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Effect of Materials on the Mechanical Properties of Fused Deposition Modeling Three-Dimensional Printed Products

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ABSTRACT

This study evaluates the three-dimensional (3D) printing materials used in Fused Deposition Modeling (FDM) printing technology. 3D printing technology has been developing strongly, becoming an effective support tool in production and research. The 3D printing process involves many stages, with many parameters affecting the quality and properties of the product, in which 3D printing material is one of many essential factors affecting that process. The study conducts a comprehensive assessment of the most common materials in 3D printing technology to determine the advantages and limitations of precisely five types of materials: Polylactic acid, acrylonitrile butadiene styrene, polyethylene terephthalate glycol-modified, thermoplastic polyurethane, and acrylonitrile styrene acrylate. With 3D printing, parameters such as sintering temperature, printing speed, and layer thickness are kept constant. These parameters are applied equally to all five material samples. The experiment evaluates the tensile strength of materials. The study results provide an overview of the properties and applicability of 3D printing materials, helping to select materials suitable for specific FDM 3D printing technology applications.

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1. Introduction

Three-dimensional (3D) printing technology was developed in the 1980s, and until now, 3D printing is a popular method. Fused Deposition Modeling (FDM) technology is one of the 3D printing methods that uses the force of extrusion of printed material into a molten filament form. The process of FDM 3D printing technology is described in Figure 1 [1].

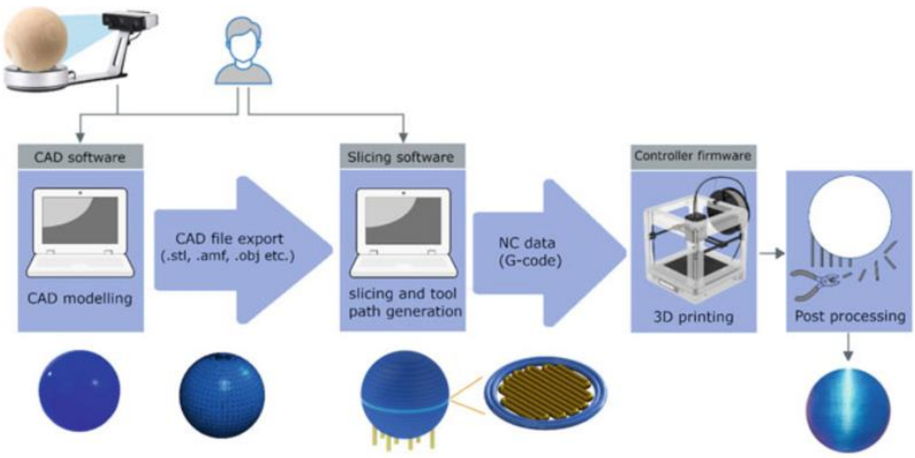

Figure 1. *Process of FDM 3D printer*

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The FDM printing process starts with designing 3D details to be printed and then exporting files with extensions such as stereolithography (STL), object (OBJ), additive manufacturing file format (AMF), etc. Next, input these files into 3D software for processing; the software will allow users to set up the necessary printing parameters. After setting the essential printing parameters, the software will compile into G-code and load into the 3D printer to start the process.

