JOURNAL of
MATERIALS and MECHATRONICS:A

e-ISSN 2717-8811
JournalMM, 2023, 4(2), 561-570
https://doi.org/10.55546/jmm.1357217

Araştırma Makalesi / Research Article

Effect of Lattice Design and Process Parameters on the Properties of PLA, ABS AND PETG Polymers Produced by Fused Deposition Modelling

Cem GÜDÜR[1], Türker TÜRKOĞLU[2*], İlker EREN[3]

[1] Balıkesir University, Engineering Faculty, Mechanical Engineering Department, Balıkesir, Türkiye,
ORCID ID: https://orcid.org/0000-0002-6836-7656, cemgudur12@gmail.com
[2] Balıkesir University, Engineering Faculty, Mechanical Engineering Department, Balıkesir, Türkiye,
ORCID ID: https://orcid.org/0000-0002-0499-9363, turker.turkoglu@balikesir.edu.tr
[3] Balıkesir University, Engineering Faculty, Mechanical Engineering Department, Balıkesir, Türkiye,
ORCID ID: https://orcid.org/0000-0003-4326-0294, ieren@balikesir.edu.tr

Geliş/ Received: 11.09.2023; **Kabul / Accepted:** 13.12.2023

ABSTRACT: In this study, tensile strengths of different polymer-based materials PLA (Polylactic Acid), ABS (Acrylonitrile Butadiene Styrene), and PETG (Polyethylene Terephthalate Glycol) were investigated by applying BCC (Body-Centered Cubic), FCC (Face-Centered Cubic) and Gyroid lattice designs with FDM (Fused Deposition Modeling) method which one of the additive manufacturing methods. In addition, weight reduction was performed in the materials with the lattice designs applied. After the mechanical tests, it was determined that the lattice structure has an important role in tensile strengths. Especially in the gyroid lattice structure, which is one of the TPMS (Triply Periodic Minimal Surface) lattice types, it was determined that the maximum strength was obtained in PLA material. In terms of % deformation, the maximum elongation was obtained for PETG material in the gyroid lattice structure. In addition, weight reduction was aimed by using lattice structure patterns, and the maximum weight reduction was found in the BCC lattice structure.

Keywords: Additive manufacturing, Lattice designs, Fused deposition modelling, PLA, ABS, PETG

*Sorumlu yazar / Corresponding author: turker.turkoglu@balikesir.edu.tr

Bu makaleye atıf yapmak için /To cite this article

Güdür, C., Türkoğlu, T., Eren İ. (2023). Effect of Lattice Design and Process Parameters on the Properties of PLA, ABS AND PETG Polymers Produced by Fused Deposition Modelling. Journal of Materials and Mechatronics: A (JournalMM), 4(2), 561-570.

1. INTRODUCTION

Additive manufacturing technology is the process of creating the desired part by adding the material used in general terms layer by layer on top of each other (Sezer et al., 2016 and Özer, 2020). The machines that perform this process are called 3D printers (3D). 3D printers, which have become widespread in recent years, were first included in our lives as a device designed and patented by Charles Hull in the 80s (Srinivasan et al., 2020). Thanks to 3D printers, it is possible to produce parts with complex structures from many materials such as plastic, metal, etc., which are difficult to produce with classical production methods. 3D printers can be used in many different fields from aviation to the automotive industry, from medicine to architecture (Kaygusuz and Özerinç, 2018; Kamer et al., 2022).

3D printers can be classified into 3 main groups according to the material to be used: liquid-based, solid-based, and powder-based (Çelik et al., 2013). In today's market, FDM (Fused Deposition Modelling) technology, which is one of the solid-based additive manufacturing technologies, is widely used. The low cost of the materials used in FDM technology, the variety of materials to be used, and easy accessibility have made this technology more widespread than other Technologies (Evlen, 2019; Başçı and Yamanoğlu, 2021). In 3D printers working with FDM technology, materials called filaments are used as production materials. Filaments are materials that are made suitable for use in 3D printers. Today, Polylactic Acid (PLA), Acrylonitrile Butadiene Styrene (ABS), and Polyethylene Terephthalate Glycol (PETG) are among the filaments used (Zhao et al., 2019; Cano-Vicent et al., 2021).

