DOI: 10.2507/33rd.daaam.proceedings.xxx

Influence of Printhead Nozzle Diameter on Mechanical Properties of FDM Printed PLA Material and Printing Time

Damir Hodžić & Adi Pandžić

This Publication has to be referred as: Katalinic, B[ranko], Park, H[ong] S[eok] & Smith, M[ark] (2022). Title of Paper, Proceedings of the 33rd DAAAM International Symposium, pp.xxxx-xxxx, B. Katalinic (Ed.), Published by DAAAM International, ISBN 978-3-902734-xx-x, ISSN 1726-9679, Vienna, Austria
DOI: 10.2507/33rd.daaam.proceedings.xxx

Abstract

There are various 3D printing parameters that affect the mechanical properties of FDM printed materials as well as the final price of the finished product. One of the influential factors on printing time is certainly the diameter of the print head nozzle. In this paper influence of print head nozzle diameter on the mechanical properties of FDM printed PLA material was analysed. Tensile and flexural mechanical properties were examined, and tensile strength, elastic modulus, flexural strength, flexural modulus, and strain are presented in results. Also, the influence of the nozzle diameter on the total printing time was analysed because the printing time directly affects the final price of the product.

Keywords: FDM; nozzle diameter; PLA; material properties; printing time.

1. Introduction

Undoubtedly, one of the technologies that increasingly influences the course of industry development is additive technologies (AM). In the last few years, a huge focus is on development of AM technologies. There are many different AM technologies on the market today, but one of the most popular and used is fused deposition modeling, better known as FDM technology [1].

Compared to the conventional manufacturing technologies, reducing the time from initial concept design to the final product is one of the main advantages of AM technologies. With this technologies, designers or engineer are able to produce the prototype or final product in just a few days, without need for special tools or developing special manufacturing process. The rapid production of small series products using AM technologies has been best proven in the crisis period during COVID 19 for making different products in medical purposes [2].

FDM 3D printing technology uses thermoplastic polymeric material as a base material, also known as a filament. Process is based on the material extrusion through a nozzle mounted in the printhead (Fig. 1). The filament is fed from a coil into the printer head, where it is heated in heater element, and in molten phase material is forced out of the printhead nozzle on to build platform. With precisely defined movement of the printer head based on G-code, the finished product is made layer by layer on the build platform [3], [4].

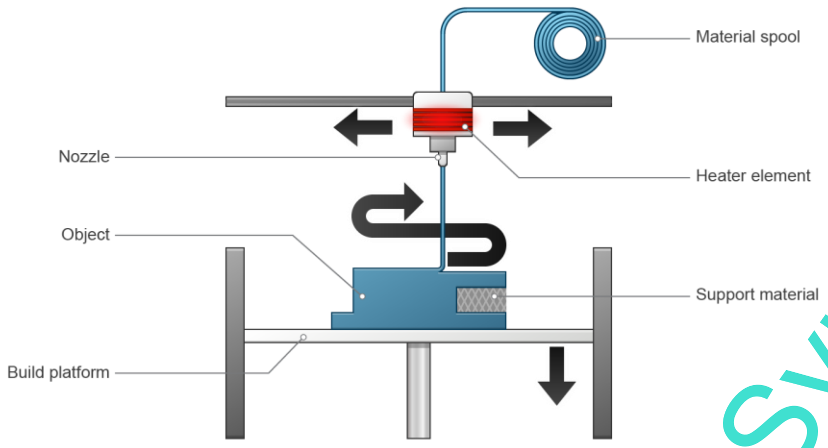

Fig. 1. A schematic of the FDM printing technology process [5]

Analysing the literature and previous research in this area, it can be concluded that many printing parameters affect the mechanical properties of FDM printed materials. Also, in addition to the mechanical properties of the printed material, the 3D printing parameters also affect other product characteristics such as surface quality, accuracy of the product geometry, porosity, total mass as well as the production time which directly affects the price of the product itself. Some of the printing parameters that affect the mechanical properties of the material as well as the total printing time are: layer height, print orientation, nozzle diameter, printing speed, infill design, printing temperature, etc. However, the choice of the right combination of printing parameters still needs further investigation because optimal process parameters defined for one material may not work well for another material [6], [7], [8].

