processing, making it suitable for extrusion. -PETG's molecular backbone is composed of repeating ester groups, which provide chemical resistance and strong interchain interactions with stable thermal behavior suitable for FFF manufacturing. The thermal properties of PETG are,

- Glass Transition Temperature: 80 °C
- No sharp melting point due to its amorphous structure
- Manufacturing temperature: 220–250 °C
- Bed manufacturing temperature: 70–90 °C
- Heat deflection temperature: 70–80 °C

PETG exhibits a favorable combination of strength, flexibility, and toughness, which makes it suitable for mechanical parts and functional prototypes that require durability. PETG's mechanical properties are shown below,

- Tensile Strength: 45–55 MPa
- Young's Modulus: 2 GPa
- Elongation at Break: 20–35%
- Impact Resistance: Higher than PLA and similar to ABS

PETG is widely regarded as a user-friendly engineering material, suffering from minimal warping, unlike ABS, PETG has low shrinkage and can be manufactured well on open-frame printers, while emitting fewer VOCs than ABS during printing. Also it offers great adhesion to PEI sheets and glass especially with the use of glue stick and absorbs less moisture than PLA, although it still benefits from dry storage for optimal results. However, PETG can string more than PLA and needs specially tuned retraction settings in order to reduce oozing. PETG is suitable for a wide range of applications, such as mechanical parts and fixtures, medical and food-safe containers, because of the certified variants of PETG, and functional prototypes. Also PETG is naturally transparent stating it ideal for clear or translucent visual models, and its resistance to UV, impact, and chemicals makes it well-suited for outdoor or industrial used components.[22, 25]

2.5.4.4. TPU

Thermoplastic Polyurethane or TPU is a flexible material used in Additive Manufacturing for the production of items like gaskets, seals, wearable components, and shock-absorbing parts. TPU is an accessible and printable elastomer for FFF manufacturing systems and offers a unique combination of flexibility, chemical resistance, and layer adhesion that makes it valuable for both prototyping and functional production.

TPU is a block copolymer made by reacting Diisocyanates, like MDI or TDI, Polyols as polyether or polyester polyols, and Chain extenders, short-chain diols. This structure results in alternating hard segments, called urethane groups and soft segments, called polyol chains, creating a phase-separated morphology that combines flexibility and strength.

There are two main types of TPU, polyether-based TPU, which is hydrolysis resistant and flexible at low temperatures, and polyester-based TPU, which is abrasion resistant and oil resistant. TPU behaves as a thermoplastic elastomer with relatively low softening and melting temperatures, but TPU doesn't have a sharp melting point due to its semi-crystalline nature and microphase separation and remains flexible over a wide temperature range. Again the thermal properties of TPU are shown below,

- Glass Transition Temperature: -40 °C
- Softening point: 60–80 °C
- Manufacturing temperature: 210–250 °C
- Bed manufacturing temperature: 30–60 °C
- Decomposition temperature: >250 °C

TPU is highly elastic and impact-resistant, that allows TPU parts to stretch and flex under load without permanent deformation, making this material suitable for dynamic components. TPU's mechanical properties are shown below,

- Shore hardness: 85A–98A (or 55D for stiffer grades)
- Tensile strength: 25–50 MPa
- Elongation at break: 300–600%
- Tear resistance: High
- Abrasion resistance: Excellent

Manufacturing with TPU via the FFF method requires special handling due to its flexibility, for the hardware needed, direct drive extruders are preferred in order to minimize filament buckling, while manufacturing speeds should be kept low in order to avoid under-extrusion, also retraction must be minimized in order to prevent clogging and filament grinding and TPU is hygroscopic and absorbs moisture quickly, which leads to poor surface quality and bubbling if the material is not dried properly before use. But adhesion to the print bed is generally good without the need of adhesives and while TPU requires more tuning, compared to PLA or PETG, it offers superior mechanical flexibility. TPU is used in various industries due to its resilience, elasticity, and durability with some examples being phone cases and protective covers, medical devices as prosthetics and flexible tubing, robotics for soft grippers or bumpers, and in the automotive industry for seals and gaskets.[23]

2.5.4.5. Nylon

Polyamide or Nylon is one of the most durable materials used in FFF manufacturing, its used for parts that require high wear resistance and strength. Originally developed for fibers and films, Nylon's properties translate well into structural applications in Additive Manufacturing, especially when durability, low friction, or chemical resistance are required.

Nylon is a polyamide consisting of repeating units linked by amide bonds. There are many variants but the common ones include, Nylon 6 or Polycaprolactam, Nylon 6,6 or Poly(hexamethylene adipamide) and Nylon 12 – Poly(dodecalactam). The differences among these types are in their molecular chain length, which affects their melting temperature, moisture absorption, and flexibility. Nylon is semi-crystalline, which contributes to its strength and chemical resistance.

Nylon's thermal properties make it suitable for high-performance FFF manufacturing and as its clear from its thermal properties shown below Nylon can withstand high operational temperatures, making it an ideal material for mechanically loaded or thermally stressed parts.

- Glass transition temperature: 45–70 °C
- Melting point: 175–265 °C (depends on the type)
- Manufacturing temperature: 240–270 °C
- Bed manufacturing temperature: 60–100 °C
- Heat deflection temperature: 120–180 °C

Nylon offers an excellent balance of strength, flexibility, and wear resistance and with its low friction coefficient and self-lubricating properties it’s an ideal material for gears, bushings, and moving parts. Nylon’s mechanical properties are shown below,

- Tensile strength: 45–90 MPa
- Young’s modulus: 1.5–3 GPa
- Elongation at break: 50–300%
- Impact resistance: Very high
- Abrasion resistance: Excellent

Although Nylon is a strong and flexible material, it poses several challenges in FFF manufacturing as it absorbs moisture quickly from air making it one of the more hygroscopic materials used in FFF and it requires dry storage or pre-drying at 70–90 °C before use. Its prone to warping, especially without an enclosed chamber machine and it suffers from stringing and oozing due to the high extrusion temperature needed for manufacturing, while requiring strong adhesion aids, such as glue sticks, PVA, or a Garolite bed. But despite its challenges Nylon provides excellent layer adhesion and strong interlayer bonding, which produces parts with great impact and fatigue resistance and thanks to its mechanical robustness and chemical resistance, Nylon is widely used in functional prototypes, especially gears, hinges, and bushings and various tooling and jigs. Also its used for automotive components and wear-resistant parts. Finally Nylon can also be mixed with fillers such as carbon fiber or glass fiber in order to create a material with improved stiffness and reduced warping that can be used in special cases and designs.[27]

2.5.4.6. PC

Polycarbonate or PC is a material with superior mechanical properties compared to common filaments like PLA and ABS. PC's high strength, impact resistance, and thermal stability extend the functional range of FFF-manufactured components, making them suitable for industrial and engineering applications.