PLA filament is one of the most widely used filaments because it is easy to work with at low temperatures and in many 3D printers. The printing temperature (on average) is around 190 °C-215 °C. It is easier to print than ABS and PETG filament. Since it has a natural structure, it has no negative effect on human health. It is compatible with open-frame printers. ABS filament is another type of filament that is frequently used today. ABS filament has high heat and impact resistance. However, ABS filament is a petroleum-based filament type. The printing temperature is higher than PLA and PETG filaments and is between 240°C-260°C on average. It is not compatible with open-case printers, a closed-case printer is required. PETG filament is among the most durable filaments. It has high hardness and is impact-resistant. It can be printed more easily than ABS filament. The Printing temperature is between 235°C-255°C on average. It is also compatible with open-frame printers (Awasthi and Banerjee, 2021; Corvi et al., 2023; Jimanez-Martinez et al., 2023).

In their study, Srinivasan et al. (Srinivasan et al., 2020) preferred PETG as filament material, and, parameters such as layer thickness, filler shape, and nozzle diameter were kept constant. However, the filler percentage varied between 20% and 100% with an increment of 10%. In total, 9 samples with different filling percentages were printed in accordance with ASTM D638 Standard. Ender 3 Pro, an FDM printer, was preferred for printing. Firstly, the surface roughnesses of the 9 samples were measured, and then mechanical properties were tested by tensile test. As a result, the sample with a 100 % fill percentage gives the highest result. Alarifi et al. focused on PETG material reinforced with carbon fiber. The filamentised composite mixture was produced in different lattice designs by FDM. Tensile, flexural, and compression tests were carried out. Experimental tests were supported by numerical studies, and it was proved that significant increases in flexural and tensile strength were obtained for PETG-Carbon fiber composite (Alarifi et al., 2023).

ABS material was preferred in the study of Dwiyati et al. (Dwiyati et al., 2019). In this study, there are 6 samples produced with ABS material. These specimens were adjusted so that the layer thickness was 0.1-0.2-0.3 mm. At the same time, all specimens were printed both axially and laterally.

All specimens were printed one by one. As a result, the axial specimen with a layer thickness of 0.3 mm has the largest force and the highest tensile strength. When the axial and lateral directions are compared, the axial specimens have greater force and tensile strength. Similarly, specimens with a layer thickness of 0.3 mm had greater strength and tensile strength. When the images of axial 0.3 and lateral 0.3 specimens were evaluated under SEM, the axial specimens were less dense and consisted of many voids. Srinivasan et al. optimized the production parameters of ABS material through fused deposition modeling. Infill density, infill pattern, and layer thickness values were determined as inputs. The effectiveness of the inputs on the mechanical properties was analyzed using a central composite design. It was determined that the most effective production parameters were infill density and layer thickness (Srinivasan et al., 2020).

PLA material was preferred in the research paper of Rismila et al. (Rismilia et al., 2019). In this study, the effect of the filling pattern and filling density on the results was investigated. Filling densities of 25%, 50%, and 75% were preferred, and grid, tri-hexagon, and concentric were preferred as filling patterns. Parameters such as printing temperature, layer thickness, and printing speed of the samples were kept constant. As a result, the sample with the concentric filling pattern with 75% filling had the highest stress. In the study of Cetin et al. on the mechanical testing of the bonding process of PLA material under hydrothermal conditions; Taguchi orthogonal array optimization was used to determine the optimum set parameters for unaged samples of 45°, 0° surface patterns (Cetin et al., 2023). Tunay et al. focused on the design of auxetic structures from PLA material by fused deposition modeling method. It was stated that auxetic structures have a serious effect on improving properties such as lightness, energy absorption capability, and impact resistance. In addition, the analysis of the variance ANOVA method was also utilized in the study. It was reported that the strut thickness parameter is the most effective parameter on mechanical properties in auxetic samples produced from PLA material. This parameter was followed by strut angle and strut orientation in order of effectiveness.

