THESIS

Md. Noman Babu

Master Science in Mechanical Engineering

Szent István Campus, Gödöllö

2023

Hungarian University of Agriculture and Life Science

Szent István Campus

Master Science in Mechanical Engineering

THESIS TITLE

Natural fibre reinforcement in composite polymer materials for additive manufacturing

Supervisor: Dr. Zoltán SZAKÁL
Associate professor

Author: Md. Noman Babu
ID: QAUA9I

Institute/Department: Institute of Technology, Department of Mechanical Engineering

Szent István Campus, Gödöllö
2023

INSTITUTE OF TECHNOLOGY MECHANICAL ENGINEERING (MSC)
Technical Development specialization

THESIS
worksheet for

Md. Noman BABU (QAUA9I)

(MSc) student

Entitled:

Natural fiber reinforcement in composite polymer materials for additive manufacturing

Task description:
The goal was to investigate the mechanical properties, especially tensile strength of different manufactured PETG filaments in comparisons with natural fiber (jute) reinforced filaments. 3 types of PETG filaments were used from 3 different manufactures. A few machines were used to prepare, make, and test the filaments. After the test the results were analyzed, and a significant improvement was found after the jute fiber reinforcement.

Department: Mechanical Engineering

Supervisor: Dr. Zoltán SZAKÁL, *Associate Professor,* MATE, Institute of Technology

Submission deadline: 09 May 2023.

Gödöllő, 20 January 2023.

Approved **Received**

(head of department) (host course leader) Noman (student)

As an independent consultant of the author of this thesis I hereby declare that the student took part in the planned consultations.

Gödöllő, 08 May 2023.

(Consultant)

Dedication

To my father, Md. Golam Mostafa, and my mother Mst. Jharana Bibi. Your hardship, love, and prayer for me to pursue higher education inspired me to attain my highest degree.

Table of Contents

List of Figures

List of Tables

1. Introduction

In contrast to subtractive manufacturing techniques, additive manufacturing (AM) is the "process of joining materials to make objects from three-dimensional (3D) model data, typically layer by layer," according to the ASTM F42 Technical Committee. [1] It is also referred to as solid freeform fabrication, additive fabrication, additive processes, direct digital manufacturing, fast manufacturing, and rapid prototyping. The word "AM" refers to additive manufacturing methods in their fullest sense, which encompasses functional components with necessary attributes for immediate industrial applications and services, as well as prototypes (for design verification, form and fit checking), tools, patterns, and concept parts. [2]

The development in process automation has significantly increased recent trends in manufacturing method improvement. Due to the intricacy of the production process, many processes are still performed by hand. The primary market constraining factors that determine the manufacturing process are the materials' source and the available time. AM methods have the potential to transform the industrial sector. [3]

Computer software and computer programming are the power of this technology. The main factor that has helped the development of AM is the ease of computation and data processing. Moreover, the demand for prototyping throughout the product development phase has led to an upsurge in AM research. AM immediately participates in the prototype process, cutting down on time and material waste. [3]

In this research, different technologies of the additive manufacturing, materials and applications were studied and a new approach of jute fiber reinforcement in PETG materials is carried out. The result shows a significant increase in Ultimate Tensile Strength (UTS) in comparison with other tested specimens i.e., recycled, original and 3D printed specimens.

2. Literature Review

One of the most crucial methods for product development is prototyping [4]. The process of turning mathematical models, rough drawings, practical physical models, and foam models into actual physical models is known as prototyping. It is simple to check for errors and manufacturing problems during the creation of scaled items. A working component's connections and overloading of the functioning components can be examined. The designs may be altered in several ways, and the modifications can be tested by making numerous prototypes. The prototyping technique simplifies iterative procedures. The defects introduced during the designing stage of the production process can be changed via prototypes. [5].

The design and manufacturing processes are typically expedited by rapid prototyping (RP). It can lead to the production of products with zero defects. By including the product in a brainstorming session, rough prototypes for improving the items may be developed quickly. [6].

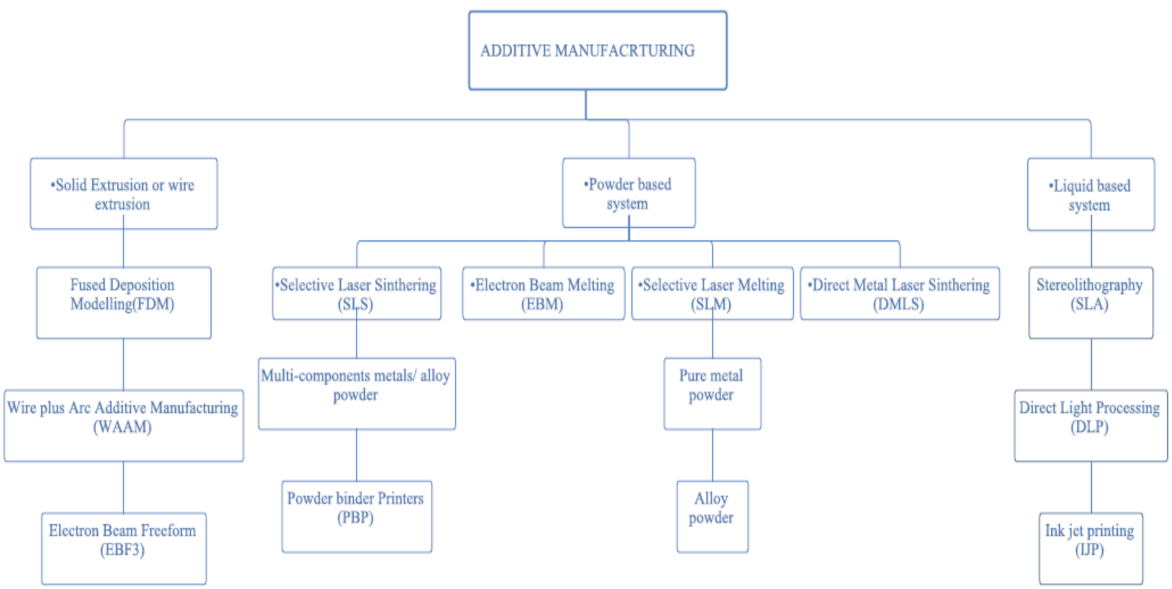

Figure 1. Classification of Additive Manufacturing. [3]

2.1 Steps of Additive Manufacturing

There are several modeling software programs available that may be used to build virtual models. The data supplied by the design engineers or the data gathered from the current designs are used to develop the designs. The term "virtual model" is often used to refer to CAD models, which are frequently produced using programs like AutoCAD, Creo, SolidWorks, Catia, and Unigraphics. [8]

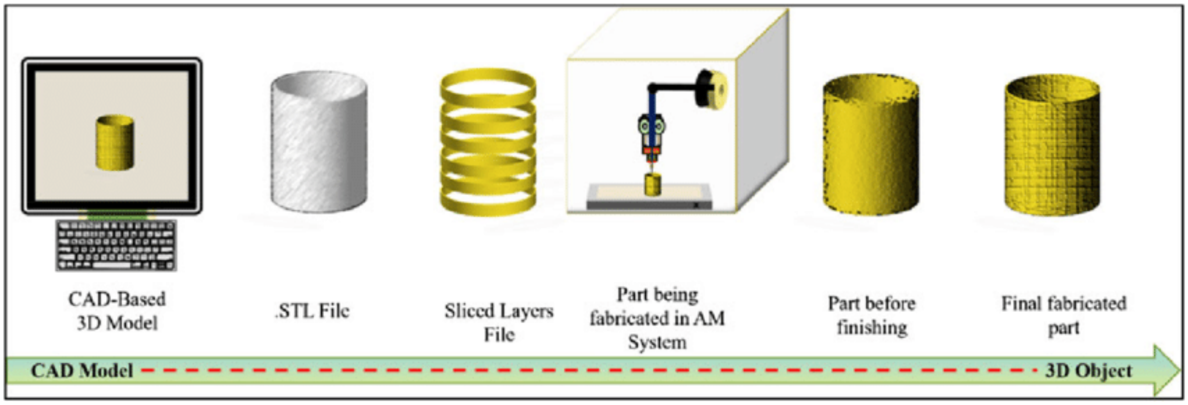

Figure 2. Overview and basic principle of additive manufacturing and processes involved in the design and fabrication of 3D objects. [7]

2.1.1 Creation of the virtual model

After the item has been virtually analyzed in analysis tools like ANSYS, COMSOL, ABAQUS, etc., the objects are produced [33]. Reverse engineering is often used to develop models. It is possible to use scanning equipment to quickly create a virtual prototype model. The machine scans using UV light, which is emitted from the source and returned after striking the item that has to be scanned. When scanning items using white or blue light as the scanning source, scanning devices with greater resolutions (more than 100 mm) are available. [9].

These scanners are crucial to the process of reverse engineering, which creates and customizes products for a variety of applications. Prosthetic parts are made by scanning the human body's bones or external structure to construct an accurate facsimile of the component.

2.1.2 Understanding the functional parts

The intricate designs made by the designers, which are carefully considered during the manufacturing process, are the functioning portions. With better accuracy, the system of the integrated parts is more accurately constructed with clearance space between the parts. These components can be produced using the AM method as separate pieces or as complete units. To harden the material, the components must undergo post-processing using a method like SLA. The moveable components made as part of an assembly will have clearance values built in for the AM process. [3]

2.1.3 Converting into STl

For the slicing procedure, the produced models are translated into Standard Triangle Language (STL) or Standard Tessellation Language. Without any of the textures, colors, or other CAD features, STL files primarily represent the surface geometry of the supplied design file. Additionally, this standard defines representations in binary and ASCII codes. The SLT file uses three-dimensional Cartesian coordinates to transform the design file's data into a triangulated surface. The unit normal and triangle vertices are ordered according to the right-hand rule. [10]

2.1.4 Slicing and creating supports.

The STL files are being used to build contour data. The horizontal slicing is carried out in accordance with the desired layer thickness. The item is uniformly cut via slicing. Slices can also be made with variable thickness, meaning that the thickness between them fluctuates depending on the machine's capabilities and the shape. Lower surface finish when layer thickness is higher [11]

De facto industry standards are widely employed in the AM sector because they can nearly always triangulate and simplify complicated surfaces [12]. The software capability is this slicing's main drawback. Not every 3DCAD software can do the slicing operation; just a few can. The most popular basic slicing program for direct slicing is called CURA. One of the other programs is Meshmixer, another is Blender. To improve the creation, supports must be built in the areas with overhanging constructions. For simple removal of the supports, water soluble PLA materials have been developed. [3]

2.1.5 Export to “g” code file

The G-code used in 3D printing is produced by the slicing program. The G-code coding procedure for CNC machines is symmetrical. The orientation of the platform and the movement of the extruder head are provided by the code that was generated. Some machines simply have the platform move in the z direction, while others have a fixed platform and an extruder that moves in all three directions. G-code, which is specially given by the machine's own software, is used to control these motions. [3]

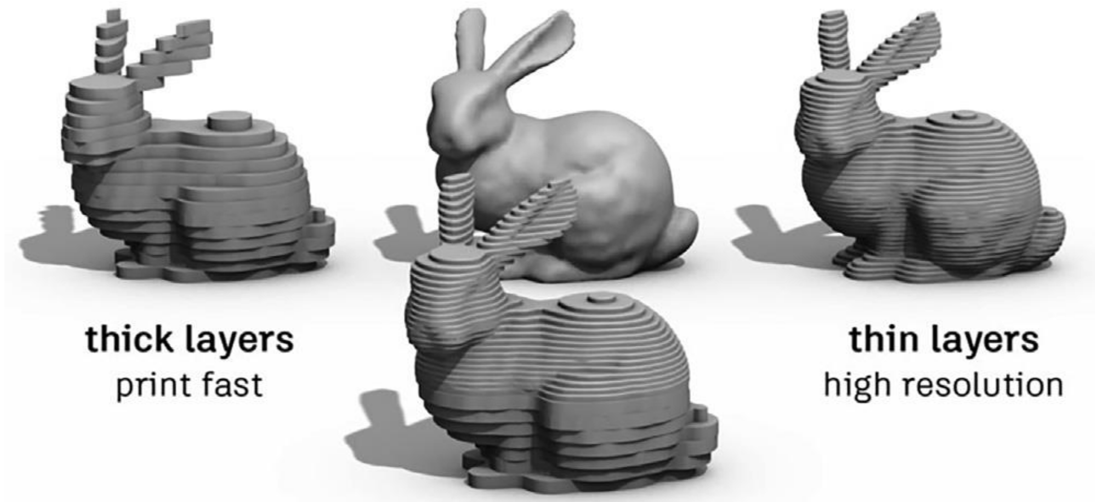

Figure 3. Slicing of an object using different thickness. [3]

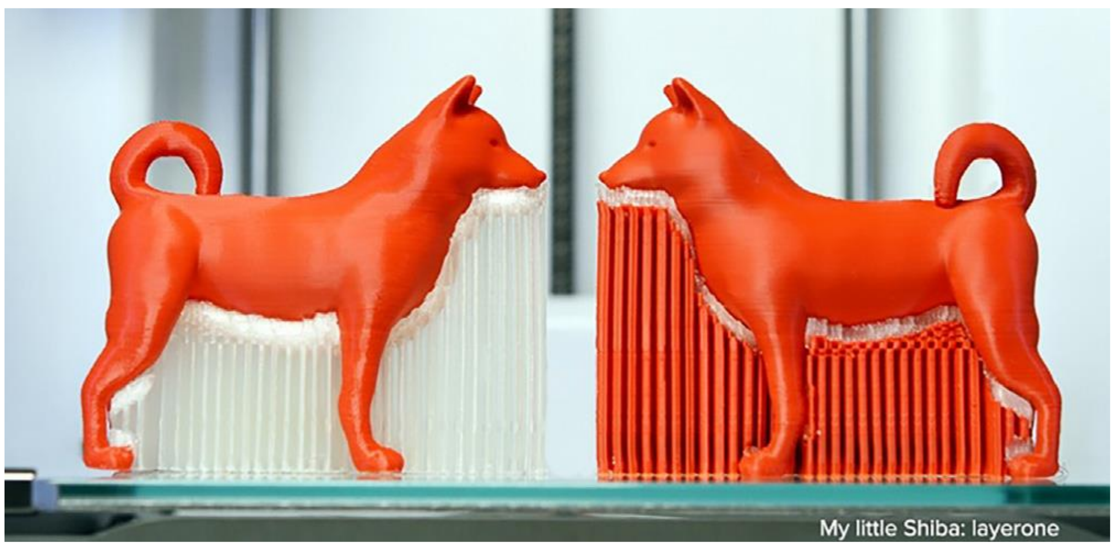

Figure 4. Left figure represents water soluble support material and right side with same material support material. [3]

2.2 Additive Manufacturing Processes

Industrial businesses, such as Electro Optical Systems (EOS) in Germany, Arcam in Sweden, MCP Tooling Technologies in the UK, Stratasys, 3D Systems, Optomec, and Z Corporation in the United States, among others, have brought many AM methods to the commercial sector [13]. The following four main categories are used to categorize AM procedures based on the condition of the starting material employed: liquid, filament/paste, powder, and solid sheet are the first three. Table 1 provides a summary of how AM processes operate with various material states. [2]

Table 1. Working Principle of AM processes [2]

State of starting material	Process	Material preparation	Layer creation technique	Phase change	Typical materials	Applications
Liquid	SLA	Liquid resin in a vat	Laser scanning/ light projection	Photopoly-merization	UV curable resin, ceramic suspension	Prototypes, casting patterns, soft tooling
	MJM	Liquid polymer in jet	Ink-jet printing	Cooling & photopolymerization UV curable acrylic	plastic, wax	Prototypes, casting patterns
	RFP	Liquid droplet in nozzle	On-demand droplet deposition	Solidification by freezing	Water	Prototypes, casting patterns
Filament/ Paste	FDM	Filament melted in nozzle	Continuous extrusion and deposition	Solidification by cooling	Thermoplastics, waxes	Prototypes, casting patterns
	Robocasting	Paste in nozzle	Continuous extrusion	–	Ceramic paste	Functional parts
	FEF	Paste in nozzle	Continuous extrusion	Solidification by freezing	Ceramic paste	Functional parts
Powder	SLS	Powder in bed	Laser scanning	Partial melting	Thermoplastics, waxes, metal powder, ceramic	Prototypes, casting patterns, metal and ceramic preforms
	SLM	Powder in bed	Laser scanning	Full melting	Metal	Tooling, functional parts
	EBM	Powder in bed	Electron beam scanning	Full melting	Metal	Tooling, functional parts
	LMD	Powder injection through nozzle	On-demand powder injection and melted by laser	Full melting	Metal	Tooling, metal part repair, functional parts
	3DP	Powder in bed	Drop-on-demand binder printing	–	Polymer, Metal, ceramic, powders	Prototypes, casting shells, tooling
Solid sheet	LOM	Laser cutting	Feeding and binding of sheets with adhesives	–	Paper, plastic, metal	Prototypes, casting models

2.2.1 Liquid

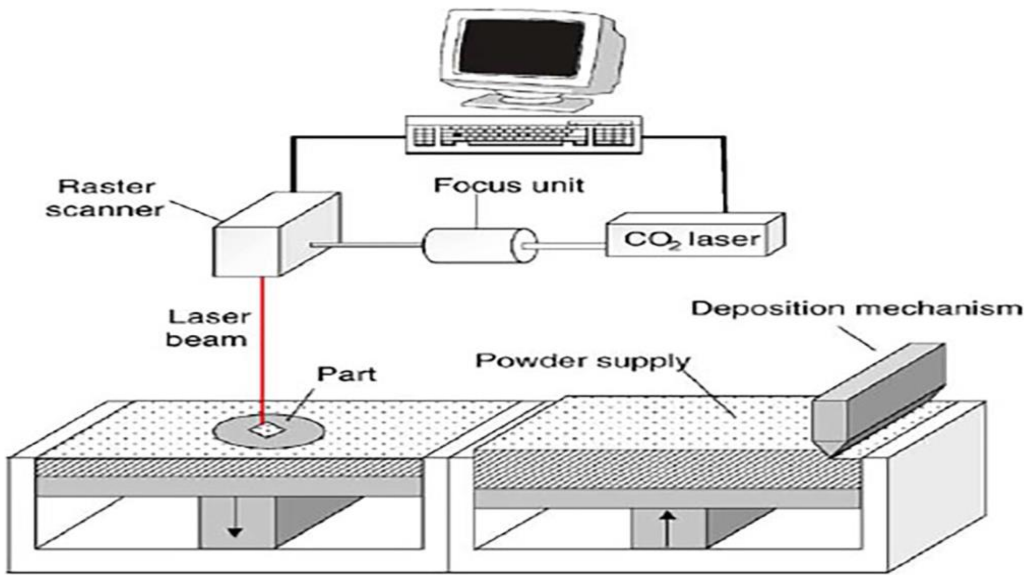

Figure 5. Selective laser Sintering (SLS) layout. [3]

The first commercially available AM technique, stereolithography (SLA) [2], works by selectively exposing a resin vat to ultraviolet (UV) light in order to solidify a liquid photosensitive resin. A CAD model is divided into layers in this procedure, and each layer is scanned by the UV light to selectively cure the resin for each cross-section. The platform lowers by one layer's thickness after each layer is constructed. The cross-section of the item is then coated with a new layer of resin using a blade that is packed with resin. The following layer is then scanned while still being adhered to the prior layer. Among the manufacturers of commercial SLA machines are 3D Systems (USA), EOS (Germany), and CMET (Japan). Along with the conventional polymeric components, variations

To create structures utilizing photo-curable polymers, researchers have also created alternative methods using digital mask generators, such as the digital micromirror device (DMD) .The DMD-based SLA technique is faster and less expensive than UV-laser-based SLA since it does not require expensive laser equipment and instead exposes a whole layer at once rather than scanning with a single laser beam. [2]

An additive manufacturing technology called Multi-Jet Modeling (MJM) use a method similar to ink-jet printing but with many nozzles. A linear array of jets is produced by the print head. On demand, each individual jet releases UV curable polymer (or wax). A UV light flashes to cure the polymer that was deposited after each single layer was built using the MJM head's back and forth movement. When a layer is finished, the platform descends by the

thickness of that layer and the following layer is added on top of the preceding layer. Until the complete component is constructed, this process is repeated. The MJM technique has benefits including lower costs, quicker development times, and office friendliness. 3D Systems is the industrial producer of the MJM apparatus. Jetted Photopolymer, a related method, deposits layers of photopolymers to create components using wide-area inkjets. Objet (Israel) created the jetted photopolymer method, which Stratasys just bought. [2]

Rapid Freeze Prototyping (RFP) is an intriguing, but not yet widely used, additive manufacturing (AM) method that creates ice objects by layer-by-layer selectively depositing and freezing water droplets. In this procedure, the temperature inside the structure is kept below the freezing point of water. Each layer is constructed by spraying water over the already-solidified ice surface using a nozzle. The ice surface of the preceding layer cools the newly formed water layer mostly by conduction. As a result, the water is quickly frozen and adheres to the top layer to create a new one. RFP employs water as the primary building material, making it a green method. Fig. 1 is an example of an ice component created by the RFP procedure. Investment casting using ice patterns is another possible industrial use, in addition to creating ice sculptures. [14].

