Article citation info:
Stecuła B, Sitko J, Stecuła K, Witkowski M, Orzeł B. Comparison of the strength of popular thermoplastic materials used in 3D printing – PLA, ABS and PET-G. Combustion Engines. 0000;XXX(X):xx-xx. https://doi.org/10.19206/CE-189386

Beniamin STECUŁA
Jacek SITKO
Kinga STECUŁA
Mirosław WITKOWSKI
Bartosz ORZEŁ

Combustion Engines
Polish Scientific Society of Combustion Engines

Comparison of the strength of popular thermoplastic materials used in 3D printing – PLA, ABS and PET-G

ARTICLE INFO

Received: 30 November 2023
Revised: 17 April 2024
Accepted: 27 May 2024
Available online: 19 July 2024

This paper presents the results of a comparative analysis of three prevalent materials used in 3D printing. PLA (Polylactic Acid), ABS (Acrylonitrile Butadiene Styrene), and PET-G (Polyethylene Terephthalate Glycol). The study includes strength testing using a tensile testing machine. Beginning with the selection of the input material used in the 3D printing process, the research aimed to provide insights into the strength properties of these materials. Autodesk Fusion 360 software was used for the precise design of the 3D model, ensuring suitability for subsequent tensile testing. The physical samples were then printed using 3D printing technology. The samples were subjected to a strength examination using a tensile testing machine. The data collection phase recorded and compiled the results of each strength test, forming the foundation for a comprehensive analysis. Using statistical methods and comparative analyzes, the data were thoroughly examined, allowing the derivation of conclusive observations and insights into the comparative strengths of PLA, ABS, and PET-G. The findings not only contribute to a deeper understanding of material performance but also provide a guide for material selection in 3D printing applications, guiding future research endeavors and industry applications in the ever-evolving landscape of additive manufacturing.

Key words: *strength, materials, 3D printing, tensile testing machines, engines, PLA, ABS, PET-G*

1. Introduction

With the continuous progress of technology, the industry connected with its production has undergone a great change. The emergence of Industry 4.0 has started a new era, where the fusion of cutting-edge technologies meets traditional manufacturing, reshaping the essence of production methods. One of the trends of this transformative wave is connected to additive technologies and advances in materials; this is a change in the way people think, design, and produce. It is related to Industry 4.0, which assumes the synergy between digital advances and physical systems [1]. This fourth industrial revolution represents a holistic evolution, including interconnected cyber-physical systems, the Internet of Things (IoT) [2], cloud computing [27], and cognitive computing [8]. These elements are converged to optimize processes, improve efficiency, and introduce more innovation in manufacturing and everyday life. Industry 4.0 also includes the development of additive technologies, covering a spectrum of techniques such as 3D printing [19], bioprinting [11], and advanced manufacturing methodologies [18, 23, 28, 36]. These technologies transcend the limitations of conventional manufacturing by enabling layer-by-layer construction, empowering designers and engineers to materialize designs with precision and customization. This change not only expedites production but also leads to material innovation that was previously unimaginable. Material innovation, as another element of the revolution, opens new possibilities. The ability to craft and manipulate materials at the microscopic level has redefined material properties, durability, strength, and functionality. Additive manufacturing, when paired with novel materials, including bioderived substances, is driving industries towards innovation and sustainability.

2. Engines and 3D printing

Industry 4.0 opens new possibilities for new research on engine topics, and the range of topics is broad, starting from studies on materials [33], through types of fuel [31], to emissions issues [32]. 3D printing is also a highly developing direction for research and practical application. 3D printing opens new possibilities in the field of vehicles and their engines. In the literature and practice, there are more and more examples of replacement of vehicle elements, and even engines parts, with elements and parts printed from popular filaments on a 3D printer. Products that come from additive manufacturing processes have broad industrial applications, including the automotive sector. The adaptability and mechanical properties of materials used as inputs in 3D printing make them pertinent for manufacturing components within engines and vehicles. Examples of 3D printing applications in the mentioned areas:

- components for the gas-discharge chamber of electric engines [24]
- solid fuel block mold geometries for hybrid engines [6]
- different gaskets in engines [29]
- air intake manifolds [30]
- pistons for engines [5]
- engine o-rings [12].

