THESIS

YOUSEF IBRAHIM
Mechanical Engineering

Gödöllő
2023

Hungarian University of Agriculture and Life Science

Szent István Campus

Mechanical Engineering Course

THESIS TITLE

Mechanical properties for composite material used 3D printing

Supervisor: Dr. Zoltán szakál
Associate professor

Consultant:

Author: **Yousef Ibrahim**
FXP5E5

Institute/Department: Institute of Technology

Gödöllő
2023

INSTITUTE OF TECHNOLOGY MECHANICAL ENGINEERING (MSC)
Technical Development specialization

THESIS

worksheet for

Yousef IBRAHIM (FXP5E5)

Engineer (MSc) student

Entitled:

Mechanical properties for composite material used 3D printing

Task description:

The purpose of this study was to investigate the behavior and properties of PLA filaments before printing, as well as printed samples, in relation to tensile testing. Tensile tests were performed on four different types of commercially produced PLA filaments to determine the Ultimate Tensile Strength (UTS) of each type. Additionally, samples were printed from each type to determine their UTS under the same printing parameters. And also, these types of filaments were re-manufactured to determine their UTS after recycling. Additionally, the filaments were re-manufactured and reinforced with hemp fibers, to investigate whether any improvement in UTS.

Department: Mechanical Engineering

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

Submission deadline: 09 day May month 2023.

Gödöllő, 20 day January month 2023.

Approved		**Received**
(head of department)	(host course leader)	(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 day May month 2023.

(Consultant)

Table of Content

List of Figures

List of Tables

1 Introduction

In 1980s, new industrial manufacturing was existed, known as Additive manufacturing or also known as 3D printing. 3D printing is a manufacturing process where objects are created by adding layers of material on top of each other, instead of removing material from a block, as it was in the subtractive manufacturing.

3D printing is the process of creating three-dimensional solid objects in the desired shape using 3D modeling software and a printer, which places successive layers of materials in different shapes to achieve a final shape that matches the digital model. This manufacturing method has succeeded in producing complex and intricate engineering parts, and these products made from metal, ceramic, polymer, and composite materials. These products have entered many industrial applications such as aerospace, automotive, medical, and even food industry.

3D printers have various manufacturing technologies that differ in the methodology of forming the product, the type of materials used, and the medium used in processing. One of the most commonly used technologies is Fused Deposition Modeling (FDM), which creates objects by depositing layers of molten polymer filament in a precise pattern. This process involves a heated extrusion nozzle that melts and extrudes the polymer filament layer by layer to create a three-dimensional object. The mechanical properties and characteristics of objects from this printer depend on many factors, most notably the properties and quality of the polymer filaments used in printing the object. Therefore, it was important to conduct many studies and research to determine the mechanical and functional properties of these filaments and its printed object. One of the most commonly used filaments is polylactic acid (PLA) filament, and PLA is a biodegradable and biocompatible thermoplastic polymer that has gained significant attention in recent years due to its environmental friendliness and suitability for various applications, which made it interesting to study the mechanical properties of its filaments, as well as its objects.

The purpose of this study is to investigate the behavior and properties of PLA filaments before printing, as well as printed samples from it, in relation to tensile testing. Tensile tests were performed on four different types of commercially produced PLA filaments to determine the Ultimate Tensile Strength (UTS) of each type and compare them with each other. Additionally, samples were printed from each type to study and determine their UTS under the same conditions and printing parameters. And also, these types of filaments were re-manufactured in the laboratory to determine their mechanical behavior with respect to tensile testing after recycling. This was done to determine if the re-manufactured process had any difference or improvement in the properties, specifically the Ultimate Tensile Strength. Additionally, the filaments were re-manufactured and reinforced with hemp fibers, which are natural fibers, to investigate whether any improvement in Ultimate Tensile Strength occurred for the different types of filaments after reinforcement.

2 Literature reviews

In this review, we will explore the history of 3D printing, its various technologies, materials, and applications. Specifically, we will delve into the Fused Deposition Modeling (FDM) technology, which is one of the most widely used 3D printing methods. We will discuss the printing process and the necessary parameters to print using FDM, as well as some of the polymers used in this method and their properties. We will focus on Polylactic Acid (PLA), a biodegradable thermoplastic material, and the parameters required to print it using FDM. Additionally, we will cover the tensile testing of PLA filaments and printed samples using FDM technology, and the effect of extrusion temperature on the printing process.

Furthermore, we will discuss the use of natural fibers such as hemp fibers to reinforce PLA and create composite material filaments with improved mechanical properties for tensile testing. We will particularly focus on the process of re-manufacturing the filaments and composite filaments containing PLA and hemp fibers, and the impact of these filaments on the tensile testing of printed specimens

2.1 History of 3D Printing

3D printing, also known as additive manufacturing, is the process of creating three-dimensional objects from a digital model by adding material layer by layer. The concept of 3D printing has been around since the 1980s, but it wasn't until the turn of the century that the technology started to evolve.

The first forms of 3D printing were developed in the mid-1980s by Chuck Hull, who invented a process called stereolithography (SLA) while working for a company called 3D Systems. Hull's process involved using a laser to harden photopolymer resin layer by layer until a 3D object was formed. [1]

In the years that followed, other forms of 3D printing were developed, including fused deposition modeling (FDM), invented by Scott Crump in 1989. FDM involves extruding a molten material, such as B. plastic, layer by layer to create a 3D object.[2]

Despite these early advances, 3D printing remained a niche technology for many years, mainly used by industrial designers and engineers. However, in the early 2000s, many important 3D printing patents expired, opening the field for new competitors and lowering the cost of 3D printers.[3]

As a result, the popularity of 3D printing exploded in the late 2000s and early 2010s with a growing number of hobbyists, makers, and entrepreneurs using the technology to create everything from jewelry to toys to prosthetics and medical implants.

Today, 3D printing is used in many industries, including aerospace, automotive, medical, and consumer goods. The technology has also become more accessible to the general public, and inexpensive 3D printers can now be purchased online and at many electronics stores. [4]

2.2 Technologies of 3D Printing

According to an article, S. S. Alghamdi et al. in 2021, classified the additive manufacturing or 3D printing technology based on the methodology of formation of the product, the type of base material used, and the medium used for processing. [5]

Figure 1. below shows that the additive manufacturing process based on the methodology of formation of the product is divided into seven categories which are: Material jetting, Vat photo polymerization, Material extrusion, Sheet lamination, Binder jetting, Powder bed fusion and Energy deposition. And there are three type of base material used in additive manufacturing process which are: Solid, Powder and Liquid. And each type contains a set of techniques. As for the medium used processing there are three kind which are: Laser beam, Ultraviolet rays or Thermal means.

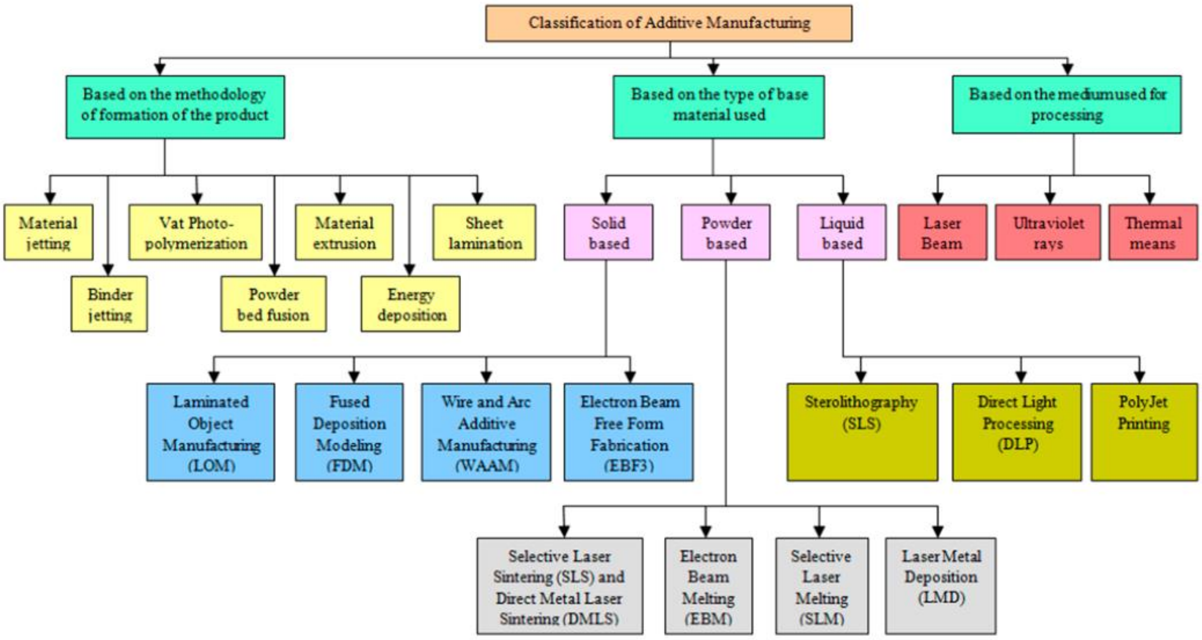


Fig 1 . Classification of additive manufacturing processes from different context. [5]

Here are the seven main technologies used in 3D printing and the materials commonly used in each technology, along with some applications:

2.2.1 Fused Deposition Modeling (FDM)

FDM is the most common 3D printing technology, in which a thermoplastic filament is melted and extruded layer by layer to build the object. The materials used in FDM are mostly thermoplastics, including ABS (acrylonitrile-butadiene-styrene), PLA (polylactic acid), PETG (glycol-modified PET), Nylon, and TPU (thermoplastic polyurethane). FDM is widely used for prototyping, tooling, and small production runs in industries such as automotive, aerospace, and consumer goods. [6]

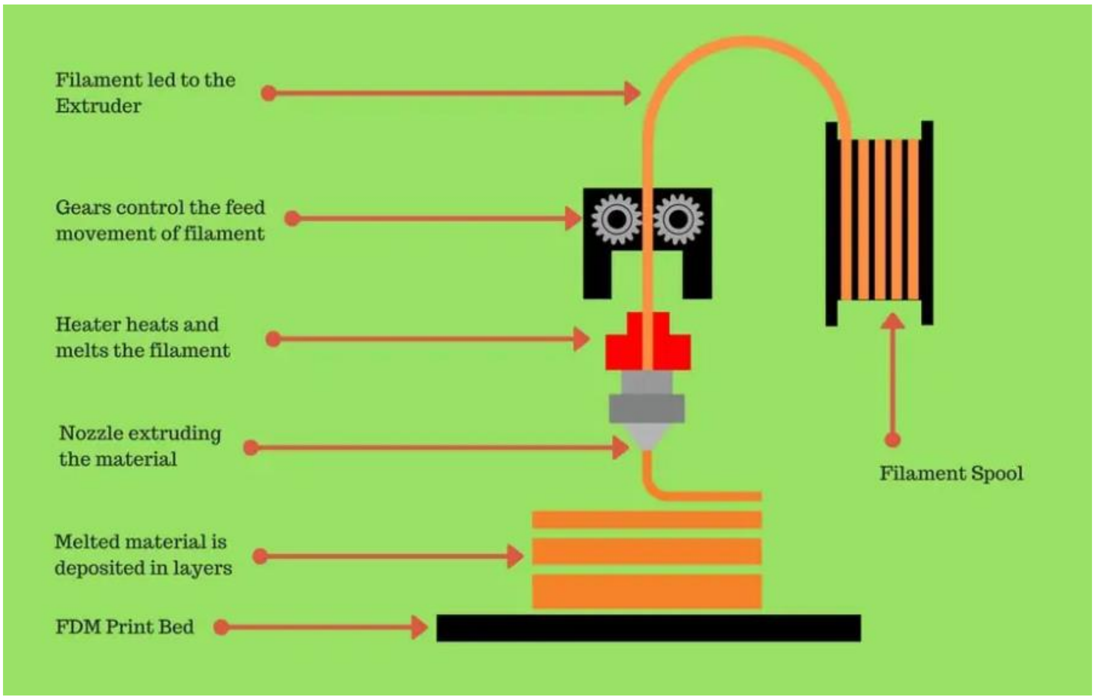


Fig 2. Fused Deposition Modeling Technology. [7]

2.2.2 Stereolithography (SLA)

SLA is a 3D printing technology that uses a UV laser to cure a liquid resin layer by layer, forming the object. The materials used in SLA are mostly photopolymers, including Standard Resins, Engineering Resins, and Dental Resins. SLA is widely used in the medical, dental, and jewelry industries. [8]

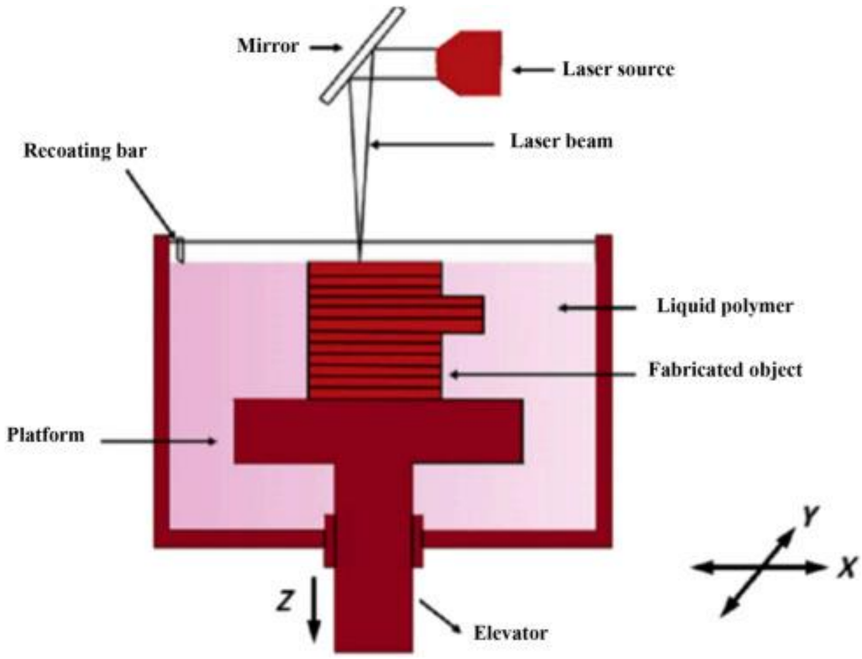


Fig 3. Stereolithography Technology. [8]

2.2.3 Digital Light Processing (DLP)

DLP is similar to SLA, but instead of using a laser, it uses a digital projector to cure the resin layer by layer. The materials used in DLP are also photopolymers, including Standard Resins, Engineering Resins, and Dental Resins. DLP is widely used in the dental and jewelry industries. [9]

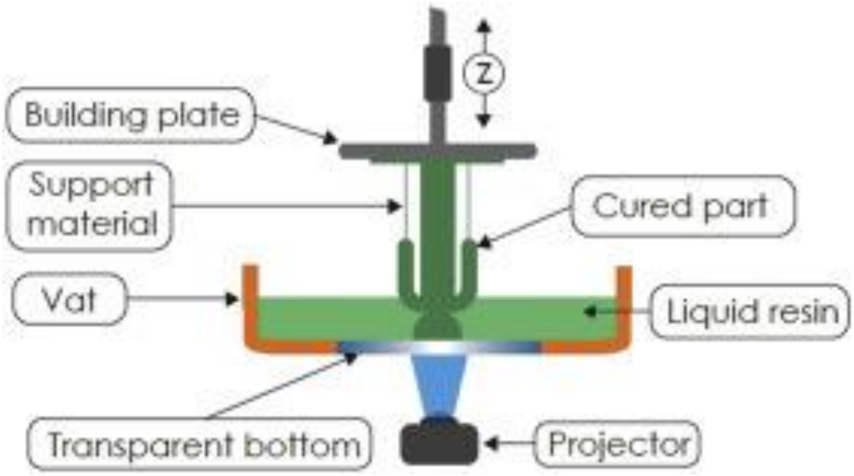


Fig4 . Digital Light Processing Technology. [9]

2.2.4 Selective Laser Sintering (SLS)

SLS uses a laser to sinter a powdered material layer by layer, forming the object. The materials used in SLS are mostly powders, including Nylon, TPU, and metal powders such as aluminum, titanium, and stainless steel. SLS is widely used in the aerospace, automotive, and medical industries.[10]

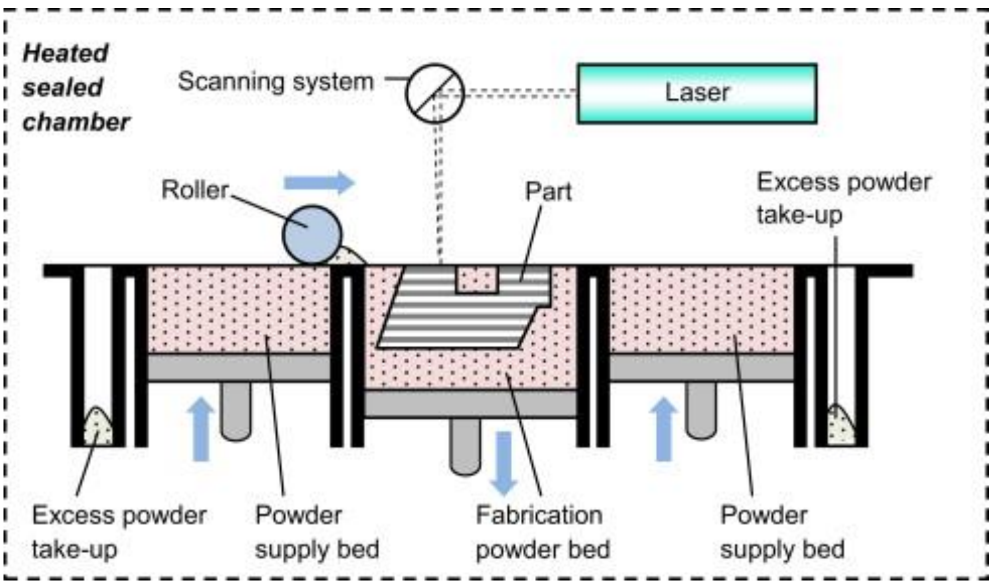


Fig 5. Selective Laser Sintering Technology. [10]

2.2.5 Binder Jetting (BJ)

BJ uses a binder to selectively bind layers of powdered material, forming the object. The materials used in BJ are mostly powders, including sand, ceramics, and metals such as steel and bronze. BJ is widely used in the automotive, aerospace, and jewelry industries. [11]

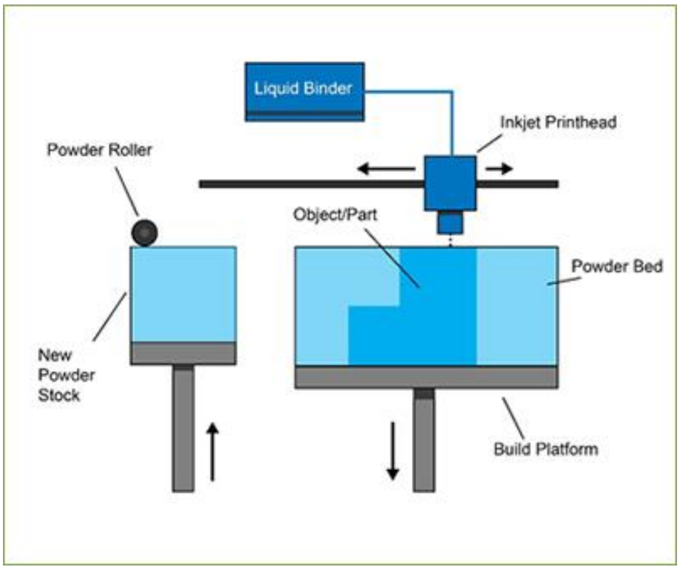


Fig 6 . Binder Jetting Technology. [12]

2.2.6 Material Jetting (MJ)

MJ uses a print head to deposit droplets of material layer by layer, forming the object. The materials used in MJ are mostly photopolymers, including Standard Resins, Engineering Resins, and Dental Resins. MJ is widely used in the dental and jewelry industries.[13]

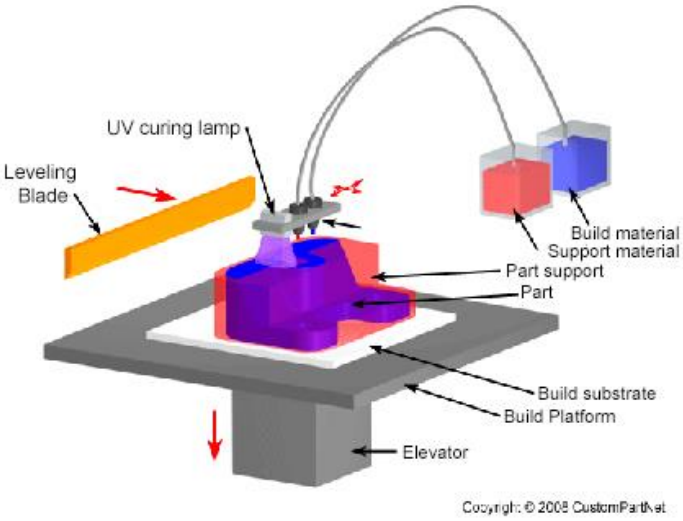


Fig 7. Material Jetting Technology. [12]

2.2.7 Directed Energy Deposition (DED)

DED uses a laser or electron beam to melt a metal wire or powder, forming the object. The process is similar in concept to material extrusion, but the nozzle has more freedom of movement and is not fixed to one axis. The materials used in DED are mostly metals, including steel, titanium, and aluminum. DED is widely used in the aerospace, defense, and automotive industries.[12]

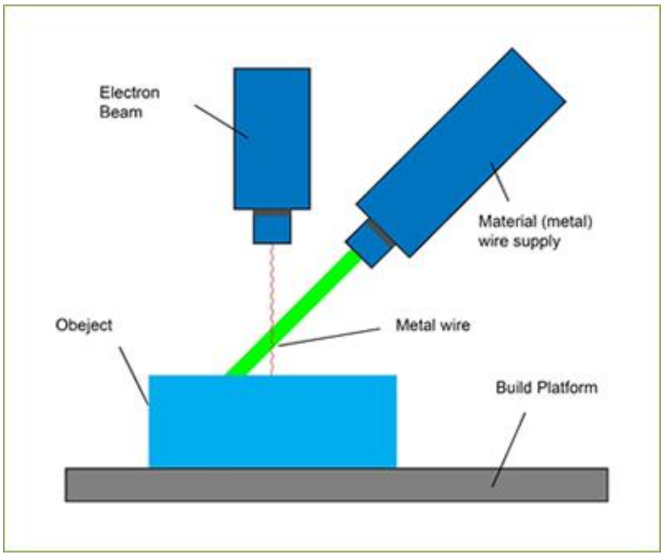


Fig 8. Directed Energy Deposition process. [12]

2.3 Materials Used for 3D Printing Technology in Manufacturing Industry

3D printing technology, has revolutionized the manufacturing industry. A wide range of materials can be used in 3D printing, depending on the requirements of the object being printed. Here are some of the commonly used materials in 3D printing technology.

