THESIS

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Mechanical Engineering (BSc)

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2023

Hungarian University of Agriculture and Life Science
Szent István Campus
Mechanical Engineering (BSc)

THESIS TI

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Summary

In summary, Additive manufacturing or 3D printing involves creating a three-dimensional object from a digital model. This technology has diverse applications in fields like architecture, industrial design, and medical industries. 3D printing involves depositing, combining, or solidifying materials under computer control to create objects layer by layer. While it offers design flexibility, its mechanical properties are limited compared to traditional production methods. To address this, the study examines the material response properties of fused deposition modeling (FDM) structures and explores factors influencing their mechanical properties and dimensional accuracy. The paper compares the maximum tensile stress of different standard samples with theoretical tensile stress of PETG material to investigate the impact of shape on maximum tensile stress of PETG. The results showed that standard sample shape influenced the maximum tensile stress of PETG, with ISO 527-2-1AB having the maximum tension value and ISO 527-2-1B the lowest tensile stress. The differences in standard specimens used in tensile testing can affect the mechanical properties of PETG due to variations in dimensional, manufacturing, and testing conditions. Therefore, it is essential to carefully control these factors to ensure accurate and consistent test results.

Sandwich structures offer a combination of high strength, low weight, energy absorption, thermal insulation, sound damping, and customization options, making them an excellent choice for a variety of applications.

Strain rate: The tensile test involves applying a load to the specimen at a constant rate. If the specimen is of a different size, the rate of deformation may differ, resulting in different strain rates. The strain rate affects the deformation behavior and mechanical properties of the material.

Stress concentration: The dimensions of the specimen can affect the distribution of stress within the material. A smaller specimen may have higher stress concentrations at the ends, leading to localized yielding or failure.

Material heterogeneity: PETG, like most polymers, is a heterogeneous material with variations in properties at the microscopic level. The mechanical properties of the material can depend on the orientation and distribution of the polymer chains, which can vary with the specimen size and shape.

Edge effects: The edges of the specimen can affect the stress distribution and deformation behavior of the material. For example, a specimen with rough edges may have higher stress concentrations, leading to premature failure.

Specimen preparation: The preparation of the specimen can affect its properties. Different cutting methods or surface treatments may introduce stress concentrations or alter the surface roughness, affecting the mechanical properties of the material.

Overall, the differences in mechanical properties observed with different dimensional standard specimens are likely due to a combination of these factors. To obtain consistent and reliable results, it is important to carefully control the specimen dimensions, preparation, and testing conditions.

INSTITUTE OF TECHNOLOGY MECHANICAL ENGINEERING (BSc)
Machine Production Technology specialization

THESIS

worksheet for

Mahmoud Sobhy Elagha (CKEIW5)

(BSc) student

Entitled:

Designing the 3D printing of a part

Task description:

The aim of this research is to compare the maximum tensile stress of different standard specimens with the theoretical tensile stress of the PETG material and investigate how the shape affects the maximum tensile stress of PETG. The tensile test data reveal that the shape of the standard specimen affects the maximum tensile stress of PETG.

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Submission deadline: 03.05.2023

Gödöllő, 20.01.2023

Approved **Received**

(Head of department) (Host course leader) (Student)

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

Gödöllő, 02.05.2023

(Consultant)

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I recommend thesis to be defended in a final exam.

The document contains state secrets or professional secrets: yes **no***[1]

Place and date: Gödöllő, Hungary. 02.05.2023

Dr. Szakál Zoltán

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[1] Please underline applicable.

DECLARATION

on authenticity and public assess of <u>thesis</u>

Student's name: Mahmoud Sobhy Elagha

Student's Neptun ID: CKEIW5

Title of the document: Designing the 3D printing of a part

Year of publication: 2023

Department: Institute of Technology

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HUNGARIAN UNIVERSITY OF AGRICULTURE AND LIFE SCIENCES,
INSTITUTE OF TECHNOLOGY

THESIS

Designing the 3D printing of a part

Mechanical Engineering (BSc), Diploma Work
(SGMMGD001BN)

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Gödöllő, Hungary
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ABSTRACT

3D printing, or additive manufacturing, is a process that constructs 3D objects from digital models by depositing, combining, or solidifying materials in a layer-by-layer approach under computer control. Despite its high design flexibility, its mechanical properties are still limited when compared to traditional production methods. To address this issue, various approaches have been proposed to estimate and enhance the mechanical properties of additive manufactured structures.

This study focuses on the material response properties of fused deposition modeling (FDM) in 3D printing. The study conducts a comparative analysis of four different samples of polymers using tensile tests based on ASTM D3039 and ISO 527-2 standards. To evaluate the effects of the chosen chopping parameters on the position of failures in the samples, the geometries of the samples are studied using calculations based on the finite element method (FEM).

The aim of this research is to compare the maximum tensile stress of different standard specimens with the theoretical tensile stress of the PETG material and investigate how the shape affects the maximum tensile stress of PETG. The tensile test data reveal that the shape of the standard specimen affects the maximum tensile stress of PETG, with ISO 527-2-1AB exhibiting the maximum value of stress and ISO 527-2-1B having the lowest tensile stress among the specimens evaluated. The data from the tensile tests suggest that the shape of the specimen affects the maximum tensile strength of PETG to varying degrees. This finding highlights the influence of the shape of the specimen on the mechanical properties of the printed material. By comparing the mechanical properties of each standard or comparing each standard to the theoretical value of the printed material, we can observe the impact of the shape on the mechanical properties of the PETG material. To enhance the mechanical properties and dimensional accuracy of FDM parts, critical factors determining the mechanical properties and dimensional accuracy of FDM parts were explored based on the experimental results.

The research focuses on the material response properties of PETG structures created using fused deposition modeling (FDM) in 3D printing and examines the factors that can affect their mechanical properties and dimensional accuracy. The study compares the maximum tensile stress of different standard samples with theoretical tensile stress of PETG material and investigates the impact of shape on maximum tensile stress of PETG. The results show that the standard sample shape influences the maximum tensile stress of PETG, with ISO 527-2-1AB having the maximum tension value and ISO 527-2-1B the lowest tensile stress. The research highlights the various reasons why the mechanical properties of PETG may differ in tensile tests with different dimensional standard specimens, such as strain rate, stress concentration, material heterogeneity, edge effects, and specimen preparation. It emphasizes the importance of carefully controlling the specimen dimensions, preparation, and testing conditions to obtain consistent and reliable results.

TABLE OF CONTENTS

NOMENCLATURE AND ABBREVIATIONS

Notation	Description	Unit
LATIN LETTERS		
A_0	Cross-section	mm^2
b_1	Width at the narrow portion	mm
b_2	Width at ends	mm
E_0	Initial modulus of tensile elasticity	MPa
E_e	Tangent modulus	MPa
E_h	String modulus	MPa
F	Tensile force	N
F_{max}	Maximum force	N
h	Preferred thickness	mm
L	The Initial distance between grips	mm
L_0	Gauge length (preferred)	mm
l_1	Length of the narrow parallel-sided portion	mm
l_2	Distance between broad parallel-sided portions	mm
l_3	Overall length	mm
L_B	The extended length of the part at the breakage	mm
L_M	The extended length of the part at the maximum force	mm
Rh	Relative humidity	%
r	Radius	mm
r_1	Small radius	mm
r_2	Large radius	mm
T	Test temperature	°C
T_g	Glass transition temperature	°C
v	Test speed	mm/min
W_B	Fracture work	J

GREEK LETTERS		
ε	Relative strain	%
ε_B	Breaking strain	%
ε_M	Elongation at the maximum force	%
σ	Tensile stress	MPa
σ_B	Breaking strength	MPa
σ_X	Stress at x% elongation	MPa
σ_Y	Yield stress	MPa

ABBREVIATIONS		
3D printing	Three-dimensional printing	
ABS	Acrylonitrile Butadiene Styrene	
AM	Additive manufacturing	
ASTM	American Society for Testing and Materials	
CAD	Computer-aided design	
DED	Directed Energy Deposition	
DLP	Digital light processing	
DOD	Drop On Demand	
EBM	Electron Beam Machining	
FDM	Fused Deposition Modelling	
FFF	Fused filament fabrication	
ISO	International Organization for Standardization	
LCD	Liquid Crystal Display	
PET	Polyethylene terephthalate	
PETG	Polyethylene terephthalate glycol	
SLA	Stereolithography	
SLM	Selective Laser Melting	
SLS	Selective Laser Sintering	
STL	Surface Tessellation Language	

1 INTRODUCTION

1.1 3D PRINTING

3D printing is an additive manufacturing technology that creates physical objects from a digital design by building them layer-by-layer. It has many applications, including rapid prototyping, product manufacturing, and custom fabrication. The process involves slicing a 3D model into thin layers, then depositing material layer by layer, often using melted plastic or metal. 3D printing has revolutionized many industries, from healthcare to aerospace, and has the potential to transform the way we design, create, and consume products.

3D printing is a manufacturing technology used to build 3D structures and objects. It falls under additive manufacturing (AM) techniques, as opposed to subtractive manufacturing methods such as CNC milling. The final object is created using 3D printing by adding layers of material on top of each other, while subtraction techniques remove material to "sculpt" an object.(Ali et al., 2022)

In the 1980s, 3D printing technologies were only considered suitable to produce functional or aesthetic prototypes, and the more appropriate term for them at the time was rapid prototyping. As of 2019, the accuracy, repeatability, and material range of 3D printing have increased so much that some 3D printing processes are considered viable as an industrial production technology, where the term additive manufacturing can be used synonymously with 3D printing.

One of the main advantages of 3D printing is the ability to produce overly complex shapes or geometries that would have been impossible to build by hand, including hollow parts or parts with internal truss structures to reduce weight. Fused deposition modeling (FDM), which uses continuous filaments of a thermoplastic material, is the most popular 3D printing process in use as of 2020.(Kopec et al., 2023)

A 3D printer makes things by depositing materials on a printing bed (also called a build platform) following the instructions from a special 3D file, which is often in an STL format. The material, typically fused thermoplastics for FFF and FDM 3D printers, is deposited layer by layer. Each layer is very thin and hardens quickly, thus forming a 3D object when layers are added. Nearly most 3D printers use plastic filament spools as consumables.(Duda and Raghavan, 2016)

1.2 MAIN 3D PRINTING TECHNOLOGIES

There are many types of 3D printing technologies that are currently available commercially or in early development. Each additive manufacturing technique requires a specific type of 3D printing material, ranging from plastic filament (PLA, ABS...) to photosensitive resin and powdery materials (metal, plastic, etc.). Each 3D printing technology has its advantages and limitations and can be used in specific applications and use cases.(Mateti et al., 2023)

1.2.1 These are three main categories of 3D printing technologies:

a. Extrusion (FFF, FDM, ...): plastic filaments are melted and deposited on the 3D printer building platform to form a layer-by-layer object.

b. Photopolymerization (SLA, DLP, MSLA, ...): The laser or liquid light projector processes the photosensitive resin directly inside the tank of the 3D printer.

c. Powder (SLS, SLM, DMLS, …): A laser sinters or melts powdered material layer by layer.

Eliminating many of the limitations of traditional manufacturing techniques, 3D printers are a great tool for rapid prototyping, and it is one of the most common uses of 3D printing. Advanced industrial-grade 3D printing systems are also used for the direct manufacturing of finished products. The advent of 3D printing is significantly impacting manufacturing and design processes in many industries.(Roberson and Sinha, 2022)

1.2.1.1 FDM (Fused Deposition Modeling) and FFF (Fused Filament Fabrication)

The most commonly used 3D-printing technology is known as FDM (Fused Deposition Modeling) or FFF (Fused Filament Fabrication), also referred to as extrusion. This process involves heating and melting a filament made of thermoplastic, typically PLA or ABS, and then feeding it through a thin nozzle in the 3D printer's print head.

The printer deposits the molten filament in layers, building the object one layer at a time. The final object's accuracy and quality depend on factors such as the 3D printer's minimum layer thickness, with thinner layers resulting in higher accuracy. This technology is compatible with a wide range of plastic filaments, particularly PLA or ABS. The print head either moves horizontally in X and Y while the print bed moves vertically in Z, or the print head moves vertically while the print bed moves horizontally.("Evaluation of 3D printing process of testing samples using DLP and FDM techniques.pdf," n.d.)

1.2.1.2 FFF (Fused filament fabrication)

Fused filament fabrication (FFF) is a type of 3D printing technology that uses a continuous filament of thermoplastic material, which is melted and extruded through a nozzle in a controlled manner to create a three-dimensional object. FFF is also known as fused deposition modeling (FDM), which is a trademarked term by Stratasys, the company that originally developed the technology.(Kalas et al., 2021)

In FFF 3D printing, the printer heats the filament and extrudes it layer by layer onto a build platform, where it cools and solidifies into the desired shape. The printer typically moves the extruder along the X, Y, and Z axes to create the object layer by layer.

FFF is a widely used 3D printing technology and is popular due to its relatively low cost and ease of use. It is commonly used in the production of prototypes, models, and functional parts in various industries, including aerospace, automotive, and medical. The materials used in FFF range from basic plastics like PLA and ABS to more advanced materials such as nylon and carbon fiber composites.("Guidance on the use of existing ASTM polymer testing standards for ABS parts fabricated using FFF.pdf," n.d.)

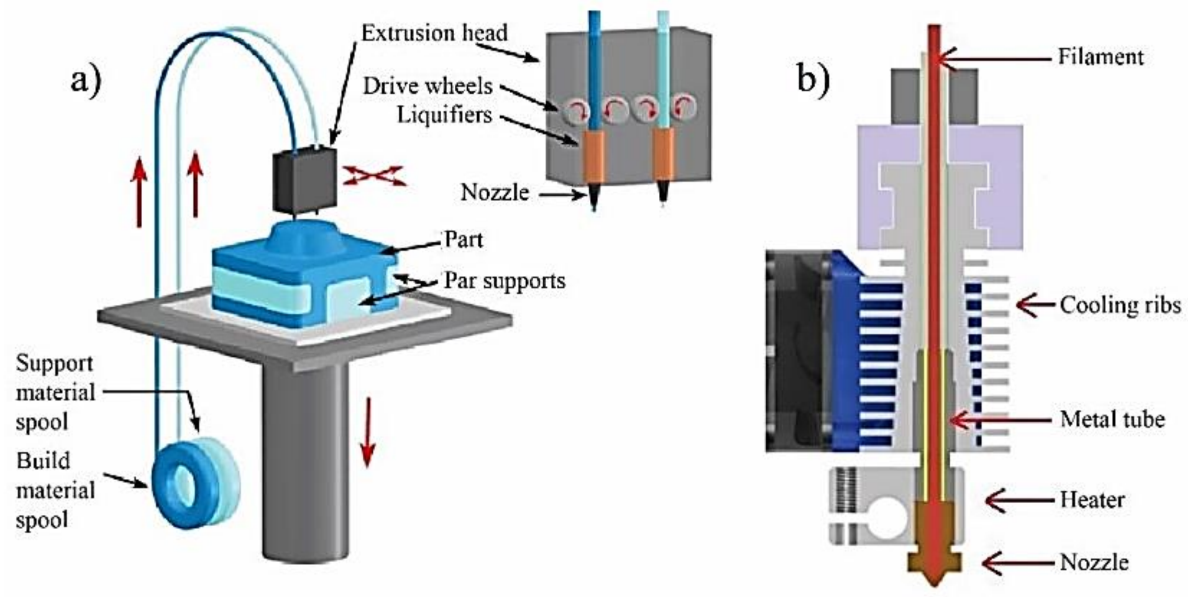


Figure 1: Fused Filament Fabrication (FFF), a) Basic parts. b) Parts of the hot end.(Dhal, 2018)

1.2.1.3 Directed Energy Deposition (DED)

Directed Energy Deposition (DED) is a type of additive manufacturing process that uses a focused energy source, such as a laser or an electron beam, to melt and fuse material as it is deposited layer-by-layer to create a three-dimensional object. DED is capable of producing parts from a wide range of materials, including metals, plastics, ceramics, and composites. This technique is often used in the aerospace, automotive, and medical industries, as well as in research and development applications. One of the advantages of DED is its ability to produce large and complex parts with high precision and accuracy. It also allows for the production of customized parts with unique geometries and features that are difficult or impossible to achieve using traditional manufacturing techniques.

There are several variations of DED, including laser-based powder bed fusion, laser metal deposition, and electron beam melting, each of which has its own strengths and limitations. DED is still a relatively new technology, and research and development efforts are ongoing to improve its efficiency, accuracy, and versatility.

Direct Energy Deposition (DED), also referred to as Directed Energy Deposition, is an advanced form of 3D printing utilized by a select few industrial 3D printer manufacturers. It is categorized as an "extrusion" technique because the printing material is gradually pushed towards a high-powered energy source, such as a laser or electron beam, resulting in direct melting and fusion. A typical DED 3D printer comprises a nozzle attached to a multi-axis arm with up to 5 axes, which deposits melted material onto a surface where it solidifies. This process is similar to material extrusion, but the nozzle can move in various directions and is not limited to a specific axis. Once deposited, the material is melted by a laser or electron beam. Direct energy deposition 3D printing can be used with polymers or ceramics, but it is primarily utilized with metal powders or wire feedstock. This 3D printing technology is commonly applied to repair or augment existing components or parts by adding additional material.("Evaluation of 3D printing process of testing samples using DLP and FDM techniques.pdf," n.d.)

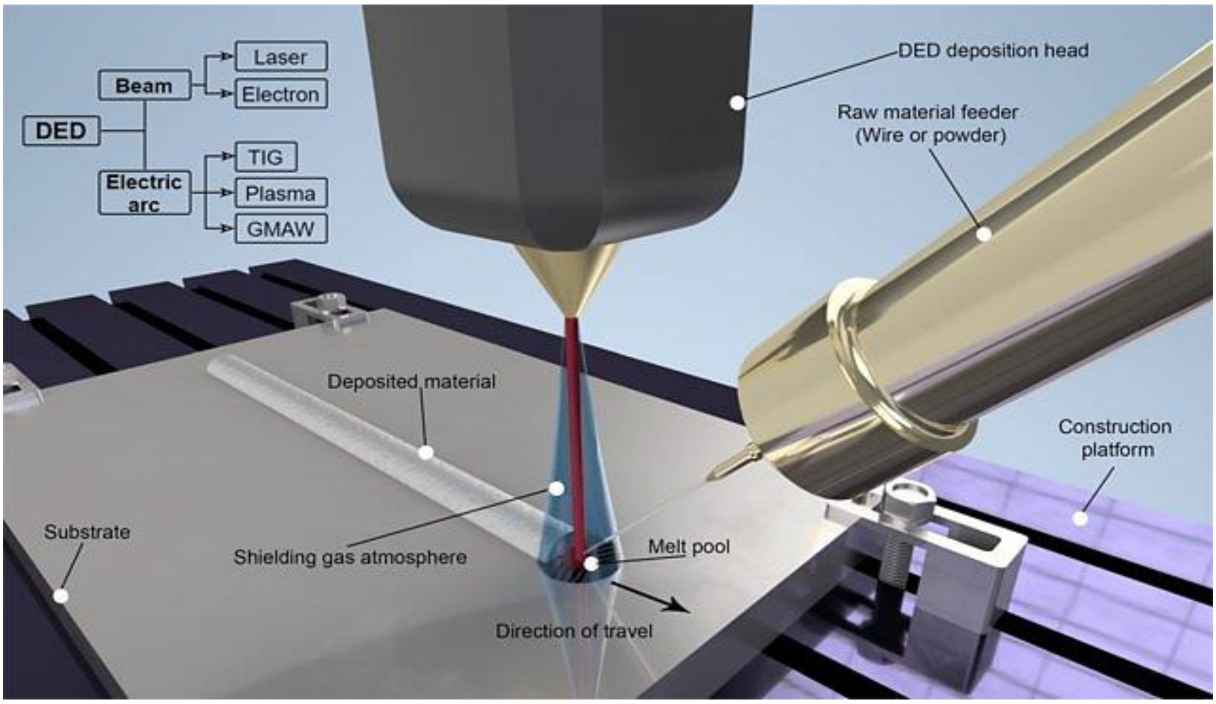


Figure 2: Illustration of the directed energy deposition (DED) process.(Dávila et al., 2020)

1.2.2 Photopolymerization and resin 3D printing: SLA and DLP

Resin 3D printers utilize the photopolymerization process, in which the resin stored in the printer's tank is cured by a laser or light source. The 3D printing resins used are light-sensitive photopolymers that solidify upon exposure to specific light beams. The printer's build tray can move either from top to bottom or vice versa, while the resin is cured layer by layer using the laser or light. Laser stereolithography solidifies the resin point by point, whereas light-projector-based printers can solidify entire layers simultaneously. Resin-based technologies are ideal for printing objects with high levels of detail and a smooth surface finish, making them commonly used in jewelry or dental applications to create molds for casting. Although they generally offer smaller build volumes than FFF printers, some large resin 3D printers are available.("Evaluation of 3D printing process of testing samples using DLP and FDM techniques.pdf," n.d.)

1.2.2.1.1 Stereolithography (SLA)

This process of additive manufacturing employs a laser beam to project ultraviolet light that helps in the solidification of a liquid resin. The resin tank, or vat, is loaded with a photo-sensitive liquid resin, commonly referred to as photopolymer resin. A UV laser beam is used to trace the shape of the 3D design in the resin tank, and it solidifies the curable resin to create the final object with high accuracy, point by point, and layer by layer.(Zhang et al., 2022)

1.2.2.1.2 DLP 3D printers (Digital Light Processing)

Digital Light Processing (DLP) is a 3D printing technology in which a digital light projector is the UV light source. The projector's resolution will determine the 3D printing resolution. DLP

3D printers offer a superior print speed because the light is projected onto an entire layer at once (versus point-by-point a laser).

1.2.2.1.3 LCD 3D printers (or MSLA, Masked Stereolithography)

MSLA or LCD resin 3D printers use an LCD screen as a photomask– like a stencil– above another light source (LED, UV…). Similarly, to DLP 3D printers, MSLA printers can solidify entire layers at a time.