2.2.2 Filament/paste

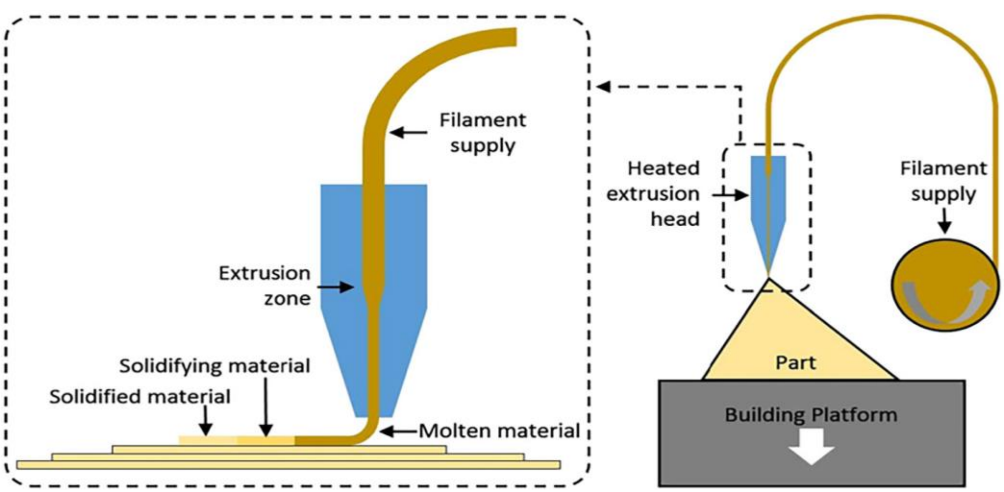

Figure 6. Fusion deposition Modelling (FDM). [3]

In the late 1980s, fused deposition modeling (FDM) was created. Stratasys Inc. (USA), a prominent maker of FDM systems. This procedure uses a moving head to deposit a thread of molten material, often made of plastic filament, onto a substrate. The material is heated within the head to a temperature just over its melting point. It is then extruded onto a substrate through a nozzle and cooled until it hardens and creates a layer. Research has advanced to the point that it now makes use of a multi-nozzle system [15], where each nozzle deposits a unique material to create things with novel features.

An additive manufacturing (AM) technology called robocasting creates 3D parts by layer-by-layer extruding aqueous ceramic pastes. Ceramic paste is extruded through a nozzle and placed on a substrate in robocasting. The vertical axis of the gantry system is raised by one layer thickness after each layer is deposited before the next layer is applied. Until the entire section is constructed, this phase is repeated. For the robocasting process to work, paste characteristics must be controlled. In order to quickly apply the next layer, the paste typically dries from a fluid-like condition to a solid-like one within 10 to 15 seconds of being applied. The deposits will emerge as liquid beads that spread out of control if the paste is too thin. Deposits that are excessively thick will resemble rope. Each layer that is deposited may have a rectangular cross section with somewhat straight walls and flat tops if the paste has the right viscosity and consistency. [2]

Similar to robocasting, the Missouri University of Science and Technology (Missouri S&T) invented a process called freeze-form extrusion fabrication (FEF) , where each layer hardens by freezing the deposited aqueous paste. In order to harden the paste once it is extruded on the substrate, the complete machine is enclosed in a freezer box that keeps the temperature below the freezing point of water. The FEF method provides a number of distinctive benefits, such as the capacity to produce functionally graded components from various materials, a much-decreased organic binder requirement, environmental friendliness, and inexpensive equipment costs. [16]

2.2.3 Powder

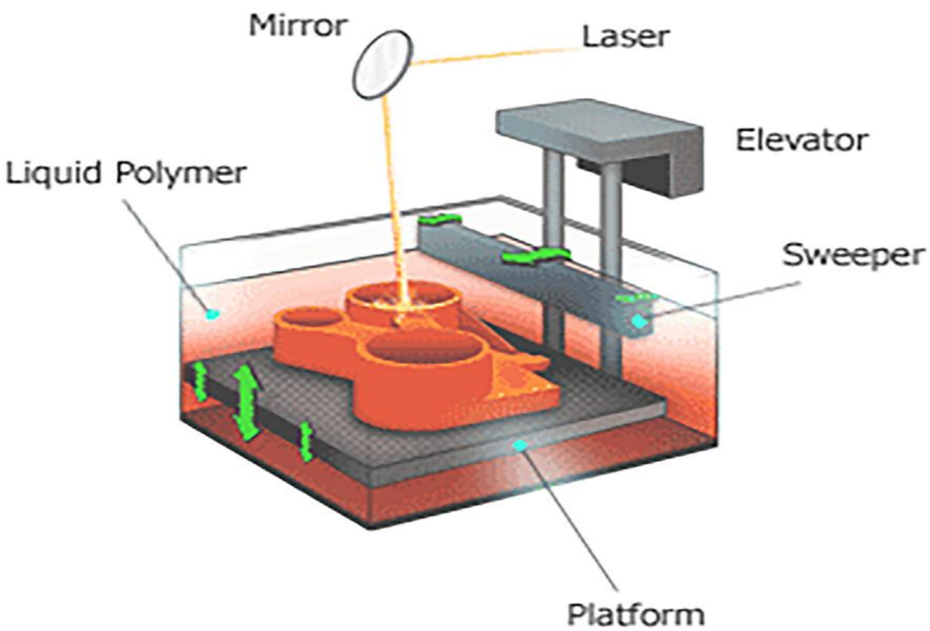

Figure 7. Stereolithography. [3]

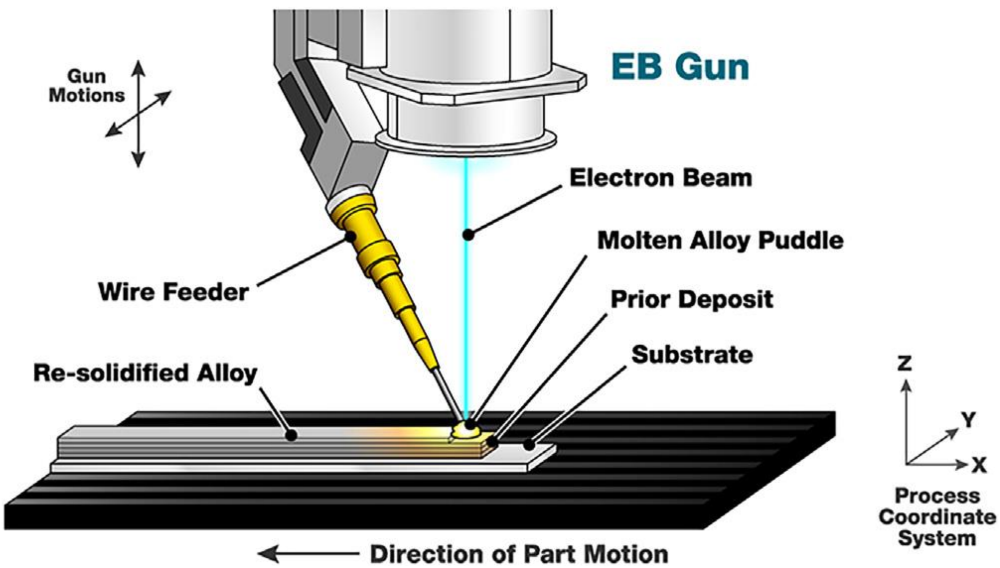

Figure 8. Nozzle of Electron Beam Melting (EBM). [3]

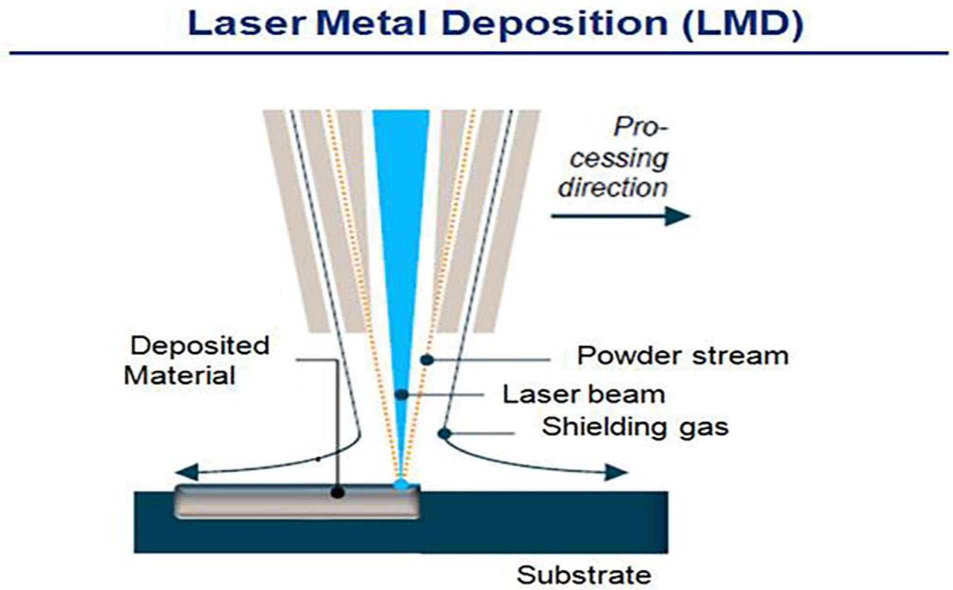

Figure 9. Direct laser metal forming/sintering (DLMF/DLMS). [3]

This group of additive manufacturing (AM) techniques focuses on applying material in powder form and selectively forming the item with a targeted heat source to create each layer. A couple of variations are Laser Metal Deposition (LMD), in which powder is sprayed and deposition locally and melted by a focused high-power laser beam, and Selective Laser Sintering (SLS), in which powder is first dispersed in a layer and then scanned selectively by a laser. The fabrication of metal components is the topic of two SLS-derived versions. They are electron beam melting (EBM), in which an electron beam serves as the heat source, and selective laser melting (SLM), in which powder is totally melted rather than just partially melted in SLS.

Three-Dimensional Printing (3DP) is a different powder-based AM technique in which a component is made from the powder bed by selectively spraying liquid binder, which hardens to form a layer. Powder-based AM techniques have two key benefits over other AM methods: they can work with a wide variety of materials, from those with low melting temperatures to those with high melting points, and they don't need any support structures to manufacture components. [2]

Selective Laser Sintering (SLSTM, or Laser Sintering (LS)) is an additive manufacturing (AM) technique that employs a laser beam to selectively fuse and sinter polymer particles by scanning cross-sections on the surface of a powder bed layer-by-layer into an object that has the desired 3-dimensional shape based on a CAD model.

The powder bed is lowered by one layer thickness after each cross-section is scanned, a fresh layer of material is applied on top, and the process is repeated until the component construction is finished. Wax, polymers, polymer/glass composites, polymer/metal powders, metals, and ceramics are just a few of the rather broad spectrum of powder materials that SLS may use to create components from. [17]

The binding processes include liquid phase sintering, partial melting, chemically driven binding, and solid-state sintering. For components made of metal and ceramic, polymer is either coated on the metal or ceramic particles or combined with them to act as a binder. To get rid of the binder and finish sintering the item, post-processing is necessary. SLS does not need support structures since the component being created is surrounded by unsintered powder, unlike certain other AM methods like SLA and FDM. 3D System and EOS are two significant commercial manufacturers of SLS equipment. [2]

A technique evolved from SLS is called selective laser melting (SLM). A strong laser beam is used to totally melt the metal powder, creating an almost entirely dense metallic object that doesn't need any more processing. Mechanical qualities that are on par with or better than those of rolled metal sheets are produced as a consequence. Due of the high energy input required to melt the metal particles, which results in issues such balling, the creation of residual stress, and component deformation, the SLM process is more challenging to regulate. Commercial SLM equipment is produced by companies including MCP Realizer, EOS, and SLM Solutions. The alloys employed in this technique right now include titanium, cobalt chromium, inconel, and stainless steel. [18]

Due to the use of a power bed, the recently developed AM method known as electron beam melting (EBM) [19] resembles the SLM procedure in several ways. The main distinction is that the energy source for the EBM process is an electron beam as opposed to a laser beam. EBM creates components by melting metal powder in a high vacuum chamber layer by layer while using an electron beam. The pieces that were created are completely thick, void-free, and incredibly powerful. Because of its higher energy density and faster scanning rate compared to SLM, EBM often has a better build rate; nevertheless, the part's surface polish is not as excellent. Arcam in Sweden created and markets the EBM procedure.

As with SLM, the powder is entirely melted by a laser beam during the AM technique of laser metal deposition (LMD), which also goes by the names Laser Engineered Net Shaping (LENS), Direct Metal Deposition (DMD), or laser cladding. This produces totally dense components without the need for post-processing. The availability of the powder material is the primary distinction between LMD and SLM. In LMD, a powder feeding nozzle (coaxial or off-axial) supplies the material locally, whereas in SLM, the component is created in a powder bed. Due to the extremely narrow heat-effect zone produced by the process, LMD may create exceedingly thin walls.

LMD may be utilized for repair and wear/corrosion protection applications since it can construct material layers directly on a 3D part's surfaces [20]. Optomec (LENSTM), AeroMet (LasformTM), and Precision Optical Manufacturing (DMDTM) are commercial LMD process providers.

The AM technique known as three-dimensional printing (3DP) [21] involves building the component in a powder bed. A liquid binder is sprayed onto a layer of powder using an inkjet printing head, where it congeals to produce a solid coating. A new layer of powder is then added as the piston holding the component falls by one layer thickness. The varieties of materials that may be employed with the 3DP process are highly versatile. Any mixture of a powdered substance and a binder with a viscosity low enough to produce droplets may be employed. 3DP may be used to create items made of plastic, ceramic, metal, and metal ceramic composite materials.

Due to density restrictions on dry powder dispersion, the components have the drawback of being porous. To produce completely functioning components, postprocessing techniques like sintering and/or infiltration are used [22]. Z Corporation, which was purchased by 3D Systems in 2012, and 3D Systems jointly market the technology.

2.2.4 Solid sheet

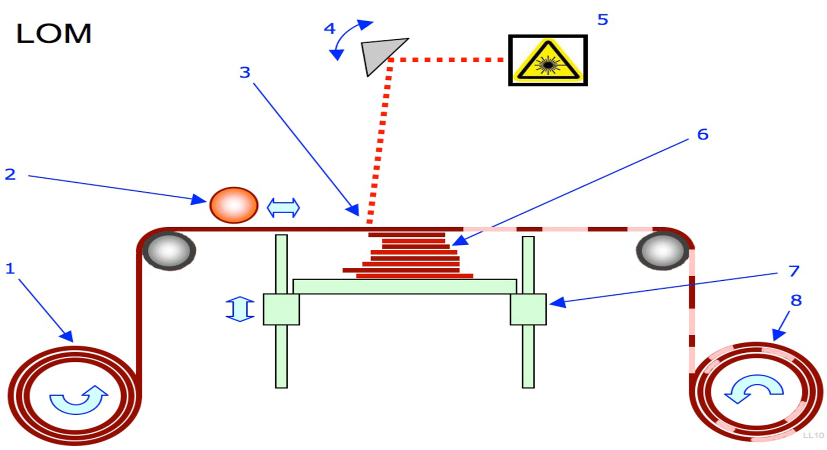

Figure 10. Laminated object manufacturing: 1 Foil supply. 2 Heated roller. 3 Laser beam. 4. Scanning prism. 5 Laser unit. 6 Layers. 7 Moving platform. 8 Waste. [23]

Solid material is supplied in sheet form for the Laminated Object Manufacturing (LOM) process. Cutting a cross-section out of the sheet and connecting it to the item being made are phases in the process. A laser is used to cut a sheet of material along the contours of the part's geometry as defined by the CAD model, which is stretched out on a flexible substrate. When a heated roller compresses the sheet and activates a heat-sensitive adhesive, the layers adhere. [2]

Plastic, laminated metal, or layers of paper with an adhesive coating can all be utilized as the materials in this method. The fundamental benefit of this technique is that it can produce finished products quickly since the laser just needs to scan the part's contour, not its whole cross-section. It is challenging to get a very excellent surface finish since the quality of the surface finish relies on the thickness of the sheet. The main commercial LOM system was developed by Helisys Inc. in the USA, which was subsequently acquired by Cubic Technologies in the USA. [23]

2.3 Materials Used for 3D Printing Technology in Manufacturing Industry

To create consistently high-quality products, 3D printing requires high quality materials that adhere to strict requirements, much like any other manufacturing process. Procedures, demands, and agreements about material controls are developed between the suppliers, buyers, and end-users of the material in order to achieve this. A broad variety of materials, such as ceramic, metals, polymers, and their mixtures in the form of hybrid, composite, or functionally graded materials (FGMs), may be produced using 3D printing technology to create completely functioning components. [24].