The adaptability and mechanical properties of materials used in 3D printing make them highly relevant for manufacturing components within engines and vehicles. This diversity is exemplified by various applications in the engine sector. For instance, 3D printing is utilized to fabricate components for gas-discharge chambers in electric engines, enabling precise customization. Additionally, it enables the creation of intricate mold geometries for solid fuel blocks in hybrid engines, enhancing efficiency. Also, 3D printing is employed in producing customized gaskets tailored to specific engine requirements. Moreover, it facilitates the manufacturing of air intake manifolds with optimized designs, leading to better engine efficiency. Furthermore, 3D printing allows for the crafting of high-strength, lightweight pistons, consequently enhancing engine performance and fuel efficiency. It also enables the production of customized engine o-rings for reliable sealing and functionality. These diverse applications underscore the adaptability and potential of 3D printing in producing a wide array of components and parts within the engine sector, offering increased customization, efficiency, and functionality in the manufacturing process.

These diverse applications illustrate the adaptability and potential of 3D printing in producing a wide array of components and parts within the engine sectors. The ability to tailor design, material selection, and manufacturing processes via 3D printing continues to revolutionize the production of various elements in vehicles and their engines, offering increased customization, efficiency, and functionality.

On the one hand, there are wide possibilities for using 3D printing in engines, and on the other hand, there is progress in input materials used in 3D printing. These two areas should be combined in research. Namely, the first stage in the above-mentioned areas should be research on the properties and capabilities of 3D printing materials that will be used in engines. For this reason, the authors undertook research on the strength of various materials used in 3D printing in order to focus on the production of selected engine components in the next stages. The strength testing stage is extremely important. This article presents only preliminary research on the strength of materials, which is only a fragment of larger research.

Based, on the above, the authors decided to conduct research in the field of comparing the strength of materials used for 3D printing. The authors selected the three most popular materials, PLA, ABS and PET-G, and conducted tests on their strength. Research included the preparation of a 3D model for the samples, the printing of the samples in each material, and carrying out strength tests on a tensile testing machine. After completing this stage of research, the authors analysed the results and drew conclusions.

3. Materials and Methods

3.1. Research Methodology

The methodology of the research included several steps:

– Step 1: Material selection: the initial phase involved a meticulous selection process to identify and choose the most prevalent materials in the 3D printing area. PLA (Polylactic Acid), ABS (Acrylonitrile Butadiene Styrene), and PET-G (Polyethylene Terephthalate Glycol) were chosen due to their widespread use, distinct properties, and relevance in various industries.
– Step 2: Design of the 3D model: to ensure consistency and accuracy in testing, the 3D model for the samples were designed using Autodesk Fusion 360 software. The model was the step before printing the samples, so the design had to be suitable for a tensile testing machine.
– Step 3: printing process: using 3D printing technology, the designed models were fabricated into physical samples using each of the selected materials – PLA, ABS, and PET-G. This step also included setting the printing parameters.
– Step 4: sample preparation: after printing the samples underwent meticulous post-processing to eliminate any inconsistencies or imperfections that could potentially impact the strength testing phase.
– Step 5: strength testing: the strength examination was conducted using a tensile testing machine capable of performing various mechanical tests. This step also included setting the machine's input parameters for strength tests – before examination began.
– Step 6: data collection: after each strength test, the computer generated the test results. Therefore, this stage of the research included the generation and collection of data from each strength test.
– Step 7: data analysis: the data collected from the strength tests were comprehensively analyzed, employing statistical methods and comparative analyzes. Based on the analysis of the test results, conclusive observations and insights were drawn regarding the comparative strengths of PLA, ABS, and PET-G.

3.2. Model designing

Autodesk's Fusion 360 software was used to prepare the model of the sample used in the experiment. Figure 1 presents a design in accordance with the E8/E8M-16a standard, with dimensions of L = 200 mm, C = 16 mm, and W = = 16 mm.

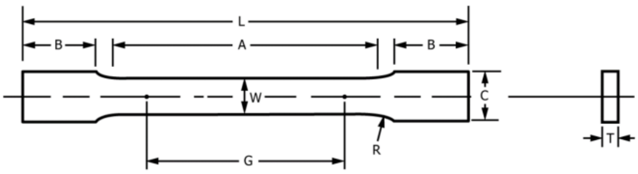

Fig. 1. A design of a round tensile specimen

Figure 2 shows a visualization of the sample in the form of a three-dimensional render.

Fig. 2. A three-dimensional render that is a visualization of a sample prepared in Autodesk's Fusion 360 software

3.3. Materials

A 3D printer allows you to produce different objects from specific materials. Popular polymer materials used for 3D printing are PLA, PET-G and ABS [35]. The study tested the strength of these materials.