2.3.1 Metals

Metal 3D printing, also known as metal additive manufacturing, involves using metal powders that are fused together to create three-dimensional objects. Metal 3D printing can be used to create parts with high strength, durability, and heat resistance, making it suitable for a wide range of applications in the aerospace, automotive, and medical industries. Some common metals used in 3D printing include titanium, stainless steel, aluminum, Cobalt-Chrome and their alloys.[14]

2.3.2 Ceramics

Ceramic 3D printing involves using ceramic powders that are fused together to create three-dimensional objects. Ceramic 3D printing can be used to create parts with high strength, hardness, and chemical resistance, making it suitable for a wide range of applications in the medical, aerospace, and defense industries. Some common ceramics used in 3D printing include zirconia, alumina, and hydroxyapatite. [15]

2.3.3 Polymers

Polymers are the most commonly used material in 3D printing. There are different types of polymer materials that can be used in 3D printing such as ABS (acrylonitrile butadiene styrene), PLA (polylactic acid), PET (polyethylene terephthalate), Nylon and polycarbonate. Each plastic has its own unique properties, making it suitable for different applications.

- **Acrylonitrile Butadiene Styrene (ABS)** is a thermoplastic material that is used in 3D printing for its toughness, durability, and heat resistance. It is commonly used in automotive parts, toys, and consumer electronics. [16]
- **Polylactic Acid (PLA)** is a biodegradable thermoplastic material that is derived from renewable resources such as corn starch and sugarcane. It is commonly used in 3D printing due to its ease of use, low toxicity, and biodegradability. PLA is used in a range of applications, including medical devices, packaging, and consumer products. [17]
- **Polyethylene Terephthalate (PET)** is a strong, lightweight, and transparent thermoplastic material that is commonly used in 3D printing for its durability and recyclability. It is used in a range of applications, including food and beverage packaging, medical devices, and consumer products. [18]
- **Nylon** is a strong and flexible thermoplastic material that is commonly used in 3D printing for its durability and wear resistance. It is used in a range of applications, including automotive parts, medical devices, and consumer products. [19]
- Polycarbonate (PC) is a tough, clear thermoplastic that is widely used in 3D printing due to its impact strength and high temperature tolerance. It is used in many applications including automotive parts, electronics and medical devices.

Table 1. below shows some mechanical and physical properties for the materials mentioned earlier.

Table 1. . Mechanical and Physical properties for polymers materials used in 3D Printing.[21]

Polyme-r	Physical		Mechanical				
	Density (g/cm^3)	Melting point (°C)	Tensile strength at		Elongation at		Young's modulus (GPa)
			yield (MPa)	Break (Mpa)	Yield (%)	Break (%)	
ABS	1.02 - 1.21	200 - 220	29.6 – 48	29.8 - 43	1.7 – 6	10 – 50	1.79 – 3.2
PLA	1.23 – 1.25	170 - 180	59 - 61	52 - 54	1 - 4	5 – 7	3.4 – 3.6
PET	1.3 – 1.4	225 - 245	50 - 75	45 - 70	3.8	30 – 70	2.8 – 3.5
Nylon	1.17 - 1.19	220 - 265	65 – 85	65 - 85	4 – 10	160 – 300	1 – 3.3
PC	1.15 – 1.2	288 - 316	61 – 69	50 – 120	6 - 7	50 - 120	2.2 – 2.5

It is important to note that the mechanical and physical properties of these polymers can vary depending on the specific formulation and printing conditions used. Additionally, the mechanical properties of 3D printed parts can be influenced by other factors such as layer orientation, infill density, and post-processing techniques. Therefore, it is important to carefully consider the specific requirements of each application and select the appropriate polymer material accordingly.

2.3.4 Bio-based materials

Bio-based materials are a relatively new class of materials used in 3D printing, and they have gained increasing attention in recent years due to their sustainability and biodegradability. These materials are derived from renewable resources, such as plants, and they are often used in applications where sustainability is a primary concern.[22]

- One of the most commonly used bio-based materials in 3D printing is **polylactic acid (PLA)**.
- Another bio-based material that is increasingly being used in 3D printing is **cellulose**. Cellulose is a natural polymer that is the main component of plant cell walls. It has excellent mechanical properties, including high strength and stiffness, making it an ideal material for 3D printing. Cellulose-based materials can be used in a variety of applications, including automotive parts, medical implants, and even food packaging. [23]
- **Lignin** is another bio-based material that is gaining attention in 3D printing. Lignin is a complex polymer found in plant cell walls. It is a byproduct of the paper and pulp industry, making it an abundant and low-cost material. Lignin-based materials can be used in a variety of applications, including automotive parts and packaging . [24]

Overall, bio-based materials have the potential to be a sustainable and environmentally friendly alternative to traditional materials used in 3D printing. They are derived from renewable resources, they are biodegradable and compostable, and they have excellent mechanical properties. As the technology for bio-based materials continues to improve, we can expect to see more and more applications of these materials in the 3D printing industry.

2.3.5 Composites material

Composite materials in 3D printing refer to the use of two or more materials, typically polymers or metals, that are combined to produce a material with enhanced properties. The benefits of using composite materials in 3D printing include increased strength, durability, and toughness, as well as the ability to tailor the properties of the material to suit a specific application.

There are several types of composite materials that can be used in 3D printing, including [25]:

- **Polymer composites:** These are made by combining a polymer with another material, such as carbon fiber, glass fiber or natural cellulose fiber, to produce a material with enhanced strength and stiffness.
- **Metal matrix composites:** These are made by combining a metal with another material, such as ceramic particles or carbon fibers, to produce a material with enhanced strength, stiffness, and thermal stability.
- **Ceramic composites:** These are made by combining a ceramic with another material, such as a metal or a polymer, to produce a material with enhanced strength, stiffness, and thermal stability.

2.4 The Applications of 3D Printing in Manufacturing Technology:

3D printing, has transformed the manufacturing industry by enabling the production of complex and customized parts at a lower cost and with greater efficiency than traditional manufacturing methods.

2.4.1 Aerospace Industry

The aerospace industry has been quick to adopt this technology due to its ability to produce lightweight parts with intricate geometries, reduced assembly time, and cost-effective production.

According to an article published in 2022 by Rouf et al. mentioned that many institutions adopted 3D printing technology in their aerospace industries. For example, Harvest Technology used plastic laser sintering from Electro-optical systems (EOS) to produce components to be used in Bell helicopters. Airbus has been using 3D printing to produce a cabin partition with a lattice structure that reduces weight and enhances passenger comfort. Boeing has also been using 3D printing to produce more than 20,000 non-structural parts for its 787 Dreamliner aircraft, including air conditioning vents, overhead bins, and armrests. NASA has been using 3D printing to create prototypes of rocket engine parts, which has reduced the development time from months to weeks. [26]

2.4.2 Automotive Industry

As mentioned by N. Shahrubudin et al. in their article that published in 2019, the use of 3D printing technology in automotive industry has caused phenomena to emerge, making it possible to create structures that are lighter and more complex quickly. For example, Local Motor in 2014 produced the first 3D-printed electric vehicle. Local Motors expanded the variety of uses for 3D printing technology beyond just the automotive industry by producing the OLLI, a 3D-printed bus. OLLI is a 3D-printed, driverless, electric, recyclable, and incredibly intelligent bus.

Ford is a pioneer in the application of 3D printing technology, using it to create prototypes and engine parts. BMW creates hand tools for testing and assembly of automobiles using 3D printing technology. SLM Solution Group AG and AUDI worked together to produce prototypes and replacement components in 2017. [27]

2.4.3 Food Industry

3D printing technology has the potential to transform the food industry by enabling the production of customized food products with high precision and accuracy. 3D-printed food is created by depositing consecutive layers one at a time that are directly derived from computer-aided design data. Certain materials can be combined and processed using 3D printing technology to create a variety of intricate structures and shapes. [27]

A. Leotiou et al., mentioned in their article that published in nanomanufacturing journal, in 2023, that food components including carbs, lipids, fiber, proteins, sugar, and hydrogels like alginate and gelatin can be used properly to create wholesome dishes that also taste good. By enhancing the capabilities of each printing technique (extrusion, sintering, melting, etc.), based on the material, reducing restrictions, and introducing new capabilities, a range of 3D printers can be used to print food. [28]

2.4.4 Healthcare and medical industry

The field of 3D printing has been revolutionizing the healthcare industry for several years. The technology has enabled healthcare professionals to produce customized medical devices, implants, and anatomical models that are tailored to the specific needs of individual patients. According to a study published in the Rapid Prototyping journal, L.Yigong et al., 2016, mentioned that 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 good mechanical properties. And Similar organ failure brought on by serious issues like sickness, accidents, and congenital deformities can also be printed out using 3D printing technology. [29]

2.4.5 Electric and Electronic Industry

The electric and electronic industry has also been utilizing 3D printing in various applications, including prototyping, production of parts, and tooling. Here are a few examples [30]:

- **Prototyping:** 3D printing has enabled electrical and electronic engineers to create rapid prototypes of new designs quickly and cost-effectively. For example, Siemens has been using 3D printing to produce prototypes of its gas turbine components. This has reduced the production time of the components from six weeks to just two days, resulting in significant cost savings.
- **Production of parts:** 3D printing has also been used to produce complex, customized parts for electrical and electronic devices. For example, General Electric has used 3D printing to produce a jet engine fuel nozzle that is 25% lighter and five times more durable than traditionally manufactured nozzles.
- **Tooling:** 3D printing has also been used to produce customized tools and jigs for electrical and electronic manufacturing processes. For example, Bosch has used 3D printing to produce customized fixtures for the production of its sensor chips. This has reduced the production time of the fixtures from two weeks to just two days.

2.5 Fused Deposition Modeling (FDM)

At the beginning of the 1990s, Scott Crump of Stratasys INC., USA, introduced the FDM technology [31]. Since 2009, the demand for FDM has grown astronomically from year to year, and many industry experts think that this technology has the ability to completely transform how many industries produce goods [32].

Fused Deposition Modeling (FDM) is a 3D printing technology that creates objects by depositing layers of molten plastic filament in a precise pattern. This process involves a heated extrusion nozzle that melts and extrudes the plastic filament layer by layer to create a three-dimensional object. [32]

Fused Deposition Modeling (FDM) has many advantages such as high surface finish, less expensive initial investment, It is simple to create complex shape, no creation of scrap and High flexibility. But, The quality when comparing this process with another types of 3D printing is not as good as like Stereolithography (SLA) and Selective Laser Sintering (SLS). The well-chosen process factors are the primary determinant of the quality of parts produced by FDM. [33]

2.5.1 The process of FDM technology

The process of Fused Deposition Modeling (FDM) involves the following steps [31][32][35]:

- **Designing the 3D model:** The first step in FDM is to design a 3D model of the object using computer-aided design (CAD) software (generally in .stl format).
- **Slicing:** The 3D model is then layered using slicing software. The software splits the model into several horizontal layers of a given thickness and creates a set of parameters, and create a G-Code to be readable by the printer.
- **Preparing the FDM printer:** The FDM printer is prepared by loading the plastic filament into the printer's extruder. The filament is fed into the extruder through a heated nozzle.
- **Printing the object:** The FDM printer reads the digital file and begins to print the object by depositing layers of molten plastic filament onto a printing bed. The 3D printers used for FDM contain an arrangement that allows it to travel vertically and a support base that is related to some degree of flexibility. An associate extruder connected to the bottom plate is responsible for heating the filament to its freezing point and then extruding it layer by layer via a nozzle to create the desired object. The extruder is equipped with the ability to move in all three directions (x, y and z). Figure 9. below shows a 3D model of the FDM printer and its components is shown, illustrating the mentioned directions of movement.

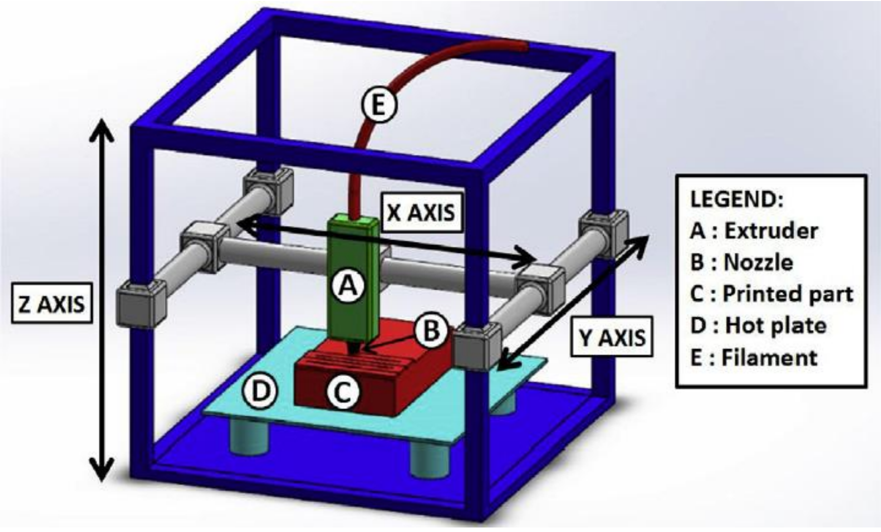


Fig 9 . 3D model of the FDM printer. [34]

- **Finishing the object:** Once the printing is complete, the object is removed from the printer and any excess material is removed. The object may need to be sanded or smoothed to achieve the desired finish.

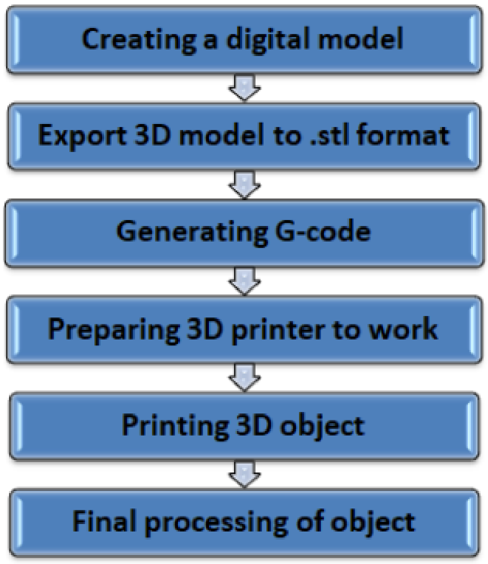


Fig 10. The steps of FDM printing process [35]

2.5.2 Parameters of FDM technology

There are several parameters that can be adjusted in FDM technology to control the quality, accuracy, and strength of the printed object. These parameters include extrusion temperature, nozzle diameter, print speed, layer height, infill density, raster angle and filament diameter [36][37]. Table 2. below shows the recommended ranges for the additional parameters in FDM technology, noting that these ranges may also vary depending on the specific FDM printer and materials being used.

Table 2. The recommended ranges for the additional parameters in FDM technology.

Parameter	Range	Reference
Extrusion temperature	160-250°C	[36][37]
Nozzle diameter	0.2-0.8 mm	[36][37]
Print speed	30-60 mm/s	[36][37]
Layer height	0.1-0.3 mm	[36][37]
Infill density	10-50%	[36][37]
Filament diameter	1.75-3.00 mm	[36]

2.5.3 Material that used in FDM technology

The most commonly used materials in FDM printing are PLA (Polylactic acid), ABS (acrylonitrile butadiene styrene), PETG (Polyethylene Terephthalate Glycol), Nylon, and TPU (Thermoplastic polyurethane).
Table 3. below shows the properties and applications for these material in FDM technology.

Table 3. Properties and applications of the materials used FDM technology.

Material	Properties	Applications	References
PLA	Biodegradable and eco-friendly, Easy to print, Low shrinkage, Low warping, Low strength and temperature resistance.	Prototyping, Educational models, Decorative objects, Toys, Food packaging.	[38],[39]
ABS	High strength and temperature resistance, Durable, Difficult to print, High shrinkage and warping.	Automotive parts, Electrical enclosures, Toys, Prototyping.	[38],[39]
PETG	Strong, impact-resistant, heat-resistant, flexible, clear	Bottles, Food containers, medical equipment, Prototyping.	[38],[40]
Nylon	High strength and flexibility, Good chemical resistance, High abrasion resistance, Prone to warping and shrinkage, Difficult to print,	Mechanical parts, Gears, Bearings, Structural parts.	[38],[40]
TPU	Flexible, rubber-like, high elasticity	Phone cases, shoe soles, seals, gaskets	[38],[40]

2.6 Polylactic acid (PLA)

PLA (polylactic acid) is a biodegradable and biocompatible polymer that has gained significant attention in recent years due to its environmental friendliness and suitability for various applications, including 3D printing. PLA is derived from renewable resources, such as corn starch or sugarcane, which make it an attractive alternative to traditional petrochemical-based polymers. [41][42]

PLA is a thermoplastic polymer that can be processed using various techniques, including extrusion and injection molding. It has an almost low melting point and can withstand temperatures up to 180°C. The material is known for its stiffness, strength, and toughness, making it an ideal candidate for various applications. Moreover, PLA is biodegradable and compostable, which makes it an attractive option for environmentally conscious consumers. [41]

PLA is one of the most widely used materials in 3D printing, particularly in FDM technology. PLA is an excellent material for FDM due to its low melting point, which makes it easy to extrude, and its ability to adhere well to the printing bed. [41]

Polylactic acid (PLA) has many advantages such as biodegradability and compostability, ease of printing, low warping, availability, and cost-effective. But, also has some disadvantages like brittleness, heat sensitivity, moisture sensitivity and limited strength. [42]

2.6.1 Parameters that used for printing PLA filaments in FDM technology

The optimal printing parameters for PLA can vary depending on the specific printer and filament being used. However, there are some general guidelines and ranges that can be used as a starting point. [43][44]. Table 4. below shows the recommended parameters for printing PLA filament.

