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HUNGARIAN UNIVERSITY OF AGRICULTURE AND LIFE SCIENCES

INSTITUTE OF TECHNOLOGY

BSc Mechanical Engineering

THESIS

MECHANICAL ANALYSIS OF 3D PRINTED PARTS

Author

Mohammed Karaja

Neptun code

CDAT51

Professor

Dr. Zoltán Szakál

Gödöllő, Hungary

2024

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ABSTRACT

The tensile characteristics of 3D-printed polymer specimens with various standard geometry forms are compared in this work. The goal is to evaluate how printing geometry and orientation affect mechanical performance. Tensile test specimens based on ASTM and ISO standards are compared to rectangular-shaped ASTM D3039 specimens with angles of 0°, 15°, and 90°. Using fused deposition modeling (FDM), polyethylene terephthalate glycol (PETG) material is employed to manufacture each specimen. Tensile strength, elastic modulus, strain, and elongation at break are measured while two printing orientations—flat and on-edge—are examined. The investigation assesses the fractured regions and looks at the weak place that is frequently located around the specimens' necks. Furthermore, a numerical analysis employing the finite element technique (FEM) is carried out to pinpoint the sites of stress risers in every kind of specimen. According to experimental data, the ASTM D3039-0TM specimen printed in the flat orientation produces the best results in terms of the broken area, while the specimen printed in the on-edge orientation demonstrates the greatest tensile qualities. The tensile characteristics of the ISO 527-2 specimens are consistently poorer, regardless of printing orientation. The study emphasizes how the rectangular form produces improved tensile qualities. For the flat and on-edge orientations, the tensile strength of ASTM D3039-0◦ was 17.87% and 21% greater, respectively, than that of the ISO 527 geometry form. The ISO 527-2 specimen showed either no or few stress raisers, according to the numerical analysis, and the greater stresses seen in the narrow section were isolated from the gripping position. The results further our knowledge of the connection between standard geometry forms, printing orientation, and the tensile characteristics of 3D-printed polymer specimens.[1]

The purpose of this study is to compare several tensile test specimens based on ASTM and ISO standards with rectangular-shaped ASTM D3039 specimens with different angles (0°, 15°, and 90°), all of which were 3D printed using polyethylene terephthalate glycol (PETG) material via FDM. The study's objective was to evaluate the weak point often present at the specimens' necks. The investigation of two distinct printing orientations—flat and on-edge—led to a thorough analysis and comparison of the differences in among the evaluated samples were tensile strength, E-modulus, strain, and elongation at break. Furthermore, Using the finite element technique (FEM), a numerical analysis was conducted to examine the broken regions.

was carried out to determine the sites of stress risers in each kind of specimen. The outcome of the experiment showed that when printed, the ASTM D3039-0° specimen had the superior tensile characteristics. whereas the flat orientation produced the best outcomes in terms of the broken region. Conversely, the ISO 527-2 specimens showed the lowest tensile characteristics despite of the direction of printing. The investigation emphasized the improved tensile characteristics attained with the shaped like a rectangle. ASTM D3039-0° had a tensile strength that was 17.87% and 21% higher. compared to the flat and on-edge orientations of the ISO 527 geometry form, respectively. According to numerical analysis, there were either none or very few stress raisers in the ISO 527-2 specimen. and the gripping point was insulated from the greater pressures seen in the narrow segment.[2]

CHAPTER 1: INTRODUCTION

3D printing is an additive manufacturing (AM) technique that enables the fabrication of various structures and complex geometries from 3D model data. It has evolved over the years, with applications in various industries such as construction, prototyping, and biomechanical. The uptake of 3D printing in the construction industry was slow and limited, but recent developments have reduced the cost of 3D printers, expanding its applications in schools, homes, libraries, and laboratories.[3]

3D printing has been extensively used by architects and designers to produce aesthetic and functional prototypes due to its rapid and cost-effective prototyping capability. However, product customization has been a challenge for manufacturers due to the high costs of producing custom-tailored products for end-users. AM can 3D print small quantities of customized products with relatively low costs, which is particularly useful in the biomedical field. Customized functional products are currently becoming the trend in 3D printing, with Wohler's Associates predicting that about 50% of 3D printing will revolve around the manufacturing of commercial products in 2020.[4]

The growing consensus of adapting the 3D manufacturing system over traditional techniques is attributed to several advantages, including high precision, maximum material savings, flexibility in design, and personal customization. A wide range of materials used in 3D printing include metals, polymers, ceramics, and concrete. However, the precision of printed parts depends on the accuracy of the employed method and the scale of printing. The advantages of 3D printing technology will continue to emerge through continuing research efforts, such as designing tools to assess life-cycle costs and improving machine design.

Additive manufacturing (AM) has evolved to meet the demand for printing complex structures at fine resolutions. Key factors include rapid prototyping, large structure printing, reducing printing defects, and enhancing mechanical properties. Fused deposition modelling (FDM) is the most common method of 3D printing using polymer filaments. Other methods include selective laser sintering (SLS), selective laser melting (SLM), liquid binding in three-dimensional printing (3DP), inkjet printing, contour crafting, stereolithography, direct energy deposition (DED), and laminated object manufacturing (LOM).[5]

FDM uses a continuous filament of a thermoplastic polymer to 3D print layers of materials. The thermoplastic of the polymer filament allows filaments to fuse together during printing and solidify at room temperature after printing. FDM has low cost, high speed, and simplicity, but has weak mechanical properties, layer-by-layer appearance, poor surface quality, and a limited number of thermoplastic materials. Powder bed fusion processes consist of thin layers of very fine powders, which are spread and closely packed on a platform. The powders are fused together with a laser beam or a binder, and subsequent layers are rolled on top of previous layers. The powder size distribution and packing determine the density of the printed part.

In addition to FDM, 3DP also uses liquid binder methods, such as liquid binding in three-dimensional printing (LDP), which has high costs and high porosity. Inkjet printing is a fast and efficient method for additive manufacturing of ceramics, used for complex structures like tissue engineering scaffolds. It uses a stable ceramic suspension, such as zirconium oxide powder in water, to form droplets that solidify to hold subsequent layers. Contour crafting is a similar technology, capable of extruding concrete paste or soil using larger nozzles and high pressure. Stereolithography (SLA), developed in 1986, uses UV light to initiate a chain reaction on a layer of resin or monomer solution. The monomers convert to polymer chains, solidifying a pattern inside the resin layer. SLA prints high-quality parts at a fine resolution as low as 10 µm but is slow, expensive, and limited in material range. It can be effectively used for additive manufacturing of complex nanocomposites.[6]

Direct energy deposition (DED), also known as laser engineered net shaping (LENS™), laser solid forming (LSF), directed light fabrication (DLF), direct metal deposition (DMD), electron beam AM (EBAM), and wire + Arc AM (WAAM), is a method used for manufacturing high-performance super-alloys. It uses a laser or electron beam to melt a feedstock material simultaneously, allowing for multiple-axis deposition and multiple materials at the same time. DED is commonly used with titanium, Inconel, stainless steel, aluminum, and related alloys for aerospace applications. [6]

It is characterized by high speeds and large work envelopes but has lower accuracy and surface quality. It is commonly used for large components with low complexity and repairs larger components. Laminated object manufacturing (LOM) is a commercially available additive manufacturing method based on layer-by-layer cutting and lamination of sheets or rolls of materials. It is used in various industries, such as paper manufacturing, foundry industries, electronics, and smart structures. LOM can result in a reduction in tooling cost and manufacturing time but has inferior surface quality and dimensional accuracy compared to powder-bed methods.[3]

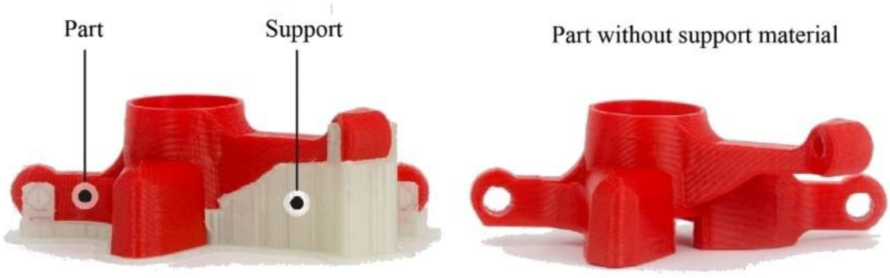

Figure 1: 3D printing with and without supporting material.

1. Additive Manufacturing Technology

1.1 Prototyping Quickly

The initial method of building a three-dimensional Rapid prototyping was an application of computer-aided design (CAD) that was created in the 1980s with the purpose of building models and prototype components. The development of this technology aims to facilitate the realization of the visions of engineers. Prototyping quickly is among the most traditional methods of additive manufacturing (AM). Not just models, but printed parts may be produced using it. One of the main innovations this method offered was time and expense savings are important to product development, human contact, which in turn affects the cycle of product development, as well as the ability to produce nearly any shape things can be somewhat challenging to automate. Still, at the It is not currently being used in the manufacture sector, but it's also used by scientists, physicians, educators, market researchers, and artists. With quick via prototyping, researchers and students may quickly construct and Examine models for research and theoretical understanding. A damaged body can be modelled by medical professionals for analysis. As improve the process planning, market researchers may observe what consumers believe about a certain new product, and quick Prototyping facilitates artists' exploration of their originality. The procedures of product development that use fast This illustrates that Time is saved by building models more quickly, and there is also the potential for more model testing. [7]

The fast-prototyping technology available today are not limited to the creation of models, with the benefits It has been feasible to produce completed objects using plastic materials. goods, naturally, were created in the beginning to increase the range of scenarios examined during the prototype phase. similar days, similar technologies go by different names, such as 3D. printing, and so forth, but their roots are all in quick experimenting. [8]

Furthermore, it is crucial to note that other technologies made quick manufacturing feasible, including computer numerical control (CNC), computer-aided manufacturing (CAM), and computer-aided design (CAD). That The combination of three technologies allowed for the three-dimensional object printing. Still, rapid prototyping isn't always the best option. Nevertheless, in certain situations, CNC machining procedures still need to be utilized. The dimensions of the parts may exceed the available additive producing printing devices. Supplies for quick prototyping remain restricted. It's evident that printing is at least an option. metals and ceramics, but not all materials that are frequently used in manufacturing.

manufacturing procedures that will be covered in more detail. This image, which is an adaptation of, uses the criterion used to divide these procedures into solid, liquid base, and both powder-based and based. The procedures comprised within these reviews have historically been thought to be the most pertinent and encouraging for the sector's future. The methods taken into consideration are fused deposition, Poly jet, and Stereolithography (SL). production of laminated objects (LOM), modelling (FDM), Pro metal, selective laser sintering (SLS), 3D printing (3DP), electron beam bending laminated engineered net shaping (LENS) melting beams (EBM). The liquid-and powder-based processes look more promising than solid-based procedures of which LOM is now the most popular. There was no EBM, Pro metal, LENS, or Poly jet. These technologies were initially designed to build models, but since then, they've grown. [9]

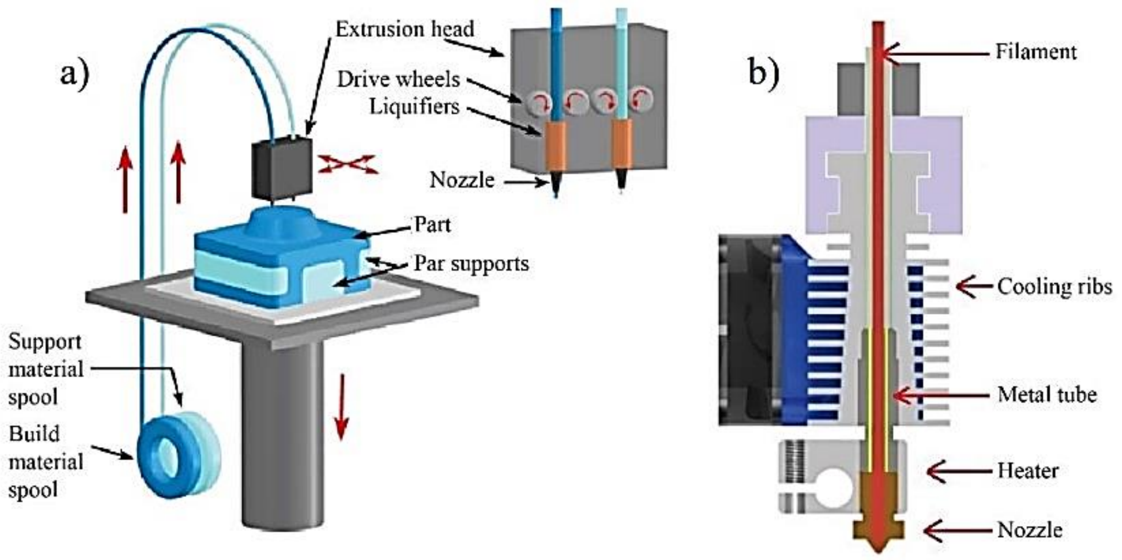

Figure 2: Fused filament Fabrication (FFF), a) Basic parts. b) Parts of the hot end.

1.2 Lithography in Stereo

After 3D Systems, Inc. created stereolithography (SL), it was the first and most popular rapid prototyping method, Consequently, the two names were once synonymous. As it is Zero a liquid-based procedure that solidifies or cures a photosensitive polymer in response to a UV The resin is touched by the laser. The procedure begins with a model in CAD software, which is subsequently converted to a STL file where the parts are "sliced into slices" and contain the details for every layer. How thick every layer is depending on the tools being used, as does the resolution. To stabilize the item and provide support for the overhanging building parts. Next, the UV laser is directed at the resin hardening areas of every layer. Once the platform is lowered once the layer is completed, and at last, when the Once the procedure is complete, the surplus is drained and reused. A more recent iteration of this procedure has been created using micro stereolithography, and it has a better resolution. That Using a procedure where the layer thickness is less than 10 µm attained. [10]

This process's fundamental idea is photopolymerization, which is the procedure wherein a liquid monomer or by application, a polymer becomes a hardened polymer. UV light, which serves as the processes' catalyst; thus, the procedure is also referred to as UV curing. Moreover, it is feasible to possess, like ceramics, particles suspended in the liquid. Errors were introduced into the finished product from the stereolithography procedure. The first is overcuring, which happens to protrude portions due to a lack of fusion with a bottom stratum.

