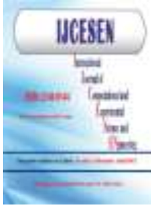
International Journal of Computational and Experimental Science and ENgineering
(IJCESEN)

Vol. 9-No.3 (2023) pp. 225-232
http://dergipark.org.tr/en/pub/ijcesen



ISSN: 2149-9144

Research Article

Optimizing Infill Parameters for Improved Mechanical Performance and Cost Savings in Additive Manufacturing

Volkan ARIKAN*

Osmaniye Korkut Ata University, Department of Mechanical Engineering, 80000, Osmaniye, Turkey
* **Corresponding Author**: **Email:** volkanarikan@osmaniye.edu.tr - **ORCID:** 0000-0002-6102-6584

Article Info:

DOI: 10.22399/ijcesen.1324071
Received : 07 July 2023
Accepted : 13 August 2023

Keywords

Additive Manufacturing
Infill Parameters
Fused Deposition Modelling
Mechanical Properties

Abstract:

In this study, compression tests were performed on the samples produced with PLA filament with different infill parameters and infill densities by additive manufacturing method and their mechanical performances & static energy absorption capabilities were evaluated. According to the results obtained, it was determined that the samples with triangular and tri-hexagonal infill parameters performed better and it has been shown that time, material and energy can be saved without losing materials mechanical performance.

1. Introduction

3D printing, also known as additive manufacturing, is a process of creating a physical object from a digital model by building it up layer by layer. The first patent for a 3D printing process was filed in 1986, but the technology has been in development for much longer than that. One of the earliest 3D printing techniques, known as stereolithography, was developed in the 1980s by Chuck Hull [1]. This process involved using a laser to cure layers of photopolymer resin, creating a solid object from a pool of liquid. Other early 3D printing techniques included selective laser sintering, which used a laser to fuse particles of plastic, metal, or ceramic powder into a solid object, and fused deposition modeling, which extruded layers of melted plastic to build up an object.

Over the years, 3D printing technology has continued to evolve and improve. Today, there are many different types of 3D printers available, ranging from small desktop models to industrial-scale machines. They can use a variety of materials, including plastics, metals, ceramics, and even living cells, to create a wide range of objects [2]. 3D printing has become increasingly popular in recent years and has a variety of applications, including prototyping, manufacturing, and even creating custom prosthetics and other medical devices.

Traditional manufacturing methods involve the removal of material to shape a part or product, while additive manufacturing methods involve the addition of material to build a part or product layer by layer. This fundamental difference leads to several other differences between the two approaches: complexity of shape, material options, lead time, cost, waste, accuracy and design freedom. There are both positive and negative aspects to each of these methods. Some of the positives include the ability to create complex and customized objects, the potential for mass customization and on-demand production, and the ability to use a wide range of materials. However, there are also some negative aspects to consider, such as the high cost of some 3D printing systems and the relatively slow speed of the printing process. Additionally, 3D printed objects may not have the same level of strength and durability as objects made using traditional manufacturing methods. There are several different methods used in additive manufacturing, also known as 3D printing. Some of the most common methods include: Stereolithography (SLA), Selective laser sintering (SLS), Fused deposition modeling (FDM),

Digital light processing (DLP), Powder bed fusion (PBF), Material jetting, Sheet lamination [3-6]
Additive manufacturing can use a wide range of materials, including plastics, metals, ceramics, and composite materials [7]. Some common materials used in additive manufacturing given in Table 1. It's worth noting that the material choices for additive manufacturing are constantly expanding, and new materials are being developed and introduced all the time.

There are several factors that can influence the mechanical properties of samples produced with additive manufacturing technology. Some of the most important factors include: material, process parameters, microstructure, part geometry, post-processing [8,9]. Overall, the mechanical properties of objects produced using additive manufacturing technology can be influenced by a combination of these and other factors. It is important to carefully consider these factors in order to optimize the mechanical performance of the finished object. There are studies on this subject in the literature and different materials and different production parameters have been evaluated.