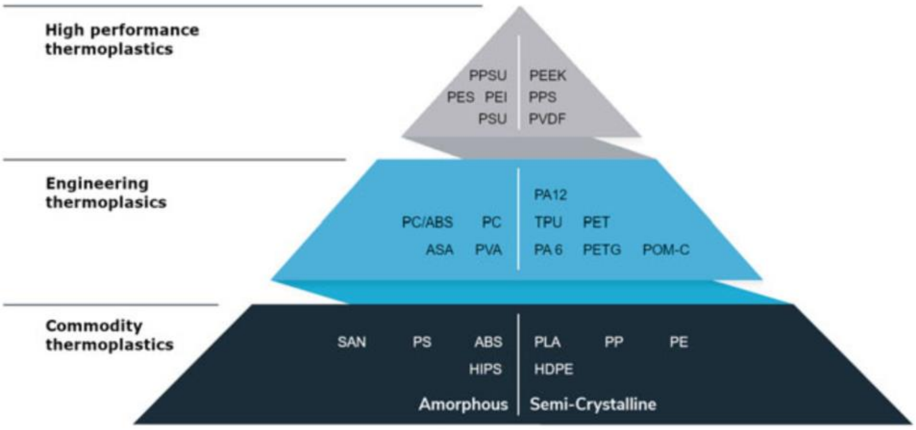

Figure 2. *Types of plastic materials used for FDM technology*

FDM technology uses everyday materials such as flexible plastic filaments with 1.75 mm and 2.85 mm diameters. The materials have different mechanical properties and include two types, amorphous and semi-crystalline plastics, divided into three groups, as shown in Figure 2 [1]. Group 1 are common materials (commodity-thermoplastics), including styrene acrylonitrile resin (SAN), polystyrene (PS), acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), polypropylene (PP), polyethylene (PE), high-impact polystyrene (HiPS), and high-density polyethylene (HDPE). Group 2 is engineering plastic materials with enhanced performance (engineering-thermoplastics), including polyamide 12 (PA12), polycarbonates (PC), PC/ABS, thermoplastic polyurethane (TPU), polyethylene terephthalate (PET), acrylonitrile styrene acrylate (ASA), polyvinyl alcohol (PVA), polyamide 6 (PA6), polyethylene terephthalate glycol-modified (PETG), and polyoxymethylene - copolymer (POM-C). Group 3 is high-performance thermoplastics, including polyphenylsulfone (PPSU), polyether ether ketone (PEEK), polysulfones (PES), polyetherimide (PEI), polyphenylene sulfide (PPS), polysulfones (PSU), and polyvinylidene fluoride (PVDF). This study focuses on five common materials: PLA, ABS, PETG, TPU, and ASA.

1.1. PLA Material

PLA is the most common material in the 3D printing industry. It is made from plant starch or sugarcane and is an environmentally friendly bioplastic. PLA is easy to 3D print, has low warping, and is suitable for applications that do not require high strength. In 2010, PLA had the second-highest consumption rate among various types of bioplastics worldwide [2]. PLA is a versatile material suitable for many applications due to its eco-friendliness, ease of 3D printing, diverse color and shape capabilities, and relatively good strength and hardness. Although not ideal for high-temperature 3D printing [3], PLA material still offers significant advantages and produces good results.

In June 2010, Nature Works became the primary producer of polylactic acid (PLA bioplastic) in the United States. The second-largest PLA producer globally is Weforyou Corporation, with an annual production capacity of 50,000 tons of neat and compounded PLA [4]. Furthermore, test samples made from PLA are stiffer and have greater tensile strength than ABS [5] and PETG [6], with optimal parameters compared to ABS and Nylon 6 based on FDM and injection molding technologies [7]. PLA is also easily combined with other additives to maintain similar mechanical properties while enhancing them compared to the original PLA [8].

1.2. ABS Material

ABS is a common thermoplastic polymer. This material is a primary plastic and is most interested in today. The physical properties of ABS plastic are complex, non-brittle, and good electrical insulation, durable through temperature and chemicals, so it is easy to process and produce in large quantities rich in designs. Application: With safety properties, no odor, good electrical insulation, high-temperature resistance, and good strength, ABS plastic is often used as children's toys, electronics, refrigeration, helmets, packaging, containers, water pipes, building materials, etc.

Most of the experiments and studies are directed toward choosing the raster angle parameter, proven to be the most significant in enhancing the mechanical behavior by the FDM method [9]. Some other studies on PC-ABS materials show the relationship between fabrication conditions and bending stiffness of the materials, which are considered optimal fabrication conditions to improve stiffness [10]. In addition, to solve the issues and explain how shrinkage can be managed by the internal geometry of the artifacts fabricated on a desktop 3D printer [11]. For the multiwall carbon nanotubes (MWCNT) enhanced ABS nanocomposite, the tensile strength of samples with a higher MWCNT ratio and raster orientation significantly influences the material's mechanical properties [12].