Another is the recently announced scanned line form. Mechanical Engineering III by the process of scanning. Because of the high viscosity of the resin liquid, the layer's thickness varies, which creates a mistake in the regulation of border position. Another mistake resulted in maybe if the component required a surface finishing procedure It is often carried out by hand. These mistakes are all reduced in high-quality equipment. It is possible to utilize various materials when constructing a component; this method is known as multiple material lithography in stereo. For printing using various materials It is necessary to empty all the resin and replace it with the fresh material. as soon as the procedure reaches the layer where the modification will take occur. This needs to happen even if the initial material to be utilized once again as printing is limited to successive levels. glue. The program requires a scheduling procedure to be mentioned.[11]

Three. The STL Record 3D Systems Inc. generated the STL file in 1987 when initially, they created the stereolithography and STL file. represents this word. Another name for it is Standard Tessellation. Spoken word. Although there are other file kinds, the STL file is the benchmark for all processes using additive manufacturing. The. The method of creating an STL file mostly turns the continuous the CAD file's geometry into a header, tiny triangles, or coordinates triplet list including the coordinates of x, y, and z vector normal to the triangles. This procedure is not precise. and the triangles are more accurate when they are smaller. The surfaces on the inside and outside are distinguished using the Vertices and the right-hand rule are unable to share a point in line.[12]

Additionally, the slicing procedure adds inaccuracies to the file. as the continuous contour is replaced by the algorithm in this instance. using distinct stair steps. To lessen this error, the method for a feature whose radius is modest in comparison to the part's dimensions need the creation of distinct STL files, and to eventually integrate them. The z-direction dimension needs to be made to have a value greater than the layer thickness.[13]

1.3 Stereolithography contour (SLC) files are among the other file formats

CLI from EOS, Hewlett-Packard, and SLI from 3D Systems Hewlett-Packard's graphics language (HPGL), Stratasys' stereolithography contour, and Fockele's F&S Schwarze and the first standards for the graphics exchange the IGES.[14]

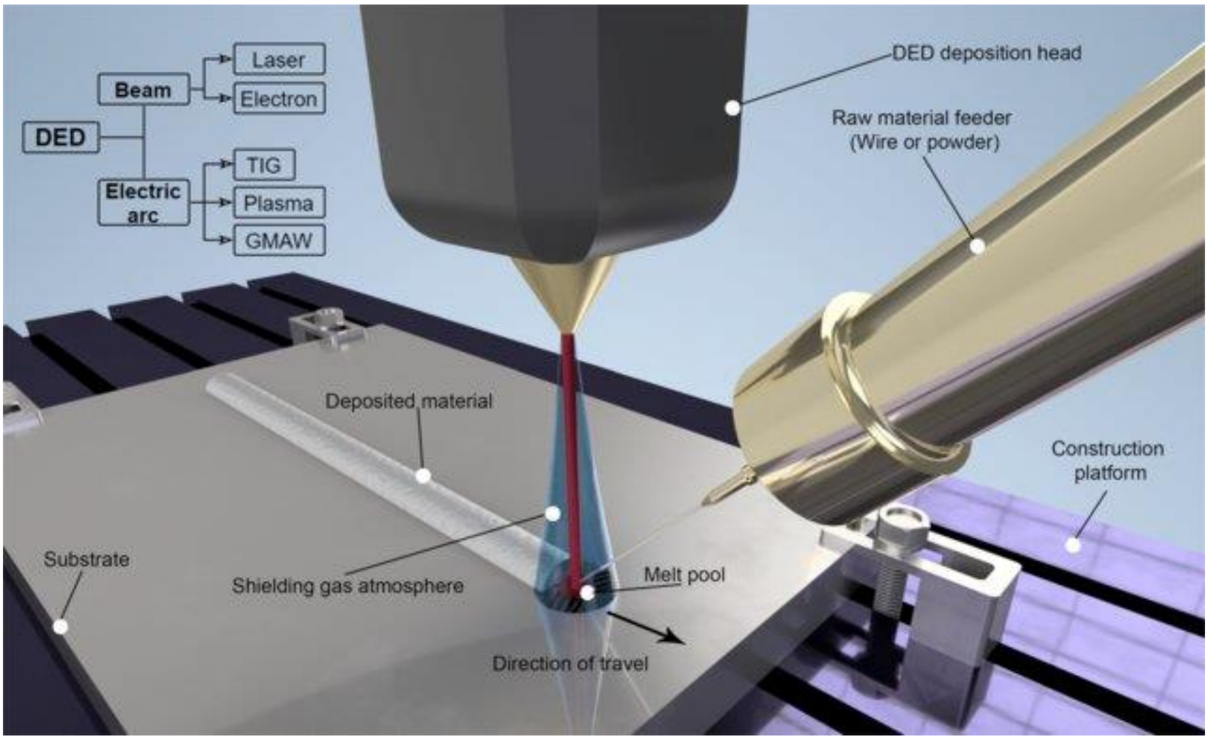

Figure 3: Illustration of the directed energy deposition (DED) Process.

1.4 4.3D

The 3DP technique, which has an MIT license, uses water-based A powder made of starch is coated with a jet of liquid binder. to print the CAD drawing's data. The pieces of powder Mechanical Engineering, ISRN, 4 Additional geometric 3-D CAD arranging CTRL/STL interfacing Translation a portion geometric Production of that model Device or procedure specifics.[15]

1.5 CAD data

Making Triangles Polyline boundaries production Edge recompense layer's edge Comparing polylines supple borders Edge recompense Each section's index till the end STL data Sort Z triangles. Data flow in STL file construction. lay in a bed of powder, and they are joined by glue when the Binder gets thrown out. This procedure is known as 3DP because to the resemblance to the method of inkjet printing utilized for printing in two dimensions on paper. This procedure can deal with an extensive range of polymers.[16]

1.5.1 Combined Deposition Simulation

In the additive manufacturing method known as fused deposition modelling (FDM), a thin plastic filament feeds a where a print head melts it and extrudes it, usually with a thickness of 0.25 mm. The supplies utilized in this procedure include Acrylonitrile butadiene styrene

(ABS), polycarbonate (PC), PC-ISO, PC-ABS mixes, and poly phenyl sulfone (PPSF), It is a PC of medicinal grade. The primary benefit of this method is that no chemical post-processing is necessary, no resins to cure, a less costly apparatus, and the materials that emerge in a procedure that is more economical. The drawbacks are since in comparison to other axes, the z axis's resolution is low 0.25 mm additive manufacturing technique), hence assuming a smooth There must be a surface, a finishing procedure, and it is a laborious technique that might take days to construct a massive complex component. Certain devices allow for two modes to save time: a completely time-saving sparse and dense modes, but clearly diminishing the mechanical characteristics. [17]

1.5.2 Pro metal

Pro metal is a method of three-dimensional printing used to construct dies and injection tools. This method uses powder as its foundation. whose stainless-steel finds application. The printing procedure takes place. when a liquid binder shoots steel particles in jets. The powder is found in a controlled powder bed. by creating pistons that, after each layer is built, lower the bed completed and a feed piston that provides the necessary materials for each stratum. Once completed, the remaining powder must be taken out. There is no need for postprocessing while creating a mold. Should As a functioning portion be constructed, infiltration, sintering, and Completing procedures are necessary. During sintering the component is heated to 350°F for a full day of hardening. [18]

the steel and binder combining in a 60% porous specimen. Bronze is incorporated into the item during the infiltration phase. powder when combined and heated to above 2000 degrees Fahrenheit. in an alloy consisting of 40% bronze and 60% stainless steel. The same procedure with varying sintering temperatures and sometimes, has been combined with other substances like tungsten zirconium copper alloy-sintered carbide powder to produce rocket nozzles; these components have superior characteristics compared to the same material's CNC machined components.[19]

1.5.3 Modular Laser Sintering

This method of printing in three dimensions uses a Using a carbon, powder is sintered or fused. radiation from a laser. The chamber is nearly as hot as melted point of the substance. Powder was fused by the laser. in a particular spot designated by the design for every layer.

The particles are arranged loosely in a bed that is managed by a piston that descends the stratum by the same amount thickness after every completed layer. This procedure provides a wide range of materials that might be employed, including plastics, metals, metal combinations, metal combinations and polymers, as well as metal and ceramic composites. Acrylic is one type of polymer that might be utilized. nylon and polyamide (styrene), which have almost identical mechanical characteristics like the injected components. Additionally, it is Utilizing reinforced polymers or composites is feasible, meaning fiberglass combined with polyamide. They could also be strengthened using copper-like metals. With metals, a binder is required. That could be a polymer binder that is taken out later by Mechanical Engineering, ISRN, 5 Backing substance nozzle Materials for support Basis Build supplies nose Build supplies.[20]

heating or combining metals that melt at quite different temperatures. High strength alumina components may be constructed. using the organic binder polyvinyl alcohol. The primary benefits of this technology are the extensive array of resources that are usable. Powder leftovers can be recycled. The fact that the precision is constrained by the size is a drawback. In the material's particles, oxidation must be prevented by carrying out the procedure in an environment with inert gas and for the procedure should take place close to the melting at a steady temperature emphasis. Another name for this procedure is direct metal laser sintering.[21]

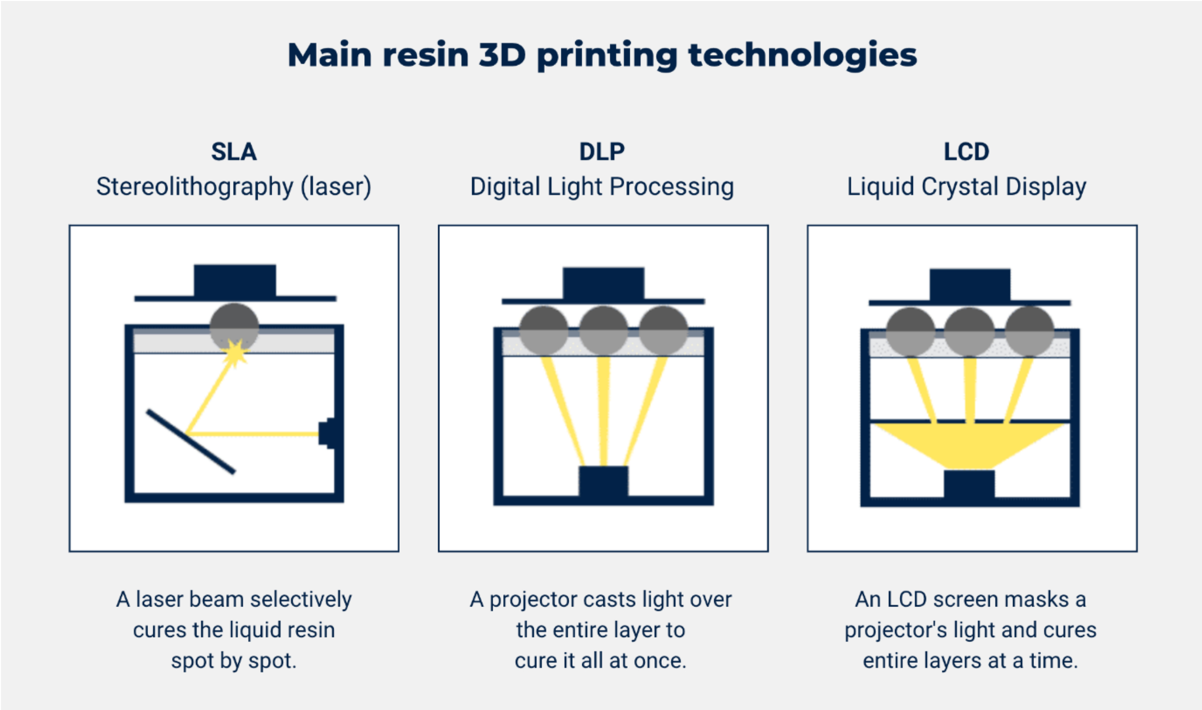

Figure 4: Main resin 3D printing technologies

1.5.4 Melting Electron Beams

Electron beam melting is a method that is comparable to SLS (EBM). Although this method is relatively new, it is expanding quickly. Within this During the procedure, an electron laser beam melts the powder. driven by a high voltage, usually between 30 and 60 KV. The method occurs in a chamber with high vacuum to prevent oxidation. problems since metal pieces are supposed to be built using it. Others The procedure is a lot like SLS than this. EBM can also handle a large range of pre alloyed metals. One of the upcoming One use for this technology is space manufacturing. as everything is carried out in a high vacuum environment.[22]

1.5.5 Net Shaping Designed Using Laser

Using this method of additive manufacturing, a part is constructed by melted metal powder sprayed into a designated area. It is heated to a molten state using an intense laser. shine. When the substance cools, it solidifies. procedure takes place in an enclosed space with an argon atmosphere. This procedure enables the application of a wide range of metals and alloys based on nickel, titanium, aluminum, vanadium, and combinations of these, such as stainless steel, tools steel, alloys made of copper, and so forth. You can also utilize alumina.

Additionally, this approach is utilized to repair sections that would be more costly or difficult to repair using conventional methods. One issue This procedure may leave behind residual strains from unequal activities involving heating and cooling that may be important in high-precision operations like the repair of turbine blades.[23]

1.5.6 Basis Laser pointer solidified substance metal grit.

Laser-engineered net shaping Ten Laminate Object Production The procedure known as Laminated Object Manufacturing (LOM) blends subtractive and additive methods to construct a component successive layer. The materials for this technique are sheets.

shape. Heat and pressure are used to fuse the layers together. application and employing a coating made of thermal adhesive. One carbon the material is sliced with a dioxide laser to fit each layer's form. Considering the data from the CAD and the 3D model, STL data. This process's benefits include its cheap cost, no need for supporting structures or post-processing throughout the process, deformation or phase change, and the potential to create substantial portions. The drawbacks are that the manufacturing material is wasted since it is removed, poor surface definition and direction dependence of the material for mechanical qualities and machinability, and intricate Building interior cavities is an extremely challenging task. This method can be applied to models made of metal, composite materials, and paper.[24]

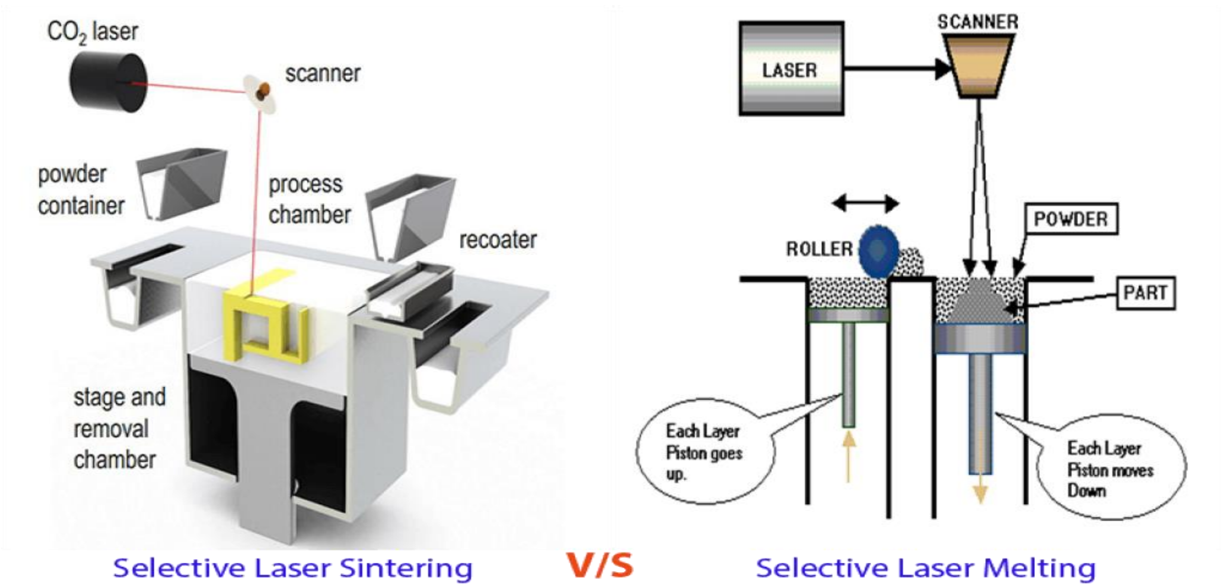

Figure 5: SLS 3D printer and SLM 3D printer

1.5.7 Pol jet

This is an inkjet additive manufacturing method. technology for producing tangible models. The printer A photopolymer is deposited by the head moving in the x and y axes. which, once each layer is completed, is dried using UV rays. This technique results in a layer thickness of 16 µm, therefore the pieces that are created have a high resolution. Still, the This process results in areas that are weaker than others, such as the use of selective laser sintering and stereolithography. A gel-like the overhang features are supported by polymer, and following the procedure, this substance is blasted with water. Along with this method, components of various hues may be constructed.[25]

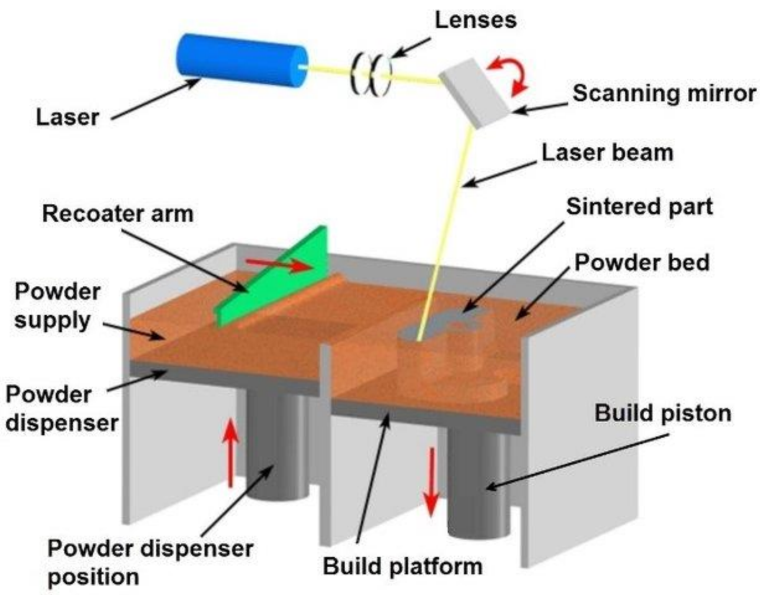

Figure 6: A schematic diagram of the direct metal laser sintering (DMLS) Process

CHAPTER 2: LITERATURE REVIEW

1. FDM

An example of a common additive manufacturing technique is fused deposition modelling, or FDM printing. Scott Crump invented it in the late 1980s, and his business, Stratasys, went on to commercialize it. Today, Stratasys is one of the top producers of 3D printers.