Polycarbonate is an amorphous thermoplastic derived from bisphenol A or BPA and phosgene. Its backbone consists of carbonate groups linked to aromatic rings, conferring high rigidity and thermal resistance. Unlike semi-crystalline polymers, PC’s amorphous structure prevents sharp melting points, resulting in a broad softening temperature range. PC’s high glass transition temperature allows printed parts to maintain mechanical integrity at elevated temperatures, making it a suitable material for parts used in demanding thermal environments. PC's thermal properties are shown below,

- Glass transition temperature: 147 °C
- Melting point: Does not have a distinct melting point due to its amorphous nature
- Manufacturing temperature: 260–310 °C
- Bed manufacturing temperature: 90–120 °C
- Heat deflection temperature: Around 130–140 °C

Polycarbonate is prized for its toughness and durability and is a material ideal for applications requiring shock absorption, mechanical stress resistance, and dimensional stability as is shown in its mechanical properties below ,

- Tensile strength: 55–75 MPa
- Impact resistance: Very high (notched Izod impact strength ~600 J/m)
- Elongation at break: 50–150%
- Flexural modulus: 2,000–2,400 MPa

PC with FFF manufacturing poses significant technical challenges and advanced slicer settings and hardware are necessary to optimize manufacturing quality. Some of the challenges are the high extrusion temperatures, that demand an all-metal hot end assembly, a capable high-temperature heated bed as well as an enclosed heated chamber and proper bed adhesion in order to prevent warpage and shrinkage, due to thermal stresses. Also PC filament is hygroscopic and must be stored dry and also be dried before manufacturing in order to avoid bubbling and poor layer adhesion. Furthermore lower manufacturing speeds are typically required in order to maintain quality and reduce defects. Due to its outstanding mechanical and thermal properties, PC is employed in functional prototypes that require high strength and heat resistance as well as end-use mechanical parts like gears, brackets and housings needing impact resistance and toughness. Also PC's biocompatibility and transparency opens its applications in medical devices and optical parts.[28]

3. Case studies for Additive Manufacturing

3.1. Introduction

In this section, two case studies are presented detailing the production of two components through Additive Manufacturing. These components were required as part of a generator restoration project undertaken by SIELMAN S.A. The components were difficult to source in respective condition. Their geometry, size, and limited production volume made them cost-prohibitive to manufacture using conventional methods. Due to the similarities between the two components, the design methodology and the equipment used are introduced here in detail.

The design process for both components was based on original reference parts, which were used as benchmarks for all measurements. A reliable 3D model was created using SolidWorks CAD software by Dassault Systemes. The CAD model was then exported as an STL file and prepared for slicing. The slicing process was carried out in Cura, a program developed by Ultimaker, ensuring full compatibility with the machine in use, providing optimal results. The components were designed exactly as the originals with no further modifications if not necessary.

All measurements were made with the use of an electronic precision caliper (Fig. 3.1) with an accuracy level of 0,01 millimeters. The dimensional drawings will be shown later according to each case study, along with selected manufacturing settings from Cura. The manufacturing settings were slightly modified standard profiles, for each material, embedded in the slicing software.

Figure 3.1. Precision calipers (Mitutoyo ABS AOS 500-181-30)

For the fabrication process, an Ultimaker S5 3D printer was employed (Fig. 3.2), equipped with a complete enclosure (Fig. 3.3) and a filament dryer. The Ultimaker S5 operates with an H-bot motion system and supports dual extrusion through two Hot End Assemblies and dual Bowden extruders. The system is capable of achieving high processing temperatures at both the hot end and the heated print bed. For these components the dual extrusion was not necessary as there were not any support structures or material changes through manufacturing.

The printer was fitted with a glass build surface from Ultimaker (Fig. 3.4), as standard from the manufacturer for this specific machine and all parts were produced with the additional application of specialized Ultimaker adhesive to improve first-layer adhesion. The enclosure ensured a stable thermal environment throughout the printing process, thereby reducing the risk of layer delamination caused by temperature fluctuations. The filament dryer was used to maintain the filament under optimal storage conditions, protecting it from dust and moisture and ensuring consistent print quality through material stability.

Figure 3.2. Ultimaker S5 FFF Additive Manufacturing machine

Figure 3.3 Enclosure

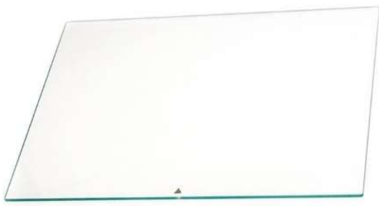


Figure 3.4. Glass manufacturing surface

The Ultimaker S5 is designed to operate exclusively with filament of 2.85 mm diameter. Consequently, all materials were sourced directly from the Ultimaker catalog to ensure full compatibility between printer, slicer, and filament, thereby guaranteeing consistent manufacturing results. The larger filament diameter provides increased rigidity, which improves feeding stability and reduces the likelihood of manufacturing issues, particularly when processing flexible materials. This filament size is the standard for the Ultimaker S5, as the system was specifically engineered around this specification.

3.2. Case study 1: Creating a relay terminal cover for a military generator.

The first case study details the development of a relay cover (Fig. 3.5), beginning with the design stage and continuing through to the final production of replacement parts. The component functions as a protective cover for the high-voltage input and output terminals of a relay, (as illustrated in Fig. 3.6) (the translucent part shown is a preliminary test piece, discussed later). The cover is essential both for protecting personnel from the risk of electrocution and for preventing potential short circuits caused by loose wires or defects during maintenance and changes on electrical connections. Each relay assembly requires two covers for its completion.

Figure 3.5. Original relay terminal cover for reference and measurement

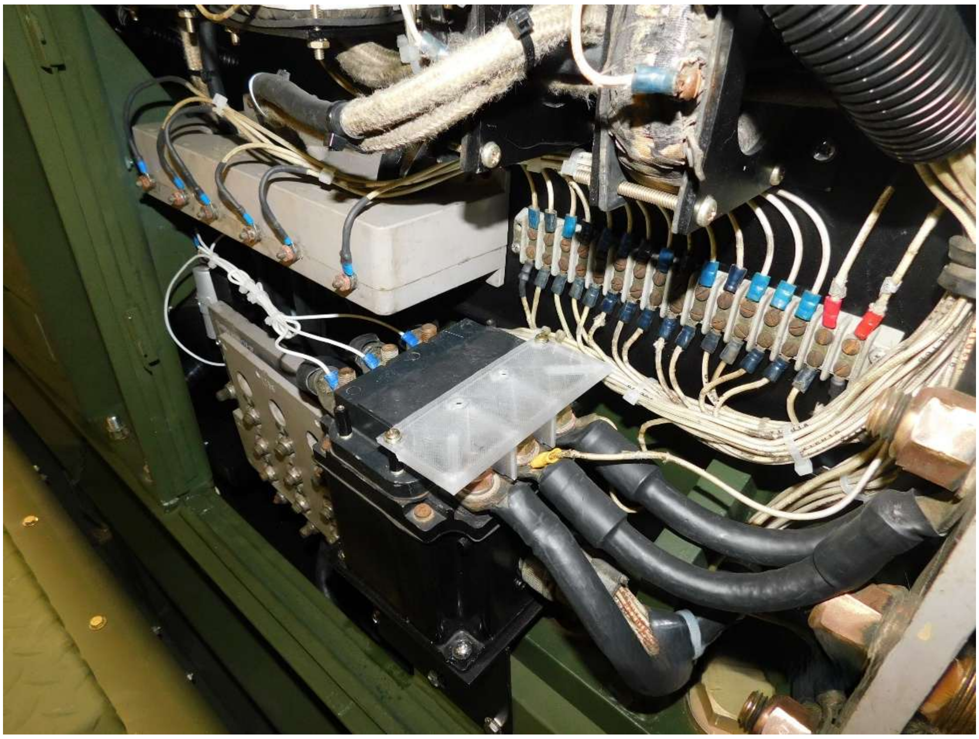


Figure 3.6. Relay and relay cover (test piece) on the machine

The original component, shown in Fig. 3.5, was manufactured from a brittle plastic material using extrusion molding, as evidenced by visible molding marks and its overall geometry. No technical drawings or parts lists were available, making it impossible to identify the exact material or precise dimensions with the available resources. Most of the original covers were found to be cracked or completely broken at their mounting positions, most likely due to over tightening during maintenance and degradation with age (Fig. 3.7). Consequently, replacement covers were required, and a total of 24 pieces had to be produced.