1.3. PETG Material

PETG is a flexible type of polyester plastic with high durability and good chemical resistance. PETG combines the flexibility of PLA and the strength of ABS, creating 3D-printed products with resistance to force, flexibility, and good impact resistance.

Regarding thermal and mechanical properties, PETG has a lower hardness than PLA, but it offers good heat resistance, impact resistance, and tensile strength compared to PLA. The chemical structure of the polymers does not change significantly during the production process [13]. Regarding the environmental impact of 3D printing materials (PLA, ABS, PETG) from production to recycling, PETG is more environmentally friendly than PLA and ABS [14]. The study has also highlighted that the mechanical properties of printed samples are greatly affected by infill density, and layer thickness changes influence the material's elasticity [15]. Compressive strength doesn't vary significantly across X, Y, and Z directions [16], and the compression of the material increases when carbon fiber is added to PETG [17]. In addition, when carbon and PETG are added, the material structure will perform better in maintaining strength after the part has local cracks [18]. Additionally, the combination of unique mechanical properties like elastic deformation and the ability to adjust hardness make these transitional materials highly useful for technical applications in light industry or healthcare [19].

1.4. TPU Material

TPU is a flexible plastic with outstanding properties such as good elasticity, abrasion resistance, and grease resistance. The chemical composition of TPU has two primary forms: TPU polyester and TPU polyether. Because of its outstanding properties, TPU is widely applied in today's life. In the field of 3D printing using FDM technology, TPU is one of the commonly used materials. For example, TPU material is used in transportation to make airless tires to replace traditional tires [20], which can be used in different terrains. In this study, the author tested the material's tensile strength, then made a sample tire and tried it with other loads. In-home appliances, TPU material is used to manufacture shoes, personal items, etc. The author analyzes the properties of the shoe sole with its star structure and the product's compressive capacity [21].

However, the current application that TPU material is applied most of all is the medical field. In research on 3D printing to manufacture biological models of body parts used in surgical training [22], the author uses the SWOT analysis method to evaluate printed material's physical properties and quality. The resulting TPU material increases product flexibility, making surgical planning and training faster, with an intuitive, realistic model that improves efficiency training. At the same time, the material is safe and has fewer complications than PLA material. In addition, other ingredients can be added to TPU, such as levofloxacin, which aims to increase the bearing capacity of TPU. Besides, TPU has good elasticity and is softer than PP material [23]. The studies focus on testing the physical and mechanical properties of materials [22]-[24] and tensile strength [21].

1.5. ASA Material

ASA is an amorphous thermoplastic polymer with properties very similar to ABS material, especially when comparing the mechanical properties and 3D printing conditions. The ASA material has a glass transition temperature of 118.5 °C. Due to its ultraviolet resistance, ASA is a perfect choice for prints for outdoor [25]. The products are made from high-strength ASA material and have good impact resistance. In addition, it can withstand higher temperatures and is resistant to rain, cold, and seawater.

A series of studies related to the mechanical properties of ASA have been conducted by researchers in various aspects. Authors often analyze the ASA material's mechanical properties to study the material's behavior [26]. Next, the comparison of mechanical properties of different materials [25], [27] is a classic method that provides an overview of material selection. Besides, studying the behavior of mixtures of materials [28], [29] also brings many significant contributions to specific applications. For example, Research focuses on developing and characterizing ASA and carbon fiber composites [28]. Using multi-material 3D printing technology coats the surface of ABS structures with an ASA layer to protect them from ultraviolet rays, humidity, and high temperatures [29].

Even though the tensile properties of some common 3D printed plastics (PLA, ABS, PETG, TPU, and ASA) have been tested and compared in the previous reports [5], [6], [22], [25], [29], [30], the further study on this topic is still necessary to expand the literature data. In this research, authors evaluate the tensile strength of the 3D printed products using the five materials mentioned above. The primary purpose of this study is to provide the mechanical properties of some common 3D plastics used in FDM technology and give users the rational selection of plastics in specific applications.