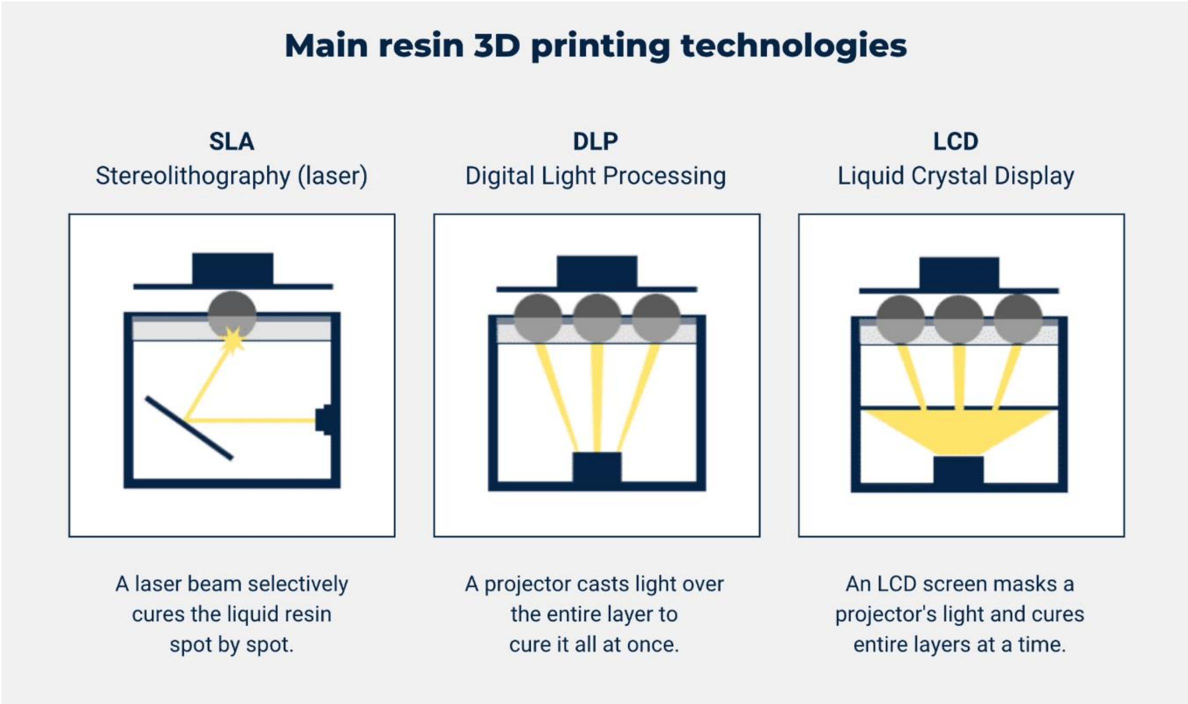


Figure 3: SLA 3D printer, DPL 3D printer, and LCD 3D printer.("Best resin 3D printers in 2023 - SLA, DLP, LCD," n.d.)

1.2.2.1.4 SLA vs DLP: resin 3D printing technologies comparison

The main difference between SLA and DLP is that in DLP, the resin is cured layer by layer, as the UV light is emitted by a projector, whereas in SLA, the object is formed dot by dot by the laser.

SLA can be more accurate than DLP but is also a potentially slower 3D printing process. Lasers are also more costly and difficult to maintain versus projectors or LCD screens which can be easily found and at a relatively low price.

1.2.2.2 Powder bed fusion: SLS, SLM, and EBM

Powder-based 3D printing is a popular method that utilizes materials such as metal powders as consumables. This method is mainly executed through two key technologies known as SLS (Selective Laser Sintering) and SLM (Selective Laser Melting). It is widely utilized in the industrial sector for 3D printing with metal, catering to different categories of industrial applications.

1.2.2.2.1 SLS 3D printers (Selective Laser Sintering)

Selective laser sintering 3D printing technology utilizes a laser beam to melt and bond powdered material (such as plastic, ceramic, or metal) together, creating a solid object. The printer's print bed is filled with the powder, and the laser follows the design pattern in the 3D printer software to build the object layer by layer. The print bed is lowered after each layer is completed, allowing for the addition of the next layer on top of the previous one. This process is similar to creating a small sandbox in the printer, with each layer adding to the final product.

1.2.2.2.2 SLM 3D printers (Selective Laser Melting*)*

SLM and SLS are similar, but SLM involves melting the powder rather than sintering it. SLM 3D printers use a powerful laser to fuse the particles together, resulting in a solid object. This method is commonly used in the aerospace and medical industries to create end-use metal parts, although plastic SLS 3D printers for office use are available. Additionally, dental SLM 3D printers are increasingly popular for producing metal dental appliances like crowns and implants.

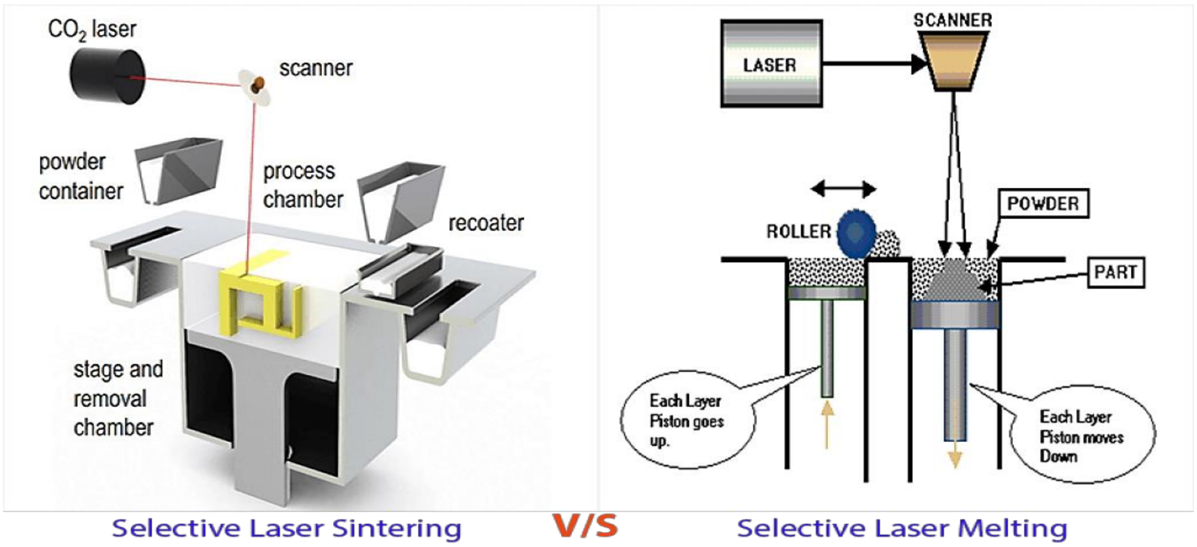


Figure 4: SLS 3D printer & SLM 3D printer.(Team, 2021)

1.2.2.2.3 EBM additive manufacturing (Electron Beam Melting)

The EBM 3D printing technique shares similarities with SLM additive manufacturing technology. Both rely on the energy generated by an external source to solidify powdered materials, typically metals or alloys, into 3D structures. However, the key difference is that EBM employs an electron beam to melt the material, while SLS utilizes sintering to fuse the particles together. As a result, EBM printers can create fully dense and complex objects with greater precision and control.(Muammel M Hanon et al., 2021)

1.2.3 Other powder 3D printing technologies (DMLS, SLM, SHS, LM, …)

Powder-based 3D printers are primarily utilized for industrial purposes, such as the rapid prototyping and direct manufacturing of various parts. Along with the aforementioned technologies, Laser Sintering, Laser Melting, Selective Heat Sintering, Direct Metal Laser Sintering, and Plaster-based 3D Printing are also available. However, the primary distinction between these advanced manufacturing technologies lies in how the powder material is melted.

EBM, EBAM, and SLM utilize a complete melting process, while SLS and LS rely on fusing powder grains. Some of the compatible 3D printing materials for SLS or SLM include titanium alloys, ceramic powders, thermoplastics, and metals, making powder-based 3D printers essential in industries such as Aerospace that require highly-resistant metal parts.(Fafenrot et al., 2019)

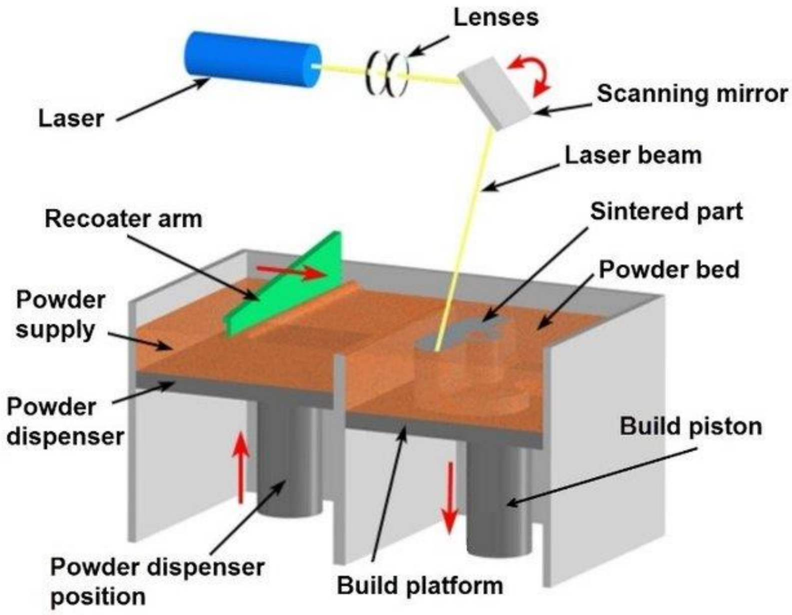


Figure 5: A schematic diagram of the direct metal laser sintering (DMLS) process.(Marrey et al., 2019)

1.2.3.1.1 Material jetting (MJM, BJ, PJ…)

Material Jetting, also referred to as MultiJet Modeling (MJM), Drop on Demand (DOD), or Thermo-Jet/Inkjet printing, is a 3D printing technology that involves the use of inkjet print heads to deposit melted material onto the build platform of the 3D printer. The material then solidifies and cools to form a 3D object layer by layer, resulting in high-quality prints and exceptional surface finishes.(Barile and Casavola, 2019)

1.2.3.1.2 Photopolymer Jetting (Poly-Jet or PJ)

Photopolymer Jetting 3D printing involves spraying a light-sensitive liquid photopolymer material onto the print bed using print heads. This material is solidified directly by a UV lamp that is connected to the print head, resulting in the formation of a solid object. Stratasys utilizes this additive manufacturing technique with their Poly-Jet 3D printing technology, which is proprietary to their company.

1.2.3.1.3 Binder Jetting (BJ)

Powdered material is bound together using a liquid bonding agent that is jetted onto it, resulting in the creation of the final object. Material jetting is the category that both Photopolymer Jetting (PJ) and Binder Jetting (BJ) fall under.

1.2.3.2 Sheet lamination

The process of creating intricate and vivid 3D objects through lamination 3D printing involves the utilization of thin sheets of material such as aluminum foil or paper. These sheets are cut based on the 3D design of the desired object using advanced tools like lasers or sharp blades. Each layer is then covered with adhesive and fused together one layer at a time, just like other methods of additive manufacturing. The level of precision achieved is primarily dependent on the thickness of the material used. Paper is a popular choice due to its affordability and ease of use. Lamination 3D printing is also referred to as Laminated Object Manufacturing (LOM) and Sheet Lamination (SL).(Jawaid et al., 2019a)

1.2.3.3 3D Bioprinting

3D bioprinting is an emerging technology that combines the principles of 3D printing with the field of tissue engineering to create functional biological tissues. It involves the layer-by-layer deposition of living cells, biomaterials, and growth factors to create a 3D structure that mimics the architecture and function of native tissues and organs.

The process of 3D bioprinting typically involves three main steps:

1. Designing a 3D model of the tissue or organ using computer-aided design (CAD) software,
2. Selecting and preparing the appropriate cells and biomaterials, and
3. Printing the 3D structure using a specialized bioprinter.(Prabhakar et al., 2021)

3D bioprinting has the potential to revolutionize the field of regenerative medicine by providing a way to create patient-specific tissues and organs for transplantation, drug testing, and disease modeling. It could also be used to create replacement tissues and organs for patients with organ failure, reducing the need for donor organs and the risk of rejection.("3D printed microfluidics and potential Biomedical Applications.pdf," n.d.) However, 3D bioprinting is still in its early stages, and there are many technical and ethical challenges that need to be overcome before it can be widely used in clinical applications.

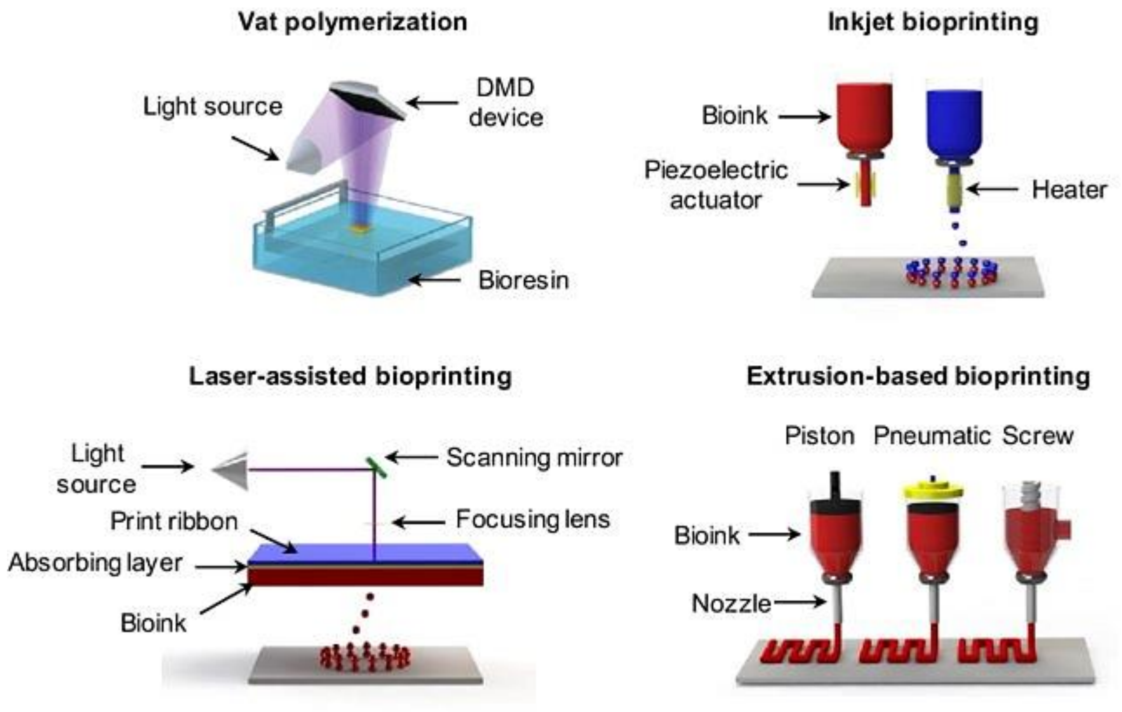


Figure 6: 3D Bioprinting Technology.(Vyas et al., 2020)

2 LITERATURE SURVEY

2.1 FDM PRINTING METHOD

Fused deposition modeling, or FDM, is a 3D printing technique that constructs models by depositing plastic filaments layer by layer through a nozzle. FDM can be used to create a wide range of designs, from simple cans and fixtures to complex geometric shapes. The technology was created and patented by Stratasys, a leading company in the additive manufacturing industry. (Stojcetovic, 2022)

FDM works by using a heated extrusion head to melt a thermoplastic filament, which is then deposited layer by layer onto a build platform. The filament diameter and feed rate are kept stable to ensure a continuous material flow. As shown in Figure 8, the filament only melts in the nozzle, allowing incoming solid material to provide the pressure needed for printing. The extrusion head moves in the x-y directions during layer deposition, and the build platform moves down in the z-direction after each layer is complete, allowing for the next layer to be deposited on top of the previous layers.(Jawaid et al., 2019b)

2.1.1 How Does FDM Work?

To start the FDM printing process, the design is first inputted into the computer of the printer. The computer runs a computer-aided design (CAD) software program that breaks down the construction into various cross-sectional layers. Next, the nozzles within the printer begin to distribute heated plastic filaments onto the building platform to form each section of the part. The design platform is lowered after each layer is completed, allowing the nozzles to create the next layer on top of the previous one.

Supports are needed for any overhanging parts in the structure due to the nature of heated plastic. These supports are added by the nozzles in the printer and removed during post-processing. Once the FDM build is finished, the surface of the part is rough, so to enhance its appearance, the manufacturers sand it to make it smoother. Painting or applying metallic paint are also available as finishing options. The process is repeated, layer by layer, until the desired part is fully built.(Mateti et al., 2023)

2.1.1.1 Advantages of FDM

- This 3D printing process offers versatility in material selection, making it compatible with a broad range of materials and providing greater flexibility in manufacturing.
- With its ability to print both small and large builds quickly, this 3D printing method is highly scalable, making it an ideal choice for projects of varying sizes.
- FDM technology provides a cost-effective solution for creating parts, as the filaments used in this method are comparatively low-cost when compared to materials used in other additive manufacturing techniques.
- Unlike supports used in other 3D printing techniques, the water-soluble filament used in FDM technology makes the support structures easier to remove, offering a more convenient and efficient post-processing experience.("Fused Deposition Modeling - an overview | ScienceDirect Topics," n.d.)

2.1.1.2 Disadvantages of FDM

- Support Structures Needed: Using FDM requires additional material, time, and post-processing compared to methods like selective laser sintering (SLS).
- Surface Roughness: Post-processing is necessary to smoothen the rough surface of FDM printed parts.
- Inconsistent Quality: FDM parts possess anisotropic mechanical properties, making them susceptible to deformation under specific circumstances.
- Lower Print Resolution: FDM produces parts with inferior resolution than printing techniques such as SLA.("Fused Deposition Modeling - an overview | ScienceDirect Topics," n.d.)

To achieve high-quality prints, it is crucial to have strong adhesion between the build plate and the first layers (table 1). This can be accomplished through the use of a heated and/or coated build plate. Additionally, proper cohesion between layers is necessary to ensure the mechanical properties of the final product are not weakened, and that layer delamination does not occur. This can be achieved by carefully controlling temperature and pressure. If necessary, FDM technology can be used to print support structures for features like holes and undercuts. Typically, these support structures are lightweight and made from the same material as the product. Alternatively, a dual extrusion head can be used to print support structures using a secondary material. While support structures are typically removed manually in commercial FDM machines, industrial-grade machines can use water-soluble materials for easier removal.(Stojcetovic, 2022)

Table 1: Factory Printing recommendations("69f7b8617de023a54dbc1f151cf8b584_PET-G műszaki adatlap.pdf," n.d.)

Recommended print settings	Recommended range
Extruder temperature	230 ± 15 °C
Table temperature	85 ± 5 °C
Print speed	40 ± 10 mm/sec
Fan power	30 – 50 %: better surface quality 0 %: better strength

2.1.2 Description and parameters of PETG Filament

- Diameter size: 1.75 mm
- Product Family: PET-G
- Filament color: grey
- RAL code: 7042

2.1.2.1 Features:

- odorless low shrinkage rate
- hydrophobic ability (does not absorb water)
- outstanding mechanical properties

- good liquidity
- excellent elasticity, high mechanical power
- very transparent, good light recyclable
- Recommended printing temperature: 230 to 250 °C.
- Table heating max. 70 - 90 °C.

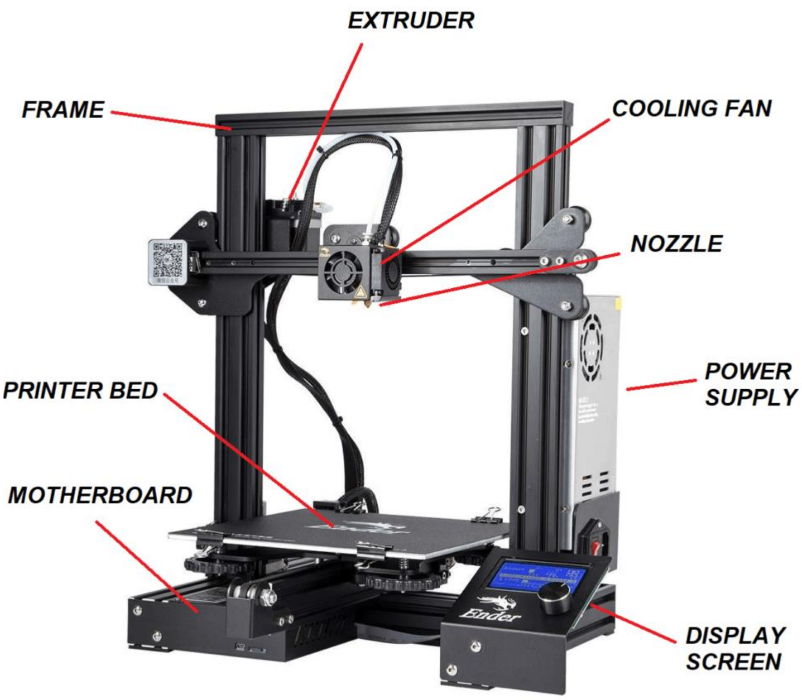


Figure 7: FDM 3D Printer.(Murugesan, n.d.)

2.1.3 Applications

FDM technology is used for the following application areas:

- Develop preliminary product concepts using FDM models to cut costs and expedite timelines.
- Prototype functional models for real-world testing to inform manufacturing decisions and minimize costs.
- Fabricate end-use parts with FDM technology to incorporate into final products without the need for traditional tools or machines.
- Produce manufacturing tools, including jigs, fixtures, and production tools, in a matter of hours with FDM technology, reducing lead time by up to 85%.

The workspace design of machines is a key factor in determining their capabilities. Machines with a heated workspace are capable of processing a broad range of raw materials, including technical materials, whereas those without can only handle low-shrinkage materials. These machines offer several benefits, such as excellent value for money, quiet operation, and the ability to work with a wide variety of materials, such as PLA, ABS, PC, PMMA, and PEEK.

However, there are some drawbacks to this technology, including lower accuracy, a visible layer-by-layer appearance, and the need for post-processing, such as surface treatment or the removal of support materials.("Sliding surface structure comparison of 3D_printed polymers using FDM and DLP technologies.pdf," n.d.)

2.2 MATERIALS

2.2.1 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.(Bhandari et al., 2019)

2.2.1.1 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.(Soleyman et al., 2022)

2.2.1.2 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), 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.(Valvez et al., 2022a)

2.2.1.3 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.(Hong and Wang, 2023)

2.2.1.4 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.

2.2.1.5 Advantages and Disadvantages of PET

2.2.1.5.1 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).(Zhou et al., 2021)

2.2.1.6 *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).(Zhou et al., 2021)

2.2.1.7 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.(Jawaid et al., 2019c)

2.2.2 PETG

PETG stands for Polyethylene Terephthalate Glycol. It is a thermoplastic polyester that is commonly used in 3D printing, as well as in a variety of other applications, such as food packaging, medical devices, and signage. PETG is known for its strength, clarity, and resistance to impact and chemicals. It is also easy to print with and can be used for both functional and aesthetic parts. PETG is a popular alternative to other filaments like PLA and ABS due to its unique properties.