One of the printing parameters that has an impact on the material mechanical properties, print quality, printing time and overall price of the printed product is the printhead nozzle diameter. In study [9], influence of nozzle diameter on the macrostructure and selected strength properties of PLA printed material was analysed. It was concluded that for nozzle diameter greater than 0,4 mm, an increase in the share of air voids between the print rasters occurred. It was stated that perhaps this phenomenon has an influence on the impact strength, because the results showed the highest impact strength values for samples with the largest voids between the rasters of the polymer material. It is also stated that the cause of this is that he voids in the sample structure may absorb some of the energy generated during the impact test. Results in this study showed highest value of impact strength when using a 0,8 mm nozzle diameter. For tensile strength, the highest values were obtained for 0,4 and 0,8 mm nozzle diameters. Also, in study [10] was concluded that higher pore size was obtained with higher nozzle diameter.

Influence of the printing nozzle diameter on tensile strength and printing time was analysed in study [11]. In this study, seven different nozzle diameters were varied, from 0.2 mm to 0.8 mm. Also, testing samples were printed with 50% and 100% infill density. Analysing the breaking force, results showed that for samples with 50% infill density breaking force was increasing with increasing the nozzle diameter. On the other hand, for samples with 100% infill density, breaking force was decreasing with the increase of the nozzle diameter. Also, printing time dependence on the nozzle diameter was presented, where for both infill densities (50% and 100%), printing time decreased with nozzle diameter increase.

In this study aim was to analyse influence of four different printhead nozzle diameters: 0,25 mm; 0,4 mm; 0,6 mm and 0,8 mm, on tensile and flexural mechanical properties of 3D printed PLA material. Also, influence of nozzle diameter on total printing time was analysed.

2. Materials and methods

In order to analyse the influence of the printhead nozzle diameter on the tensile and flexural mechanical properties of FDM printed PLA material, a detailed experimental study was carried out, presented through the flow diagram in Fig 2.

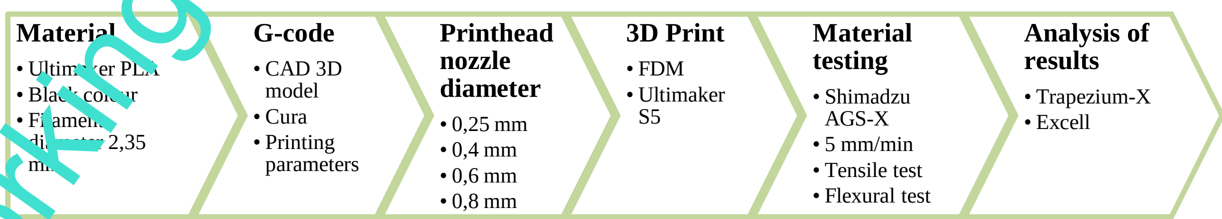

Fig. 2. Experiment flow diagram

The material used in the tests was thermoplastic polymer polylactic acid (PLA), produced by Ultimaker company, in black colour. Certainly, one of the most commonly used materials in FDM technology, which is also biodegradable material. Mechanical properties defined by manufacturer are presented in table 1.

Material properties	Test method	Typical value
Tensile strength [MPa]	ASTM D3039 (5 mm / min)	52,5 MPa
Tensile elastic modulus [GPa]	ASTM D3039 (1 mm / min)	3,25 GPa
Strain at brake [%]	ASTM D3039 (5 mm / min)	7,8 %
Flexural strength [MPa]	ISO 178 (5 mm / min)	96,8 MPa
Flexural modulus [GPa]	ISO 178 (1 mm / min)	3,02 GPa
Flexural strain at brake [%]	ISO 178 (5 mm / min)	4,8 %
Charpy impact strength (at 23 °C)	ISO 179-1 / 1eB (notched)	3,9 kJ/m²
Hardness	ISO 7619-1 (Durometer, Shore D)	84 Shore D

Table 1. FDM printed PLA material properties by Ultimaker manufacturer

Tensile and Flexural test specimens 3D models were designed using CAD software Solidworks 2022. Tensile test specimen were designed according to ISO 527, while the flexural test specimen was designed according to ISO 178, presented on Fig. 3.