Figure 3.7. Original failed relay terminal cover

Dimensions of the original part were measured with electronic calipers, as described previously (Fig. 3.8). A CAD model was created in SolidWorks, followed by the generation of a technical drawing (Fig. 3.9). While mold extrusion is an efficient process for mass production due to its repeatability and speed, it is economically impractical for small production runs because of the high cost of mold fabrication. Therefore, Fused Filament Fabrication was selected as the most suitable alternative, offering flexibility, cost-effectiveness, and rapid turnaround. The CAD model was exported as an STL file and prepared for slicing.

Figure 3.8. Basic measurements with caliper of original component

Fused Filament Fabrication was selected as it is able to produce plastic components with success and repeatability. This specific component was not load bearing and did not require extreme working conditions, not exiting the limits of this specific Additive Manufacturing method. Before final production the manufactured component has to be tested in order to prove its performance and validate this specific manufacturing method.

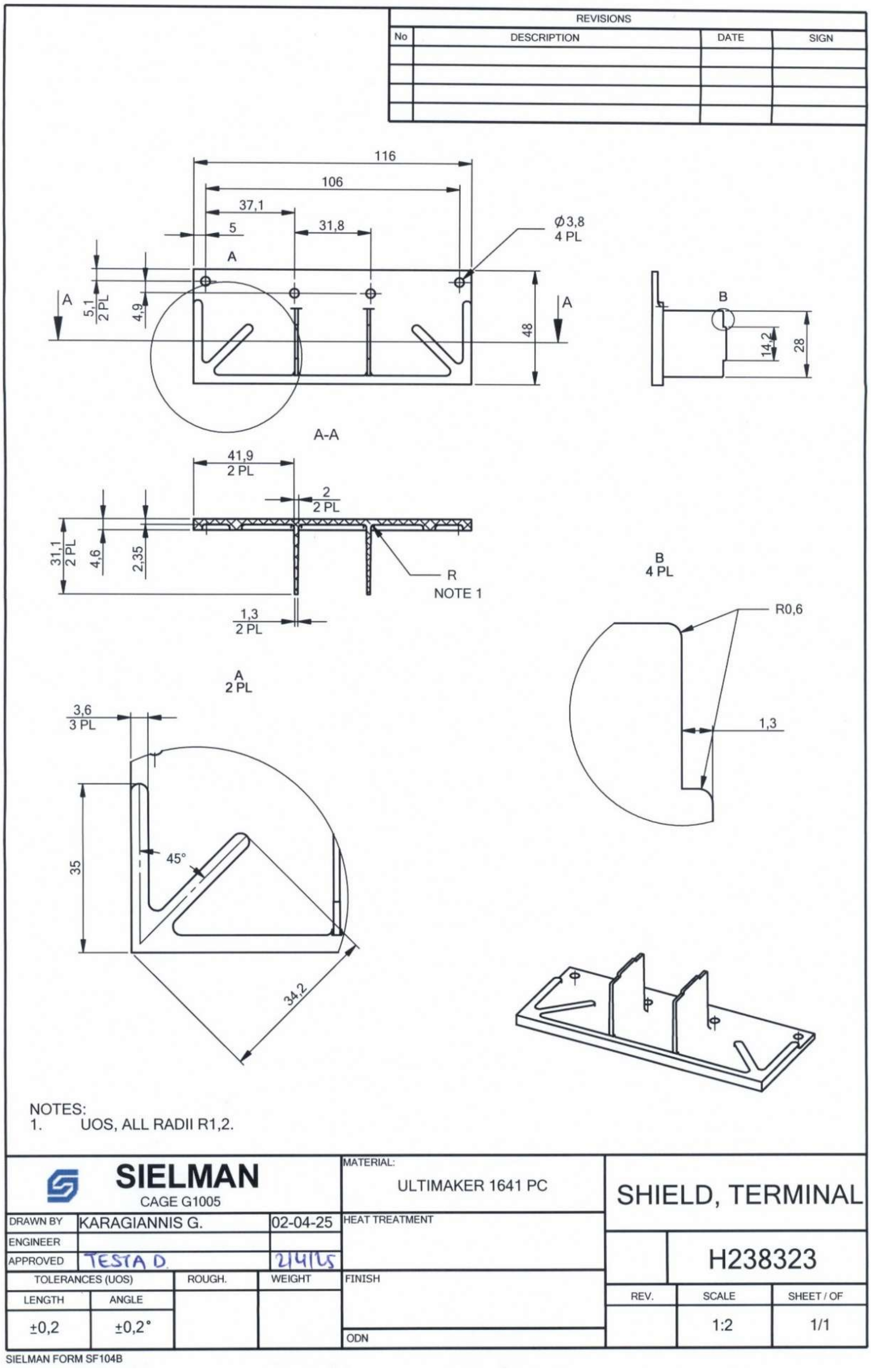


Figure 3.9. Drawing of the part for manufacturing

Polycarbonate filament from the Ultimaker catalog was selected for manufacturing due to its favorable mechanical strength and thermal resistance. Based on the relay's operating environment, maximum temperatures in the range of 60 to 90 degrees Celsius could be present. Although the relay is located at a safe distance from the generator's exhaust and cooling systems, it could still reach elevated temperatures during prolonged operation. Polycarbonate was therefore the optimal choice, providing the highest working temperature capability among the available materials in the Ultimaker catalog, over 105 degrees Celsius, while also offering superior mechanical performance (Fig. 3.10). In addition, PC was available in a black color, which ensured a final aesthetic result close to that of the original component [33].

Mechanical properties

All samples were 3D printed. See 'Notes' section for details.

	Test method	Typical value		
		XY (Flat)	YZ (Side)	Z (Up)
Tensile (Young's) modulus	ASTM D3039 (1 mm / min)	2394 ± 98 MPa	2352 ± 77 MPa	2255 ± 77 MPa
Tensile stress at yield	ASTM D3039 (5 mm / min)	53.3 ± 1.2 MPa	58.5 ± 0.9 MPa	No yield
Tensile stress at break	ASTM D3039 (5 mm / min)	43.2 ± 1.5 MPa	54.8 ± 1.0 MPa	25.2 ± 2.1 MPa
Elongation at yield	ASTM D3039 (5 mm / min)	6.1 ± 0.3%	5.9 ± 0.2%	No yield
Elongation at break	ASTM D3039 (5 mm / min)	9.2 ± 0.9%	6.7 ± 0.3%	2.0 ± 0.1%
Flexural modulus	ISO 178 (1 mm / min)	1619 ± 81 MPa	2052 ± 95 MPa	2032 ± 43 MPa
Flexural strength	ISO 178 (5 mm / min)	89.4 ± 2.3 MPa at 6.9% strain	98.4 ± 3.5 MPa at 6.1% strain	32.3 ± 3.7 MPa at 1.5% strain
Flexural strain at break	ISO 178 (5 mm / min)	No break (>10%)	No break (>10%)	1.5 ± 0.2%
Charpy impact strength (at 23 °C)	ISO 179-1 / 1eB (notched)	11.6 ± 1.4 kJ/m²	-	-
Hardness	ISO 7619-1 (Durometer, Shore D)	81 Shore D	-	-

