TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

ACTA TECHNICA NAPOCENSIS

Series: Applied Mathematics, Mechanics, and Engineering
Vol. 68, Issue I, March, 2025

RESEARCH OF PROTOTYPES MADE THROUGH FDM TECHNOLOGY

Slavi LYUBOMIROV, Emil VELEV, Snezha SHOTAROVA
Ionut GEONEA, Cristian COPILUSI, Laurentiu RACILA, Cosmin MIRITOIU

Abstract: *The authors present material testing of 3D printed prototypes in the paper, offering practical insights for both the industrial and academic communities to enhance mechanical and digital design in the context of additive manufacturing for specific fused deposition modeling (FDM) technology [1,2]. The authors present and argue the choice of material for designing an automotive industry element, the suspension rod [8]. With their versatile properties, these materials are subjected to experimental tests to evaluate selected mechanical properties that can be successfully adapted to CAD/CAM/CAE systems for engineering analyses [3].*

Keywords: *FDM technology, filament research, mechanical properties, model design, CAD/CAM/CAE systems.*

1. INTRODUCTION

The level of automation in several areas of technological design is fundamental when choosing the necessary methods to ensure its quality. Design automation ensures the systematic use of computers in the design process and the reasonable distribution of functions between the designer, technologist, and the computer [1, 4, 5, 6, 8, 9].

The use of computer-aided design not only increases the productivity of the technologist but also significantly enhances the working conditions of the designers. It also quantitatively automates mental-formal (non-creative) work, develops simulation models to reproduce a technologist's activity, and improves his ability to make project decisions under partial or complete uncertainty in emerging project situations [2, 7].

This paper's research objects are prototypes of parts with complex shapes manufactured on additive devices from spatially curved layers within the framework of FDM technologies [3, 6, 8, 9]. The research aims to obtain theoretical and practical information about methods of forming a product from spatial curvilinear layers and their influence on the strength and durability of the obtained products [10].

The research focuses on an FDM-based method for additively manufacturing products with complex shapes by molding them from spatial layers.

The research evaluated selected mechanical properties of three types of filaments: PLA, PC, and ABS [10].

The study discusses the influence of the sample production method on selected mechanical properties and the errors made in measuring selected mechanical properties [8]. In addition to evaluating the mechanical properties of the selected thread, the scientific material shows how to adapt the determined material constants to the computational model of the finite element method and presents the effectiveness of topological optimization in the engineering of a design that allows reducing the weight of the selected sample by about 20% compared to the initially accepted value [12, 13].

2. METHODS OF MANUFACTURING THE RESEARCHED PROTOTYPES

Prototyping methods are divided according to the method of application and bonding of the layers, as well as according to the aggregate state and structure of the material [5, 7, 11]. Within

Received: 14.01.25; **Similarities**: 05.03.25: **Reviewed**: 14.01./14.01.25: **Accepted**:12.03.25.

this division, three main types of technologies currently in use can be justified:

- Technologies based on material extrusion: FDM, LMD, LDM [12];
- Technologies based on liquid input material: LCD, MLCD, SLA, DLP, HARP [13];
- Technologies based on powder-form charge material: SLS, DMLS, jet synthesis [14].

An illustrative representation of all additive manufacturing methods is shown in Figure 1.

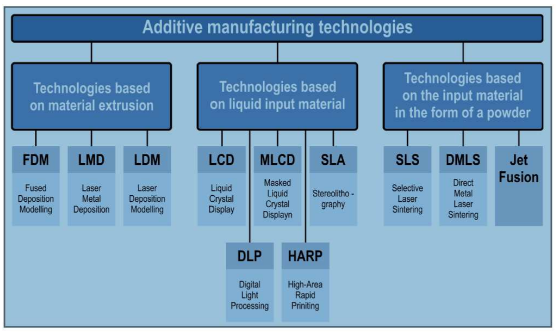


Fig.1. Additive manufacturing methods.

For research and analysis purposes, it has been decided to manufacture all structural elements using fused deposition modeling (FDM) technology based on material extrusion using PLA, PC, and ABS as input materials [15, 16]. The technology of Fused Deposition Modeling (FDM) or Fused Filament Fabrication (FFF) is an additive manufacturing process that belongs to the material extrusion family [14, 20]. In FDM 3D printing, the object is built by selectively depositing molten material in a predetermined path layer by layer. The materials used are thermoplastic polymers in thread form [16].

Good layer adhesion is of the utmost importance in FDM technology. As the molten thermoplastic is extruded through the nozzle, it is pressed against the previous layer [21]. The high temperature and pressure melt the surface of the last layer and allow the new layer to bond to the pre-printed part [21].

The strength of the connections between the different layers is always lower than the fundamental strength of the material. Therefore, FDM parts are anisotropic – their strength in the Z axis is always less than in the X and Y planes. Therefore, when designing FDM parts, it is essential to consider their orientation [11, 18].

It should be noted that FDM parts are not densely printed to reduce printing time and save materials. Instead, the outer perimeter is traced using a shell, and the interior is filled with a low-density internal structure called infill. The fill and shell density significantly affect a given part's strength. For FDM printers, the default setting is 25% fill density and 1mm shell density, which is a good compromise between power and speed for fast printing.