2.2.2.1 History of PET and PETG

In 1941, two British scientists, John Whinfield and James Dickson, combined PET and PETG using esterification to heat glycols with terephthalic acid. This resulted in a long-chain molecule of PET that could be transformed into fibers with high dissolubility and melting point. The material quickly became mainstream in the textile industry by 1946, and by 1952, it was being used in the food packaging industry. PET was even being used to manufacture carbonated drinks, alcohol, mineral water, and beer bottles by 1976. However, due to its high crystallization temperatures and opacity, demand grew for a more robust material. PETG was then created, replacing ethylene glycol in the molecular chain with a larger monomer, cyclohexane dim ethanol, which stopped the crystallization associated with PET. This new material flooded the market and was readily accepted by manufacturers for its toughness and excellent mechanical and chemical properties. Its low-molding temperature also makes it highly compatible with applications requiring deep cuts, die cuts, and precise molding, as well as having good bonding properties with solvents or adhesives. The versatile properties of PETG make it suitable for manufacturing techniques such as bending, drilling, thermoforming, die-cutting, 3D printing, routing, and other heat-forming fabricating methods.(Kannan et al., 2020)

2.2.2.2 How is PETG Made?

PETG represents a significant improvement over the original polymer PET. The development of this successor involved introducing ethylene glycol into the molecular chain along with a larger monomer, which is then blended with cyclohexane dim ethanol. This addition plays a crucial role in preventing the crystallization of PET. The production of PETG utilizes a straightforward two-step melt-phase process, which involves combining two monomers and a small amount of water. One of the key advantages of PETG is its superior heat resistance when compared to PET. This increased resistance helps to lower the melting point and inhibit crystallization.(Jindal, 2022)

2.2.2.3 Key Properties of PETG

- Polyethylene terephthalate glycol, being a copolymer, possesses a unique combination of properties derived from PET and glycol. This blend also effectively addresses the overheating issues associated with PET, making it a desirable material for various applications.
- With its fast-thermoforming cycle and brake formability up to 0.080" thickness, drying is not necessary before processing this material in thermoforming. Additionally, it is cost-effective compared to other thermoplastics such as polycarbonate and polyethylene.
- The material boasts excellent impact resistance, comparable to mainstream thermoplastics, and is less brittle than acrylic. It also exhibits fantastic chemical resistance, equivalent to other thermoplastics.
- However, to avoid warping during ABS 3D printing, a heating plate is required. Polyethylene terephthalate glycol is more susceptible to scratches than PLA, and it is advisable to store it in a dry and cool environment due to its poor moisture resistance.
- Overall, the material has good thermal stability, making extrusion an effortless process. It is also easily processed through injection molding and 3D printing.(Malyadri et al., 2022)

2.2.2.4 Advantages & Disadvantages

2.2.2.4.1 Advantages

- Food Safe and Recyclable: PETG filament is safe to use in food containers and beverage bottles. It is also fully recyclable, significantly reducing the adverse effects on the environment and increasing its chances of adoption as environmental safety is one of the top priorities.

- Easy Coloring: PETG plastic is easily colorable to achieve the desired appearance. It is also naturally transparent, which improves its overall applications.
- Strong as well as cost-effective: PETG's strength and excellent impact resistance make it ideal for glazing applications and high-end displays. That quality also makes it suitable for 3D printing applications like rapid prototypes and signages.
- Meagre Damaging: polyethylene terephthalate glycol provides great damage resistance that can even compete with polycarbonate, a more popular and mainstream material; however, it is also smooth and easy to fabricate, making it ideal for both practitioners and professionals.
- Non-Toxic and Odorless: It's non-toxic and almost odor-free, making it more comfortable to process in any location.(Szykiedans et al., 2017)

2.2.2.4.2 Disadvantages

- No Inaccuracies with Parameters: Accurate parameters are necessary with every thermoplastic, but for PETG, the necessity moves one notch. While 3D printing PETG, it is advised to use the correct temperatures. Following the attributes set by the material manufacturer and supplier would be the best option. Typically, a cold base is used with temperatures – 210-260 ºC extruder and 60-80 ºC base. For achieving optimum results with 3D printing, a slow printing speed is recommended (30 – 35 mm/s)
- Susceptible to Oozing: Polyethylene terephthalate glycol is more susceptible to oozing than ABS or PLA. That means it can create some inefficiencies in 3D printing. Changing certain setting changes with bridging and retraction should be made to reduce oozing. They can also come in handy for post-processing works like removing blemishes.
- Brittleness: PETG material inevitably absorbs water, which makes it brittle. To tackle that, it should be stored in a dry environment.
- Environmental Problems: Although PETG is recyclable, if not disposed of correctly, it can harm the environment as, like all other plastics, it does not decompose for hundreds of years. That can leave microplastics in landfills in the ocean.

2.2.2.5 PETG Applications

There are several products made from PETG. Because of the versatility, PETG is truly a powerful general-use plastic. It is especially prominent in industrial settings. But there are some simple commercial applications as well. Here are some of the most popular.

2.2.2.5.1 Medical Applications

PETG's inflexible composition enables it to withstand the demanding sterilization process, rendering it well-suited for the creation of medical implants and packaging materials used in various medical devices and pharmaceutical products.(Prabhakar et al., 2021)

Figure 8: PETG Medical Sterile Packaging.("Toling Corporation (M) Sdn Bhd | PETG (Polyethylene terephthalate Glycol-modified)," n.d.)

2.2.2.5.2 Beverage Containers

PETG is commonly utilized to manufacture water, soda, cooking oils, and food and beverage storage containers that comply with FDA regulations, due to its exceptional chemical resistance. Additionally, its lightweight property reduces transportation costs for businesses, making it an even more appealing option for such applications.(Singh et al., 2022)

Figure 9: PETG water tumbler.("Toling Corporation (M) Sdn Bhd | PETG (Polyethylene terephthalate Glycol-modified)," n.d.)

2.2.2.5.3 Machine Protection

PETG is a top-rated material utilized in the production of machine guards and protective gear due to its exceptional properties, such as easy formability, durability, and transparency, which ensure a prolonged lifespan. Moreover, these guards are frequently employed in the food processing sector and are recognized for their superior quality when compared to polycarbonate.

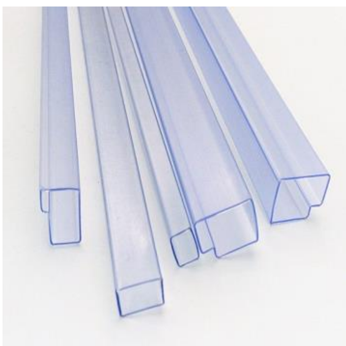


Figure 10: PETG IT Tube.("Toling Corporation (M) Sdn Bhd | PETG (Polyethylene terephthalate Glycol-modified)," n.d.)

2.2.2.5.4 Displays

PETG material is extensively utilized for stands and displays in various retail settings, including malls, restaurants, and other establishments. Its exceptional coloring and shaping features make it an excellent choice for signage applications.(Singh et al., 2022)

Figure 11: PETG Refrigerator Boxes.("Toling Corporation (M) Sdn Bhd | PETG (Polyethylene terephthalate Glycol-modified)," n.d.)

2.2.2.5.5 3D Printing Prototypes

I always leave the best for the end, and in this case, it is rapid prototyping. PETG is currently the most extensive and fastest-growing application, thanks to its incredible printability and exceptional layer adhesion. It is not only odorless, chemical-resistant, and tough, but it also has lower shrinkage rates in prints compared to other primary 3D printing materials. However, to prevent bed adhesion issues, it is essential to use a cooling fan and an additional build plate while printing with PETG.

2.2.2.6 Is PETG Plastic Toxic?

While solid PETG resin is not toxic, inhaling its vapors can lead to serious health issues, which are released during heating. As a precaution, operators should wear protective gear and face masks during production. When it comes to environmental impact, traditional plastics can take decades to decompose in landfills. However, PETG's easy recyclability mitigates some of the damage as the polymer chains can be broken down into their original components. These components can then be repurposed as raw materials for the production of new polymers. This is fantastic news for the environment as it reduces the need for natural resources and helps to combat water and land pollution. The production of new plastics requires a significant amount of time, resources, and water, while recycling plastic reduces these burdens.(Bremer et al., 2022)

2.2.2.7 What is the Future of PETG Material?

The future of PETG material looks promising as it is expected to grow at a CAGR of 5.7% from 2020 to 2027, according to a report by Grand View Research. The increasing demand for sustainable packaging solutions, the growth of the automotive and construction industries, and the rise in demand for medical devices are some of the key factors driving the growth of the PETG market. The future of PETG material looks bright as it continues to find new applications in various industries and the demand for sustainable packaging solutions and 3D printing materials continue to grow. (Prabhakar et al., 2021)

3 EXPERIMENTAL METHOD

3.1 TENSILE TEST

A crucial material science and engineering test is tension testing, where a sample is exposed to controlled tension until it breaks. The test yields essential data, such as ultimate tensile strength, breaking strength, maximum elongation, and reduction in area. Additional properties, including Young's modulus, Poisson's ratio, yield strength, and strain-hardening characteristics, can be calculated from the measurements obtained.(Rahman and Zhafer Firdaus Syed Putra, 2019)

3.1.1 Different Tensile tests

The main difference between these testing machines is how the load is applied to the materials.

3.1.1.1 The Strip Method (AS2001.2.3.1)

The Strip Method involves taking a 50mm x 200mm sample of the fabric and securing the entire width of the material in the testing machine's clamps. The fabric is then stretched at a steady pace of 100mm per minute until it breaks, and the highest force and extension at the point of rupture are measured in Newtons per 50mm (N/50mm). These measurements are dependent on the fabric's gauge length, which is set at 200mm, and the material's break elongation rate, which falls between 8% and 75%.

3.1.1.2 The Grab Method (AS2001.2.3.2)

The Grab Method involves taking a fabric sample that is approximately 100mm long and 100mm wide. The center part of the sample is then clamped in the testing machine, and the fabric is stretched at a constant rate of 50mm/min until it breaks. The maximum force required to rupture the fabric is measured in Newtons (N).

It is essential to note that the results obtained from each method can differ significantly. The primary reason for this variation is the effective width of the fabric being extended. With the strip method, the effective width is limited to the cut width of the sample (in this case, 50mm). On the other hand, the Grab Method includes the part of the sample held by the jaws and a proportional effect of the sample overhanging the jaws. It is, therefore, crucial to specify the method used when reporting results.(Rahman and Zhafer Firdaus Syed Putra, 2019)

3.1.2 Aim of the Tensile test

The objective of conducting tensile tests is to guarantee the consistency and reliability of the outcomes. The test typically involves applying a particular load until the specimen fractures or fails, and therefore necessitates the utilization of specimens with uncomplicated shapes that can be produced with precision. In this regard, for polymer materials, rectangular specimens are commonly utilized, while circular cross-sections are frequently employed for metals.

3.1.2.1 Theoretical background

During a tensile test, a specimen with standardized dimensions is firmly held at both ends and gradually stretched at a constant rate under controlled conditions such as tensile speed, temperature, and moisture content. The resulting force required to elongate the specimen is measured and recorded in relation to the degree of stretching, until the specimen reaches its breaking point. Based on the specimen's geometry, specific material properties can be calculated and utilized in designing complexly-shaped polymer components. (Ergene and BOLAT, 2022)

3.1.3 Mechanical characteristics determined from tensile tests.

During the tensile test, the force is measured continuously and recorded until the specimen ruptures, which is typically indicated by a sudden decrease in force. To calculate the elongation of the specimen, the displacement recorded by the tensile machine can be used, but a more accurate result is obtained by using two parallel markings in the middle of the specimen and continuously measuring and recording the change with a probe, strain gauge, or optically.(Subbarao et al., 2021)

The result of the tensile test is the force-elongation (F-Δl) curve of the material under given measurement conditions (temperature, humidity, measurement speed). In practical applications, it is usually more important to know specific material properties. To do this, the tensile curve can be parameterized to a stress-relative strain (σ-ε) curve, where stress σ [MPa] is obtained by dividing the force F [N] by the initial cross-section of the specimen A_0 [mm^2] and plotted on the stress axis.

$$\sigma = \frac{F}{A_0} \text{ [MPa]} \quad (1)$$

The tensile stress [MPa] expresses the force [N] exerted on a cross-section of 1 mm^2 of a specimen with a normal vector equal to the tensile direction.

Relative strain $\boldsymbol{\varepsilon}$ is the ratio of the strain of the specimen *Δl* [mm] and the initial measurement length $\boldsymbol{L_0}$ [mm]:

$$\varepsilon = \frac{\Delta l}{l_0} \cdot 100 \text{ [\%]} \quad (2)$$

The degree of relative elongation is commonly indicated either in percentage form (e.g., 5%) or as a dimensionless quantity (e.g., 0.05), denoting precisely how much longer the sample has become at the time of measurement compared to its unloaded state.

The tensile strength (σ_M) refers to the engineering stress observed at the first local peak in the tensile curve. This value can coincide with either the yield stress or the breaking strength.

Breaking strength (σ_B) represents the ratio of the force measured right before the specimen ruptures (i.e., breaks apart) to its initial cross-sectional area.

Yield stress (σ_Y) is defined as the stress level at which elongation of the material starts to increase without a corresponding rise in stress. For metallic structural materials, this is typically a well-defined boundary, separating elastic behavior below the yield stress from plastic deformation above it. However, for polymers exhibiting viscoelastic behavior, deformation may persist even at lower stress levels, and in some cases, the concept of yield stress may not be applicable. Other materials may experience multiple yield strains of over 100%, accompanied by the formation of a neck in the specimen and changes in its internal structure.

In certain polymer materials, stress whitening can provide a visual indication of the onset of yield.(Vamshinath et al., 2022a)

For softer, rubber-like materials, the allowable level of deformation often dictates their practical use. In such cases, the stress value at a predetermined elongation percentage (e.g., σ_{50} = 20 MPa at 50%) may be of greater significance.

Deformation indices can also be determined using a stress-relative elongation diagram. The most important of these is $\boldsymbol{\varepsilon_M}$ elongation at the maximum force:

$$\varepsilon_M = \frac{L_M - L_0}{L_0} \cdot 100\ [\%] \quad (3)$$

where $\boldsymbol{L_0}$ is the initial, unloaded length of the examined part of the specimen, and $\boldsymbol{L_M}$ is the extended length of the examined part of the specimen at the maximum force.

$\boldsymbol{\varepsilon_B}$ breaking strain:

$$\varepsilon_B = \frac{L_B - L_0}{L_0} \cdot 100\ [\%] \quad (4)$$

L_B is the length that the specimen extends when it breaks, and the tensile curve provides insight into the material's behavior. Materials with high elongation at break are tough, while those with low elongation at break are brittle. The steepness of the curve at the beginning indicates the material's stiffness, while low slopes indicate softness.

The tensile modulus of elasticity is a critical technical feature that expresses the slope of the tensile curve and the material's elongation response to a specific force load. In some cases, high stiffness is necessary, while in others, high deformation with minimal forces is desired.

The tensile modulus ($\boldsymbol{E}$) can be determined in various ways from the curve σ(ε), and the flexural modulus of elasticity is similarly interpreted. The initial modulus of tensile elasticity ($\boldsymbol{E_0}$) is obtained by drawing a tangent slope to the stress-relative elongation curve at its origin. However, even a slight deviation from the exact tangent will result in a significant inaccuracy in the tensile elastic modulus value, making this method impractical.(Hanon et al., 2020)

$$E_0 = \frac{\sigma_0}{\varepsilon_0}\ [MPa] \quad (5)$$

String modulus $\boldsymbol{E_h}$: the slope of a straight line connecting any two points of the curve (but typically chosen in the initial section). According to the relevant standard, the slope of the line passing through the curve points corresponding to the relative elongation values of 0,05% and 0,25% must be determined, i.e., the general

$$E_h = \frac{\sigma_2 - \sigma_1}{\varepsilon_2 - \varepsilon_1}\ [MPa] \quad (6)$$

the values measured between $\sigma_2 = \sigma_{0,0025}$ and $\sigma_1 = \sigma_{0,0005}$ substituted, and the value of the expression, in this case, is 0.002. In one case of string modulus, when the line's slope connecting the desired point of the curve with the origin is determined, this, of course, varies from point to point.(Valvez et al., 2022b)

Tangent modulus $\boldsymbol{E_e}$: the slope of the tangent drawn to any point on the curve. Since the tensile curve is usually not linear even in the initial stage (unlike its metals), the slope of its tangent also changes from point to point.

Fracture work $\boldsymbol{W_B}$: The area under the tensile curve $F(\Delta l)$ is the fracture work:

$$W_B = \int_0^{\Delta l} F \cdot dl \ [J] \tag{7}$$

Brittle materials have a lower breaking work, while tough materials have a higher breaking work. The modulus of elasticity and fracture work tend to have an inverse relationship. However, since most mechanical applications require both high toughness and high modulus of elasticity, designers must compromise and select materials that are optimized for the given structure.

In the calculation of stresses, actual force is divided by the initial cross-section to obtain apparent or engineering stresses. During elongation, the cross-section of the specimen decreases, and dividing the instantaneous force by the instantaneous cross-section provides real stress. The instantaneous cross-section ($\boldsymbol{A_p}$) can be approximated by applying the principle of volume retention, as demonstrated by the following equation.(“The Quantitative Research of Interaction between Key parameters and the effects on Mechanical property in FDM.pdf,” n.d.)

$$A_0 \cdot L_0 = A_P \cdot L_P \ \rightarrow \ A_P = \frac{A_0 \cdot L_0}{L_P} = \frac{A_0 \cdot L_0}{L_0 + \Delta l_P} \tag{8}$$

where $\boldsymbol{A_0}$ is the initial cross-section, $\boldsymbol{L_0}$ is the initial measurement length, $\boldsymbol{L_p}$ is the instantaneous length of the initial measurement length $\boldsymbol{L_0}$,

$$L_P = L_0 + \Delta l_P \tag{9}$$

$\boldsymbol{\Delta l_p}$ is the instantaneous elongation of the initial measurement length read from the force-elongation curve. This calculation method can only be used until the tensile test of the specimen is constant until the density is constant and the cross-section of the specimen decreases equally along its length, i.e., from the onset of local contraction or the neck formation The relationship also neglects the change in cross-section at both ends of the dogbone shaped specimen.

3.1.4 Effect of measurement Conditions

3.1.4.1 Test speed

The testing speed for metals or polymer matrix composites typically averages 3 mm/min, while for thermoplastic polymers or elastomers, the rates can be much higher due to the possibility of hundreds of percent relative elongation. ISO 527 has established a specified test speed value. When materials (polymers) with viscoelastic properties are tested at higher tensile rates, they tend to exhibit a stiffer and more brittle behavior, which usually leads to higher strength. This occurrence is due to the fact that, at high test rates, long polymer molecules are unable to settle in the direction of drawing within a sufficient amount of time.(Ergene and BOLAT, 2022)

3.1.4.2 Test temperature

Polymers are highly sensitive to even slight temperature changes, which can have a significant impact on their stiffness, strength, and failure behavior. One key characteristic of polymers is their glass transition temperature (T_g), below which they behave like a glass, with low deformability and a nearly linear stress-strain relationship due to rigid molecular chains and limited micro-Brownian motion. As the temperature rises above Tg, the polymer chains begin to move and reconfigure, becoming more flexible and tougher due to the increased segmental movement and random or continuous changes in their spatial structure.(Ergene et al., 2023)

3.1.4.3 Moisture Content

Hydrophilic polymers, such as polyamides, polyesters, natural polymers, and specific fiber-reinforced composites, can take in moisture up to 1-5% of their weight, which can alter their properties. This effect is due to the plasticizing nature of moisture, which causes a decrease in the modulus of elasticity, while the elongation at break increases.

3.1.4.4 Grips and Fixtures

When conducting polymer tensile testing, it is essential to consider the type of grips utilized to hold specimens. These grips should not introduce any flaws or tears as such imperfections could become a starting point for failure. Any failure outside of the gauge length zone would invalidate the test. Specialized grips are also necessary for testing films and tapes since they can break at relatively low forces. For low-strength films and tapes, rubber or flat metal grip faces are suitable. (Vamshinath et al., 2022b) It is important to select the appropriate grip or fixture for your specific polymer sample to ensure accurate and reliable test results. The choice of grip or fixture will depend on the sample's size, shape, and mechanical properties.

Here are some common grips and fixtures used for polymer tensile tests:

- Wedge grips: These grips are designed to hold flat samples and are commonly used for testing thin films and sheets of polymer. They have serrated jaws that grip the sample and prevent it from slipping during testing.
- Threaded grips: These grips are designed for testing thicker samples and have threaded jaws that can be adjusted to accommodate different sample thicknesses. They are commonly used for testing polymers in the form of rods or tubes.
- Pneumatic grips: These grips use compressed air to hold the sample in place during testing. They are ideal for testing brittle or fragile polymer samples that may crack or break under the pressure of other grips.
- Mechanical grips: These grips use a mechanical clamping mechanism to hold the sample in place during testing. They are versatile and can be used for testing a wide range of polymer samples.
- Bending fixtures: These fixtures are used to test the flexural strength of polymer samples. They typically consist of two supports that hold the sample in place and apply a bending load to it.

4 MATERIALS AND METHOD.

4.1 THE PRINTING METHOD I USED (FDM).

Fused Deposition Modeling (FDM) is a popular 3D printing method that creates objects layer by layer by melting and extruding thermoplastic filament through a nozzle. The process begins with a 3D model being created in CAD software and then sliced into layers. The 3D printer reads these layers and then starts to deposit the material layer by layer until the object is complete. The extruded filament is melted and then solidifies almost instantly, creating a solid object.

FDM printing is relatively inexpensive compared to other 3D printing methods, making it an accessible technology for home and small business use. It is also widely used in prototyping, product development, and low-volume production. FDM printers can use a variety of materials such as ABS, PLA, PETG, nylon, and TPU.(Kohn et al., 2021)

One of the main advantages of FDM printing is the ability to create complex geometries and internal structures. However, the printing resolution and surface finish can be limited by the nozzle size and layer height. Additionally, FDM printed parts may have visible layer lines and may not be as strong as parts printed using other methods.

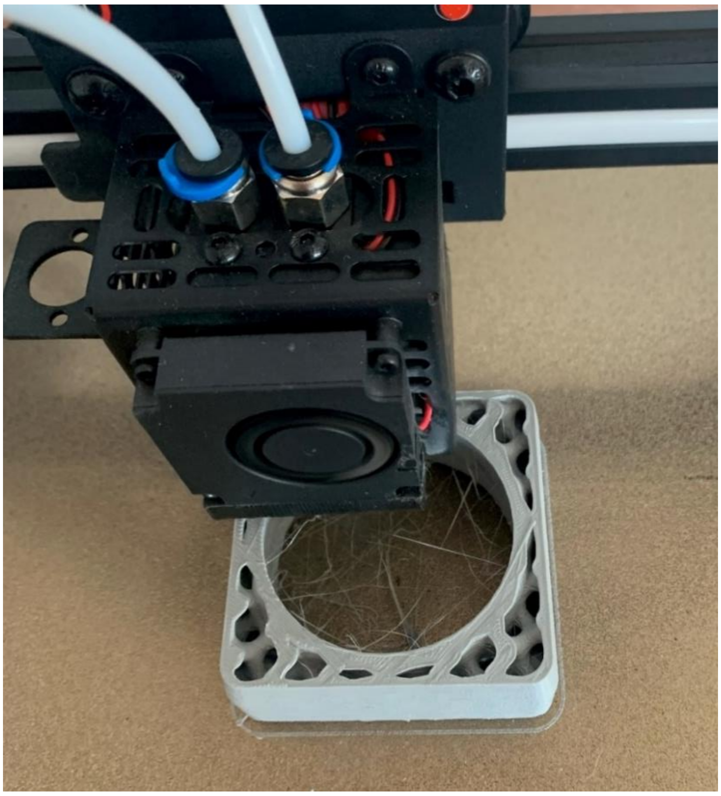


Figure 12: Fused Deposition Modeling (FDM).

4.1.1 Printing parameters

I used Ultimaker Cura software to set up the printing parameter and to convert the printing File to G-code so that the printer can Read it.(“69f7b8617de023a54dbc1f151cf8b584_PET-G műszaki adatlap.pdf,” n.d.)