2. Materials and Methods

2.1. Materials

This research uses PLA, PETG, ABS, ASA, and TPU materials. These materials were sampled with dimensional specifications based on ASTM D638 type IV, as shown in Figure 3. Experiments were carried out in 25 samples. Each material corresponds to five models.

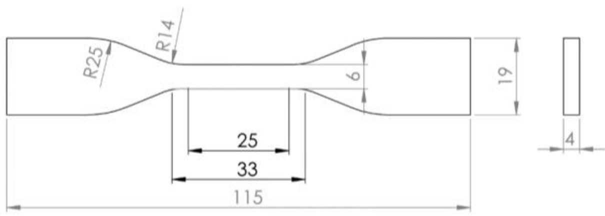

Figure 3. *Dimension of test sample according to ASTM D638 type IV standard*

2.2. Printing parameters

All pieces were 3D printed by FDM technology with the same set of parameters, as shown in Table 1. In which the infill of the samples is 100%.

Table 1. *Printing parameters of test samples by 3D FDM printer*

Parameters	PLA	PETG	ABS	ASA	TPU
Initial layer height (mm)	0,2				
Layer height (mm)	0,1				
Line Width (mm)	0,6				
Wall Thickness (mm)	1,2				
Infill (%)	100				
Print Temperature (Degrees Celsius)	200	230	240	240	200
Bed Temperature (Degrees Celsius)	60	80	120	120	60
Speed (mm/s)	60				

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The experiment samples are assigned codes according to the letters A, B, C, D, and E and the numbers 1, 2, 3, 4, and 5. PLA material is assigned the letter A with five samples: A1, A2, A3, A4, and A5, shown in Figure 4(a). Similarly, ABS, PETG, TPU, and ASA materials are assigned the letters B, C, D, and E for other materials, as shown in Figure 4(b, c, d).

(a) *(b)* *(c)* *(d)* *(e)*

Figure 4. *The samples of 5 types of materials: (a) PLA, (b) ABS, (c) PETG, (d) TPU, (e) ASA*

2.3. Tensile tests

The experiment is executed according to the standard method of tensile testing of plastic materials. Using the Testometric M350-10CT machine to test the tensile strength is shown in Figure 5. With the parameter settings: pulling speed 50 mm/min, pulling force 10 N, the cross-sectional area of the tensile specimen is 24 mm^2, and the deformation test length is 25 mm.

Figure 5. *Testometric M350-10CT machine*

3. Results and Discussion

The results of the tensile testing experiment on the Testometric M350-10CT machine with images of broken samples after testing are shown in Figure 6. Samples A, B, C, and E do not differ much in deformation, especially sample D, which has much more significant deformation than the other samples. On the other hand, because the printed outer layer's structure is a border, the broken samples have fibers. This result can be overcome when printing with a different profile.

Figure 6. *Tensile test samples of five materials after experiments*

The collected data includes tensile force (F) and material elongation (Elongation or ΔL). Data processing is performed to determine stress and strain. Applying the stress calculation formula according to the ASTM D638 standard, we have the following:

$$\sigma = \frac{F}{A_0} \quad (1)$$

Where σ is the stress (unit N/mm^2 or MPa, $1N/mm^2$= 1 MPa), F is the applied tensile force on the test specimen (unit N), A_0 is the cross-sectional area of the specimen (unit mm) and $A_0 = 24\ mm^2$. On the other hand, strain is calculated using the following formula:

$$\varepsilon = \frac{\Delta L}{L_0} = \frac{L - L_0}{L_0} \quad (2)$$

Where ε is the strain (%), L_0 is the initial gauge length according to ASTM D638 type IV standard (unit mm) and $L_0 = 25\ mm$, L is the gauge length after performing the tensile test (mm), ΔL is the elongation of the material before and after the trial (mm). Based on formulas (1) and (2), we can establish the relationship between stress and strain for the 25 test specimens. Each material will have five tensile test specimens.