One key strength of FDM is the wide range of materials available [20]. These can be widespread thermoplastics (PLA, ABS, PC), engineering materials (PA, TPU, PETG), or high-performance thermoplastics (PEEK, PEI) [17]. The material used affects the printed part's mechanical properties, precision, and cost [14, 15, 17].

3. EXPERIMENTAL STUDIES OF SAMPLES

To determine the selected mechanical properties of the sample thread, the European-British standard BS-EN ISO 527 for plastics was meticulously followed in a uniaxial tensile test. The BS EN ISO 527-1 standard sets out the general principles for determining the tensile properties of plastics and plastic composites under specified conditions. It provides key data on plastics' tensile strength, modulus, and elongation at ambient, elevated, or reduced temperature.

The study used nine samples printed using FDM technology on PLA, PC, and ABS filaments. For 3D design, the Solid Edge 2022 software environment was used.

In this case, the CreatWare program was used, allowing 3D objects to be printed using the CreatBot 3D printer. The program will enable users to change printing parameters such as layer height, shell thickness, nozzle temperature, retraction speed, cooling fan percentage speed, etc. during printing.

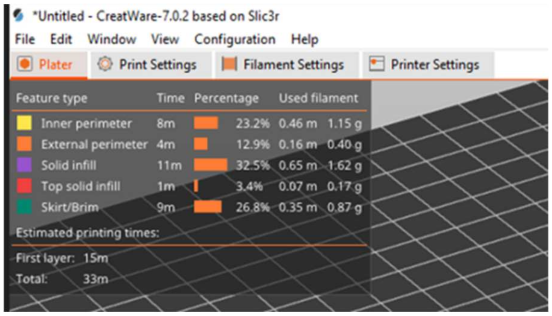


Fig. 2. Print values for ABS filament *(Source: Authors).*

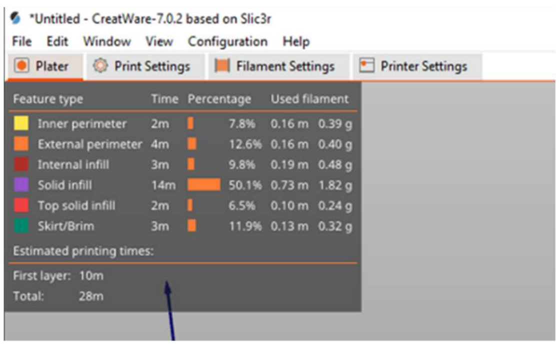


Fig. 3. Print values for PC filament *(Source: Authors).*

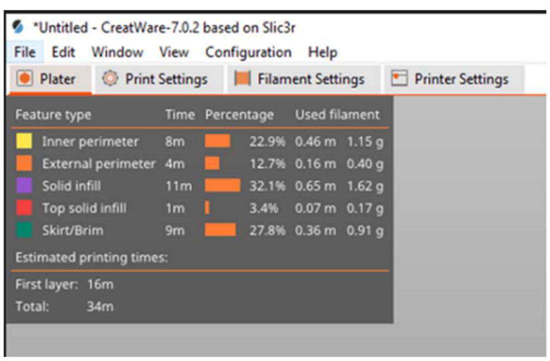


Fig. 4. Print values for PLA filament *(Source: Authors).*

The air temperature near the device during the production of the samples was 20 °C, and its humidity was about 70%.

The generated G-code file for the embedded device profile and modified device material, structure, and motion settings. A mesh fill type is proposed, which is a shape-like structure consisting of two sets of intersecting walls at right angles at a constant distance from each other, creating empty areas of square-based cuboids. This structure does not change along the Z-axis. As can be concluded in [12], in which a similar test was performed for such an infill, the increase in strength is not entirely linear, and there are spikes in strength for specific infill values. Therefore, three different types of filling - 30%, 60%, and 90% - were chosen to minimize material consumption. Also, three samples were made for each specimen to minimize testing errors.

The experiment investigated the effects of filling density, different filaments, and layer thickness on the mechanical properties (such as tensile, bending, and compressive strength) of samples created using FDM technology [18, 19].

The authors note that the relationship between mechanical properties and process parameters (filling density and layer thickness) is positive. Based on the research, it can be said that the mechanical properties increase with the increase in the filling density and layer thickness.

A set of monotonic tensile tests was performed on the 3D-printed plastics. The experiment tested 9 "dog bone" test specimens, and the percentage of infill, geometry of infill, load orientation, strain rate, and material were varied.

The results obtained by the authors show that the ultimate tensile strength decreases as the percentage of filler decreases, and that the geometry of the hexagonal pattern filler is more substantial and stiffer than the rectilinear filler [21]. The finite element method results show that the rectilinear infill shows less deformation than the hexagonal infill when the same load is applied.

4. EVALUATION OF SELECTED MECHANICAL PROPERTIES OF PLA, PC, AND ABS FILAMENTS

The object of investigation and measurement of various indicators is a detail representing an automobile rod performing a suspension level function, which is made of three different materials, presented in the following figure.