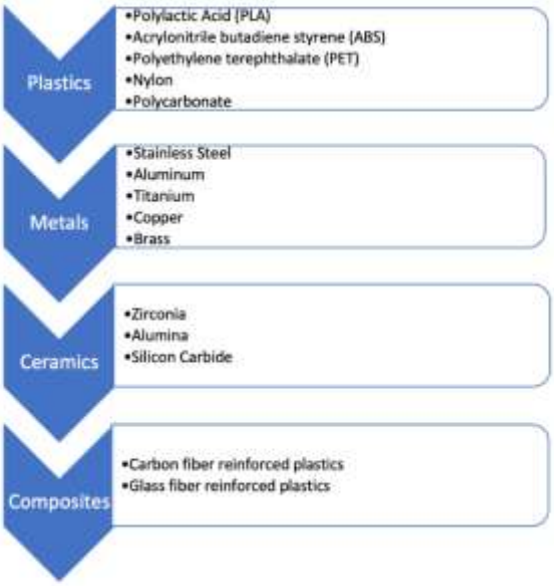


Figure 1. *Materials used in additive manufacturing*

Vicente et al. [10] determined infill patterns and infill density as parameters and applied tensile tests to the samples produced from ABS filament. As a result of their tests, they stated that the samples with 100% fill rate reached the highest strength values. Motoparti et al. [11] investigated how printing parameters such as build direction and raster angle affect compression modulus and yield strength. In their studies, they applied compression tests to the samples produced from ABS material. They reported that the build direction and raster angle are important parameters that affect the yield strength of the samples. Abbas et al. [12] applied compression tests to PLA samples produced with different infill densities in their study. According to their results, they showed that increasing the infill density increased the compressive strength. Chacon et al. applied three-point bending tests to PLA samples produced with different variations of build orientation, layer thickness and feed rate. They reported that ductility decreased as the layer thickness and feed rate increased [13]. Lebedev et al. [14] compared the mechanical properties of the samples produced by hot press and 3D printing methods. They found that the samples produced by the hot press method showed better mechanical performance. Panes et al. [15], in their study comparing PLA and ABS materials, produced samples with different layer thicknesses and different fill rates. They stated that the infill density is a very important factor. Nadernezhad et al. [16] performed mechanical and thermal tests on the samples they produced using different variations of parameters such as layer thickness, infill density, infill pattern. They reported that the residual thermal stresses increase as the layer thickness increases, and decreasing the infill density decreases the material strength. Ezeh and Susmal [17] investigated the effect of build direction on fatigue strength in their study. Tanveer et al. [18] investigated the effect of infill density on the tensile and impact strength of the material. They showed that the impact strength changes proportionally with the infill density. Yao et al. [19] subjected the samples produced at different angles and with different layer thicknesses to tensile tests. According to the results they obtained, they showed that the tensile strength of the samples with small printing angles decreased. Samykano et al. [20] produced different values of layer thickness, raster angle and infill density in their study. Tensile and hardness tests were applied to the samples they produced. They reported that the optimum density ratio to be selected for the ABS sample is 80%. Aloyaydi et al. [21] applied low velocity impact tests to the samples they produced using different infill patterns. They reported that samples with a triangular pattern showed the best performance in absorbing energy. Gunasekaran et al. [22] applied tensile, impact, bending and hardness tests to PLA samples produced at different infill densities. They reported that the increase in infill density increased the mechanical performance of the material. Rajpurohit and Dave [23] produced samples using PLA material with different raster angles, raster widths and layer thicknesses. They compared the impact performance of the samples they produced and emphasized that the raster angle is an important parameter affecting the impact strength. Yadav et al. [24] applied compression tests to the samples they produced with different infill patterns. They reported that the infill pattern with Hilbert curve design gave the best results. Farazin and Mohammadimehr [25] investigated the effects of infill density, infill pattern and layer thickness on tensile and compression strengths. They reported that the material showed a more brittle character at high densities. Mishra et al. [26] performed impact tests on the samples they produced with different infill patterns and densities, and reported that they reached the best absorbed energy value at 85% density. In their study, Patil [27] et al. compared the surface roughness of the materials they produced under variables such as different infill patterns, densities, velocity and layer thickness. They showed that the infill density had the most significant effect on the GRG (Gray Relational Grade). Samykano [28] compared the tensile and hardness strengths of the materials produced at different infill densities and reported the optimum printing parameters.