Table 2. Materials and corresponding AM processes [2]

Material	Type	AM process(es)	Material(s)
Polymers [a])	Thermo-setting	SLA, MJM	Photo-curable polymers
	Thermo-plastic	MJM	Wax
		SLS	Polyamide 12, GF polyamide, polystyrene
		FDM	ABS, PC-ABS, PC, ULTEM
		3DP	Acrylic plastics, wax
Metals [a)]		SLM	Stainless steel GP1, PH1 and 17-4, cobalt chrome MP1, titanium Ti6Al4V, Ti6Al4V ELI and TiCP, IN718, maraging steel MS1, AlSi20Mg

		LDM/LENS	Steel H13, 17-4 PH, PH 13-8 Mo, 304, 316 and 420, aluminum 4047, titanium TiCP, Ti-6-4, Ti-6-2-4-2 and Ti6-2-4-6, IN625, IN617, Cu-Ni alloy, cobalt satellite 21
		EBM	Ti6Al4V, Ti6Al4V ELI, cobalt chrome
Ceramics b)		SLA	Suspension of Zirconia, silica, alumina, or other ceramic particles in liquid resin
		FDM	Alumina, PZT, Si3N4, zirconia, silica, bioceramic
		SLS	Alumina, silica, zirconia, ZrB2, bioceramic, graphite, bioglass, and various sands
		3DP	Zirconia, silica, alumina, Ti3SiC2, bioceramic, and various sands
Composites b)	Uniform composites	FDM	Polymer-metal, polymer-ceramic, short fiber-reinforced composites
		3DP	Polymer-matrix, metal-ceramic, ceramic-ceramic short fiber-reinforced composites
		LOM	Polymer-matrix, ceramic-matrix, fiber and particulate reinforced composites
		SLS, SLM	Metal-metal, metal-ceramic, ceramic-ceramic, polymermatrix, short fiber-reinforced composites
	FGM	LMD/LENS	CoCrMo/Ti6Al4V, TiC/Ti, Ti/TiO2, Ti6Al4V/IN718
		FDM	PZT
		FEF	Al2O3/ZrO2

Notes: a) Commercially available materials for AM processes; b) materials under research and development [2]

2.3.1 Metals

Due to the benefits offered by this approach, metal 3D printing technology has attracted a lot of attention in the industrial, aerospace, and automotive industries . Metal materials offer exceptional physical qualities, making them suitable for application in a variety of sophisticated manufacturing processes, including the printing of human organs and aircraft components. Aluminum alloys, cobalt-based alloys , nickel-based alloys , stainless steels , and titanium alloys are a few examples of these materials. [25]

A cobalt-based alloy is appropriate for use in dental applications for 3D printing. Its high specific stiffness, robustness, high recovery capability, elongation, and heat-treated conditions are the reasons for this. Additionally, the use of nickel base alloys in 3D printing technology may be used to make aeronautical parts . Nickel base alloy-based 3D-printed objects can be utilized in hazardous locations. This is due to its strong corrosion resistance and ability to withstand temperatures of up to 1200 °C . [25]

Finally, titanium alloys may also be used to build the thing utilizing 3D printing technology. Unique qualities of titanium alloys include ductility, strong resistance to corrosion and oxidation, and low density. It is utilized, for instance, in aircraft components and the biomedical industry where there are high strains, high operating temperatures, and high stresses. [25]

2.3.2 Polymers

The fabrication of polymer components, from prototypes to functional constructions with challenging geometries, is a common use of 3D printing technology [26]. Through the application of consecutive layers of extruded thermoplastic filament, such as polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), polypropylene (PP), or polyethylene (PE), a 3D printed object may be created using fused deposition modeling (FDM) [26].

PEEK and PMMA thermoplastic filaments, which have greater melting points, may now be utilized as 3D printing materials [34]. Due to their low cost, low weight, and processing flexibility, 3D printing polymer materials in liquid state or with low melting point are widely employed in the industry. Most typically, polymer-based materials played a significant part in biomaterials and medical device goods as inert materials, helping to ensure the devices' effective operation and provide mechanical support in many orthopaedic implants [25].

2.3.3 Ceramics

By optimizing the conditions and setting up appropriate mechanical qualities, 3D printing technology today can manufacture 3D printed objects from ceramics and concrete without noticeable pores or fractures . Ceramic is sturdy, long-lasting, and flame-resistant. Ceramics may be utilized in almost any geometry and shape because of their fluid condition before setting, making them ideal for the design of new structures and buildings . Ceramic materials are important in the dentistry and aerospace industries, claims . Examples of these materials include zirconia, bioactive glasses , and alumina . [25]

For instance, 3D printing technology has the ability to process alumina powder. Alumina is a superb ceramic oxide with many uses, including as a catalyst, adsorbent, in microelectronics, in chemicals, in the aerospace industry, and in other high-tech fields . Alumina requires a sophisticated curing process [38]. Complex-shaped alumina components with high after-sintering densities and high green densities may be manufactured utilizing 3D printing technology . [25]

Additionally, in a subsequent experiment, dancing parts were created using a stereolithographic (SLA) machine to manufacture glass-ceramic and bioactive glass. It greatly enhances this material's bending strength. The possibility to use bioactive glass in pertinent therapeutic structures like scaffolds and bone will increase with the mechanical strength. It is possible to create solid bulk ceramics with high densities, extremely homogenous microstructures, and high compression and bending strengths utilizing stereolithographic ceramic manufacturing (SLCM) . Zirconia is the primary building material in the nuclear power industries, and it is used for element tubing. Zirconium devoid of havnium is ideal for this purpose due to its low radiation sensitivity and low thermal neutron absorption [27].

2.3.4 Composites

High-performance industries have been transformed by the outstanding adaptability, light weight, and tailorable features of composite materials. Carbon fiber reinforced polymer composites and glass fiber reinforced polymer composites are two examples of composite materials. A large portion of the aerospace industry uses carbon fiber reinforced polymer composite structures because of their high specific stiffness, strength, superior corrosion resistance, and good fatigue performance . In addition, glass fiber reinforced polymer composites have a wide range of uses in 3D printing applications and have a large range of prospective applications due to their excellent performance and cost-effectiveness. [25]

High thermal conductivity and a modest coefficient of thermal expansion characterize fiberglass. Fiberglass is also non-flammable and unaffected by the curing temperatures used in manufacturing processes, making it an excellent material for use in 3D printing . [25]

2.3.5 Smart materials

Smart materials are those that have the capacity to change an object's geometry and shape in response to environmental factors like heat and moisture . Self-evolving structures and soft robotic systems are examples of 3D printed items made with intelligent materials. As 4D printing materials, smart materials can also be categorized. form memory alloys and form memory polymers are two examples of group smart materials [28]. Some shape-memory alloys, such as nickel-titanium , can be used to micro-electromechanical systems and biomedical implants.

Temperatures used during the transformation process, as well as the repeatability of microstructure and density, are crucial considerations in the manufacture of 3D printed nickel-titanium goods. Shape memory polymer (SMP), on the other hand, is a sort of functional material that reacts to stimuli like light, electricity, heat, certain types of chemicals, and so on [28]. Shape memory polymer's complex shapes might be produced quickly and simply by employing 3D printing technology. Based on the component density, surface roughness, and dimensional correctness, this material's quality is assessed [28].

2.3.6 Specials materials

Examples of specific materials include:

• Food: Using food materials like chocolate, meat, sweets, pizza, spaghetti, sauce, and so forth, 3D printing technology can process and generate the appropriate shape and geometry . Because consumers may change the contents of materials without diminishing the nutrition or flavor of the ingredients, 3D-food printing can manufacture nutritious meals [29].

• Lunar dust: Using a 3D printing technology, it is possible to create multi-layered items directly from lunar dust, which might be useful for future moon settlement [30].

• Textile: With the advancement of 3D-textile printing technology, the jewelry and apparel industries will soar. Short processing times for products, lower packaging costs, and lower supply chain expenses are some benefits of 3D printing technology in the fashion sector [31].

2.4 Application of Additive Manufacturing

2.4.1. Aerospace industry

Unparalleled design flexibility in component and manufacturing is made possible by 3D printing technology. The aircraft sector can create complicated, enhanced, and lightweight parts using 3D printing, which might minimize the amount of energy and resources needed. . Using 3D printing technology can also result in fuel savings as it can utilize less material to make aeronautical parts.

Furthermore, the manufacture of replacement parts for particular aircraft components, such engines, has made extensive use of 3D printing technology. Parts of the engine are readily damaged and need to be replaced frequently. As a result, the use of 3D printing technology to get such spare parts is an excellent idea. [25]. Nickel-based alloys are increasingly favoured in the aerospace sector because of their tensile qualities, oxidation/corrosion resistance, and damage tolerance. [25].

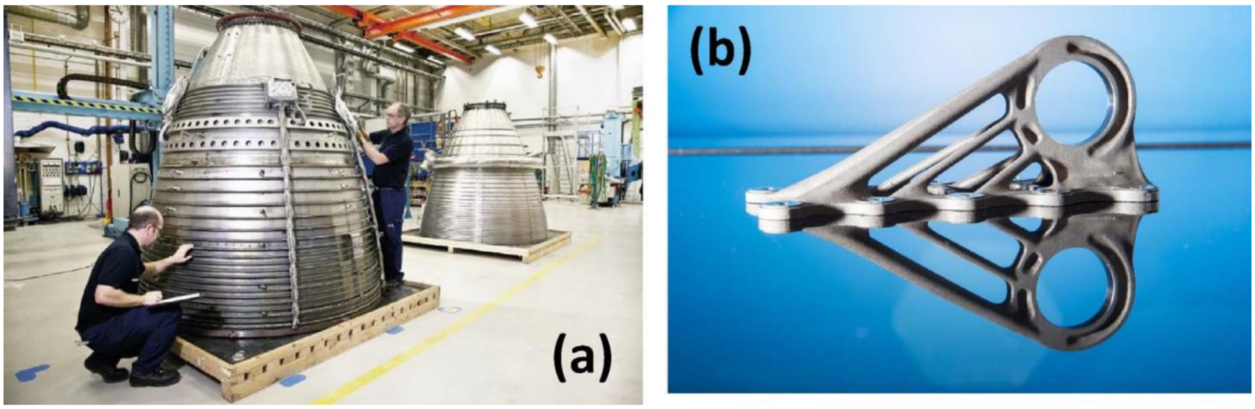

Figure 11. (a) In the foreground, Vulcain 2 demonstration nozzle with more than 50 kg of DED material [32]; (b) AM Titanium brackets for AW350 XWB [33].

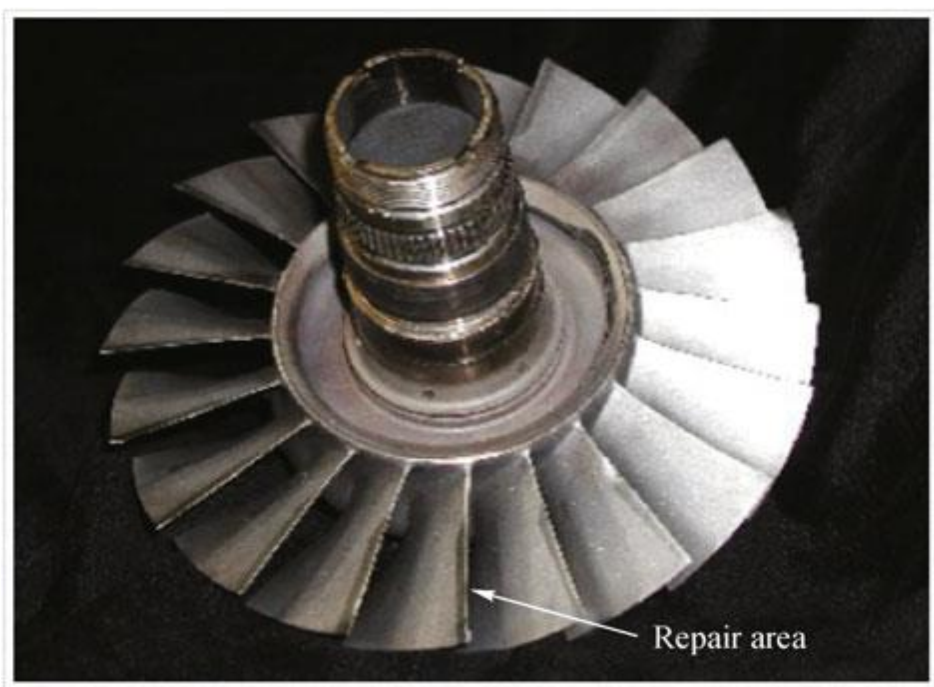

Figure 12. Damaged blisk repaired using LENS (Source: Optomec [33])

2.4.2. Automotive industry

Today's 3D printing technology has drastically altered our industry's ability to create, develop, and produce new products. The 3D printing phenomenon has brought new shines to the car sector by enabling lighter and more complex constructions in a short amount of time. For instance, Local Motor produced the first electric vehicle printed in three dimensions in 2014. By producing a 3D-printed bus dubbed OLLI, Local Motors expanded the spectrum of uses for 3D printing technology beyond only automobiles. OLLI is a 3D printed, electric, recyclable, and incredibly intelligent bus. Additionally, Ford is a pioneer in the application of 3D printing technology and uses it to create prototypes and engine parts. [25]. BMW also employs 3D printing to create hand tools for testing and assembling automobiles. In contrast, AUDI and SLM Solution Group AG worked together in 2017 to create prototypes and replacement components. [25]. As a result, the use of 3D printing technology in the automobile sector allows businesses to experiment with different ideas and focus early on in the development process, leading to the creation of optimal and efficient car designs. In addition, 3D printing technology helps cut down on resource use and waste. Additionally, 3D printing technology may save money and time, making it possible to test new ideas quickly. [25].

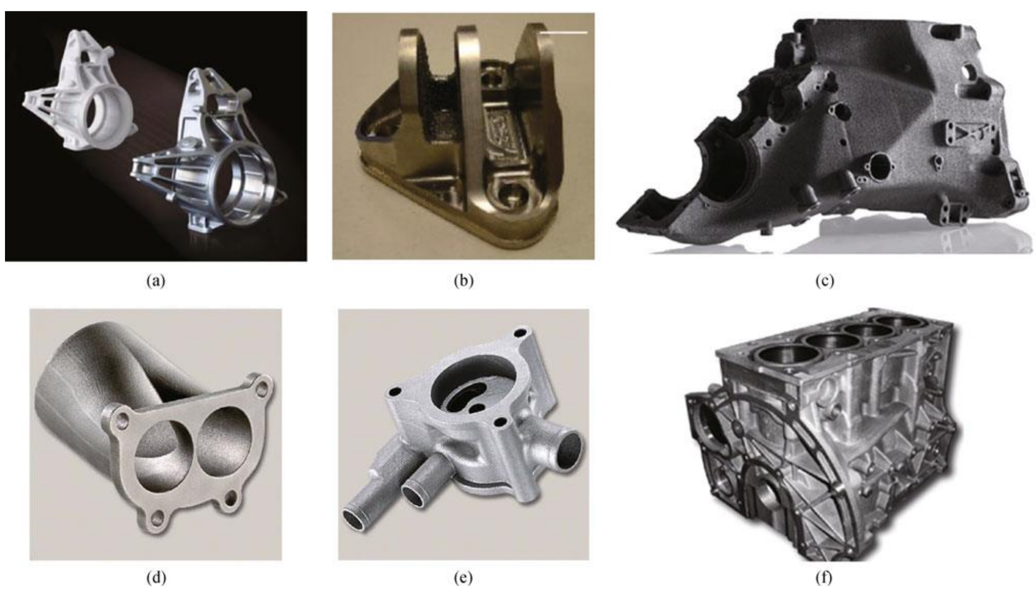

Figure 13. (a) F1 upright (right) cast via rapid casting process using polystyrene patterns produced by SLS (left) (Source: CRP Technology[35]); (b) suspension mounting bracket for Red Bull Racing produced by LENS (Source: Optomec [34]); (c) race car gear box produced by EBM (Source: Arcam [124]); (d) exhaust manifold produced by SLM (Source: Concept Laser [36]); (e) oil pump housing produced by SLM (Source: Concept Laser [37]); (f) engine block cast using the mold and cores fabricated by 3DP (Source: Prometal [38])

2.4.3. Food industry

Technology such as 3D printing has made the food business possible as well as the aircraft sector. Presently, there is an increasing demand for the creation of customized foods for people with specific dietary needs, such as athletes, children, pregnant women, and patients, who require a different amount of nutrients by reducing the amount of unnecessary ingredients and enhancing the presence of healthy ingredients. [25]. However, creating personalised foods requires careful planning and innovative execution, which is where the use of 3D-food printing comes into play.

Food layer fabrication, also known as 3D-food printing, is created by depositing successive layers one at a time that are directly produced from computer-aided design data. [25]. Specific materials may be combined and processed using 3D printing technology to create a variety of intricate structures and shapes. . It is possible to construct novel food dishes with intricate and intriguing designs and shapes using sugar, chocolate, pureed foods, and flat foods like spaghetti, pizza, and crackers.

The creation of food using 3D printing technology is highly energy efficient, cost-effective, and ecologically benign. Due to its ability to generate new methods for food modification and to adapt to each person's tastes and needs, 3D printing of food may be beneficial for humans and be healthy. It would be conceivable to create diets that impose themselves without the requirement for exercise by allowing food preparation and ingredients to be automatically changed to the consumer's information. [25].