The presented models' designs used the CAD/CAM software SolidWorks 2022.

Samples numbered 1, 2, and 3 are printed from PLA filament. This is one of the most popular materials used in 3D printing to make various prototypes, concept models, or mock-ups. PLA produces details with high accuracy, strength, and minor distortions when printing in the temperature range of 195°C - 220°C.

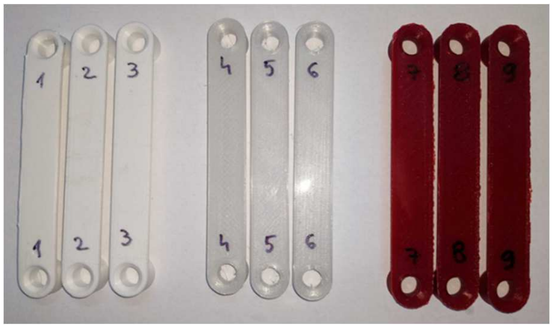


Fig. 5. View of the examined specimens *(Source: Authors).*

Samples 4, 5, and 6 are printed with a 3D printer consumable - polycarbonate (PC) filament.

Due to its physical properties, PC is an ideal 3D filament for printing parts that must be strong, durable, and retain shape in high-temperature environments, such as electrical, mechanical, or automotive components.

Samples 7, 8, and 9 are printed with a 3D printer consumable: ABS (acrylonitrile butadiene styrene), one of the most widely distributed amorphous plastics.

When working with ABS in 3D printing, a working range of 235°C - 255°C is recommended, and it is also necessary to heat the printer bed to 90°C - 110°C. The only disadvantage of ABS is the release of a slight odor during the printing process.

The following photographic material presents the examined details, with the letter A from each filament indicating the tests.

5. EXPERIMENTAL RESEARCH

The specimens were mounted on a bending test machine. During the bending tests, the deformation occurred at the midpoint of the test material, and the bending force caused the concave surface or fracture bending. Bending tests are usually performed to determine the ductility or fracture resistance of said material. During these tests, the material is shaped into a specific shape. The force is applied to the test specimen at its midpoint to form a concave surface with a curvature radius determined per the basic standard.

Fig. 6. Specimens of ABC filament placed for examination *(Source: Authors).*

The tested specimen is placed horizontally on the two supports, as shown in Fig. 7, and then a force is applied to the midpoint, deforming the sample into a U-shape.

The specimen's bending test determines the material's flexibility, bending strength, breaking strength, and fracture resistance. These properties indicate the behaviour of a material under pressure.

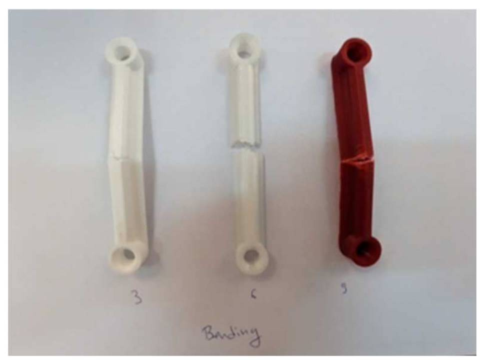


Fig. 7. View of the specimens after the bending tests *(Source: Authors).*

Expressing forces in decanewtons (symbol: daN) as presented in Table 1 or kilonewtons (symbol: kN) is standard practice.

Table1.
Tabular results of the conducted research *(Source: Authors)*

	1 mm	2 mm	3 mm	4 mm	Fleche (mm)
Eprouvette 3 (blanche-alb)	30	39	-	-	
Eprouvette 6 (grise-gri)	20	27	35	40	Force (daN)
Eprouvette 9 (rouge-rosu)	20	32	40	-	

6. MEASUREMENT RESULTS OF SELECTED MECHANICAL PROPERTIES

The nine uniaxial tensile tests were performed.

The prototypes' research and measurements were performed on an Instron tensile testing machine. These tensile specimens are tested on a machine that pulls the specimen to failure at a programmed rate.

The load cell precisely measures the stress applied to the specimen, and the extensometer measures how much it stretches. This allows the machine to generate a stress-strain curve for analysis.

Force, displacement, and "stress" (how much the material stretches) are measured, and strain-stress curves are displayed graphically to provide insight into many material properties.

Commonly reported mechanical properties include ultimate tensile stress (the maximum stress a part experiences in tension) and elongation at break (how much the "gauge length" stretches before breaking) [17]. The modulus of elasticity can be calculated from these values by dividing the overstress by the stress.

The software product used was **Bluehill 3**, which is designed to work with a universal testing machine up to 2000 kN from Instron®.