We can say there are several ways to increase the strength of a part produced by additive manufacturing against compression force; using a high-strength material, increasing the layer thickness, using a honeycomb or lattice structure, using support structures, using post-processing techniques, optimizing the design, material, process parameters, microstructure, part geometry. Overall, the mechanical properties of objects produced using additive manufacturing technology can be influenced by a combination of these and other factors. It is important to carefully consider these factors in order to optimize the mechanical performance of the finished object. In this study, sandwich samples were produced by the additive manufacturing method. Fused deposition modeling (FDM) method was chosen as the production method. Production was carried out with different infill densities and infill parameters, and then the static energy absorption amounts were measured by performing compression tests. Thus, the effects of production parameters on the static energy absorption ability were investigated.

2. Material and Method

In this study, fused deposition modeling was used as the production method. Fused Deposition Modeling (FDM) is a type of 3D printing technology that creates a physical object by laying down and fusing successive layers of material, typically thermoplastic filament (such as ABS or PLA), layer by layer. The material is melted and extruded through a heated nozzle onto a build platform, where it solidifies and forms the desired shape. The process is controlled by computer-aided design (CAD) software. FDM is a low-cost and accessible 3D printing technology, widely used for prototyping and producing small batch production runs.

The printing processes of the samples were made with Ender-3 S1 printer. The Ender-3 S1 is a 3D printer made by Creality. It is a more compact and lightweight version of previous model, designed for use in smaller spaces. It has a build volume of 220 x 220 x 250 mm and a print resolution of up to 100 microns. The printer is powered by a 32-bit motherboard and uses a filament sensor to automatically pause printing when the filament runs out or breaks. It is capable of printing with a variety of materials, including PLA, PETG, TPU, ABS and more. It features a removable, flexible magnetic build plate for easy removal of printed objects and an upgraded extruder to improve print quality.

In this study all samples were produced using Polylactic Acid (PLA) filament. PLA is a biodegradable and environmentally friendly 3D printing material made from renewable resources such as corn starch or sugarcane. It is one of the most popular 3D printing materials due to its easy printability, low warping, and low odor. PLA is a strong and stiff material with good layer adhesion, making it suitable for a wide range of applications. It is commonly used for prototyping and model making. One of the main advantages of PLA is that it does not require a heated bed, making it easier to print with and more suitable for use on basic 3D printers. However, it has a lower melting temperature compared to other materials like ABS, which means it may deform or warp when exposed to high temperatures. It is also more brittle than other materials. Overall, PLA is a good choice for 3D printing and for projects that do not require high levels heat resistance. In Table 1, the infill parameters used in the printing process and the general printing parameters are given. The masses of all samples were measured and given in Table 2. It was observed that the masses of the samples with the same infill density were close to each other. The samples were produced as three pieces for each combination and this study has total 60 samples of 15 different combinations (Fig. 2), which consists 5 different infill patterns and 3 different densities. The compression tests (Fig. 3) were carried out on a 200kN capacity universal testing machine and force-displacement data collected. The test speed was chosen as 4 mm/min, with a total test time of 1-3 minutes.

3. Results and Discussion

Force and displacement data were obtained from compression tests and force-displacement graphs were created. There are three points to note in these charts. These are the maximum force reached until the crush starts, the average force at which the crush occurs, and the crush stroke. As can be seen in figure 4, it is seen that the compressive strength of the samples increases as the infill density increases for all infill pattern types.

Table 1. *Infill and printing parameters.*

Infill Parameters	***Infill Pattern***	***Line (Li)***	***Cubic (Cu)***	***Octet (Oc)***	***Triangles (Ta)***	***Trihexagon (Th)***
	Infill Density (%)	*10*	*10*	*10*	*10*	*10*
		15	*15*	*15*	*15*	*15*
		20	*20*	*20*	*20*	*20*
Printing Parameters	***Layer Height***	***Top Thickness***	***Bottom Thickness***	***Infill Density***	***Bed Temperature***	***Print Speed***
	0.2 mm	*1 mm*	*1 mm*	*0,1*	*60*	*50mm/s*