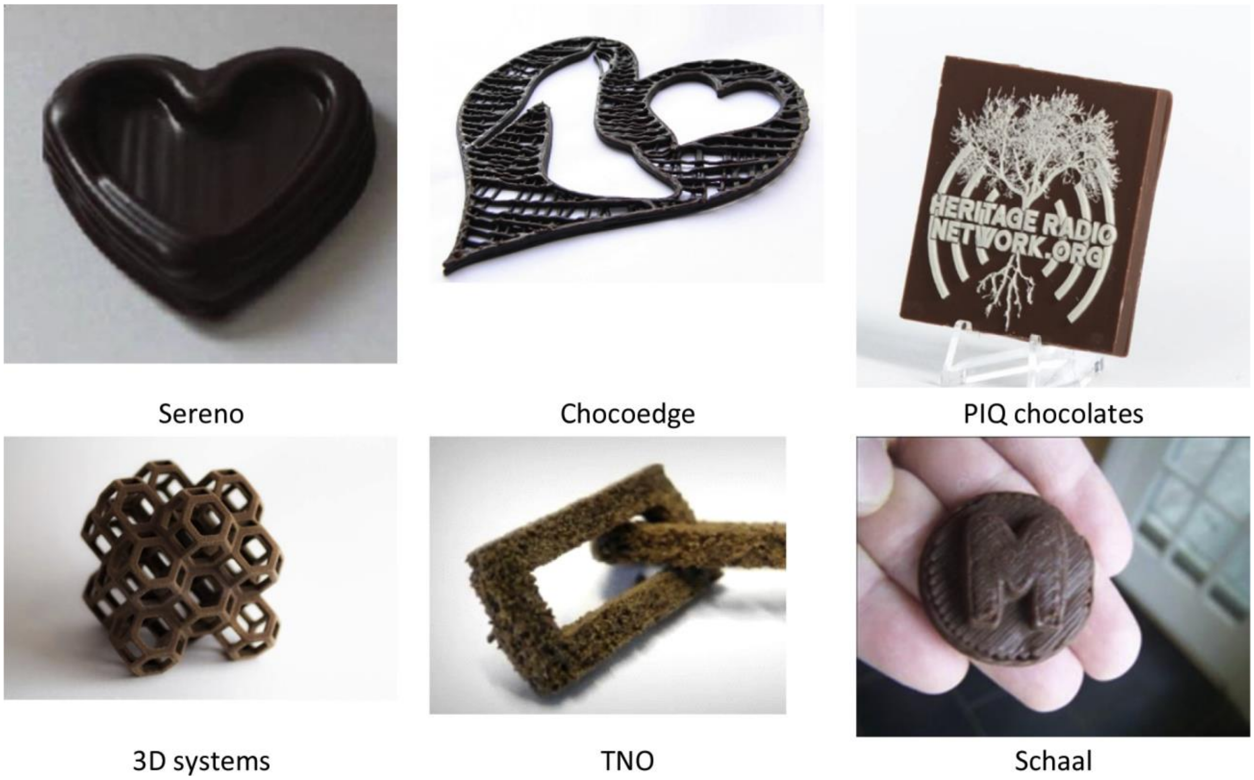

Figure 14. The current state of the art of chocolate printing relies on three techniques: Robocasting, 3DP, and SLS. The robocasting processes have difficulty maintaining temper, but cannot make intricate 2D designs onto seed layers. 3DP and SLS processes tend to produce a granular texture which is most similar to chocolate powder.

2.4.4. Healthcare and medical industry

The application of 3D printing technology has been reported for the creation of 3D skin [60], bone and cartilage , replacement tissues , organs , cancer research , and finally, models for communication, teaching, and visualization. The following are some benefits of 3D printing technology for biomedical products:

The natural structure of the skin may be duplicated using 3D printing technology at a lesser cost. Chemical, cosmetic, and medicinal items can be tested on 3D printed skin. Therefore, testing items on animals does not need to be done. By employing a duplicate of the skin, the researcher will be able to obtain an exact result. .

• By employing 3D printing technology to print drugs, efficiency may be increased. Dropped size and dose can be accurately controlled, there is excellent consistency, and it is possible to create dosage forms with complicated drug-release patterns. [25].

• Bony holes in the cartilage or bone brought on by damage or illness can be filled with printed cartilage and bone thanks to 3D printing technology. Because it focuses on generating bone, maintaining it, or improving its function in vivo, this therapy differs from others that involve auto-grafts and allografts.

• The function of the tissues can also be improved, maintained, or replaced using 3D printing technology. The 3D-printed replacement tissues have a linked pore network, are biocompatible, have the right surface chemistry, and have acceptable mechanical characteristics.

• Similar organ failure brought on by serious issues like sickness, accidents, and congenital deformities may also be printed out using 3D printing technology.

• Technologies like 3D printing have the potential to speed up cancer research since they can create highly controlled models of cancerous tissues. The patients can obtain more dependable and precise information by utilizing 3D printing technology.

• To aid neurosurgeons in learning surgical procedures, 3D printed models can be used. As a 3D model is a simulation of a genuine patient's pathological state, it can increase accuracy, take the trainer less time when executing clinical procedures, and offer chances for hands-on training for surgeons. [25]

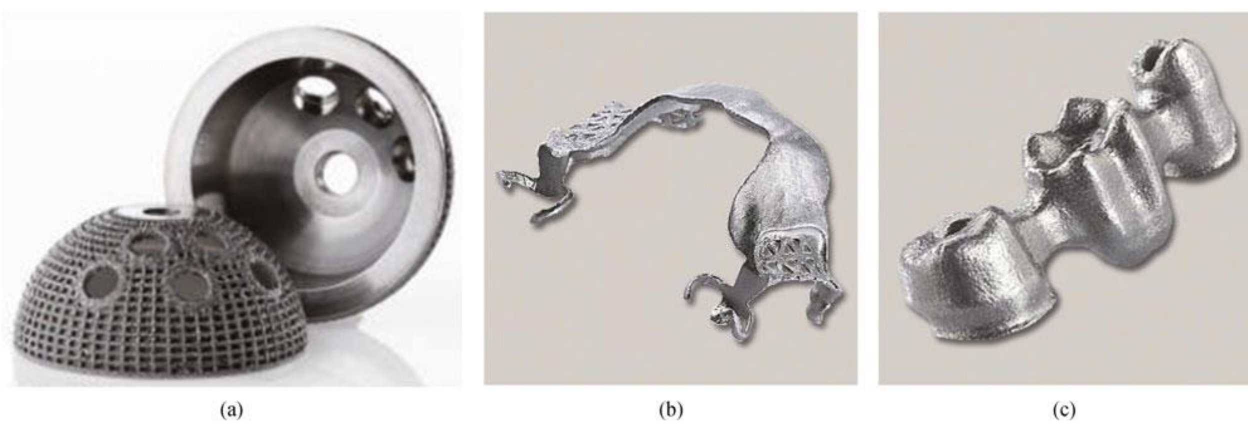

Figure 15. (a) Acetabular cups with designed porosity (material: Ti6Al4V) produced using EBM (Source: Arcam [36]); (b) dental

prosthesis (material: Ti6Al4V) produced using SLM (Source: Concept Laser [37]); (c) 3-unit dental bridge (material: CL111 CoCr) produced using SLM (Source: Concept Laser [37])

Figure 16. (a) Hip stems with mesh, hole and solid configurations fabricated using EBM (Source: [40]); (b) functional hip stems with designed porosity (no porosity,<2 vol% porosity, and 20 vol% porosity) fabricated using LENS (Source: [41])

2.4.5. Architecture, building, and construction industry

Technology for 3D printing may be seen as an ecologically friendly derivative that offers countless opportunities for realizing geometric complexity. Construction companies may employ 3D printing technology to generate large buildings or individual construction elements. Better use of 3D printing technologies will be made possible by the development of BIM (Building Information Modelling). Building information modeling, which can communicate information and knowledge about 3D buildings, is a digital representation of functional and physical properties. It may serve as a trustworthy source of information for decisions all throughout the building's life cycle, from conception to destruction. [25]. The built environment may be designed, developed, and maintained more effectively with the help of this creative and cooperative technology. With the use of 3D printing technology, businesses can quickly and affordably design and produce the building's appearance, as well as prevent delays and assist identify trouble areas. Construction engineers and their clients can converse more effectively and clearly thanks to 3D printing technology. A customer's expectations are often based on a concept, and 3D printing makes it simple to realize that vision outside of the archaic use of paper and pencil . The Apis Cor Printed House in Russia and the Canal House in Amsterdam [25] are two examples of 3D printed structures.

Figure 17. (a) First 3D printed house by DusArchitects [42]; (b) 3D printed house by WinSun [2].

2.4.6. Fabric and Fashion Industry

When 3D printing technology is used in the retail sector, the market will start to see 3D printed footwear, jewelry , consumer products, and clothes . Though it may not seem like a natural match, fashion and 3D printing are starting to coexist in everyday life all around the world. Large corporations, such as Nike, New Balance, and Adidas, are attempting to establish the mass manufacture of 3D printed shoes. These days, 3D printed athletic shoes, bespoke shoes, and sneakers are manufactured [25].

Additionally, the use of 3D printing technology can expand fashion design's creative options. In fact, it enables the creation of forms without the need of molds. With the use of 3D printing technology, the fashion industry is able to design and create clothing utilizing a mesh system and print embellishments for conventional textiles. In addition, 3D printing technology may be used to create leather goods and accessories in addition to products for the fashion sector. Jewelry, timepieces, accessories, and so forth are some examples. [25].

The goal of producing fashion items using 3D printing technology, according to merchants and designers, is to improve product design by providing customers with personalized and unique products.The use of 3D printing technology in product creation has several benefits, including on-demand bespoke fit and style. In the interim, the cost of the supply chain may be decreased by adopting 3D printing technology. Last but not least, 3D printing technology can quickly produce and transport modest quantities of goods [25].

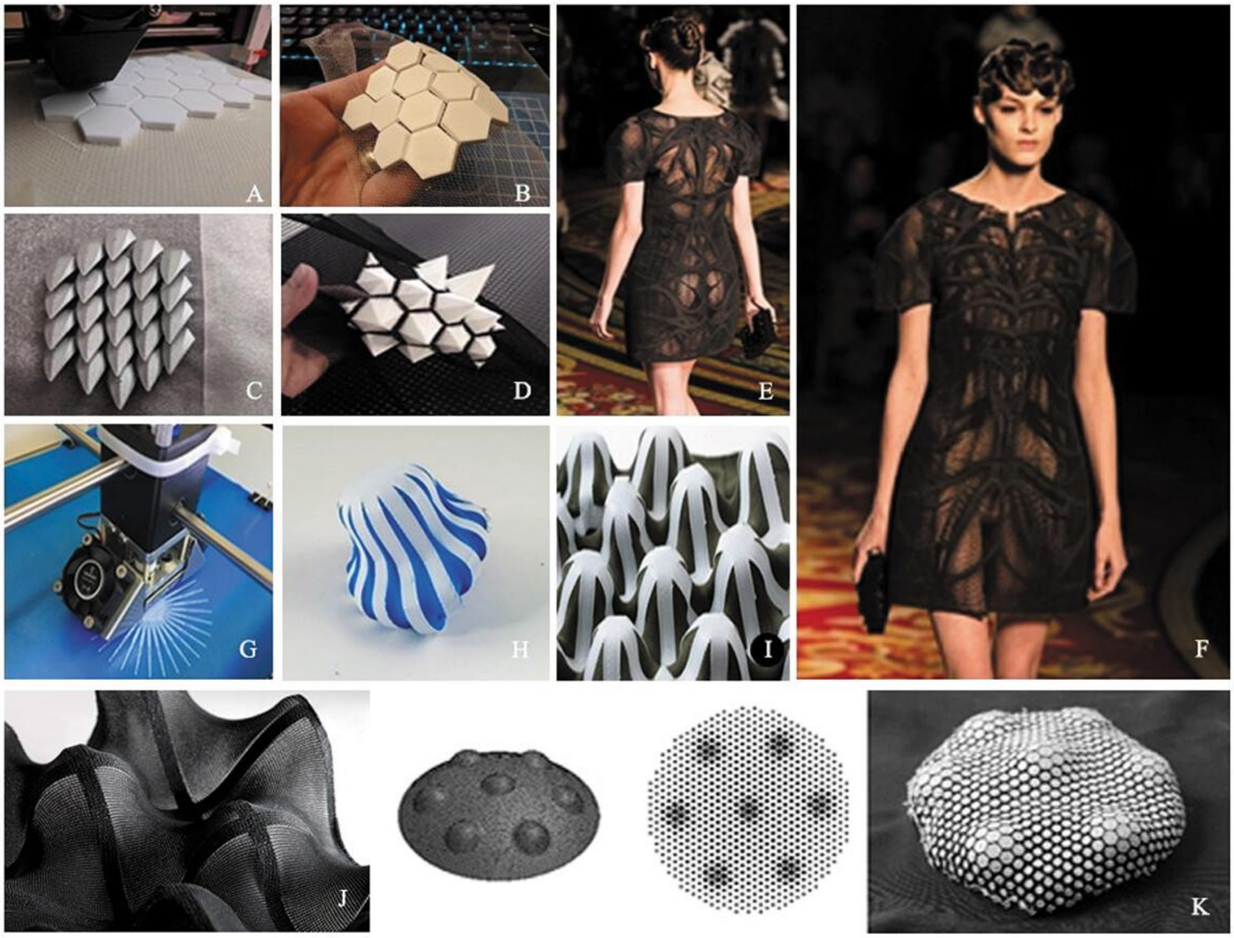

Figure 18. Some exciting examples of how additive manufacturing can be integrated with textiles/fabrics. (a), (b): Hexagons; image from: (CitationDrainSmith) (c): Dragon scales; Image from: (CitationShorey) (d): Hexagonal pyramids; image from: https://www.geeetech.com/blog/2018/02/3d-printing-on-fabric-is-easier-than-you-think/ (e), (f): TPU additive manufactured (via Selective Laser Sintering) standalone dress (left and middle images) made in collaboration with Iris van Herpen, Julia Koerner and the company Materialise; Image from: https://www.materialise.com/en/cases/iris-van-herpen-debuts-wearable-3d-printed-pieces-at-paris-fashion-week (g), (h): Self-forming structures on stretched fabric showing intrinsic curvature. After additive manufacturing plastic onto a textile surface, the resultant print forms a 3D object reminiscent of a jellyfish; Image from: (CitationGabe Fields) (i), (j) Regions of alternately positive and negative Gaussian curvature. Image from: (CitationGabe Fields, XXXX, CitationYYYY, XXXX) (k): CAD model, that is used to generate the pattern to print onto fabric and then the resulting stricture with intrinsic curvature; Image from: (CitationGabe Fields). [43]

2.4.7. Electric and Electronic Industry

Manufacturers are beginning to see the promise of 3D printing realized in a variety of fascinating ways as it becomes more and more accessible to the sciences, technology, and industrial areas. Today, a variety of 3D printing technologies have already been widely used to structural electronic devices, including electrodes, active electronic materials, and devices with mass customisation and adaptable design. [25].

By leveraging the Fused Deposition Modelling of 3D printing technology, the manufacturing process for the 3D electrode offers a low-cost and time-efficient method for mass producing electrode materials. Unlike conventional electrodes made of aluminum, copper, or carbon, the 3D electrode's shape and surface area are easily adaptable to a specific application. Additionally, the completely automated, highly precise 3D printing procedure for the 3D electrode allowed for the quick completion of the manufacturing process for eight electrodes in just thirty minutes. [25].

Additionally, any electronic device or component that has the ability to control and magnify electric flow charges is considered an active electronic component. In addition, active gadgets also include those that have a power source. Silicon-controlled rectifiers, transistors, diodes, operational amplifiers, light-emitting diodes (LEDs), batteries, and so on are examples of active electronic components. Due to their extensive capabilities, these components often need manufacturing techniques that are much more involved than those employed for passive components. [25].

The processing of products and their electronics is facilitated by 3D printing technology. With the use of multi-material printing technology, Industry Revolution 4.0 may embrace the effectiveness of electronic systems, allowing for the creation of more creative designs in a single step. [25].

There is an urgent need for the creation of green electronic devices with cheap manufacturing costs, excellent safety, high dependability, and quick production to combat environmental pollution in today's society. [25].

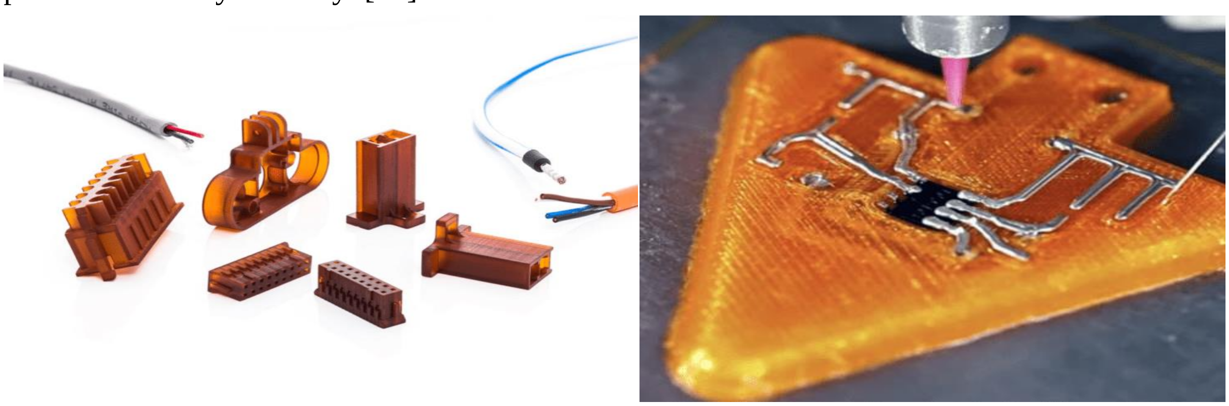

Figure 19. Left)3D printed parts used in the electronics industry (Source: Cubicure)

Right) Printer printing onto a plastic surface (Image: Technocrazed) [44]

3. Material and Methods

3.1 Materials

In our experiment we used composite polymer material (PETG). These materials are widely used in additive manufacturing, especially for FDM 3D printing. These materials have better melting and cooling properties which makes it suitable for additive manufacturing. In this section we will discuss the basic properties and compare both materials.

3.1.1 PETG: Polyethylene terephthalate glycol-modified

The material known as polyethylene terephthalate glycol-modified, or PETG for short, is primarily utilized in industrial applications such as advertising displays and electronic insulators. Additionally, there are a number of medical applications for it, including dental aligners, implants, and packaging for medical components. In the 3D printing world, PETG is commonly utilized in models that need great shock opposition or some adaptability, similar to snap-to-fit parts. Because it is non-toxic, FDA-approved, and does not deteriorate in water, it is also a preferred material for food-related prints. [45]

The substance PET, which was developed in 1941 for use as synthetic fiber in the textile industry, served as the basis for PETG. Beginning in the early 1950s, PET was used to package food, and starting in the mid-1970s, it was also utilized to make bottles. PET, the most widely used plastic in the world, is still utilized for all of them, notably plastic bottles.

PET, on the other hand, has drawbacks. At high temperatures, it tends to crystallize, making it opaque and weakening its structure. It loses its strength and becomes bubbly, making it incompatible with 3D printing. These drawbacks were overcome when PETG was developed.