Table 4. The recommended parameters for printing PLA filaments. [43][44]

Parameter	Recommended Range
Extrusion Temperature	180°C - 230°C
Bed temperature	50°C - 70°C
Print speed	30mm/s - 80mm/s
Layer height	0.1mm - 0.3mm
Cooling	0% - 100% (depending on the print)

2.6.2 PLA filament tensile testing

Todd Lecher and Megan Waytashek conducted a research study in 2014, in this study they tested generic brand PLA filament (before being printed) in the MTS Insight load frame (Tensile testing machine). They clamped the specimen of 200 mm length by using the Bollard style grips shown in figure 9. in the MTS insight load frame. They relied on studying different specimen at each raster orientations angle (0^o, 45^o and 90^o). They found that the specimen with a raster orientation angle of 45^o were the strongest, with an average ultimate tensile strength of 64.03 MPa and an average elongation at break of 2.5%. While, the specimen with 0^o and 90^o recorded ultimate tensile strengths of 58.45 MPa for 0^o and 54.01 MPa for 90^o and an average elongation at break were of 2.02% for 0^o and 4.14% for 90^o. Figure 10. below shown the Stress-stain diagram at each raster orientation. [45]

Fig 11. PLA filament testing using Bollard style grips(left), lose up of clamping method (right).[45]

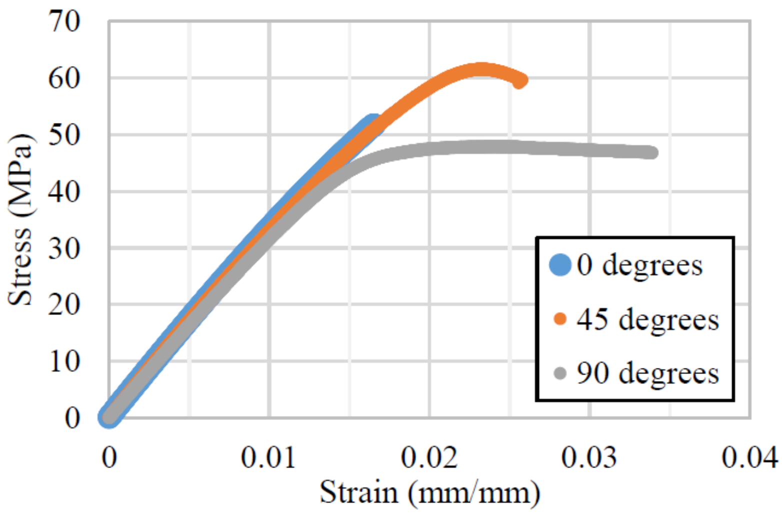


Fig 12. Stress-strain diagram at each raster orientation.[45]

2.6.3 Tensile test of specimens made of PLA filament manufactured with FDM technology:

In 2017, Cezary et al. conducted a tensile test on PLA samples that were 3D printed using FDM method and printed under high quality. They found that all samples broke in the working section, and the peak stress value was between 38 and 38.4 MPa, and the strain at peak stress was between 5 and 5.3%. [46]

Figure 13. below shows an image of the samples tested. In addition, stress-strain diagram of the samples that achieved the best results in the tensile test.

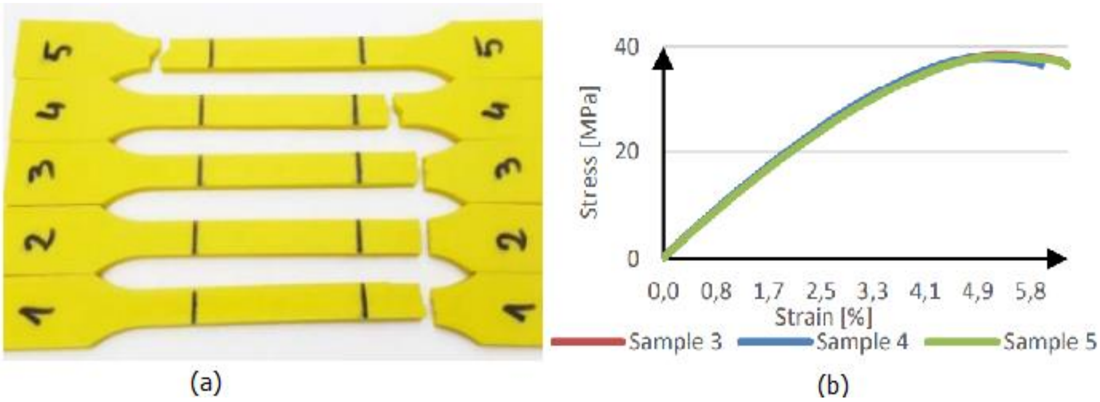


Fig 13. (a)- PLA_ results of tensile test. (b)- PLA_ Stress-strain diagram.[46]

2.6.4 Effect of extrusion temperature on tensile test for PLA specimens

In 2022, Vasile et al., studied the effect of printing nozzle temperature on ultimate tensile strength of PLA samples printed using the FDM technique, according to the ISO-527 standard. The researchers chose printing nozzle temperatures ranging from 180°C to 230°C, which are related to the PLA melting point (170 to 180 °C). the results mentioned that the higher UTS was between 210 -215 °C.

The tendency to use lower temperatures for PLA printing is related to its susceptibility to thermal degradation at high temperatures, in addition to economic issues such as lower energy consumption. At the same time, at low printing temperatures (under 180 °C) melting might not be complete and Interlayer diffusion might not take place. Low printing temperatures can induce delamination, or the peeling away of layers, as well as bigger air gaps between raster lines, which reduce tensile strength. [47]

2.7 Composite Filaments

Composite materials, such as composite filaments, are made up of two or more parts or phases together to produce special qualities that neither component could produce on its own. In the majority of composites, the matrix and reinforcement are the two main components. Enhancing the matrix's characteristics is frequently the aim of the development of composites.

According to an article published in Journal of Manufacturing and Materials Processing by A. Dey et al., in 2021, mentioned that pure thermoplastic filaments now in use have drawbacks such low strength and stiffness when it comes to fulfilling the enhanced performance of fused filament fabrication (FFF) construct parts.

High temperatures cause thermoplastics to soften and lose their ability to take on their original shape. In many instances, a product made from thermoplastic filaments is unable to satisfy a certain set of functional specifications. When compared to the characteristics of injection molded components, the properties of FFF built parts are frequently insufficient. So, in order to improve the properties of thermoplastic filament, they were reinforced either by particles, fibers, or non-particles to form composite filaments where the thermoplastic is the matrix. As shown in Figure 14. different types and forms of reinforcement are used as composites filament materials. [48]

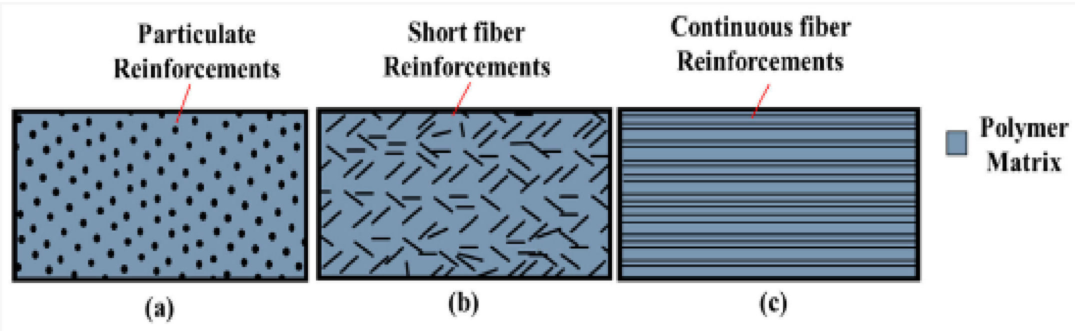


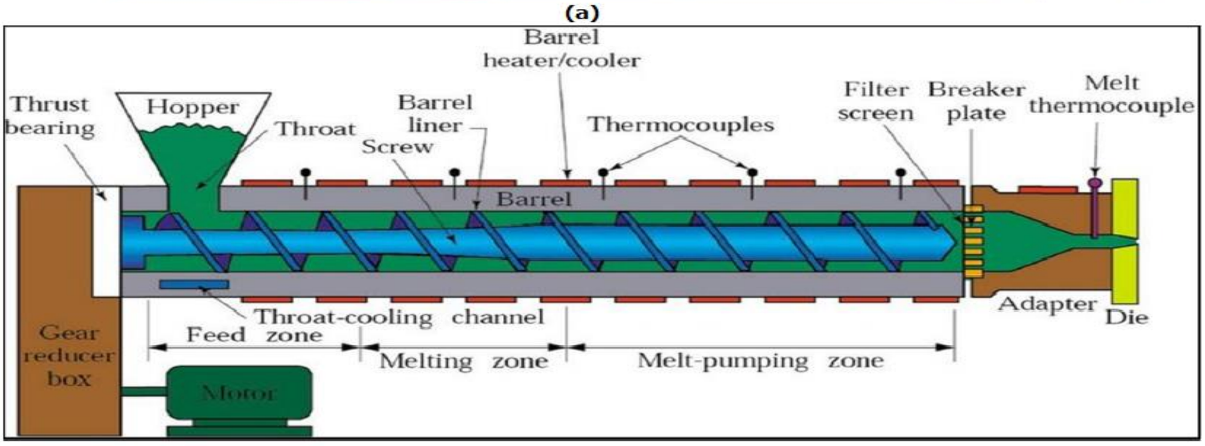
Fig 14. Types and forms of reinforcement materials: (a) Particulate reinforcement , (b) Short fibers reinforcement , and (c) Continuous fibers reinforcement. [48]

2.7.1 Composite Filaments Manufacturing for FDM

P.DUDEK, published an article in 2013, Described the mechanism of manufacturing composite filaments for FDM printing, as mentioned,
the filament used in the FDM procedure must have a particular diameter, strength, and other characteristics. A single screw extruder was created for a filament made from a composite composition. There is a difference in diameter between the die and the generated filament as a result of the die swell phenomena during the extrusion of a polymer. The machine features an adjustable screw speed, pressure, and temperature to obtain a constant diameter and minimize this deviation. Once the filament's ideal diameter is found, all of these variables are looked at and chosen (1.75mm). A separate calibrating nozzle was utilized for a smooth filament. The calibrating nozzle and heat sealing for low-temperature materials (PLA, PE) are constructed of copper.

The calibrating nozzle for high-temperature materials (ABS, PA) is composed of aluminum. Figure 15(a) shows the extruder station for manufacture filament, and its parts Figure 15(b). [50]

(a)



(b)

Fig 15. (a) Extruder station for manufacture filament for FDM printer [49], (b) Extruder parts [50]

2.8 Natural Fiber Reinforced PLA Composites

Fibre-reinforced polymer (FRP) composites are high-strength fibers that have a special interaction when placed in a polymer matrix. Fiber reinforced PLA polymer for 3D printing is an emerging trend in the field of additive manufacturing. It has gained immense popularity due to its potential to enhance the strength, stiffness, and toughness of the printed parts.

The low mechanical properties of PLA limit its application in high-performance engineering parts. So, to overcome this limitation, T. Mukherjee et al., published an article in Journal of polymer and environment, in 2011, mentioned that PLA have reinforced with natural cellulose fibers because of its properties. such as, low-cost alternative to carbon and glass fibers, abundantly available, low density, renewable, and biodegradable . and classified this natural fiber as shown in Figure 16. [51]

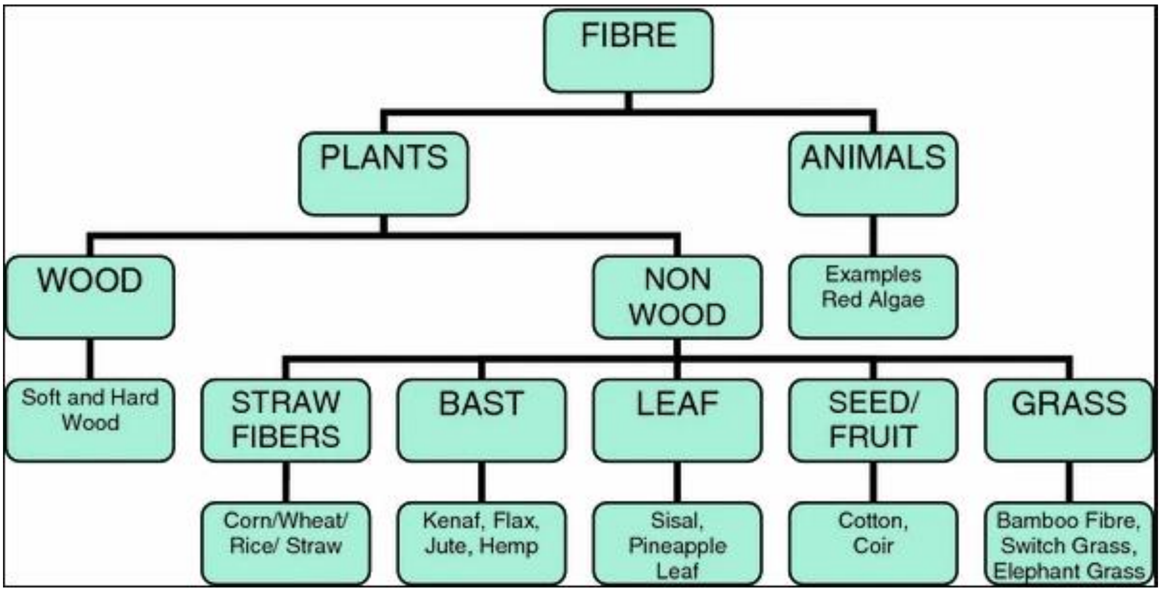


Fig 16. Classification of natural fiber. [51]

2.8.1 Effect of Hemp fiber reinforced PLA composites on Tensile strength in FDM

An article published to the *journal of composite science* explores hemp and other fiber reinforced PLA using FDM. D. Stoof et al., in 2017, study measured the tensile strength of each composite using hemp at weight percentages of 0, 10, 20, and 30%. Tensile strength was found to be 35 MPa for composite that was 0% hemp, and increased to 38 MPa for composite that was 10% hemp. Tensile strength decreased to 29 MPa and 25 MPa for 20% and 30% hemp, respectively, after 10% hemp. Figure 17. below shows the result of this experiment. [52]

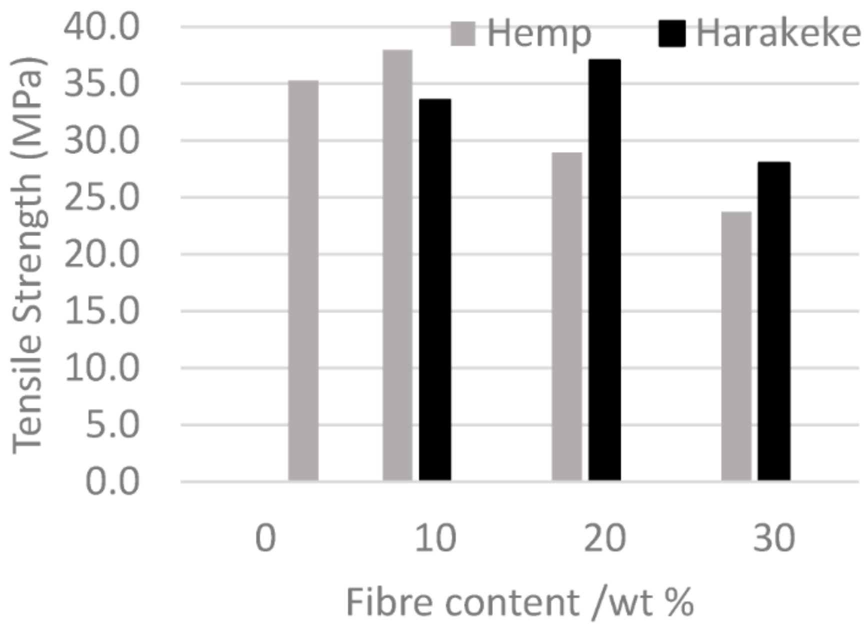


Fig 17. Tensile strength of PLA/hemp composite printed specimen. [52]

3. Materials and Methods

Laboratory experiments were conducted on the samples at the Materials Science Laboratory at the Hungarian University of Agriculture and Life Sciences in Gödöllő (Szent István campus).

3.1 Introduction

Over the past four decades, the use of 3D printing for tooling and high-speed manufacturing has promised the manufacture of components with complex geometries from computer designs. Thermoplastic polymers are one of the common and widely used materials in printing processes and their products have been used in many applications. Due to the need to obtain better mechanical and functional properties from pure polymer molded parts, the possibility of reinforcing these polymers with fibers to obtain better properties from was investigated.

This research involved working with the material polylactic acid (PLA), which is a thermoplastic biodegradable polymer commonly used in 3D printing processes. The mechanical properties of different types of PLA were studied in relation to tensile testing. Tensile strength test was conducted on four types of PLA filaments obtained from different companies.

This experiments include conducting a tensile strength test on:

- The filaments (before being printed) using a Bollard-style grips to clamp the filaments on the tensile strength test machine.
- Printed samples of these different types of PLA filaments using an FDM printer. 3 tensile samples was printed from each type
- PLA filaments that were re-manufactured in the laboratory using a single-screw extruder by re-manufactured the filaments that manufactured in the companies.
- And the re-manufactured PLA filaments reinforced with hemp fibers.

The 3D design of the samples was created using a Solid Edge software, and ISO 527-2-5A standard was adopted in design. The design was converted to STL format for export to the slicing software. The slicing software used is Ultimaker Cura, which is one of the most popular slicer applications in the 3D printing world because of how simple it is to use, how powerful it is, and how many different 3D printers it can be used with. Through using Cura, we were able to convert the STL format into a G-Code, which is a language that can be read by the FDM printer we used, with the sliced file containing print parameters that we used.

The testing on the samples after printing was performed using tensile testing machine type Zwick Roell Z100, in accordance with ISO 527-1 standard.

3.2 Materials

3.2.1 PolyLactic acid (PLA) Filaments

Four different types of PLA filaments were used to perform a tensile strength test on them. Each one of them obtained from different manufacturer.

Table 5 shows the type and the manufacturer of each of the filaments used, as well as information on the diameter, the net weight of filaments in the spool, printing temperature, and color of these filaments.

Table 5. Types and information about filaments material used.

	Type	Manufacturer	Diameter (mm)	Net Wight (g)	Print Temperature (°C)	Color
1	PLA	CREALITY	1.75	200	195 – 220	White
2	rPLA	3D JAKE	1.75	1000	200 – 220	Black
3	HD PLA	Fiberlogy	1.75	850	200 – 230	Grey
4	PLA Carbon	Spectrum	1.75	500	190 – 220	Black

Here some information about the properties of this filaments from the companies that made each of them.