Table 2. *Sample masses.*

Infill Density (%)	**Cu**			**Li**			**Oc**			**Ta**			**Th**		
	10	15	20	10	15	20	10	15	20	10	15	20	10	15	20
Mass (g)	20,16	24,22	28,65	20,1	24,38	28,55	20,17	24,17	28,5	20,15	24,63	28,74	20,15	24,28	28,75

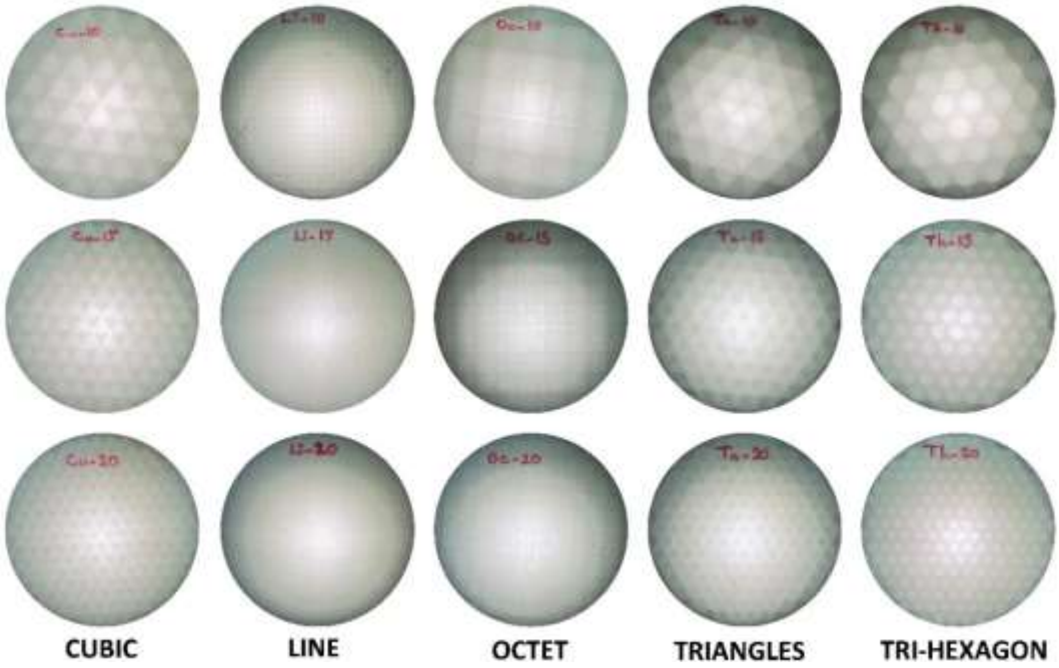


Figure 2. *Sample types*

Figure 3. *Compression test*

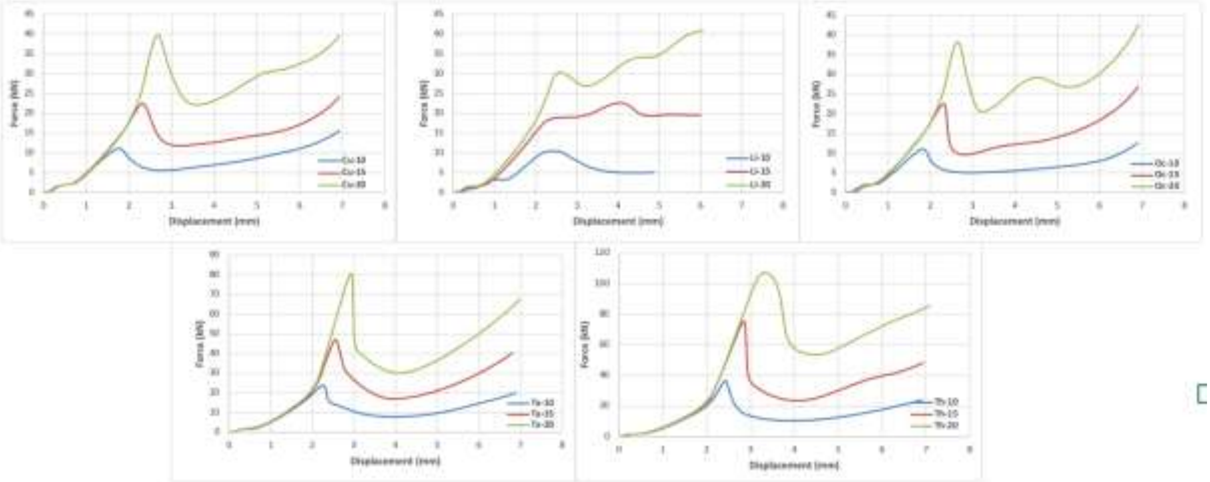


Figure 4. *Force-Displacement curves of the tested samples with respect to infill densities.*