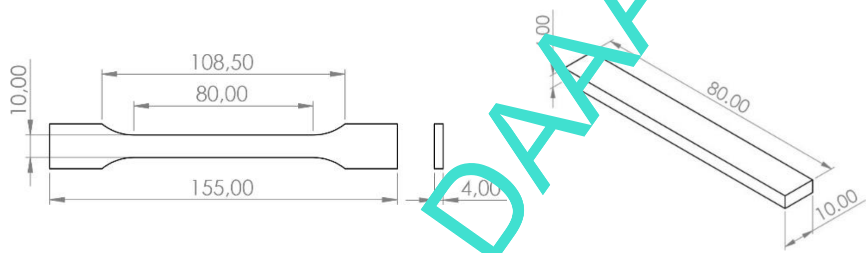

Fig. 3. Tensile test specimen according to ISO 527 (left) and flexural test specimen according to ISO 178 (right)

G-code with 3D printing parameters was prepared using Ultimaker Cura slicer. For all specimens, printing parameters are defined by default Ultimaker printing profile "Normal" for Ultimaker black PLA filament and for four different nozzle diameters: 0,25 mm; 0,4 mm; 0,6 mm; and 0,8 mm. Also, although the printhead nozzle diameter was changed, a layer height of 0,15 mm was used for printing all samples (Fig. 4).

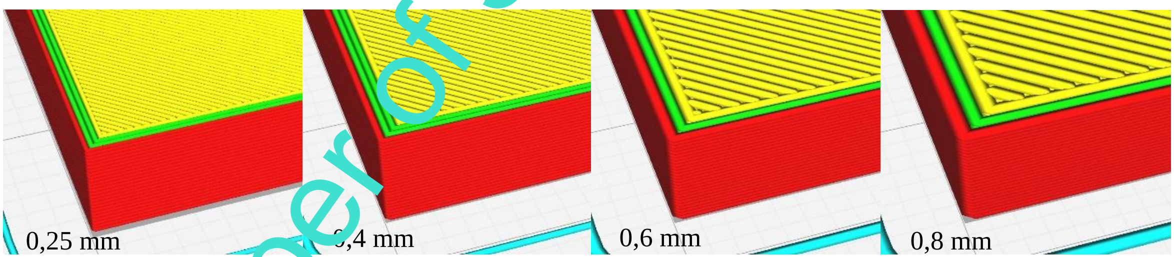

Fig. 4. Example of 3D printing product with different printhead nozzle diameter

After the g-code was defined, 3D printing was performed using the FDM "Ultimaker S5" desktop 3D printer. Ultimaker S5 is composite-ready dual extrusion professional desktop 3D printer with 330x240x300 mm build volume.

Tensile and flexural testing specimens were printed in five replicas and presented on Fig 5. All specimens are tested on Shimadzu AGS-X universal testing machine with capacity of 10 kN with testing speed of 5 mm/min. Data monitoring was performed using Shimadzu Trapezium-X software. After data collection, the results were processed using the Excel program and presented in further text.

Fig. 5. Tensile and flexural FDM 3D printed specimens

3. Results and discussion

After the 3D printing of the test samples, the tensile and flexural mechanical properties were analysed. Stress-strain diagrams for tensile and flexural mechanical properties are presented on Fig. 6, where curves representing the mean values of five replicas of each sample.