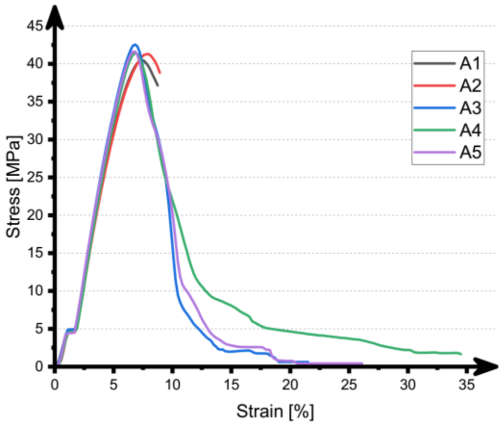

Figure 7. *Stress and Strain diagram of PLA*

Table 2. *The tensile test data of PLA material*

No.	Peak Load (N)	Young's Modulus (MPa)	Peak Stress (MPa)	Strain at Peak Stress (%)
A1	972.0	533.9	40.5	7.2
A2	991.2	533.9	41.3	7.6
A3	1022.4	513.5	42.6	6.7
A4	993.6	598.1	41.4	6.4
A5	998.4	641.6	41.6	6.5

For PLA material, the results of the five tensile test specimens are presented in Figure 7 and Table 2. The values at the peak stress from 40.5 to 42.6 MPa correspond to those at the peak strain from 6.4 to 7.6%. The highest stress value is 42.6 MPa, achieved in specimen A3. The deal of the highest strain is 7.6%, which is achieved in specimen A2. The value of Young's modulus is from 513.5 to 641.6 MPa.

For ABS material, the results of the five tensile test specimens are presented in Figure 8 and Table 3. The values at the peak stress from 39.9 to 43.8 MPa correspond to those at the peak strain from 6.8 to 7.4%. The highest stress value is 43.8 MPa, and the deal of the highest strain is 7.4% in the same B5 experimental specimen. The value of Young's modulus is from 446.4 to 535.1 MPa.

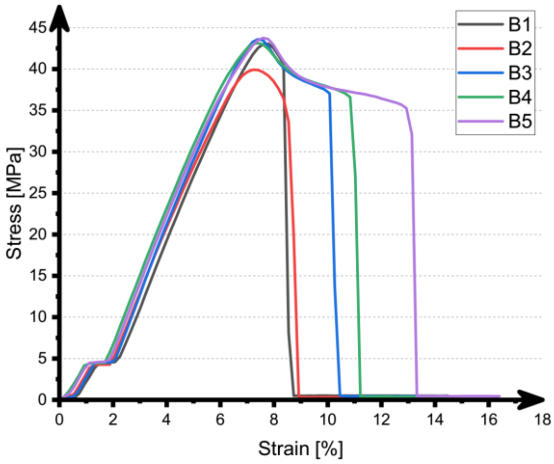

Figure 8. *Stress and Strain diagram of ABS*

Table 3. *The tensile test data of ABS material*

No.	Peak Load (N)	Young's Modulus (MPa)	Peak Stress (MPa)	Strain at Peak Stress (%)
B1	1032.0	498.9	43.0	7.2
B2	957.6	446.4	39.9	6.8
B3	1046.4	535.1	43.6	6.9
B4	1034.4	463.4	43.1	7.2
B5	1051.2	508.0	43.8	7.4

For PETG material, the results of the five tensile test specimens are presented in Figure 9 and Table 4. The values at the peak stress from 52.9 to 55.3 MPa corresponded to those at the peak strain from 9.1 to 9.9%. The highest stress value is 55.3 MPa, and the highest strain is 9.9% in the same C3 experimental specimen—the value of Young's modulus from 464.7 to 510.0 MPa. The experimental results obtained stress and strain values that are not much different from the previous research of Özen et al. The difference may occur due to the difference between the printing parameters of the two experiments [31].