Here's a brief rundown of how FDM functions:

1. Filament Material: The raw material used in FDM is thermoplastic filament. Polylactic acid (PLA), polyethylene terephthalate glycol (PETG), acrylic butadiene styrene (ABS), and other materials are used.

2. Filament Loading: The 3D printer's heated extrusion nozzle is filled with filament.

3. Heating and Extrusion: The filament is heated to the melting point by the nozzle. After the material has melted, the extruder follows a preset route to deposit the melted material layer by layer. Using the Layer-by-Layer Construction method, the item is constructed in layers, with each layer fused to the preceding layer during the cooling process. Until the full 3D model is produced, these steps are repeated.

5. Build Platform: The item is constructed on a vertically movable platform. With the addition of each layer, the platform gradually descends.

6. Support Structures: Temporary support structures may be introduced during the printing process if the design contains an overhang or an unsupported portion. The supports may be taken out after the print is finished.

7. Cooling and Solidification: A stable structure is formed as each layer cools and solidifies during deposition.[26]

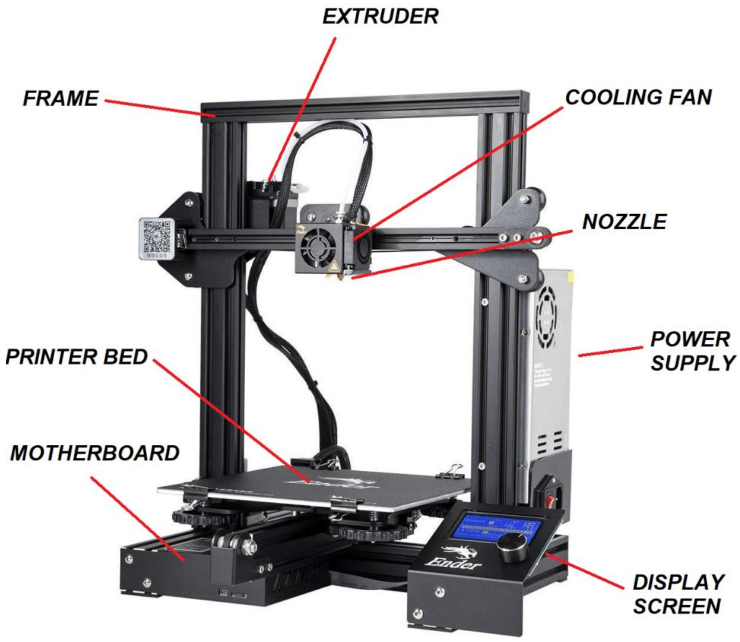

Figure 7: FDM 3D Printer

1.1. FDM offers several benefits

- Material Variety: A large selection of thermoplastic materials is supported by FDM.
- Affordability: A broad range of people may afford FDM printers due to their reasonable cost.
- Ease of operate: The printing procedure is simple and FDM printers are easy to operate.

But it also has certain drawbacks:

- Resolution: Surface finish may be affected by visible layer lines in FDM printing.
- Speed: FDM printing might take a while, depending on how intricate the design is.
- Removal of Support: The procedure of removing support structures can be labor-intensive and occasionally difficult.
- Notwithstanding these drawbacks, FDM is nevertheless a well-liked option for 3D printing because of its adaptability, affordability, and accessibility to a large variety of materials.[27]

1.2. Design Points to Remember

1. Supports and Overhangs: Printing overhangs without support structures is a challenge for FDM. It's crucial to design your model with support removal in mind if you want the intended outcomes.

2. Orientation of Layer: The strength and surface polish of your model may be impacted by its orientation. In general, relative to the Z axis, layers are stronger along the X and Y axes.[28]

1.2.1. Post-Application

1. Removal Support: Support structures can be taken down manually or with the use of extra tools. A second material can be utilized as a soluble support that is readily removed from printers that have twin extruders.

2. Finishing Surfaces: Layer lines may be seen in FDM prints. A variety of post-processing methods can be used to enhance the surface finish, including sanding and the use of chemical solutions. [22]

Resources

1. Options for Materials: A wide range of materials may be used with FDM, including as flexible materials, common plastics, and composite filaments with extra features like heat resistance or improved strength.[29]

2. Eco-Friendly Choices: Compared to certain other polymers, FDM filaments that are biodegradable and ecologically favorable include PLA.

1.3. Use Cases

1. Modeling: Because FDM is affordable and can create concept models fast, it is frequently utilized for rapid prototyping.

2. Components That Work: Although the mechanical qualities may not be as good as those made with other modern manufacturing processes, it is used to create functioning parts.[30]

3. Instructional: Due to its cost and ease of use, FDM is frequently utilized in educational settings, giving students first-hand experience with 3D printing.

Figure 8: PETG Medical Sterile Packaging

1.3.1. Developments

1. Printing on Multiple Materials: Multi-material printing is possible with certain sophisticated FDM printers, allowing for the production of more intricate and varied things.

2. Control of Layer Height: Smoother surfaces and finer details are possible due to improved control over layer height.[31]

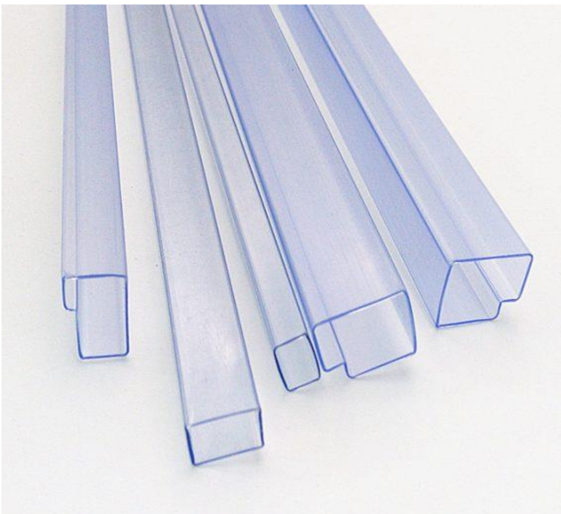

Figure 9: PETG IT Tube

Difficulties

Warping: First Warping, particularly in bigger prints, can result from uneven cooling of the printed material. This problem can be lessened with enclosed print rooms and heated print beds.

2. Accuracy and Flexibility: It can be difficult to achieve high accuracy and tight tolerances because of the intrinsic characteristics of layer-by-layer deposition.

3. Restrictions on Materials: Despite the wide range of materials available, certain high-performance applications can call for materials that aren't appropriate for FDM.[32]

1.3.2. Future Prognosis

FDM is still developing, much like many other technologies. Engineers and researchers are always trying to increase the material options, speed, and resolution. Recent advancements could alleviate some of the existing restrictions and create new opportunities for FDM across a range of sectors.[33]

In conclusion, FDM is a flexible and widely available 3D printing method that has advantages and disadvantages. Its relevance in the field of additive manufacturing is demonstrated by the fact that it is widely used in numerous disciplines.

Figure 10: PETG Refrigerator Boxes

2. How to use FDM TECHNOLOGY

Using a thermoplastic filament, fused deposition modelling (FDM) is a well-liked 3D printing technique that builds three-dimensional things layer by layer. A basic manual for utilizing FDM technology is provided here:

1. Select a 3D Printer: Pick an FDM-compatible 3D printer. Several well-known brands are MakerBot, Prusa, Ultimaker, and Reality.

2. Select the Correct Filament: The filament used in FDM printers is usually thermoplastic, such as PLA, ABS, PETG, or similar materials. Select a filament based on the needs of your project.

3. Set Up 3D Model: Make your object's 3D model or acquire one in an appropriate file format (such as STL, OBJ, etc.).

4. Slice the Model: To create the G-code and divide the 3D model into layers, use slicing software (such as Cura, Prusa Slicer, or Simplify3D). The 3D printer uses a collection of instructions called G-code to move and extrude the filament.

5. Load Filament: Fill the 3D printer with the selected filament. Observe the detailed guidelines supplied by the printer's manufacturer.

6. Calibrate the Printer: Verify that the nozzle height is correctly calibrated, and that the printer bed is level. For layer adhesion to be successful, this step is essential.

7. Setup Print Parameters: Modify the temperature, print speed, layer height, infill density, and supports, if necessary, in the slicing program.

8. Preheat the Printer: Set the printer's temperature to the one suggested by the filament of choice. This guarantees accurate extrusion.

9. Initiate Printing: Scoop out the G-code file and transfer it to the 3D printer. Get the printing process started.

10. Keep an Eye on the Print: Watch the print closely to make sure everything goes as planned. Deal with any problems right away.

11. Post-Processing: Let the item cool on the bed when printing is finished. Carefully remove it, and if needed, carry out post-processing operations like painting, sanding, or removing supports.

12. Maintain the Printer: Clean the print bed, nozzle, and other parts on a regular basis. When necessary, lubricate moving components. Observe the manufacturer's recommendations for maintenance.

13. Experiment and Iterate: To optimize parameters for various prints, FDM printing frequently necessitates some experimenting. Gain knowledge from every print to raise the calibre of subsequent endeavors.

14. Troubleshooting: Recognize frequent problems and how to solve them. Warping, stringing, and difficulties with layer adhesion are typical challenges.

Always follow the detailed instructions supplied by the provider of filament and the manufacturer of your 3D printer, since various printers and materials may have different needs.[34]

3. Nozzle Effects in FDM Technology

Your query appears to include a small bit of misunderstanding. The process of 3D printing known as fused deposition modelling, or FDM, involves heating thermoplastic filament and extruding it layer by layer via a nozzle to produce three-dimensional objects. In FDM technology, "nozzle effects" usually refers to a variety of elements pertaining to the nozzle that the filament is extruded through.[35]

Here are some crucial things to remember:

1. Nozzle Diameter: The printing speed and layer resolution are influenced by the nozzle's diameter. Finer details are possible with smaller nozzles, but longer print times might be the outcome.

2. Nozzle Temperature: The nozzle's temperature is essential for correctly melting the filament. Temperature requirements vary for different materials, and using the incorrect temperature might result in problems like under- or over-extrusion.

3. Layer Height: The layer height establishes the separation between every layer. Layer adhesion, surface polish, and overall print quality all show the influence of nozzles.

Fourth, Nozzle Clogs: There are several causes of nozzle blockages, including dirt in the filament and incorrect temperature settings. To avoid blockages, regular cleaning and maintenance are necessary.

5. Material Compatibility: The flow characteristics of various materials differ. For optimal extrusion, the nozzle and selected filament must work together.

6. Printing Speed: The printing speed also exhibits nozzle effects. Increased speeds may cause problems such as ringing artifacts or poor layer adhesion.

7. Cooling Fan: A cooling fan aimed at the nozzle is present in certain 3D printers. The cooling of the printed layers may be influenced by the fan's direction and speed, which can change the print quality.

8. Nozzle Height and Bed Levelling: To guarantee that the initial layer sticks to the build plate properly, the nozzle height and bed levelling must be calibrated correctly.

9. Retraction Settings: When the nozzle is traveling between non-printing zones, retraction is the process of drawing the filament back slightly. Retraction settings that are off might cause oozing and stringing.

When using FDM 3D printing, it is essential to comprehend and optimize these nozzle-related aspects to get high-quality prints. Nozzle-related problems may be addressed and minimized through regular maintenance, calibration, and configuration experimenting.[36]

4. Layer Thickness Effect on FDM

The quality, strength, and look of the produced product are greatly influenced by the layer thickness in Fused Deposition Modelling (FDM), a popular 3D printing process.

The following are some ways that layer thickness affects FDM printing:

1. Resolution and Surface Finish: Higher resolution and a smoother surface finish are the outcomes of less layer thickness. Prints with greater depth and intricacy are possible with finer layers.

2. Print Speed: Slower print rates are often needed for thinner layers. This is so that the finer layers can properly solidify, requiring the printer head to move more slowly.

3. Print Time: Thinner layer printing often requires a longer print time. The number of layers and the printing time are closely correlated.

4. Strength and Durability: Part strength may be enhanced by thicker layers since they can create a stronger link between layers. On the other hand, overly thick layers may lead to poor adhesion between layers and decreased strength overall.

5. Fitness to the Construction Plate: If bed levelling is a problem, thicker layers may stick to the build plate more readily. Finding a balance is crucial, though, as too thick layers might lead to inadequate adherence from inadequate contact with the build plate.

6. Printability of Supports: Since thicker layers tend to peel away more cleanly, they might be easier to remove than thinner layers. On the other hand, the shape of the printed item may also have an impact.

7. Print Precision: The printer can produce more accurate representations of the 3D model, especially for curves, rounded surfaces, and fine details, when thinner layers are used.

8. Material Usage: Accurate material utilization is typically the outcome of finer layers. Although they might use more material, thicker layers might expedite the printing process.

9. Compatibility with Printers: Different ideal layer thicknesses are associated with different 3D printers. Referring to the printer's specs and instructions is crucial for establishing the required layer thickness.

10. Printability of Fine elements: thinner layers are required to precisely recreate detailed elements in your model. These subtleties might be obscured or inaccurately shown by thick layers.

In conclusion, there are trade-offs between print resolution, strength, print time, and other considerations when choosing layer thickness in FDM printing. The ideal layer thickness frequently relies on the needs of the produced object as well as the 3D printer's capabilities. It might take some trial and error to determine the perfect balance for a certain application.[37]

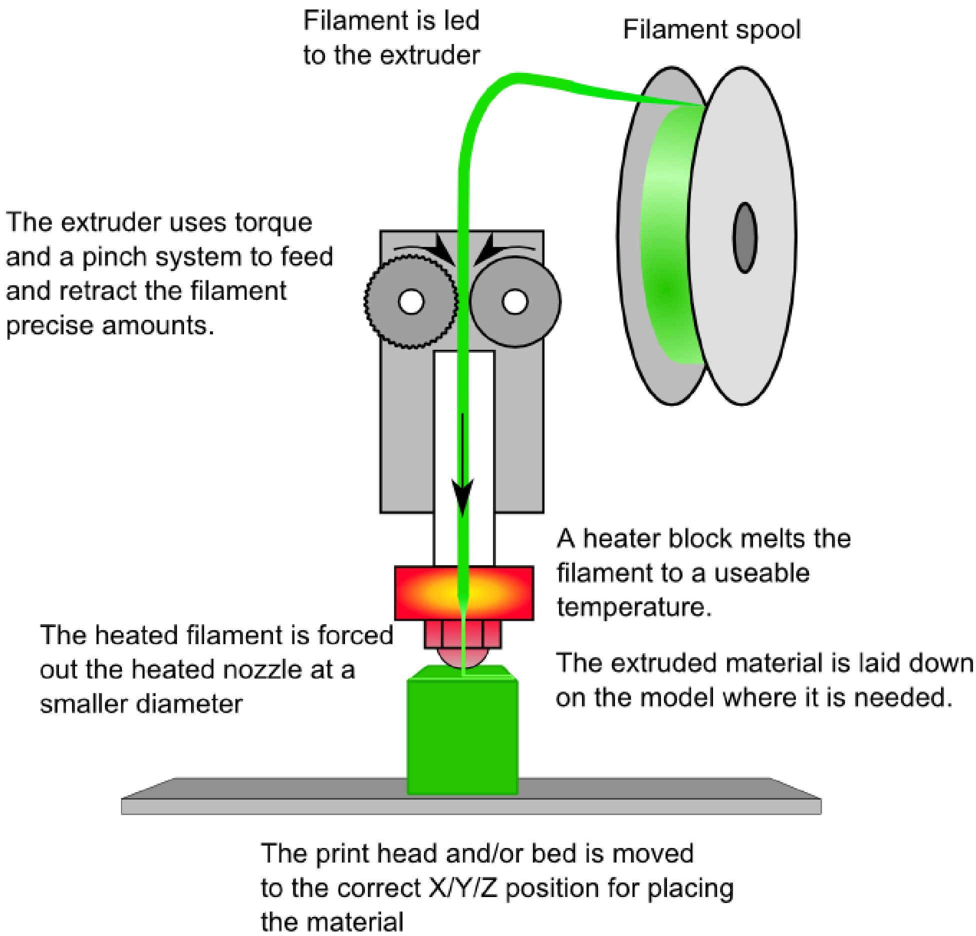

Figure 11: FDM printing technology

CHAPTER 3: MATERIALS AND METHODS

1. Composites and polymers

1.1. PET

Polyethylene terephthalate, commonly known as PET Plastic (or sometimes PETE), is a popular thermoplastic used across various industries such as textiles, films, electronics, packaging, and automobiles. Its primary utilization is in the textile industry, where it is commonly referred to as Polyester. PET plastic boasts several attractive properties like chemical and thermal resistance, dimensional stability, and impressive strength-to-weight ratio. It is colorless, semi-crystalline, and virtually shatterproof, making it applicable across multiple industries. PET plastic is also highly recyclable, with a recycling symbol of “1”. With an annual production of 56 metric tons, it is the most widely used thermoplastic in the world, with the textile industry consuming 60% of it, and the packaging and bottling industry accounting for 30% of its usage [37]. PET Copolymers PET or PETE is a homopolymer that can be altered to form copolymers (polyethylene terephthalate glycol-modified) to suit specific uses. PETG is usually produced using modifiers like cyclohexane dim ethanol (CHDM) and isophthalic acid, which react mainly with crystallization, leading to a reduction or alteration of the polymer's temperature [38].