Table 3: Used Printing program: Ultimaker Cura(Taqdissillah et al., 2022)

Printing Parameters			
Quality		**Material**	
Layer Height	0.2 mm	Printing temperature	230 °C
Initial layer Height	0.24 mm	Printing temperature initial layer:	230 °C
line width	0.4 mm	Initial printing temperature:	220 °C
Wall line width	0.4 mm	Final printing temperature:	215 °C
Infill line width	0.4 mm	Build Plate Temperature	85 °C
Walls		**Speed**	
Outer wall extruder	Extruder 1	Print speed	60 mm/s
Wall thickness	0.8 mm	Infill speed	60 mm/s
Wall line count	1	Wall speed	30 mm/s
Horizontal Expansion	0.0 mm	Initial layer speed	30 mm/s
Infill		**Cooling**	
Infill Extruder	Extruder 1	Fan speed	40 %
Infill Density	100 %	**Build Plate Adhesion**	
Infill line Distance	0.3 mm	Build plate adhesion type	Skirt
Infill Pattern	Lines	Build plate adhesion Extruder	Extruder 1

4.1.2 Filament used in the 3D printing.

PETG (Polyethylene Terephthalate Glycol) filament is known for its excellent impact resistance, chemical resistance, and temperature resistance. It has a higher melting point than PLA, making it suitable for printing objects that will be exposed to high temperatures. PETG is also less brittle than ABS, making it less prone to cracking or breaking during printing or use. In addition to its mechanical properties, PETG filament is easy to print with and produces high-quality prints with minimal shrinkage or warping. It is also a food-safe material, making it suitable for printing items that come in contact with food.("8f1e139ae0c6c11315ff174de39402cd_PET-G nyomtatási segédlet.pdf," n.d.)

Figure 13: PETG Filament for 3D-printing.("Filanora Filatech PETG filament 1,75mm szürke," n.d.)

4.1.3 Mechanical properties of the used material

Table 4: Factory typical properties of polyethylene terephthalate glycol modified (PETG). ("69f7b8617de023a54dbc1f151cf8b584_PET-G műszaki adatlap.pdf," n.d.)

ISO		
Test	Property	Values
	PHYSICAL	
ISO 1183	Density (g/cm^3)	**1.3**
	MECHANICAL	
ISO 527	Tensile strength (MPa) = **maximum flexural stress**	**42.5 MPa**
ISO 527	Elongation at break (%):	**7.4**
ISO 527	Tensile modulus (Mpa)	**5250**
ISO 178	Bending strength (Mpa)	**70**
ISO 179	Impact strength (kJ/m^2)	**6.5**
	THERMAL	
ISO 75	Heat resistance temperature HDT (°C) at 0.45 MPa	**75**
DSC	Glass transition temperature Tg (°C)	**76**
	ELECTRICAL	
IEC 60093	Surface resistance (ohm/cm^2)	**> 10E6 – 10E9 <**

4.2 TENSILE TEST PARAMETERS.

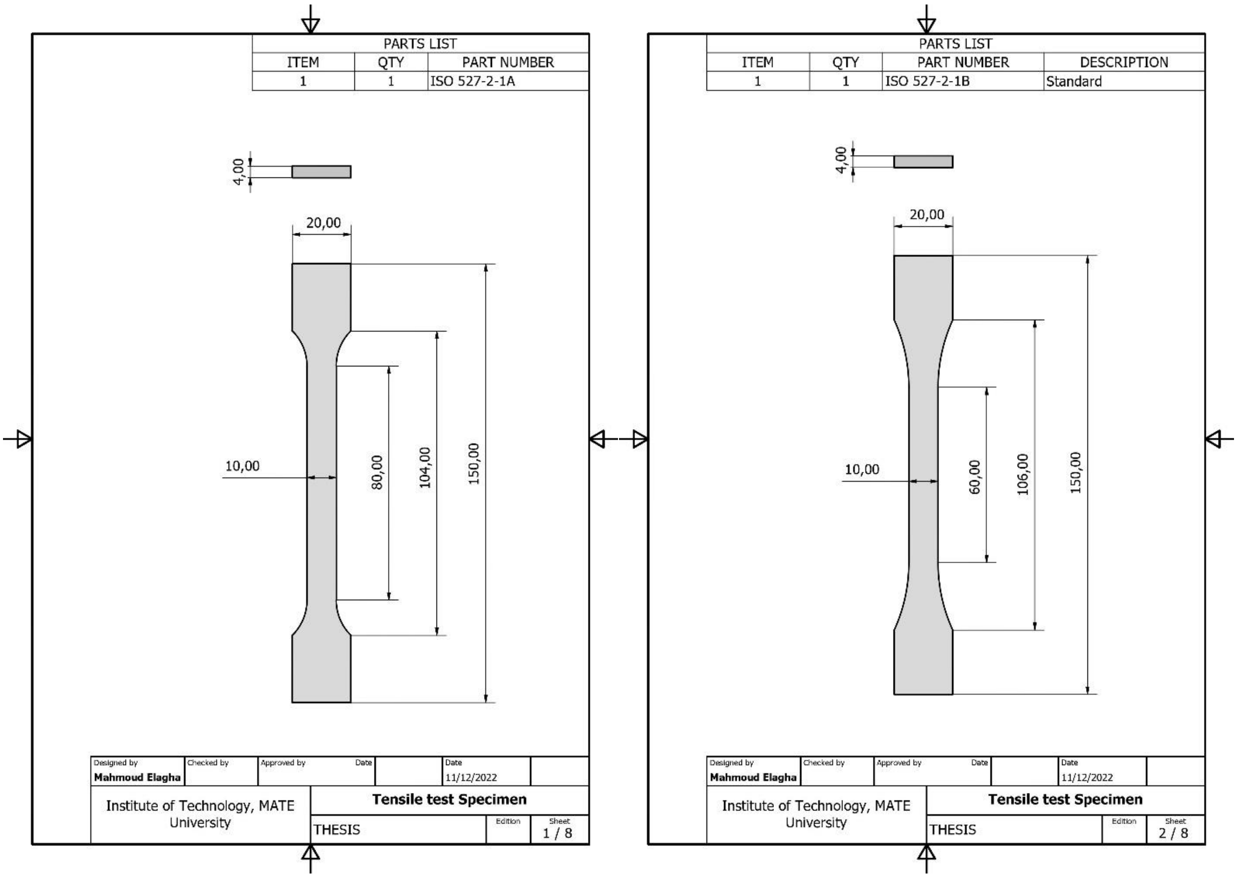
- Head load Speed: 3 mm/s

4.2.1 Tensile test specimen

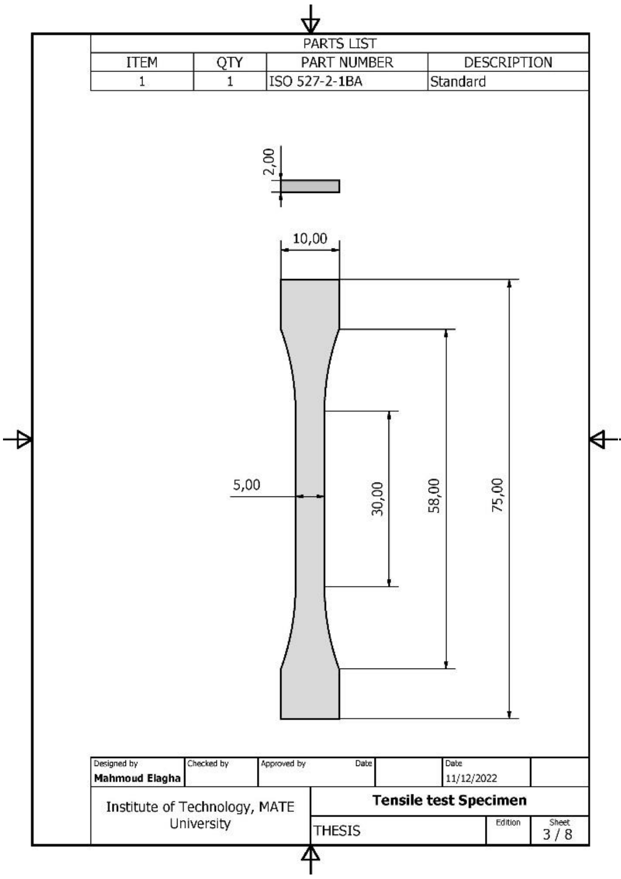
Various manufacturing processes, including injection molding, 3-D printing, and CNC machining, can be used to create specimens for testing purposes. The type of specimen prepared depends on the testing objectives and the governing test method or specification. Typically, a standardized cross-section is used for a tensile specimen, featuring two shoulders and a gauge section in between. The shoulders and grip section are larger than the gauge section by 33% to facilitate gripping, while the smaller diameter of the gauge section enables deformation and failure to occur in that area. The shoulders of the specimen are manufactured in different ways to mate with different grips in the testing machine. Various systems have their own advantages and disadvantages. For example, shoulders designed for serrated grips are simple and inexpensive to manufacture, but the technician's skill is essential for proper alignment. A pinned grip assures good alignment, while threaded shoulders and grips also offer good alignment, but the technician must thread each shoulder into the grip at least one diameter's length to avoid stripping the threads before the specimen fractures.(Kohn et al., 2021) In large castings and forgings, extra material is added to make test specimens, which may not be a precise representation of the entire workpiece due to variations in the grain structure. In smaller workpieces or when critical parts of the casting must be tested, a workpiece may be sacrificed to make the test specimens. For workpieces machined from bar stock, the test specimen can be made from the same piece as the bar stock. For soft and porous materials, such as electro nonwovens made of nanofibers, the specimen is typically a sample strip supported by a paper frame to facilitate mounting on the machine and prevent member damage.(Hanon et al., 2019)

4.2.1.1.1 Different standards of specimens which I used.

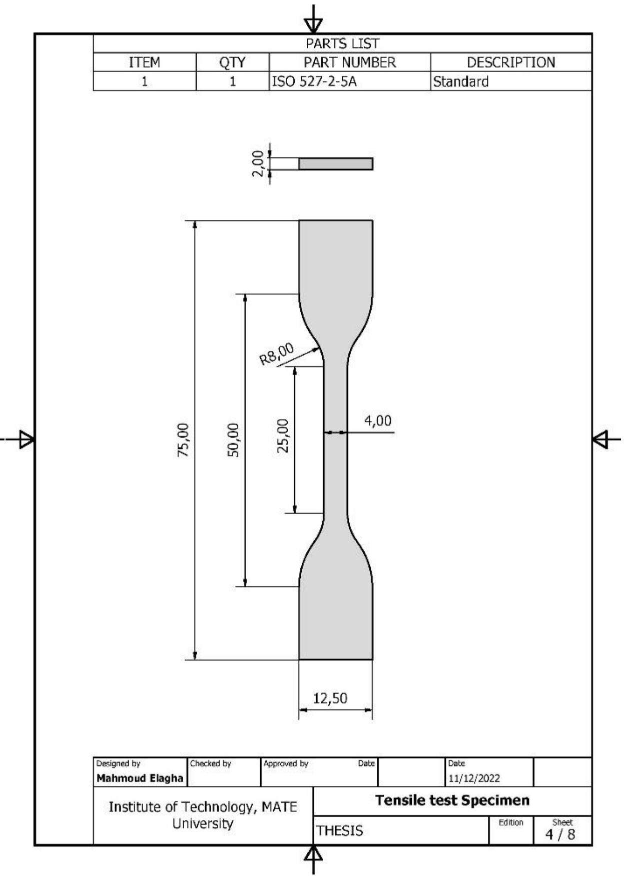
The design of standard specimens can vary depending on the type of material being tested. The MSZ EN ISO 527 standard provides specific specifications and recommendations for the test specimens based on the material being tested, including precise dimensions. For thermoplastic polymeric materials, the most common type of specimen used is the type 1A injection molded specimen. However, if the material of a specific machine element needs to be characterized, types 1B, 1BA, or 1BB specimens can be machined by cutting. For thermosetting matrix polymer composites, type 2 specimens are typically used. The standard shape for polymeric specimens is a dumbbell or dog bone shape, with a total length of l3 ≥15 and 0 mm and a gripping distance of 115 mm (Type 1A). The cross-section of the specimens is typically 4 x 10 mm (d x b1), with a wider section at the ends. The dumbbell shape is used to prevent linearity in the rigid grips, and in the case of polymer matrix composites (Type 2), tabs are added at the ends to achieve the same effect(“ISO 527-3,” n.d.). In our study, we printed 4 different standard specimens (with different dimensions), and we printed each standard 3 times, for the tensile test measurement: (“ISO 178:2019(en), Plastics — Determination of flexural properties,” n.d.)



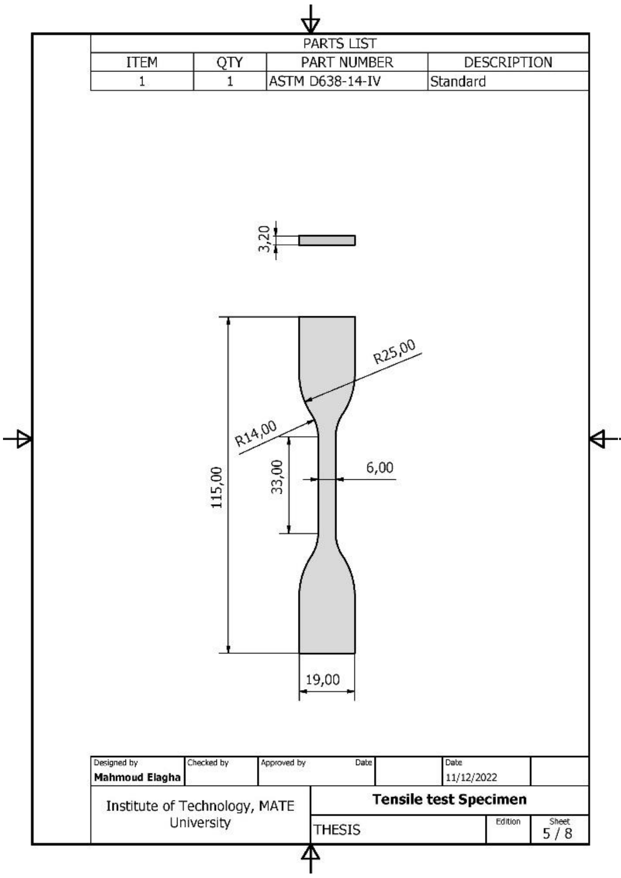
(a) (b)


PARTS LIST
ITEM QTY PART NUMBER DESCRIPTION
1 1 ISO 527-2-1BA Standard
2,00
10,00
5,00
30,00
58,00
75,00
Designed by Mahmoud Elagha
Date 11/12/2022
Institute of Technology, MATE University
Tensile test Specimen
THESIS
Sheet 3 / 8

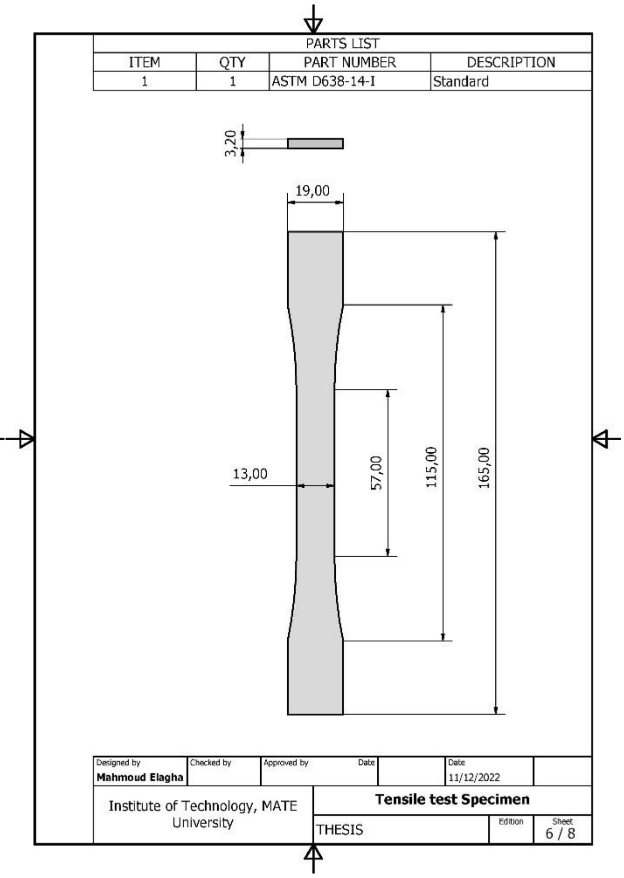
(c)


PARTS LIST
ITEM QTY PART NUMBER DESCRIPTION
1 1 ISO 527-2-5A Standard
2,00
R8,00
4,00
75,00
50,00
25,00
12,50
Designed by Mahmoud Elagha
Date 11/12/2022
Institute of Technology, MATE University
Tensile test Specimen
THESIS
Sheet 4 / 8

(d)


PARTS LIST
ITEM QTY PART NUMBER DESCRIPTION
1 1 ASTM D638-14-IV Standard
3,20
R25,00
R14,00
6,00
115,00
33,00
19,00
Designed by Mahmoud Elagha
Date 11/12/2022
Institute of Technology, MATE University
Tensile test Specimen
THESIS
Sheet 5 / 8

(e)


PARTS LIST
ITEM QTY PART NUMBER DESCRIPTION
1 1 ASTM D638-14-I Standard
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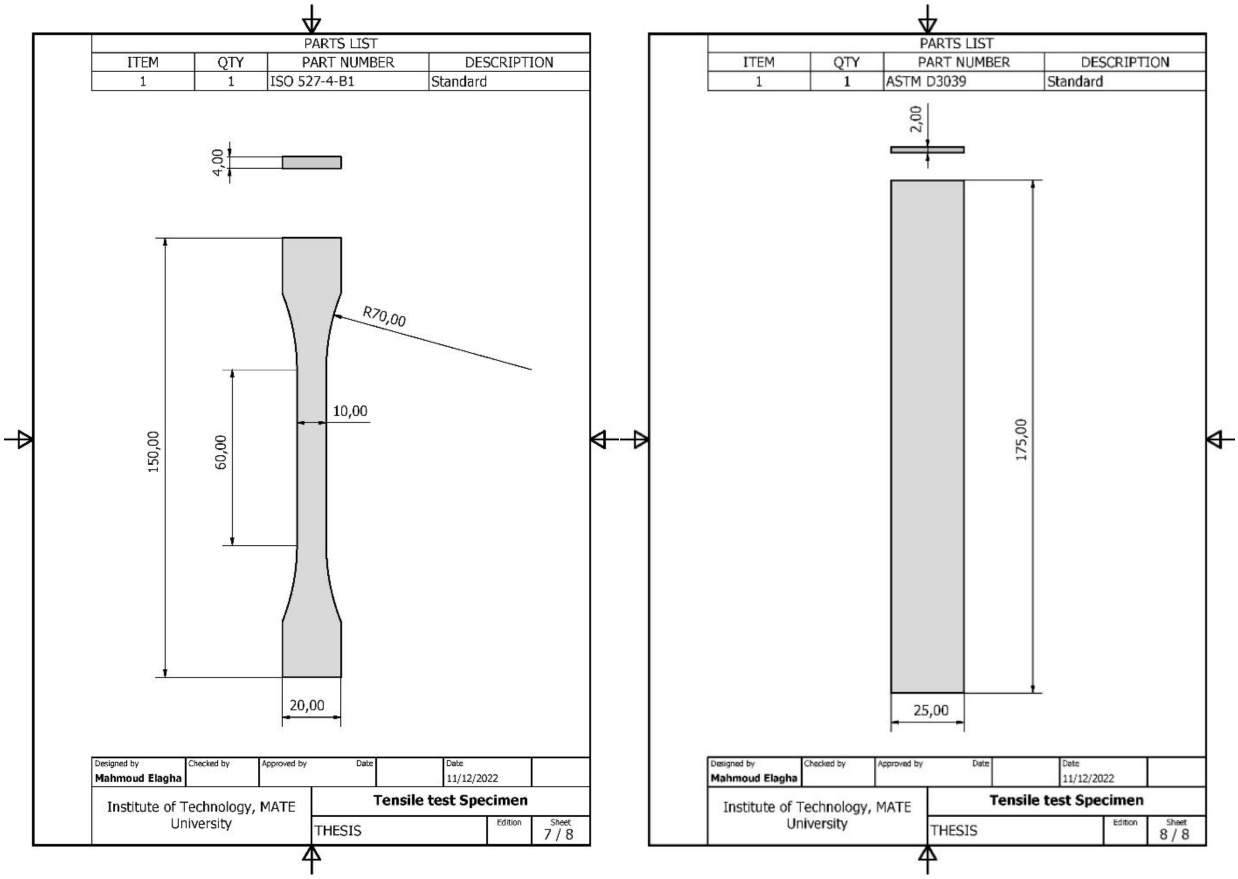
19,00
13,00
57,00
115,00
165,00
Designed by Mahmoud Elagha
Date 11/12/2022
Institute of Technology, MATE University
Tensile test Specimen
THESIS
Sheet 6 / 8

(f)



(g) (h)

Figure 14: (a, b, c, d, e, f, g, h) Dimensions of different standard tensile test specimens.("ISO-178-2010.pdf," n.d.)

4.2.2 Zwick/Roell Z100 type computer-controlled universal tensile tester

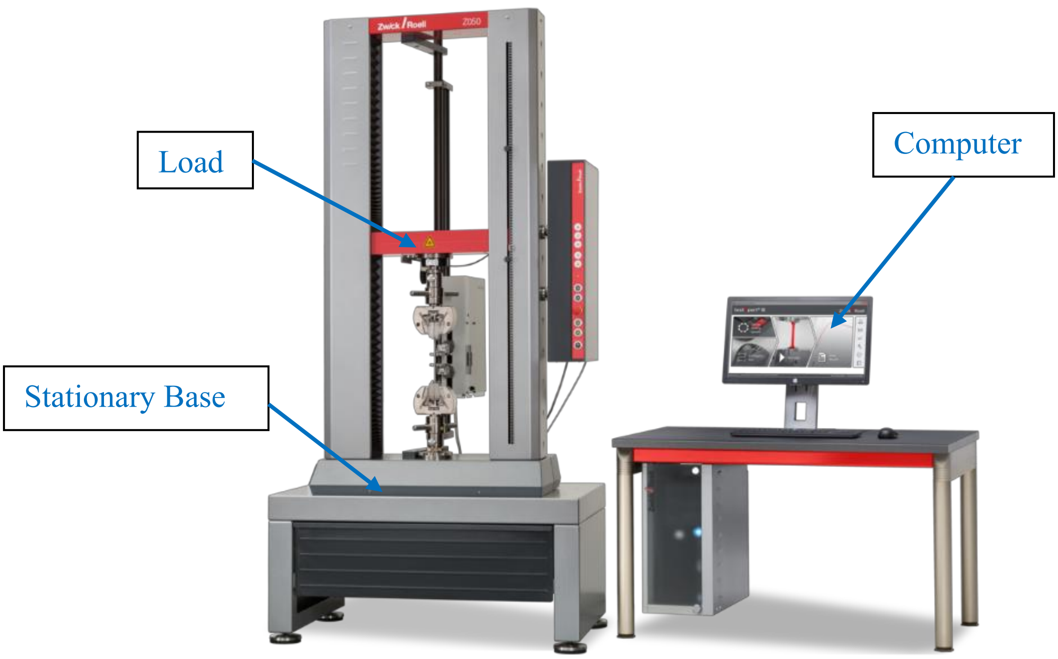


Figure 15: Zwick/Roell Z100 type computer-controlled universal tensile tester.("ProLine_Z005_up_to_Z100_Materials_Testing_Machine_PI_EN.pdf," n.d.)