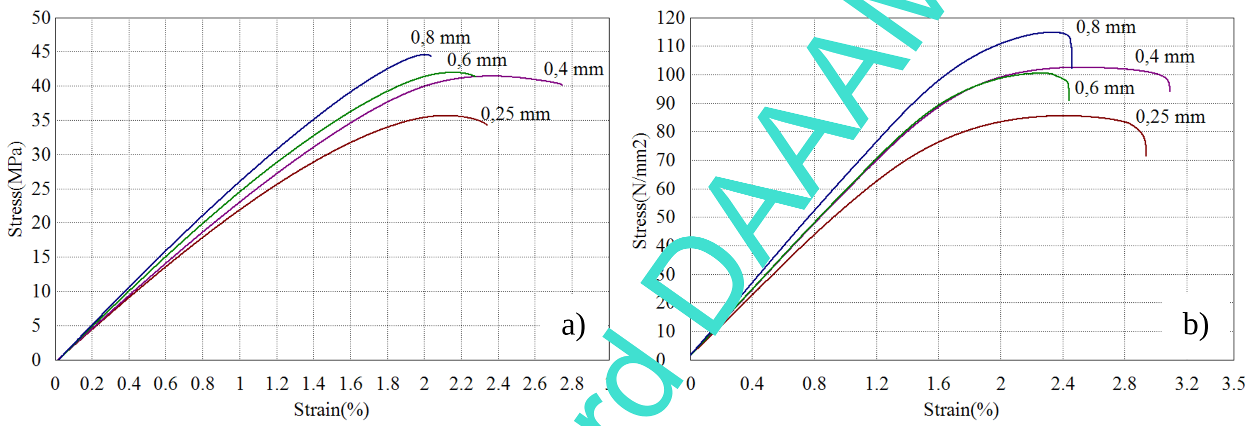

Fig. 6. Stress-strain diagrams for tensile (a) and flexural (b) mechanical properties of FDM printed PLA material with different printhead nozzle diameter

Influence of printhead nozzle diameter on tensile strength and elastic modulus is presented on the diagrams in Fig. 7. The diagrams show a linear increase in tensile strength and elastic modulus increasing printhead nozzle diameter. The highest tensile strength values (44,6 MPa) were measured for samples made with a 0,8 mm nozzle diameter. Samples 3D printed with a 0,25 mm nozzle diameter showed the lowest tensile strength values. For samples 3D printed with 0,4 mm and 0,6 mm nozzles diameter, tensile strength values were measured with a very small difference, no more than 0,3%. Analysing the elastic modulus, the highest values (2,8 GPa) can be seen for samples made with a 0,8 mm nozzle diameter, while the lowest values (2,4 GPa) were measured for samples printed with a nozzle diameter of 0,25 mm. Compared to the tensile strength, the elastic modulus has a larger difference (4%) in values for samples printed with a nozzle diameter of 0.4 and 0.6 mm.

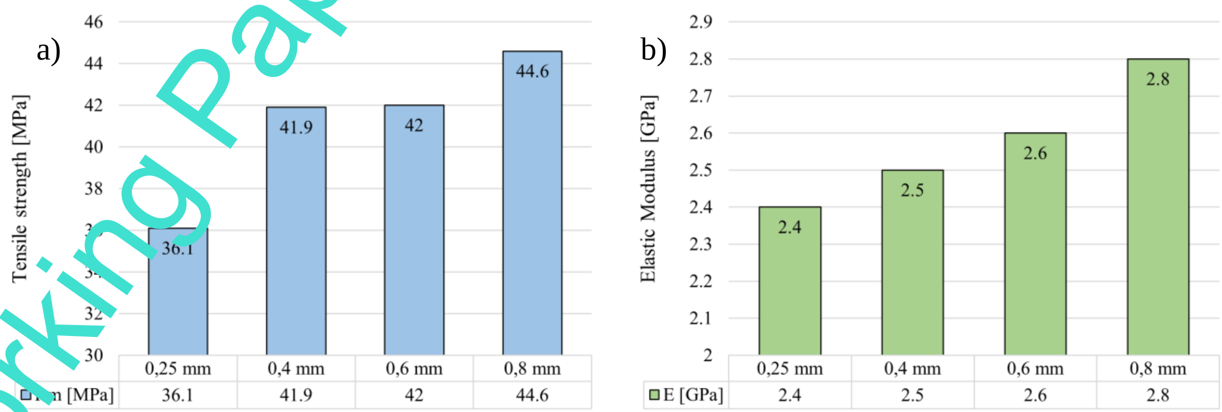

Fig. 7. Influence of printhead nozzle diameter on tensile strength (a) and elastic modulus (b)