PETG and PBT are chemically produced differently, while having comparable chemical compositions. A lengthy chain of polyethylene terephthalate is produced by esterifying glycol and terephthalic acid, claims TWI Global, to produce PET. In contrast, cyclohexane di-methanol, a bigger monomer, is used to create PETG in place of ethylene glycol. By avoiding PET's tightly packed molecules, crystallization is less likely. [45]

PETG combines the qualities of PET with glycol as a copolymer. Due to this combination, there are fewer overheating problems with PET. The major characteristics of polyethylene terephthalate glycol are ductility, transparency, chemical and impact resistance, and hardness. PETG is a readily extruded polymer with strong thermal stability that is especially suitable for purposes involving food. For 3D printing, polyethylene terephthalate glycol works exceptionally well. [46]

PETG is simpler to work with and has similar printing settings to ABS. For instance, PETG prints without an enclosure because it is largely odorless. It needs a lot of heat, just like ABS. The ideal nozzle temperature is typically between 220 °C and 260 °C. Additionally, PETG requires a heated bed with a temperature range of 60 to 80 °C. [45]

In our experiment we used 3 types of PETG from different manufactures as our base materials for the experiments. The properties of these base materials are given below:

Table 3 : Used 3 types of PETG from different manufactures

PETG Types	Manufactures	Diameter	Net Weight	Printing Temperature	Colour
Carbon PETG	Spectrum	1.75 mm	0.5kg	230-255	Black
PETG-Black	Extrudr	1.75 mm	1.10kg	210-235	black
PETG-Blue	Filanora	1.75 mm	1 kg kg	210-235	blue

Table 4 : Material properties of PETG (Extrudr) [47]

Maximum Stress	High
Elongation at Break	high flexibility
Temperature Resistance	Up to 90°C
Ease of Printing	slightly advanced
Visual Quality	gloss-like finish with vibrant colors
Layer Adhesion	very good
Impact Resistance	very good

Table 5 : Printing Properties of PETG (Extrudr) [47]

Printing Temperature	230°C
Print Bed Temperature	80°C
Printing Speed	50 mm/s
Botton Layer	30
Top Layer	50

Table 6 : Material properties of Carbon PETG (Specturm) [48]

Matte surface quality	High
Shrinkage	No
Mechanical properties	Good
Compression resistance	Higher than pure PETG
VICAT	80°C
Abrasion resistance	Improved compared to pure PETG
Plasticization temperature	Higher than pure PETG
Hardness and rigidity	Improved compared to pure PETG

Table 7 : Printing properties of Carbon PETG (Specturm) [48]

Printing temperature	230-250°C
Bed temperature	70-90°C
Print speed	30-70 mm/s
Recommended shell thickness	0.40 - 2.70mm
Recommended layer height	≥ 0.15mm
Cooling	75-100%

Table 8 : Material Properties of PETG (Filanora) [49]

Product line	PET-G
Product types	PET-G Filament
Filament colour	blue
Diameter:	1.75 mm
Shrinkage rate	Low
Hydrophobic ability	does not absorb water
mechanical properties	Excellent
Recyclable	Yes

Table 9 : Printing Properties of PETG (Filanora) [49]

Product line	PET-G
Product types	PET-G Filament
Filament colour	blue
Diameter:	1.75 mm
Shrinkage rate	Low
Hydrophobic ability	does not absorb water
mechanical properties	Excellent
Recyclable	Yes

3.1.2 Jute Fiber

The most popular natural fiber used as reinforcement in green composites is jute. Jute is one of the low-cost natural fibers and is now the bast fiber with the highest production volume. It is a type of bast fiber from the Tiliaceae family, and its formal name is corchorus capsularis since it is extracted from plants of the corchorus genus. Although jute is naturally associated with the Mediterranean, the best types for its cultivation are presently provided by Bangladesh, India, China, Nepal, Thailand, Indonesia, and Brazil.[50,51].

Moisture, acid, and UV light resistance in jute fibers is lower. On the other hand, their fine texture and fire and heat resistance offer a wide variety of applications in sectors including textile, construction, and automotive [52].

Table 10: Chemical constituents of jute fiber. [53]

Cellulose (%)	Hemicellulose (%)	Lignin (%)	Wax & Pectin (%)
61.2	23.2	13.7	0.5
61–73.2	13.6–20.4	12–16	-
61–71	14–20	12–13	-

Table 11: Physio-mechanical properties of jute fiber.[53]

Density (g/cm3)	Tensile Strength (MPa)	Young's modulus (GPa)	Elongation at break (%)
1.3	393–773	26.5	1.5–1.8
1.3–1.46	393–800	10–30	1.5–1.8
1.3–1.45	393–773	13–26.5	1.16–1.5

3.2 Equipments

In our experiment we used a few machines for material preparation and testing. In this section, a brief overview of used machines and equipment will be explained.

3.2.1 FDM 3D printer

A FDM 3D printer was used to print standard specimens for tensile testing of the PETG materials. In this case, we used Greeetech, A20M FDM 3D printer. Geeetech A20M 3D printer is reliable, cost-effective and easy-to-operate. It has printing accuracy of 0.1 mm, deliver exquisite prints with delicate texture, sleek contour and stable structure. [54] The working principle of FDM 3D printer is discussed in details in the literature review section. Table 12 shows the printing parameter of Greeetech, A20M FDM 3D printer.

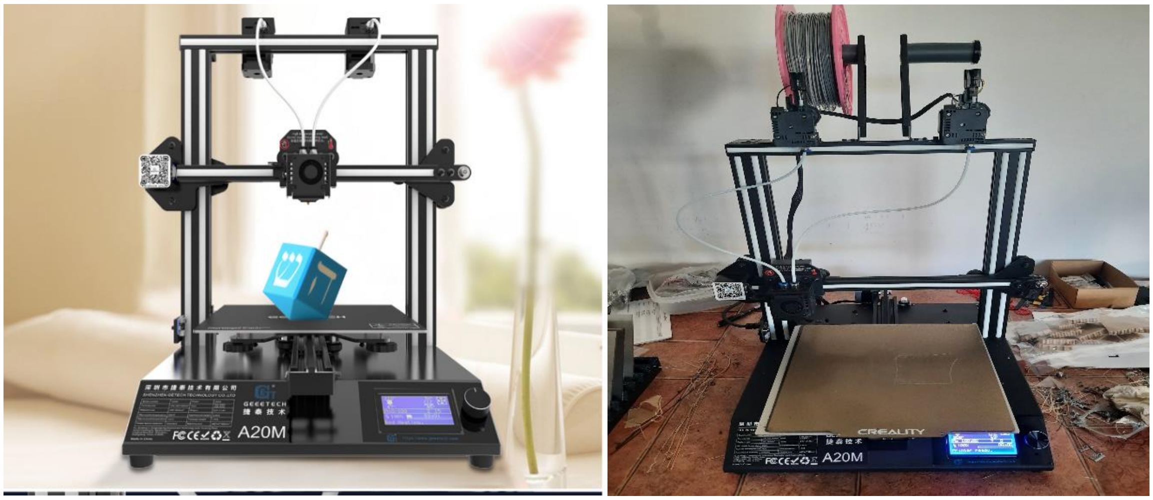

Figure 20. Greeetech, A20M FDM 3D printer (left: website photo, Right: Used in LAB)

Table 12. Printing parameter of Greeetech, A20M FDM 3D printer [54]

Printing technology	FDM
Build volume	255*255*255 mm³
Printing accuracy	0.1mm
Positioning precision	X/Y : 0.011mm. Z : 0.0025mm
Printing speed	120 mm/s (max) : 120 mm/s (max)
Filament diameter	1.75mm
Nozzle diameter	0.4mm
Filament	ABS/PLA/wood-polymer/PVA/HIPS/PETG
Max temp for hotbed	100℃
Max temp for extruder	250℃
Control software	Repetier-Host, Simplify 3D, Cura, Slic3r
File format	.STL, G.code

3.2.2 Filament cutter and material mixture

During our experiment we used The WŻ-1 grinder to cut our filaments and mix our filament with jute fiber. The WŻ-1 grinder is one of the most popular universal laboratory hurricane grinders. At first, filament was cut by hand scissor with suitable small pieces and then it was poured into the grinder. Then the grinder cuts the filament in very small pieces in 5 seconds. The same process was repeated while mixing the jute fiber with filaments.

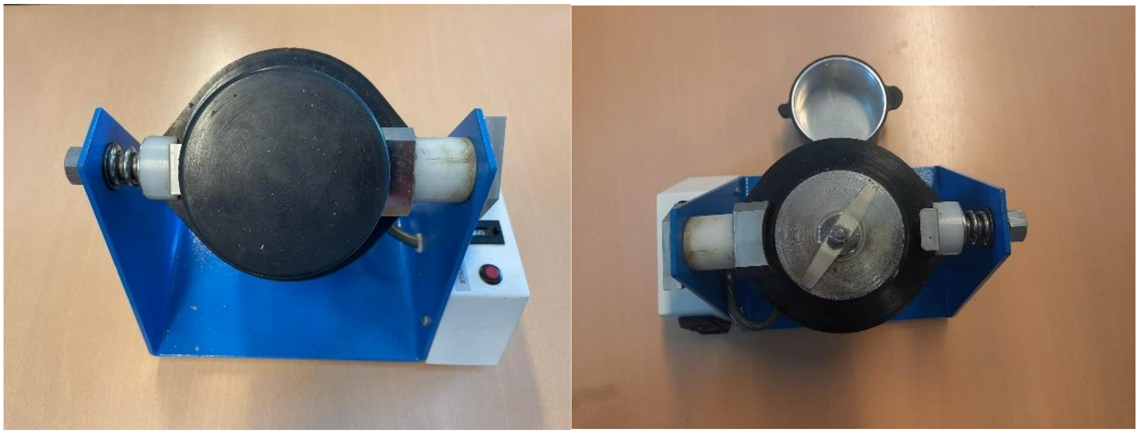

Figure 21. The WŻ-1 grinder for filament cutting and mixing

3.2.3 Axio Lab A1 Microscope

Axio Lab A1 Microscope was used to take good quality pictures of the jute fiber. After taking a close picture of the small piece of jute fiber (nearly 1-2 mm), the length and the diameter of the fiber was calculated (as shown in the picture below). The diameter of the jute fiber was 79.71 µm.

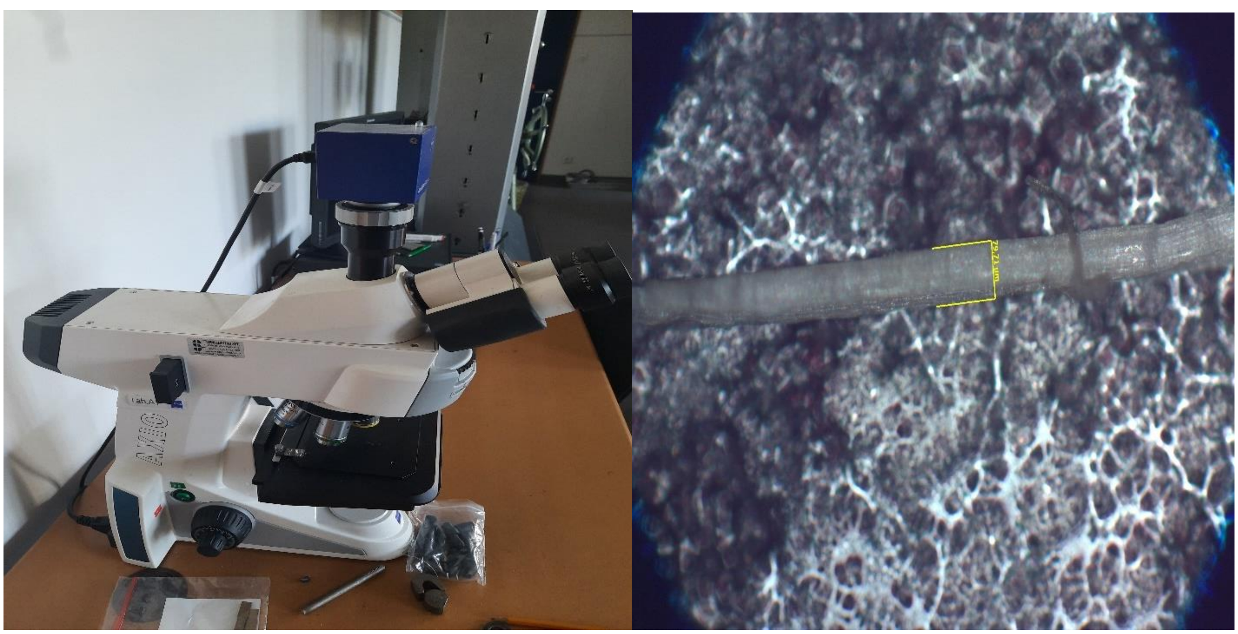

Figure 22. Axio Lab A1 Microscope and a Close picture of jute fiber

3.2.4 Filament maker

A filament maker machine was used to make the filament after cutting the filament by the WŻ-1 grinder machine. The small pieces of filaments were poured into the filament maker's feeding house and then the machines make the filaments. The similar process is used to make the reinforced jute fiber PETG filament. The machine's parts was mostly build by 3D printer and was build-in-our-laboratory.

Working procedure of filament maker are : 1) Pour the cuts filament / jute fiber mixed filament into the house 2) Set the machine temperature (200 degree Celsius) 3) Wait until the machine reaches the set temperature 4) Start the machine to make filament and adjust the required feeding speed 5) Start the filament collector from the machine.

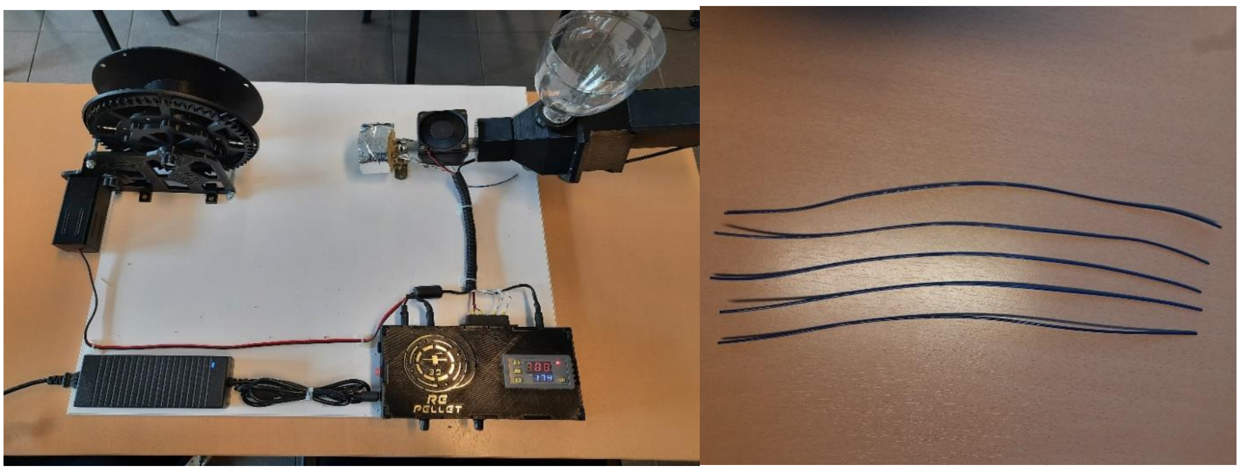

Figure 23. Filament maker and the produced filaments

3.2.5 Bollard style tensile grips

After making filament and jute reinforced filament using the filament maker machine, tensile test was performed to test the filament's mechanical properties. In this case we used a special grippers, the bollard style gripper, to hold the filament for tensile test instead of using the conventional gripper used by the tensile test machine. We had to use the special bollard type gripper because of the circular shape of the filament and for the small diameter of the filament. Otherwise, it's not possible to grip the filament using the conventional grips used by the machine for tensile testing.

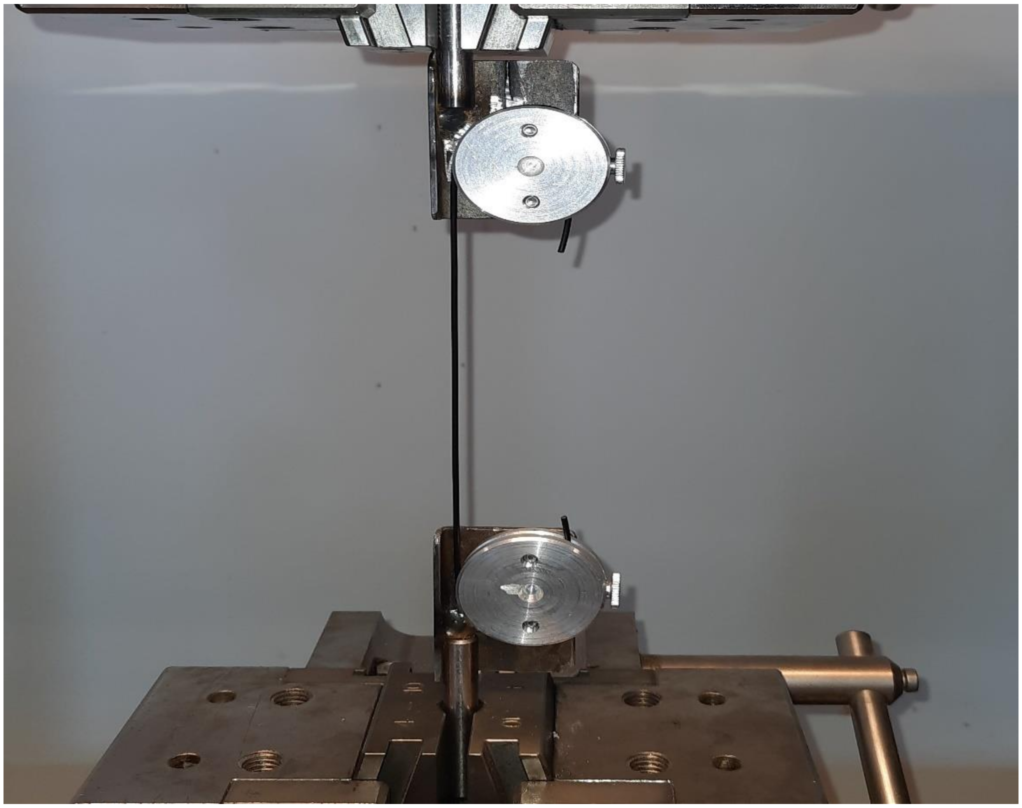

Figure 24. Bollard style tensile grips

3.2.6 Zwick Z100 materials testing machine

A Zwick Z100 materials testing machine was used for tensile testing of the filaments and the reinforced filaments. The ZWICK Z100 testing machine is equipped with tools that facilitate strength tests of round, screwed, grip head diameter M8 to M16, and flat samples with thicknesses up to 8 mm. Users can perform static tensile tests on any material at room temperature or at temperatures up to 1200^{o}C. Essential extent of offered tests through Zwick Z100 machine for tests at raised temperature. The parameters required by the standards PN-EN ISO 6892-1 and PN-EN ISO 6892-2 were determined during the static tensile test, static compression test, and Young module E, Etc. determinations.