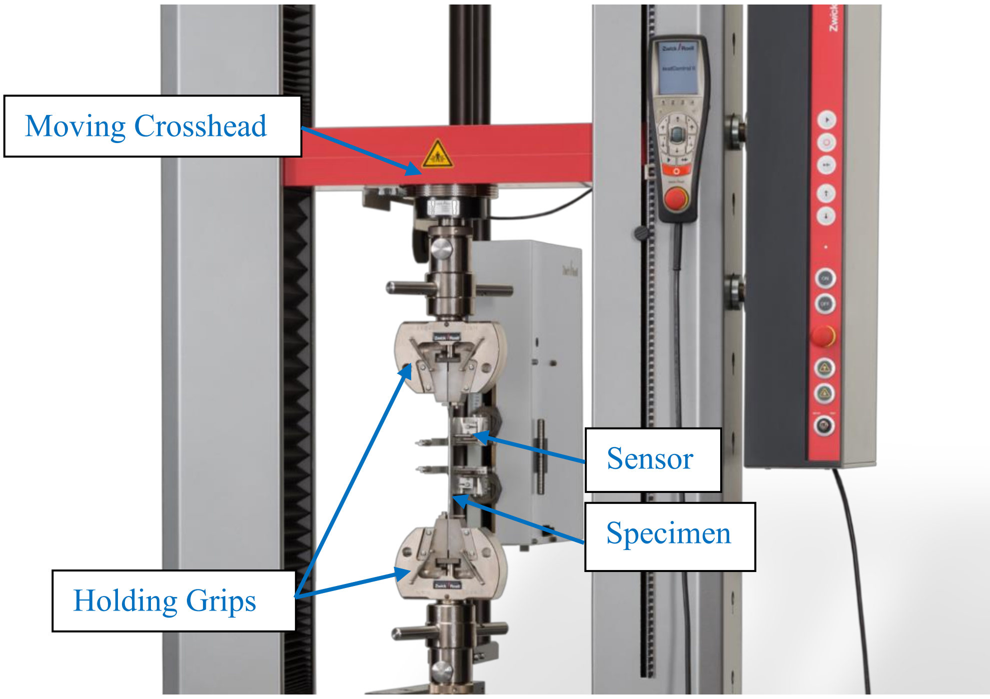


Figure 16: Close view on the Grip and Fixture.

Table 5: ProLine Z100 (Materials Tensile Testing Machine) datasheet("ProLine_Z005_up_to_Z100_Materials_Testing_Machine_PI_EN.pdf," n.d.)

Type	Z100 TN	Unit
Item No.	**1025089**	
Test load F_{max}	100	KN
Height, travel distance of the moving crosshead	1275[1]	mm
Width	640	mm
Height with leveling elements	1829 ... 1834	mm
Width	1070	mm
Width with machine electronics	1205	mm
Depth with machine electronics	645	mm
With machine electronics, approx.	530	kg
Connection, stud	Ø 60	mm
Average noise level at v_{max} measured at 1 m distance from the front of the machine	60	dB(A)
Crosshead speed v_{min} … v_{max}	0.0005 ... 300	mm/min
Crosshead return speed, max.	400	mm/min
Deviation from the set drive speed, max.	0.05	% Of v_{actual}
Drive travel resolution	0.0123	µm
Power supply	230	V, 1Ph/N/PE
Power consumption (full load), approx.	1600	VA

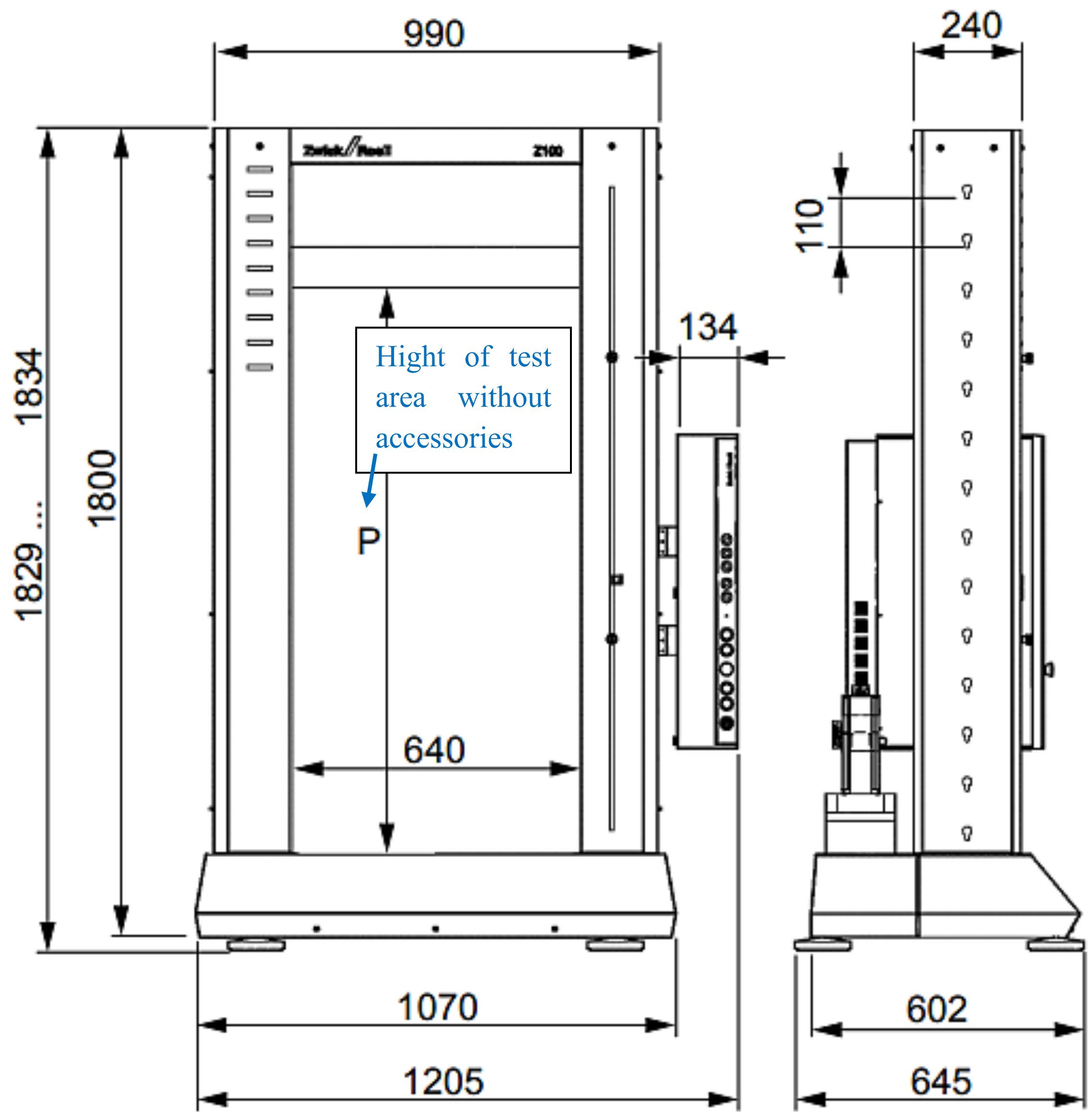


Figure 17: Proline Z100 TN, Dimensions.

4.3 RE-DESIGNING COOLING HOUSE FOR THE FILAMENT MAKER

4.3.1 A filament maker

It is a machine used to create 3D printing filament from raw materials, such as plastic pellets or flakes. The process involves heating the raw materials until they melt and then extruding the molten plastic through a small hole to form a continuous filament.("Filanora Filatech PETG filament 1,75mm szürke," n.d.)

Filament makers are commonly used by 3D printing enthusiasts and professionals who want to create custom filament colors or experiment with varied materials that are not commercially available. They can also be used to recycle plastic waste into usable 3D printing filament, which is an eco-friendly way to reduce waste and save money. There are several types of filament makers available, ranging from small desktop models for hobbyists to large industrial machines for commercial use. Some filament makers are standalone devices, while others can be attached to 3D printers to create a closed-loop system that allows for continuous filament production and printing.

4.3.1.1 Cooling in Extrusion Process

Cooling is an essential part of the extrusion process because it helps to solidify and stabilize the shape of the extruded product. Cooling can be accomplished using either air or liquid flow, depending on the specific requirements of the process.

Air cooling is often used for extruded products that do not require rapid cooling or for processes that do not generate excessive heat. Air cooling can be accomplished using fans or blowers that direct cool air onto the extruded product as it emerges from the die. This method of cooling is simple and cost-effective, but it may not be effective for products that require rapid cooling or for processes that generate high levels of heat. Liquid cooling, on the other hand, is typically used for extruded products that require rapid cooling or for processes that generate high levels of heat. Liquid cooling can be accomplished using water or other coolants that flow over the surface of the extruded product, absorbing heat and carrying it away from the product. This method of cooling is generally more effective than air cooling, but it can be more complex and expensive to implement.(Romeijn et al., 2022)

Overall, the choice between air and liquid cooling in the extrusion process will depend on factors such as the type of product being extruded, the desired cooling rate, and the available equipment and resources.

4.3.2 Gyroid lattice

I used Gyroid Lattice which have excellent isotropic strength properties and can be used effectively inside 3D prints.

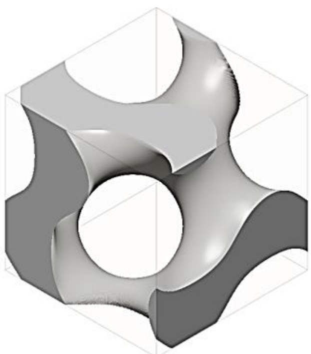


Figure 18: Gyroid Lattice per cell.

The gyroid structure is a complex three-dimensional geometric structure that is often found in nature and can also be artificially generated. It has a repeating pattern of interconnected, curved surfaces that form a continuous network of interlocking channels.("Increased_efficiency_Gyroid_structures_by_tailored.pdf," n.d.)
The gyroid structure was first discovered by mathematicians Alan Schoen and his colleagues in the 1970s. It has since been found to occur in a variety of biological systems, such as the exoskeletons of some insects, the skin of some sea creatures, and in some plants.

The gyroid structure is also of interest to researchers in materials science and engineering because of its unique properties. For example, it has a very high surface area to volume ratio, which makes it useful for applications such as catalysis, energy storage, and filtration. It also has a high mechanical strength and low density, which make it potentially useful for lightweight structural materials.(Popovski et al., 2021)

In addition to its scientific applications, the gyroid structure has also been used in art and design, as its intricate and visually appealing structure can be used to create interesting patterns and textures.

4.3.3 Shape optimization

It is a technique used in mechanical design engineering to optimize the shape of a component or structure to achieve better performance, reduce weight, or meet certain design criteria. It involves applying mathematical algorithms to determine the best shape for a given design problem while considering various constraints, such as material properties, manufacturing limitations, and cost.(Zhou et al., 2022)

4.3.3.1 Autodesk Fusion 360

Shape optimization can be made by Autodesk Fusion 360, It is used in a wide range of applications, including aerodynamics, structural design, and fluid dynamics. It can also be used to improve the efficiency of complex systems, such as engines, turbines, and aircraft. There are various techniques used in shape optimization, including topology optimization, parametric optimization, and gradient based optimization. These methods involve varying the shape of the design and calculating the resulting performance metrics to determine the optimal shape.(Alam, 2023)

Overall, shape optimization plays a crucial role in mechanical design engineering, allowing engineers to create more efficient and effective designs while reducing costs and improving performance.

Table 6: Volumetric Lattice and Mesh Setup

Volumetric Lattice			
Cell Shape	Gyroid		
Proportions	Uniform		
Size	10.00 mm		
Distribution	Uniform		
Solidity	0.30		
Region 1	1.00 mm	1.00 mm	1.00 mm
Region 2	2.00 mm	2.00 mm	2.00 mm
Create Mesh			
Refinement	High		
Element Size	0.138		

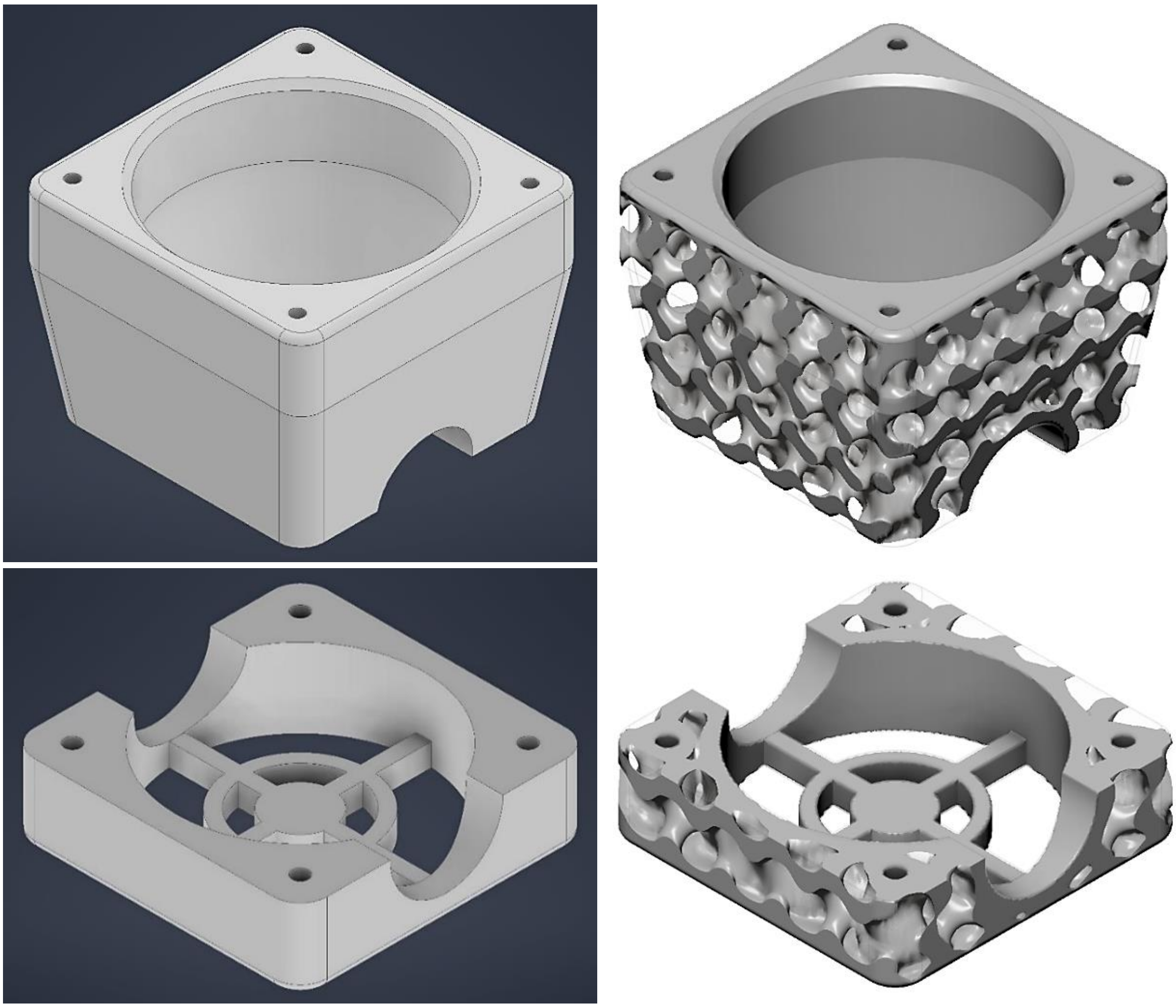


Figure 19: The original shape of the Cooling house & the new shape of the cooling house.

4.3.4 Advantages of the New design:

- Less Weight: the total weight of the new design is smaller than the original one.
- Printing time is very small compared to the original one.
- Material less material used in the printing.
- Lower production cost, which means more profits.
- High Strength-to-Weight Ratio: The core material of a sandwich structure provides strength and stiffness, while the face sheets provide durability and protection. This results in a high strength-to-weight ratio, making them ideal for lightweight applications where strength is a key requirement.
- Energy Absorption: Sandwich structures are excellent at absorbing energy from impacts, making them ideal for applications where protection is important, such as in the construction of helmets, body armor, and crash barriers.
- Thermal Insulation: The thick core material of sandwich structures provides excellent thermal insulation, making them ideal for use in environments where temperature control is important, such as in aerospace and marine applications.

- Sound Damping: Sandwich structures can also provide effective sound damping, making them ideal for use in acoustic barriers and noise-reducing panels.
- Customization: Sandwich structures can be customized to meet specific requirements by selecting appropriate face sheet materials, core materials, and thicknesses, making them versatile and adaptable to a wide range of applications.

Overall, sandwich structures offer a combination of high strength, low weight, energy absorption, thermal insulation, sound damping, and customization options, making them an excellent choice for a variety of applications.(Zaharia et al., 2020)

5 RESULTS AND DISCUSSION

5.1.1 D638-14-I Specimen

The figure 20 below, shows the examination results of 3D-printed specimens of the same standard (D638-14-I), and the average of them (yellow line). From the results, we got that the maximum tensile stress is 35 MPa. The average values of the three specimens are also provided in the table. The average tensile strength at yield is 35.0 MPa, the average tensile strength at break is 32.0 MPa, and the average elongation at break is 4.4%. The tensile modulus of elasticity is 1889.6 MPa, and the average thickness and width of the specimens are 3.2 mm and 13.0 mm, respectively.

I have noticed that:

- The specimen is broken.
- The broken point is always close to the moving grip.

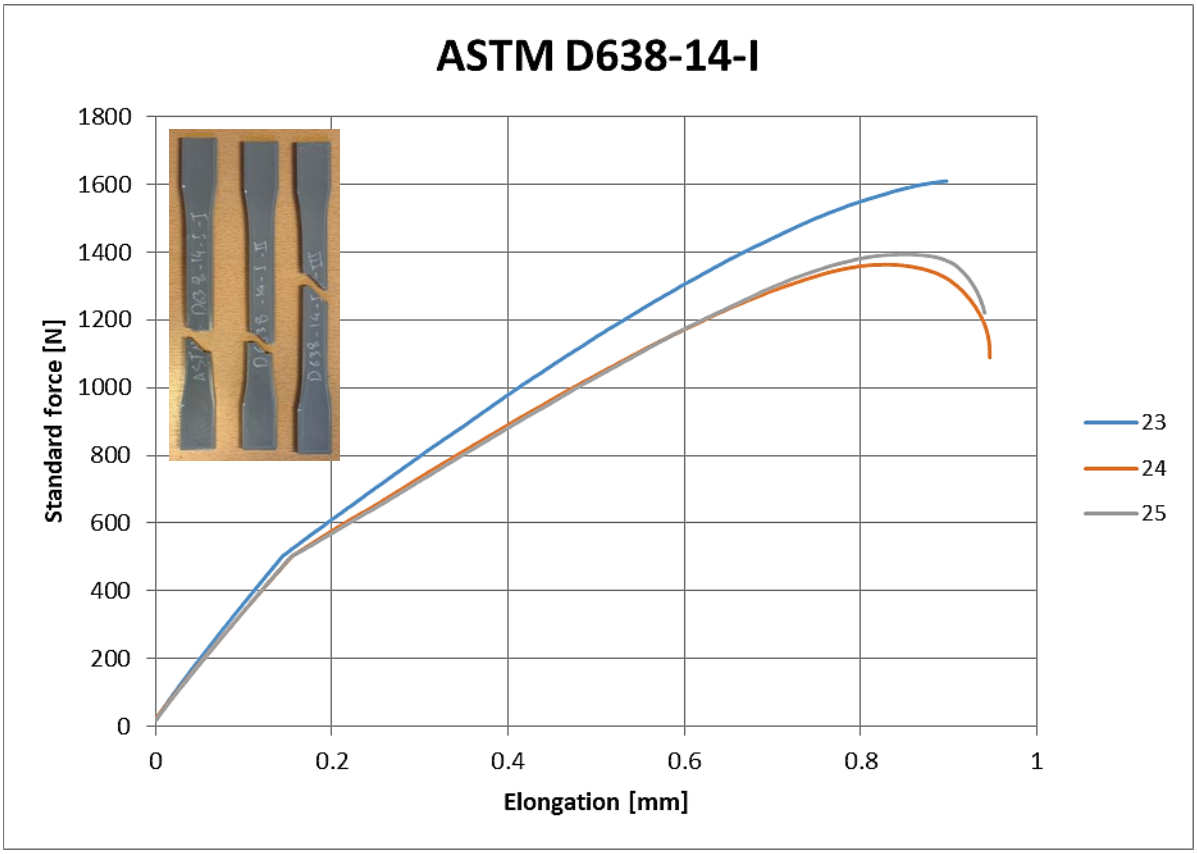


Figure 20: Tensile test graph of ASTM D638-14-I.

Table 7: Results of D638-14-I

ASTM D638 -14-I	E_t	σ_{x1}	σ_M	ε_M	ε_{tM}	σ_B	ε_B	ε_{tB}	b	h	A_0
	MPa	MPa	MPa	%	%	MPa	%	%	mm	mm	mm^2
Specimen 23	1969.2		38.7	3.7	4.1	29.6	4.4	4.8	13.0	3.2	41.6
Specimen 25	1859.2		33.5	3.4	4.4	33.5	3.4	4.4	13.0	3.2	41.6
Specimen 24	1840.4		32.8	3.3	4.1	32.8	3.3	4.1	13.0	3.2	41.6
Average	**1889.6**	**0.0**	**35.0**	**3.5**	**4.2**	**32.0**	**3.7**	**4.4**	**13.0**	**3.2**	**41.6**

5.1.2 ISO 527-4-B1 Specimen

The figure 21 below, shows the examination results of 3D-printed specimens of the same standard (ISO 527-4-B1), and the average of them (yellow line). From the results, we got that the maximum tensile stress is 33.4 MPa. Overall, the results suggest that the material being tested has a relatively low strength and stiffness, as indicated by the low values for σ_M and σ_{x1}, and a relatively high ductility, as indicated by the relatively high values for ε_M, ε_{tM}, ε_B, and ε_{tB}. However, it is important to note that these results are based on a small sample size and may not be representative of the material as a whole.

I have noticed that:

- The specimen is broken.
- The broken point is always close to the moving grip.