- **PLA (CREALITY) White:**

Table 6. Mechanical and Recommended printing Properties of PLA White (CREALITY). [52]

Mechanical properties	Value
Tensile Strength	51 MPa
Bending Strength	86 MPa
Parameter	**Recommended value**
Printing Temperature	195-230 ºC
Bed Temperature	0-60 ºC

- **rPLA (3D JAKE) Black** : rPLA filaments is a fully recycled filaments made from the leftover materials of PLA manufacturing. The materials are collected, shredded, and reprocessed directly into production, allowing for waste reduction. [53]

Table 7. Mechanical and Recommended printing properties of rPLA 3D JAKE. [53]

Mechanical Properties	**Typical value**	**Test method**
Tensile strength	63 MPa	ISO 527
Elongation	4%	ISO 527
Tensile Modulus	3251 MPa	ISO 527
Parameter	**Recommended value**	
Printing temperature	200 – 220 ºC	-
Bed Temperature	35 – 60 ºC	-

- **HD PLA (Fiberlogy) Grey** : HD PLA can be utilized in place of ABS. It can be heated up after being printed normally as PLA to give it ABS-like characteristics. This enables to forgo printing on this material and prevent any problems related to printing, such as shrinkage, unpleasant smell, and breathing in potentially harmful fumes. Additionally, the material is more heat- and impact-resistant after annealing. [54]

Table 8. Mechanical and Recommended printing properties of HD PLA (Fiberlogy).[54]

Mechanical Properties	**Typical value**	**Test method**
Tensile strength	51 MPa	ISO 527
Elongation	3.5 %	ISO 527
Tensile Modulus	2400 MPa	ISO 527
Parameter	**Recommended value**	
Printing Temperature	200 – 230 ºC	-
Bed Temperature	50 – 70 ºC	-

- **PLA Carbon (Spectrum) Black :** PLA Carbon Spectrum is a filament made of 90% PLA and 10% carbon fibers. This blend of PLA and carbon fibers contributes to a considerable increase in rigidity, hardness, and tensile resistance, while still retaining the same low shrinkage and good adhesion to the typical build platform as pure PLA. [55]

Table 9. Mechanical and Recommended printing properties of PLA Carbon (Spectrum) Black. [55]

Mechanical Properties	Typical value	Test method
Tensile strength	65 MPa	ISO 527
Elongation	0.5 %	ISO 527
Tensile Modulus	12500 MPa	ISO 527
Parameter	**Recommended value**	
Printing Temperature	190 - 220 ºC	-
Bed Temperature	0 - 45 ºC	-

Fig 18. PLA Filaments : HD PLA Fiberlogy, rPLA 3D JAKE, PLA White CREALITY, and PLA Carbon Spectrum. (bottom to top)

3.2.2 Hemp Fiber

Hemp fiber, derived from the cannabis plant, which is related to the cannabis plant, is considered to be one of the strongest members of the natural fiber family. Because of their biodegradability and lower density than synthetic fibers, these fibers are now widely accepted as reinforcements in composite materials. These materials also have inherent mechanical, thermal, and acoustic properties. [56]

The PLA polymer reinforced with hemp fibers was studied to obtain composite filaments with improved mechanical properties, especially in terms of tensile strength. This will result in printed products from these composite filaments that possess better functional properties. Additionally, the possibility of reinforcing PLA with hemp fibers will result in lightweight and environmentally friendly products, as they are made of two biodegradable materials.

Table 10. below shows the physical and mechanical properties of hemp fiber according to an article published in journal of fibers by P. Manaia et al., in 2019 . [57]

Table 10. The physical and mechanical properties of hemp fiber. [57]

Fiber	**Length (mm)**	**Density (g/cm^3)**	**Tensile strength (MPa)**	**Young's Modulus (GPa)**
Hemp	5-55	1.4	550-1110	30-70

In this reaches, a Hemp reel was obtained from MATE University's materials sciences laboratory (Figure 19). Hemp fiber was prepared from this reel.

Fig 19. Hemp reel

A tensile strength test was carried out on a piece of hemp reel with a length of 150 mm and a diameter of 1.2 mm, and the results showed that the ultimate tensile strength value was 180MPa.

To better understand, the hemp fiber when it distribution within the composite filaments, it was necessary to know the size of small piece of hemp reel, a ZEISS microscope from MATE University's materials sciences laboratory was used. when magnification (10×10) the photo (Figure 20) shows that the length was 35.05µm and the width was 23.78 µm.

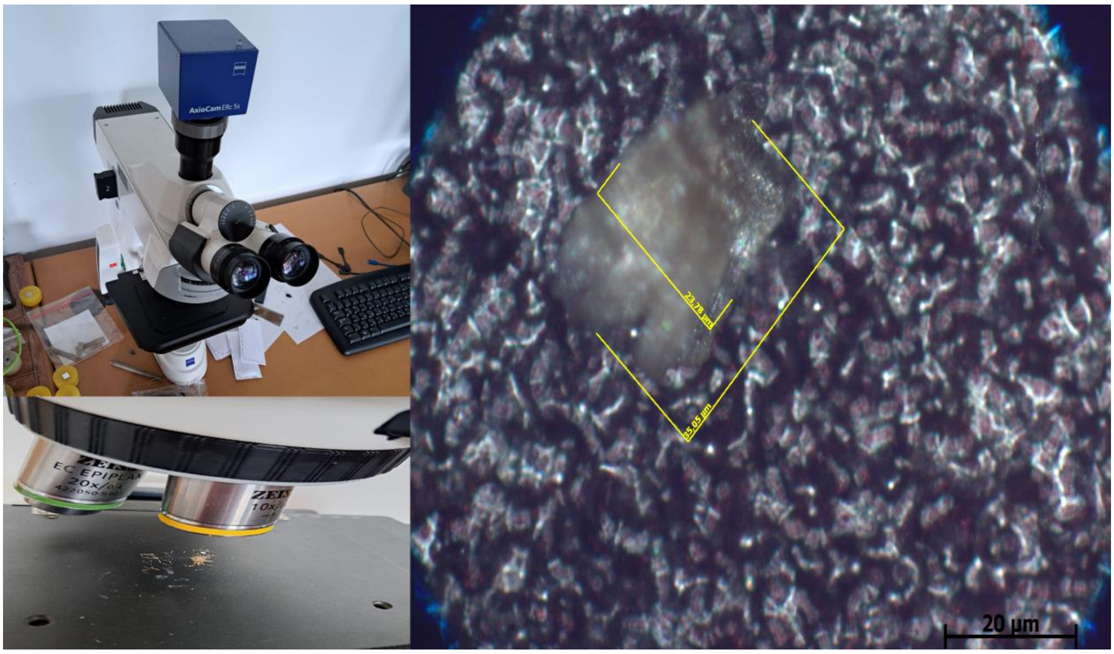


Fig 20. Microstructure of hemp piece with magnification ×100.

3.3 Sample Preparation

One of the task that conducted in this research was printing samples of PLA filaments that were obtained from the companies that mentioned before, in order to conduct a tensile strength test on them and compare the results with the tensile strength test that conducted on the filaments. Samples preparation was carried out in two steps: the first step was selecting the 3D model that wanted to print and preparing it for the printing program (The Slicer), and the second step was printing the samples using the FDM printer for conduct the tensile test on them. 3 samples was printed from each filament.

3.3.1 The Printing Program (the slicing software)

The design of the samples was created using Solid Edge software, while adhering to the ISO 527-2-5A standard. Once the design was completed, it was then converted into STL format, which is a standard file format used in 3D printing. The STL file was then imported into the slicing software, where the printing parameters were set and a G-Code file was generated for printing on the FDM printer.

Ultimaker Cura 5.1.0 was used to convert the ISO 527-1-2A.stl file into a G-Code. And set the printing parameters that used to print the samples. Figure 21 below shows a screenshot of the main interface of the program, indicating the profile of the sample that have been selected to be printed in this orientation, flat orientation was adopt on the printer's bed. And the raster orientation angle is ±45º, so if the first layer was +45º then, the second layer would be -45º, and so on.

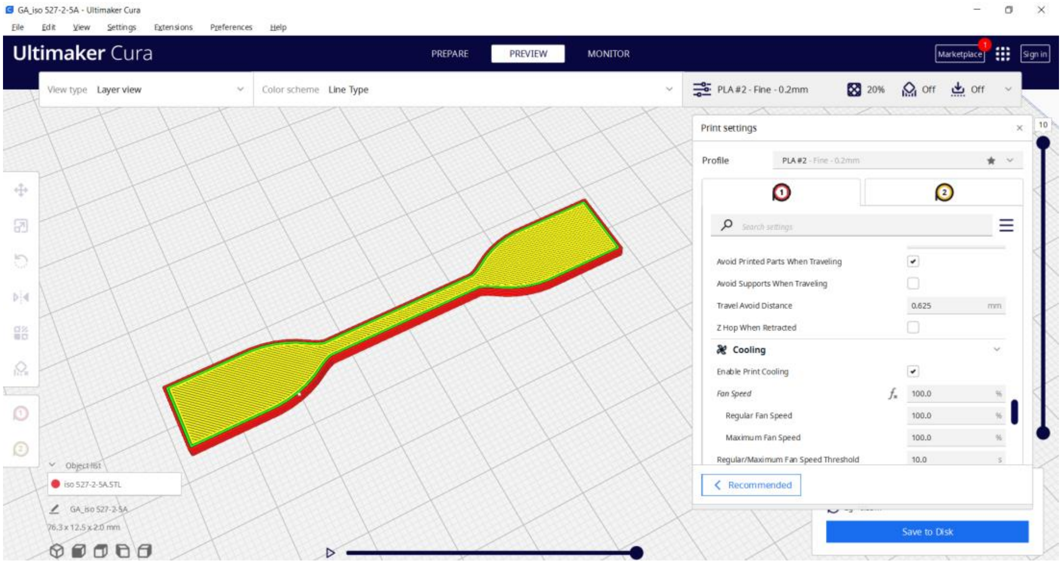


Fig 21. The main interface of the Ultimaker Cura 5.1.0 .

To set the printing parameters in Ultimaker Cura software, the height of each layer must be selected first. Since PLA filaments with a 1.75mm diameter were used, a layer height of 0.2mm, which is the recommended value, was chosen. Moreover, to match the 0.4mm nozzle diameter of the printer, the line width was set to 0.4mm. All the selected quality parameters are presented in Figure 22 below.

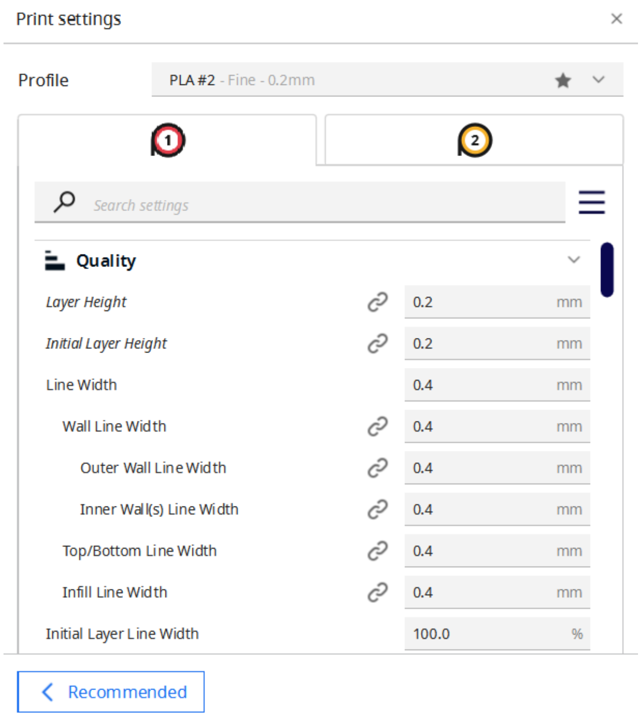


Fig 22. The Quality Setting

The samples was printed with 10 layers, without any infill settings selected. Consequently, the number of top layers set to 5 and the number of bottom layers to 5 also, as indicated in Figure 23.

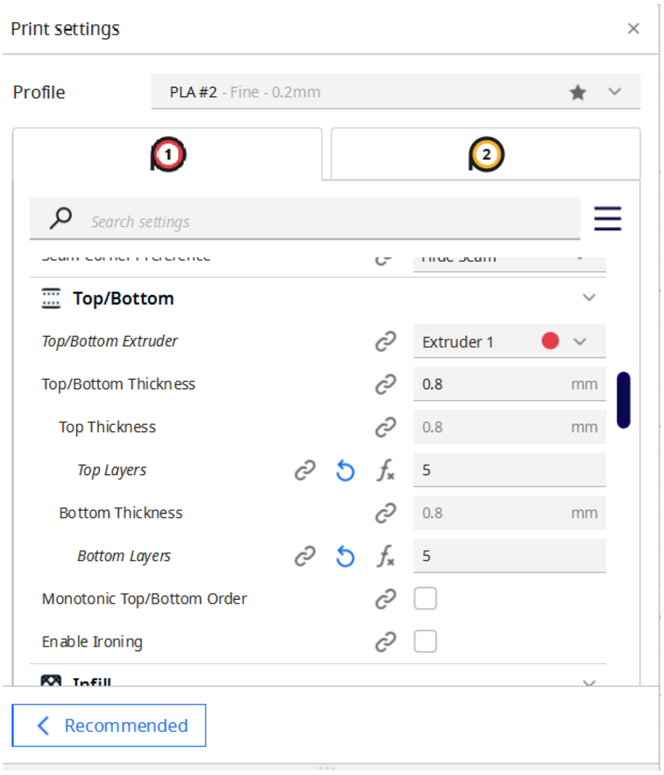


Fig 23. The Top/Bottom Setting.

Since the melting temperature of PLA is between 170-180 ºC, the printing temperature should not be lower than 180 ºC to ensure complete polymer melting and layer adhesion. The temperature should also not exceed 230 ºC due to the tendency of PLA to degrade at high temperatures. Anyway, for PLA polymer, the recommended printing temperature should be higher than 200 ºC. Therefore, the printing temperature was set to 205 ºC for the entire printing process. Figure 24 below shows the material settings. For the bed temperature, it was set at 60 ºC.

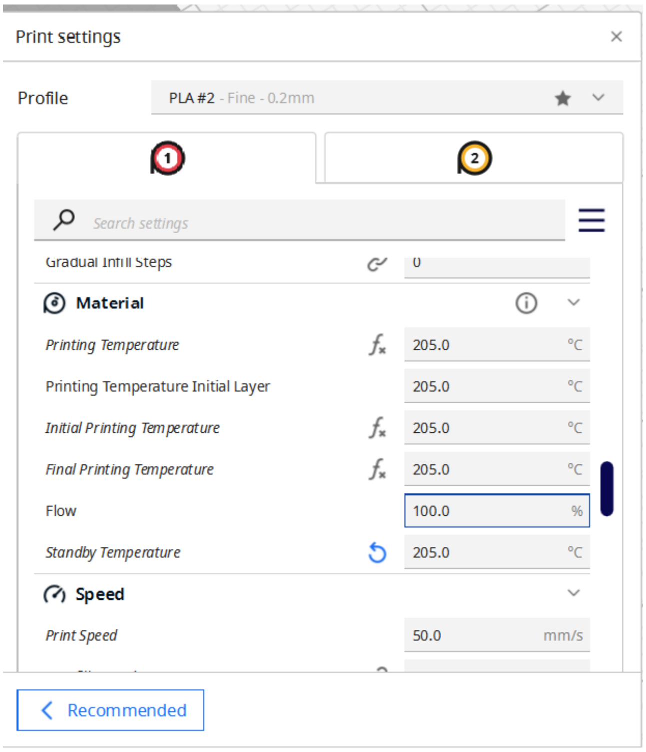


Fig 24. The Material Settings.

As for printing speed, the movement of the printer head has been set to at 50 mm/s. after that Ultimaker Cura had made the calculation of extrusion flow. The infill speed was set at the same temperature but since there is no infill setting, It will not affect the printing and quality of the samples. The Top/Bottom speed was set at 30 mm/s, lower than the printing speed to increase the reliability of closure on the top/bottom layers.

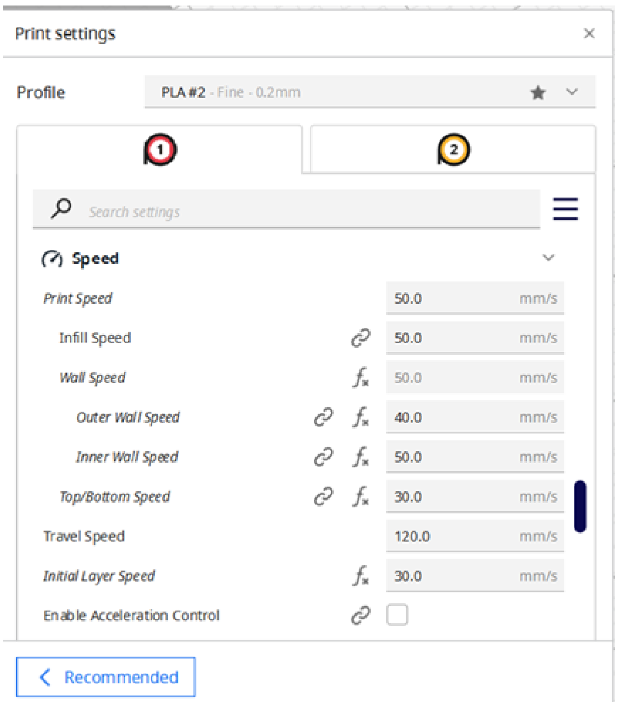


Fig 25. The Speed Setting.

Since PLA is the material that used, it is recommended to operate the cooling fans to have a good quality products. Therefore, The fan speed was set to the maximum speed of 100% during printing as shown in figure 26.

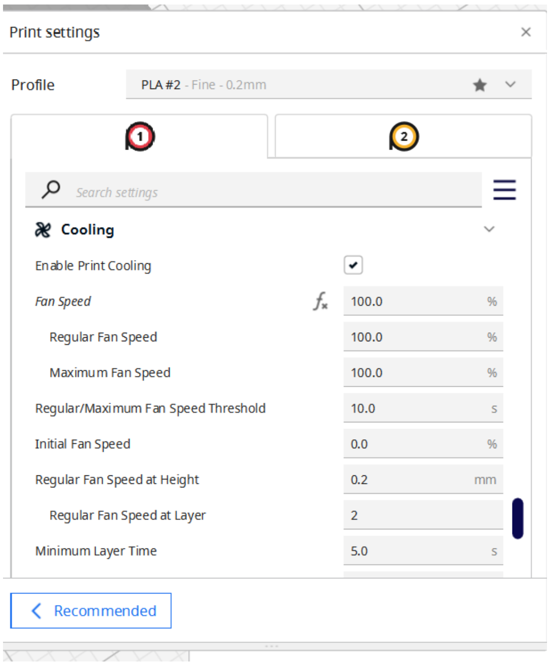


Fig 26. The Cooling Setting.

One of the problems we encountered while using the Cura software was the starting point for each path in a layer. As shown in the figure 27, all of them started from the same location on each layer, resulting in a vertical line on the z-axis. This will be noticeable accurately when printing the sample.

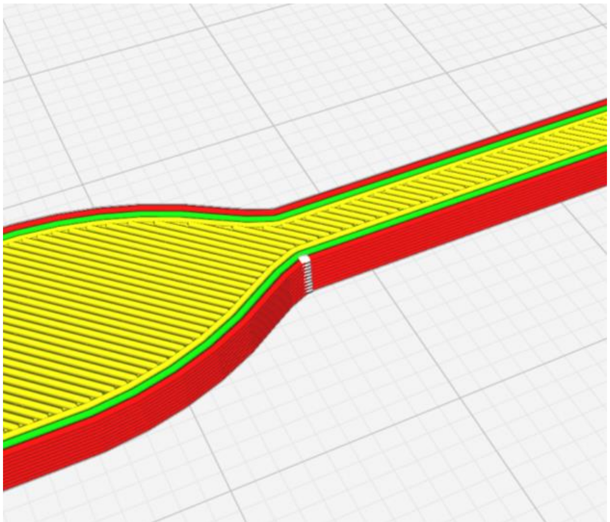


Fig 27. The starting point for each path in a layer.

This situation was avoided by specifying the starting point of the path in each layer randomly, so that the starting point will not be distinguished when printing each layer. This will improve the appearance and shape of the sample after printing. Figure 28 below shows the starting point of printing each layer after set it randomly.

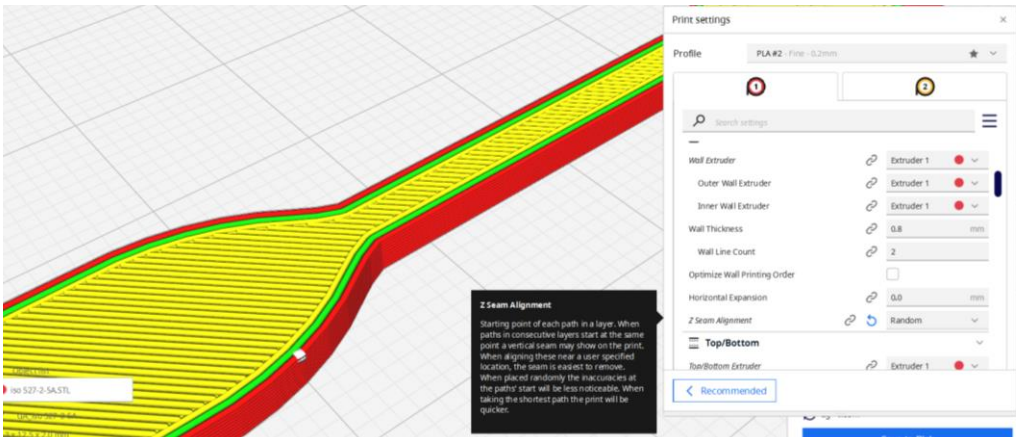


Fig 28. The starting point for each path in a layer after set it randomly.

Table 11. below shows the parameter that we selected to print.