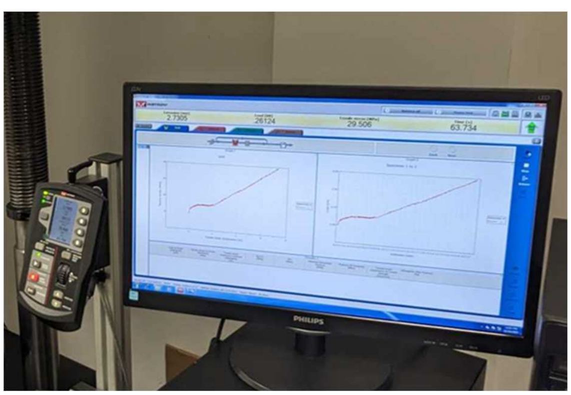


Fig. 8. Desktop view of the Bluehill 3 software product *(Source: Authors)*.

Prototype testing was carried out with a universal testing machine up to 2000 kN, which includes electromechanical and hydraulic systems to perform static testing, including tensile, compression, bending, peeling, tearing, shearing, friction, drilling, and other mechanical tests.

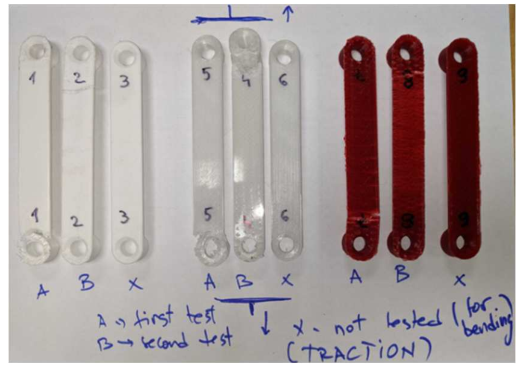


Fig. 9. View of the samples after the tests have been carried out *(Source: Authors)*.

The results of the studies are presented and graphically visualized in the software environment Bluehill 3. The two diagrams are visualized in the software environment. The first diagram shows a relationship between the tensile stress in [MPa] and the tensile strain (stretch) in the percentage of elongation [%]. The second diagram gives the relationship between load in [kN] and elongation in [mm]. The maximum load of the test material before failure can be calculated from these diagrams. In the upper part of the working field, the numerical data for the elongation in [mm], the load in [kN], and the tensile stress in [MPa] can be seen.

This diagram shows the relationship between the stresses that occur in the test body—a specimen—and the change in its length. In this case, it is elongation since the test is tense. The displaced yield Rp 0.2 [MPa] is the tensile stress in a uniaxial tensile test where the plastic elongation corresponds to 0.2% of the extensometer length. The specimen was elongated by 0.2% in the plastic range based on the initial length. The tensile strength Rm in [MPa] (also tensile strength) is a characteristic value of the material used to evaluate the strength behavior. Tensile strength is the maximum mechanical tensile stress a specimen can undergo. The results of the studies indicated in Fig. 10 to 15 give the "stress-strain" curves. Force, displacement, and "stress" (how much the material stretches) are measured, and strain-stress curves are graphically displayed to provide insight into many material properties.

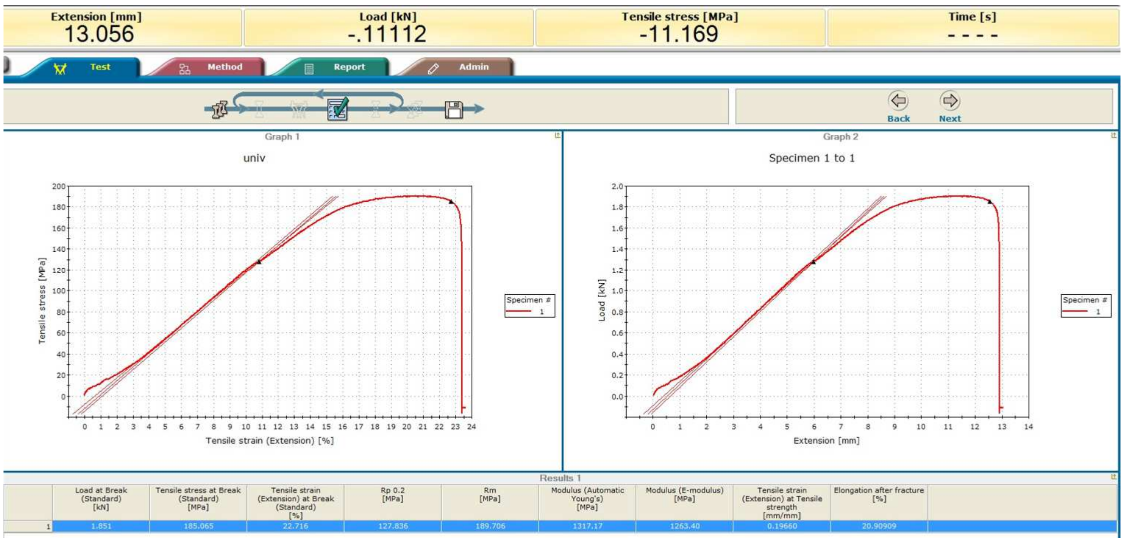
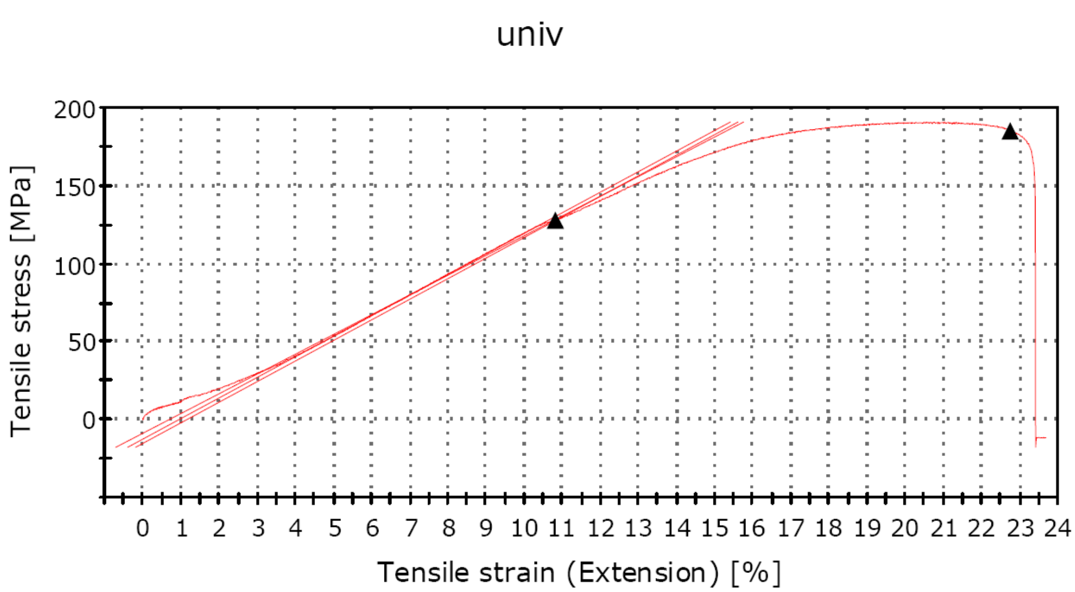