Lattice structures are three-dimensional structures consisting of one or more repeating unit cells. Each cell consists of uprights connected to each other at nodes within it. Lattice structures can be named as periodic or stochastic lattice structures according to the regular or irregular repetition of the unit cell. On the other hand, lattice structures can be categorised into three different categories according to their shapes; strut-based lattice structures, triple periodic minimum surface lattice structures and shell lattice structures. FCC and BCC belong to the group of strut-based lattice structures, while Gyroid belongs to the group of Triply Periodic Minimum Surface. Sokullu et al. produced Ti6Al4V material in FCC, BCC, Gyroid, Primitive and Diamond lattice structure designs. According to the tensile test results, they reported that the maximum tensile strength was obtained from the TPMS-based lattice structure and the minimum tensile strength was obtained from the strut-based BCC lattice structure (Sokullu et al., 2022)

Weight reduction processes in machine parts constitute one of the objectives of industrial manufacturing operations. The use of different lattice structure patterns in the design of the manufacturing part without compromising mechanical properties and the production of parts by additive manufacturing method stands out as one of the important advantages of FDM technology. In this study, the effect of using different lattice types in the design of 3 different materials on the mechanical properties was investigated. The lattice productions carried out in the design are considered material-oriented and the results are presented comparatively.

2. MATERIALS AND METHODS

2.1 Materials

In this study, specimens with FCC, BCC, and Gyroid structures were produced using FDM device (Figure 1). PLA, PETG, and ABS filaments were used as filler materials in the production of these samples. All filaments used during the study were purchased from the same supplier and the diameter of these filaments was 1.75 mm.

2.2 Method

The specimens were first designed in Topology software, in accordance with the ISO 527/2 standards. Ultimaker Cura, an open-source slicing program, was preferred for creating G-Codes of the designed samples. In Ultimaker Cura Programme, many parameters such as the position of the sample to be produced on the printing table, printing speed, printing temperature, table temperature, layer height, and fan speed were determined. Among these parameters, nozzle diameter (0.4 mm), support status (no support), the diameter of filaments used (1.75 mm), layer height (0.2 mm), and printing speed (50 mm/s) were kept constant. Production parameters are given in Table 1.

Figure 1. 3D Printer used for his study

Table 1. Production parameters

Material	Production Temperature (°C)	Table Temperature (°C)
PLA	210	60
PETG	230	75
ABS	245	95

The printing temperature and table temperature as variable values were determined according to the filament properties, and the most suitable values were preferred. Variable parameters are shown in the table above. All adjusted samples were printed on Creality Cr5 ProH 3D printer. The same 3D printer was preferred for all samples. The preferred 3D printer can print all 3 filaments used. Tensile tests were carried out in a LABOMAK brand test machine with a capacity of 20 kN (Figure 2.). Tests were carried out at a speed of 5 mm/s. Tensile tests of PLA, ABS, and PETG materials produced by additive manufacturing were performed according to ISO 527/2 standard.

Figure 2. Tensile test device used for testing specimens (Labomak)

3. RESULTS AND DISCUSSION

The designed lattice structure patterns are shown in Figure 3. In the study, three productions of each design were carried out and the graphs given are the results of the samples where average values were obtained. Images of the specimens after the tensile test were added to the study. In Figure 4; it is determined that lattice structure patterns have a significant effect on strength. It can be seen that the strength and deformation levels change as the types of lattice structure patterns change on the material. It was determined that PLA was the material with the highest strength among materials with the BCC lattice type. In addition, when evaluated within the scope of the percentage deformation, it was determined that PLA was the material that showed the maximum shape change before deformation. For BCC lattice type pattern, PETG material was also found to show high strength after PLA. It was determined that the results for the BCC lattice type pattern of ABS material were relatively low.

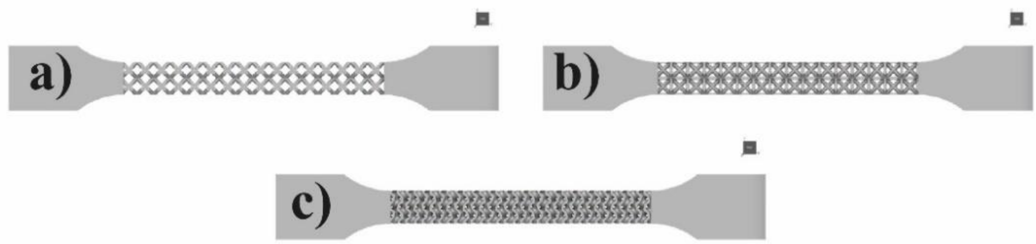

Figure 3. Lattice designs a) BCC b) FCC c) Gyroid

The 3-dimensional tensile test results of the specimens produced with the FCC lattice type using the FDM method are shown in Figure 5. While the highest strength was obtained in the materials produced with PLA material and FCC lattice types, it was observed that the maximum ductility was obtained from PETG material in terms of percentage deformation. In ABS material, it was determined that the lowest mechanical results were obtained as in the BCC lattice type.