Table 11. The printing parameters for samples tested.

Parameter	Value
Layer Height	0.2 mm
Printing Width	0.4 mm
Printing Temperature	205 ºC
Bed Temperature	60 ºC
Print speed	50 mm/s
Initial layer speed	30 mm/s

Figure 29. shows the dimension and characteristic length of the ISO 527 -2-5A Specimen. Where L_G: is the gauge-length (Where the Stress and Strain is measured). And L_{gh}: is the initial distance between the grip-heads.

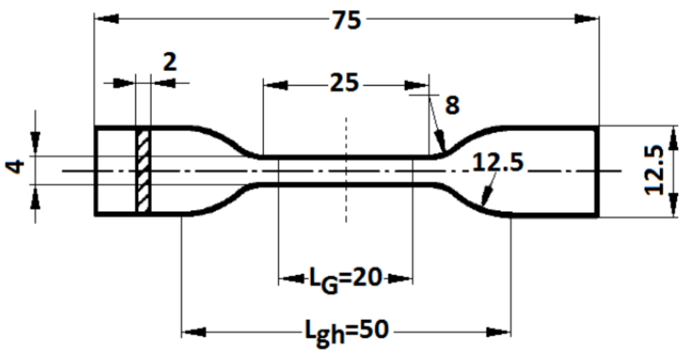


Fig 29. Dimensions (mm) of the ISO 527 - 2 - 5A Specimen. (58)

3.3.2 Fused Deposition Modeling (FDM) used

Fused Deposition Modeling (FDM) was used to create tensile samples of the four types of PLA filaments obtained from the companies mentioned earlier. A GEEETECH A20M printer from MATE University's materials sciences laboratory was used (Figure 30). For each filament, 3 tensile samples were printed to test (Figure31).

Fig 30. GEEETECH A20M printer used to print tensile samples

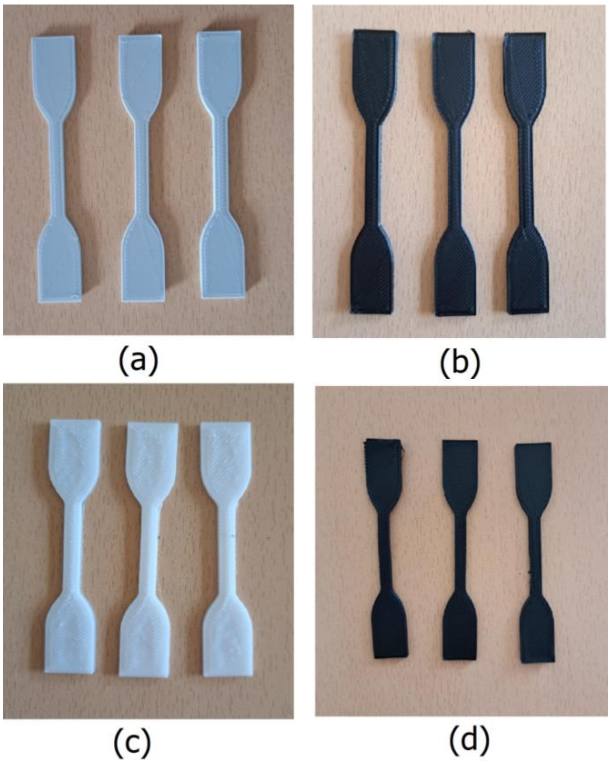


Fig 31. The Samples after printed : (a) HD PLA – (b) rPLA – (c) PLA White – (d) PLA Carbon.

3.4 Filament Preparation

The task was to make a new filaments by re-manufactured the original filaments from the companies, this was done in order to test their ultimate tensile strength and compare the results with the ultimate tensile strength test of the original filaments. The preparation stage involved cutting the original filament into fine particles using a filament cutting machine, and then feeding them into a single screw extruder machine to manufacture the new filaments.

3.4.1 Filament Cutter

The filaments cutting machine available in the Materials Science laboratory at the Hungarian University of Agriculture and Life Sciences was used (Figure 32-b). A portion of the commercially manufactured filament was cut into pieces and placed in the cutting machine's box (Figure 32-a). The box was then attached to the machine and rotated for 7 seconds to obtain fine particles (Figure 32-c). All the four types of PLA filament were cut separately and prepared for manufacturing new filaments (Figure 33).

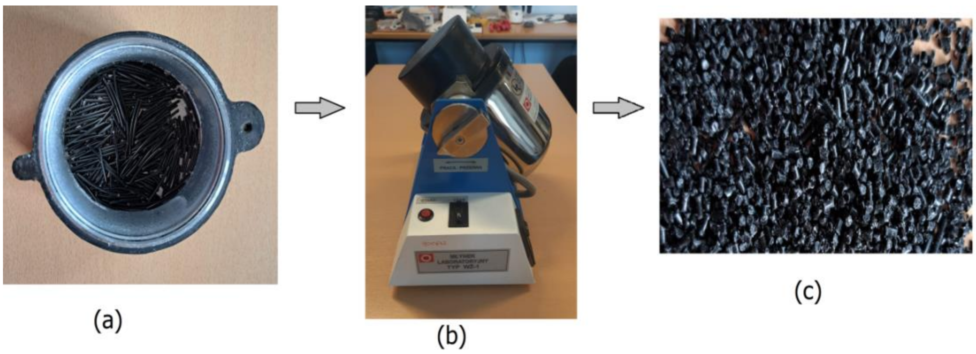


Fig 32. Filament cutting process.

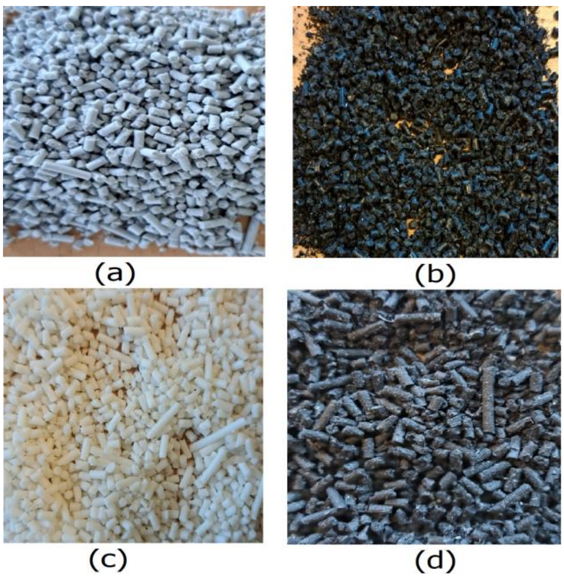


Fig 33. PLA filaments particles after cutting: (a)- HD PLA, (b)- rPLA, (c)- PLA White, (d) PLA Carbon.

3.4.2 Single Screw Extruder (Filaments Maker)

A single screw extruder machine was used to re-manufactured the original filaments, the machine that used was available in the materials sciences laboratory in the university (Figure 34).

To make new PLA filaments using a single screw extruder, the particles PLA are fed into the barrel of the machine and heated to a specific temperature, since the PLA polymer was used the setting temperature was set at 185 ºC , to ensure the material's melting, the speed of extrude was the maximum speed on the machine. The screw inside the barrel then rotates and moves the molten PLA material forward, while also mixing and homogenizing it to ensure consistent quality.

Once the PLA material has been melted and homogenized, it is forced through a die that shapes the material into the desired size and shape of the filament, in this research the diameter of the new filaments ranging between 0.4 to 1.4 mm. The filament is cooled by a fan and prepared to use in the test (Figure 35).

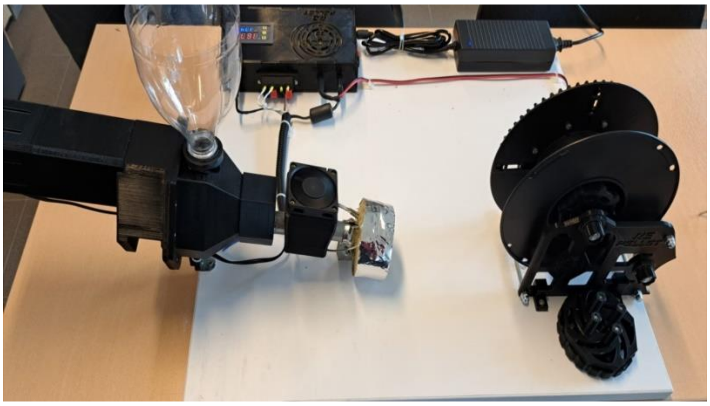


Fig 34. A single screw machine to make filaments

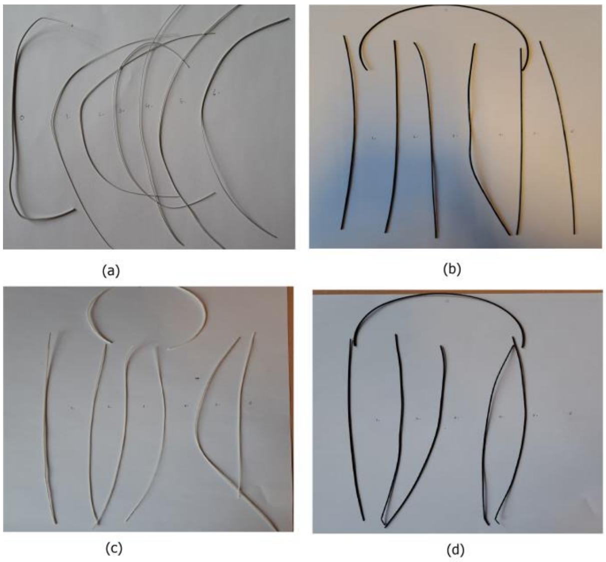


Fig 35. The re-manufactured filaments: (a) HD PLA – (b) rPLA – (c) PLA White – (d) PLA Carbon.

3.4.3 Composite filament preparation

New filaments were manufactured in the laboratory to conduct a tensile strenght test on them, which are composite filaments composed of the particles PLA made it from commercial filaments reinforced with hemp fiber.

The steps of manufacturing composite filaments are similar to those of manufacturing unreinforced filaments in terms of preparing the particles and making the filaments using a single-screw extruder. The addition here was to add the hemp fibers to the PLA particles (Figure 36), and then put it the barrel of the machine, and the setting temperature was also the same 185 ºC. The filament is cooled by a fan and prepared to use in the test (Figure 37). The Carbon PLA filaments were very sensitive and had a very high density, and they could not be reinforced due to the difficulty of re-manufactured them in the filament extrusion machine.

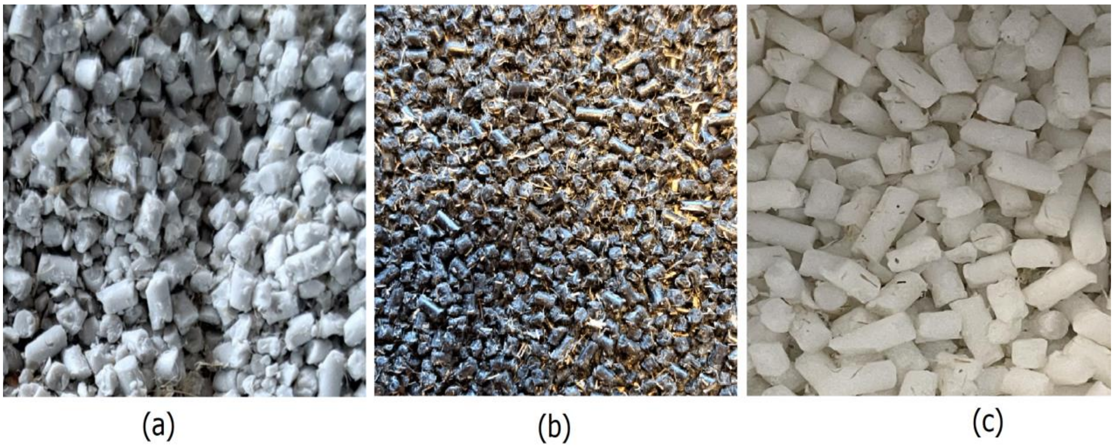


Fig 36. PLA filaments particles reinforced with hemp fiber: (a) HD PLA, (b) rPLA, (c) PLA White .

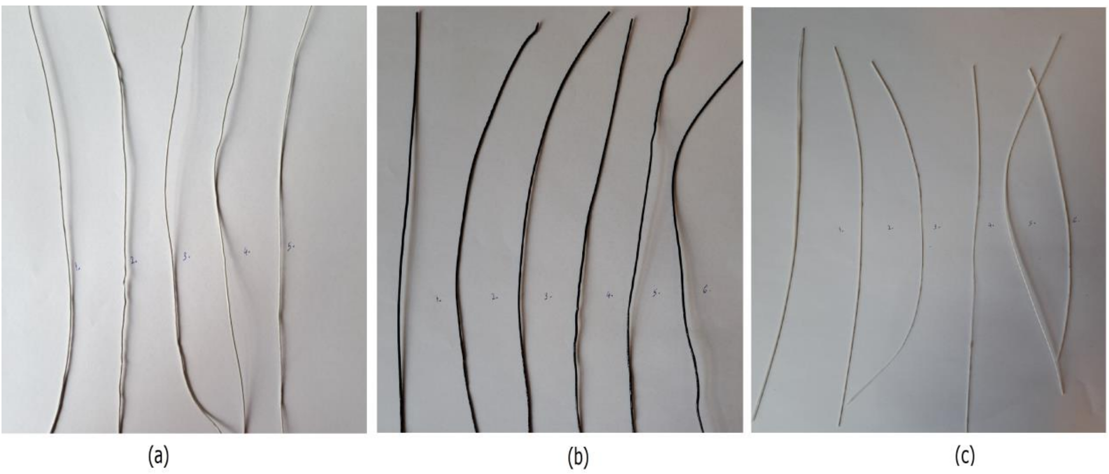


Fig 37. The re-manufactured filaments reinforced with hemp: (a) HD PLA – (b) rPLA – (c) PLA White.

3.5 Tensile Strength Test

The tensile test is widely used to provide basic information for material design regarding its strength, and as an acceptance test to verify material compliance with standard specifications. In a tensile test, the test sample is subjected to a continuously increasing uniaxial tensile force, while the sample elongation is simultaneously monitored as a function of the tensile force (load). The stress-strain curve is plotted from load and elongation measurements.

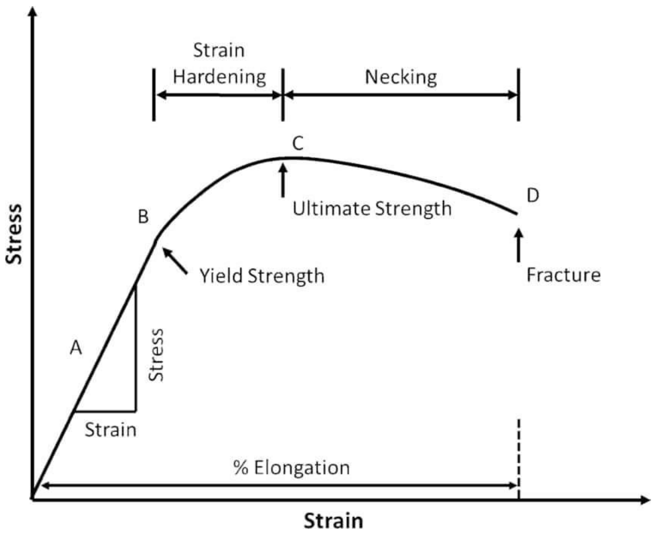


Fig 38. The Stress – Strain Curve . [59]

The stress is measured by dividing the load by the original cross-section area of the test specimen:

$$\sigma = \frac{F}{A} \tag{1}$$

Where:

σ : The Stress. $[\frac{N}{mm^2}]$

F: The Load. [N]

A: The Cross-section Area. [mm^2]

The strain used in the stress-strain curve is the average linear strain, which is measured by the following equation.

$$\varepsilon = \frac{\Delta L}{L_0} \,.\, 100 = \frac{L - L_0}{L_0} \,.\, 100 \tag{2}$$

Where:

ε: The Strain. [%]

ΔL: The Change in Gauge Length. [mm]

L_0: The initial Gauge Length. [mm]

3.5.1 Tensile Strength Test Machine

The Zwick Roell Z100 testing machine with ISO 527-1 standard was utilized to conduct tensile strength experiments on the PLA filaments and printed samples. This machine is available in the material science laboratory at MATE university (Figure 39).

The Zwick Roell Z100 is a universal testing machine used for testing the tensile strength of various materials. It is an electromechanical testing machine that can perform tests such as tensile, compression, bending, and shear testing.

The Zwick Roell Z100 has a maximum force capacity of 100 KN and a maximum test speed of 2000 mm/min. It has a range of fixtures and grips that can accommodate various types of specimens, including metals, plastics, composites, and rubber.

To operate the machine, the specimen set up in the appropriate grips, input the test parameter (dimensions of test specimens, temperature, humidity, test speed, pre-load,etc) into the Zwick Roell software according to the ISO 527 - 1, and then start the test. During the test, the machine applied a load to the specimen and record the tensile force and strain, and the data was written to an Excel file to analysis it. From analysis the data, various mechanical properties of the material can be calculated, including the ultimate tensile strength that we need to determined . These properties provide important information on the suitability of the PLA material for different applications.

Fig 39. The Zwick Roell Z100 testing machine.

3.5.2 Bollard style tensile grips

Bollard style tensile grips are a type of grip used in materials testing, particularly for tensile testing. Bollard style tensile grips are designed to hold the filament, in place during a tensile test. They typically feature two cylindrical grips that are mounted on a testing machine, with one grip being fixed and the other being movable. The movable grip is connected to the testing machine's load cell, which measures the amount of force being applied to the specimen.

Bollard style tensile grips were produced in the workshop of the Hungarian University of Agriculture and Life Sciences to be attached to the current tensile testing machine for filament testing. Figure 40 demonstrates the method of attaching the grips to the tensile testing machine, while Figure 41 shows the preparation of the filament for tensile testing using the grips.

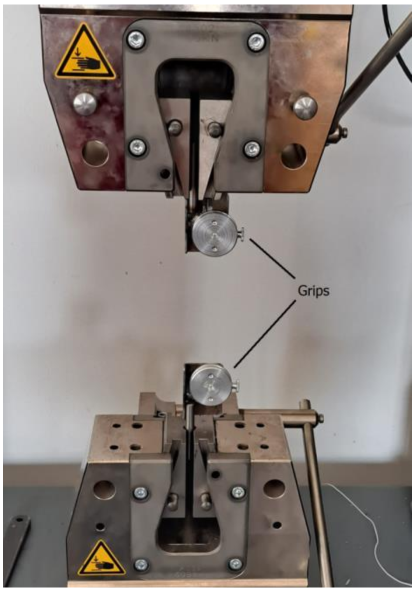


Fig 40. The Bollard style tensile grips .

Fig 41. The filament testing using the bollard style tensile grips.

3.6 Test Procedure

Tensile strength experiments were conducted on the commercial original filaments, re-manufactured filaments, re-manufactured filaments reinforced with hemp fibers, and printed samples, all using the Zwick Roell Z100 machine with ISO 527 - 1 standard for the test. The tests were conducted at room temperature of 20°C and 70% humidity, with a test speed of 5 mm/min and a preload of 10 N. The results were recorded until reaching the maximum tensile force for each sample, and the data was written in an Excel file for analysis and obtaining Ultimate Tensile Strength (UTS) using the stress and strain calculation equations mentioned earlier.

3.6.1 Test Procedure on The Original Filaments

The different types of PLA filaments (HD PLA, rPLA, PLA White, PLA Carbon) that obtained from the companies (Fiberlogy, 3D JAKE, CREALITY, Spectrum) have been conducted tensile strength test on, to determine the Ultimate Tensile Strength (UTS) for each of filament (before being printing). A 30 cm long and 1.75 mm diameter sample of each type were clamping using bollard-style grips in the Zwick Roell Z100 tensile testing machine, under the previously mentioned testing conditions. The distance between the grips was set to 120 mm. As shown in Figure 42.