Fig. 10. Tensile curve for a specimen made of PLA filament *(Source: Authors)*.



	Load at Break (Standard) [kN]	Tensile stress at Break (Standard) [MPa]	Tensile strain (Extension) at Break (Standard) [%]	Rp 0.2 [MPa]
1	1.851	185.065	22.716	127.836

	Rm [MPa]	Modulus (Automatic Young's) [MPa]	Modulus (E-modulus) [MPa]	Tensile strain (Extension) at Tensile strength [mm/mm]
1	189.706	1317.17	1263.40	0.19660

	Elongation after fracture [%]
1	20.90909

Fig. 11. Tabular presentation of sample 2 - PLA filament test results *(Source: Authors)*.

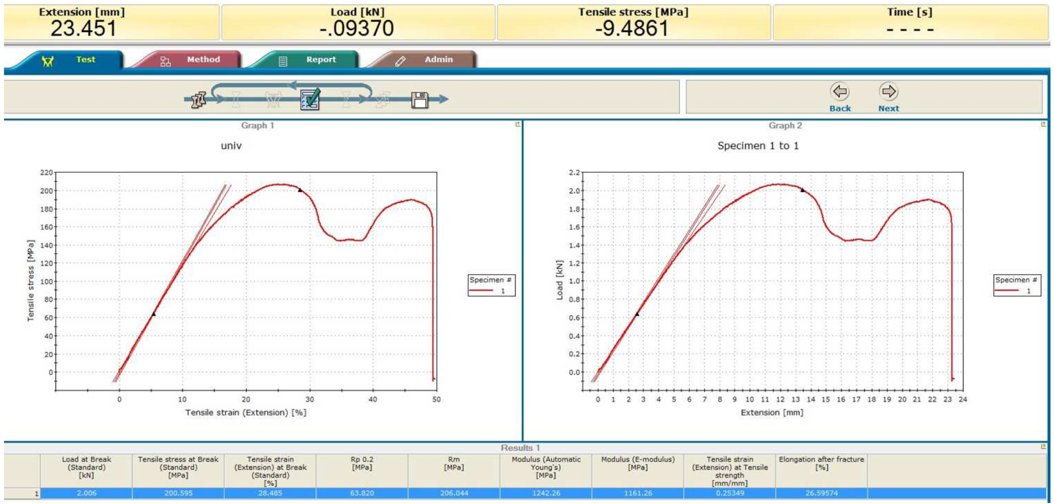
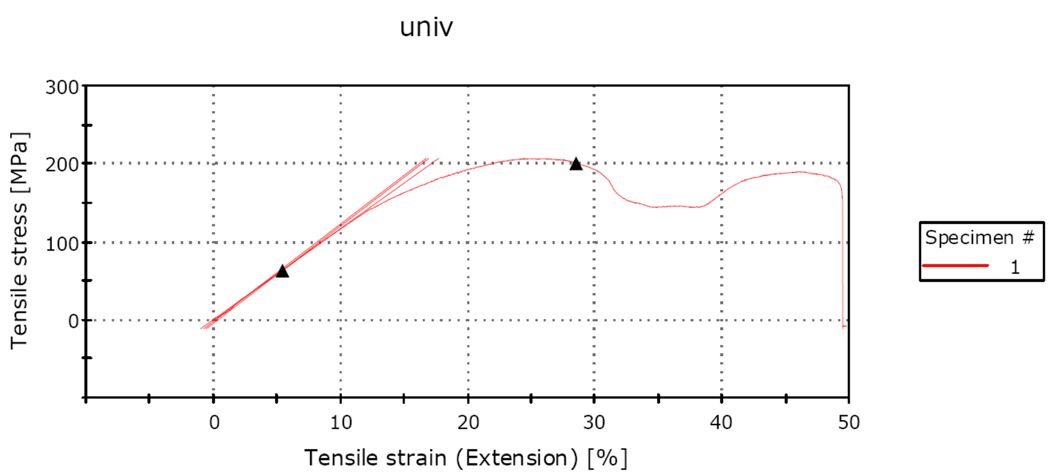