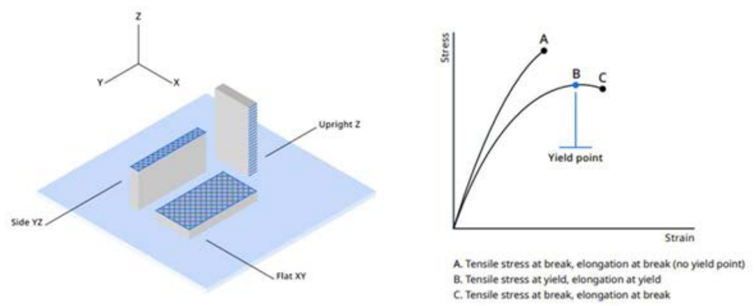


Figure 3.10. Mechanical properties of Polycarbonate from material datasheet [33]

The STL file was imported into the slicer software, Cura, with an "advanced PC" profile from the slicer program. The slicing profile was set to Fine mode, corresponding to a 0.1 mm layer height. Adjustments were made to increase extrusion temperature to 280 degrees Celsius (in accordance with the datasheet and prior experience with the material) and to increase wall thickness to six walls (1.2mm), improving strength compared with the default profile. The increase of the temperature was selected in order to reduce possible extrusion problems in the time-extensive manufacturing needed.

Since black Polycarbonate filament was initially unavailable, the first test pieces were manufactured using transparent Polycarbonate (Figs. 3.11 and 3.12). The first test revealed dimensional deviations, which were corrected by scaling the STL file by 1% in the slicer software. After this adjustment, the second test part matched the drawing specifications. The covers were subsequently evaluated for dimensional compliance and fit on the relay (Fig. 3.13), as well as for thermal and vibrational performance under real-world operating conditions. The generator was operated at full load for an extended period, during which the covers were installed, removed, and subjected to repeated handling. The parts withstood testing successfully, validating both the design and the chosen manufacturing process.

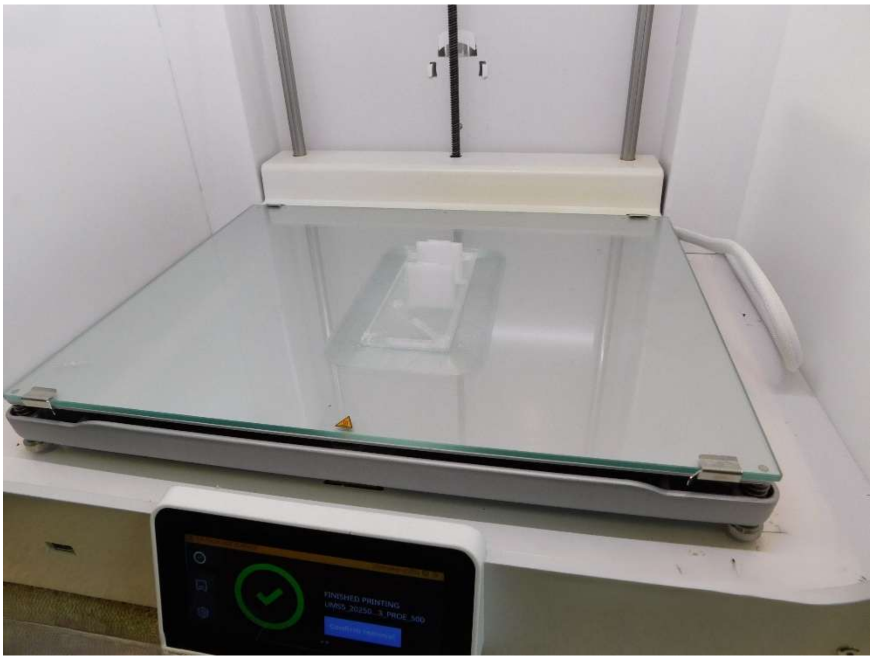


Figure 3.11. FFF Manufacturing of the first test part.

Figure 3.12. FFF manufactured parts with the original part

Figure 3.13. FFF manufactured part on the relay

For the production of 24 units, overnight manufacturing was adopted to optimize machine usage and reduce project duration. The slicer’s experimental “one at a time” mode was selected to eliminate stringing between multiple parts, since each cover was manufactured sequentially rather than simultaneously. This approach also ensured that potential manufacturing failures, as first layer adhesion issues, would affect only a single part rather than the entire batch.

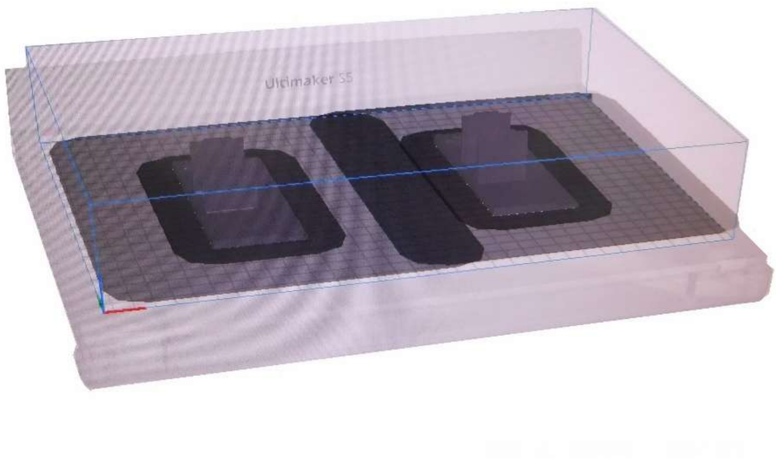


Figure 3.14. Two parts manufacturing machine set up

With the availability of black PC filament, a pilot production run was conducted. Two parts were produced simultaneously (Fig. 3.14) to validate the adjusted profile and confirm the new material's performance. Post-processing involved removal of the brim and minor cleanup of excess material around the mounting holes (Fig. 3.15). Both parts were then measured and confirmed to be dimensionally compliant.

Figure 3.15. Cleanup with the use of a 3.8mm brill bit

During extended testing, it was observed that some covers exhibited layer delamination at the base of the two perpendicular features that separate the wire terminals (Fig. 3.16). Although these features were not intended to bear significant loads, improvements were necessary to enhance reliability. Layer delamination is a common limitation of Fused Filament Fabrication Additive Manufacturing, particularly in thin, perpendicular features on the Z axis as the ones present on this component.

To address this issue, a revised design was produced (Fig. 3.17). The base thickness of the two separator features was increased by 0.5 mm, while the wall count was reduced by two layers (0.4mm reduction) to allow sufficient infill. This modification was intended to improve the structural integrity without affecting the part's fit or compatibility with the relay assembly. The defect was present in a small portion of the manufactured components but required a design revision to ensure better repeatability between the components and more ensuring results.

Figure 3.16. Layer delamination on perpendicular features

This defect was an expected result of the Fused Filament Fabrication manufacturing method. The component was originally designed to be produced via mold extrusion a different manufacturing procedure with different design constriction. The design of figure 3.17 was produced to mimic the original component, thus changes needed in order to facilitate the Additive Manufacturing method. The revised design only changed the absolute necessary features to produce a component suited for Fused Filament Fabrication. The aim of the revised section was to increase volume for material infill in the specific feature on the component.