Diagrams on Fig. 8 is presenting the influence of printhead nozzle diameter on flexural strength and flexural modulus. By examining the flexural mechanical properties, similar results were obtained as with the tensile tests results. The highest flexural strength values (114.9 MPa) were obtained for a 0,8 mm nozzle diameter, while the lowest values (85.7 MPa) were obtained for a 0,25 mm nozzle diameter. The highest value of flexural modulus (6,3 GPa) was obtained for 0.8 mm nozzle diameter, while the lowest flexural modulus (5,2 GPa) was obtained for 0,25 mm nozzle diameter. Also, with an increase in the nozzle diameter from 0.25 mm to 0.8 mm, a linear increase in flexural strength and flexural modulus can be seen, which was previously shown in tensile mechanical properties results.

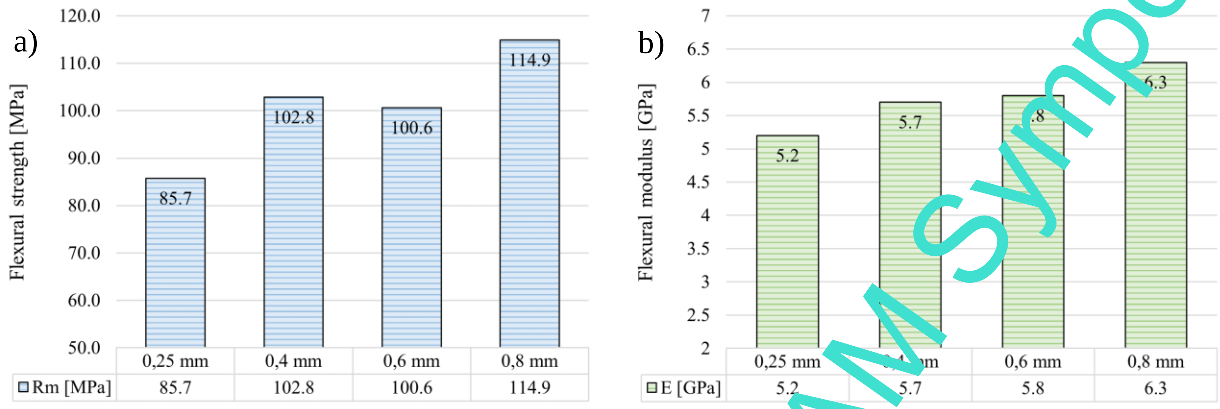

Fig. 8. Influence of printhead nozzle diameter on flexural strength (a) and flexural modulus (b)

In addition to the tensile and flexural strength, the tensile and flexural strain at brake was also analysed, and results are presented in diagrams on Fig 9. Similar changes of strain are observed when the nozzle diameter increases for both cases. With an increase in nozzle diameter from 0,25 mm to 0,4 mm, an increase in strain is seen, then with an increase in diameter from 0,4 mm to 0,8 mm, a decrease in the value of strain can be seen. Also, it should be noted that the same flexural strain values were measured for nozzle diameters of 0.6 mm and 0.8 mm.