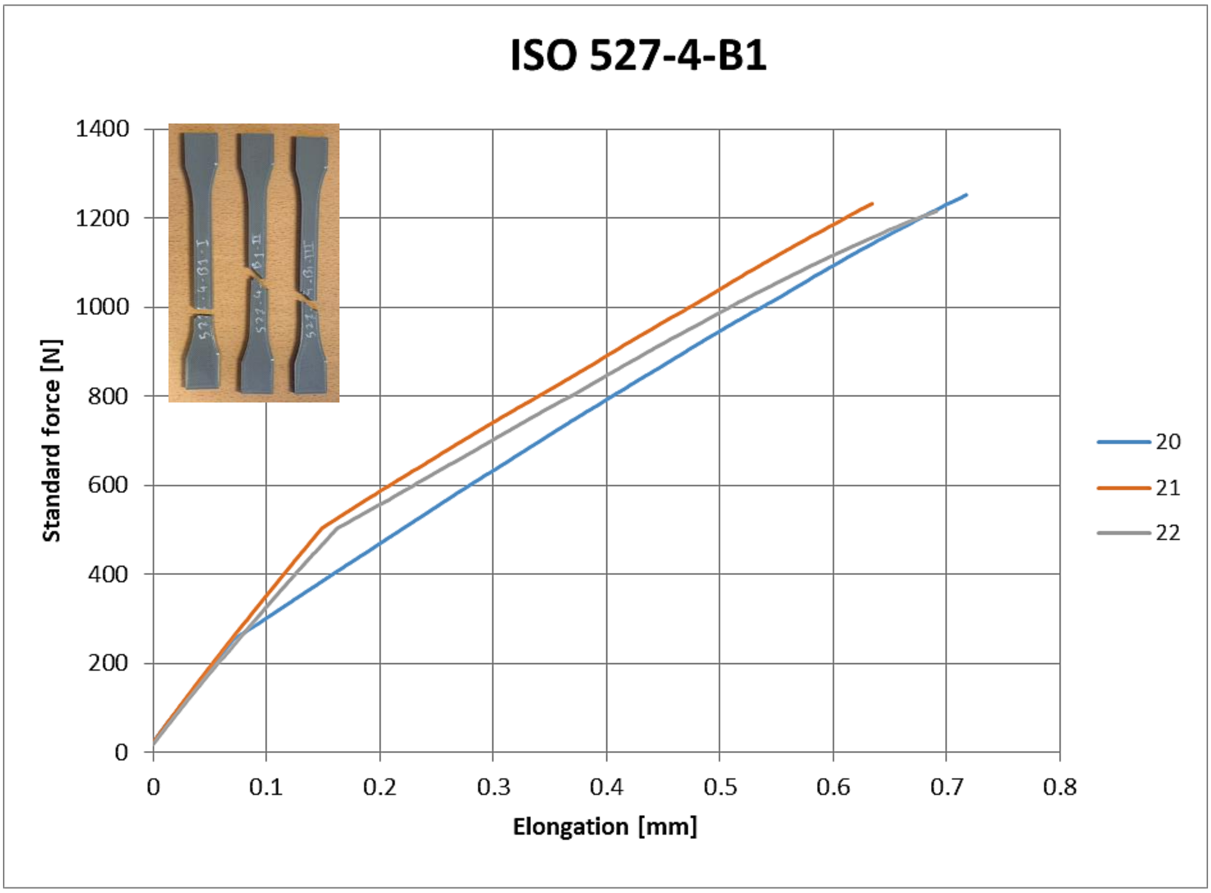


Figure 21: Tensile test graph of ISO 527-4-B1.

Table 8: Results of ISO 527-4-B1

ISO 527 -4-B1	E_t	σ_{x1}	σ_M	ε_M	ε_{tM}	σ_B	ε_B	ε_{tB}	b	h	A_0
	MPa	MPa	MPa	%	%	MPa	%	%	mm	mm	mm^2
Specimen 22	1836.5		32.2	3.3	4.3	32.2	3.3	4.3	10.0	4.0	40.0
Specimen 21	1992.3		36.6	3.6	4.2	27.0	4.7	5.3	10.0	4.0	40.0
Specimen 20	2026.5		31.3	2.9	3.2	31.3	2.9	3.2	10.0	4.0	40.0
Average	**1951.8**	**0.0**	**33.4**	**3.3**	**3.9**	**30.2**	**3.6**	**4.3**	**10.0**	**4.0**	**40.0**

5.1.3 ISO 527-2-1BA Specimen

The figure 22 below, shows the examination results of 3D printed specimens of the same standard (ISO 527-2-1BA), and the average of them (yellow line). From the results, we got that the maximum tensile stress is 43.1 MPa. Overall, the data indicates that the material being tested has a relatively high tensile strength and modulus, with a maximum tensile strength of around 43 MPa and an average tensile modulus of around 1940 MPa. However, the material also exhibits relatively low ductility, with an average strain at break of only 17.9% and a true strain at break of 5%. The dimensions of the specimens (width, thickness, and original cross-sectional area) are kept constant throughout the testing, which makes it easier to compare the mechanical properties of the material across different specimens.

I have noticed that:

- The specimen is not broken.
- The elongation section is always close to the moving grip.

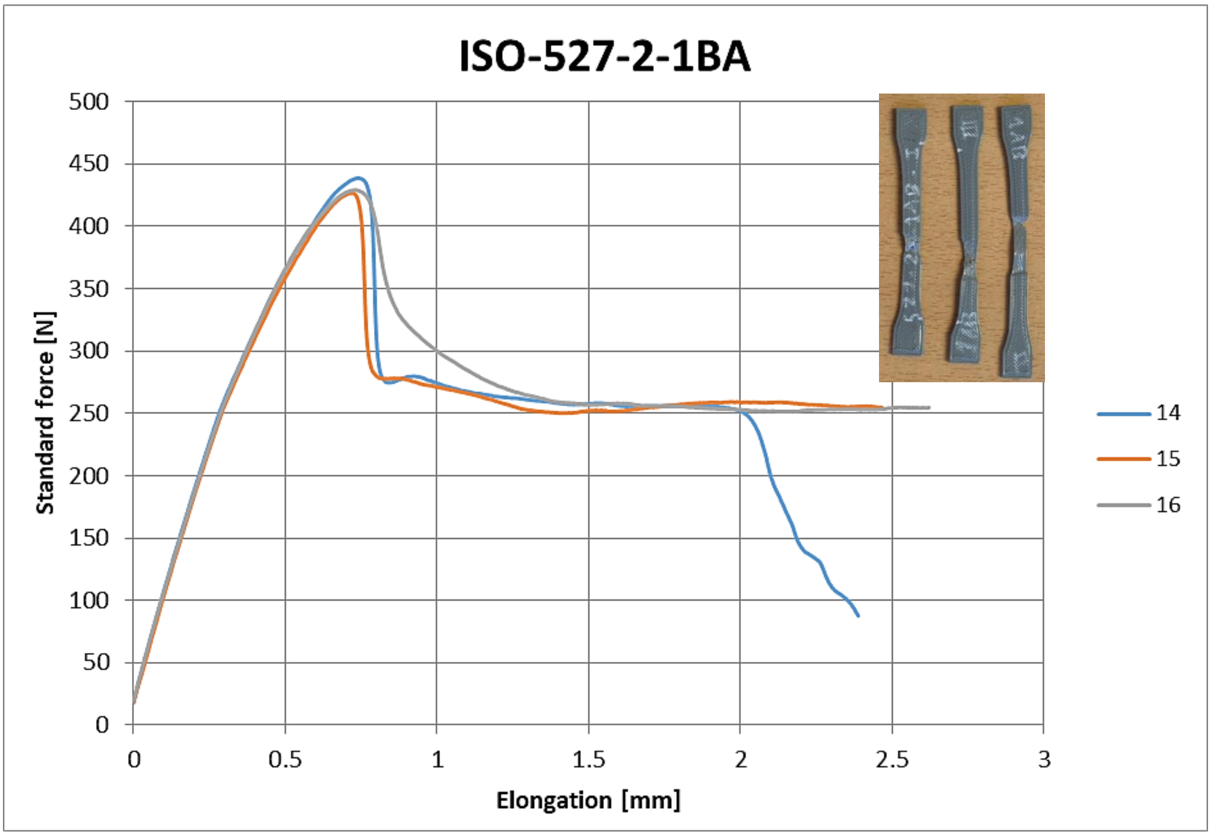


Figure 22: Tensile test graph of ISO 527-2-1BA.

Table 9: Results of ISO 527-2-1BA

ISO 527-2-1BA	E_t	σ_{x1}	σ_M	ε_M	ε_{tM}	σ_B	ε_B	ε_{tB}	b	h	A_0
	MPa	MPa	MPa	%	%	MPa	%	%	mm	mm	mm^2
Specimen 14	1966.8		43.9	3.0	3.4	8.8	9.6	10.0	5.0	2.0	10.0
Specimen 15	1928.1	25.4	42.7	2.9	3.6	8.5	25.0	25.7	5.0	2.0	10.0
Specimen 16	1925.1	25.4	42.9	2.9	3.2	8.6	17.5	17.9	5.0	2.0	10.0
Average	**1940.0**	**17.0**	**43.1**	**2.9**	**3.4**	**8.6**	**17.4**	**17.9**	**5.0**	**2.0**	**10.0**

5.1.4 ISO 527-2-1A Specimen

The figure 23 below, shows the examination results of 3D-printed specimens of the same standard (ISO 527-2-1A), and the average of them (yellow line). From the results, we got that the maximum tensile stress is 29.9 MPa. the average values show that the specimens had a tensile modulus of 2013.6 MPa, a tensile strength at yield of 29.9 MPa, a tensile strength at maximum of 2.6 MPa, a strain at maximum of 3.7%, a true strain at maximum of 3.7%, a tensile strength at break of 29.9 MPa, a strain at break of 2.6%, and a true strain at break of 3.7%.

I have noticed that:

- The specimen is broken.
- The broken point is always close to the moving grip.

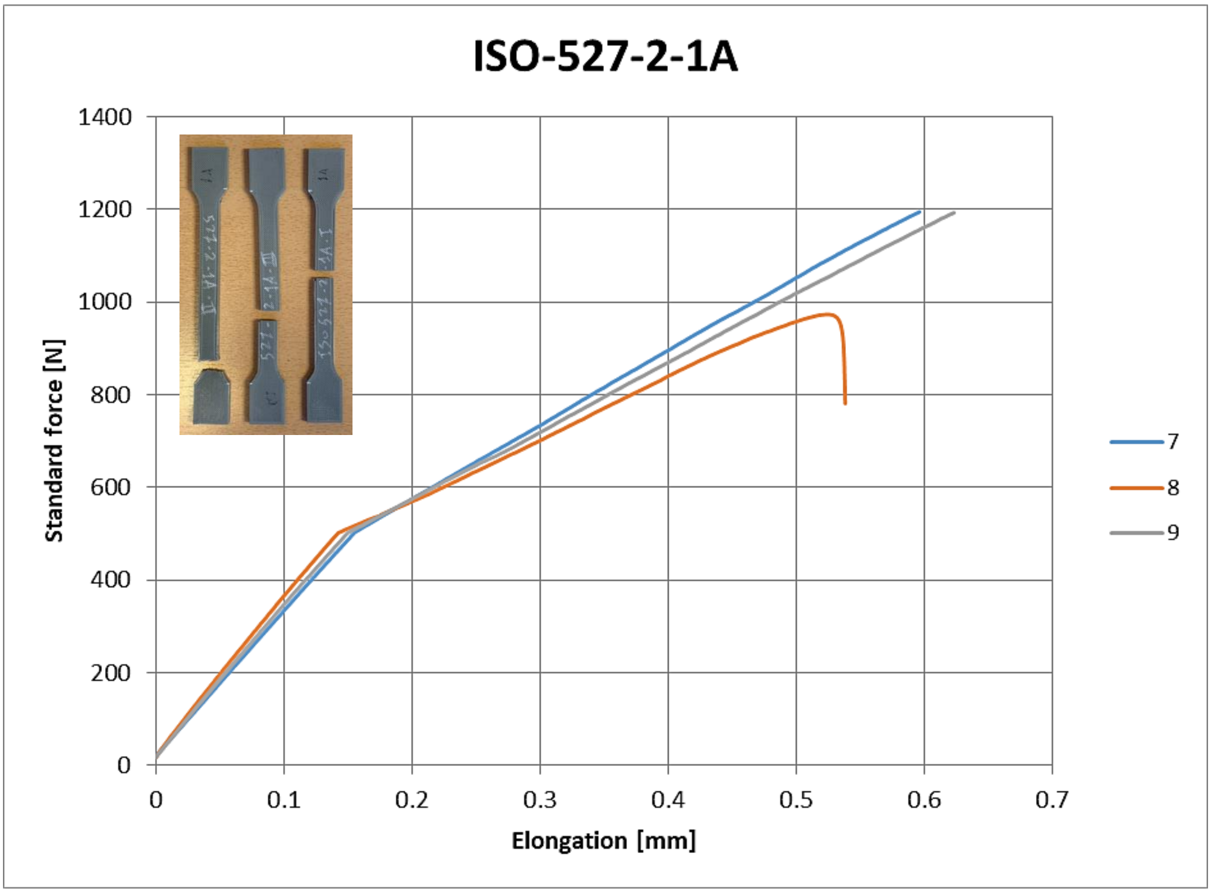


Figure 23: Tensile test graph of ISO 527-2-1A.

Table 10: Results of ISO 527-2-1A specimen.

ISO 527 -2-1A	E_t	σ_{x1}	σ_M	ε_M	ε_{tM}	σ_B	ε_B	ε_{tB}	b	h	A_0
	MPa	MPa	MPa	%	%	MPa	%	%	mm	mm	mm^2
Specimen 7	1943.0		31.2	2.5	3.0	31.2	2.5	3.0	10.0	4.0	40.0
Specimen 8	2097.2		24.3	2.1	4.2	24.3	2.1	4.2	10.0	4.0	40.0
Specimen 9	2000.7		34.3	3.1	4.0	34.3	3.1	4.0	10.0	4.0	40.0
Average	**2013.6**	**0.0**	**29.9**	**2.6**	**3.7**	**29.9**	**2.6**	**3.7**	**10.0**	**4.0**	**40.0**

5.1.5 ISO 527-2-1B Specimen

The figure 24 below, shows the examination results of 3D-printed specimens of the same standard (ISO 527-2-1B), and the average of them (yellow line). From the results, we got that the maximum tensile stress is 27.2 MPa. The table shows the results of a tensile test on three specimens (Specimen 4, 5, and 6) conducted according to the ISO 527-2-1B standard. The average values of the measured parameters are also provided.

I have noticed that:

- The specimen is broken.
- The broken point is always close to the moving grip.

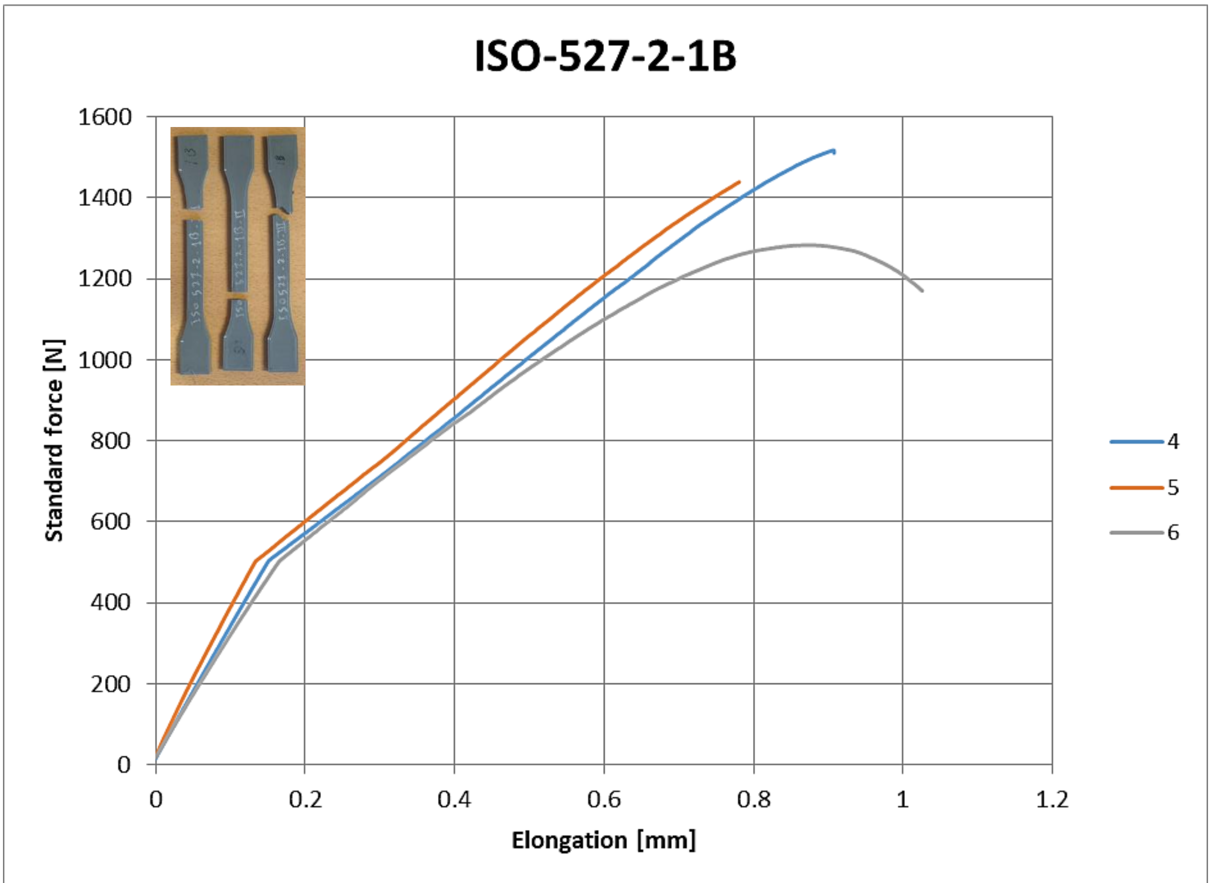


Figure 24: Tensile test graph of ISO 527-2-1B.

Table 11: Results of ISO 527-2-1B

ISO 527 -2-1B	E_t	σ_{x1}	σ_M	ε_M	ε_{tM}	σ_B	ε_B	ε_{tB}	b	h	A_0
	MPa	MPa	MPa	%	%	MPa	%	%	mm	mm	mm^2
Specimen 4	1607.4		30.3	3.6	5.5	30.3	3.6	5.5	10.0	4.0	40.0
Specimen 5	1100.7		19.0	3.5	4.6	19.0	3.5	4.6	10.0	4.0	40.0
Specimen 6	1807.0		32.1	3.5	4.1	23.1	4.4	5.1	10.0	4.0	40.0
Average	**1505.0**	**0.0**	**27.2**	**3.5**	**4.7**	**24.1**	**3.9**	**5.1**	**18.3**	**4.0**	**40.0**

5.1.6 ISO 527-2-5A Specimen

The figure 25 below, shows the examination results of 3D-printed specimens of the same standard (ISO 527-2-5A), and the average of them (yellow line). From the results, we got that the maximum tensile stress is 30.9 MPa. The table contains data for three specimens tested according to the ISO-527-2-5A standard. The variables measured include tensile strength, yield strength, ultimate elongation, and various strain measurements at different stages of the test.

I have noticed that:

- The specimen is not broken.
- The elongation section is always close to the moving grip.

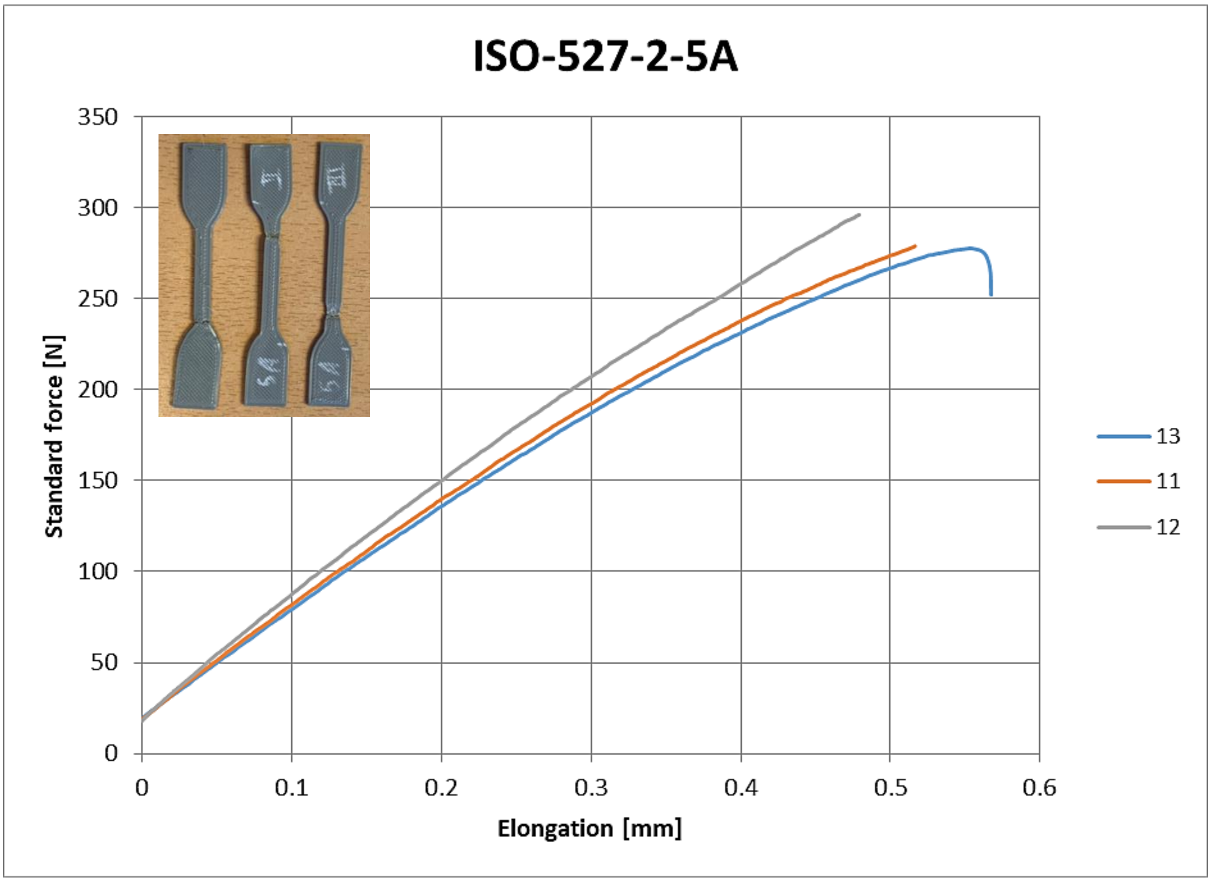


Figure 25: Tensile test graph of ISO 527-2-5A.

Table 12: Results of ISO 527-2-5A

ISO-527 -2-5A	E_t	σ_{x1}	σ_M	ε_M	ε_{tM}	σ_B	ε_B	ε_{tB}	b	h	A_0
	MPa	MPa	MPa	%	%	MPa	%	%	mm	mm	mm^2
Specimen 13	1201.2		27.8	2.2	2.3	27.8	2.2	2.3	5.0	2.0	10.0
Specimen 11	1052.6		30.4	2.6	2.8	6.1	7.1	7.3	5.0	2.0	10.0
Specimen 12	1421.5		34.6	2.7	3.0	6.9	6.8	7.1	5.0	2.0	10.0
Average	**1225.1**	**0.0**	**30.9**	**2.5**	**2.7**	**13.6**	**5.4**	**5.6**	**5.0**	**2.0**	**10.0**

5.1.7 ASTM 638-14-IV Specimen

The figure 26 below, shows the examination results of 3D-printed specimens of the same standard (ASTM 638-14-IV), and the average of them (yellow line). From the results, we got that the maximum tensile stress is 42.8 MPa. The data presented in the table is related to mechanical testing of three specimens of a material using the ASTM-638-14-IV standard.

I have noticed that:

- The specimen is not broken.
- The elongation section is always close to the moving grip.