Fig. 12. Graphical representation of sample 4 – filament PC test results *(Source: Authors)*.



	Load at Break (Standard) [kN]	Tensile stress at Break (Standard) [MPa]	Tensile strain (Extension) at Break (Standard) [%]	Rp 0.2 [MPa]
1	2.006	200.595	28.485	63.820

	Rm [MPa]	Modulus (Automatic Young's) [MPa]	Modulus (E-modulus) [MPa]	Tensile strain (Extension) at Tensile strength [mm/mm]
1	206.044	1242.26	1161.26	0.25349

	Elongation after fracture [%]
1	26.59574

Fig. 13. Tabular presentation of test results of sample 4 - filament PC *(Source: Authors)*.

Commonly reported mechanical properties include ultimate tensile stress (maximum stress a part experiences in tension) and elongation at break (how much the "gauge length" stretches before breaking) [17]. The modulus of elasticity can be calculated from these values by dividing the overstress by the stress. In the presented studies, the modulus of elasticity of a material is determined by generating a stress-strain curve for the material.

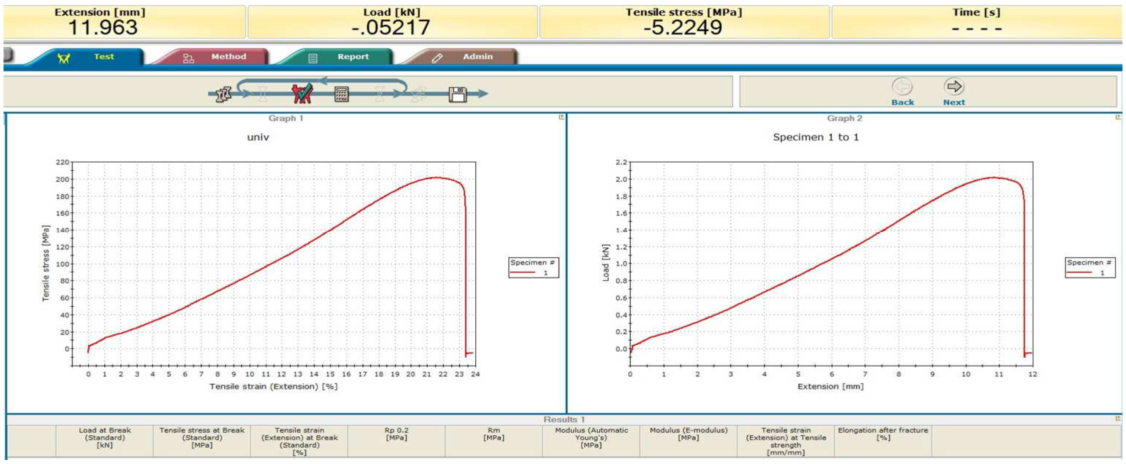
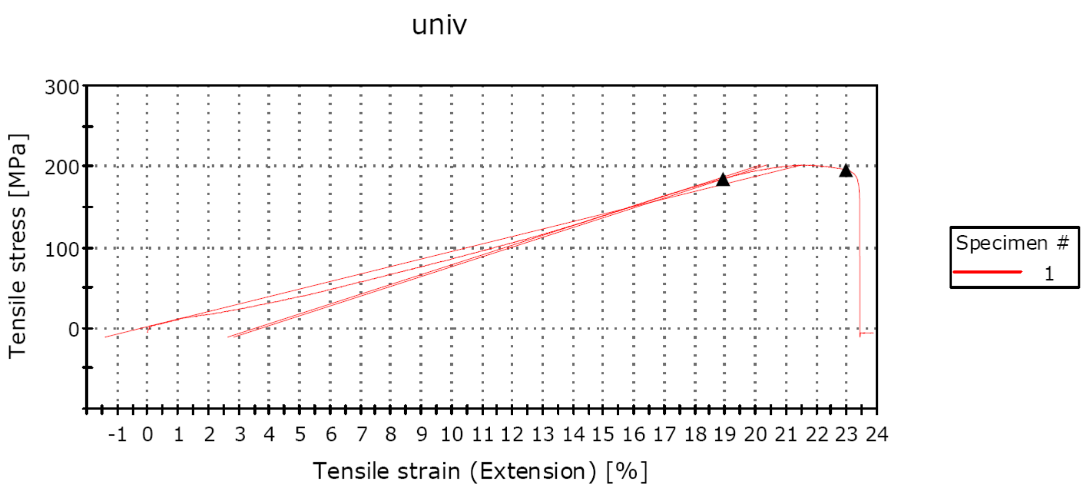


Fig. 14. Graphic representation of sample 7 - ABS filament test results *(Source: Authors)*.