1.1.1. PET Characteristics

PET or polyethylene terephthalate has many ancillary properties:

• PET, also known as polyethylene terephthalate, possesses various notable properties. One of its strengths lies in its chemical resistance, as it can withstand exposure to water, food, and natural elements like bacteria and fungi. As a result, PET is a suitable material for use in food packaging.

• PET is naturally transparent, but it may not be as visually appealing as other highly transparent polymers like Polycarbonate and Acrylic. In cases where high transparency is necessary, it is recommended to use these other polymers instead of PET.

• PET plastic is solid and robust, making it shatterproof. Therefore, it can be used as an alternative to glass in various applications.

• Polyethylene terephthalate is primarily classified as a thermoplastic based on its response to heat. However, there are also numerous variants of polyesters that are considered thermosets. The difference between thermoplastics and thermosets is primarily determined by their reaction to heat. Thermoplastics melt at their respective melting points (for polyester, this is 260°C), SZENT ISTVÁN CAMPUS pg. 21 and this melting process can occur multiple times without significant degradation. This is especially advantageous in injection molding applications. In contrast, thermosets can only be burned once, as their chemical composition changes during the first heating process, which cannot be reversed. Subsequent attempts to heat them will lead to the polymer burning, rendering them unsuitable for recycling [38].

1.1.2. PET Made

The production of PET plastic, like other thermoplastics, involves breaking down hydrocarbon fuels into smaller components known as "fractions." By combining specific fractions with catalysts, plastic can be formed through a process known as polymerization or polycondensation. However, the main difference with PET lies in the fact that it requires a combination of hydrocarbon ethylene glycol and terephthalic acid [39][40].

1.1.2.1. Processing Conditions for PET Plastic

PET is perfectly compatible with injection molding, Blow Molding, Extrusion Molding, and 3D Printing processes. PET plastic is using for extruding produce films and sheets. It is advisable to dry polyethylene terephthalate for up to 2-3 hours before processing.

Table 2: Processing conditions of PET plastic Injection Molding Blow Molding Extrusion Molding 3D Printing Melt temperature – 280-310°C. Melt temperature – 200 to 245°C Extrusion temperature – 270- 290°C Advised temperature – 40 and 260°C Mold temperature: 140-160°C Mold temperature – 10-50°C NA Bed Temperature – 100°C Most preferred for transparent applications. Blow Molding is commonly utilized for manufacturing transparent bottles. PET can be utilized to produce films and sheets, which can be thermoformed later. Most preferred to manufacture products with complicated geometries like toys, gifts, and novelty items. The recommended screw L/D ratio is 18-22. NA Extrusion speed around 100 RPM Retraction speed should be slow at 30mm/s or less [38][40].

1.1.2.2. Advantages and Disadvantages of PET

Advantages

• PET possesses a high strength-to-weight ratio (a rare quality found). Thus, easy, and inexpensive to transport.

• It is available in abundance and is inexpensive compared to other thermoplastics. • It is moisture resistant.

• It shows fantastic electrical insulating properties.

• PET is smack and fracture-proof, making it a suitable alternative to glass in many applications.

• It exhibits high resistance to organic matter and water, which can become advantageous or a nuisance depending on the application.

• PET is approved to be safe with food and beverages. Agencies like FDA, Health Canada and EFSA have given it a free flag.

• Polyethylene terephthalate can be recycled. Recycling includes a series of washing processes; after that, it can be reused.

• It is transparent to microwave radiation.

• Compared to its closest competitor, Polybutylene terephthalate (PBT), PET shows higher heat distortion temperature (HDT) [40][41].

Disadvantages

Polyethylene terephthalate comes with great qualities, and the positives obviously outshine the negatives, but we should still look at them.

• PET is not biodegradable.

• PET is vulnerable to oxidation (But nothing is rock solid proof about this) [40][41].

1.1.3. Recycling of PET & its Effects on the Environment

Polyethylene Terephthalate (PET) is a highly sustainable material that can be recycled 100%. It is the most widely recycled thermoplastic globally and can easily be identified with recycling code "1". PET stands out as the preferred choice for recycled material because of its low diffusion coefficient. The collection process for used PET products is specialized and involves a washing or chemical breakdown of the material into small PET flakes. These recycled flakes are used in a variety of applications, such as strapping, films, sheets, food and beverage containers, carpets, and fleece bags [38][40][41].

1.1.4. Biomaterials

Of course! A class of materials known as biomaterials works with biological systems to assess, cure, improve, or substitute any organ, tissue, or bodily function. They are essential to many medical applications, including as tissue engineering, medication delivery systems, prostheses, and implants.

Below is a summary of the various facets associated with biomaterials:

1. Explanation: - Biomaterials are materials designed to work with biological systems in the context of medicine, such as in regenerative medicine, treatments, and diagnostics.

2. Biomaterial Types: Metals: Frequently utilized for orthopedic implants (titanium alloys, for example). Polymers: Adaptable polymers (like polyethylene and polyurethane) utilized in a variety of medical applications. Ceramics Utilized in orthopedic and dental implants because of their biocompatibility (hydroxyapatite, for example). Composite materials are composed of many materials blended to improve qualities.

3. Uses: Implants: Augmentation or replacement of biological tissues (e.g., pacemakers, hip implants), prosthetics; man-made tools designed to supplement or improve the performance of missing bodily components. Medical Delivery Systems: Managed medication release for certain medical interventions. Tissue Engineering Producing biological tissue that are functional for use in transplantation or regenerative medicine.

4. Biocompatibility: A material's capacity to carry out its intended function devoid of immunological or poisonous reactions in the body.

5. Challenges: Immune Response Foreign contaminants might cause the body's defensive mechanisms to respond. Degradation Materials must be made to break down at a pace that doesn't interfere with tissue repair. Infection Infections linked to biomaterials are a cause for worry.

6. New Developments: Nano technology Utilizing nanoscale materials to improve tissue engineering and medication delivery. 3D Printing: Accurate creation of intricate biomaterial structures. Smart Biomaterials Materials that are responsive to variations in the biological milieu.

7. Regulatory Aspects: Tight rules to guarantee biomaterials' effectiveness and safety in medical applications.

8. Future Directions: Persistent investigation into bioactive materials, customized healthcare, and sophisticated manufacturing methods.

9. Specific Biomaterials in Focus: Hydrogels Water-absorbing polymers that are biocompatible and have a high-water content that are employed in tissue engineering and medication delivery. Biodegradable polymers are those that can decompose naturally over time, negating the need for implant removal surgery. Bioactive Glasses These are glasses that stimulate cellular responses by interacting with biological systems; they are frequently employed in bone regeneration.

10. Tissue Engineering: - Definition: The use of life sciences and engineering concepts and techniques to the creation of biological replacements to preserve, enhance, or restore tissue function.

Scaffolds: Usually constructed of biodegradable materials, they offer structural support for tissue regrowth.

11. Nanotechnology in Biomaterials: Nanoparticles utilized in targeted therapeutic medication delivery systems. Nanofibers: Promote cell attachment and development by mimicking the structure of the extracellular matrix.

12. 3D Printing in Biomaterials: Customization enables the production of implants and tissues tailored to the individual patient. Materials: A wide variety of biomaterials, such as metals, ceramics, and polymers, may be utilized in 3D printing.

13. Difficulties and Ethical Issues: Long-Term Consequences, knowing how biomaterials interact with the body over the long term. Ethical Use of Biomaterials: Keeping ethical issues like informed consent and privacy in check while simultaneously advancing technology.

14. Sustainable Biomaterials: Environmental Impact, creating biomaterials with less of an impact on the environment Considering biomaterials' complete life cycle, from manufacture to disposal.

15. Interdisciplinarity and Collaboration: Medical and Engineering Collaboration Successful biomaterials development requires cooperation between material scientists and medical practitioners - Filling up the gaps between clinical applications and laboratory research.

16. Patient-Centric Approaches: Personalized Medicine Adapting biomaterials to unique patient attributes. Improving treatment results by using a tailored strategy.

17. Global Impact: - Access to Biomaterials: - Reducing inequalities in access to cutting-edge medical technology and biomaterials throughout the world. Ensuring availability affordability, especially in environments with limited resources.

18. Training and Instruction: - Transdisciplinary Instruction Promoting educational initiatives that close the knowledge gap between materials science, biology, and medicine Educating the future generation of biomaterials specialists.

19. Public Knowledge: Informatics Raising public understanding of the value of biomaterials in medical treatment Resolving issues and encouraging knowledge of the advantages and disadvantages.

20. Result: - Biomaterials are still essential to the development of new medical procedures and technology. To overcome obstacles and realize the full potential of biomaterials in enhancing human health, continued research and cooperation are crucial.

Biomaterials is a dynamic field that is always changing in response to scientific and technological breakthroughs. To improve people's quality of life everywhere, researchers and experts in this sector are committed to stretching the envelope of what is conceivable.[42]

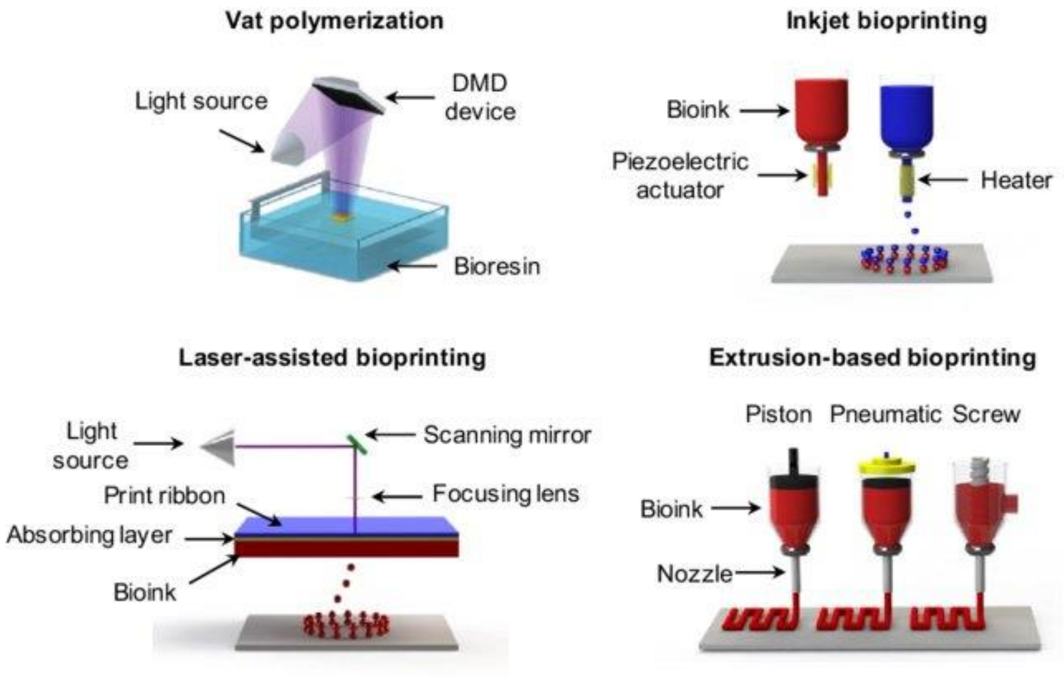

Figure 12: 3D Bioprinting Technology

1.2. PETG

Polyethylene Terephthalate Glycol is referred to as PETG. It is a member of the polyester family and a thermoplastic polymer. PETG is renowned for its adaptability, toughness, and transparency in a range of applications. The following are some of the main attributes and applications of PETG [43][44]:

1. Openness: Because PETG is transparent and clear, it can be used in situations where it's crucial to have visual clarity.

2. Sturdiness: Compared to many other polymers, it is more durable due to its outstanding impact resistance. It is resilient enough to endure moderate to severe knocks without cracking or breaking.

3. Chemical Resistance: PETG may be used in situations where exposure to chemicals is a problem since it is resistant to a wide range of chemicals, including acids and alkalis.

4. Ease of Processing: Working with PETG is simple. With common tools and equipment, it may be thermoformed, drilled, and cut.

5. Healthy Food: It is frequently used for food containers, packing materials, and other items that come into touch with food since it is regarded as food safe.

6. 3D Printing: Because PETG is transparent, long-lasting, and simple to print, it's a widely used material for 3D printing. In comparison to PLA (Polylactic Acid), it provides superior impact resistance, and in comparison, to ABS (Acrylonitrile Butadiene Styrene), it is less likely to warp.

7. Displays & Signage: PETG is utilized to make point-of-sale materials, displays, and signage because of its durability and transparency.

8. Medicinal Usages: Because of its clarity and chemical resistance, PETG is utilized in the medical area for products including face shields, parts of medical equipment, and protective barriers.

9. Construction: PETG is utilized in bottles, clamshell packaging, blister packs, and other packaging applications.

10. Initialization: In the consumer products, automotive, and aerospace sectors, it is frequently used for prototyping and producing functioning parts.

11. UV Resistance: PETG is suited for outdoor applications where extended exposure to sunlight is anticipated because to its strong resistance to ultraviolet (UV) radiation. This characteristic aids in preventing the material's deterioration or yellowing over time.

12. The ability to recycle: PETG is a material that can be recycled, which is good for the environment. Recycling PETG helps lessen the negative effects that plastic waste has on the environment.

13. Versions with Water Clear: Certain PETG formulations are made expressly to be "water clear," which refers to their extraordinary transparency due to certain optical characteristics. They are therefore perfect for uses where optical purity is crucial.

14. Thermoforming: PETG can be heated and melded into a variety of forms by thermoforming procedures, which make it a good fit. This characteristic is very helpful in industrial operations that call for intricate patterns or complicated forms.

15. Insulation Using Electricals: PETG is utilized in electrical applications because of its insulating qualities. Electrical insulators, electronic component housings, and other electrical devices can be made using it.

16. Personalized Colors: PETG is available in a range of hues despite being transparent. Its applicability in situations where aesthetics and branding are crucial is expanded by its color possibilities.

17. Physical Opposition: PETG has strong resistance to several solvents as well as other substances. This feature is useful in situations where it's important to minimize chemical exposure.

18. Hygienic Applications: PETG may be used in places where cleanliness is important, such medical settings and cleanroom applications, because of its chemical resistance and ease of washing.