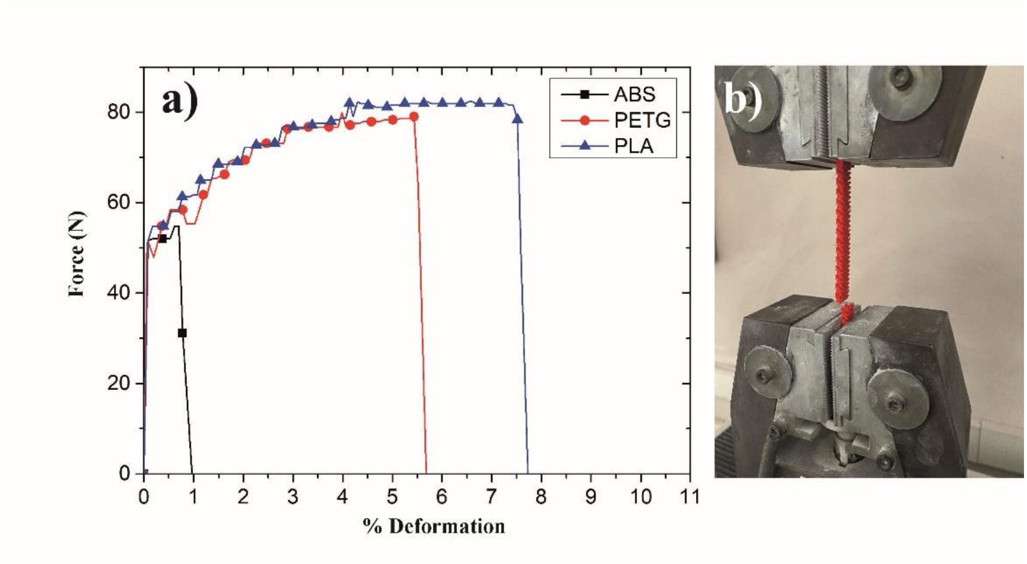

Figure 4. Tensile test results of BCC lattice designs

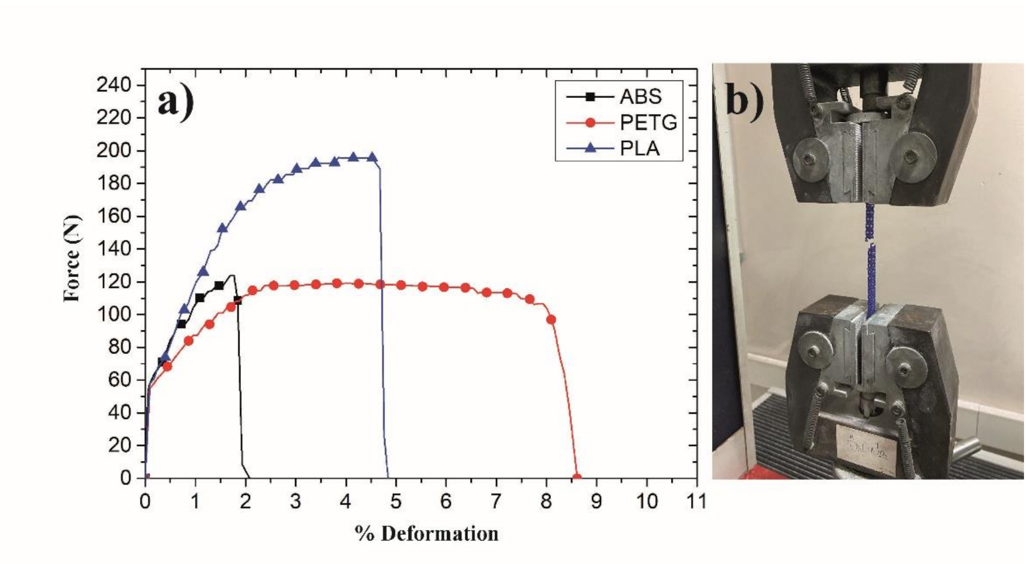

Figure 5. Tensile test results of FCC lattice designs

In all specimens subjected to tensile tests, it was determined that the deformation occurred at the midpoints. In addition, while the BCC and FCC lattice types are specified as Strut-Based, the Gyroid lattice structure is specified in the literature as the TPMS (Triply Periodic Minimum Surface) structure created using surface formations obtained from mathematical formulas (Zhao et al., 2019). Because of the designed gyroid structure, the strength was significantly increased for all materials used in the study. While the maximum strength for the gyroid structure was obtained from PLA material, it was determined that the strength increased considerably in ABS material, unlike the BCC and FCC lattice design (Figure 6). It was also determined that significant progress was made in the percentage deformation for PETG material. The reason for these high mechanical properties is based on the fact that gyroid structures have stretch-dominated behavior. This situation was explained by the two primary characteristics of TPMS lattices: their increased stability in failure mechanisms and their ability to reduce stress concentrations by doing away with joints.

Lattice structure patterns contribute to weight reduction as well as the mechanical properties they provide to material design. They have potential use, especially in sectors such as the automotive and aerospace industries that require weight reduction. In this study, weights were significantly reduced with BCC, FCC, and gyroid lattice structure patterns compared with the fully filled specimen.

The weight of fully filled tensile test specimens for PLA, ABS, and PETG were calculated as 10.04 g, 8.4 g, and 10.32 g, respectively. Because of the lattice structure patterns applied to the specimens, weight change percentages were determined in BCC, FCC, and gyroid structures for PLA, ABS, and PETG specimens. For PLA material produced with different lattice types by the FDM method, 31.92%, 29.87%, and 26.33% weight reductions were achieved in BCC, FCC, and gyroid lattice types, respectively. After the application of BCC, FCC, and gyroid lattice design to ABS material, 29.50%, 26.37%, and 21.75% weight reductions were achieved, respectively. For PETG material, 33.33%, 31.01%, and 27.58% weight reduction were achieved after the application of BCC, FCC, and gyroid lattice design, respectively. To achieve a better strength-to-weight ratio, some novel attempts have recently been made to design lightweight structures based on porous TPMS. The strength of intricate structures can be increased with the aid of this technique, while the consumption of materials can be reduced.