	Load at Break (Standard) [kN]	Tensile stress at Break (Standard) [MPa]	Tensile strain (Extension) at Break (Standard) [%]	Rp 0.2 [MPa]
1	1.959	195.935	22.934	184.575

	Rm [MPa]	Modulus (Automatic Young's) [MPa]	Modulus (E-modulus) [MPa]	Tensile strain (Extension) at Tensile strength [mm/mm]
1	201.995	1213.17	928.13	0.21596

	Elongation after fracture [%]
1	21.20000

Fig. 15. Tabular presentation of sample 7 - ABS filament test results *(Source: Authors)*.

Commonly reported mechanical properties include ultimate tensile stress (maximum stress a part experiences in tension) and elongation at break (how much the "gauge length" stretches before breaking) [17]. The modulus of elasticity can be calculated from these values by dividing the overstress by the stress. In the presented studies, the modulus of elasticity of a material is determined by generating a stress-strain curve for the material. The slope of the curve's straight (linearly elastic) part is then calculated. Firstly, the material is stretched by a machine that measures the applied force and the change in length resulting from that force and plots these values on a stress-strain curve. The stress-strain curve has a linear part at the beginning. Calculating the slope of this part of the curve determines the modulus of elasticity.

To determine the selected mechanical properties of the printed samples of three different PLA, PC, and ABS filaments, the European-British standard BS-EN ISO 527 for plastics performed a uniaxial tensile test.

The investigated PLA, PC and ABS filaments are characterised by relatively good mechanical properties, which can be successfully used in constructing automotive elements and other engineering fields.

7. CONCLUSION

Material testing of 3D printed prototypes was performed to provide the industrial and academic communities with a basis for improving mechanical and digital design in additive manufacturing.

The study discusses the influence of the sample production method on selected mechanical properties and the errors made in measuring them.

The study printed nine samples using FDM technology using three different filaments: PLA, PC, and ABS [21]. Tensile strength testing is a fundamental engineering and materials science test widely used for various manufacturing methods, such as injection molding, machining, and industrial-grade 3D printing (additive manufacturing) [17]. In terms of 3D printing, the test provides insight into the quality and mechanical behavior of a 3D printed material and determines how it will behave under load [17]. Tensile testing also helps manufacturers to ensure that their process is consistent and in line with industry standards. Furthermore, Tension testing is functional when conducting research and development activities on a new or changing material, manufacturing method, or product application.

Acknowledgement „This study is financed by the European Union-NextGenerationEU, through the National Recovery and Resilience Plan of the Republic of Bulgaria, project № BG-RRP-2.004-0001-C01“.

8. REFERENCES

[1] Alhallak, K., Hagi-Pavli, E., & Nankali, A. (2023). *A review on clinical use of CAD/CAM and 3D printed dentures*. British Dental Journal. https://doi.org/10.1038/s41415-022-5401-5.

[2] Eryildiz, Meltem. *Effect of Build Orientation on Mechanical Behaviour and Build Time of FDM 3D-Printed PLA Parts*: An Experimental Investigation. 2021, 5. 116-120. 10.26701/ems.881254.

[3] Graba, M., & Grycz, A. (2023). Assessment of the Mechanical Properties of Selected PLA Filaments Used in the UAV Project. Materials. https://doi.org/10.3390/ma16031194.

[4] Grechi, G.; Fiorucci, M.; Marmoni, G.; Martino, S. *3D Thermal Monitoring of Jointed Rock Masses through Infrared Thermography and Photogrammetry*. Remote Sens. 2021, 13, 957. [CrossRef].

[5] J. Persad and S. Rocke, *"A Survey of 3D Printing Technologies as Applied to Printed Electronics,"* in IEEE Access, vol. 10, pp. 27289-27319, 2022, doi: 10.1109/ACCESS.2024.3157833.

[6] Juan Pou, Antonio Riveiro, Paulo Davim, *Additive Manufacturing, Elsevier, eBook* ISBN: 9780128184127, First published May 21, 2021.

[7] M. Abdelmomen, F. O. Dengiz and M. Tamre, "*Survey on 3D Technologies: Case Study on 3D Scanning, Processing and Printing with a Model*" 2020 21st International Conference on Research and Education in Mechatronics (REM), Cracow, Poland, 2020, pp. 1-6, doi: 10.1109/REM49740.2020.9313881.