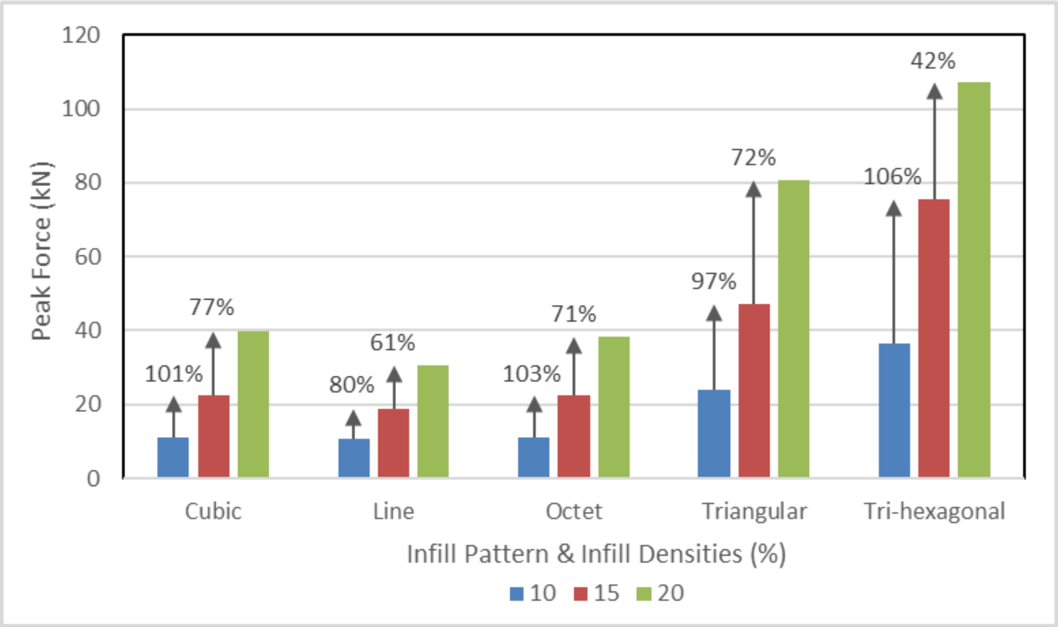


Figure 5. *Peak force values of samples with respect to infill pattern and densities.*

When the slope of the curves until the first damage is evaluated, it is seen that the increase in the infill density does not show a change in the stiffness of the structures. Since the increase in the infill density increases the cross-sectional area, the maximum force values are improved. Therefore, an increase in the inner density, that is, filling it with a denser infill pattern, did not contribute to the stiffness of the material. Again, as seen in Figure 4, as the density increases, the crush stroke value decreases and densification begin earlier. In this state, the early initiation of densification provides an increase in the amount of static energy absorbed by the material. When the graph of the samples with Line (Li) infill pattern is examined, it is seen that they reach lower maximum force values, but considering the force values at which crushing occurs, it is seen that these are the samples where the average crushing force is closest to the peak force value. Based on these data, it can be said that the crush resistance is higher and that can make sample with line infill pattern safer at the time of damage.

In figure 5, the peak force values reached by the samples with different infill patterns and densities are given. It has been previously stated that the strength increases with the increase of infill density. In this graph, we can see more clearly at what rate this increase occurs in samples with different infill patterns. It is seen that the samples with the highest percentage increase in the peak force value due to the increase in infill density are the samples with cubic, octet and triangular infill patterns respectively. If the graphics are evaluated in terms of Infill patterns, it is seen that the lowest strength values are in the samples with line (Li) pattern, and the highest strength is in the samples with tri-hexagonal (Th) and triangle (Ta) pattern types. In Figure 6, force displacement curves of samples filled with different patterns with 20% infill density are shown. From this graph, it can be said that the stiffnesses of the samples with Cubic, Line and Octet infill patterns are close to each other, while the stiffness of the samples with Triangle and Tri-hexagonal patterns is higher. When the samples with the line pattern with the lowest compressive strength were examined, Li20 (Line pattern, %20 infill density) sample which has the highest infill density reached a maximum value of 30.45 kN. On the other hand, Th10 sample, which is the lowest density sample produced with tri-hexagonal pattern, reached up to 36 kN load. In this context, it seems, it’s possible to work at lower infill density rates by applying tri-hexagon pattern instead of producing at 20% infill density with line pattern. Thus, production time will be shortened, raw materials will be saved and costs will be reduced.