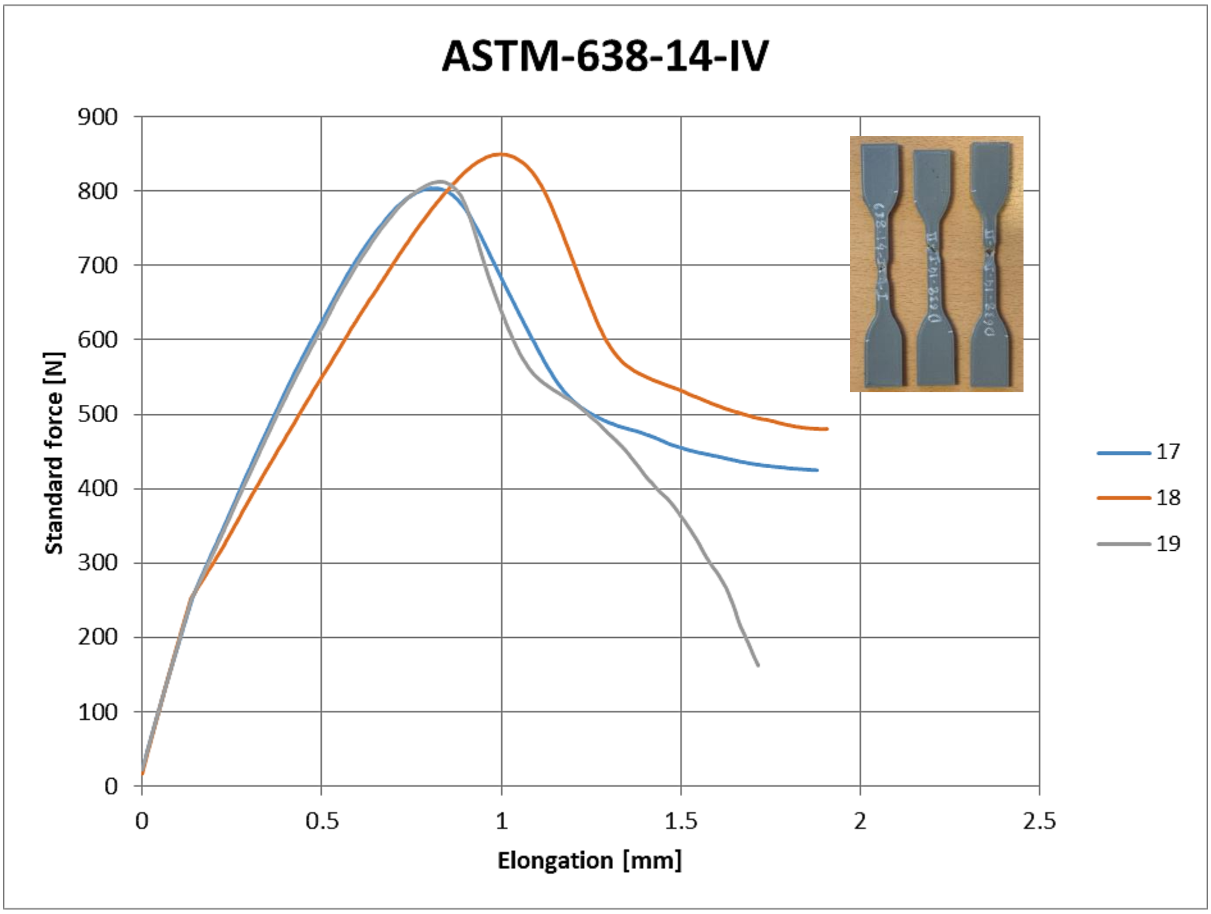


Figure 26: Tensile test graph of ASTM 638-14-IV.

Table 13: Results of ASTM 638-14-IV

ASTM-638 -14-IV	E_t	σ_{x1}	σ_M	ε_M	ε_{tM}	σ_B	ε_B	ε_{tB}	b	h	A_0
	MPa	MPa	MPa	%	%	MPa	%	%	mm	mm	mm^2
Specimen 17	2106.3	21.9	41.9	3.2	3.4	8.4	13.0	13.2	6.0	3.2	19.2
Specimen 19	2152.3		42.3	3.3	3.6	8.5	6.9	7.1	6.0	3.2	19.2
Specimen 18	2210.1	24.7	44.3	4.0	5.2	8.9	14.9	16.1	6.0	3.2	19.2
Average	**2156.2**	**15.5**	**42.8**	**3.5**	**4.1**	**8.6**	**11.6**	**12.2**	**6.0**	**3.2**	**19.2**

5.1.8 ASTM-D3039 Specimen

The figure 27 below, shows the examination results of 3D-printed specimens of the same standard (ASTM-D3039), and the average of them (yellow line). From the results, we got that the maximum tensile stress is 28.5 MPa. The given data represents the results of a mechanical testing of three specimens using the ASTM-D3039 standard.

I have noticed that:

- The specimen is broken.
- The broken point is always close to the moving grip.

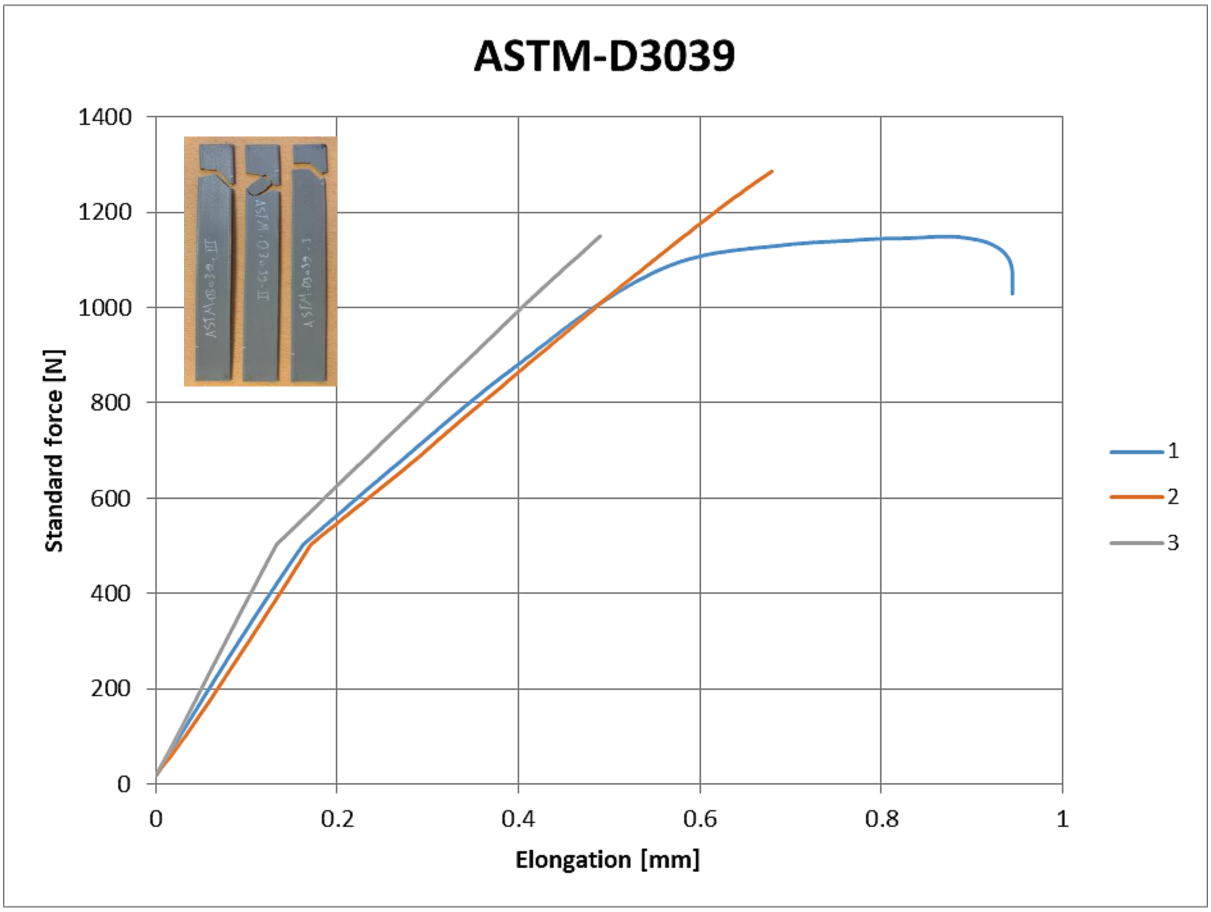


Figure 27: Tensile test graph of ASTM-D3039.

Table 14: Results of ASTM-D3039

ASTM-D3039	E_t	σ_{x1}	σ_M	ε_M	ε_{tM}	σ_B	ε_B	ε_{tB}	b	h	A_0
	MPa	MPa	MPa	%	%	MPa	%	%	mm	mm	mm^2
Specimen 1	1480.5		23.0	3.5	3.9	23.0	3.5	3.9	25.0	2.0	50.0
Specimen 2	1451.2		29.7	3.7	5.2	29.7	3.7	5.2	25.0	2.0	50.0
Specimen 3	1838.0		32.8	3.7	4.3	32.8	3.7	4.3	25.0	2.0	50.0
Average	**1589.9**	**0.0**	**28.5**	**3.6**	**4.5**	**28.5**	**3.6**	**4.5**	**25.0**	**2.0**	**50.0**

5.1.9 Average Tensile test of all standard specimens

Figure 28 below shows the average tensile test results of all specimens I examined. It can be seen from the figure below that the maximum tensile stress on average ranges between (27.15 MPa and 43.15 Mpa) (see; Table 15)

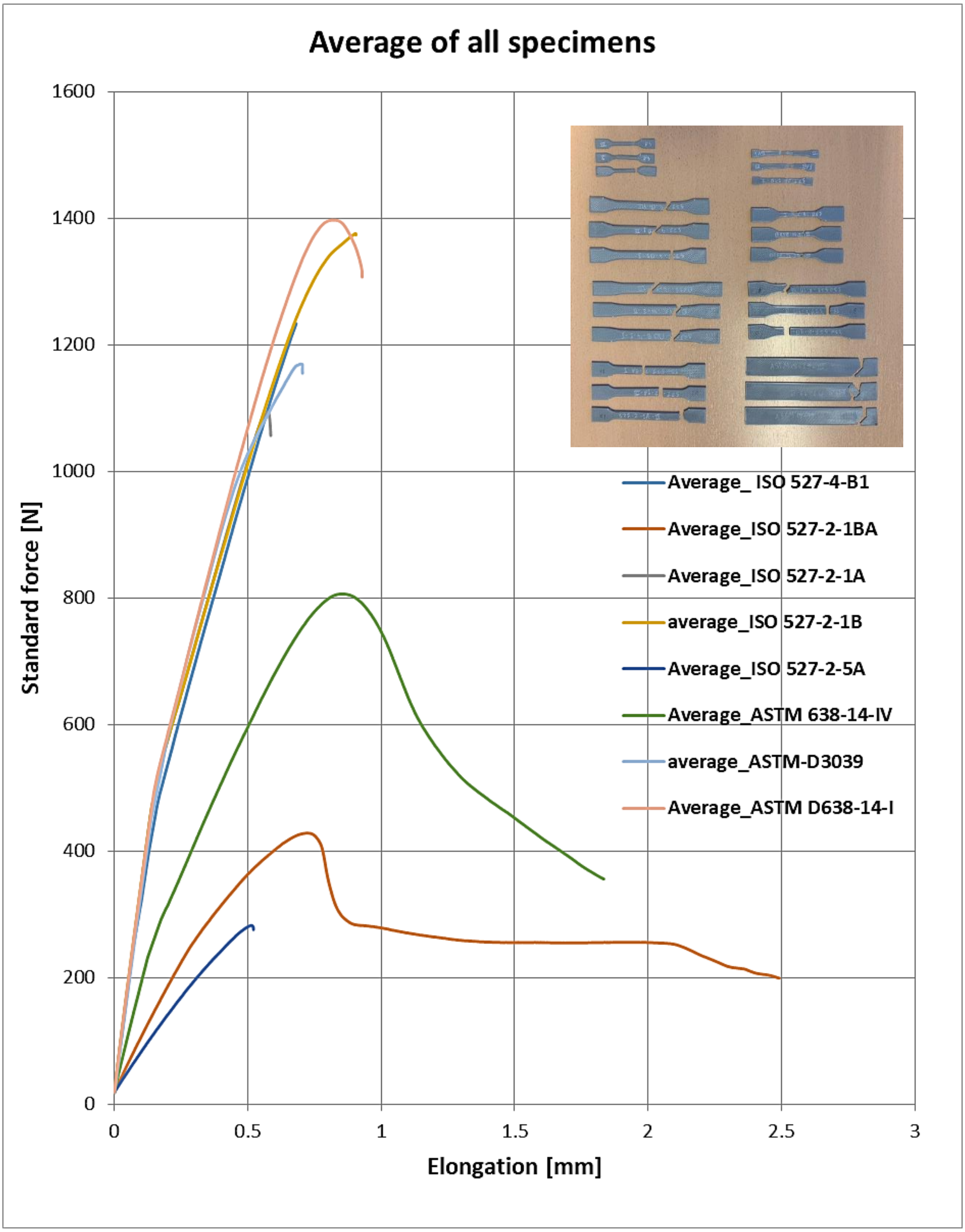


Figure 28: Average tensile test graph of all measured specimens.

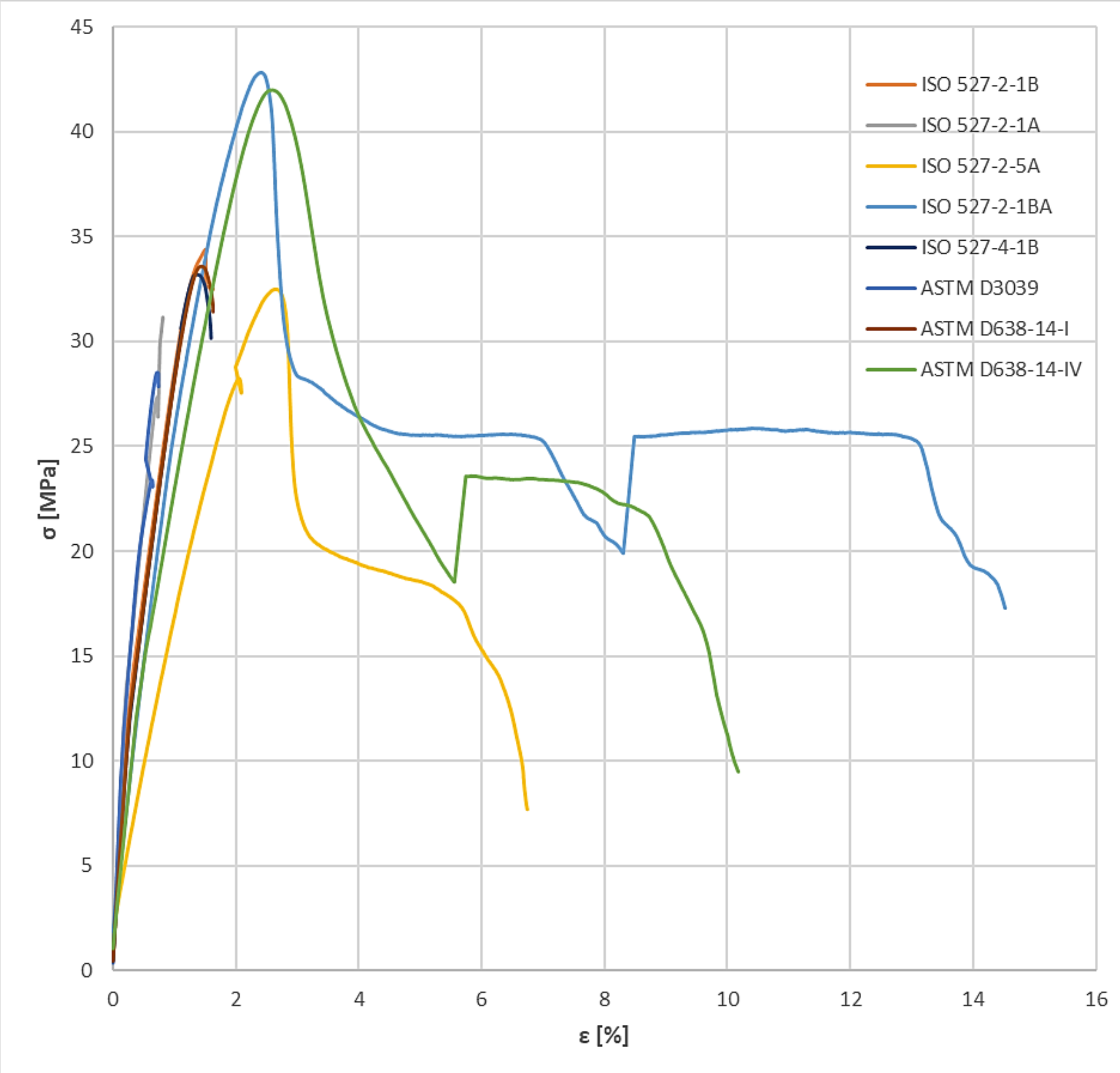
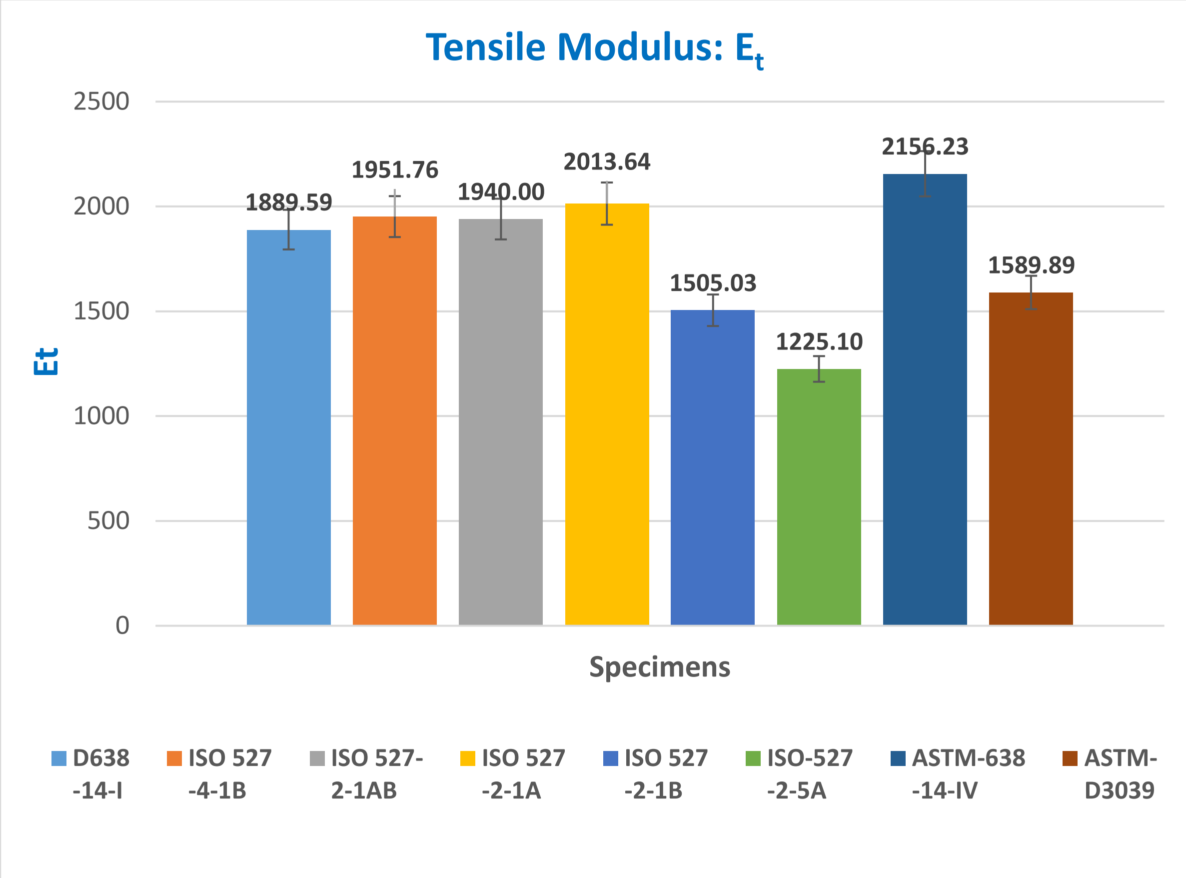
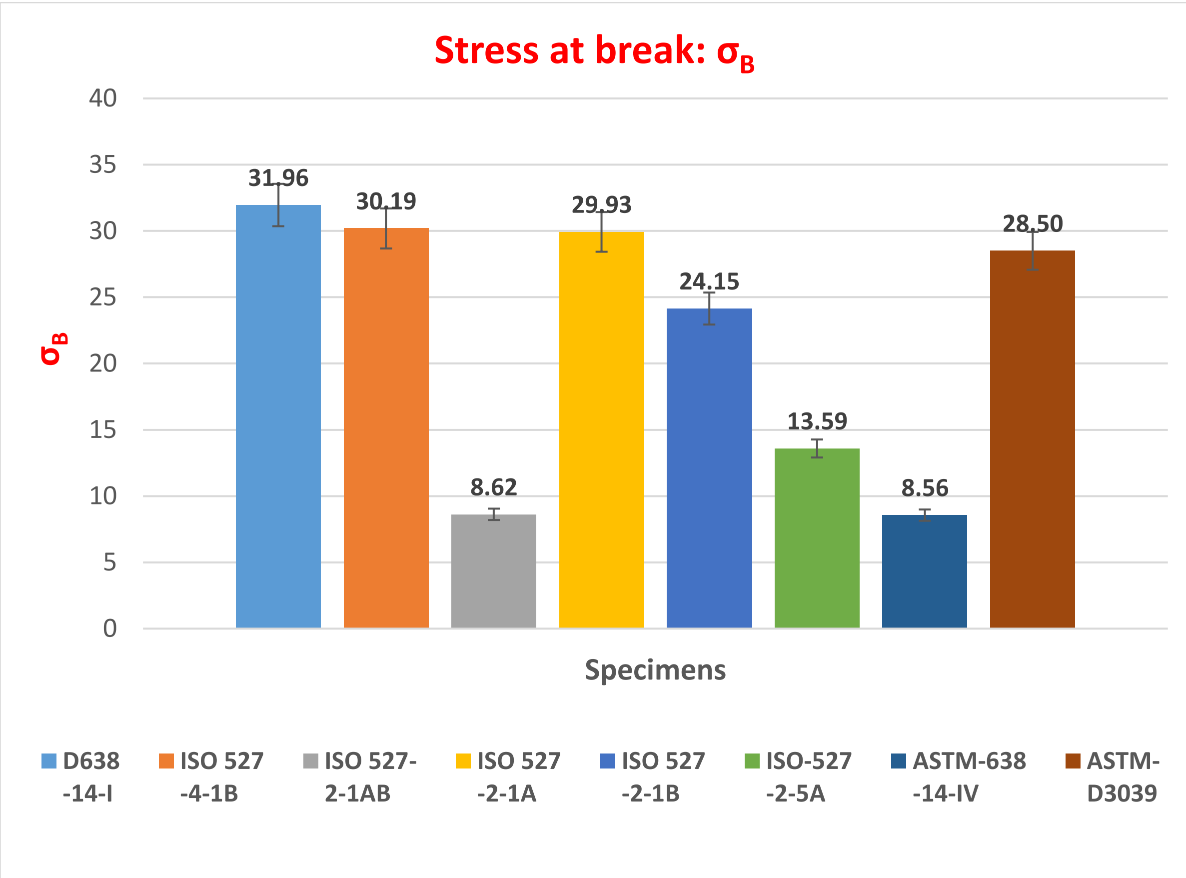