[8] Marcin Graba and Andrzej Grycz. *Assessment of the Mechanical Properties of Selected PLA Filaments Used in the UAV Project*, Materials 2023, 16(3), 1194; https://doi.org/10.3390/ma16031194 - 30 Jan 2023

[9] Pepe, M.; Costantino, D. UAV P*hotogrammetry and 3D Modelling of Complex Architecture for Maintenance Purposes*: The Case Study of the Masonry Bridge on the Sele River, Italy. Period. Polytech. Civ. Eng. 2020, 65, 191–203.

[10] Yusuf Effri Prastyo Budi, Tedjo Sukmono. *Effectiveness of CAD-CAM Application for the Development design and implementation of maintenance tools*, September 2023, Jurnal Penelitian Pendidikan IPA 9(9):671-680, DOI: 10.29303/jppipa. v9i9.4859.

[11] Zhang, Xu, Mingyang Li, Jian Hui Lim, Yiwei Weng, Yi Wei, Daniel Tay, and Hung Pham. "*Automation in Construction Large-Scale 3D Printing by a Team of Mobile Robots.*" Automation in Construction, April (2018): 98–106.
[12] Zhiming Liu, Jiadong Teng, Bo Liu. Multi-dimensional *Abstraction and Decomposition for Separation of Concerns*, Conference: International Symposium on Dependable Software Engineering: Theories, Tools, and Applications, January 2024, DOI: 10.1007/978-981-99-8664-4_9.
[13] http://3dprintingindustry.com/3d-printing-basics-free-beginners-guide (accessed on 10 April 2024).
[14] https://arissta3d.com/index.php/category/uncategorized/.
[15] www.stratasys.com (accessed on 16 May 2024).
[16] https://3dprint.com/4517/carbon-nanotube-3d-print-filament/ (accessed on 14 June 2024).
[17]https://www.protolabs.com/resources/blog/tensile-testing-for-3d-printing-materials/
[18] https://www.researchnester.com/reports/us-3d-printing-market-analysis-opportunity-outlook-2024/88 (accessed on 2 July 2024).
[19] https://www.3dhubs.com/knowledge-base/introduction-metal-3d-printing/ (accessed on 19 July 2024).
[20] https://www.fraxus3d.com/3d-printing
[21]https://3dcentroamerica.com/misc/perimeter-3d-printing.html

CERCETĂRI PRIVIND PROTOTIPURI FABRICATE PRIN TEHNOLOGIA FDM

Rezumat: În această lucrare autorii prezintă testări experimentale ale epruvetelor fabricate prin tehnologia 3D în vederea îmbunătățirii caracteristicilor mecanice. Rezultatele obținute aduc un aport seminificativ prin contribuțiile oferite în rândul comunităților industriale și academice asupra proiectării și fabricării aditivate. De asemenea cercetările întreprinse sunt menite să îmbunătățească bazele de date specifice fabricării prin tehnologia (FDM). Autorii prezintă și argumentează alegerea materialului care poate fi utilizat în proiectarea unui element din industriei auto și anume tija dintr-un sistem de suspensie. Aceste materiale sunt supuse unor testări experimentale pentru a evalua proprietățile mecanice selectate care pot fi adaptate cu succes la sistemele CAD/CAM/CAE prin analize și tehnici inginerești.
Keywords: *FDM technology, filament research, mechanical properties, model design, CAD/CAM/CAE systems.*

Slavi LYUBOMIROV, Professor. PhD. Eng., Vice-dean of Faculty of Physics and Technology, Paisii Hilendarski University of Plovdiv, Department of Mechanical Engineering and Transport, slavilyubomirov@uni-plovdiv.bg, +359 897 989868, 24 Tsar Assen Str., Plovdiv, Bulgaria.

Emil VELEV, Assis. Prof. PhD. Eng., Department of Mechanical Engineering and Transport, emil.velev@gmail.com, +359 878805438, 24 Tsar Assen Str., Plovdiv, Bulgaria.

Snezha SHOTAROVA, Assis**.** Prof. Eng., Faculty of Physics and Technology, Department of Power Engineering and Communications, shotarovas@uni-plovdiv.bg, +359 887677975 24 Tsar Assen Str., Plovdiv, Bulgaria.

Ionut GEONEA, Assoc. Prof. PhD. Eng., Faculty of Mechanics, Applied Mechanics and Civil Engineering Department, ionutgeonea@edu.ucv.ro, +40251543739, Calea Bucuresti 107, Craiova, Romania.

Cristian COPILUSI, Assoc. Prof. PhD. Eng., Faculty of Mechanics, Applied Mechanics and Civil Engineering Department, cristian.copilusi@edu.ucv.ro, +40251543739, Calea Bucuresti 107, Craiova, Romania.

Laurentiu RACILA, Assoc. Prof. PhD. Eng., Faculty of Mechanics, Applied Mechanics and Civil Engineering Department, laurentiu.racila@edu.ucv.ro, +40251543739, Calea Bucuresti 107, Craiova, Romania.

Cosmin MIRITOIU, Assoc. Prof. PhD. Eng., Faculty of Mechanics, Applied Mechanics and Civil Engineering Department, sorin.dumitru@edu.ucv.ro, +40251543739, Calea Bucuresti 107, Craiova, Romania.