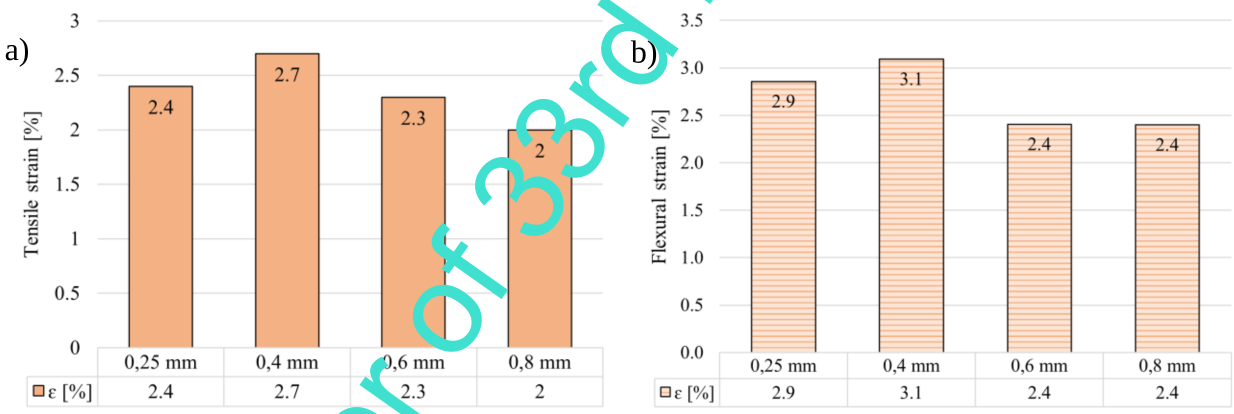

Fig. 9. Influence of printhead nozzle diameter on tensile (a) and flexural (b) strain

The effect of the printhead nozzle diameter on the total printing time was also analysed, whereby the total printing time refers to the 3D printing of one test sample for testing tensile mechanical properties. Influence of printhead nozzle diameter on total printing time is presented on Fig 10.

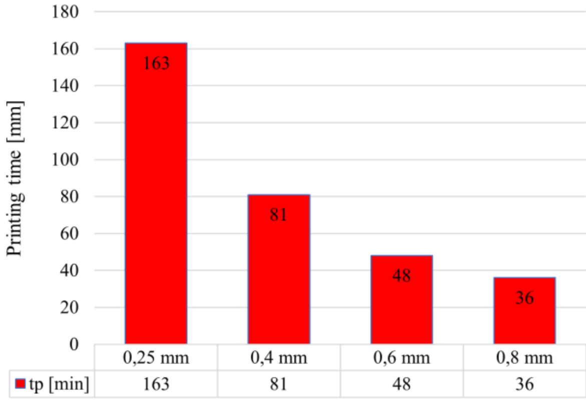

Fig. 10. Influence of printhead nozzle diameter on total printing time (tp)

As expected, with the nozzle diameter increase, the total printing time decreases. Significantly longer printing time with a nozzle diameter of 0.25 mm is visible compared to other nozzle diameters, where the difference is up to four times higher.

Table 2 presents the overall results of the nozzle diameter influence on the tensile and flexural mechanical properties of the FDM printed PLA material, as well as on the total printing time.

Nozzle diameter [mm]	**0,25**	**0,4**	**0,6**	**0,8**	**Ultimaker TDS***
Tensile strength [MPa]	36.10	41.90	42.00	44.60	52,5 MPa
Elastic modulus [GPa]	2.40	2.50	[illegible]	2.80	3,25 GPa
Tensile strain [%]	2.40	2.70	[illegible].30	2.00	7,8 %
Flexural strength [MPa]	85.74	102.83	100.61	114.89	96,8 MPa
Flexural modulus [GPa]	5.20	5.70	5.80	6.30	3,02 GPa
Flexural strain [%]	2.86	3.09	2.41	2.40	4,8 %
Total printing time [min]	163.00	81.00	48.00	36.00	-
*Material mechanical characteristics from Ultimaker PLA material technical data sheet.					

Table 2. Overall results – Printhead nozzle diameter influence on tensile and flexural mechanical properties and total printing time

4. Conclusion

The research showed an influence of the printhead nozzle diameter on the tensile and flexural mechanical properties of FDM printed PLA material. Some of the main conclusions are:

- With the increase of the printhead nozzle diameter, the tensile strength, elastic modulus, flexural strength, and flexural modulus increased linearly.
- All analysed mechanical properties, tensile and flexural, change pretty much the same with the change in printhead nozzle diameter.
- The highest values of tensile strength and elastic modulus were measured for samples made with a 0,8 mm nozzle diameter, and the lowest values for 0,25 mm diameter.
- The highest values of flexural strength and modulus were measured for samples made with a 0,8 mm nozzle diameter, and the lowest values for 0,25 mm diameter.
- Maximum tensile and flexural strain at brake values were measured for 0,4 mm printhead nozzle diameter.
- Changing the printhead nozzle diameter it can be seen the same change for both the tensile and flexural measured mechanical properties.
- Total printing time was linearly decreasing with printhead nozzle diameter increase, which was expected.