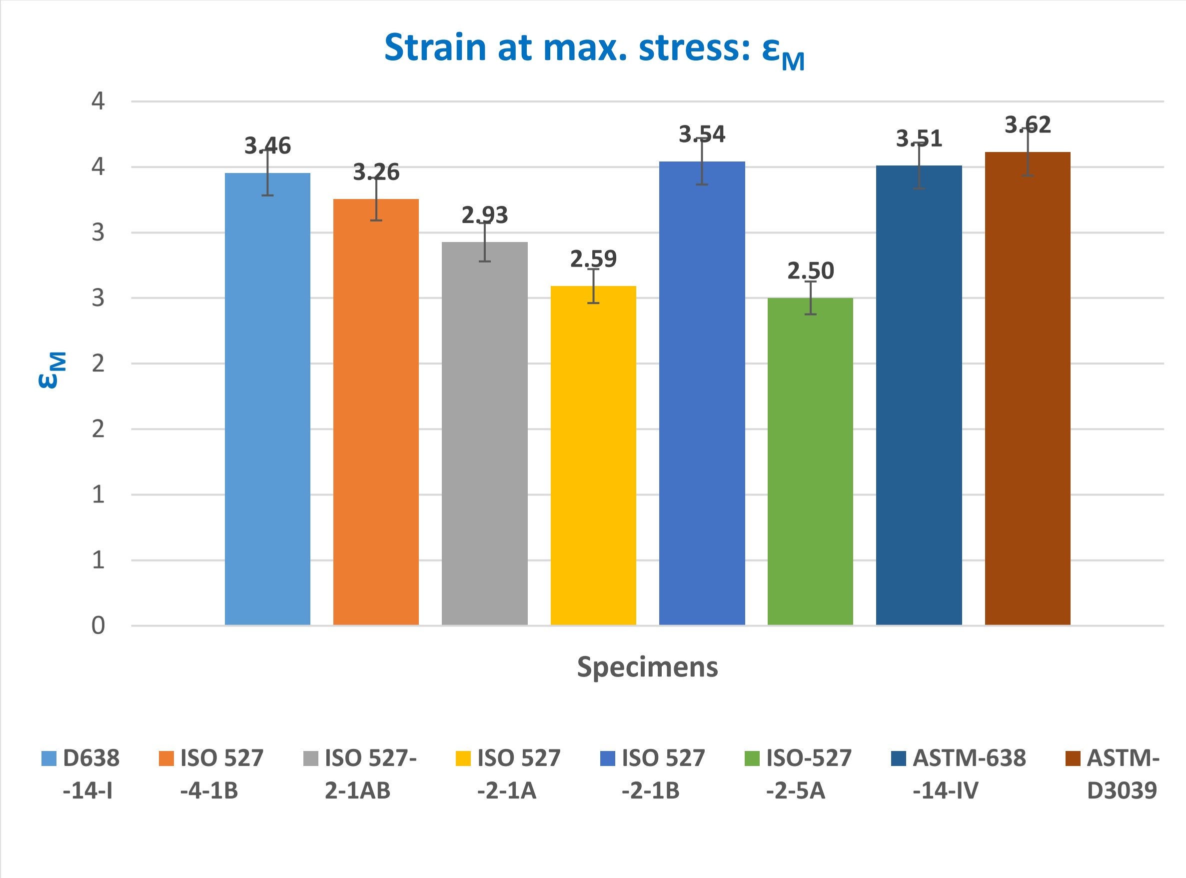
Figure 29: The tensile stress and Relative strain curves.

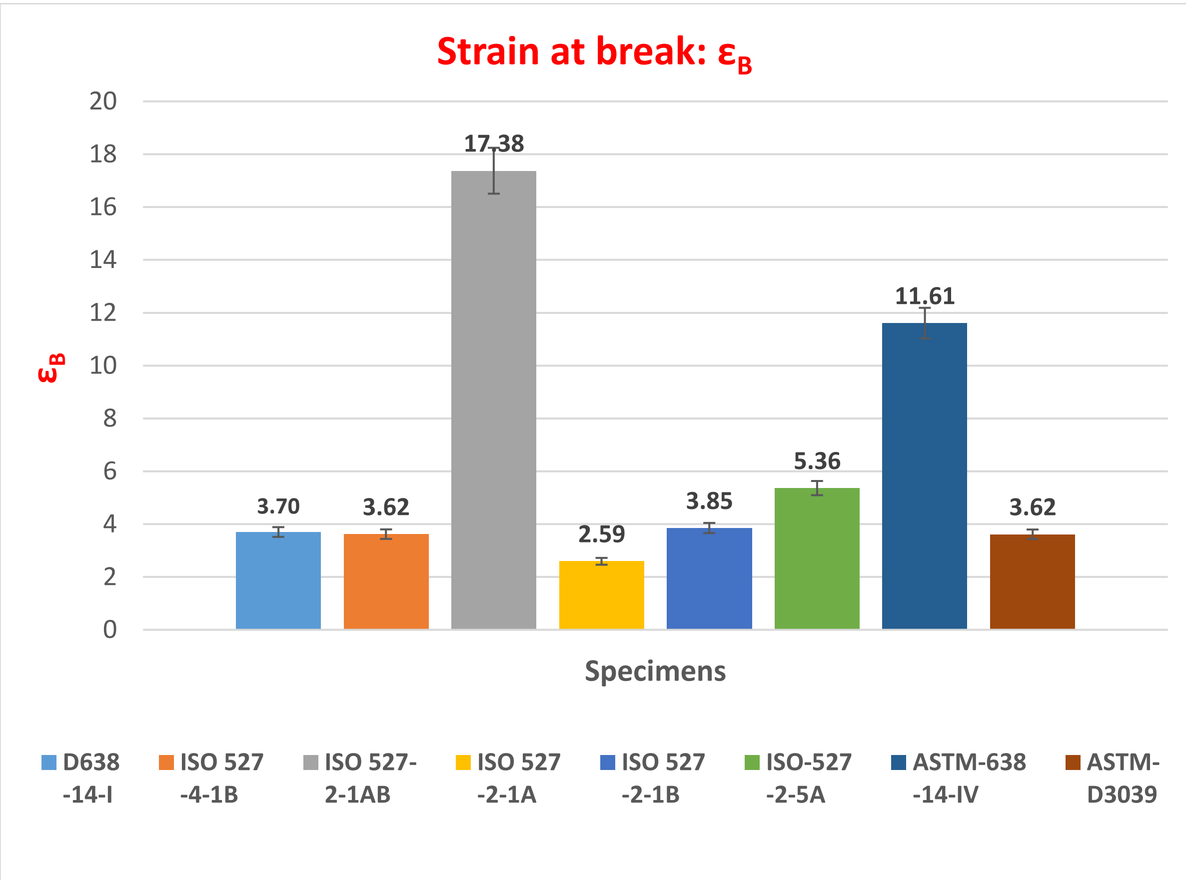
Table 15: Comparison of tensile test data for different standard specimens.

Comparison of Tensile test data for different standard specimens											
Specimen			Maximum point			Breakpoint			Dimensions		
	E_t	σ_{x1}	σ_M	ε_M	ε_{tM}	σ_B	ε_B	ε_{tB}	b	h	A_0
	MPa	MPa	MPa	%	%	MPa	%	%	mm	mm	mm^2
D638-14-I	1889.59	0.00	35.01	3.46	4.20	31.96	3.70	4.44	13.00	3.20	41.60
ISO 527-4-1B	1951.76	0.00	33.39	3.26	3.89	30.19	3.62	4.25	10.00	4.00	40.00
ISO 527-2-1BA	1940.00	16.95	43.15	2.93	3.43	8.62	17.38	17.88	5.00	2.00	10.00
ISO 527-2-1A	2013.64	0.00	29.93	2.59	3.71	29.93	2.59	3.71	10.00	4.00	40.00
ISO 527-2-1B	1505.03	0.00	27.15	3.54	4.75	24.15	3.85	5.06	18.33	3.33	56.67
ISO-527-2-5A	1225.10	0.00	30.94	2.50	2.72	13.59	5.36	5.58	5.00	2.00	10.00
ASTM-638-14-IV	2156.23	15.52	42.83	3.51	4.07	8.56	11.61	12.17	6.00	3.20	19.20
ASTM-D3039	1589.89	0.00	28.50	3.62	4.49	28.50	3.62	4.49	25.00	2.00	50.00


Tensile Modulus: Et
2500
2000
1500
1000
500
0
Et
1889.59
1951.76
1940.00
2013.64
1505.03
1225.10
2156.23
1589.89
Specimens
D638 -14-I
ISO 527 -4-1B
ISO 527-2-1AB
ISO 527 -2-1A
ISO 527 -2-1B
ISO-527 -2-5A
ASTM-638 -14-IV
ASTM-D3039


Stress at break: σB
40
35
30
25
20
15
10
5
0
σB
31.96
30.19
8.62
29.93
24.15
13.59
8.56
28.50
Specimens
D638 -14-I
ISO 527 -4-1B
ISO 527-2-1AB
ISO 527 -2-1A
ISO 527 -2-1B
ISO-527 -2-5A
ASTM-638 -14-IV
ASTM-D3039


Strain at max. stress: εM
εM
4
4
3
3
2
2
1
1
0
3.46
3.26
2.93
2.59
3.54
2.50
3.51
3.62
Specimens
D638 -14-I
ISO 527 -4-1B
ISO 527-2-1AB
ISO 527 -2-1A
ISO 527 -2-1B
ISO-527 -2-5A
ASTM-638 -14-IV
ASTM-D3039


Strain at break: εB
εB
20
18
16
14
12
10
8
6
4
2
0
3.70
3.62
17.38
2.59
3.85
5.36
11.61
3.62
Specimens
D638 -14-I
ISO 527 -4-1B
ISO 527-2-1AB
ISO 527 -2-1A
ISO 527 -2-1B
ISO-527 -2-5A
ASTM-638 -14-IV
ASTM-D3039

5.1.9.1 Maximum tensile stress σ_M

The figure 30 below, shows the examination results of Maximum tensile stress of 3D printed specimens from different standards.

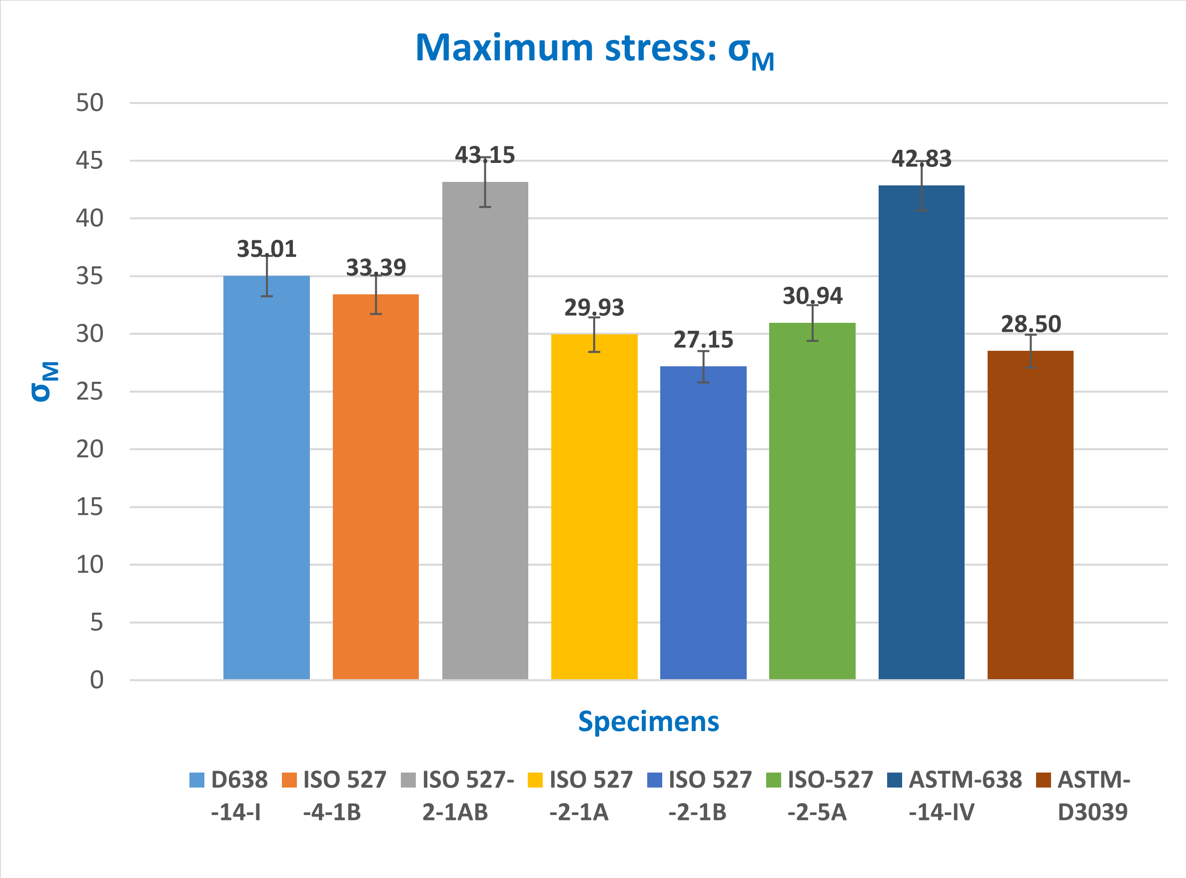


Figure 30: chart of the Maximum tensile stress values.

From the results in table 15, we got that:

1. ISO 527-2-1BA has a maximum tensile stress value of 43.15 MPa.
2. ASTM D638-14-IV has the 2nd tensile stress value of 42.83 MPa.
3. ASTM D638-14-I has the 3rd tensile stress value of 35.01 MPa.
4. ISO 527-4-1B has the 4th tensile stress value of 33.39 MPa.
5. ISO 527-2-5A has the 5th tensile stress value of 30.94 MPa.
6. ISO 527-2-1A has the 6th tensile stress value of 29.93 MPA.
7. ASTM-D3039 has the 7th tensile stress value of 28.5 MPa.
8. ISO 527-2-1B has a minimum tensile stress value of 27.15 MPa.

Table 15, shows the tensile test data for different standard specimens, including the maximum point, breakpoint, and dimensions of each specimen. The dimensions include the specimen width (b), height (h), and initial cross-sectional area (A_0) in millimeters. The maximum point is the highest stress point that the specimen can withstand before it starts to deform plastically. The breakpoint is the point where the specimen breaks completely.

- The data is presented in different units, such as megapascals (MPa) for stress, and percentages (%) for strain. The data also includes different types of standard specimens such as D638-14-I, ISO 527-4-1B, ISO 527-2-1BA, ISO 527-2-1A, ISO 527-2-1B, ISO-527-2-5A, ASTM-638-14-IV, and ASTM-D3039.
- The highest maximum point value is observed in the ASTM-638-14-IV specimen with a value of 2156.23 MPa, followed by ISO 527-2-1A with a value of 2013.64 MPa, and ISO 527-4-1B with a value of 1951.76 MPa. The lowest maximum point value is seen in the ISO-527-2-5A specimen with a value of 1225.10 MPa.
- The breakpoint values are observed to be highest in the ASTM-638-14-IV specimen with a value of 15.52%, followed by ISO 527-2-1BA with a value of 16.95%, and ISO 527-2-1B with a value of 3.54%. The lowest breakpoint value is seen in the D638-14-I specimen with a value of 0.00%.
- The dimensions of the specimens vary considerably, with the largest cross-sectional area observed in the ASTM-D3039 specimen with a value of 50.00 mm^2, followed by ISO 527-2-1B with a value of 56.67 mm^2, and D638-14-I with a value of 41.60 mm^2. The smallest cross-sectional area is observed in ISO-527-2-5A with a value of 10.00 mm^2.

Overall, the data suggests that the different standard specimens used in the tensile test have significantly different properties, including maximum point, breakpoint, and dimensions. Therefore, it is important to carefully select the appropriate standard specimen for the specific application.

6 CONCLUSION AND SUGGESTIONS

6.1 NEW SCIENTIFIC RESULTS.

From a mechanical engineering perspective, the main focus was on the maximum tensile stress and depending on the tensile test data which we measured from these different standard specimens we can figure out that there is a variety between the maximum tensile stress values measured of each standard and the theoretical tensile stress of the PETG plastic introduced from the produced factory.

From table 4:

ISO 527	**Manufactory Tensile strength (MPa) = Maximum tensile stress**	42.5 MPa

6.2 NOTES

6.2.1 First Note

From the results in table 15, we got that:

- ISO 527-2-1BA has a maximum tensile stress value of **43.15** MPa.
- ASTM D638-14-IV has the 2nd tensile stress value of **42.83** MPa.
- ASTM D638-14-I has the 3rd tensile stress value of **35.01** MPa.
- ISO 527-4-1B has the 4th tensile stress value of **33.39** MPa.
- ISO 527-2-5A has the 5th tensile stress value of **30.94** MPa.
- ISO 527-2-1A has the 6th tensile stress value of **29.93** MPa.
- ASTM-D3039 has the 7th tensile stress value of **28.5** MPa.
- ISO 527-2-1B has a minimum tensile stress value of **27.15** MPa.
- Those 3 standard specimens (ISO 527-2-1BA, ISO 527-2-5A, ASTM 638-14-IV) : did not brake during the Tensile test like the other standards.

6.2.2 Second Note

The shape or geometry can affect the mechanical properties of 3D printed materials. The following are some factors that can be affected:

- Surface area: The surface area of a 3D printed part can affect its strength and stiffness. A larger surface area can result in a weaker part due to the presence of more defects, such as voids or cracks, which can propagate through the material.
- Orientation: The orientation of the printed part can affect its mechanical properties. For example, printing a part in the vertical orientation may result in a stronger part due to the alignment of the layers with the applied load.

- Layer thickness: The thickness of each printed layer can also affect the mechanical properties of the part. Thinner layers can result in a smoother surface finish and higher resolution but may also be weaker due to the reduced adhesion between layers.
- Infill pattern: The infill pattern used in 3D printing can also affect the mechanical properties of the part. For example, using a honeycomb pattern can result in a stronger and lighter part compared to a solid infill.
- Material properties: Finally, the properties of the material being printed can also affect the mechanical properties of the part. Different materials have different strengths, stiffness, and other properties, which can affect the performance of the printed part.

6.2.3 Third Note

The mechanical properties of Polyethylene Terephthalate Glycol (PETG) can differ in tensile testing with different standard specimens due to several factors. Some of these factors are:

- Dimensional differences: The dimensions of the standard specimens used in tensile testing can vary. The width and thickness of the specimens can have a significant effect on the mechanical properties of the material, such as the tensile strength and modulus.
- Manufacturing variances: The manufacturing process of the standard specimens can result in variations in the material properties. For example, the molding or extrusion process can result in differences in the cooling rate or orientation of the polymer chains, which can affect the mechanical properties.
- Sample preparation: The method used to prepare the samples for testing can also have an impact on the mechanical properties. For instance, if the samples are not prepared properly or if they are contaminated, the test results can be affected.
- Testing conditions: The testing conditions, such as the temperature, humidity, and rate of loading, can also influence the mechanical properties of the material. For example, a change in temperature can cause the polymer chains to either contract or expand, which can affect the tensile strength and modulus.

6.2.4 Forth Note

The dimensional differences of standard specimens used in tensile testing can have a significant effect on the mechanical properties of a material, such as the tensile strength and modulus, because these properties are dependent on the microstructure and macrostructure of the material. The microstructure of a material refers to its internal structure at the atomic or molecular level, while the macrostructure refers to the material's overall shape, size, and arrangement of its constituents. When a material is subjected to tensile testing, it is subjected to a uniaxial force that pulls the material in opposite directions, causing it to deform. The amount of force required to cause the material to deform is a function of the material's mechanical properties, including its tensile strength and modulus. The tensile strength is the maximum stress that a material can withstand before it fails, while the modulus is a measure of a material's stiffness or resistance to deformation.

- The standard specimens used in tensile testing are typically cylindrical or rectangular in shape, with specific dimensions that are defined by various testing standards, such as ASTM or ISO. The dimensions of the specimens can have a significant effect on the mechanical properties of the material being tested because they affect the stress distribution within the material during the test.
- For example, if the diameter of a cylindrical specimen is too small, the stress at the center of the specimen can be much higher than the stress at the outer surface, leading to premature failure of the material at the center. Similarly, if the cross-sectional area of a rectangular specimen is too small, the stress at the edges can be much higher than the stress in the center, leading to premature failure at the edges.
- In addition, the length of the specimen can also affect the mechanical properties of the material, particularly the modulus. If the length of the specimen is too short, the ends of the specimen can affect the stress distribution, leading to inaccurate measurements of the modulus.

Therefore, it is important to use standard specimens with precise and consistent dimensions to ensure accurate and reliable measurements of the mechanical properties of a material. Any variations in the dimensions of the specimens can introduce errors and affect the validity of the results.

7 SUMMARY

In summary, Additive manufacturing or 3D printing involves creating a three-dimensional object from a digital model. This technology has diverse applications in fields like architecture, industrial design, and medical industries. 3D printing involves depositing, combining, or solidifying materials under computer control to create objects layer by layer. While it offers design flexibility, its mechanical properties are limited compared to traditional production methods. To address this, the study examines the material response properties of fused deposition modeling (FDM) structures and explores factors influencing their mechanical properties and dimensional accuracy. The paper compares the maximum tensile stress of different standard samples with theoretical tensile stress of PETG material to investigate the impact of shape on maximum tensile stress of PETG. The results showed that standard sample shape influenced the maximum tensile stress of PETG, with ISO 527-2-1AB having the maximum tension value and ISO 527-2-1B the lowest tensile stress. The differences in standard specimens used in tensile testing can affect the mechanical properties of PETG due to variations in dimensional, manufacturing, and testing conditions. Therefore, it is essential to carefully control these factors to ensure accurate and consistent test results.

Sandwich structures offer a combination of high strength, low weight, energy absorption, thermal insulation, sound damping, and customization options, making them an excellent choice for a variety of applications.

Strain rate: The tensile test involves applying a load to the specimen at a constant rate. If the specimen is of a different size, the rate of deformation may differ, resulting in different strain rates. The strain rate affects the deformation behavior and mechanical properties of the material.

Stress concentration: The dimensions of the specimen can affect the distribution of stress within the material. A smaller specimen may have higher stress concentrations at the ends, leading to localized yielding or failure.

Material heterogeneity: PETG, like most polymers, is a heterogeneous material with variations in properties at the microscopic level. The mechanical properties of the material can depend on the orientation and distribution of the polymer chains, which can vary with the specimen size and shape.

Edge effects: The edges of the specimen can affect the stress distribution and deformation behavior of the material. For example, a specimen with rough edges may have higher stress concentrations, leading to premature failure.

Specimen preparation: The preparation of the specimen can affect its properties. Different cutting methods or surface treatments may introduce stress concentrations or alter the surface roughness, affecting the mechanical properties of the material.

Overall, the differences in mechanical properties observed with different dimensional standard specimens are likely due to a combination of these factors. To obtain consistent and reliable results, it is important to carefully control the specimen dimensions, preparation, and testing conditions.

8 APPENDICES

8.1 REFERENCES

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