3.3.1. PLA

It is a polymer produced from lactic acid [25]. It is a biodegradable material produced from renewable sources [20]. PLA is considered a non-toxic material, [13] but the authors of the article "Photolytic degradation elevated the toxicity of polylactic acid microplastics to developing zebrafish by triggering mitochondrial dysfunction and apoptosis." point out that PLA microplastics have a higher toxicity after degradation, in the context of a threat to aquatic ecosystems [21]. PLA prints are hard and brittle. The melting point of PLA filaments is low, about 175°C [37]. It is one of the most popular materials for 3D printing. It is often used in home or school 3D printers.

3.3.2. PET-G

It is a polyethylene terephthalate with the addition of glycol [10]. It is also a frequently used material in 3D printing. It has high resistance to damage and is malleable [26]. It is a material that biodegrades quickly, is harmless to humans and does not exhibit significant toxicity [7]. Prints made of PET-G material are stiff and have a glossy surface. It is worth noting the low hygroscopicity of this material, as well as its elasticity and lower shrinkage [3]. It is also often used in home and school 3D printers.

3.3.3. ABS

It is an acrylonitrile-butadiene styrene [34]. Also often used in 3D printing. It is a durable material, but at the same time, it has an easy ability to process [17], e.g., by drilling or grinding it. ABS printing produces harmful fumes, which is why ABS 3D printing should be done with adequate ventilation [22]. ABS also has a high degree of thermal shrinkage, compared to a low degree of thermal shrinkage in the case of PLA and PETG materials. This can lead to the so-called warping of ABS prints [9]. The coating of objects printed with ABS material can be smoothed with acetone, but this changes the structure and mechanical properties of the prints [13].

3.4. 3D printing process

Samples were printed from three types of materials: PLA, PET-G and ABS. The printing process was carried out according to the specifics of the manufacturer of a given 3D printer. For each 3D printer, the same sample output 3D model was used.

Samples made of PET-G material were printed on a Prusa i3 MK3S+ printer, and materials PLA and ABS were used in an Anycubic 4MAX pro printer. These are models of 3D printers that allow you to print from such materials. The 3D model was prepared for printing using Slicer and Ultimaker Cura software, which saved the model in a format known to a 3D printer. The Slicer program used was Prusa Slicer. In this program, printing parameters such as layer height and infill pattern have been assigned. Then, the file prepared for the 3D printer was saved on a memory card, which was placed in the 3D printer. The appropriate project was selected from the 3D printer menu to start the 3D printing process. After its completion, the model was properly described (Fig. 3).

Fig. 3. Printed and labeled samples

3.4.1. 3D printing settings

The 3D models were printed from each material in three different versions. Models with a layer height of 0.1 mm, 0.2 mm and 0.3 mm. A grid infill pattern and an infill density of 20% were used in all 3D prints. The models were printed vertically, and there was no need for supports. An extruder nozzle with a diameter of 0.4 mm was used. Speed of printing was adjusted by slicer software depending on used material and the print move types. The speed of printing the PETG model with 0.1 mm layer height is presented in Fig. 4. The nozzle and print bed temperatures have been adjusted to the characteristics of the material being used. For PLA material, the nozzle temperature was in the range of 210–215°C, and the printbed temperature was 60°C. For PET-G material, the nozzle temperature was 230°C, and the printbed temperature was in the range of 85–90°C. For ABS material, the nozzle temperature was 235°C, and the printbed temperature was 95°C.

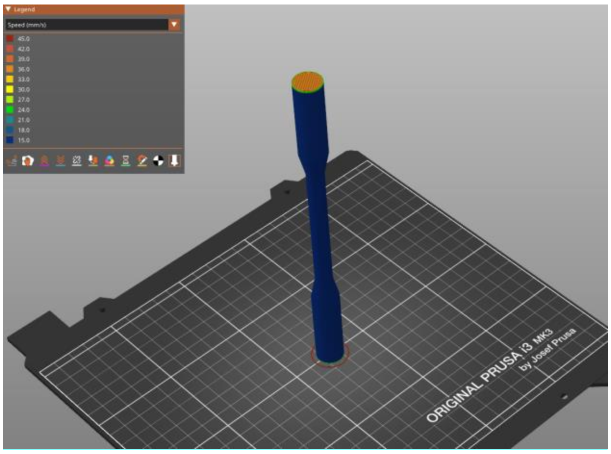

Fig. 4. Speed of printing PETG model with 0.1mm layer height

3.4.2. Filaments used during the 3d printing process

3D models were printed with PLA, PET-G and ABS materials.

For PET-G models, filament Devil Design PET-G Yellow was used. This filament has a diameter of 1.75 mm. Referring to the manufacturer's product card [38], this filament has a diameter tolerance of ±0.05 mm and an oval tolerance of + 0.02 mm. The recommended nozzle temperature during printing is in the range of 220–250°C, and the recommended printbed temperature is in the range of 70–80°C. However, the manufacturer of the Prusa 3D printer, in its profile for the Devil Design PET-G filament, specified a nozzle temperature of 230°C and a printbed temperature in the range of 85–90°C.