Figure 25. Zwick Z100 materials testing machine

3.3 Methods

Several methodologies were performed during our work period, including tensile test of the original PETG, recycling the used PETG, making jute fiber reinforced PETG, tensile testing and result analysis of those different types of PETG. In this section a short overview of those methodologies will be explained.

3.3.1 Printing the standard specimen using FDM 3D printer

At the beginning, 3 types of PETG materials were printed with the ISO 527-2-5A standard. For the designing the standard, Solid Edge software was used and then it was converted to STL file to import it in a slicing software. The slicing software, Ultimaker Cura 5.1.0, set the printing parameter and the position of the specimen in the bed and a G-Code file was generated which is the standards for FDM printer.

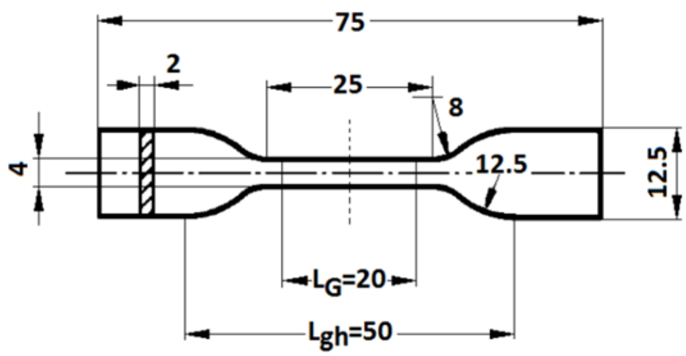

Figure 21. The ISO 527 - 2 - 5A Specimen (mm) [55]

The printing parameter using by slicing software, Ultimaker Cura 5.1.0, are given below (see pictures):

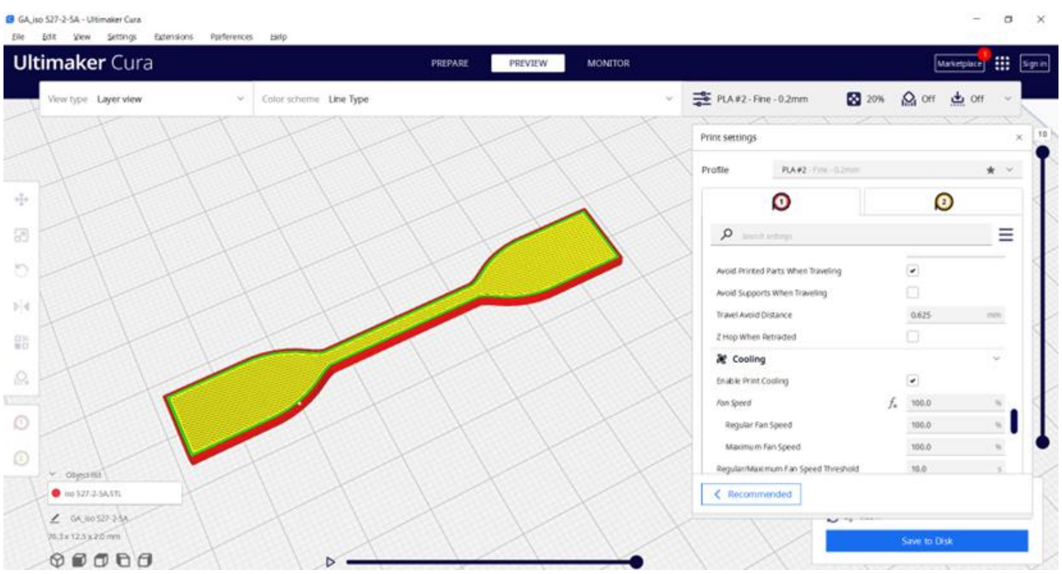

Figure 22. The main interface of the Ultimaker Cura 5.1.0 .

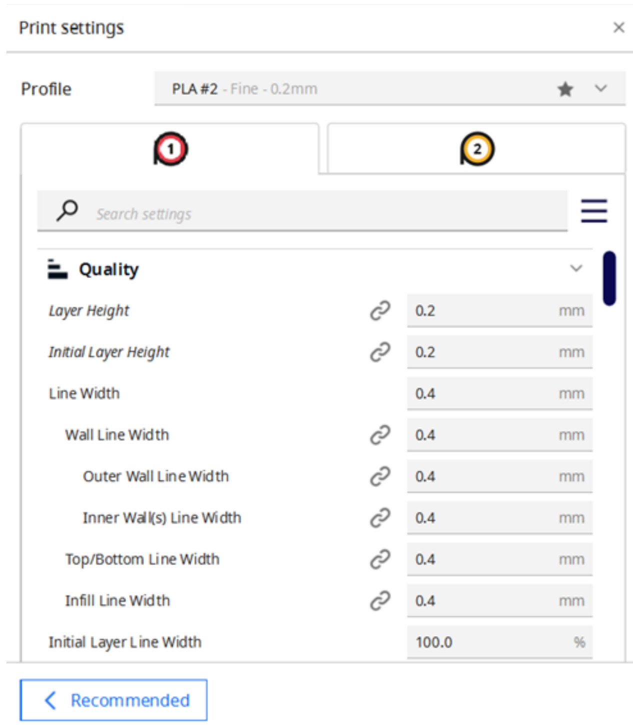

Figure 23. The Quality Setting

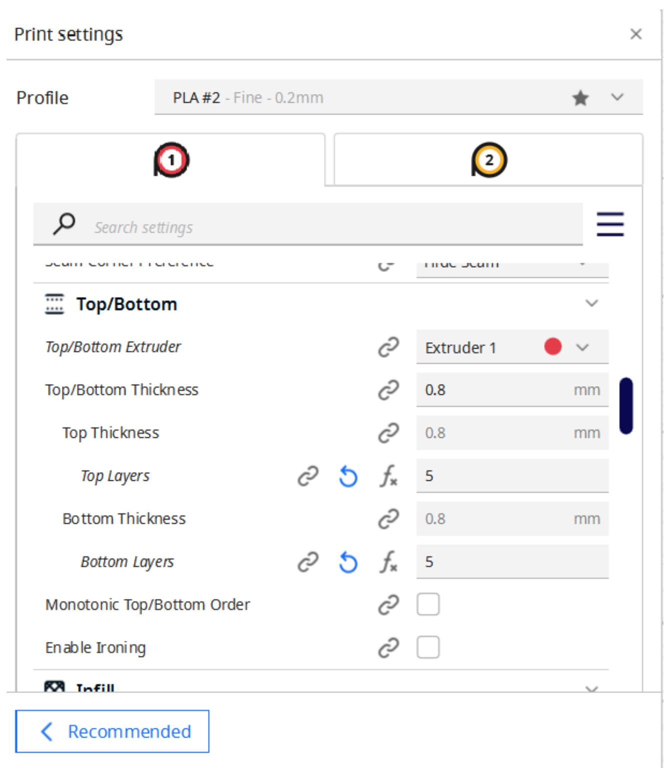

Figure 24. The Top/Bottom Setting

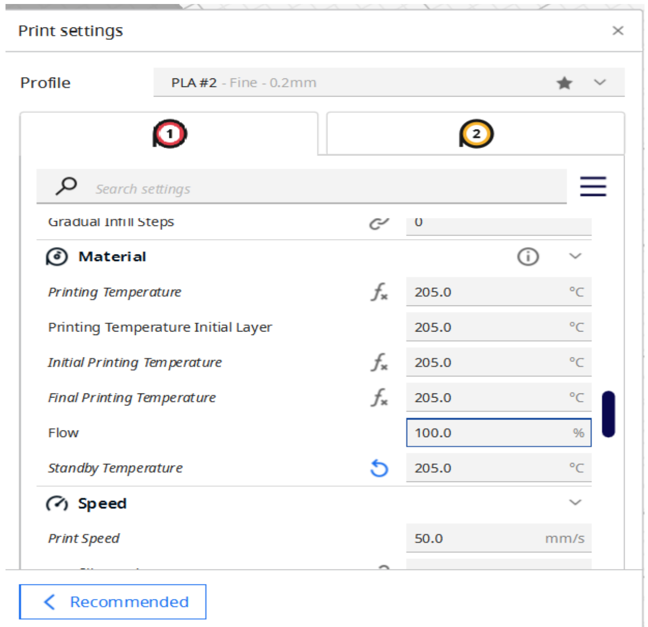

Fig 25. The Material Settings

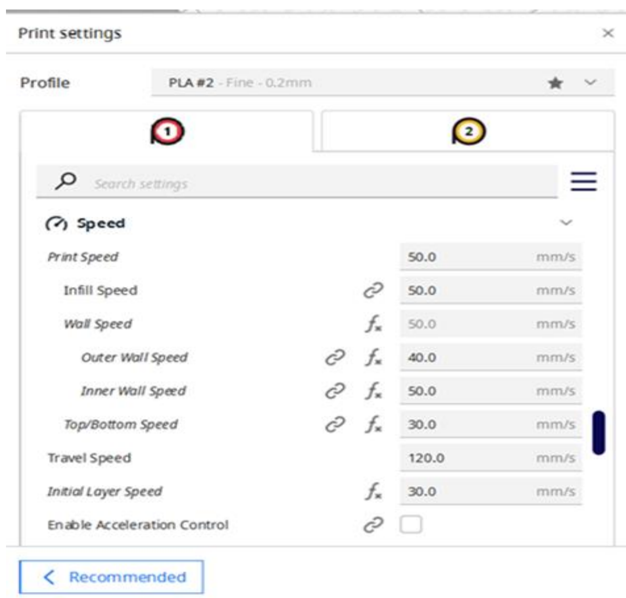

Figure 26. The Speed Setting

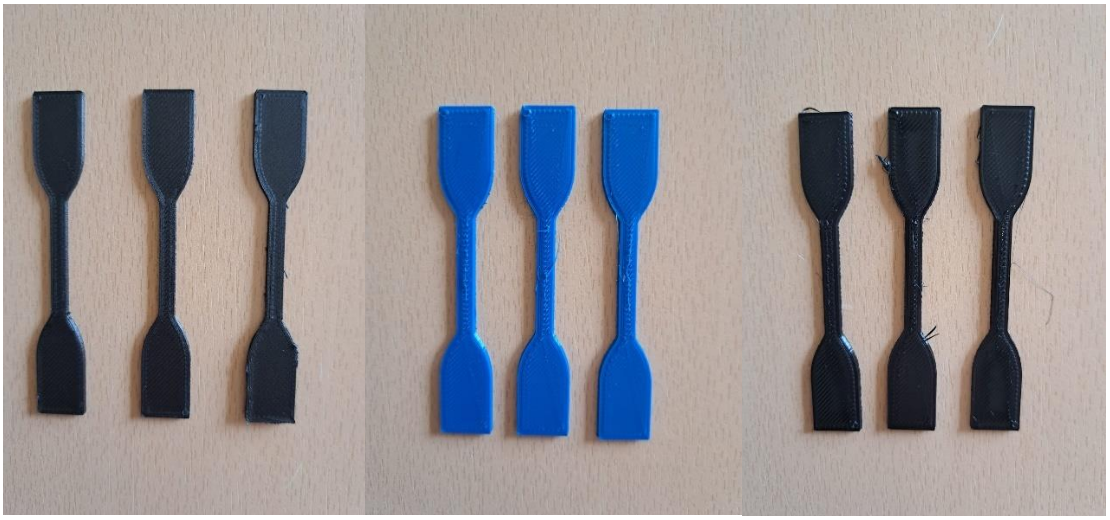

Figure 27. Printed Specimens using FDM 3D printer (left to right: Extrudr, Filanora and Spectrum)

3.3.2 Testing the tensile test of the 3D printed PETG specimen.

After printing the 3D printed standard specimens, it was tested in the tensile test machine. A set of 3 samples were printed from each type of PETG filament and tested. The results were saved in an excel file for comparing and discussion with other tensile tested specimens.

Figure 28. Tensile test of the printed PETG standards

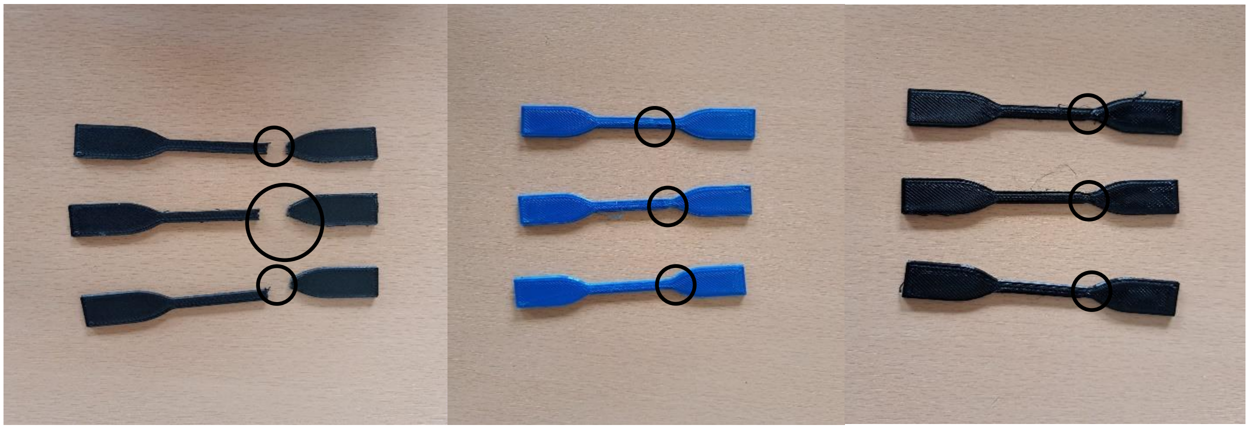

Figure 29. Tested specimens of 3D printed standards (left to right: Spectrum-Carbon, Filanora-Blue, Extrudr-Black)

3.3.3 Testing the tensile test of original PETG: Filaments

We tested the original PETG filaments to know their tensile strength. Later, these measures help us to compare the results of recycled PETG filaments and jute fiber reinforced PETG fiber. In our thesis we used 3 types of PETG: 1) Carbon PETG, Black 2) PETG, Black 3) PETG, Blue from different manufactures. Tensile tests were carried out for 3 types of PETG, and the result was stored in the excel file. Tensile tests were performed by a tensile test machine, Zwick Z100 materials testing machine, and special bollard type grippers were used to grip the small cylindrical filaments. The length of the test specimens was 300 mm and the length between the two-testing point (in bollard grip) was 150 mm.

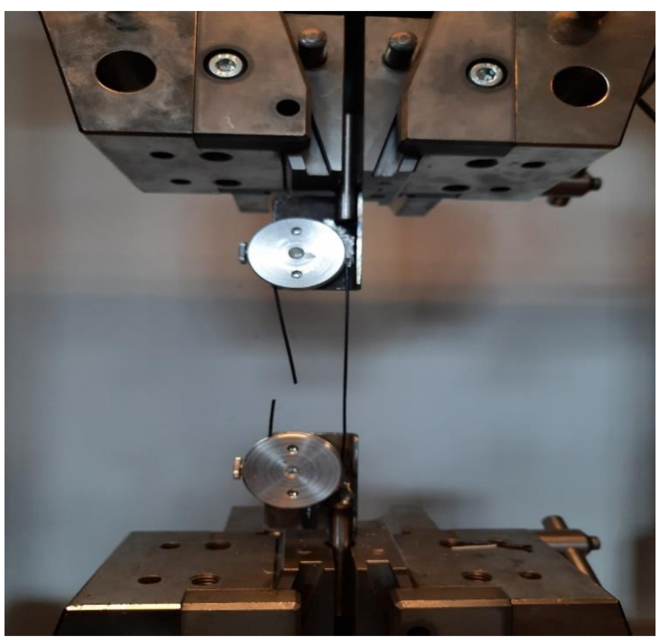

Figure 30 : Tensile testing of original PETG filaments

3.3.4 Recycling the used PETG filaments and making new filaments.

As a part of our experiments, used PETG filaments were collected for recycling then it was recycled using the filament maker. At first, collected filaments were cuted into small pieces (1-2 mm length) by using the grinder machine and then it was poured into the filament maker machine. The set temperature of the filament maker was 200 °C , the feeder speed and the filament collector speed was controlled depending on the filament output of the machine.

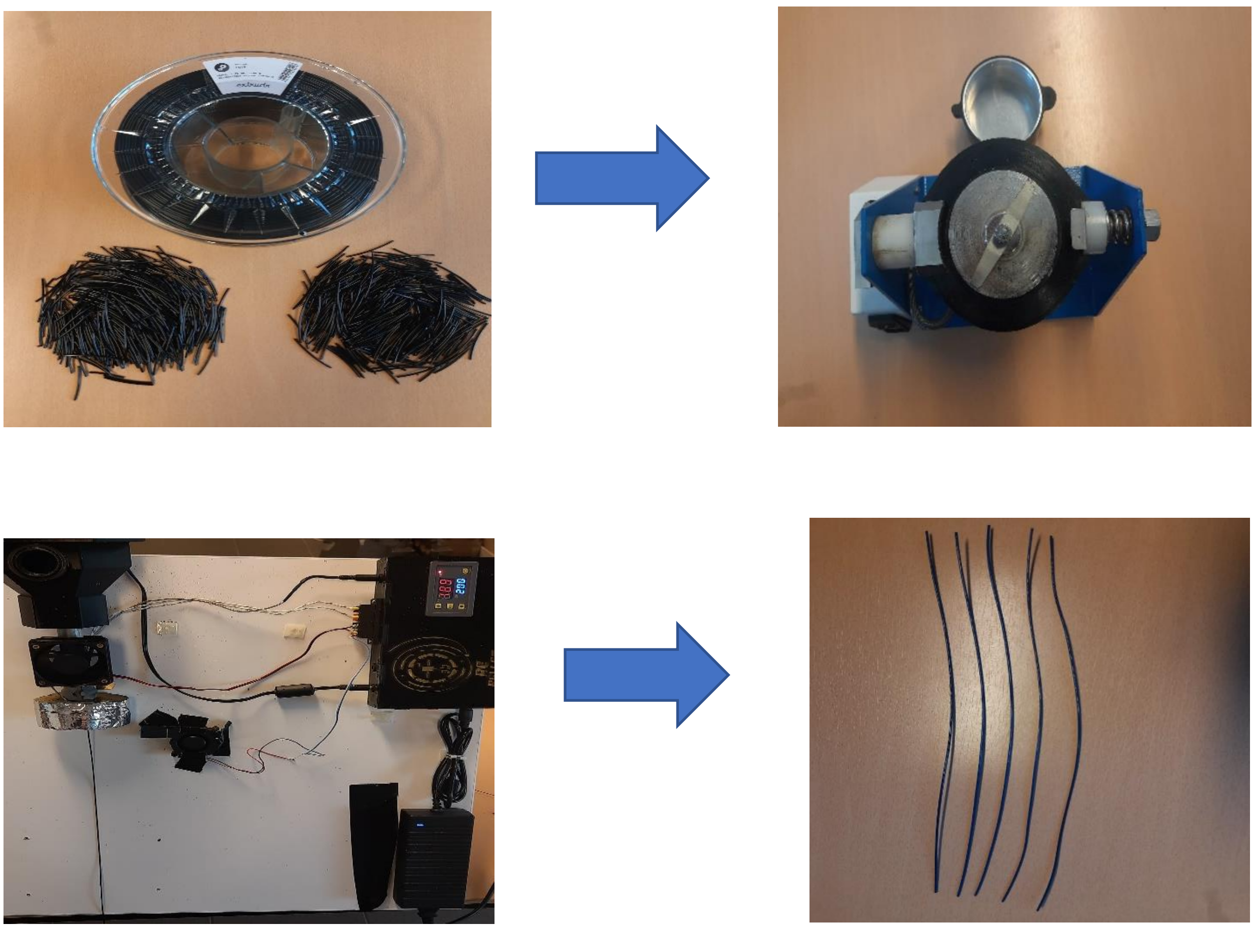

Figure 31. Recycling the used PETG filaments and making new filaments

3.3.5 Testing the tensile test of recycled PETG filaments

A similar process as section 3.3.1 was repeated for tensile test of the recycled PETG. The used 2 types of PETG were recycled and tested. The length of the test specimens was the same, 300 mm, and the cross sections was also on average the same. At least 5 specimens of each recycled PETG were tested.