19. Portable: Because PETG is lightweight, it is useful in situations where weight is an issue, such lightweight packaging or automobile components.

20. PETG against PET: PET (polyethylene terephthalate) and PETG are similar, however they are not the same. PETG is a modified type of PET that has had glycol added to improve several of its qualities, such as making it better suited for 3D printing.

It is noteworthy that the characteristics of PETG may differ according on the production process and formulation employed by various vendors. As with any material, it is advised to review the recommendations and specifications provided by the manufacturer for the specific PETG type being used.[44][45][46].

31. Creep Resistance: PETG can tolerate extended loads or stresses without deforming over time because of its strong creep resistance. In situations where dimensional stability is critical, this characteristic is indispensable.

32. 3D Printing's Dimensional Accuracy: PETG is preferred in 3D printing due to its dimensional precision. It can generate printed objects that are accurate and dimensionally stable since it shrinks less than certain other filaments.

33. Recycling Made Easy: One crucial factor pertaining to the environment is the recyclable nature of PETG. PETG is frequently recycled into a variety of goods, such as strapping materials, garment fibers, and more.

34. Dissipative Properties That Are Static: It is possible to create certain PETG formulations to have static dissipative qualities. This qualifies them for use in industries like the production of electronic components, where static electricity regulation is crucial.

35. Insulation against Heat: PETG offers some degree of thermal insulation, but not as much as some other materials. In situations when the least amount of heat transfer is needed, this may be helpful.

36. Nature of Hydrophobia: Because PETG is naturally hydrophobic, water is repelled by it. Applications where resistance to moisture absorption is crucial can benefit from this feature.

37. Flexibility: PETG has some elasticity, which enables it to bend without cracking. This flexibility is useful in some situations, such flexible packaging, or when parts might need to slightly deform.

38. Production Procedures: PETG may be produced by several production processes, including as blow melding, extrusion, and injection melding. Its extensive application across several sectors is partly due to the processing technologies' adaptability.

39. Certifications and Standards: PETG can have to adhere to industry certifications or norms, depending on the use. Medical device restrictions, for instance, may apply to devices utilized in the medical industry.

40. High-Definition Uses: For situations where optical clarity is crucial, PETG is the preferred material. Clear packaging and displays are among the applications that can benefit from its transparency and long-lasting clarity.

Like with any material, successful and efficient usage depends on knowing the needs of the application as well as the qualities and capabilities of the selected PETG formulation. Technical data sheets, which include comprehensive details regarding the qualities of the material as well as suggested processing procedures, are frequently supplied by manufacturers.[47]

Figure 13: PETG filament.

1.2.1. Carbon fiber

High-performance carbon fiber is renowned for its outstanding strength-to-weight and durability ratios. It is made up of closely packed, incredibly strong carbon fibers that are thin, flexible, and held together by a polymer matrix. Every industry and application that calls for lightweight, high-strength materials uses carbon fiber. [48][49].

Here is a detailed explanation of carbon fiber:

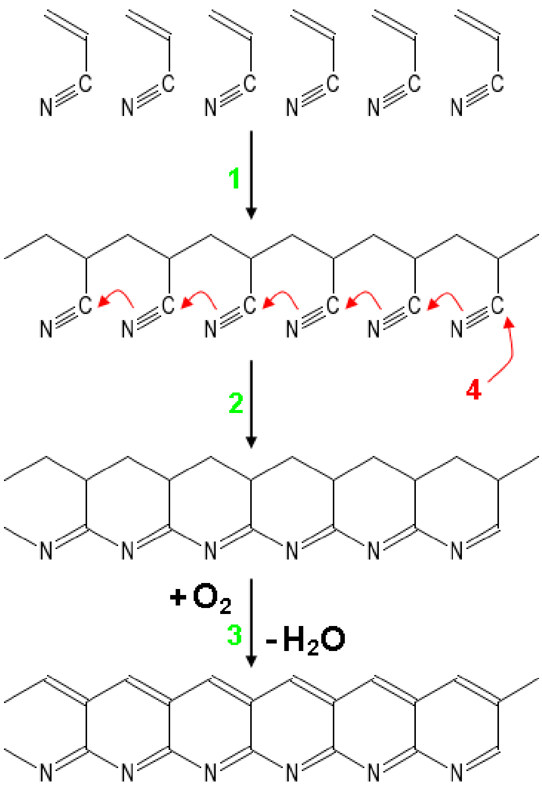

Figure 14: Chemical bonds of PETG.

1.2.1.1. Features

- High Tensile Strength: The tensile strength of carbon fiber is higher than that of many metals. It is renowned for having a fantastic strength-to-weight ratio, which makes it perfect for applications requiring lightweight, high-strength materials.
- Lightweight: Carbon fiber is far lighter than metals like steel or aluminum, making it the material of choice in areas like aircraft and automobiles where weight reduction is crucial.
- Low Density: Because of the material's low density, it is lightweight and floats in water.
- Carbon fiber has an outstanding degree of stiffness, which offers superior structural rigidity and stability.
- Corrosion Resistance: Carbon fiber has an advantage over metals in outdoor and marine applications because it is resistant to corrosion and rust.
- Low Thermal Expansion: Carbon fiber has a low thermal expansion rate, so even when temperatures change, it keeps its structure and dimensions.
- Carbon fiber is electrically conductive, but not as electrically conductive as metals. It can be utilized in situations where electrical conductivity is necessary, such as in aircraft to defend against lightning strikes.
- Carbon fiber can endure high temperatures without significantly degrading, while the precise temperature limit depends on the resin matrix employed.[50]

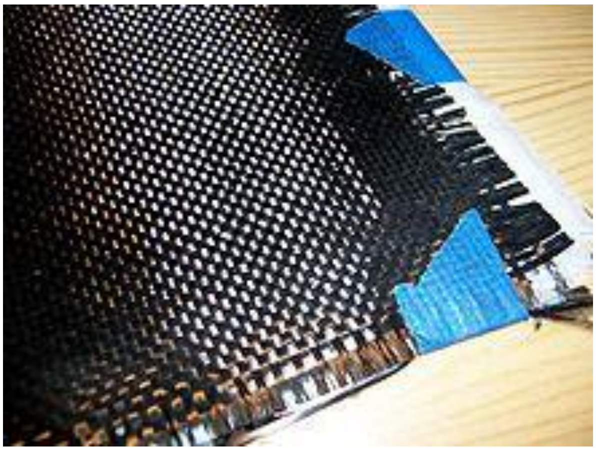

Figure 15: Carbon fiber

1.2.1.2. Production Method

The process of making carbon fiber includes the following steps:

- Pitch or polyacrylonitrile (PAN) are frequent precursor materials used at the beginning of a process. The raw material is processed chemically and spun into fibers.
- When fibers are heated to high temperatures (about 1,800°C) in a controlled atmosphere without oxygen, non-carbon components are removed, and carbon-rich fibers are produced.
- Graphitization (Optional): To improve a material's qualities, further heat treatment (graphitization) may be used in some circumstances.
- Matrix Impregnation: In a procedure known as impregnation, the carbon fibers are mixed with a polymer matrix (such as epoxy).
- Curing: The impregnated substance is cured to solidify the polymer matrix, frequently using heat or chemicals.
- Lamination: To produce the finished material with precise structural properties, many layers of the cured carbon fiber composite are piled and bonded together.[51]

1.2.1.3. Applications

There are several sectors and uses for carbon fiber, including:

- Aerospace: To reduce weight and increase fuel economy, carbon fiber composites are often employed in airplanes, spacecraft, and unmanned aerial vehicles (UAVs).
- Automotive: Body panels, chassis parts, and interior components made of carbon fiber are used in high-performance automobiles and sports cars to increase strength and save weight.
- Sports and recreation: Sports equipment including tennis rackets, golf clubs, bicycles, and fishing rods are made of carbon fiber.
- Marine: Due to its corrosion resistance and lightweight characteristics, it is used in boat hulls, masts, and other components.
- Civil engineering: Carbon fiber reinforced composites are used for seismic retrofitting, strengthening, and restoration of infrastructure.

- Medical Devices: Lightweight and durable components for medical devices like X-ray tables and prosthetic limbs are made of carbon fiber.
- Consumer Products: Due to its aesthetic appeal and durability, carbon fiber is utilized in luxury products, luggage, and consumer electronics.[52]

1.3. PLA

Polylactic acid (PLA) is the most widely studied and used biodegradable aliphatic polyester. It is a leading biomaterial with numerous applications in medicine and industry, replacing conventional petrochemical-based polymers [53].

Environmental, economic, and safety concerns have driven packaging scientists and producers to partially replace petrochemical-based polymers with biodegradable ones. Polylactic acid (PLA), a leading candidate, is a thermoplastic, high-strength, and high-modulus polymer that can be made from renewable resources to produce a variety of components for use in industrial packaging and biocompatible/bioabsorbable medical devices. It is easily processed on standard plastic equipment to yield molded parts, film, or fibers [53][54].

1.3.1. PLA characteristics

- PLA properties depend on its component isomers, processing temperature, annealing time, and molecular weight.
- Crystallinity is a very important property of polymers, and it influences many polymer properties, including hardness, modulus, tensile strength, stiffness, crease, and melting points.
- PLA crystals can grow in three structural positions: α, β, and γ forms.
- PLA properties may be controlled using special catalysts of isotactic and syndiotactic content with different enantiometric units.
- The melting temperature (Tm) and glass transition temperature (*Tg*) of PLA decrease with decreasing amounts of PLLA.
- The density of amorphous and crystalline PLLA has been reported as 1.248 g/ml and 1.290 g/ml, respectively.
- PLA solubility:
    - Soluble in dioxane, acetonitrile, chloroform, methylene chloride, 1,1,2-trichloroethane, and dichloroacetic acid.

  - Partly soluble in ethyl benzene, toluene, acetone, and tetrahydrofuran when cold, but readily soluble when heated to boiling temperatures.
  - Not soluble in water, alcohols, and unsubstituted hydrocarbons.
  - Crystalline PLLA is not soluble in acetone, ethyl acetate, or tetrahydrofuran.
- PLA degrades by hydrolysis after several months of exposure to moisture.
- PLA degradation occurs in two stages: first a reduction in molecular weight, followed by metabolism of lactic acid and low molecular weight oligomers to carbon dioxide and water by microorganisms.
- The rate of PLA degradation is determined by polymer reactivity with water and catalysts, as well as particle size and shape, temperature, moisture, crystallinity, isomer content, residual lactic acid concentration, molecular weight, water diffusion, and metal impurities from the catalyst.
- In vitro studies have shown that pH and molecular weight play a role in PLA degradation, and that in vivo studies can be used to predict in vivo degradation rates [54][55].

The following table (Table 1) represents the physical characteristics of commercial PLA.

Table 1: General characteristics of a commercial amorphous PLA, injection mold grade (96:4 L:D ratio content produced by NatureWorks Co [53]

Characteristics		**Unit**	**Amount**
Physical	Mw	g/mol	66,000
	Specific gravity	-	1.27
	Solid density	g/cm^3	1.252
	Melt density	g/cm^3	1.073
	T_g	°C	55
	T_m	°C	165
	Specific heat (Cp) 190 °C 100 °C 55 °C	J/kg°C	 2060 1955 1590
	Thermal conductivity 190 °C 109 °C 48 °C	W/m °C	 0.195 0.197 0.111
Optical	UV light transmission 190 to 220 nm 225 to 250 nm	%	 < 5% 85%

	> 300 nm		95%
	Visible light transmission	%	95%
	Color L* a* b*	-	 90.64 ± 0.21 -0.99 ± 0.01 -0.50 ± 0.04
Mechanical	Tensile strength	MPa	59
	Elongation at break	%	7
	Elastic modulus	MPa	3500
	Shear modulus	MPa	1287
	Poisson's ratio	-	0.36
	Yield strength	MPa	70
	Flexural strength	MPa	106
	Unnotched Izod	J/m	195
	Notch Izod impact	J/m	26
	Rockwell hardness	HR	88
	Heat deflection temp	°C	55
	Vicat penetration	°C	59
	Ultimate tensile strength	MPa	73
	Percent of elongation	%	11.3
	Young's modulus	MPa	1280
Rheological	Cross WLF viscosity model n Tau D1 D2 D3 A1 A2	 Pa Pa-s K K/P K	 0.25 1.00861×10^5 3.31719×10^9 373 0 20.2 51.6

1.3.2. Applications

Food packaging [56]

PLA can be used in items such as:

- Packaging films: These films are used for packaging due to their twist retention properties
- Food contact articles: such as cups, cutlery, straws, plates… etc.
- Food containers
- Bottle labels
- Teabags: due to its excellent infusion properties
- Grocery bags: used to produce about 45% of shopping bags

Biomedical applications [56]

Polylactic acid (PLA) is a biodegradable plastic that has been widely studied for its potential in medical applications. Due to its excellent biocompatibility and bioresorbability, PLA is a promising material for tissue engineering, implant delivery systems, wound healing, and biomaterial creation.

PLA is often blended or copolymerized with other polymers to create materials with desired properties. The surface properties of PLA can also be modified to improve its biocompatibility.

Examples of the biomedical applications of PLA are the following

- Drug delivery: microspheres, microcapsules, nanoparticles, RNA/DNA delivery
- Tissue engineering: 3D electro-spun fibrous scaffolds for bone regeneration
- Implants: fixation of fractured bone in the form of plates, pins, screws, and wires
- Others: drug eluting stents, bio-absorbable medical implant, sutures in dermatology and cosmetic applications e.g. scar rejuvenation

1.4. ABS

Acrylonitrile-Butadiene-Styrene (ABS) is a widely used thermoplastic polymer known for its excellent combination of mechanical properties, impact resistance, and ease of processing. ABS is a terpolymer composed of three key monomers: Acrylonitrile (A), Butadiene (B), and Styrene (S). The combination of these monomers results in a polymer with a unique set of properties that make it suitable for a wide range of applications. The proportion of each monomer can be adjusted to tailor the material's characteristics for specific requirements.

ABS is a blend of two materials: styrene-acrylonitrile (SAN), a hard and brittle plastic, and cross-linked polybutadiene, a soft rubber. The SAN phase provides strength and rigidity, while the polybutadiene phase provides toughness and impact resistance [57][58].

1.4.1. ABS characteristics

ABS is a popular choice for many applications because of its unique properties, including:

- **High impact resistance and mechanical Properties:** ABS exhibits excellent mechanical properties, including high impact resistance, good tensile strength, and ductility. This combination of properties makes it ideal for applications requiring toughness and durability.

- **Good heat resistance and thermal Stability:** ABS has a relatively low glass transition temperature (around 105°C), which allows it to maintain its mechanical properties at relatively low temperatures. However, it is not suitable for high-temperature applications.
- **Good chemical resistance:** ABS has good resistance to a variety of chemicals, including acids and bases, making it suitable for applications where exposure to certain solvents and acids is a concern.
- **Dimensional Stability:** ABS has good dimensional stability, which is important for applications where tight tolerances are required.
- **Surface Finish:** ABS can be easily molded, and it has good surface finish properties, making it suitable for products with aesthetic considerations.
- **Flammability:** ABS is inherently flammable and requires the addition of flame retardants for some applications.
- **Easy manipulation:** ABS is relatively easy to mold into a variety of shapes and sizes.
- **Low cost:** ABS is relatively inexpensive to produce, which makes it a cost-effective choice for many applications.

The following table (Table 2) represents the different characteristics of ABS

Table 2: characteristics of ABS [57][58]

Property	**Value**
Temperature range	-20 to 80°C
Tensile modulus at 73°F	246000 – 410000 (ASTM D638 test method)
Tensile strength yield at 73°F	4949 – 7260 psi (ASTM D638 test method)
Tensile strength break at 73°F	3830 – 7420 psi (ASTM D638 test method)
Elongation at break	23 – 25%
Flexural modulus	2.25 – 2.28 GPa / 326 – 331 ksi
Flexural yield strength	60.6 – 73.1 MPa: 8790 – 10600 psi
Izod impact, notched	2.46 – 2.94 J/cm
Hardness	88 – 110 Rockwell units
Heat deflection temperature	94 – 104 °C
Heat resistance grades	105 – 121°C

1.4.2. Types of ABS

There are various grades and types of ABS based on the ratio of acrylonitrile, butadiene, and styrene monomers. Different formulations are used for specific applications. For example, ABS with a higher acrylonitrile content tends to have improved chemical resistance, while ABS with a higher butadiene content has better impact resistance.