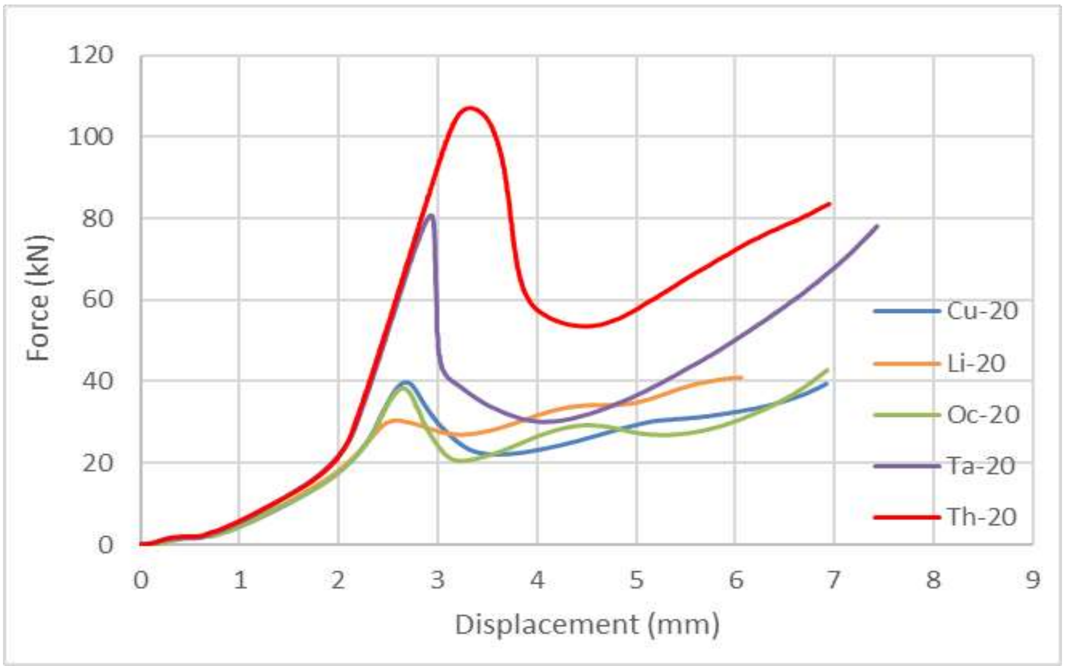


Figure 6. *Force-displacement curves of samples produced at 20% infill density with different infill patterns.*

4. Conclusion

In this study, the compression performance of samples with different infill parameters and infill densities was investigated. The following conclusions can be drawn from the mechanical characterization carried out through experimental analysis;

- As the infill density increases, the compressive strength of the material increases.
- The increase in density did not make a significant difference in the stiffness of the material.
- The change of the infill pattern increased the stiffness of the structure. The samples produced with Triangular and tri-hexagonal patterns had more rigid structures.
- Despite the same percentage increase in density, the samples showing the best increase in material strength were cubic, octet and triangular samples, respectively. From this point of view, it can be said that these samples are more sensitive to the increase in density.
- The most successful samples in terms of static energy absorbing ability were triangular and tri-hexagonal samples.
- It was observed that the crushing force and peak force were closer to each other in the samples with line pattern. This showed that the structure would operate in a safer range in case of sudden damage.
- According to the data obtained, it is possible to produce structures with lower densities and higher strength by using triangular and tri-hexagonal infill patterns. In this way, it will provide significant savings in terms of material, time and energy.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper
- **Acknowledgement:** The authors declare that they have nobody or no-company to acknowledge.
- **Author contributions:** The authors declare that they have equal right on this paper.
- **Funding information:** The authors declare that there is no funding to be acknowledged.
- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