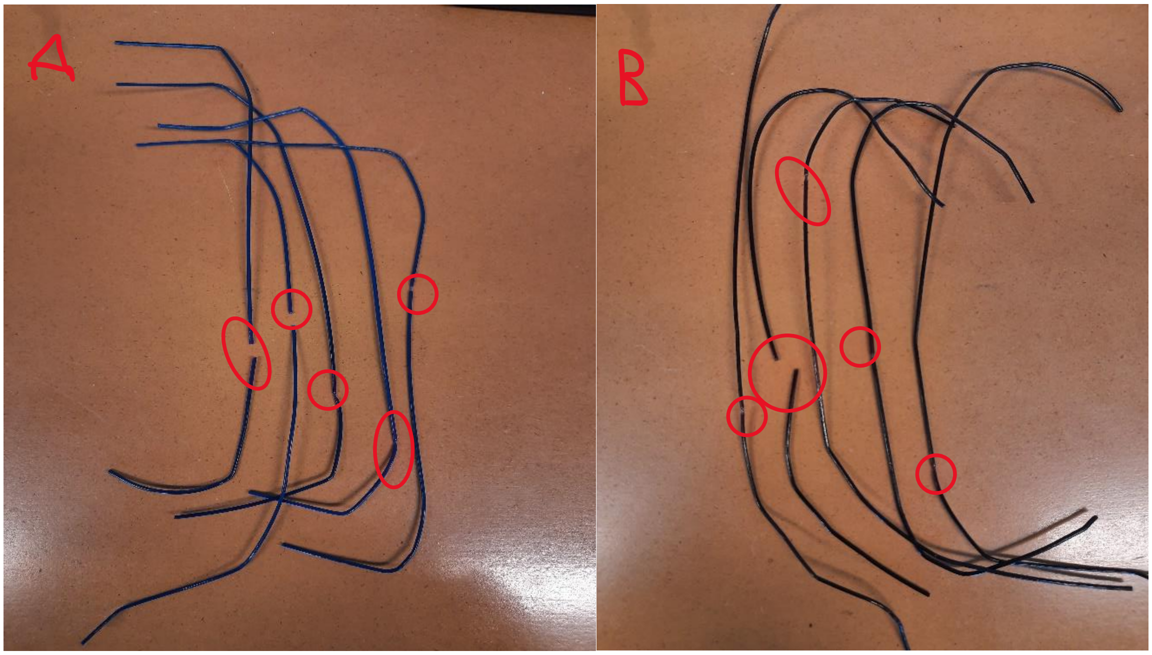

Figure 32. Tested recycled PETG (A: Filanora, B: Extruder)

3.3.6 Making the jute fiber reinforced PETG.

This section of the research was very crucial and challenging. The natural fiber, jute fiber, were cut into small pieces, 1-2 mm, by hand scissors and the mixed with PETG filament. Together with the filament and the jute fiber were cuted and mixed by the grinder machine. The ratio of the jute fiber and the filament was 1:10 that means we used 10% of jute fiber for the reinforcement. The next step was to make the reinforced filament by using the filament maker. The process was similar as mentioned above, the set temperature of the machine was 180 ^{o}C. After making the reinforced filament, it was collected and cuted into small specimens, 300mm, for the tensile test.

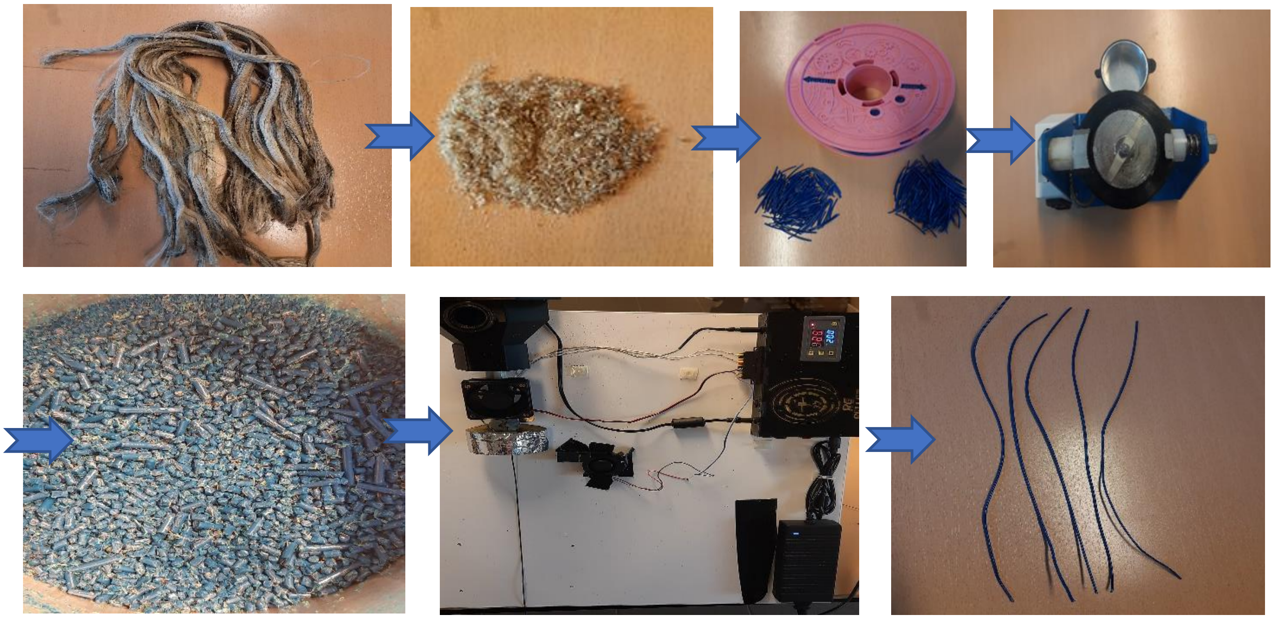

Figure 33. Making the jute fiber reinforced PETG filaments

3.3.7 Testing the jute reinforcement PETG Filament

This was the last and final step of the experiments, the jute fiber reinforced PETG specimens were tested in Zwick Z100 materials testing machine. A special bollard type gripper was used to grip the cylindrical filament. At least 5 specimens of of each type of reinforced PETG were tested and the results were stored in an excel file for analysis.

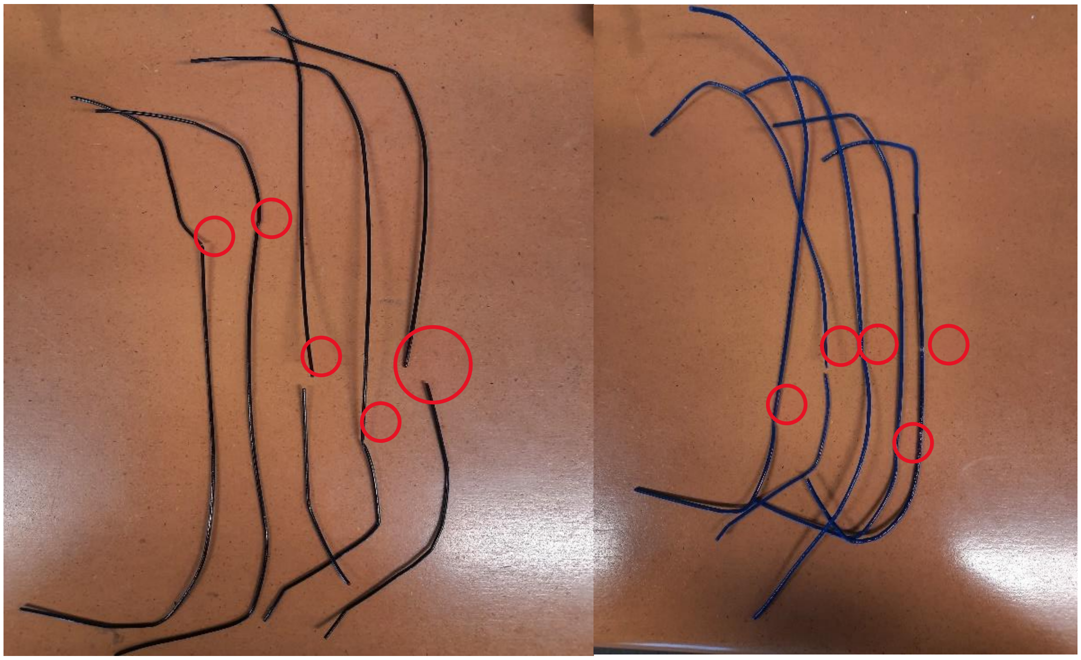

Figure 34. Tensile test of the jute fiber reinforced filament (left: Extrudr, Right: Filanora)

4. Results and Discussions

4.1 Tensile test of the 3D printed PETG specimens

A set of 3 specimens were printed using FDM 3D printer with the standard ISO 527-2-5A for each of the PETG materials. PETG-Extrudr and PETG-Filanora shows a similar UTS result, about 45 MPa, where PETG-carbon shows a relatively less UTS after the test. The results suggest that PETG with carbon reinforcement has less UTS compared to standard PETG materials. In the result analysis, we got the Force and Strain diagram of the tested specimens and we recalculated the result for Stress and Strain diagram. For the recalculation , the cross section was area 8 mm^2 (4*2) and the length of the specimen was 25mm (according to the standard). This test was performed to show the UTS characteristics of the used specimens which is used to compare with other tested specimens.

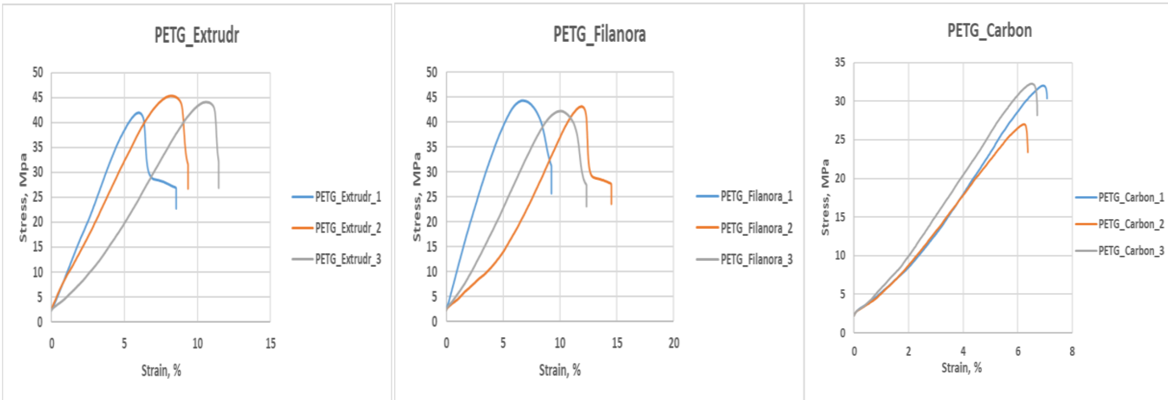

Figure 35. Tensile test of the 3D printed PETG specimens

4.2 Tensile test of the original PETG filaments

The tensile test results of the original PETG filaments shows the opposite trends compared to the 3D printed PETG specimens. Here, UTS of the carbon reinforced specimens has the highest position (50 MPa) and the other two specimens show a similar UTS results (about 45 MPa). The UTS results of original PETG filaments differ from the 3D printed specimens because of the cross section and the length of the tested specimens. Here, the cross section area of the tested filaments was 2.40 mm^2 and the length of the specimens were 150 mm where the cross section and the length of the 3D printed specimens were 8 mm^2 and 25 mm respectively.

Filament length: 150 mm
Diameter: 1.75 mm
Cross Section: $\pi r^2 = 2.40\ mm^2$

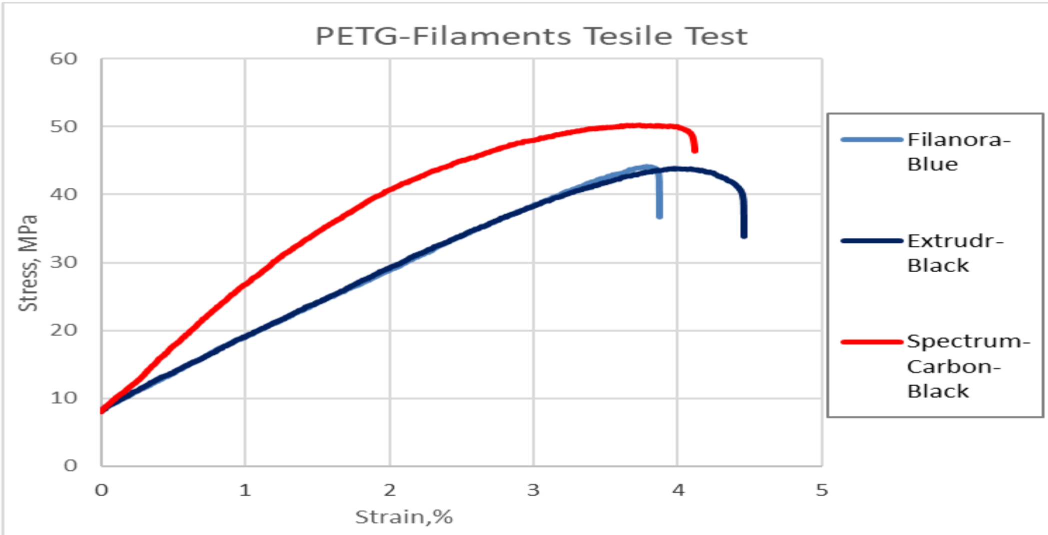

Figure 36. Tensile test of the original PETG filaments

4.3 Tensile test of the recycled PETG and Jute reinforced PETG filaments

In the last stage of our experiment's test, we got some interesting and desired results. We recycled the used PETG filaments (Extrudr and Filanora) and were not able to recycle and reinforced Spectrum-Carbon filaments due to technical issues. After recycling the Extrudr and Filanora filaments we tested the filaments for tensile test. A set of 5 specimens were tested for each filaments type. The UTS of the both recycled filaments were almost the same, average 42.42 MPa for Extrudr-PETG and 42.52 MPa for Filanora-PETG. As expected, the UTS of jute reinforced PETG was higher than the recycled PETG, on average 49 MPa for Extrudr -PETG which shows 15.5 % increase in UTS compared to recycled extrudr-PETG. It was on average 50 MPa for Filanira-PETG which shows 17.74 % increase in UTS compared to recycled PETG.

Table 13. Tensile test results of recycled and reinforced PETG

Recycled PETG, Extrudr (Black)				
Sl	Fmax (N)	Do (mm)	A mm2	UTS (Mpa)
1	68.89	1.4	1.539384	44.751667
2	49.1	1.2	1.130976	43.41383
3	73.93	1.5	1.76715	41.835724
4	73.81	1.5	1.76715	41.767818
5	71.34	1.5	1.76715	40.370087

Recycled PETG, Filanora (Blue)				
Sl	Fmax (N)	Do (mm)	A mm2	UTS (Mpa)
1	68.3	1.4	1.539384	44.36839671
2	76.58	1.5	1.76715	43.33531392
3	97.81	1.7	2.269806	43.09178846
4	92.88	1.7	2.269806	40.91979667
5	72.2	1.5	1.76715	40.85674674

Jute Reinforced PETG, Extrudr (Black)				
Sl	Fmax (N)	Do (mm)	A mm2	UTS (Mpa)
1	60.68	1.2	1.130976	53.6527742
2	66.83	1.3	1.327326	50.349349
3	63.36	1.3	1.327326	47.7350704
4	62.04	1.3	1.327326	46.7405897
5	61.78	1.3	1.327326	46.5447072

Jute Reinforced PETG , Filanora (Blue)				
Sl	Fmax (N)	Do (mm)	A mm2	UTS (Mpa)
1	68.59	1.3	1.327326	51.675323
2	67.31	1.3	1.327326	50.710978
3	77.9	1.4	1.539384	50.604657
4	88.79	1.5	1.76715	50.244744
5	83.15	1.5	1.76715	47.053165

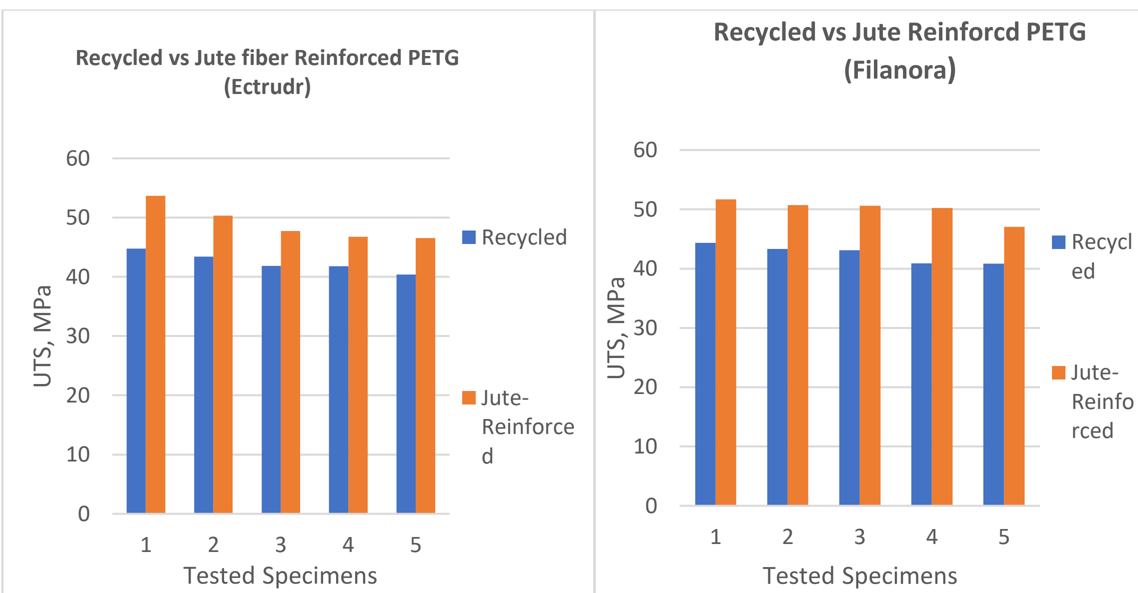

Figure 37. Recycled vs Jute fiber Reinforced PETG filaments test results

In overall comparison of all the test that has been carried out in this experiments, it shows that after jute reinforcement the UTS has increased significantly. In comparison with the original filament test, the jute fiber reinforced filament has higher UTS value. It shows that it has increased on average 12.5% for both of the PETG-Extrudr and PETG-Filanora filaments.