1.4.3. Applications

ABS is a versatile material with a wide range of applications. It is used in a variety of industries, including [58][59]:

- **Automotive**: ABS is used for interior and exterior automotive components, such as dashboards, trim, grilles, and bumpers, due to its impact resistance and ease of processing.
- **Appliance**: ABS is used to make appliance parts such as refrigerator doors, washing machine cabinets, and vacuum cleaner housings.
- **Electronics**: ABS is used in the production of housings for electronic devices, including computer cases, televisions, and home appliances, due to its excellent surface finish and moldability.
- **Toys and Recreational Products:** ABS is commonly used in the manufacture of toys, such as LEGO bricks and action figures, as well as sporting goods, and recreational equipment such as helmets and skateboards, due to its impact resistance and ease of molding.
- **Medical devices:** ABS is used in the production of various medical devices and equipment, such as instrument housings and components, syringes, and prosthetic limbs, due to its biocompatibility and ease of sterilization.
- **3D Printing:** ABS is a popular material for 3D printing due to its good printability and mechanical properties.

1.5. PA

Polyamide polymers, commonly known as nylons, are a class of synthetic polymers with a wide range of applications due to their excellent combination of mechanical, thermal, and chemical properties.

Polyamides are a group of polymers containing amide (-CONH-) linkages along their molecular chains. They are characterized by their unique combination of properties, including high tensile strength, good impact resistance, excellent abrasion resistance, and thermal stability. The properties of polyamides can be tailored to specific applications by varying their chemical structure, which primarily depends on the type and arrangement of monomers used in their synthesis [60].

1.5.1. Characteristics of Polyamide Polymers

Chemical Structure: The basic chemical structure of polyamides consists of alternating amide groups (–CONH–) in the polymer chain. The specific arrangement of monomers varies among different types of polyamides [60][61][62].

Mechanical Properties: Polyamides exhibit high tensile strength and are known for their toughness and durability. They have good resistance to impact, making them suitable for structural applications.

Thermal Stability: Polyamides generally have good thermal stability, with melting points that range from 150°C to 300°C, depending on the type. This property allows them to be used in high-temperature applications.

Chemical Resistance: Polyamides are resistant to many chemicals, oils, and solvents. Their resistance to alkalis is generally better than their resistance to acids.

Water Absorption: Polyamides can absorb moisture, which may affect their mechanical properties. This property needs to be considered in applications where moisture absorption is a concern.

Dielectric Properties: Some polyamides have excellent electrical insulating properties, making them suitable for electrical and electronic applications.

The following table (Table 3) exhibits the mechanical properties of PA 6 (Nylon 6).

Table 3: Mechanical properties of PA 6 [61]

Property	Typical value
Density (g/cm^3)	1.13
Tensile strength (MPa)	66.5
Compressive strength (MPa)	68
Strain at break (%)	210
Tensile modulus (GPa)	2.4
Printing temperature (°C)	250 - 270

1.5.2. Types of Polyamide Polymers

There are several types of polyamides, but the most common ones include [60][61]:

- **Nylon-6 (Polyamide-6):** This polyamide is made from caprolactam and is known for its ease of processing, good impact resistance, and excellent abrasion resistance.
- **Nylon-66 (Polyamide-66):** Nylon-66 is made from hexamethylenediamine and adipic acid and is valued for its high melting point and excellent mechanical properties.
- **Nylon-11 and Nylon-12:** These polyamides are used in various specialized applications, such as automotive fuel lines and pneumatic tubing, due to their excellent chemical resistance.

1.5.3. Applications of Polyamide Polymers

Polyamide polymers are widely used in various industrial and consumer applications, including [60][61]:

- **Textiles:** Nylon is extensively used in the textile industry to produce clothing, hosiery, and fabrics.
- **Engineering Plastics:** Polyamides are used in the manufacture of various engineering components, such as gears, bearings, and structural parts, due to their excellent mechanical properties.
- **Automotive Industry:** Nylon is used for making various automotive parts, such as engine components, fuel lines, and air intake systems, because of its durability and resistance to automotive fluids.
- **Electrical and Electronics**: Some polyamides are used in electrical and electronic components due to their excellent dielectric properties and heat resistance.

- **Medical Devices:** Biocompatible polyamides are used in medical applications, including surgical instruments and implantable devices.
- **Packaging:** Polyamides are used in flexible packaging materials and films due to their moisture resistance.
- **Consumer Goods:** Nylon is found in a wide range of consumer products, including zippers, ropes, and sportswear.
- **Aerospace and Defense:** Polyamides are used in aircraft and military applications due to their lightweight and high-strength properties.

2. Measurement method

2.1. Tensile test definition

A basic mechanical test called a tensile test, often called a tension test, is used to ascertain the mechanical characteristics of materials, specifically how they react to an applied tensile (pulling) force. This test is crucial for creating and assessing materials for structural and engineering applications because it gives scientists and engineers a better understanding of how a material responds to different loading scenarios [63].

The procedure for a standard tensile test is as follows:

1. Sample Preparation: The material of interest is used to create a tiny, uniform specimen. The specimen often has well defined dimensions and is shaped like a cylindrical or rectangular object. Depending on the material, the preparation procedure might entail molding, cutting, or machining.

2. Mounting: Next, the specimen is placed within a specialized testing apparatus known as a universal testing apparatus or a tensile testing apparatus. The specimen is safely held in place by the machine's grips or clamps without causing any damage to it.

3. Application of Force: By drawing the specimen in opposing directions, the testing apparatus exerts an axial tensile force on it. This force is usually delivered steadily and gradually, with a consistent rate of deformation.

4. Deformation Measurement: The apparatus measures the specimen's deformation, notably the change in length, while the force is applied. The strain, or the ratio of the changed length to the initial length, is computed using this information.

5. Stress Calculation: To find the stress, divide the applied force by the specimen's cross-sectional area. Force (F) / Cross-sectional Area (A) equals stress (σ).

6. Data Collection: Information about the applied force and the related elongation or deformation of the specimen is gathered during the test.

7. Stress-Strain Curve: A stress-strain curve, which illustrates the connection between stress and strain for the material, is plotted using the data that was gathered. The mechanical characteristics of the material, such as its elastic modulus, yield strength, ultimate tensile strength, and elongation, are all well-represented by this curve.

8. Sample Failure: The test is carried out repeatedly until the specimen finally breaks. The ultimate tensile strength of the material is frequently ascertained by recording the point of failure. Important words for tensile testing are as follows Elastic Modulus Also referred to as Young's Modulus, this number indicates how stiff a material is and is derived from the first linear segment of the stress-strain curve. Yield Strength This is the stress at which the material starts to permanently deform (plastically) without breaking.

9. Ultimate Tensile Strength: The highest stress that a material can bear before breaking is known as this. Ductility This term describes the plastic deformation limit of a material, which is commonly expressed as the percentage elongation at fracture. In materials science and engineering, tensile testing is an essential technique that helps researchers and engineers develop structures, choose the right materials for a certain application, and guarantee the dependability and safety of different parts and goods. Failure Analysis after Failure A post-failure study may be carried out to look at the fracture surface after the specimen fails. Whether the fracture was brittle or ductile, this investigation can shed light on the failure mechanism. Whereas brittle fractures emerge more abruptly and lack considerable plastic deformation, ductile fractures frequently show necking and deformation [64].

10. Implements and Importance: Material Selection When choosing materials for applications, tensile testing is essential. Engineers must comprehend a material's behavior under various loads and environmental circumstances. Tensile testing is a quality control method used by manufacturers to make sure that materials fulfil predetermined specifications for mechanical properties. Research and Development Tensile testing is a tool used by researchers to investigate and create novel materials with improved mechanical

characteristics. Structural create Materials used to create structures like buildings, bridges, and airplanes must be able to endure tensile pressures. Tensile characteristics are crucial for this [65].

11. Influential Factors on Test Outcomes: Temperature Variations in temperature have a big impact on mechanical qualities. Strain Rate The rate of force application might affect how the material reacts. Specimen Geometry The specimen's size and form may have an impact on the outcomes. Surface Conditions Defects or irregularities in the surface may affect the test outcomes.

12. Differences in Tensile Examination: Creep Testing This method involves observing the material's deformation over time by applying a continuous force for a prolonged amount of time. Stress Relaxation Testing consists of applying a steady strain and tracking the gradual reduction in stress.

13. International Standards and Testing Norms: Standardized protocols established by ASTM International, ISO (International Organization for Standardization), and other organizations are frequently followed while conducting tensile testing. These guidelines guarantee the comparability and uniformity of test findings from various testing facilities.

14. Technological improvements and Automation: Thanks to technological improvements, testing apparatuses of today are outfitted with advanced sensors, automation, and data gathering systems, facilitating testing processes that are more precise and effective.

15. Tensile Testing Restrictions: Ideal situations: Although real-world applications may entail more complicated loading situations, tensile tests are designed under ideal conditions. Size Effects The size of the specimen might affect the outcome for small-scale materials or structures. Environmental Effects: distinct materials may show distinct characteristics in a given environment [66].

To sum up, tensile testing is a basic technique for describing the mechanical characteristics of materials. It offers crucial data for material selection, design, and quality assurance in a variety of sectors. Improved and novel materials for a variety of applications are developed because of ongoing research and improvements in testing techniques, which deepen our understanding of material behavior under various loading scenarios [67].

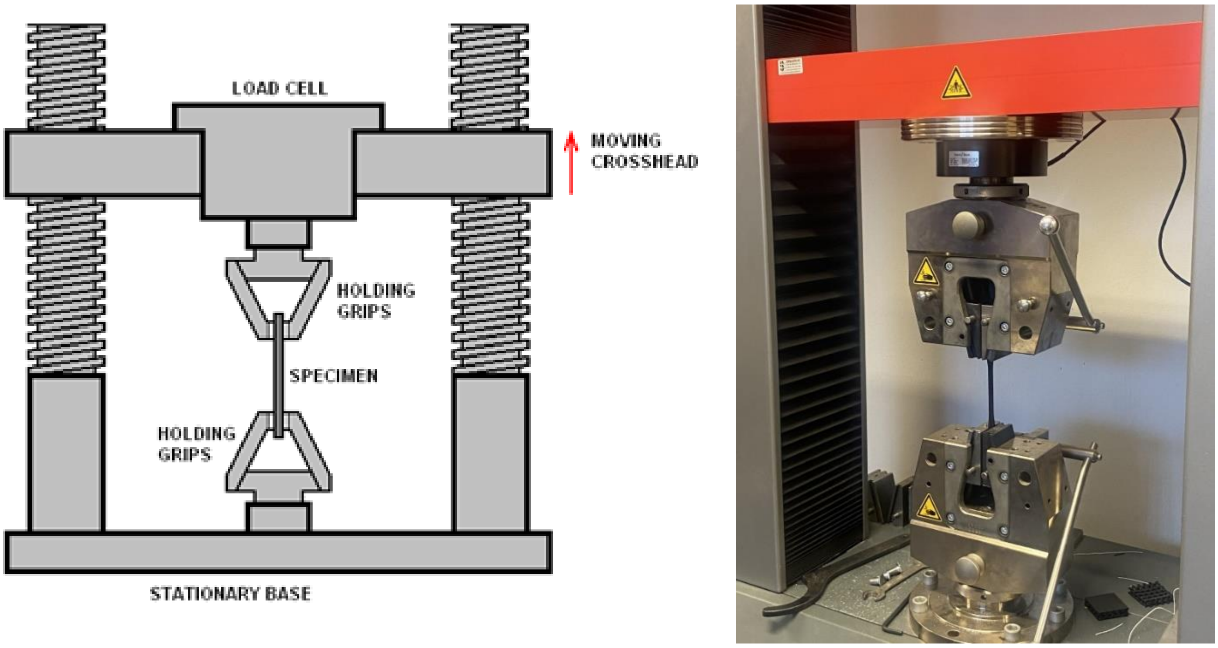

Figure 16: Tensile test machine

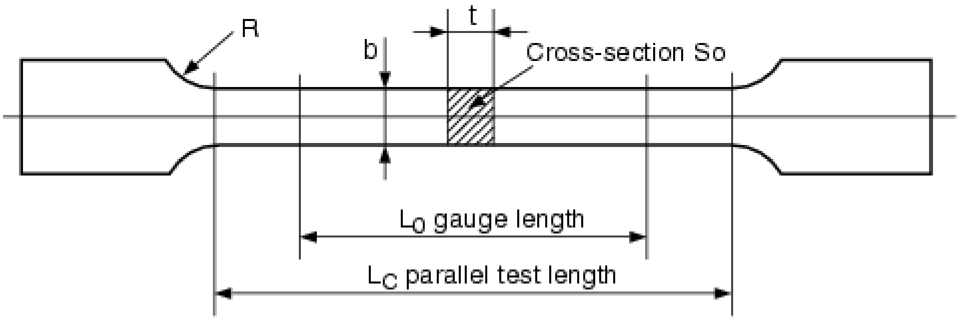

Figure 17: Dimension of tensile test specimen

2.2. Preparation of 3D printed samples

Solidworks software was used to create a 3D CAD design, which was then converted to the stl format in order to make it compatible with 3D printing software. The part was then prepared using the Ultimaker Cura software (4.13.1 version). The part was then generated using the same software as a machining file (G-Code file) and sent to the Ultimaker S3 3D printer.

2.3. Tensile test

After preparing the 3D printed samples, it was time to proceed with the tensile test. The samples were printed using the parameters presented in Table 4

Table 4 : Printing parameters of the samples

Printing Parameters			
Quality		Top/Bottom	
Layer Height	0.2 mm	Top Thickness	0.8
Initial layer height	0.24 mm	Top layers	2
Line width	0.4 mm	Bottom Thickness	0.8
Wall line width	0.4 mm	Bottom layers	2
Walls		Speed	
Wall thickness	0.8	Infill Speed	30 mm/s
Wall line count	2	Wall Speed	25 mm/s
Infill			
Infill Extruder		Extruder 1	
Infill density		100%	

CHAPTER 4: RESULTS

Tensile testing is a commonly employed method to investigate how materials respond to tensile (stretching) loads. In a typical tensile test, a specimen is subjected to progressive deformation until it reaches the point of rupture, providing valuable insights into the ultimate tensile strength of the material. Throughout the test, the applied force (F) and the elongation (ΔL) of the specimen are continuously recorded.

Experimental tests for definition of tensile strength of samples with line and Tri hexagonal shape were realized. The samples were prepared using with different infill density, different printing speed and printing temperature. the following figures 18, 19 and 20 represent the before and after test results.