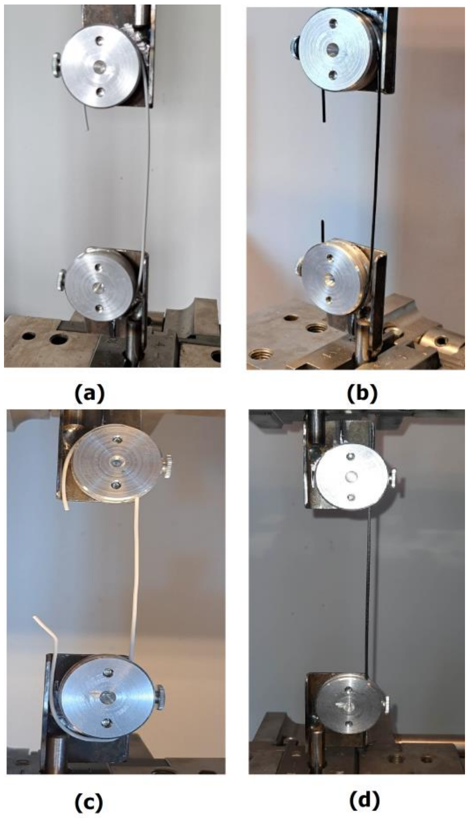


Fig 42. The original filaments test.

Once it was confirmed that the samples were correctly positioned and the parameters were accurately entered into the computer, the experiment was started while ensuring that no external force was applied. The test was stopped after verifying that the maximum tensile force was achieved, and the information for each test was saved in an Excel file for later analysis.

3.6.1.1 Measured results

After analyzing the results obtained from the Excel file for each filament, we obtained the stress-strain curves for each filament, and the curves were as shown in Figure 43. The results found in the Excel file showed the relationship between the axial force applied on the samples and the resulting elongation. Using these values, we were able to calculate the stress and strain, as mentioned in equations (1) and (2) earlier, because the stress-strain curve accurately illustrates the sample behavior when exposed to force in relation to the change in its original shape. The applied force is divided by the cross-section area of the product, and thus the curve effectively describes the results. Additionally, the stress-strain curve can be easily used to compare and evaluate different samples based on properties such as elongation, elasticity, stretch, and as in the case of our search into the ultimate tensile strength.

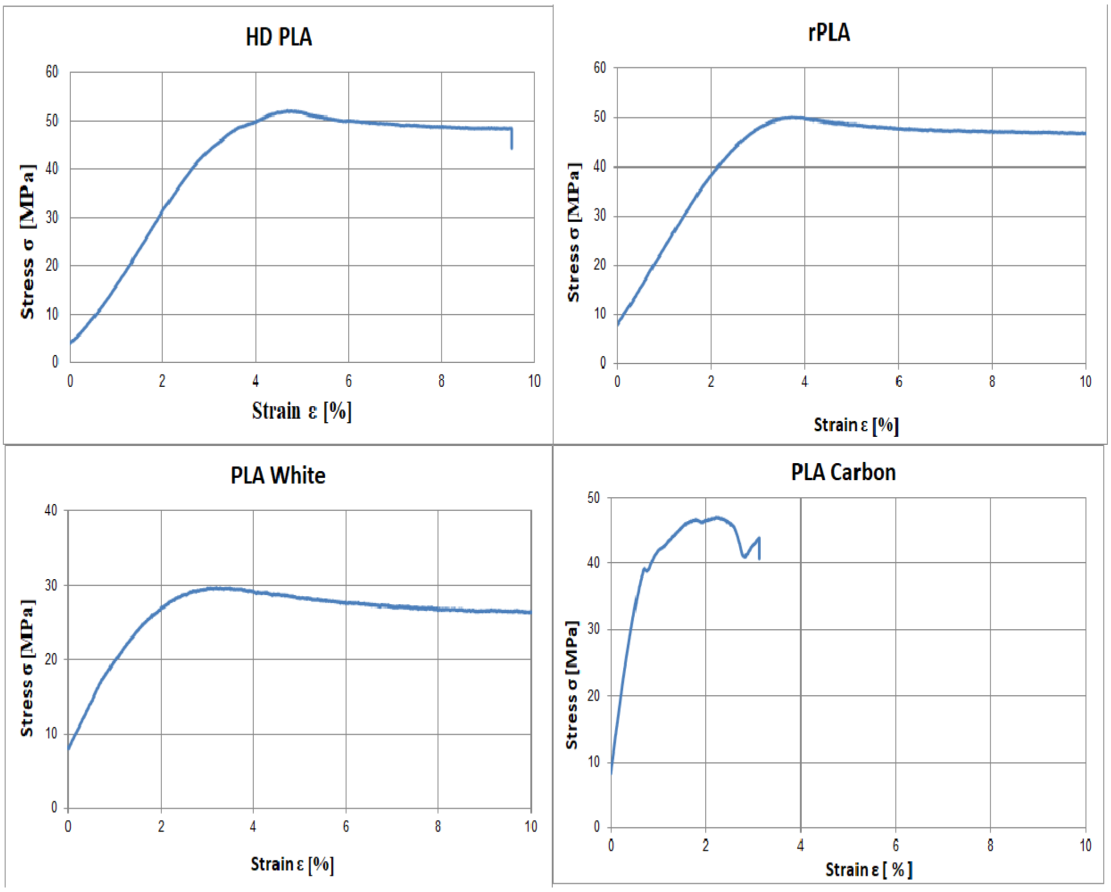


Fig 43. Stress-Strain curve for Original Filaments.

3.6.2 Test Procedure on The Re-manufactured Filament

After re-manufacturing the commercial filaments using a single-screw extruder, new PLA filaments of each type were obtained. These filaments had an inconstant diameter and the diameter ranging was from 0.4 mm to 1.4 mm. From each type of filament, several samples were cut, each 30 cm long and the diameter was obtained by taking several measurements along the sample. Then, the smallest diameter was used in the calculations as it is the weakest point of the sample and the one that will be affected by the force. It should be noted that the difference in diameter within one sample did not exceed 0.1 mm. After that the sample were clamping using bollard-style grips in the Zwick Roell Z100 tensile testing machine, under the previously mentioned testing conditions. The distance between the grips was set to 120 mm.

Again, Once it was confirmed that the sample was correctly positioned and the parameters were accurately entered into the computer, the experiment was started while ensuring that no external force was applied. The test was stopped after verifying that the maximum tensile force was achieved. Then, these value was recorded to be used in calculating the ultimate tensile strength for each sample. Figure 44 below shows the sample after the test.

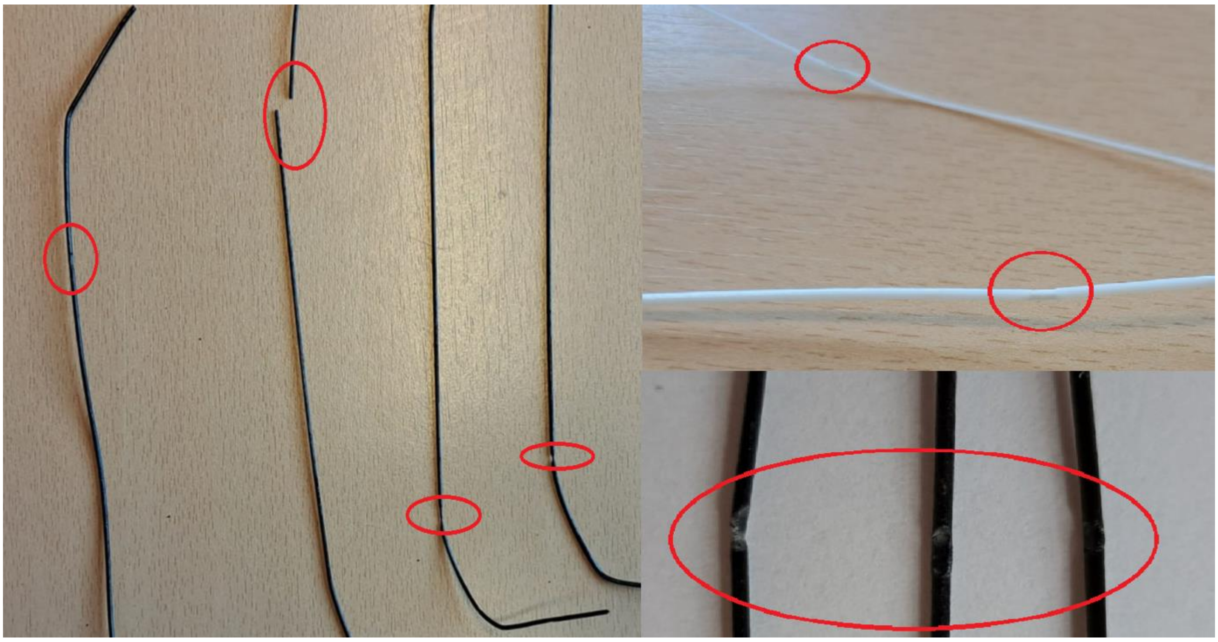


Fig 44. Shows The Re-manufactured filaments after tensile test.

3.6.2.1 Measured results

After conducting experiments on samples ranging in number based on the amount of usable filaments for each type, which varied from 6 to 10, we obtained the maximum tensile force value for each sample. From this, we were able to determine the ultimate tensile strength value by dividing the maximum tensile force experienced by each sample by its cross-sectional area. The cross-sectional area varied from sample to sample according to their diameter.

The results were as indicated in the tables (12-13-14-15).

Table 12. Results of the tensile test on re-manufactured **HD PLA** filament.

	HD PLA			
	F_{max} [N]	Diameter [mm]	A [mm^2]	UTS [MPa]
1	15.8	0.6	0.28	**55.9**
2	12	0.5	0.19	**61.1**
3	30.6	0.8	0.50	**60.9**
4	46.8	1	0.79	**59.6**
5	27.9	0.9	0.64	**43.9**

Table 13. Results of the tensile test on re-manufactured **rPLA** filament.

	rPLA			
	F_{max} [N]	Diameter [mm]	A [mm^2]	UTS [MPa]
1	68.2	1.2	1.13	**60.3**
2	61.2	1.2	1.13	**54.1**
3	61.6	1.2	1.13	**54.5**
4	59.6	1.1	0.94	**62.7**
5	48.2	1	0.79	**61.4**

Table 14. Results of the tensile test on re-manufactured **PLA White** filament.

	PLA White			
	F_{max} [N]	Diameter [mm]	A [mm^2]	UTS [MPa]
1	12.91	0.6	0.28	**45.7**
2	26.02	1.1	0.94	**27.4**
3	33.509	1.2	1.13	**29.6**
4	26.66	1.2	1.13	**23.6**
5	25.36	1.1	0.94	**26.7**

Table 15. Results of the tensile test on re-manufactured **PLA Carbon** filament.

	PLA Carbon			
	Fmax [N]	Diameter [mm]	A [mm^2]	UTS [MPa]
1	49.8	1.2	1.33	**44.0**
2	49.39	1.2	1.13	**43.7**
3	42.87	1.1	0.95	**45.1**
4	47.24	1.1	0.95	**49.7**
5	49.13	1.2	1.13	**43.5**

3.6.3 Test Procedure on The Re-manufactured Filament Reinforced with Hemp Fiber

The experiments were conducted using the same steps and conditions as those used for the original filaments and the re-manufactured filaments. The same length of samples (30 cm) was tested, and the grips distance was (120 mm), as previously. Similarly, in the re-manufactured filament test, we obtained inconstant filaments diameters. Therefore, the diameter of each sample was calculated by taking multiple measurements for each sample. the aim of the tests was to obtain maximum tensile force value for each sample, to determine the effect of adding of hemp fibers on the ultimate tensile strength value that we want to calculate from the data.

3.6.3.1 Measured results

After performing calculations based on the results obtained from the experiments, the ultimate tensile strength was calculated by dividing the maximum tensile force by the cross-sectional area of each sample. The results are as shown in the tables (16-17-18).

Table 16. Results of the tensile test on re-manufactured **HD PLA** filament + Hemp.

	HD PLA + HEMP			
	F_{max} [N]	Diameter [mm]	A [mm^2]	UTS [MPa]
1	42.8	1.2	1.13	**37.9**
2	40.3	1.3	1.33	**30.4**
3	51.4	1.3	1.33	**38.7**
4	27.8	1	0.79	**35.4**
5	17.3	0.7	0.38	**45.0**

Table 17. Results of the tensile test on re-manufactured **rPLA** filament + Hemp.

	rPLA + HEMP			
	F_{max} [N]	Diameter [mm]	A [mm^2]	UTS [MPa]
1	75.5	1.2	1.13	**66.8**
2	32.17	0.9	0.64	**50.6**
3	56.9	1.3	1.33	**42.9**
4	32.87	0.8	0.50	**65.4**
5	55.54	1.3	1.33	**41.9**

Table 18. Results of the tensile test on re-manufactured **PLA White** + Hemp.

	PLA White + HEMP			
	F_{max} [N]	Diameter [mm]	A [mm^2]	UTS [MPa]
1	21.83	1	0.79	**27.8**
2	11.09	0.6	0.28	**39.2**
3	13.5	0.6	0.28	**47.8**
4	16.58	0.7	0.38	**43.1**
5	22.07	0.9	0.64	**34.7**

3.6.4 Test Procedure on The Printed Samples

After designing the samples with the ISO 527-2 - 5A standard and printing them using the FDM printer, where 3 samples of each type were printed.

The tensile test was performed on the samples using the Zwick Roell Z100 tensile testing machine under the same conditions as the filaments, except for a preload which was 20 N and using grips specified for testing samples according to ISO 527-1 standard. The sample was secured in the upper and lower clamping areas, and an axial tensile load was applied to the upper half of the sample while keeping the lower part fixed. The method of sample setup is shown in the Figure 45 .

Fig 45. Sample Setup.

After ensuring that the sample is properly positioned and secured, and that the parameters in the computer have been entered accurately, the test was started while ensuring that there were no external forces affecting the results. The test was stopped after verifying that the maximum tensile force was achieved, and the information for each test was saved in an Excel file for later analysis. Figure 46 below shows the samples after the test, where we can see that HD PLA and PLA Carbon have fractured in the working area after reaching the maximum force directly.

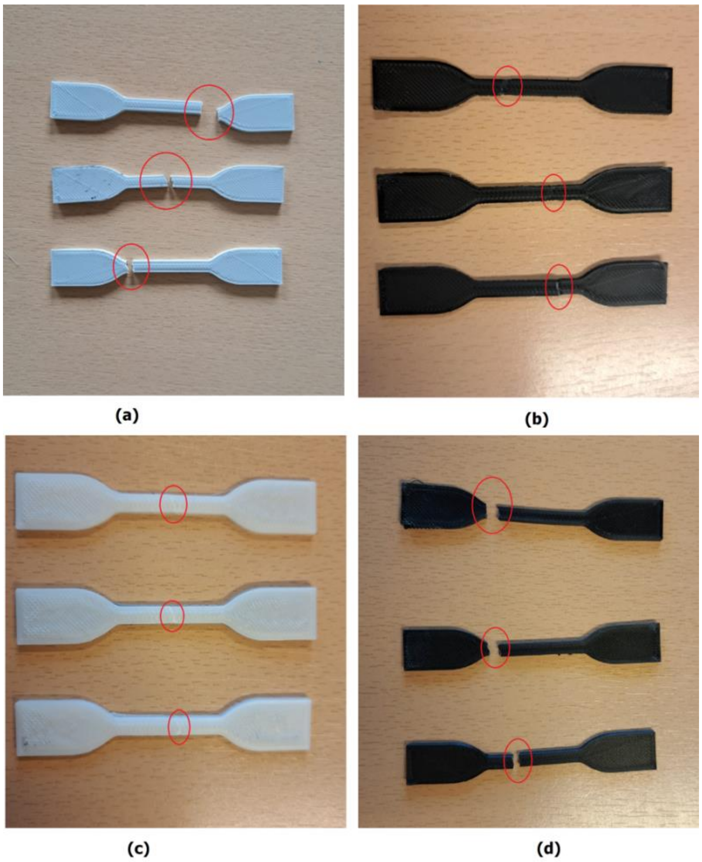


Fig 46. The Samples After Test.

3.6.4.1 Measured results

After analyzing the results obtained from the Excel file for each sample, the stress and strain values were calculated for each sample to obtain the stress-strain curve for each of them. Then, the stress-strain curves for samples of the same type were merged into one curve, in order to obtain the average ultimate tensile strength for each type and compare it with the ultimate tensile strength of other types. The results are shown in the Figures (47-48-49-50).

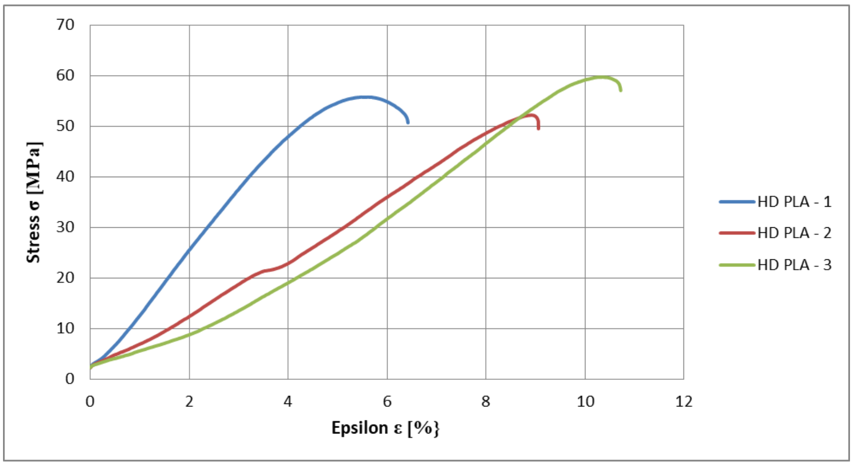


Fig 47. **HD PLA** samples results.

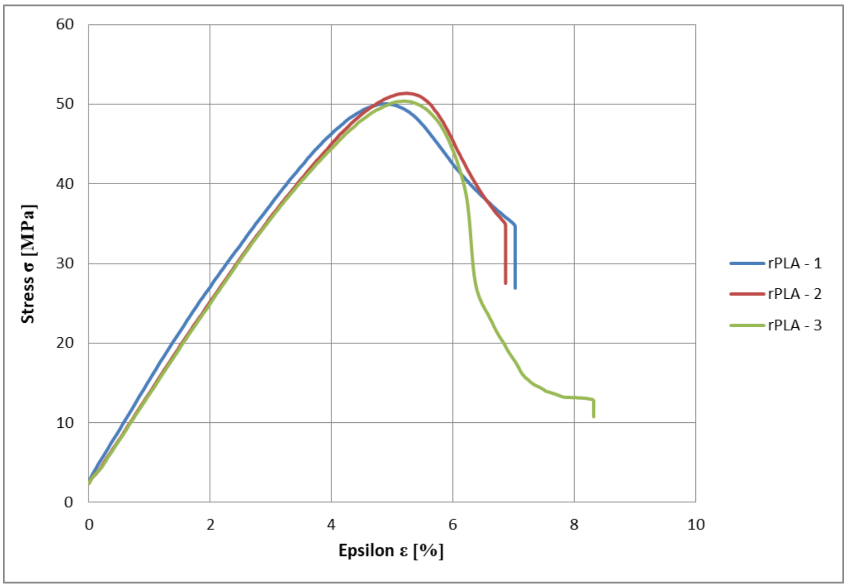


Fig 48. **rPLA** samples results.

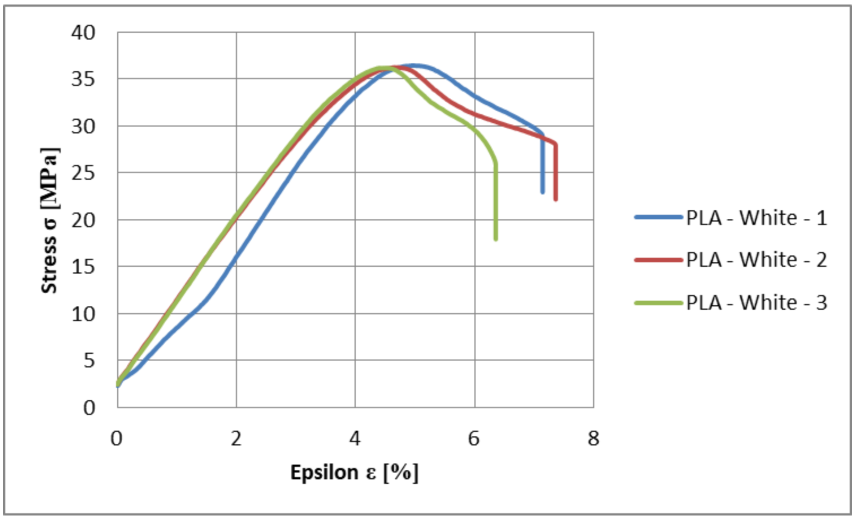


Fig 49. **PLA White** samples results.