For PLA models, filament Devil Design PLA Bright Yellow was used. This filament has a diameter of 1.75 mm. Referring to the manufacturer's product card [39], this filament has a diameter tolerance of ±0.05 mm and an oval tolerance of + 0.02 mm. The recommended nozzle temperature during printing is in the range of 200–235°C, and the recommended printbed temperature is in the range of 50–60°C.

For ABS models, filament Devil Design ABS+ White was used. This filament has a diameter of 1.75 mm. Referring to the manufacturer's product card [40], this filament has a diameter tolerance of ±0.05 mm and an oval tolerance of + 0.02 mm. The recommended nozzle temperature during printing is in the range of 230–240°C, and the recommended printbed temperature is in the range of 90–100°C.

3.5. Characteristics of the machine

For the research, we used the Universal Material Testing Machine (Fig. 5) named model QC-503M2F (100kN). The manufacturer of the machine used for testing declares that it meets the following features [11]:

- compliance with standards: ISO 7500-1, ASTM E4, ASTM D-76, DIN5122, JIS B7721/B7733, EN 1002-2, BS1610, GB T228
- this series model is able to withstand a load of more than 100 kN
- qualified for ASTM, ISO, JIS, GB standard
- application to plastics, textiles and metals
- max capacity: 100 kN
- force units: gF, kgF, N, kN, tons
- pressure: kPa, MPa, bar, mm-Aq, mm-Hg

Measurement parameters:

- specimen diameter: 10 mm
- preload: 15 N
- minimum force from which we check the condition 50 N
- test speed: 15 mm/min.

Fig. 5. Jaws of the QC-503M2F Universal Testing Machine, general view

Other features described by the manufacturer [4]:

- automatic reading of load cell property information
- automatic reading of information from the displacement sensor
- force display, displacement display, time display, stress display, and strain display
- external analog input (2-channel simultaneous voltage or current readout)
- test force automatically reset
- self-definable test force calibration
- breakage detection
- automatic return
- force overload protection.

4. Results

4.1. Results of strength examination

The subject of the study were samples made of PETG, ABS and PLA, made in the 3D printing technique.

Samples with a diameter of 10 mm and a filling of 20% (characterized by lower material consumption, which translates into lower cost and shorter time of printing the sample) were tested. The technique of layered printing with layer thicknesses was used:

- 0.1 mm
- 0.2 mm
- 0.3 mm.

A static tensile test of the material was used for the tests.

Tests at room ambient temperature, about 20ºC, allowed us to draw many conclusions. The tested samples were characterized by similar strength compared to the steel sample, which is the comparative material:

- PETG 6 MPa
- PLA 5.8 MPa
- ABS 5.4 MPa
- steel reference sample 480 MPa.

According to a scientific website Matweb, the tensile strength of beforementioned materials is approximately:

- PETG 45 MPa [14]
- ABS 38 MPa [15]
- PLA 60 MPa [16].

4.2. Analysis of results

It can be noted that the obtained in the study tensile strength of PETG, PLA, and ABS materials are several times lower than values from the scientific website Matweb. This could be due to 20% filling of 3D models and as a consequence of the layering nature of 3D printing. It should be noted that the break has always occurred between the layers. The obtained results are different because this research was meant to be unique in terms of testing not the material itself but the use of this material in the context of 3D printing.

The ABS material in our measurements had the least tensile strength, which agrees with the data presented, while PLA and PETG had similar values, so further testing on a larger number of samples is indicated. The lowest tensile strength was found in the printed plastic with a layer of 0.3 mm. A selected graph of a material PETG is presented in the Fig. 6.

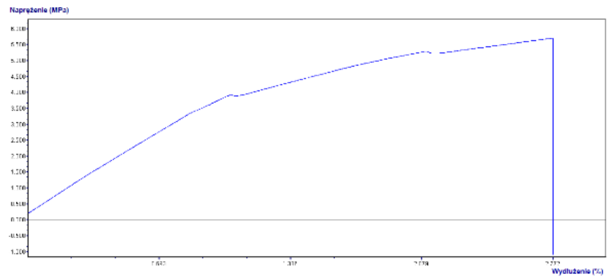

Fig. 6. Diagram showing the result of the tensile test of a PETG sample with a density of 20 % and a printing layer of 0.3 mm

ABS plastic (Fig. 7) is characterized by the highest elongation, up to 5%, with an average tensile force of approx. 5.4 MPa. This proves that the material is highly plastic, maintaining optimal tensile strength. The highest strength up to 6 MPa, ABS achieves for a layer with a thickness of 0.1 mm.