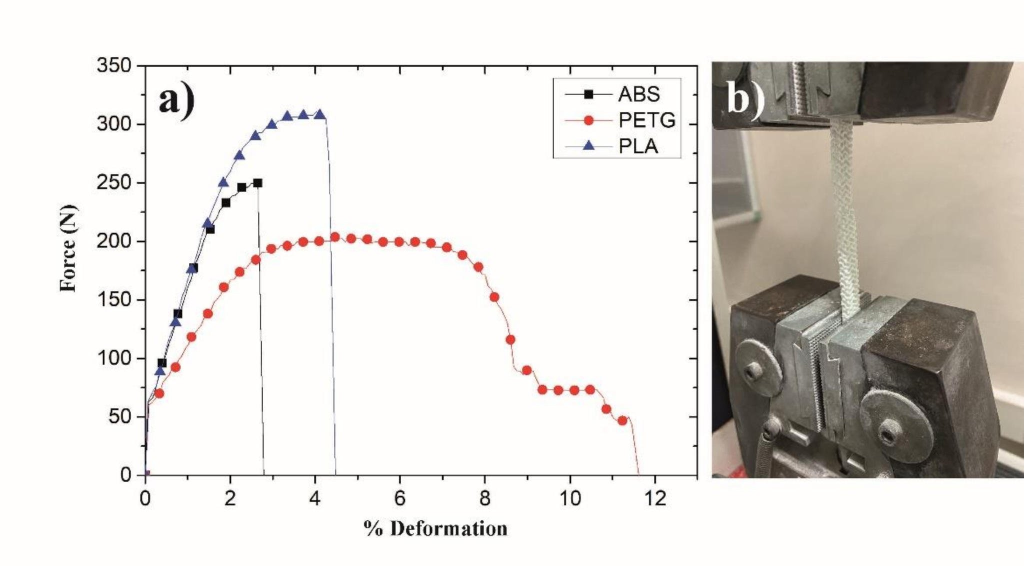

Figure 6. Tensile test results of gyroid lattice designs

Lattice structures are designed for weight reduction in the part. In addition to the weight reduction process, the mechanical properties of the lattice structured parts must be at an acceptable level. The tensile strength values of solid samples were determined as 60.14 MPa, 44.85 MPa and 58.46 MPa for PLA, ABS and PETG, respectively.

In Table 2, tensile test results of specimens produced from different lattices and different plastics are compared.

Table 2. Tensile test results of lattice specimens

	ABS		**PETG**		**PLA**	
	Force (N)	**%Def**	**Force (N)**	**%Def**	**Force (N)**	**%Def**
BCC	i)56.26	i)1.20	i)77.53	i)5.09	i)85.12	i)8.36
	ii)54.80	ii)0.96	ii)80.27	ii)5.91	ii)80.85	ii)7.68
	iii)50.12	iii)0.94	iii)79.24	iii)5.68	iii)82.34	iii)7.72
FCC	i)122.12	i)2.02	i)119.19	i)8.61	i)201.83	i)5.23
	ii)123.95	ii)2.07	ii)122.07	ii)8.98	ii)195.55	ii)4.83
	iii)126.18	iii)2.93	iii)117.6	iii)8.21	iii)194.16	iii)4.79
Gyroid	i)249.66	i)2.78	i)202.72	i)11.61	i)290.18	i)5.01
	ii)252.28	ii)3.02	ii)201.66	ii)10.95	ii)285.64	ii)4.33
	iii)249.09	iii)2.66	iii)205.01	iii)12.07	iii)289.49	iii)4.67

Figure 7 shows the deformation images of the specimens after the tensile test. Red colour represents PLA material, white colour represents ABS material and blue colour represents PETG material.

Figure 7. Deformation images after tensile test

4. CONCLUSION

In this study, the FDM technology was used to successfully create PLA, ABS, and PETG materials in BCC, FCC, and gyroid lattice structure patterns.

- The PLA material demonstrated the highest strength for the BCC lattice type and failed under a maximum force of 82.3 N, according to the tensile test findings. Additionally, it was found that the same material (7.7%) shows the high percentage of elongation.
- As a result of the tensile test performed by applying the FCC lattice structure pattern to the sample, it was reported for PLA material that was observed under a maximum percentage elongation was obtained from PETG material (8.6%).

- In a gyroid lattice structure pattern, the PLA material showed the greatest strain at a maximum force of 310.9 N, whereas the PETG material showed the greatest percentage deformation (11.6%).
- The BCC lattice design was found to achieve the greatest weight reduction. For PLA, ABS, and PETG materials, a highest weight decrease of 31.9%, 29.5%, and 33.3% was attained.

5. ACKNOWLEDGEMENTS

No financial support was received for this study.

6. CONFLICT OF INTEREST

Authors approve that to the best of their knowledge, there is not any conflict of interest or common interest with an institution/organization or a person that may affect the review process of the paper.

7. AUTHOR CONTRIBUTION

Cem GÜDÜR conceived and designed the study. Türker TÜRKOĞLU collected data and wrote the manuscript. İlker EREN interpreted the results of this study.

8. REFERENCES

Alarifi I., Mechanical Properties and Numerical Simulation of FDM 3D Printed PETG/carbon Composite Unit Structures, Journal of Materials Research and Technology, 23, 656-669, 2023.

Awasthi P., Banerjee S., Fused Deposition Modeling of Thermoplastic Elastomeric Materials: Challenges and Opportunities, Additive Manufacturing, 46, 1-18, 2021.

Başçı Ü.G., Yamanoğlu R., New Generation Production Technology: Additive Manufacturing via FDM, International Journal of 3D Printing Technologies and Digital Industry, 5, 339-352, 2021.

Cano-Vicent A., Tambuwala M., Hassan S., Barh, D., Aljabali A., Birkett M., Arjunan A., Serrano-Aroca A., Fused Deposition Modeling: Current Status, Methodology, Applications and Future Prospects, 47, 1-19, 2021.