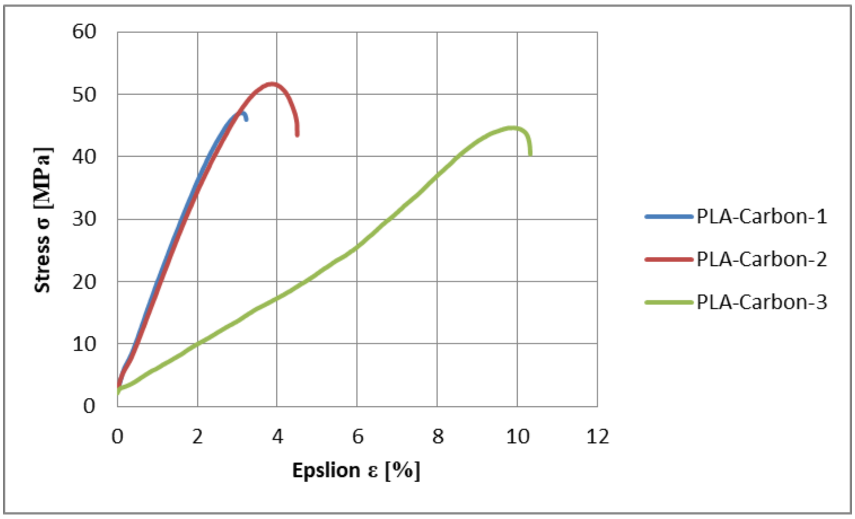


Fig 50. **PLA Carbon** samples results.

4. Results and Discussion

4.1 Results and discussion of the original filament test

After conducting the tensile test on the original filaments from the companies, and analyzing the results and obtaining the stress-strain curve for each type, these curves were combined as shown in Figure 51 to analyze and discuss the results relation to UTS for each type.

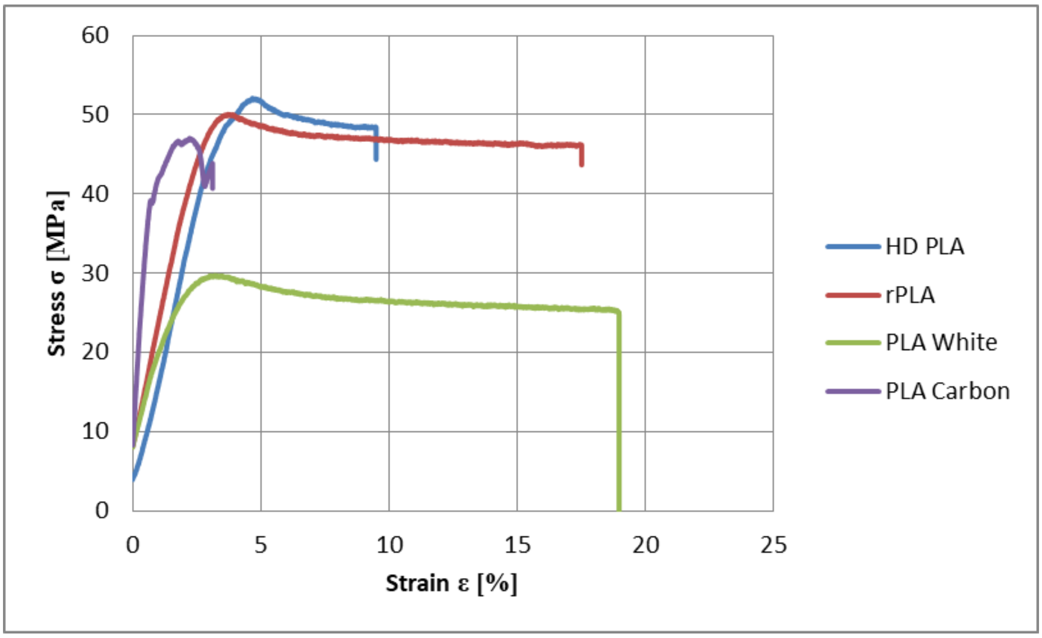


Fig 51. Stress-Strain Curves for The Original Filaments.

The results showed differences in the ultimate tensile strength values for each type and from company to company. The **HD PLA** type manufactured by ***Fiberlogy*** recorded the best result with an ultimate tensile strength of **(52.1 MPa),** it should be noted that this type of PLA filament is made to be used as a replacement for ABS. The second-best results were recorded for the **rPLA** type, manufactured by ***3D JAKE*** company, with an ultimate maximum tensile strength value of **(50.3 MPa)**, rPLA is fully recycled filaments made from the leftover materials of PLA manufacturing. The **PLA Carbon** Filament, manufactured by ***Spectrum***, recorded an ultimate tensile strength of **(47.1 MPa)**, PLA Carbon is a PLA polymer reinforced with 10%wt Carbon. The lowest value of ultimate tensile strength recorded was **(29.7 MPa)** for the **PLA White** type manufactured by ***CREALITY***, the name of PLA White comes from the color of PLA filament that used in experiment which is white, and that is just for the ease of distinguishing and differentiating it from other types.

The difference in the Ultimate Tensile Strength values for the different types of PLA can be attributed to variations in production methods and chemical composition. Even storage conditions can play a significant role, as well as the product's susceptibility to environmental factors such as humidity, where PLA is known to be a hygroscopic material, which means that it absorbs moisture from the surrounding environment, this can have a negative impact on its properties, including its strength and durability.

4.2 Results and discussion of the printed sample test

Three samples of each filament type were printed under uniform printing conditions and parameters to determine the Ultimate Tensile Strength (UTS) values for each sample after printing within these parameters. The average UTS for the three samples of each type was calculated, and the averages of the results were collected for each type and plotted on a stress-strain diagram for analysis. Figure 52 shows these results.

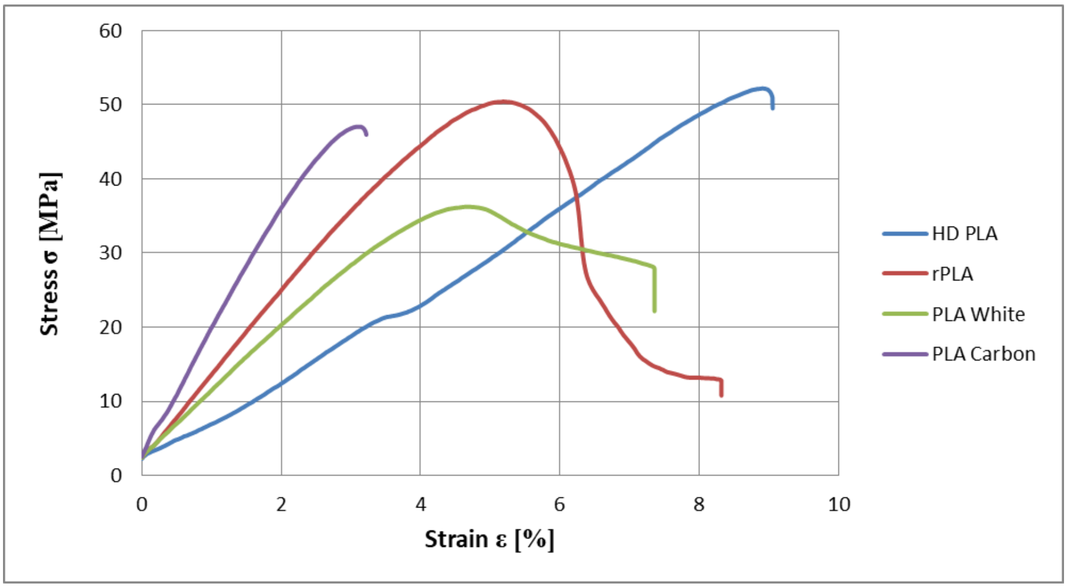


Fig 52. Stress-Strain Curves for The Printed Samples.

From the stress-strain curves of the averages of ultimate tensile strength for each filament type, it was found that the UTS values for **(HD PLA, rPLA, PLA White, and PLA Carbon)** filaments were, respectively, **(52.18, 50.41, 36.23, and 47.02)MPa.**

All types showed nearly the same values as the ones obtained from the filament tests for these types, except for PLA White, which improved noticeably to some extent. However, in general, when looking at these results, it can be said that the printing conditions and parameters were suitable for all samples, or at least their properties did not decrease significantly in terms of UTS. It should be mentioned that during the test, samples of HD PLA and PLA Carbon were directly broken upon reaching their maximum tensile force.

4.3 Results and discussion of test Re-manufactured filament

After conducting experiments on the re-manufactured filaments of each type, the average of Ultimate Tensile Strength (UTS) was calculated for the five samples that gave the best results, and compared with the UTS for the original filaments. The results were as shown in Figure 53.

	HD PLA			
	Fmax [N]	Diameter [mm]	A [mm2]	UTS [Mpa]
Original	125.27	1.75	2.40	52.1
1	15.8	0.6	0.28	**55.9**
2	12	0.5	0.20	**61.1**
3	30.6	0.8	0.50	**60.9**
4	46.8	1	0.79	**59.6**
5	27.9	0.9	0.64	**43.9**
Average				**56.3**

	rPLA			
	Fmax [N]	Diameter [mm]	A [mm2]	UTS [MPa]
Original	120.93	1.75	2.40	50.3
1	68.2	1.2	1.13	**60.3**
2	61.2	1.2	1.13	**54.1**
3	61.6	1.2	1.13	**54.5**
4	59.6	1.1	0.95	**62.7**
5	48.2	1	0.79	**61.4**
Average				**58.6**

	PLA White			
	Fmax [N]	Diameter [mm]	A [mm2]	UTS [MPa]
Original	71.51	1.75	2.40	29.7
1	12.91	0.6	0.28	**45.7**
2	26.02	1.1	0.95	**27.4**
3	33.509	1.2	1.13	**29.6**
4	26.66	1.2	1.13	**23.6**
5	25.36	1.1	0.95	**26.7**
Average				**30.6**

	PLA Carbon			
	Fmax [N]	Diameter [mm]	A [mm2]	UTS [Mpa]
Original	113.13	1.75	2.40	47.1
1	49.8	1.2	1.13	**44.0**
2	49.39	1.2	1.13	**43.7**
3	42.87	1.1	0.95	**45.1**
4	47.24	1.1	0.95	**49.7**
5	49.13	1.2	1.13	**43.5**
Average				**45.2**

Fig 53. Results for The Re-manufactured Filaments.

The average of UTS for the re-manufactured **HD PLA** filament was **(56.3 MPa),** And this is a better value than the original, which was **(52.1 MPa)**. The average Ultimate Tensile Strength (UTS) of the re-manufactured **rPLA** filament was also found to have achieved a better value than the original filament, with a UTS of **(58.6 MPa)** compared to the original filament's UTS of **(50.3 MPa)**. For the re-manufactured **PLA White** filament, the average of the test results also gave a slightly better value than the original, with a value of **(30.6 MPa)** compared to **(29.7 MPa)** for the original filament. Regarding the re-manufactured filament type **PLA Carbon**, the results were negative, as the test results for the average of UTS showed a significant decrease compared to the original filament. The average UTS for its samples was **(43.9 MPa)**, while the original filament was **(47.1 MPa)**. However, it should be noted that one of the samples gave a better UTS value than the original filament.

In discussing what happened in this experiment, it is worth noting that PLA material is one of the materials that can be recycled and reused several times. Our test results and methods confirmed that recycled products gave good properties and even better than the original in most types. As for the PLA carbon, its negative results can be attributed to the fact that it requires special attention due to the presence of carbon fibers, and the presence of these fibers limits the possibility of re-manufacturing.

4.4 Results and discussion of test Re-manufactured filament reinforced with hemp fiber

After conducting experiments on the re-manufactured filaments that reinforced with hemp fiber of each type, the average of Ultimate Tensile Strength (UTS) was calculated for the five samples that gave the best results, and compered with the UTS of the original filaments. The results were as shown in Figure 54. It should be noted again that no reinforcement tests have been conducted on **PLA Carbon** filaments due to the difficulty of re-manufacturing them with the filament-making machine used.

	HD PLA + HEMP			
	Fmax [N]	Diameter [mm]	A [mm2]	UTS [MPa]
Original	125.27	1.75	2.40	52.1
1	42.8	1.2	1.13	**37.9**
2	40.3	1.3	1.33	**30.4**
3	51.4	1.3	1.33	**38.7**
4	27.8	1	0.79	**35.4**
5	17.3	0.7	0.38	**45.0**
Average				**37.5**

	rPLA + HEMP			
	Fmax [N]	Diameter [mm]	A [mm2]	UTS [MPa]
Original	120.93	1.75	2.40	50.3
1	75.5	1.2	1.13	**66.8**
2	32.17	0.9	0.64	**50.6**
3	56.9	1.3	1.33	**42.9**
4	32.87	0.8	0.50	**65.4**
5	55.54	1.3	1.33	**41.9**
Average				**53.5**

	PLA White + HEMP			
	Fmax [N]	Diameter [mm]	A [mm2]	UTS [MPa]
Original	71.51	1.75	2.40	29.7
1	21.83	1	0.79	**27.8**
2	11.09	0.6	0.28	**39.2**
3	13.5	0.6	0.28	**47.8**
4	16.58	0.7	0.38	**43.1**
5	22.07	0.9	0.64	**34.7**
Average				**38.5**

Fig 54. Results for The Re-manufactured Filaments reinforced with Hemp fiber.

The tensile test results on hemp-reinforced **HD PLA** filament showed a lower tensile strength than the original, with an average of **[37.5 MPa]**. In contrast, reinforcing **rPLA** with these fibers had a positive effect, with the average UTS of its samples reaching **[53.5 MPa]**, which is better than the original value as shown in the tables. The most improved type, which showed positive and very good results with the reinforcement of hemp fibers, is **PLA White**, with an average UTS of **[38.5 MPa]** for its samples, which is also a better value than the original.

Discussing these results, it can be said that fiber reinforcement in general requires precise and different conditions and techniques for each type. The purpose of this study was to understand the behavior of each type when adding hemp fibers to them, and the positive results confirm that it is possible to improve the tensile strength of samples by adding hemp fibers to them. Thus, products made from these composite filaments can enter into applications.

5 Conclusion

After conducting tensile tests and obtaining the UTS values of samples from the filament types (HD PLA, rPLA, PLA White, PLA Carbon) manufactured by several companies, as well as samples printed from these types under the same conditions and printing parameters, remanufactured filaments were also tested from these types, as well as remanufactured filaments reinforced with hemp fibers. The following conclusions were drawn:

- When determining the UTS value for the different types of original filaments (before printing), the HD PLA type recorded the best results with a UTS of 52.1 MPa, while the other type (rPLA, PLA White, PLA Carbon) recorded (50.3, 29.7, 47.1)MPa, respectively.
- The difference in manufacturing conditions, chemical composition, and storage conditions of PLA filaments can affect their UTS values.
- When printing samples from different types of PLA filaments under same printing conditions and parameters, the UTS results were (52.8, 50.4, 36.23, 47.02)MPa, for the types (HD PLA, rPLA, PLA White, PLA Carbon, respectively.
- When comparing the results of the samples before and after printing, we notice no difference in the values of the tensile strength of the samples before and after printing, except for PLA White, which recorded better values after printing.
- It was observed that the printed samples from HD PLA and PLA Carbon types broke immediately after reaching the maximum tensile force during the tensile test.
- When remanufacturing filaments from the original filaments and conducting tensile tests on them, the average of UTS values of the samples from (HD PLA, rPLA, PLA White, PLA Carbon) were (56.3, 58.6, 30.6, 45.2)MPa, respectively.
- The average UTS values of the samples from HD PLA, rPLA, and PLA White gave better values than the original filament. While the filament remanufactured from PLA Carbon had an average UTS value lower than the original filaments. However, one of its samples gave a better UTS value than the original.
- When re-manufactured the filaments and reinforcing the types (HD PLA, rPLA, and PLA White) with hemp fibers, the average UTS recorded (37.5, 53.5, 38.5)MPa, respectively.
- The results of reinforcing with hemp fibers gave positive results for the average UTS of samples of both rPLA and PLA White, And this was compared to the UTS value of the original filament. While, the HD PLA type did not show any positive results at all, as the UTS values for its samples decreased compared to the original filament's UTS value.

- For HD PLA, When discussing the results of the various experiments that we conducted on the samples and filaments, we conclude that the best UTS value was achieved when re-manufactured filaments experiments were performed. This indicates the recyclability of this type of PLA. This type showed negative results when reinforced with hemp fibers, achieving its worst UTS value without reinforcement. However, the printed samples and the original filament showed values close to those presented by the manufacturer, indicating good moisture resistance.

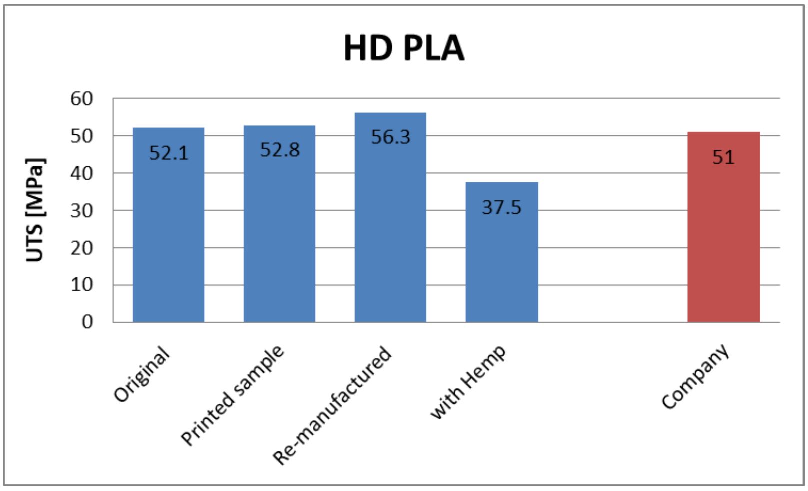


Fig 55. The results of the UTS of **HD PLA**.

- For rPLA, the best UTS value was achieved when it was re-manufactured, and the UTS value when reinforced with hemp fibers was lower than that, but its value is better than the original and printed. The values obtained for the original and printed samples were close to each other, but did not reach the values provided by the manufacturer.

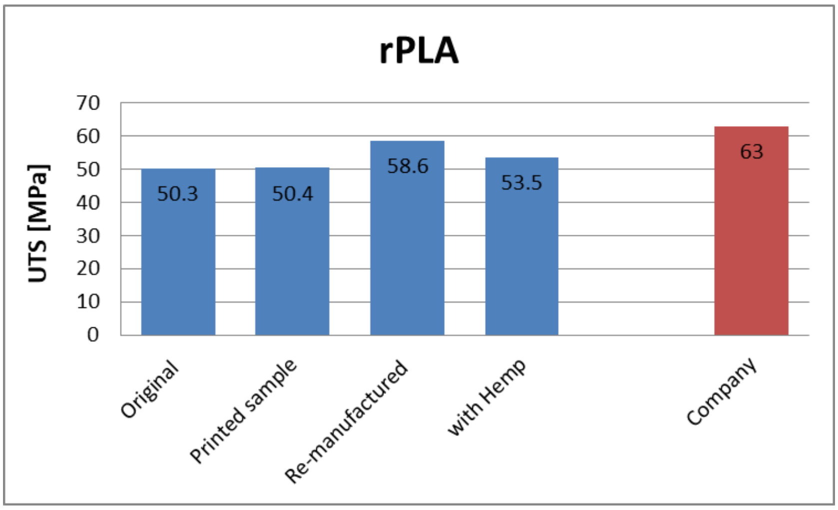


Fig 56. The results of the UTS of **rPLA.**

- For PLA White, the experiments conducted on its filaments, from printing with the selected parameters to remanufactured the filament and also reinforcing them with hemp fibers, all gave better tensile strength values than the original ones. Indeed, the remarkable point here is that reinforcing with hemp fibers had a significant impact on increasing the material's tensile strength, achieving the best result. It was found that the UTS values provided by the manufacturer were not achieved in all the experiments conducted on the filament.