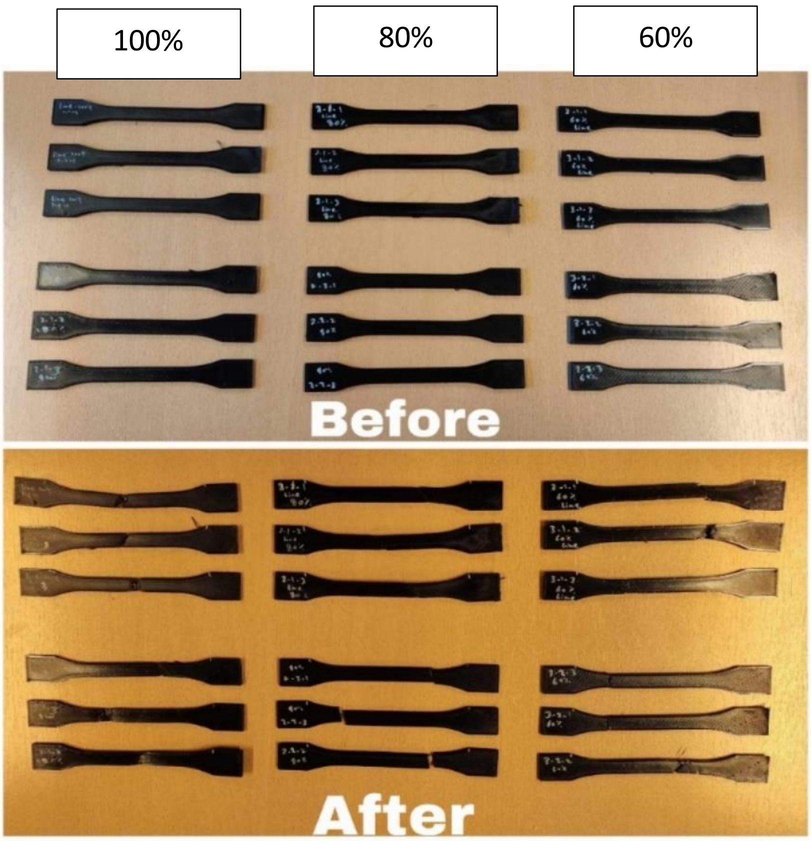

Figure 18: line and Tri hexagon samples with different Infill density

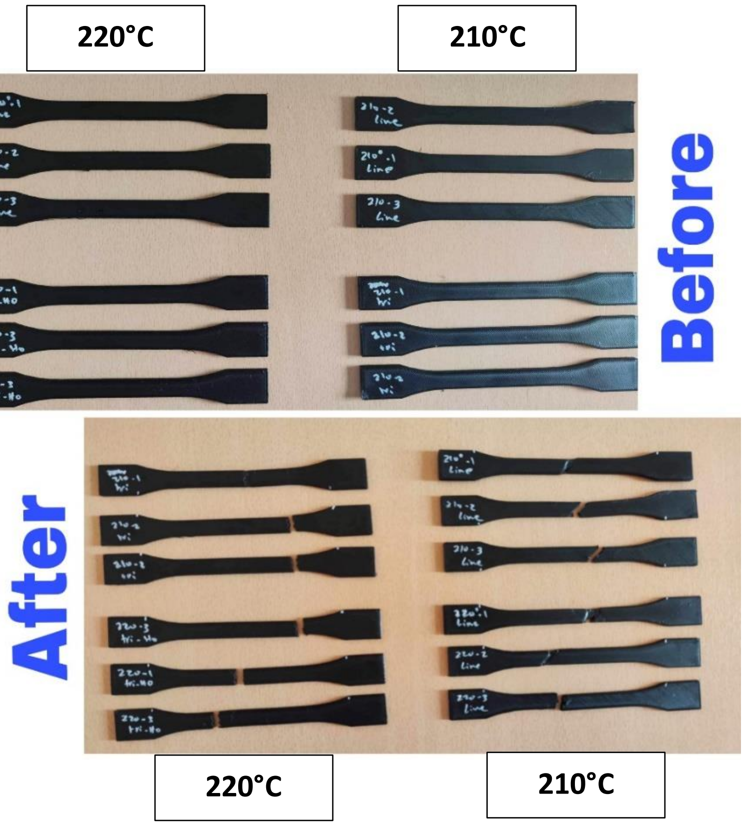

Figure 20: Line and Tri-hexagonal samples with different printing Temperature

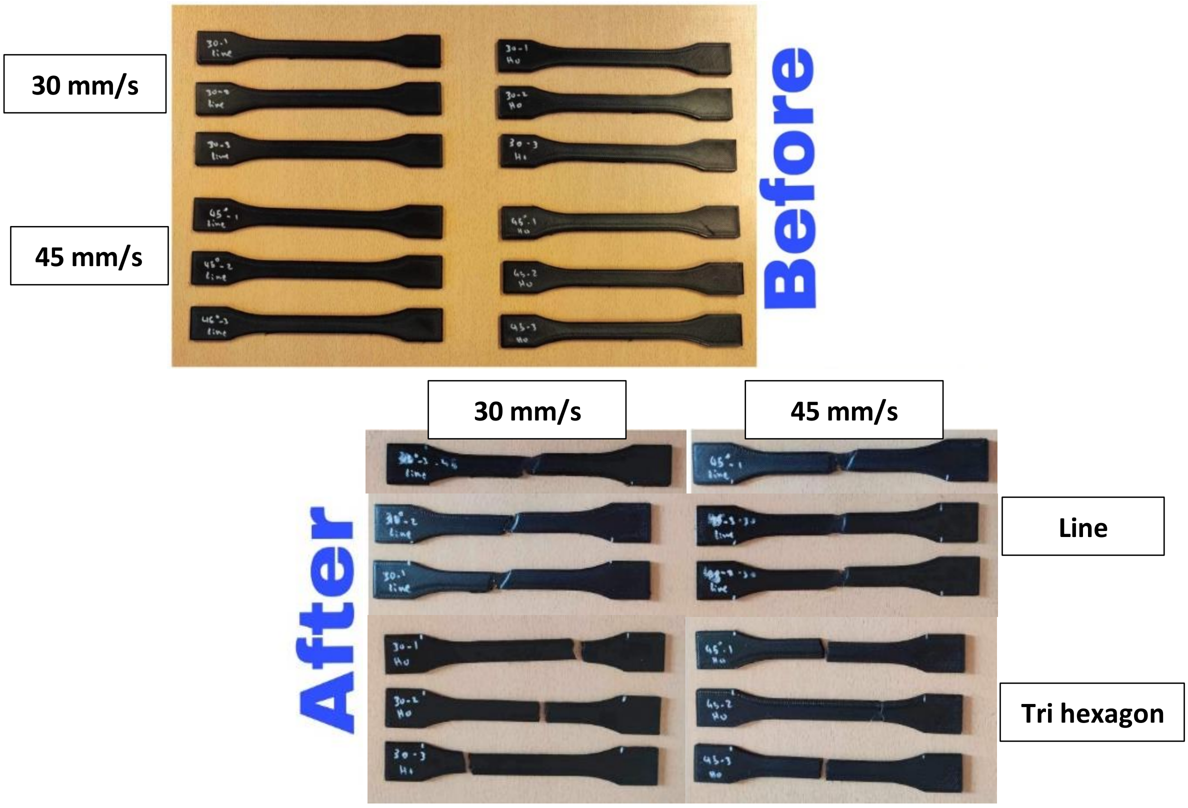

Figure 19: line and tri hexagonal samples with different printing speed

According to the observations of the tested samples, the breaking point differs between each condition, whether it is the infill density, the printing temperature or speed.

Figure 18 represents the results obtained from testing the tensile strength of material samples with different infill densities (100%, 80%, 60%). A difference in material behavior was observed, where the material was harder to break when using a 100% infill density, in comparison with the lower densities tested (80%, 60%), indicating a possible effect of the infill density on the tensile strength of the material.

Figure 19 represents the results obtained from testing the tensile strength of material samples printed in different printing temperatures (220°C, 210°C). According to figure 19, a distinction in the breaking point can also be noted, where in the sample printed in 220°C had a perpendicular break in the cross-section of the specimens, whereas the samples printed in a lower temperature (210°C) had an angular break, suggesting an effect of the printing temperature on the material structure.

Figure 20 represents the results obtained from testing the tensile strength of material samples printed with different printing speeds (45 mm/s, 30 mm/s). Based on the figure 20, a difference in the material behavior was observed when changing between line and Tri hexagonal shapes. The specimens with Tri hexagonal shape had an almost clean break, whereas in the case of the line shape, the material stretched before breaking.

Material characteristics are frequently described in terms of two critical parameters: stress (σ), which is the force per unit area ($\sigma = F/A$), and strain (ε), representing the percentage change in length ($\varepsilon = \Delta L/L$). Stress is derived by dividing the measured force by the cross-sectional area of the specimen, while strain is calculated by dividing the change in length by the initial length of the specimen. These stress and strain values are subsequently plotted on a graph, referred to as a stress-strain curve, usually presented as an XY plot.

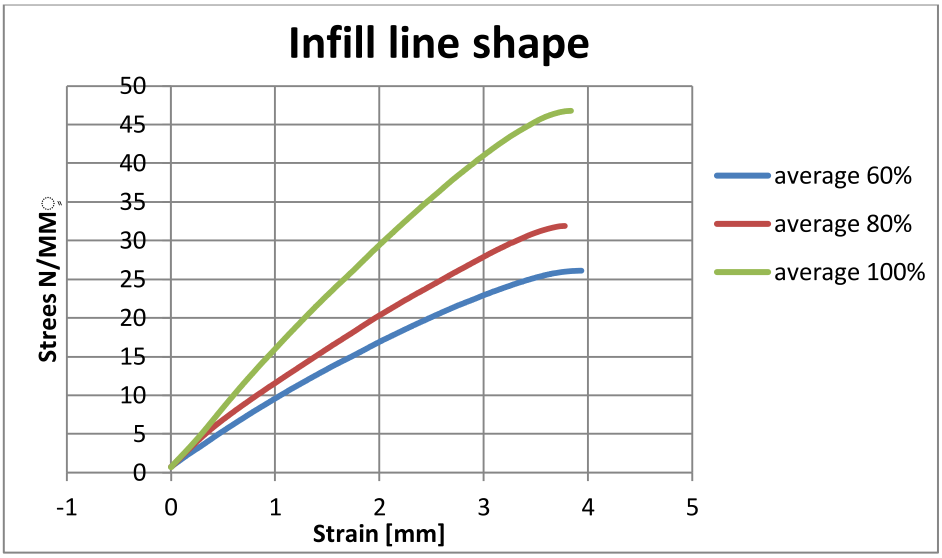

Figure 21: stress-strain curve obtained from testing line shape samples with different infill densities (100%, 80%, 60%)

Figure 21 represents the Stress-Strain plot obtained from the tensile strength testing of line shape specimens with different infill densities (100%, 80%, 60%). The following observations can be extracted:

1. infill 100% - Max Force: 1338.842 N at Strain: 3.83%
    - In the first group, specimens with a 100% infill displayed remarkable strength, with a maximum force of 1338.842 N. This substantial force resistance can be attributed to the solid internal structure with minimal voids.
2. Infill 80% - Max Force: 912.82 N at Strain: 3.77%
    - A transition to 80% infill led to a decrease in maximum force to 912.82 N. Although still strong, the reduction in infill percentage resulted in a slight decrease in mechanical strength, likely due to the presence of more voids within the specimen.
3. Infill 60% - Max Force: 747.3 N at Strain: 3.93%
    - At 60% infill, the maximum force further decreased to 747.3 N. This substantial decrease is primarily due to the significantly lower material density in the specimens, resulting in a more fragile structure.

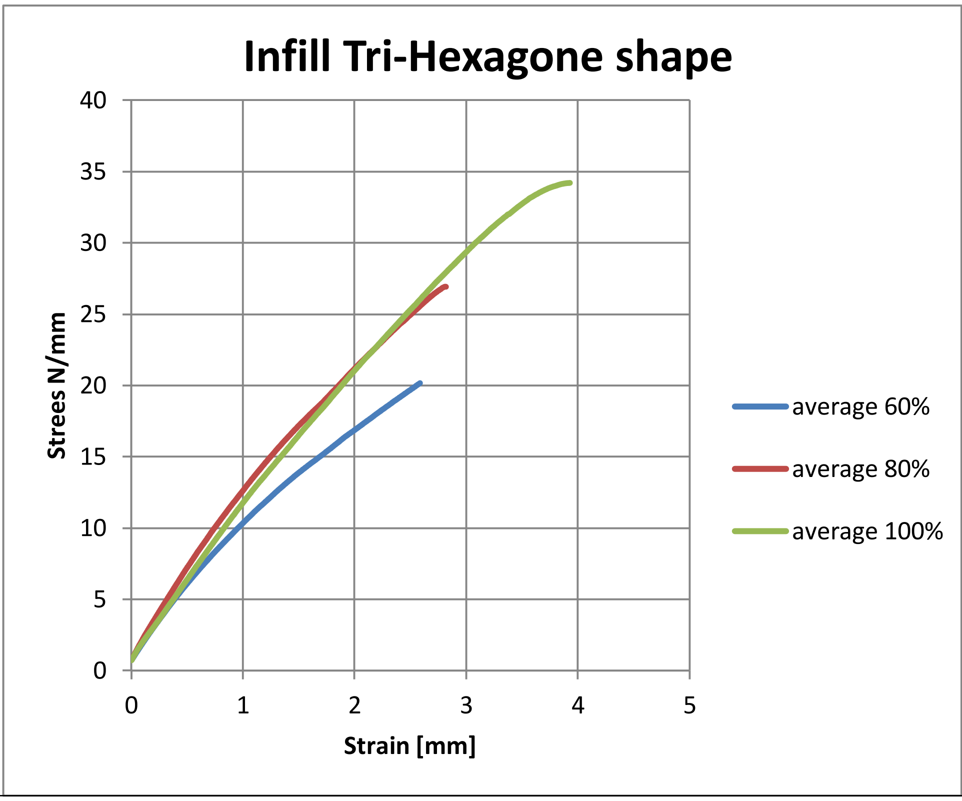

Figure 22: stress-strain curve obtained from testing line shape samples with different infill densities (100%, 80%, 60%)

Figure 22 represents the Stress-Strain plot obtained from the tensile strength testing of Tri hexagonal specimens with different infill densities (100%, 80%, 60%). The following observations can be extracted:

1. Infill 100% - Max Force: 979.109 N at Strain: 3.929%
    - In the second group of specimens with a triangular hexagonal infill pattern, the 100% infill specimens demonstrated a maximum force of 979.109 N. This force resistance is impressive and can be attributed to the dense internal structure.
2. Infill 80% - Max Force: 783.154 N at Strain: 3.1772%
    - Reducing the infill to 80% resulted in a decrease in maximum force to 783.154 N. The shift to a slightly less dense structure had an impact on strength, but the specimens remained relatively robust.
3. Infill 60% - Max Force: 735.295 N at Strain: 4.590%

- Finally, specimens with 60% infill exhibited a maximum force of 735.295 N. The most noticeable change here is the increase in strain to 4.590%, possibly due to the structural changes affecting the deformation characteristics of the material.

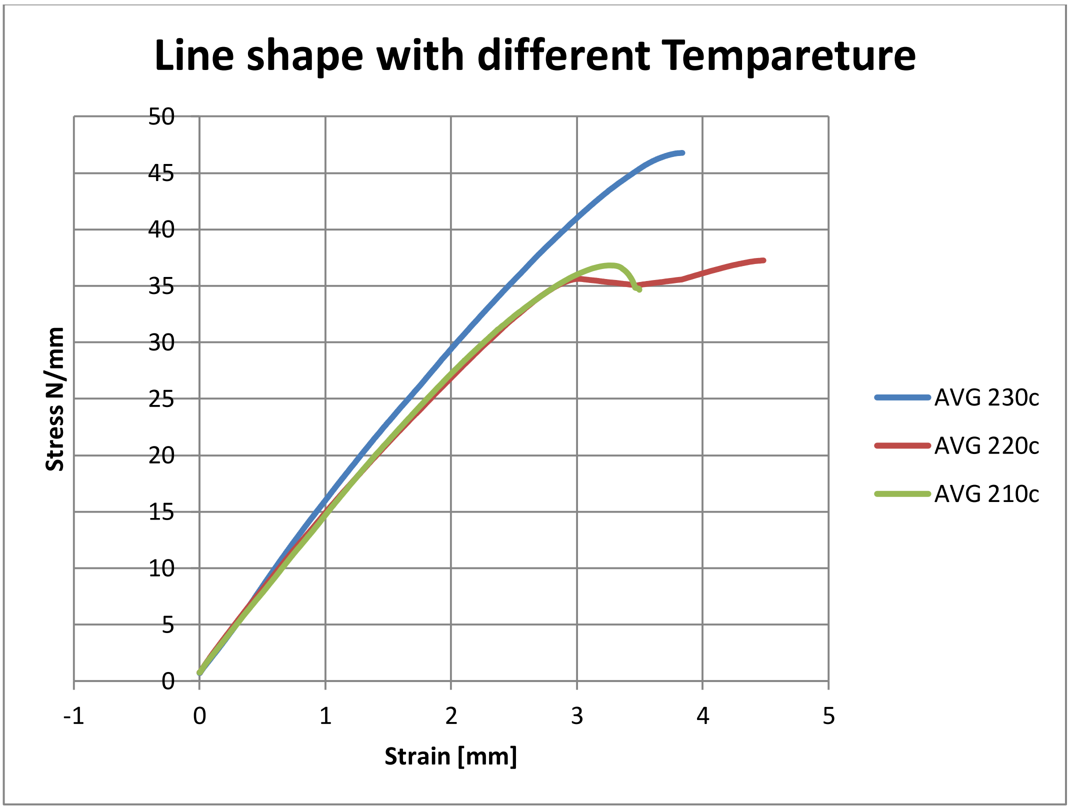

Figure 23: stress-strain curve obtained from testing line shape samples with different printing temperatures (230°C, 220°C, 210°C)

Figure 23 represents the Stress-Strain plot obtained from the tensile strength testing of line shape specimens with different printing temperatures (230°C, 220°C, 210°C). The following observations can be extracted:

1. At 230 degrees Celsius - Max Force: 1338.89 N at Strain: 3.83%

    - In this group, specimens printed at 230 degrees Celsius displayed impressive strength, with a maximum force of 1338.89 N. The elevated temperature may have allowed for better layer adhesion, resulting in higher strength.