Çelik İ., Karakoç İ., Çakır C., Duysak A., Hızlı Prototipleme Teknolojileri ve Uygulama Alanları, Dumlupınar Üniversitesi Fen Bilimleri Enstitüsü Dergisi, 31, 53-70, 2013.

Cetin E., Fossi, C., Experimental Investigation on Mechanical Strength of Adhesively Bonded 3D-Printed Joints Under Hygrothermal Conditions Using Taguchi Method, International Journal of Adhesion and Adhesives, 126, 103472, 2023.

Corvi A., Collini L., Sciancalepore C., Kumar A., Analysis and Modeling of Damage Mechanism in FDM 3D-Printed Lattice Structure Under Compression Loading, Journal of Mechanical Science and Technology, 37, 1089-1095, 2023.

Dwiyati S., Kholil A., Riyadi R., Putra S., Influence of Layer Thickness and 3D Printing Direction on Tensile Properties of ABS Material, Journal of Physics: Conference Series, 1042, 1-7, 2019.

Evlen H., Investigation of the Effect of Infill Rate on Mechanical Properties of TPU and TPE Specimens Produced in 3D Printer, Dokuz Eylül University Faculty of Engineering Journal of Science and Engineering, 21, 793-804, 2019.

Jimanez-Martinez M., Varela-Soriano J., Carreon J., Mechanical Fatigue of PLA in Additive Manufacturing, Engineering Failure Analysis, 149, 1-19, 2023.

Kamer M., Temiz Ş., Yaykaşlı H., Kaya A., Akay O., Comparison of Mechanical Properties of Tensile Test Specimens Produced with ABS and PLA Material at Different Printing Speeds in 3D Printer, Journal of the Faculty of Engineering and Architecture of Gazi University, 37, 1197-1211, 2022.

Kaygusuz B., Özerinç S., 3 Boyutlu Yazıcı ile Üretilen PLA Bazlı Yapıların Mekanik Özelliklerinin İncelenmesi, Makina Tasarım ve İmalat Dergisi, 16, 1-16, 2018.

Özer G., Eklemeli Üretim Teknolojileri Üzerine Bir Derleme, Nigde Omer Halisdemir University Journal of Engineering Sciences, 9, 606-621, 2020.

Rismilia M., Hidajat S.C., Permana I.G.R, Hadisujoto B., Muslimin M., Triawan F., Infill Pattern and Density Effects on the Tensile Properties of 3D Printed PLA Material, Journal of Physics: Conference Series, 1402, 1-7, 2019.

Sezer H.K., Eren O., Börklü H.R., Karbon Fiber Takviyeli ABS Filamanet Üretimi ve Mekanik Özelliklerinin Araştırılması, 1. 3B Baskı Teknolojileri Uluslararası Sempozyumu, İstanbul/Türkiye, May 5-7, 2016, pp:1-12.

Sokullu B., Gulcan O., Konukseven E., Mechanical Properties Comparison of Strut-Based and Triply Periodic Minimal Surface Lattice Structures Produced by Electron Beam Melting, Additive Manufacturing, 60, 103199, 2022.

Srinivasan R., Pridhar T., Ramprasath L., Charan N., Ruban W., Prediction of Tensile Strength in FDM Printed ABS Parts Using Response Surface Methodology (RSM), Materials Today: Proceedings, 27, 1827-1832, 2020.

Srinivasan R., Ruban W., Deepanraj A., Bhuvanesh R., Bhuvanesh T., Effect on Infill Density on Mechanical Properties of PETG Part Fabricated by Fused Deposition Modeling, Materials Today: Proceedings, 27, 1838-1842, 2020.

Tunay M., Cetin E., Energy Absorption of 2D Auxetic Structures Fabricated by Fused Deposition Modeling, Journal of the Brazilian Society of Mechanical Sciences and Engineering, 45, 500, 2023.

Zhao Y., Chen Y., Zhou Y., Novel Mechanical Models of Tensile Strength and Elastic Property of FDM AM PLA Materials: Experimental and Theoretical Analyses, Materials and Design, 181, 1-10, 2019.