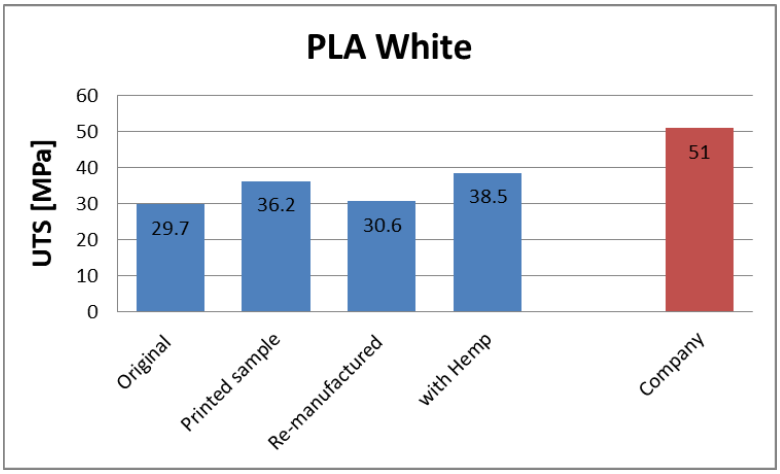


Fig 57 . The results of the UTS of **PLA White.**

- For PLA Carbon, It was not possible to reinforce it using hemp fibers in the filaments extrusion machine used due to the weight of its particles and their content of carbon, which requires better manufacturing standards. This filament showed consistent results in terms of UTS, although the worst results were observed when it was remanufactured.

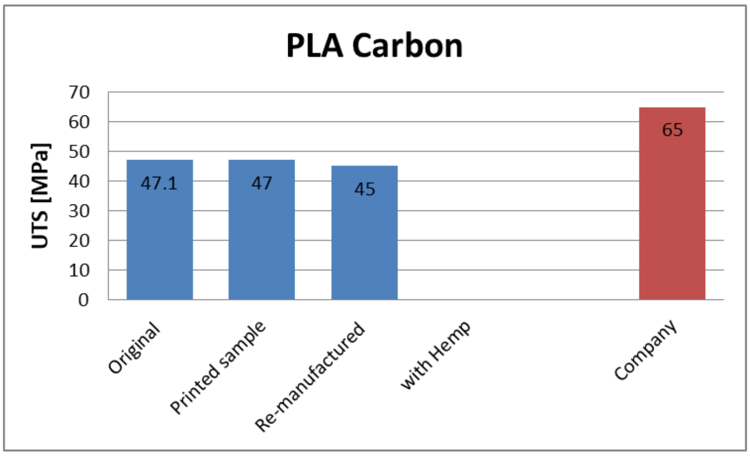


Fig 58. The results of the UTS of **PLA Carbon.**

Summary

In 3D printing, three-dimensional solid objects of the desired shape are created using 3D modeling software and a printer that lays down successive layers of materials of different shapes to obtain the final shape that corresponds to the digital model. This manufacturing method has been successful in producing intricate and complex engineered parts, and these products are made from metal, ceramic, polymer, and composite materials. These products have found their way into many industrial applications such as in aerospace, automotive, medical and even in the food industry. One of the most commonly 3D printing used technology is Fused Deposition Modeling (FDM), The process involves a heated extrusion nozzle that melts and extrudes the polymer filament layer by layer into a three-dimensional object. The mechanical properties and characteristics of the objects in this printer depend on many factors, mainly the properties and quality of the polymer filament used to print the object. Polylactic acid (PLA) is a biodegradable thermoplastic polymer, its filaments used widely to print in FDM technology due to its ease of printing, and environmental friendliness, which made it interesting to study the mechanical properties of its filaments, as well as its objects. The aim of this study was to investigate the behavior and properties of PLA filaments before printing, as well as printed samples, in relation to tensile testing. Tensile tests were performed on four different types of commercially produced PLA filaments (HD PLA, rPLA, PLA White, PLA Carbon) to determine the Ultimate Tensile Strength (UTS) of each filament (before printing), Bollard style tensile grips used in the test to secure the filament on the tensile testing machine, ISO 527-1 standard was utilized to conduct tensile strength experiments on the PLA filaments, and the results were 52.1 MPa for HD PLA and (50.3, 29.7, 47.1) MPa for (rPLA, PLA White, PLA Carbon) respectively. Additionally, samples were printed used ISO 527 - 2 -5A from each type to determine their UTS under the same conditions and printing parameters, and the average UTS for each sample (HD PLA, rPLA, PLA White, PLA Carbon) was (52.8, 50.4, 36.2, 47.0)MPa, respectively. And also, these types of filaments were re-manufactured in the laboratory used single screw extruder machine to determine their UTS after recycling, and the average UTS for each sample (HD PLA, rPLA, PLA White, PLA Carbon) was (56.3, 58.6, 30.6, 45.2)MPa, respectively. Additionally, the filaments were re-manufactured and reinforced with hemp fibers, which are natural fibers, to investigate whether any improvement in UTS occurred for the types (HD PLA, rPLA, PLA White) and the average UTS for each type was (37.5, 53.5, 38.5)MPa.

DECLARATION

on authenticity and public assess of mater's thesis

Student's name: Yousef Ibrahim

Student's Neptun ID: FXP5E5

Title of the document: Mechanical properties for composite material used 3D printing
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 an 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 sytem of the Hungarian University of Agriculture and Life Sciences.

Place and date: Gödöllő, 2023 year May month 08 day

Student's signature

STATEMENT ON CONSULTATION PRACTICES

As a supervisor of Yousef Ibrahim (FXP5E5), 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/don't recommend the final **master's thesis** to be defended in a final exam.

The document contains state secrets or professional secrets: yes **no**

Place and date: Gödöllő, 2023 year May month 08 day

Internal supervisor

References

[1] Ngo, T.D., Kashani, A., Imbalzano, G., Nguyen, K.T., Hui, D.: Additive manufacturing (3d printing): A review of materials, methods, applications and challenges. Composites Part B: Engineering 143, 172–196 (2018), https://www.sciencedirect.com/science/article/pii/S1359836817342944

[2] Rahim, T.N.A.T., Abdullah, A.M., Akil, H.M.: Recent developments in fused deposition modeling-based 3d printing of polymers and their composites. Polymer Reviews 59(4), 589–624 (2019), https://doi.org/10.1080/15583724.2019.1597883

[3] Lipson, H., Kurman, M.: Fabricated: The New World of 3D Printing (2013)

[4] Altıparmak, S.C., Xiao, B.: A market assessment of additive manufacturing potential for the aerospace industry. Journal of Manufacturing Processes 68, 728–738 (2021), https://www.sciencedirect.com/science/article/pii/S1526612521004102

[5] Saleh Alghamdi, S., John, S., Roy Choudhury, N., Dutta, N.K.: Additive manufacturing of polymer materials: Progress, promise and challenges. Polymers 13(5) (2021), https://www.mdpi.com/2073-4360/13/5/753

[6] Masood, S.: 10.04 - advances in fused deposition modeling. In: Hashmi, S., Batalha, G.F., Van Tyne, C.J., Yilbas, B. (eds.) Comprehensive Materials Processing, pp. 69–91. Elsevier, Oxford (2014), https://www.sciencedirect.com/science/article/pii/B9780080965321010025

[7] manufactur3dmag.com: Fdm-diagram (2013), https://manufactur3dmag.com/wp-content/uploads/2018/01/FDM-Diagram.jpg, [Online; accessed May 1, 2023]

[8] Rohani Shirvan, A., Nouri, A., Wen, C.: 12 - structural polymer biomaterials. In: Wen, C. (ed.) Structural Biomaterials, pp. 395–439. Wood head Publishing Series in Biomaterials, Woodhead Publishing (2021), https://www.sciencedirect.com/science/article/pii/B9780128188316000100

[9] Davoudinejad, A.: Chapter 5 - vat photopolymerization methods in additive manufacturing. In: Pou, J., Riveiro, A., Davim, J.P. (eds.) Additive Manufacturing, pp. 159–181. Handbooks in Advanced Manufacturing, Elsevier (2021) , https://www.sciencedirect.com/science/article/pii/B9780128184110000070

[10] Leong, K.F., Liu, D., Chua, C.K.: 10.09 - tissue engineering applications of additive manufacturing. In: Hashmi, S., Batalha, G.F., Van Tyne, C.J., Yilbas, B. (eds.) Comprehensive Materials Processing, pp. 251–264. Elsevier, Oxford (2014), https://www.sciencedirect.com/science/article/pii/B9780080965321010104

[11] Yang, J., Li, N., Shi, J., Tang, W., Zhang, G., Zhang, F.: Multimaterial 3D Printing Techology. 3D Printing Technology Series, Academic Press (2021), https://www.sciencedirect.com/science/article/pii/B9780081029916000148

[12] bout additive manufacturing. https://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturin [Online; accessed March 16, 2023]
[13] What is material jetting? https://www.treatstock.co.uk/guide/article/126-what-is-material-jetting , [Online; accessed May 1, 2023]
[14] Gibson, I., Rosen, D., Stucker, B.: Additive Manufacturing Technologies 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing. springer (2015), https://eprints.ukh.ac.id/id/eprint/183/1/2015B ookAdditiveM anufacturingT echnolog.pdf
[15] Chen, Z., Li, Z., Li, J., Liu, C., Lao, C., Fu, Y., Liu, C., Li, Y., Wang, P., He, Y.: 3d printing of ceramics: A review. Journal of the European Ceramic Society 39(4), 661–687 (2019), https://www.sciencedirect.com/science/article/pii/S0955221918306782
[16] Selvamani, S.K., Samykano, M., Subramaniam, S.R., Ngui, W.K., Kadirgama, K., Kanagaraj, G., Idris, M.S.: 3D printing: Overview of ABS evolvement. AIP Conference Proceedings 2059(1) (01 2019), https://doi.org/10.1063/1.5085984 , 020041
[17] Elmrabet, N., Siegkas, P.: Dimensional considerations on the mechanical properties of 3d printed polymer parts. Polymer Testing 90, 106656 (2020), https://www.sciencedirect.com/science/article/pii/S0142941820306243
[18] Sepahi, M.T., Abusalma, H., Jovanovic, V. et al. Mechanical Properties of 3D-Printed Parts Made of Polyethylene Terephthalate Glycol. J. of Materi Eng and Perform 30, 6851–6861 (2021). https://doi.org/10.1007/s11665-021-06032-4
[19] Wojtyla, S., Klama, P., Baran, T.: Is 3d printing safe? analysis of the thermal treatment of thermoplastics: Abs, pla, pet, and nylon. Journal of Occupational and Environmental Hygiene 14(6), D80–D85 (2017), https://doi.org/10.1080/15459624.2017.1285489 , pMID: 28165927
[20] Domingo-Espin, M., Puigoriol-Forcada, J.M., Garcia-Granada, A.A., Llum`a, J., Borros, S., Reyes, G.: Mechanical property characterization and simulation of fused deposition modeling polycarbonate parts. Materials Design 83, 670–677 (2015), https://www.sciencedirect.com/science/article/pii/S0264127515004244
[21] Polymer properties. https://omnexus.specialchem.com/polymer-properties , [On
line; accessed March 21, 2023]
[22] Shahbazi, M., J¨ager, H.: Current status in the utilization of biobased polymers for 3d printing process: A systematic review of the materials, processes, and challenges. ACS Applied Bio Materials 4(1), 325–369 (2021). https://doi.org/10.1021/acsabm.0c01379
[23] Dai, L., Cheng, T., Duan, C., Zhao, W., Zhang, W., Zou, X., Aspler, J., Ni, Y.: 3d printing using plant-derived cellulose and its derivatives: A review. Carbohydrate Polymers 203, 71–86 (2019), https://www.sciencedirect.com/science/article/pii/S0144861718310919

[24] Yu, O., Kim, K.H.: Lignin to materials: A focused review on recent novel lignin applications. Applied Sciences 10(13) (2020), https://www.mdpi.com/2076-3417/10/13/4626
[25] Blanco, I.: The use of composite materials in 3d printing. Journal of Composites Science 4(2) (2020), https://www.mdpi.com/2504-477X/4/2/42
[26] Rouf, S., Malik, A., Singh, N., Raina, A., Naveed, N., Siddiqui, M.I.H., Haq, M.I.U.: Additive manufacturing technologies: Industrial and medical applications. Sustainable Operations and Computers 3, 258–274 (2022), https://www.sciencedirect.com/science/article/pii/S2666412722000125
[27] Shahrubudin, N., Lee, T., Ramlan, R.: An overview on 3d printing technology: Technological, materials, and applications. Procedia Manufacturing 35, 1286–1296 (2019), https://www.sciencedirect.com/science/article/pii/S2351978919308169 , the 2nd International Conference on Sustainable Materials Processing and Manufacturing, SMPM 2019, 8-10 March 2019, Sun City, South Africa
[28] Leontiou, A., Georgopoulos, S., Karabagias, V.K., Kehayias, G., Karakassides, A., Salmas, C.E., Giannakas, A.E.: Three-dimensional printing applications in food industry. Nanomanufacturing 3(1), 91–112 (2023), https://www.mdpi.com/2673-687X/3/1/6
[29] L.Yigong, Q. Hamid, J. Snyder, W. Chengyang, & S. Wei, "Evaluating fabrication feasibility and biomedical application potential of in situ 3D printing technology," Rapid Prototyping Journal, Vol.22, No.6, pp. 947 – 955, 2016.
[30] Espera, A., Dizon, J.R., Chen, Q., Advincula, R.: 3d-printing and advanced manufacturing for electronics. Progress in Additive Manufacturing 4 (09 2019). https://doi.org/10.1007/s40964-019-00077-7
[31] Jandyal, A., Chaturvedi, I., Wazir, I., Raina, A., Ul Haq, M.I.: 3d printing – a review of processes, materials and applications in industry 4.0. Sustainable Operations and Computers 3, 33–42 (2022), https://www.sciencedirect.com/science/article/pii/S2666412721000441
[32] Rahim, T.N.A.T., Abdullah, A.M., Akil, H.M.: Recent developments in fused deposition modeling-based 3d printing of polymers and their composites. Polymer Reviews 59(4), 589–624 (2019), https://doi.org/10.1080/15583724.2019.1597883
[33] Mohamed, O.A., Masood, S.H. & Bhowmik, J.L. Optimization of fused deposition modeling process parameters: a review of current research and future prospects. Adv. Manuf. 3, 42–53 (2015). https://doi.org/10.1007/s40436-014-0097-
[34] Daminabo, S., Goel, S., Grammatikos, S., Nezhad, H., Thakur, V.: Fused deposition modeling-based additive manufacturing (3d printing): techniques for polymer material systems. Materials Today Chemistry 16, 100248 (2020), https://www.sciencedirect.com/science/article/pii/S2468519420300082
[35] Rizescu, D., Daniel, B., Rizescu, C., Moraru, E.: Study behavior of geneva mechanism using 3d printing technology. IOP Conference Series: Materials

Science and Engineering 514, 012032 (06 2019). https://doi.org/10.1088/1757-899X/514/1/012032
[36] Ngo, T. D., Kashani, A., Imbalzano, G., Nguyen, K. T. Q., & Hui, D. (2018). Additive manufacturing (3D printing): A review of materials, methods, applications and challenges. Composites Part B: Engineering, 143, 172-196. https://www.sciencedirect.com/science/article/pii/S1359836817342944#sec2.2
[37] Gibson, I., Rosen, D. W., & Stucker, B. (2014). Additive manufacturing technologies: 3D printing, rapid prototyping, and direct digital manufacturing. Springer. https://link.springer.com/book/10.1007/978-1-4939-2113-3
[38] Mogan, J., Harun, W.S.W., Kadirgama, K., Ramasamy, D., Foudzi, F.M., Sulong, A.B., Tarlochan, F., Ahmad, F.: Fused deposition modelling of polymer composite: A progress. Polymers 15(1) (2023), https://www.mdpi.com/2073-4360/15/1/28
[39] Mishra, V., Negi, S., Kar, S., Sharma, A., Rajbahadur, Y., Kumar, A.: Recent advances in fused deposition modeling based additive manufacturing of thermoplastic composite structures: A review. Journal of Thermoplastic Composite Materials pp. 1–39 (05 2022). https://doi.org/10.1177/08927057221102857
[40] Kothari, P., Parate, G., Kulkarni, C., Soitkar, N., Khot, G.: Review on 3d printing and its applications in engineering 10, 13462 (10 2021). https://doi.org/10.15680/IJIRSET.2021.1010011
[41] Liu, Z., Wang, Y., Wu, B. et al. A critical review of fused deposition modeling 3D printing technology in manufacturing polylactic acid parts. Int J Adv Manuf Technol 102, 2877–2889 (2019). https://doi.org/10.1007/s00170-019-03332-x
[42] lyas, R., Sapuan, S., Harussani, M., Hakimi, M., Haziq, M., Atikah, M., Asyraf, M., Ishak, M., Razman, M., Nurazzi, N., Norrahim, M., Abral, H., Asrofi, M.: Polylactic acid (pla) biocomposite: Processing, additive manufacturing and advanced applications. Polymers 13(8) (2021), https://www.mdpi.com/2073-4360/13/8/1326
[43] PLA Filament - Complete Guide. https://3dinsider.com/pla-filament-complete-guide/ , [Online; accessed April 7, 2023]
[44] Ultimaker cura - printing profiles. https://ultimaker.com/software/ultimaker-cura/ ,
[Online; accessed April 7, 2023]
[45] Letcher, T., Waytashek, M.: Material property testing of 3d-printed specimen in plaon an entry-level 3d printer. vol. 2 (12 2014). https://doi.org/10.1115/IMECE2014-39379
[46] Grabowik, C., Kalinowski, K., ´Cwikla, G., Paprocka, I., Kogut, P.: Tensile tests of specimens made of selected group of the filament materials manufactured with fdm method. MATEC Web of Conferences 112, 04017 (01 2017). https://doi.org/10.1051/matecconf/201711204017
[47] Cojocaru, V., Frunzaverde, D., Miclosina, C.O., Marginean, G.: The influence of the process parameters on the mechanical properties of pla

specimens produced by fused filament fabricationmdash;a review. Polymers 14(5) (2022), https://www.mdpi.com/2073-4360/14/5/886
[48] Dey, A., Roan Eagle, I.N., Yodo, N.: A review on filament materials for fused filament fabrication. Journal of Manufacturing and Materials Processing 5(3) (2021), https://www.mdpi.com/2504-4494/5/3/69
[49] Dudek, P.: Fdm 3d printing technology in manufacturing composite elements. Archives of Metallurgy and Materials Vol. 58, iss. 4, 1415–1418 (2013). https://doi.org/10.2478/amm-2013-0186
[50] Kristiawan, R.B., Imaduddin, F., Ariawan, D., Ubaidillah, Arifin, Z.: A review on the fused deposition modeling (fdm) 3d printing: Filament processing, materials, and printing parameters. Open Engineering 11(1), 639–649 (2021), https://doi.org/10.1515/eng-2021-0063
[51] Mukherjee, T., Kao, N. PLA Based Biopolymer Reinforced with Natural Fibre: A Review. J Polym Environ 19, 714–725 (2011). https://doi.org/10.1007/s10924-011-0320-6
[52] Cr 1.75mm pla 3d printing filament 1kg. https://store.creality.com/products/cr-1-75mm-pla-3d-printing-filament-1kg?spm=..product_3ec7c258-2724-43c8-98be-cae2f6dfffc0.header_1.1&spm_prev=..collection_b55960dc-bbb9-47c1-a06f-657301786e15.header_1.1 , [Online; accessed April 20, 2023]
[53] rPLA Black. https://www.3djake.hu/3djake/rpla-fekete?sai=8009 , [Online; accessed April 20, 2023]
[54] Fiberlogy HD PLA Grey 1.75mm | 0.85Kg. https://www.vital3d.co.uk/product/10149929/fiberlogy-hd-pla-grey-1-75mm-0-85kg , [Online; accessed April 20, 2023]
[55] Improved hardness and rigidity. https://spectrumfilaments.com/en/filament/pla-carbon/ , [Online; accessed April 20, 2023]
[56] Shimpi, N.G.: Biodegradable and biocompatible polymer composites. Wood head Publishing Series in Composites Science and Engineering, Woodhead Publishing (2018). https://www.sciencedirect.com/science/article/pii/B9780081009703020010
[57] Manaia, J.P., Manaia, A.T., Rodriges, L.: Industrial hemp fibers: An overview. Fibers 7(12) (2019), https://www.mdpi.com/2079-6439/7/12/106
[58] 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
[59] stress-strain curve. https://www.merefa2000.com/2021/04/stress-strain-curve.html , [Online; accessed April 29, 2023]