References

[1] S.K. Selvamani, W.K. Ngui, K. Rajan, M. Samykano, Reji Kumar R, Avinash M. Badadhe, (2022). Investigation of bending and compression properties on PLA-brass composite using FDM, *Physics and Chemistry of the Earth* 128. 10.1016/j.pce.2022.103251

[2] Rajan, K., Samykano, M., Kadirgama, K., Harun, W.S.W., Rahman, M.M., 2022. Fused deposition modeling: process, materials, parameters, properties, and applications. *Int. J. Adv. Manuf. Technol.* 120 (3–4); 1531–1570. 10.1007/s00170-022-08860-7

[3] T.D. Ngo, A. Kashani, G. Imbalzano, K.T.Q. Nguyen, D. Hui. (2018) Additive manufacturing (3D printing): a review of materials, methods, applications and challenges, *Compos. Part B Eng.* 143;172–196. 10.1016/j.compositesb.2018.02.012

[4] O. Abdulhameed, A. Al-Ahmari, W. Ameen, S.H. Mian. (2019). Additive manufacturing: challenges, trends, and applications. *Adv. Mech. Eng.* 11 (2); 1-27. 10.1177/1687814018822880

[5] K.V. Wong, A. Hernandez, (2012). A review of additive manufacturing, *ISRN Mech. Eng.* 1–10 10.5402/2012/208760

[6] M. O. Oteyaka, F. H. Çakir, M. A. Sofuoglu. (2022). Effect of infill pattern and ratio on the flexural and vibration damping characteristics of FDM printed PLA samples, *Materials Today Communications* 33. 10.1016/j.mtcomm.2022.104912

[7] Kumaresan, R., Samykano, M., Kadirgama, K., Ramasamy, D., Keng, N.W., Pandey, A.K., (2021). 3D printing technology for thermal application: a brief review. *J. Adv. Res. Fluid Mech. Therm. Sci.* 83 (2);84–97. 10.37934/arfmts.83.2.8497

[8] Braconnier, D.J., Jensen, R.E., Peterson, A.M., (2020). Processing parameter correlations in material extrusion additive manufacturing. *Addit. Manuf.* 31 10.1016/j.addma.2019.100924.

[9] Md. Qamar Tanveer, Gautam Mishra, Siddharth Mishra, Rohan Sharma (2022). Effect of infill pattern and infill density on mechanical behaviour of FDM 3D printed Parts- a current review, *Materials Today: Proceedings* 62;100-108. 10.1016/j.matpr.2022.02.310

[10] M. Fernandez-Vicente, W. Calle, S. Ferrandiz, A. Conejero. (2016). Effect of Infill Parameters on Tensile Mechanical Behavior in Desktop 3D Printing, 3D Print, *Addit. Manuf.* 3 (3): 183–192. 10.1089/3dp.2015.0036

[11] K.P. Motaparti, G. Taylor, M.C. Leu, K. Chandrashekhara, J. Castle, M. Matlack, (2016). Effects of build parameters on compression properties for ULTEM 9085 parts by fused deposition modeling, Solid Free. *Fabr. 2016 Proc. 27th Annu. Int. Solid Free. Fabr. Symp. - An Addit. Manuf. Conf. SF*F. 964–977.

[12] D. Abbas, D. Mohammad Othman, H. Basil Ali, C. Author (2017). Effect of infill Parameter on compression property in FDM Process, *Int. J. Eng. Res. And Application* Www.Ijera.Com. 7; 16–19. 10.9790/9622-0710021619.