2. At 220 degrees Celsius - Max Force: 1066.39 N at Strain: 4.48%

    - Reducing the printing temperature to 220 degrees Celsius led to a decrease in the maximum force, which was 1066.39 N. This reduction in temperature may have affected the material's ability to bond, resulting in a slightly weaker structure with higher strain.

3. At 210 degrees Celsius - Max Force: 1057.25 N at Strain: 3.49%

    - Further lowering the temperature to 210 degrees Celsius produced a maximum force of 1057.25 N. While the temperature decrease had a minimal effect on the maximum force, the specimens showed lower strain, indicating a different deformation behavior due to the altered temperature profile.

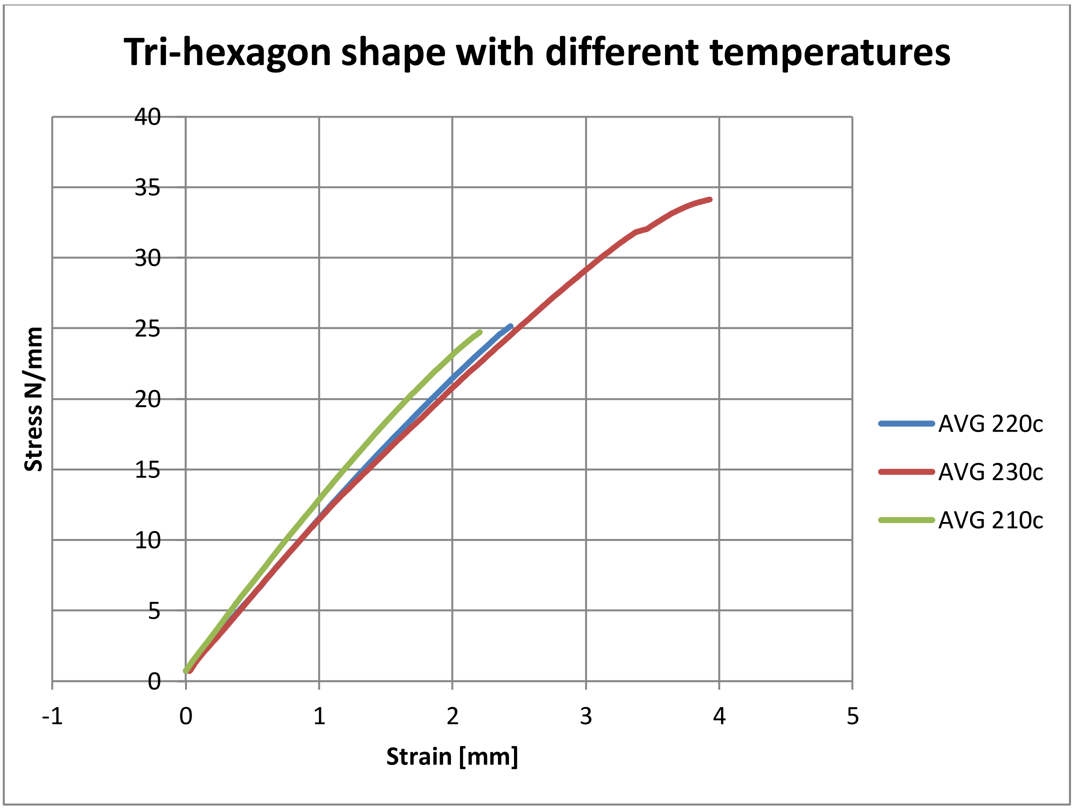

Figure 24: stress-strain curve obtained from testing Tri hexagon shape samples with different printing temperatures (230°C, 220°C, 210°C)

Figure 24 represents the Stress-Strain plot obtained from the tensile strength testing of Tri hexagonal specimens with different printing temperatures (230°C, 220°C, 210°C). The following observations can be extracted:

1. At 230 degrees Celsius - Max Force: 979.10 N at Strain: 3.92%

   - In this group, specimens printed at 230 degrees Celsius exhibited a maximum force of 979.10 N, with a corresponding strain of 3.92%. The higher temperature likely facilitated better material bonding, resulting in robust specimens.

2. At 220 degrees Celsius - Max Force: 886.9 N at Strain: 3.58%

   - Reducing the printing temperature to 220 degrees Celsius led to a decrease in the maximum force, which measured 886.9 N, while the strain was 3.58%. This reduction in temperature may have impacted the interlayer adhesion, causing a slight decrease in strength and a change in deformation behavior.

3. At 210 degrees Celsius - Max Force: 767.4 N at Strain: 2.58%

   - Further reducing the temperature to 210 degrees Celsius resulted in a maximum force of 767.4 N and a strain of 2.58%. The specimens became noticeably less robust, and the lower temperature led to a change in deformation characteristics.

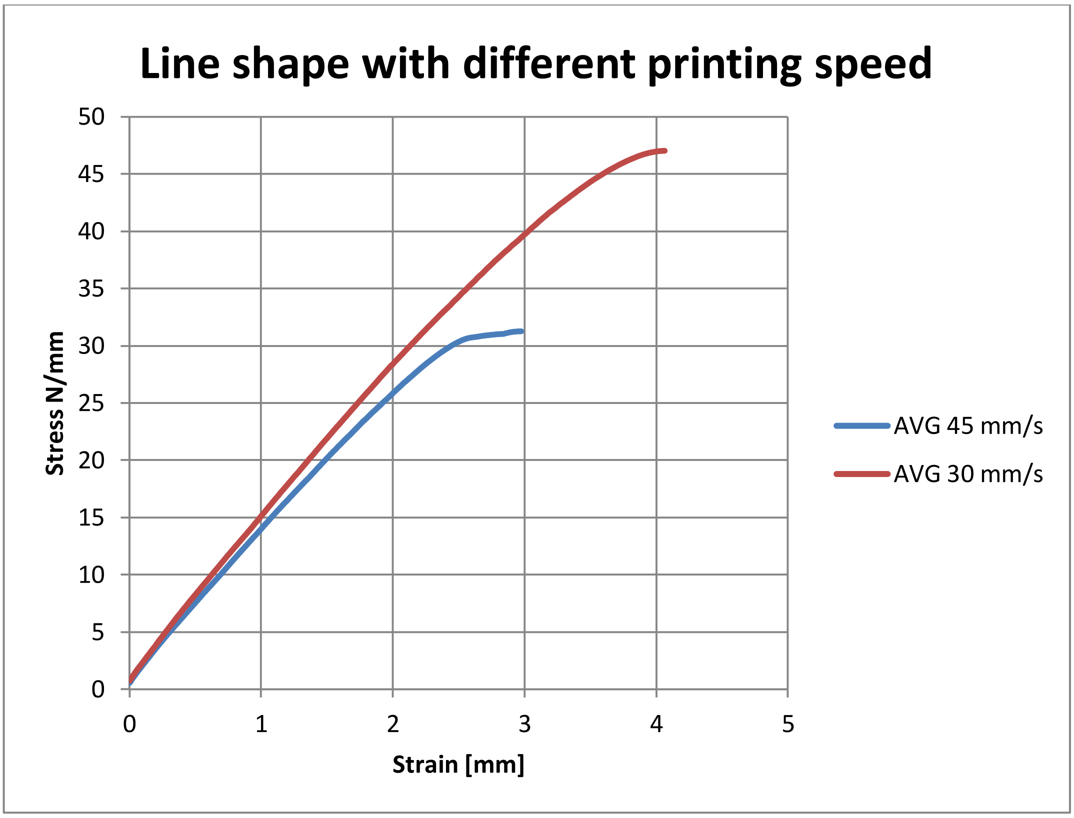

Figure 25: stress-strain curve obtained from testing line shape samples with different printing speed (45 mm/s, 30 mm/s)

Figure 25 represents the Stress-Strain plot obtained from the tensile strength testing of line shape specimens with different printing speed (45 mm/s, 30 mm/s). The following observations can be extracted:

1. At 45 mm/s speed - Max Force: 894.84 N at Strain: 2.9%
    - In this group, specimens were printed at a speed of 45 mm/s, resulting in a maximum force of 894.84 N and a strain of 2.9%. The higher printing speed led to specimens with slightly lower force resistance but a lower strain at failure.
2. At 30 mm/s speed - Max Force: 1346.1 N at Strain: 4.06%
    - Reducing the printing speed to 30 mm/s significantly increased the maximum force to 1346.1 N. The slower speed allowed for better material adhesion and bonding, resulting in stronger specimens with a slightly higher strain at failure.

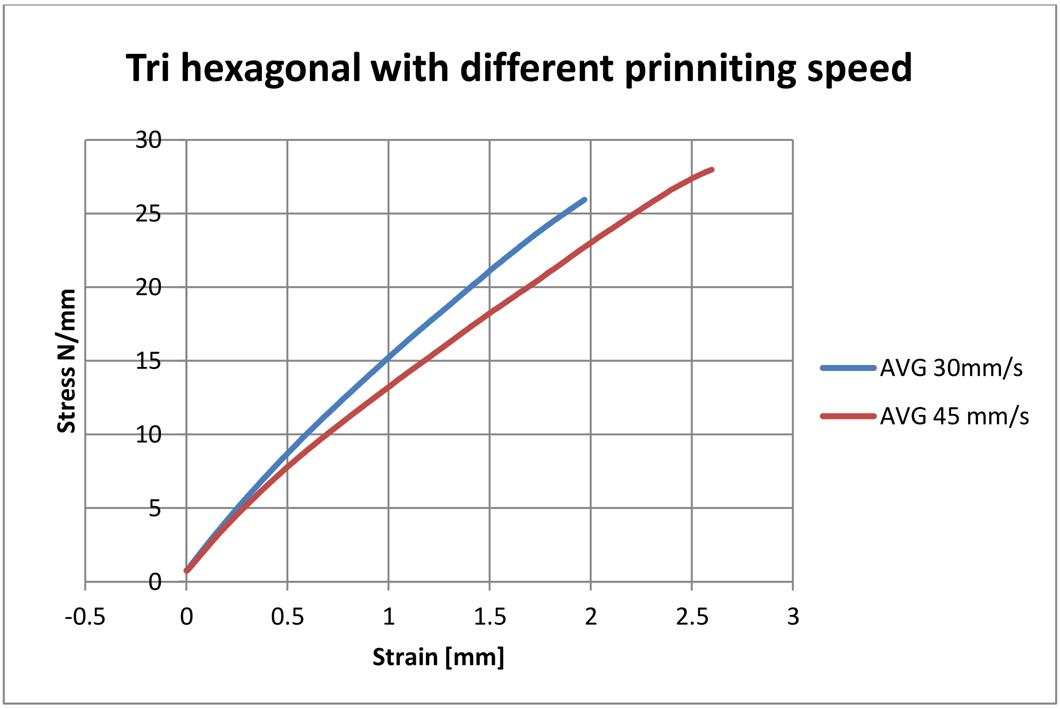

Figure 26: stress-strain curve obtained from testing Tri hexagon shape samples with different printing speed (45 mm/s, 30 mm/s)

Figure 26 represents the Stress-Strain plot obtained from the tensile strength testing of Tri hexagonal specimens with different printing speed (45 mm/s, 30 mm/s). The following observations can be extracted:

1. t 45 mm/s speed - Max Force: 942.52 N at Strain: 3.74%
   - In this group, specimens were printed at a speed of 45 mm/s, resulting in a maximum force of 942.52 N and a strain of 3.74%. The higher printing speed produced specimens with a specific force and strain profile.
2. At 30 mm/s speed - Max Force: 1024.021 N at Strain: 3.37%
   - Reducing the printing speed to 30 mm/s resulted in an increased maximum force of 1024.021 N and a strain of 3.37%. The slower speed allowed for a stronger bonding of material layers, leading to increased force resistance with a different strain response.

The tables 5, 6, and 7 provide a comprehensive overview of the results obtained for both specimen shapes under different infill densities, printing temperatures, and printing speeds.

Table 5: Results obtained for both specimen shapes under different infill densities

Specimen Shape	Parameter	100% infill	80% infill	60% infill
Line	Max Force (N)	1338.842	912.82	747.3
	Strain (%)	3.83%	3.77%	3.93%
Tri-Hexagonal	Max Force (N)	979.109	783.154	735.295
	Strain (%)	3.929%	3.1772%	4.590%

Specimen Shape	Parameter	230°C	220°C	210°C
Line	Max Force (N)	1338.89	1066.39	1057.25
	Strain (%)	3.83%	4.48%	3.49%
Tri-Hexagonal	Max Force (N)	979.10	886.9	767.4
	Strain (%)	3.92%	3.58%	2.58%

Table 6: results obtained for both specimen shapes under different printing temperatures

Table 7: results obtained for both specimen shapes under different printing speeds

Specimen Shape	Parameter	45 mm/s	30 mm/s
Line	Max Force (N)	894.84	1346.1
	Strain (%)	2.9%	4.06%
Tri-Hexagonal	Max Force (N)	942.52	1024.021
	Strain (%)	3.74%	3.37%

CONCLUSION

In this study, we conducted a comparative analysis of tensile test results for two different specimen shapes, line and tri-hexagonal, with a focus on infill density, printing temperature, and printing speed. Our findings offer valuable insights into the impact of these parameters on the mechanical properties of 3D printed specimens.

I. Infill Density

For both line and tri-hexagonal specimen shapes, the infill density played a significant role in determining the mechanical strength. In general, a higher infill density led to stronger specimens. The 100% infill specimens exhibited impressive maximum forces, with 1338.842 N for the line shape and 979.109 N for the tri-hexagonal shape. This increased strength was attributed to the dense internal structure with minimal voids.

As the infill density decreased to 80% and 60%, a corresponding reduction in maximum force was observed in both specimen shapes. The specimens with 80% infill still retained considerable strength, although with a slight decrease, while the 60% infill specimens showed a more noticeable decrease in maximum force. Additionally, the change in infill density influenced the strain at failure, with higher infill densities generally resulting in lower strains.

II. Printing Temperature

The printing temperature had a noticeable effect on the mechanical properties of the specimens. For both line and tri-hexagonal shapes, a higher printing temperature (230 degrees Celsius) yielded stronger specimens, with maximum forces of 1338.89 N and 979.10 N, respectively. The elevated temperature likely promoted better material bonding, resulting in robust specimens.

Reducing the printing temperature to 220 degrees Celsius and further to 210 degrees Celsius led to a decrease in maximum force in both specimen shapes. The lower temperature appeared to affect the interlayer adhesion, resulting in a slight decrease in strength and changes in deformation behavior.

III. Printing Speed

The printing speed also played a significant role in the tensile properties of the specimens. In general, reducing the printing speed from 45 mm/s to 30 mm/s resulted in stronger specimens for both line and tri-hexagonal shapes. The specimens printed at 30 mm/s displayed increased maximum forces, indicating that the slower speed allowed for better material layer bonding and enhanced force resistance.

Moreover, the change in printing speed influenced the strain at failure. Slower printing speeds were associated with different strain responses, with 30 mm/s specimens often exhibiting slightly higher strains at failure than their 45 mm/s counterparts.

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