The elongation before tearing tested by us was:

- PETG 2.5%
- PLA 1.1%
- ABS 3.4%.

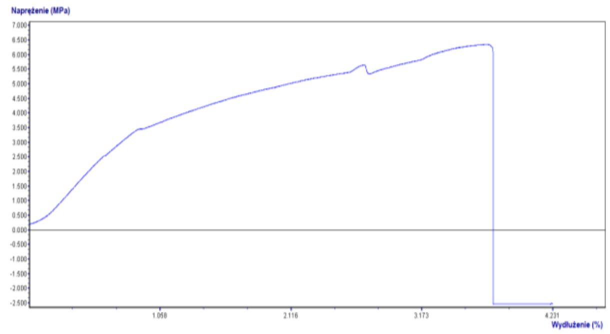

Fig. 7. Diagram showing the result of the tensile test of an ABS sample with a density of 20 % and a printing layer of 0.1 mm

PLA material (Fig. 8), printed with a layer of 0.1 mm, has the highest tensile strength of approx. 7.5 MPa and the highest plasticity of approx. 1.5% compared to prints with a different layer thickness. PLA is characterized by the highest rigidity, hardness, and abrasion resistance among the tested materials.

The non-uniform course of diagrams, especially for ABS and PET-G plastics with a characteristic step, visible around 2/3 of the elongation (Fig. 7 and 8), may result from the influence of internal forces on or between polymer chains. It is advisable to perform additional tests for the above-mentioned materials with a filling of up to 80%. This will make it possible to compare the results of strength and plasticity as well as the reaction of plastics to statically increasing mechanical load.

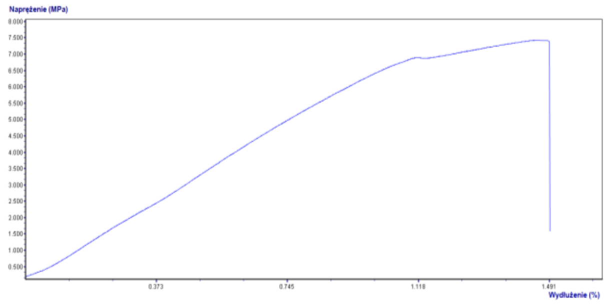

Fig. 8. Diagram showing the result of tensile testing of a PLA sample with a density of 20 % and a printing layer of 0.1 mm

5. Conclusions

Summarizing the results of the research, it can be concluded that the used testing machine is also suitable for testing polymers intended for 3D printing, and its selection turned out to be right. The results of the tests allow to compare the strength of 3D models printed from PLA, PET-G, and ABS. An important conclusion is that the selection of 3D printing parameters, as well as the selection of the polymer material used, affects the durability of the printed models. Changing the height of the 3D printing layer causes a change in the strength of a given model. It is advisable to explore the research, e.g. by comparing 3D prints with a different degree of filling.

To improve the quality of the designed materials, their properties can be tested when the 3D printing model will be made with thicker layers or using two different materials.

The research presented in the article is only the initial stage of larger research on the strength of materials used in 3D printing. Expanding from the foundational strength testing of PLA, ABS, and PET-G materials, future research will focus on optimizing these materials for engine-specific conditions, possibly through composite formulations or altered manufacturing processes. Subsequent stages will involve fabricating actual engine components via 3D printing and subjecting them to rigorous performance tests simulating real-world engine stresses. Additionally, analyzing the lifecycle and environmental impact of these materials and fostering collaborations with engine manufacturers would ensure alignment with industry needs and sustainable advancements in additive manufacturing for engine components.

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Beniamin Stecuła, MEng. – Faculty of Applied Mathematics, Silesian University of Technology, Poland.
e-mail: *beniamin.stecula@polsl.pl*

Jacek Sitko, DEng. – Faculty of Organization and Management, Silesian University of Technology, Poland.
e-mail: *jacek.sitko@polsl.pl*

Kinga Stecuła, PhD – Faculty of Organization and Management, Silesian University of Technology, Poland.
e-mail: *kinga.stecula@polsl.pl*

Mirosław Witkowski, MEng. – Faculty of Applied Mathematics, Silesian University of Technology, Poland.
e-mail: *miroslaw.witkowski@polsl.pl*

Bartosz Orzeł, MEng. – Faculty of Organization and Management, Silesian University of Technology, Poland.
e-mail: *bartosz.orzel@polsl.pl*