Table 14. UTS of all tested PETG specimens

Sl No	Test type (MPa) / PETG type	3D printed standard specimens test (MPa)	Original filaments test (MPa)	Recycled filament test (MPa)	Jute reinforced filament test (MPa)
1	PETG- Extrudr-Black	43.84	43.86	42.43	49.00
2	PETG- Filanora-Blue	43.32	44.17	42.51	50.05
3	PETG-Spectrum-Carbon-Black	30.42	50.20	-	-

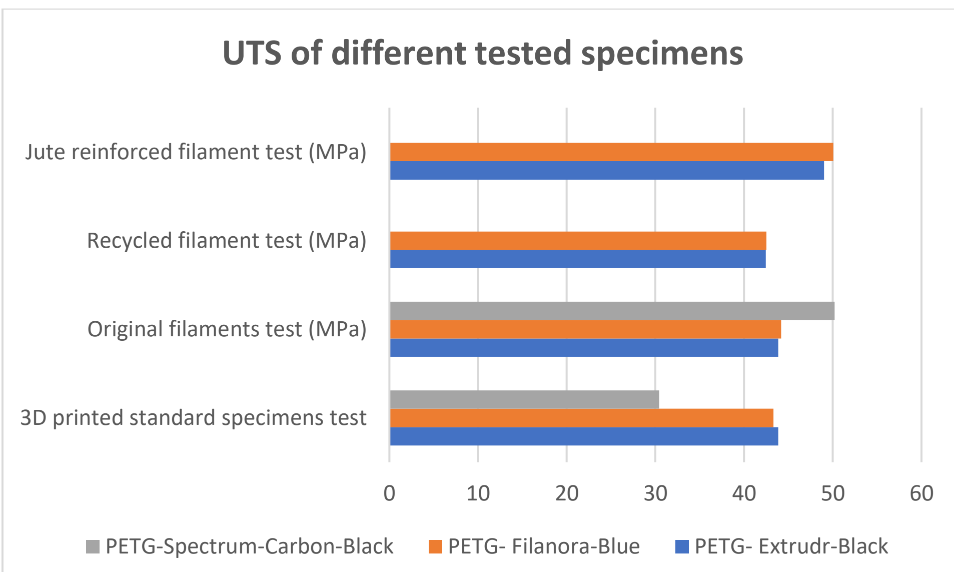

Figure 38. UTS comparison of different tested specimens

5. Conclusion

In conclusion, after a wide range of experiments for the different specimens of PETG materials, including 3D printed standard test, original PETG filament test, recycled PETG filament test and the jute fiber reinforced PETG filament test. The results have shown that the UTS of the filaments has increased after the jute fiber reinforcement. The UTS has increased about 12.5 % in comparison with original filament test, PETG-Extrudr and PETG-Filanora and the jute fiber reinforced filament. Also, the UTS has shown its maximum value in comparison with recycled PETG filaments (PETG-Extrudr and PETG-Filanora) and jute fiber reinforced recycled PETG which is 16% increased in UTS. The above results suggest that the jute fiber reinforcement in PETG filaments during recycling has promising results in terms in increasing UTS of the filaments which will open a new door of recycling business of used PETG materials and will contribute to minimizing the material waste and environmental pollutions. A broad range of research is required to explore the full potential of natural fiber reinforcement of the PETG materials and to overcome the limitations that had to faced in this research.

Summary

Now a days, additive manufacturing (3D printing) is gaining more popularity day by day due to its unique advantages and printing characteristics. In this research the main aim was to investigate the effect of natural fiber (jute fiber) reinforcement in the PETG filaments. The results of this research have shown significant increase in UTS of the reinforcement filaments after tensile tests. The main steps and findings of this research is given below:

- The research objective, needs and steps were redefined before starting the actual work.
- A wide range of literature was reviewed regarding the additive manufacturing technology, additive manufacturing processes, materials used in additive manufacturing, applications of additive manufacturing in different industries, etc.
- According to the research requirements a few machines were collected and developed. In our experiment we used a newly designed special machine, filament maker, which was used to make recycled and natural fiber reinforced filaments. Also, a filament cutter and mixture, a tensile test machine, a microscope, a FDM 3D printer was used.
- A few types of filament test including original PETG filament test, recycled PETG filament test, jute fiber reinforced filament test and FDM 3D printed standard test were carried out to compare the results.
- After all the test, the results were analyzed, the overall result shows that the jute reinforcement has increased the UTS of the PETG materials.

DECLARATION

On authenticity and public assess of final mater's thesis

Student's name : Md. Noman Babu

Student's Neptun ID : QAUA9I

Title of the document : Natural fibre reinforcement in composite polymer material for additive manufacturing

Year of publication : 2023

Department : Mechanical Engineering

I declare that the submitted final master's thesis is my own, original individual creation. Any parts taken from another author's work are clearly marked and listed in the table of contents.

If the statements above are not true, I acknowledge that the Final examination board excludes me from participation in the final exam, and I am only allowed to take final exam if I submit another final master's thesis.

Viewing and printing my submitted work in a PDF format is permitted. However, the modification of my submitted work shall not be permitted.

I acknowledge that the rules on Intellectual Property Management of Hungarian University of Agriculture and Life Sciences shall apply to my work as an intellectual property.

I acknowledge that the electric version of my work is uploaded to the repository system of the Hungarian University of Agriculture and Life Sciences.

Place and date: Gödöllő, 2023 May 08

Noman

Student's signature

STATEMENT ON CONSULTATION PRACTICES

As a supervisor of Md. Noman Babu (QAUA9I), I here declare that the final master's thesis has been reviewed by me, the student was informed about the requirements of literary sources management and its legal and ethical rules.

I recommend the final master's thesis to be defended in a final exam.

The document contains state secrets or professional secrets: No

Place and date: Gödöllő, 2023 May 08

Internal supervisor

(Dr. Zoltán SZAKÁL)

References

[1] ASTM. ASTM F2792–10 standard terminology for additive manufacturing technologies

[2] Nannan GUO, Ming C. LEU, Additive manufacturing: technology, applications and research needs, Higher Education Press and Springer-Verlag Berlin Heidelberg 2013 Front. Mech. Eng. 2013, 8(3): 215–243, DOI 10.1007/s11465-013-0248-8

[3] K. Rajaguru a, T. Karthikeyan b, V. Vijayan a, Additive manufacturing – State of art, Materials Today: Proceedings 21 (2020) 628–633

[4] A Review of Additive Manufacturing, International Scholarly Research Network

[5] ISRN Mechanical Engineering, Volume 2012, Article ID 208760, 10 pages.

[6] H. Bikas, P. Stavropoulos, G. Chryssolouris, Additive manufacturing methods and modelling approaches: a critical review, Int. J. Adv. Manuf. Technol. (2015).

[7] Kiran, A. S. K., Veluru, J. B., Merum, S., Radhamani, A., Doble, M., Kumar, T. K. S., & Ramakrishna, S. (2018). Additive manufacturing technologies: an overview of challenges and perspective of using electrospraying. *Nanocomposites*, *4*(4), 190–214. https://doi.org/10.1080/20550324.2018.1558499

[8] Jennifer Loy, The future for design education: preparing the design workforce for additive manufacturing, Int. J. Rapid Manufact. 5 (2) (2015) 199–212

[9] Jing Chen, Chaoli Ma, James Case Williams, Additive manufacturing of high value Ti components: opportunities and challenges, Int. J. Add. Subtract. Mater. Manufact. 1 (2) (2017) 119–132.

[10] Hu Jing, Study on stl-based slicing process for 3d printing, Solid Freeform Fabrication 2017 Proceedings of the 28th Annual International Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference, 2017.

[11] S. Ashley, Rapid prototyping systems, Mech. Eng. 113 (4) (1991) 34.

[12] Zhengyan Zhang, Sanjay Joshi, An improved slicing algorithm with efficient contour construction using STL files, Int. J. Adv. Manuf. Technol. 80 (2015) 1347–1362.

[13] Goldsberry C. Rapid change in additive manufacturing landscape. http://www.plasticstoday.com/articles/rapid-change-additive-manufacturing- landscape. 2009

[14] Liu Q, Sui G, Leu M C. Experimental study on the ice pattern fabrication for the investment casting by rapid freeze prototyping. Computers in Industry, 2002, 48(3): 181–197

[15] Bellini A, Shor L, Guceri S I. New developments in fused deposition modeling of ceramics. Rapid Prototyping Journal, 2005,11(4): 214–220

[16] Liu H J, Leu M C. Research on extrusion velocity in freeform extrusion fabrication of aqueous alumina paste. Key Engineering Materials, 2009, 419–420: 125–128

17] Levy G N, Schindel R, Kruth J P. Rapid manufacturing and rapid tooling with layer manufacturing (LM) technologies, state of the art and future perspectives. CIRP Annals-Manufacturing Technology,2003, 52(2): 589–609

[18] Kruth J P, Froyen L, Van Vaerenbergh J, Mercelis P, Rombouts M,Lauwers B. Selective laser melting of iron-based powder. Journal of Materials Processing Technology, 2004, 149(1–3): 616–622

[19] Heinl P, Müller L, Körner C, Singer R F, Müller F A. Cellular Ti-6Al-4V structures with interconnected macro porosity for bone implants fabricated by selective electron beam melting. Acta Biomaterialia, 2008, 4(5): 1536–1544

[20] Gasser A, Backes G, Kelbassa I, Weisheit A, Wissenbach K. Laser additive manufacturing: laser metal deposition (LMD) and selective laser melting (SLM) in turbo-engine applications. Laser Material Processing, 2010, 2: 58–63

[21] Sachs E, Cima M, Cornie J. Three-dimensional printing: rapid tooling and prototypes directly form a CAD model. CIRP Annals-Manufacturing Technology, 1990, 39(1): 201–204

[22] Bak D. Rapid prototyping or rapid production? 3D printing processes move industry towards the latter. Assembly Automation, 2003, 23(4): 340–345

[23] Wikipedia contributors. (2022). Laminated object manufacturing. *Wikipedia*. https://en.wikipedia.org/wiki/Laminated_object_manufacturing

[24] A. M. T. Syed, P. K. Elias, B. Amit, B. Susmita, O. Lisa, & C. Charitidis, "Additive manufacturing: scientific and technological challenges, market uptake and opportunities," Materials today, Vol. 1, pp. 1-16, 2017.

[25] Shahrubudin, N., Lee, T. R., & Ramlan, R. (2019). An Overview on 3D Printing Technology: Technological, Materials, and Applications. *Procedia Manufacturing*, *35*, 1286–1296. https://doi.org/10.1016/j.promfg.2019.06.089

[26] M. A. Caminero, J. M. Chacon, I. Garcia-Moreno, & G. P. Rodriguez, "Impact damage resistance of 3D printed continues fibre reinforced thermoplastic composites using fused deposition modelling," *Composite Part B: Engineering,* Vol. 148, pp. 93-103, 2018.

[27] T. Lanko, S. Panov, O. Sushchyns'ky, M. Pylypenko, & O. Dmytrenko, "Zirconium Alloy Powders for manufacture of 3D printed particles used in nuclear power industry," *Problems of Atomic Science and Technology,* Vol. 1, No. 113, pp. 148-153, 2018.

[28] Y. Yang, Y. Chen,Y. Wei, & Y. Li, "3D Printing of shape memory polymer for functional part fabrication," *The International Jurnal of Advanced Manufacturing Technology,* Vol. 84, No. 9, pp. 2079-2095, 2015.

[29] P. Singh, & A. Raghav, "3D Food Printing: A Revolution in Food Technology," *Acta Scientific Nutritional Health,* Vol. 2, No.2, pp. 1-2, 2018.

[30] A. Goulas, & R. J. Friel, "3D printing with moondust," *Rapid Prototyping Journal,* Vol. 22, No.6, pp. 864-870, 2016.

[31] M. D. Ugur, B. Gharehpapagh, U. Yaman, & M. Dolen, "The role of additive manufacturing in the era of Industry 4.0," *Procedia Manufacturing,* Vol. 11, pp. 545-554, 2017.

[32] Additive Manufacturing | GKN technology 2016 | GKN Group. http://www.gkn.com/en/our-technology/2016/additive-manufacturing/. 19/10/2017.

[33] Innovative 3D-printing by Aibus Aircraft. http://www.aircraft.airbus.com/galleries/photo-gallery/dg/idp/47642-a350-xwb-bracket-produced-with-3dprinting/?return_id=3170. 29/10/2017.

[34] Clowers, C. (2022, April 19). *Optomec - 3D PRINTING SOLUTIONS FOR AN ADDITIVE MANUFACTURING WORLD*. Optomec. http://www.optomec.com/

[35] CRP Technology srl. (2023, April 5). *CRP Technology. Industrial 3d printing for production in Windform*. CRP Technology. http://www.crptechnology.com/

[36] Arcam A B. http://www.arcam.com

[37] Concept Laser Gmb H. http://www.concept-laser.de/

[38] Prometal R C T. http://www.prometal-rct.com/

[39] Lipton, J. H., Cutler, M., Nigl, F., Cohen, D., & Lipson, H. (2015). Additive manufacturing for the food industry. Trends in Food Science and Technology, 43(1), 114–123. https://doi.org/10.1016/j.tifs.2015.02.004

[40] Harrysson O, Cansizoglu O, Marcellin-Little D J, Cormier D R, West H A II. Direct metal fabrication of titanium implants with tailored materials and mechanical properties using electron beam melting technology. Materials Science and Engineering C, 2008, 28(3): 366–373

[41] Bandyopadhyay A, Krishna B V, Xue W, Bose S. Application of 240 Front. Mech. Eng. 2013, 8(3): 215–243 laser engineered net shaping (LENS) to manufacture porous and functionally graded structures for load bearing implants. Journal of Materials Science. Materials in Medicine, 2009, 20(S1 Suppl 1): 29–34

[42] 3D Print Canal House – DUS Architects. http://houseofdus.com/project/3d-printcanal-house/. 23/10/2017.

[43]Textile additive manufacturing: An overview Edmund M. Keefe, Jack A. Thomas, Gary A. Buller & Craig E. Banks | https://doi.org/10.1080/23311916.2022.2048439

[44] Bouriaud, M. (2022). Additive Manufacturing in Electronics. Xometry Europe. https://xometry.eu/en/additive-manufacturing-in-electronics/

[45] Fuentes, L. (2021c). What Is PETG? – Simply Explained. *All3DP*. https://all3dp.com/2/what-is-petg-material-plastic/

[46] *What is PETG? (Everything You Need To Know)*. (n.d.). https://www.twi-global.com/technical-knowledge/faqs/what-is-petg#:~:text=Polyethylene%20terephthalate%20glycol%2C%20known%20as,durability%2C%20and%20formability%20for%20manufacturing

[47] Extrudr - High Quality Filament. (n.d.). https://www.extrudr.com/en/material/petg/

[48] Czapla, M. (2022, October 26). PET-G Carbon - Spectrum Filaments. Spectrum Filaments - Spectrum Filaments - Polski Producent Filamentu 3D. https://spectrumfilaments.com/en/filament/pet-g-carbon/#:~:text=Spectrum%20PET%2DG%20Carbon%20is,for%20the%20pure%20PET%2DG.

[49] Filanora Filatech PETG filament 1,75mm kék. (n.d.). https://www.filanora.eu/filanora-filatech-petg-filament-175mm-kek

[50] Singh, H., Singh, J., Singh, S., Dhawan, V., & Tiwari, S. (2018). A Brief Review of Jute Fibre and Its Composites. Materials Today: Proceedings, 5(14), 28427–28437. https://doi.org/10.1016/j.matpr.2018.10.129

[51] Omar Faruk, Andrzej K Bledzki, Hans-Peter Fink, Mohini Sain, 2012,"Biocomposites reinforced with natural fibers:2000-2010", Progress in
Polymer Science, 37, pp.1552–1596.

[52] Michael A. Fuqua, Shanshan Huo and Chad A. Ulven, 2012,"Natural Fiber Reinforced Composites", Polymer Reviews, 52, pp.259–320.

[53] Chandekar, H., Chaudhari, V., & Waigaonkar, S. (2020). A review of jute fiber reinforced polymer composites. *Materials Today: Proceedings*, *26*, 2079–2082. https://doi.org/10.1016/j.matpr.2020.02.449

[54] Geeetech A20M Dual Extruder, Filament Detector and Break-resuming Function, 250X250X250mm Geeetech A20M Dual Extruder 3d printer [800-001-0600] - $279.00 : geeetech 3d printers onlinestore, one-stop shop for 3d printers,3d printer accessories,3d printer parts. (n.d.). geeetech.com. https://www.geeetech.com/geeetech-a20m-mixcolor-3d-printer-upgraded-mother-board-lcd-p-1122.html

[55] Romero, A., Piovan, M.T., Mainetti, C., Stechina, D., Mendoza, s., Mart´ın, H., Maggi, N.: Tensile properties of 3d printed polymeric pieces: Comparison of several testing setups. Ingenier´ıa e Investigaci´on 41, e84467 (03 2021). https://doi.org/10.15446/ing.investig.v41n1.84467