[13] J.M. Chacón, M.A. Caminero, E. García-Plaza, P.J. Núñez, (2017). Additive manufacturing of PLA structures using fused deposition modelling: Effect of process parameters on mechanical properties and their optimal selection, *Mater. Des.* 124; 143–157. 10.1016/j.matdes.2017.03.065

[14] S.M. Lebedev, O.S. Gefle, E.T. Amitov, D.V. Zhuravlev, D.Y. Berchuk, E.A. Mikutskiy. (2018). Mechanical properties of PLA-based composites for fused deposition modeling technology, *Int. J. Adv. Manuf. Technol*. 97 (1-4): 511–518. 10.1007/s00170-018-1953-6

[15] A. Rodríguez-Panes, J. Claver, A. Camacho. (2018). The Influence of Manufacturing Parameters on the Mechanical Behaviour of PLA and ABS Pieces Manufactured by FDM: *A Comparative Analysis, Materials (Basel)*. 11 :1333. 10.3390/ma11081333

[16] A. Nadernezhad, S. Unal, N. Khani, B. Koc. (2019). Material extrusion-based additive manufacturing of structurally controlled poly(lactic acid)/carbon nanotube nanocomposites, *Int. J. Adv. Manuf. Technol.*102(5-8):2119–2132. 10.1007/s00170-018-03283-9

[17] O.H. Ezeh, L. Susmel. (2019). Fatigue strength of additively manufactured polylactide (PLA): effect of raster angle and non-zero mean stresses, *Int. J. Fatigue.*126:319–326. 10.1016/j.ijfatigue.2019.05.014

[18] M.Q. Tanveer, A. Haleem, M. Suhaib. (2019). Effect of variable infill density on mechanical behaviour of 3-D printed PLA sample: an experimental investigation, *SN Appl. Sci.* 1: 1701. 10.1007/s42452-019-1744-1

[19] T. Yao, Z. Deng, K. Zhang, S. Li. (2019). A method to predict the ultimate tensile strength of 3D printing polylactic acid (PLA) materials with different printing orientations, *Compos. Part B Eng.* 163:393–402. 10.1016/j.compositesb.2019.01.025

[20] M. Samykano, S.K. Selvamani, K. Kadirgama, W.K. Ngui, G. Kanagaraj, K. Sudhakar. (2019). Mechanical property of FDM printed ABS: influence of printing parameters, *Int. J. Adv. Manuf. Technol.* 102 (9-12): 2779–2796. 10.1007/s00170-019-03313-0

[21] B. Aloyaydi, S. Sivasankaran, A. Mustafa. (2020). Investigation of infill-patterns on mechanical response of 3D printed poly-lactic-acid, *Polym. Test.* 87. 10.1016/j.polymertesting.2020.106557

[22] K.N. Gunasekaran, V. Aravinth, C.B. Muthu Kumaran, K. Madhankumar, S. Pradeep Kumar. (2021). Investigation of mechanical properties of PLA printed materials under varying infill density, *Mater. Today Proc.* 45: 1849–1856. 10.1016/j.matpr.2020.09.041

[23] S.R. Rajpurohit, H.K. Dave. (2021). Impact strength of 3D printed PLA using open source FFF-based 3D printer, *Prog. Addit. Manuf.* 6 (1): 119–131. 10.1007/s40964-020-00150-6

[24] P. Yadav, A. Sahai, R.S. Sharma. (2021). Strength and Surface Characteristics of FDM Based 3D Printed PLA Parts for Multiple Infill Design Patterns, *J. Inst. Eng. Ser. C.* 102 (1): 197–207. 10.1007/s40032-020-00625-z

[25] A. Farazin, M. Mohammadimehr. (2021). Effect of different parameters on the tensile properties of printed Polylactic acid samples by FDM: experimental design tested with MDs simulation, *Int. J. Adv. Manuf. Technol. 118:103-118.* 10.1007/s00170-021-07330-w

[26] P.K. Mishra, P. Senthil, S. Adarsh, M.S. Anoop. (2021). An investigation to study the combined effect of different infill pattern and infill density on the impact strength of 3D printed polylactic acid parts, *Compos. Commun.* 24. 10.1016/j.coco.2020.100605

[27] P. Patil, D. Singh, S.J. Raykar, J. Bhamu. (2021). Multi-objective optimisation of process parameters of Fused Deposition Modeling (FDM) for printing Polylactic Acid (PLA) polymer components, *Mater. Today Proc.* 45: 4880–4885. 10.1016/j.matpr.2021.01.353

[28] M. Samykano. (2021). Mechanical Property and Prediction Model for FDM-3D Printed Polylactic Acid (PLA), *Arab. J. Sci. Eng.* 46 (8): 7875–7892. 10.1007/s13369-021-05617-4