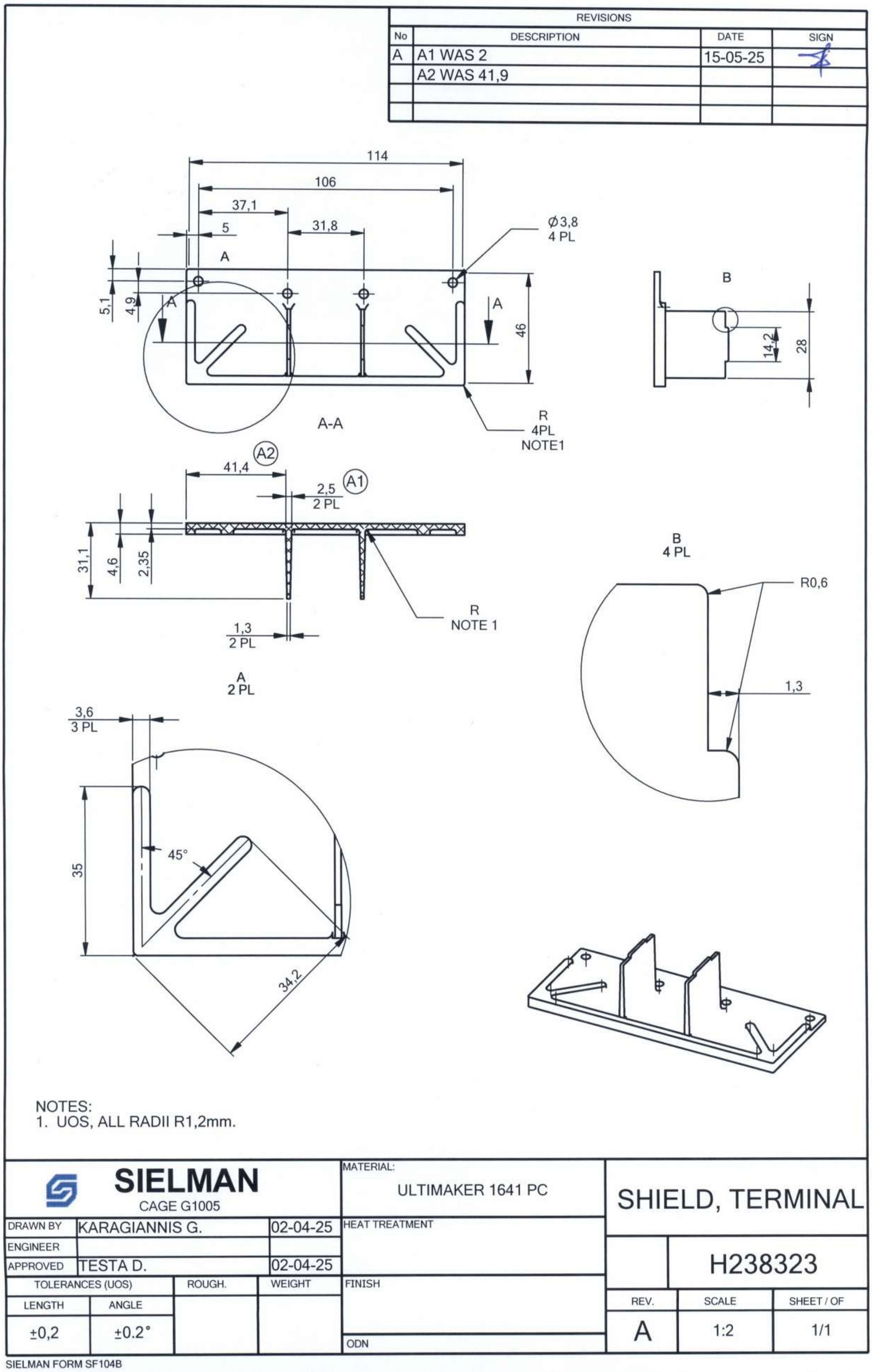


Figure 3.17. Revision A of the drawing

The selected infill pattern, shown in Fig. 3.18, was designed to function as an elastic core within the otherwise brittle polycarbonate shell. Given that polycarbonate can be prone to brittleness, the internal infill structure was expected to improve performance under bending stress, from possible mishandling, and overall reliability. A new test manufacturing run was therefore conducted following the design revision to confirm that these modifications achieved the desired results. The features on the revised component could retain significantly more bending stresses before any fractures occurred.

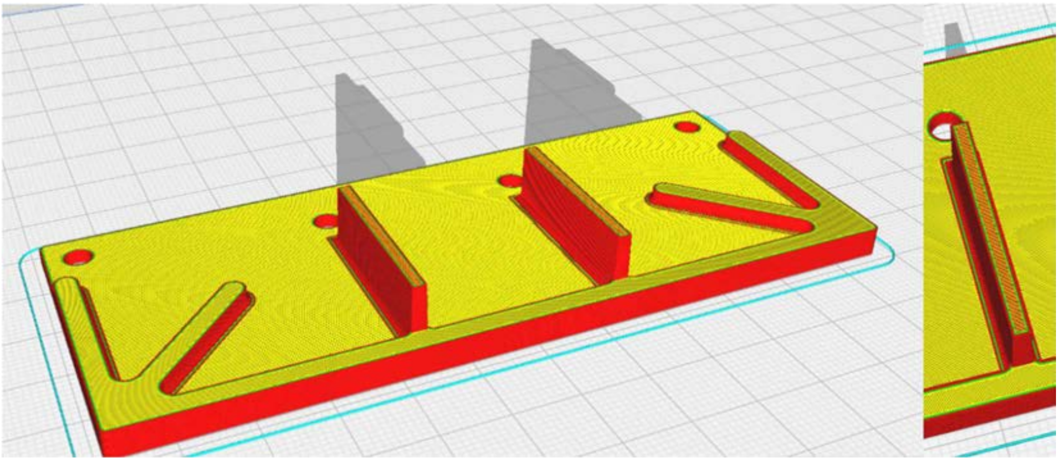


Figure 3.18. Part manufacturing structure through slicer software

After successful validation of the revised design, the setup for mass production was established. Due to the limitations of the slicer's "one at a time" mode, the effective build volume of the printer was reduced in order to prevent potential collisions between the print head assembly and completed parts. As a result, a maximum of four parts could be manufactured per build cycle, requiring six separate manufacturing batches to complete the total production run of 24 covers (Fig. 3.19).

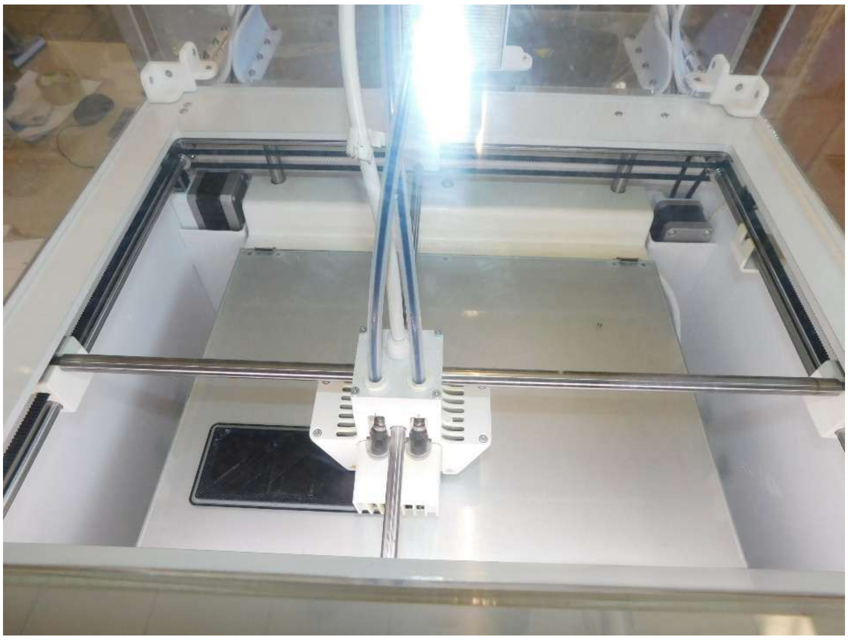


Figure 3.19. FFF Manufacturing of a batch of parts

Each part was individually inspected during the production process to verify the absence of layer delamination and to ensure dimensional accuracy (Fig. 3.21). Upon completion of the full production batch, the covers were submitted to the quality control department, where they underwent visual inspection, dimensional verification, and fit testing. The components could not be further tested as there were not any available original technical drawings or details. The component was validated through the design phase for fit, working performance and durability in working conditions. All 24 covers successfully passed inspection and were approved for assembly (Fig. 3.21).