Through future research, the same analysis should be done but for other materials, to see if the change in nozzle diameter shows the same effect as with FDM printed PLA material. Also, the influence of the nozzle diameter on other mechanical properties, as well as on other properties of FDM printed materials in general, should also be analysed.

5. References

[1] Pandzic, A. & Hodzic, D. (2021). Mechanical Properties Comparison of PLA, Tough PLA and PC 3D printed Materials with Infill Structure – Influence of Infill Pattern on Tensile Mechanical Properties, IOP Conf. Series: Materials Science and Engineering, 1208, DOI: doi:10.1088/1757-899X/1208/1/012019

[2] Muminović, A. J.; Pandzic, A.; Pervan, N. & Delic, M. (2022). Product Development and Design Inside Industry 4.0 From Rapid Prototyping to Additive Manufacturing, Special Editions ASAB&H CCII, DTS, Vol. 20, pp. 69-80, DOI: 10.5644/PI2022.202.21

[3] Khosravani, M. R.; Schuurmann, J.; Berto, F. & Reinicke, T. (2021). On the Post-Processing of 3D-Printed ABS Parts, Polymers, Vol. 13, No. 10, DOI: 10.3390/polym13101559

[4] Hodzic, D. & Pandzic, A. (2021). Influence of Infill Design on Compressive and Flexural Mechanical Properties of FDM Printed PLA Material, Proceedings of the 32nd DAAAM International Symposium, pp.0191-0199, B. Katalinic (Ed.), Published by DAAAM International, ISBN 978-3-902734-33-4, ISSN 1726-9679, Vienna, Austria, DOI: 10.2507/32nd.daaam.proceedings.029

[5] https://make.3dexperience.3ds.com/processes/3D-printing, (2018). 3D Printing – Additive: Introduction to 3D Printing – Additive processes, Accessed on: 2022-09-15

[6] Pandzic, A.; Hodzic, D.; Hajro, I. & Tasic, P. (2020). Strength Properties of PLA Material Obtained by Different Models of FDM 3D Printer, Proceedings of the 31st DAAAM International Symposium, pp.0315-0322, B. Katalinic (Ed.), Published by DAAAM International, ISBN 978-3-902734- 29-7, ISSN 1726-9679, Vienna, Austria, DOI: 10.2507/31st.daaam.proceedings.044

[7] Gebisa, A. W. & Lemu, H. G. (2018). Investigating Effects of Fused-Deposition Modeling (FDM) Processing Parameters on Flexural Properties of ULTEM 9085 using Designed Experiment, Materials, Vol. 11, No. 4, DOI: 10.3390/ma11040500

[8] Pandzic A.; Hodzic D. & Milovanovic A. (2019). Effect of Infill Type and Density on Tensile Properties of PLA Material for FDM Process, Proceedings of the 30th DAAAM International Symposium on Intelligent Manufacturing and Automation, Zadar, ISSN: 1726-9679, ISBN 978-3-902734-22-8, Katalinic, B. (Ed.), pp. 545-554, Published by DAAAM International, Vienna, DOI: 10.2507/30th.daaam.proceedings.074

[9] Czyzewski, P.; Marciniak, D.; Nowinka, B.; Borowiak, M. & Bielinski, M. (2022). Influence of Extruder's Nozzle Diameter on the Improvement of Functional Properties of 3D-Printed PLA Products, Polymers, Vol. 14, No. 2, 356, DOI: 10.3390/polym14020356

[10] Corral-Buj, I.; Bagheri, A.; Fernandez, A. D. & Lopez, C. R. (2019). Influence of Infill and Nozzle Diameter on Porosity of FDM Printed Parts with Rectilinear Grid Pattern, 8th Manufacturing Engineering Society International Conference, Vol. 41, pp. 288-295, DOI: 10.1016/j.promfg.2019.09.011

[11] Kinski, W. & Pietkiewicz, P. (2020). Influence of the Printing Nozzle Diameter on Tensile Strength of Produced 3D Models in FDM Technology, Agricultural Engineering, Vol. 24, No. 3, pp. 31-38, DOI: 10.1515/agriceng-2020-0024