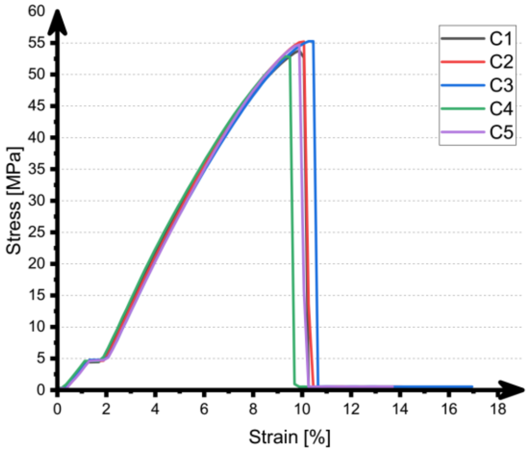

Figure 9. *Stress and Strain diagram of PETG*

Table 4. *The tensile test data of PETG material*

No.	Peak Load (N)	Young's Modulus (MPa)	Peak Stress (MPa)	Strain at Peak Stress (%)
C1	1291.2	510.0	53.8	9.6
C2	1324.8	474.3	55.2	9.7
C3	1327.2	469.5	55.3	9.9
C4	1269.6	487.9	52.9	9.1
C5	1312.8	464.7	54.7	9.5

For TPU material, the results of the five tensile test specimens are presented in Figure 10 and Table 5. The values at the peak stress from 21.2 to 26.6 MPa corresponded to those at the peak strain from 743.2 to 929.3%. The highest stress value is 26.6 MPa, and the highest strain is 929.3% in the same D2 experimental specimen—the value of Young's modulus from 31.9 to 33.6 MPa. The previous research by Wang et al. shows that TPU material has considerable strain and conversely minor stress [20] as the results of the experiment performed.

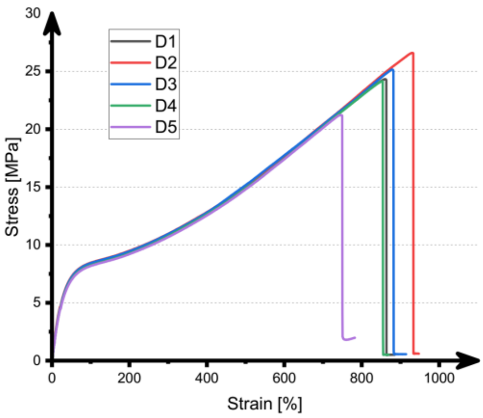

Figure 10. *Stress and Strain diagram of TPU*

Table 5. *The tensile test data of TPU material*

No.	Peak Load (N)	Young's Modulus (MPa)	Peak Stress (MPa)	Strain at Peak Stress (%)
D1	583.2	33.0	24.3	858.5
D2	638.4	33.5	26.6	929.3
D3	604.8	33.6	25.2	876.3
D4	580.8	33.2	24.2	850.4
D5	508.8	31.9	21.2	743.2

For ASA material, the results of the five tensile test specimens are presented in Figure 11 and Table 6. The values at the peak stress from 35.3 to 37.6 MPa corresponded to those at the peak strain from 6.4 to 6.6%. The value of the highest stress is 37.6 MPa, and the deal of the highest strain is 6.6% in the same E5 experimental specimen. The value of Young's modulus is 387.2 to 453.9 MPa.

Through the experimental parameters of each material, it can be seen that the value of the average tensile stress of the materials increases in order from TPU, ASA, PLA, ABS, to PETG materials, corresponding to the values 24.3, 36.6, 41.5, 42.7, and 54.4 MPa, are shown in Figure 12. The deal of average strain at the peak increases in order from ASA (6.5%), PLA (6.9%), ABS (7.1%), PETG (9.6%), and TPU (851.5%). Figure 13 describes the stress and strain diagram of five types of materials with TPU (sample close to the mean D1), ASA (piece close to the mean E3), PLA (model relative to the mean A5), ABS (sample close to the mean B4), PETG (sample close to the mean C5). It shows that TPU

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material has the most minor peak stress but has a much more significant strain than the other four types due to its good plasticity and elasticity. The PETG material has the most outstanding peak stress. The remaining three types of materials are ASA, PLA, and ABS, with little difference in stress and strain.