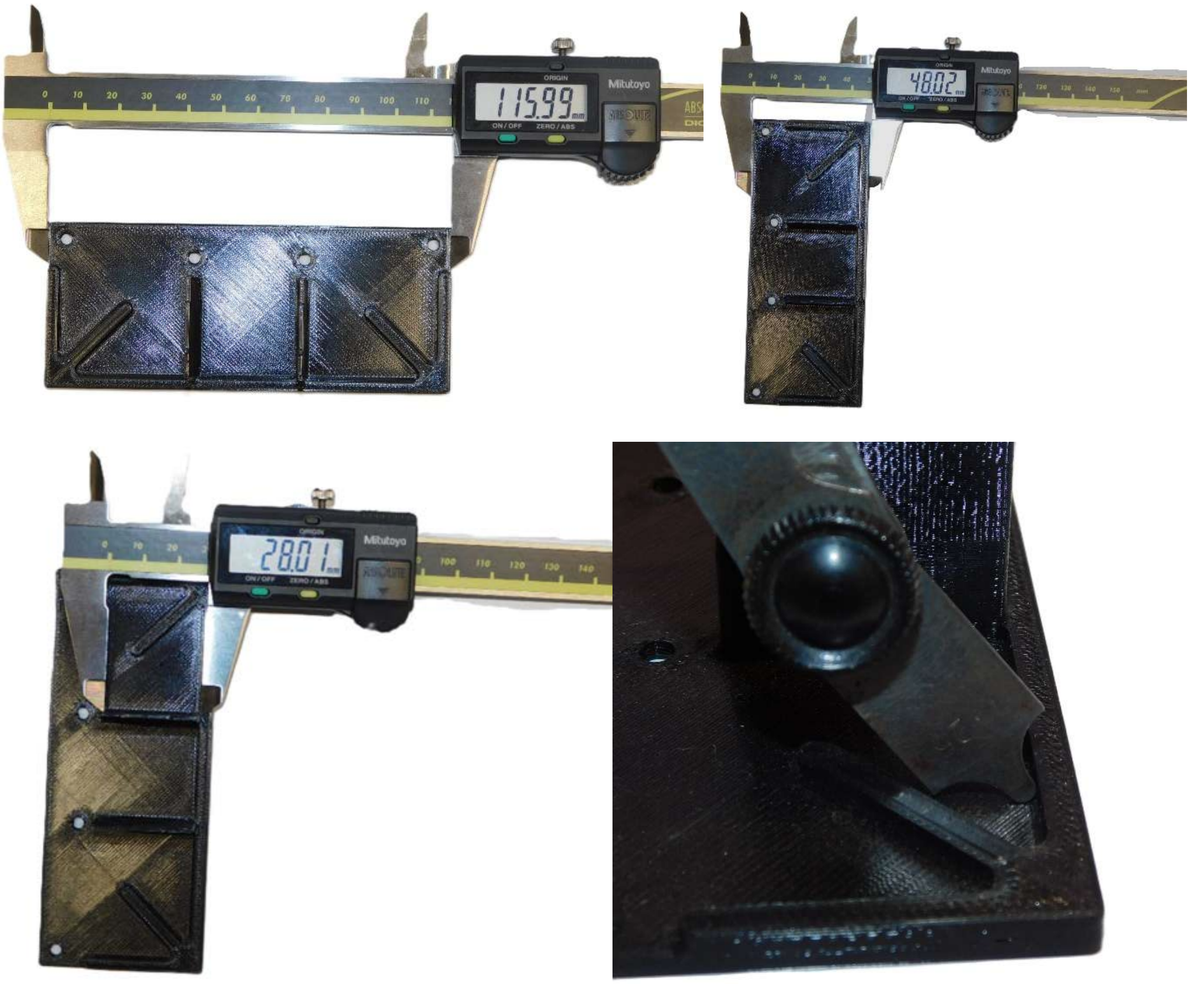


Figure 3.20. Basic measurements with caliper of FFF manufactured component

Figure 3.21. Finished product on the corresponding relay

3.3 Case study 2: Creating a rubber plug for a military generator.

The second case study details the development of a rubber plug (Fig. 3.22), covering the process from CAD design to the production of the final units. This component served as a protective cover for the regulators of the machine's ECU, preventing the ingress of dust and moisture. The ECU was located in the generator's engine compartment, in a medium-heat position away from the exhaust system, the cooling system, and the engine itself (Fig. 3.23). A total of 60 plugs were required to satisfy the company's internal production needs, as most of the original components were missing.

Figure 3.22. Original rubber plug, for measurements and analysis

Figure 3.23. Generator ECU and regulator openings for coverage

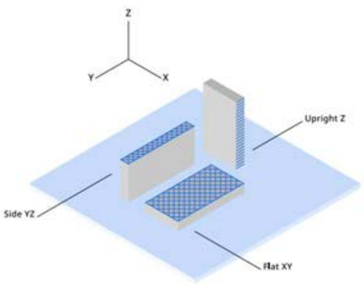
The plug was identified as being manufactured from a rubber-like material, though the exact composition could not be determined due to the absence of technical drawings or parts lists specifying its properties or dimensions. Dimensional data were obtained using an electronic caliper (as described in the introduction) and a Mitutoyo measuring projector, owing to the component's small size and relatively complex geometry.(Fig 3.24)

Figure 3.24. Basic measurements with caliper

A CAD model of the plug was generated in SolidWorks, utilizing the revolve feature, and a corresponding technical drawing was produced (Fig. 3.26). The original component had been manufactured via mold extrusion, as indicated by visible extrusion marks. While molding is highly efficient for large-scale production due to its repeatability and speed, the creation of molds for such a limited production volume would have been economically impractical. Consequently, Fused Filament Fabrication Additive Manufacturing was identified as the most suitable method, offering versatility, reduced cost, and rapid turnaround. An STL file was exported from SolidWorks for slicing, completing the design stage.

The selected material was TPU-95A, sourced from the Ultimaker catalog. This material was chosen for its thermal resistance and elastic properties, closely replicating the behavior of the original rubber component. According to the manufacturer's datasheet, TPU-95A has a maximum service temperature of approximately 116 °C and a melting temperature of 216.8 °C, while its mechanical properties are presented in Fig. 3.25 [34].

	Test method	Typical value		
		XY (Flat)	YZ (Side)	Z (Up)
Tensile (Young's) modulus	ASTM D3039 (1 mm / min)	67 ± 6 MPa	67 ± 2 MPa	56 ± 3 MPa
Tensile stress at yield	ASTM D3039 (50 mm / min)	No yield	No yield	No yield
Tensile stress at break	ASTM D3039 (50 mm / min)	23.7 ± 2.1 MPa	37.9 ± 1.6 MPa	6.4 ± 0.5 MPa
Elongation at yield	ASTM D3039 (50 mm / min)	No yield	No yield	No yield
Elongation at break	ASTM D3039 (50 mm / min)	>560%	>700%	82.3 ± 18.4%
Flexural modulus	ISO 178 (1 mm / min)	62.6 ± 1.7 MPa	55.1 ± 2.4 MPa	62.6 ± 2.0 MPa
Flexural strength	ISO 178 (5 mm / min)	4.1 ± 0.0 MPa at 9.4% strain	3.8 ± 0.1 MPa at 9.8% strain	4.3 ± 0.1 MPa at 9.7% strain
Flexural strain at break	ISO 178 (5 mm / min)	No break (>10%)	No break (>10%)	No break (>10%)
Charpy impact strength (at 23 °C)	ISO 179-1 / 1eB (notched)	36.0 ± 6.6 kJ/m²	-	-
Hardness	ISO 7619-1 (Durometer, Shore D)	48 Shore D	-	-
	ISO 7619-1 (Durometer, Shore A)	96 Shore A	-	-



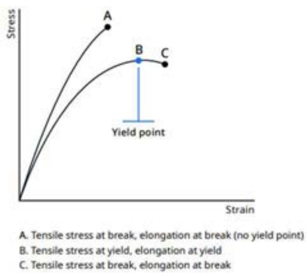


Figure 3.25. Mechanical properties of TPU-95A from material datasheet [34]

To validate the design and manufacturing plan, a test piece was produced to evaluate dimensional accuracy, mechanical functionality, and fit with the corresponding component. Initial measurements indicated the necessity of a 1% dimensional scaling increase in the slicer software to compensate for material shrinkage. After this adjustment, the test part was deemed compliant and suitable for use (Fig. 3.27).

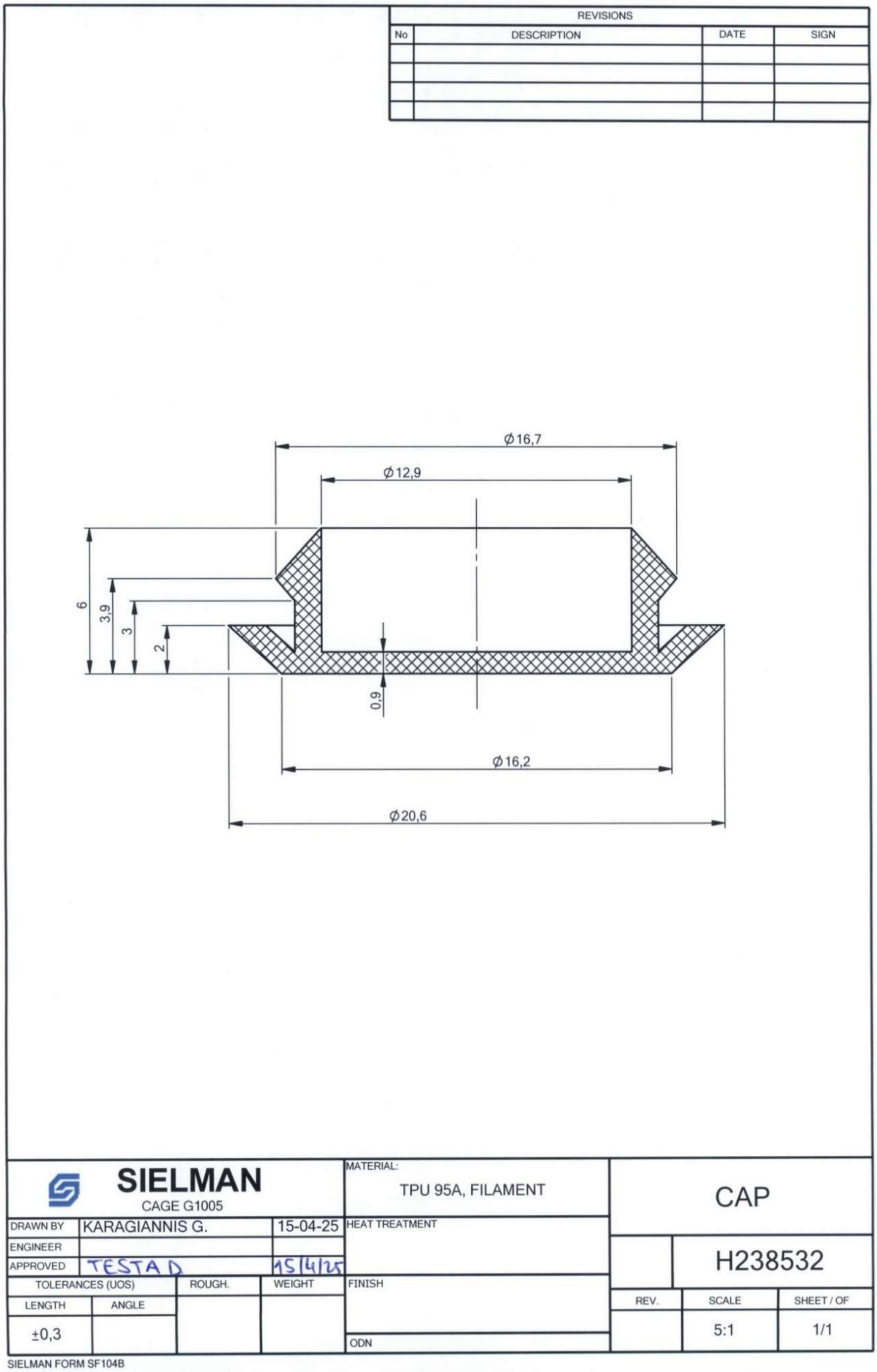


Figure 3.26. Drawing of the part for perspective

Figure 3.27. Test part manufactured with Additive Manufacturing

The manufactured component was tested for fit. It required to maintain a seal in its working condition preventing dust and moisture from entering the ECU unit. The material can withstand the specific working conditions with no deformation over time, so there was no further testing needed.

A second validation run was conducted, in which four plugs were manufactured simultaneously. While dimensional accuracy was confirmed, noticeable stringing occurred along the toolpaths due to the elastic nature of TPU-95A (Fig. 3.28). Although expected, this defect negatively affected surface finish and required additional post-processing.

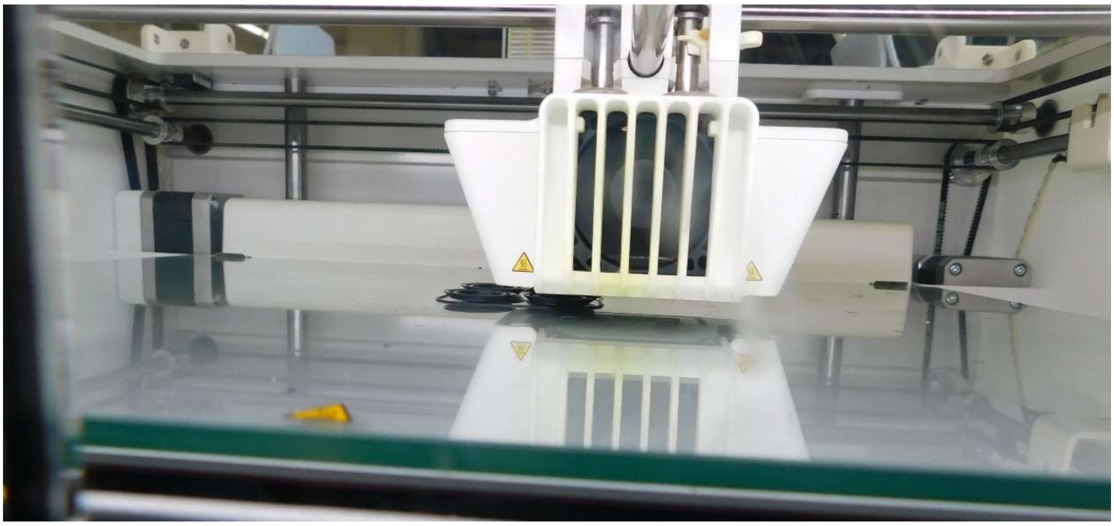


Figure 3.28. Second test, manufacturing of 4 pieces simultaneously

To mitigate stringing, the slicer's "one at a time" mode was employed. This setting enabled the printer to fabricate each part individually within the same build sequence, thereby eliminating unnecessary travel moves. While this mode reduced the maximum production capacity of the printer, it significantly improved surface quality.