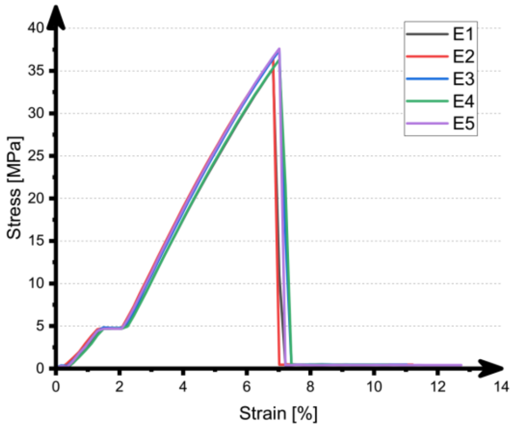

Figure 11. *Stress and Strain diagram of ASA*

Table 6. *The tensile test data of ASA material*

No.	Peak Load (N)	Young's Modulus (MPa)	Peak Stress (MPa)	Strain at Peak Stress (%)
E1	847.2	423.9	35.3	6.4
E2	873.6	420.6	36.4	6.5
E3	897.6	441.8	37.4	6.6
E4	871.2	387.2	36.3	6.6
E5	902.4	453.9	37.6	6.6

The tensile test results obtained stress and strain values similar to the previous experiment of Grabowik et al. [25]. In particular, the stress and strain values of PLA, ABS, and ASA materials are 39, 35, and 32 MPa, respectively, similar to the average peak stress of PLA, ABS, and ASA in experiments 41.5, 42.7, and 36.6 MPa.

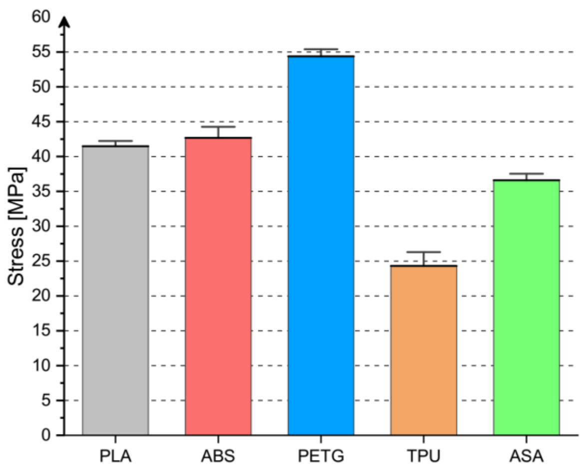

Figure 12. *The average tensile stress of 5 materials*

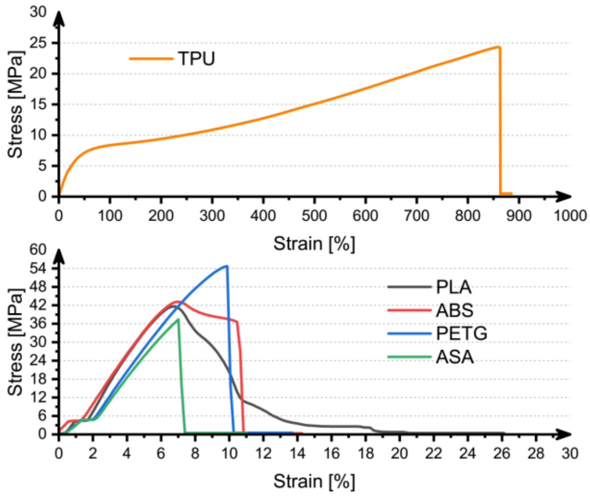

Figure 13. *Stress and strain curve of 5 materials*

4. Conclusions

According to the experiment and analysis result of materials after the tensile test, it can be concluded that TPU material has the lowest stress but conversely has the most significant strain. Thus, TPU material is suitable for applications with small hardness, flexibility, and elasticity as medical tools and biomimetic models of human and animal body parts. PETG material has the most stress and relatively small strain. It suits the applications requiring high stiffness, such as components, equipment, machine parts bearing, and impact resistance. The three materials, PLA, ABS, and ASA, do not differ much in stress and strain. They are suitable for household appliances, children's toys, water pipes, boxes, and packaging.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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