The slicing profile was further optimized by selecting "Fine" mode, corresponding to a 0.1 mm layer height. This ensured high surface quality without excessive build time or nozzle clogging, given the small size of the plug. The component was printed solid, with four walls, as the thin walls would not allow for a sufficient infill structure (Fig. 3.29). Printing speed was set to 70 mm/s, reducing manufacturing time. A skirt was used for nozzle priming because brim adhesion was avoided due to material residue. Based on the datasheet, extrusion temperature was set to 230 °C, with the heated bed disabled. To improve first-layer adhesion, a thin layer of adhesive was applied to the glass build surface, resolving adhesion issues, though requiring post-build cleaning with water.

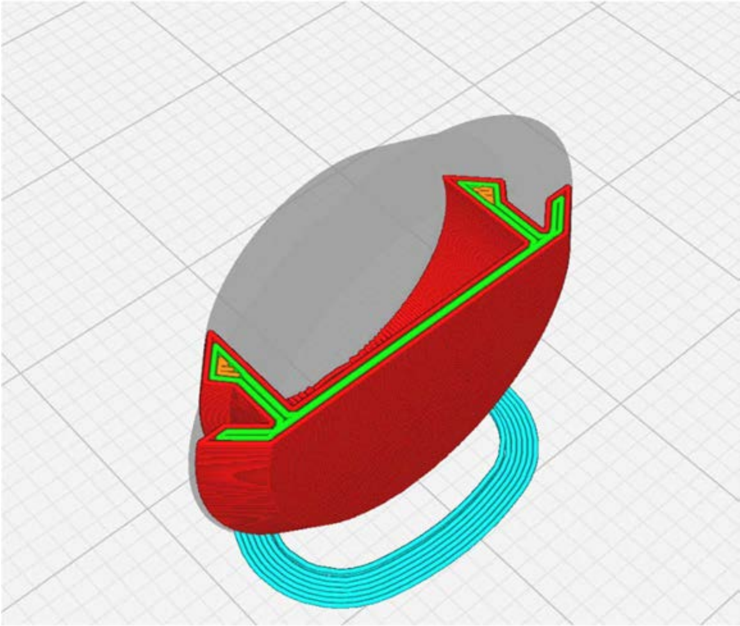


Figure 3.29. Material lines for the creation of the part, from the slicer software

Production was carried out in batches of five plugs at a time, due to the limitations imposed by the “one at a time” mode (Fig. 3.30). Each part was fabricated sequentially, resulting in components that were ready for use immediately upon removal from the machine.

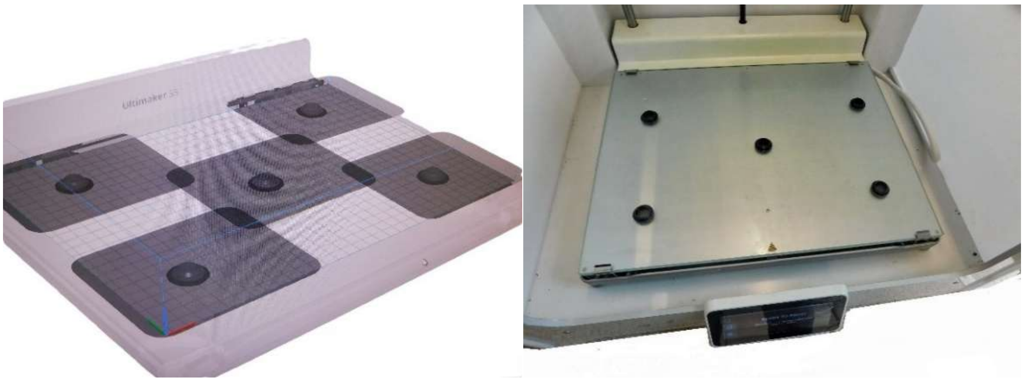


Figure 3.29. Production set up, slicer software and machine after a fabrication cycle

After every build cycle, the glass plate was cleaned with water to remove adhesive residue, followed by the reapplication of a thin adhesive layer. The same G-code could then be reused for subsequent cycles, ensuring dimensional repeatability. From each batch, one component was measured for dimensional compliance, and all plugs were visually inspected for defects. Minor post-processing, limited to material cleanup, was performed where necessary before submission to quality control.

Following the successful fabrication of 60 plugs (Fig. 3.31), the entire lot was submitted to quality control. The plugs were tested for dimensional compliance, surface quality, and assembly fit with the corresponding ECU component. The components could not be further tested as there were not any available original technical drawings or details. The component was validated through the design phase for fit, working performance and durability in working conditions. The major concern of the manufactured component was layer delamination or tears from repeated usage. Because of the elastic properties of the material these defects were not present. The batch successfully passed quality control and was released for operational use.

Figure 3.31. Parts from the production ready for quality control

4. Conclusion

This thesis has demonstrated that Additive Manufacturing methods have matured into reliable solutions not only for prototyping but also for functional components in many applications. The analysis of Additive Manufacturing methods showed that Fused Filament Fabrication remains the most widely adopted approach due to its low cost and ease of use. In contrast, stereolithography, selective laser sintering and Multi Jet Fusion offer superior accuracy and mechanical performance, but with higher equipment and processing costs. Furthermore, Direct Metal Laser Sintering has expanded the scope of Additive Manufacturing into metallic and advanced polymer parts, addressing demanding industrial requirements. However all of these methods remain yet a specialty and not an obtainable resource in a traditional manufacturing environment.

Analyzing the FFF manufacturing machine concluded that material selection plays a critical role in the success of each application. Polylactic acid or PLA remains the most accessible filament due to its ease of processing but is limited by low mechanical and thermal resistance. Acrylonitrile butadiene styrene or ABS and polyethylene terephthalate glycol or PETG offer higher toughness and temperature resistance, while thermoplastic polyurethane or TPU and nylon are suited for flexible and wear-resistant components. Polycarbonate demonstrated strong potential for industrial parts requiring enhanced mechanical durability, as it was demonstrated on the first case study.

The case studies confirmed that correct process, design and material selection can solve real industrial challenges by reducing lead time and production costs. In particular, the integration of Additive Manufacturing in this specific applications highlighted its practical value, enabling on-demand replacement of critical spare parts in a short timeline and cost with FFF Additive Manufacturing.

Overall, this thesis illustrates the transition of Additive Manufacturing from a tool of rapid prototyping to a fully established production technology. Future developments are expected to focus on material innovation, productivity improvements, and cost reduction, paving the way for even broader adoption in industrial and academic contexts.

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