Available online at www.sciencedirect.com

ScienceDirect

Procedia Structural Integrity 56 (2024) 190–197

Structural Integrity Procedia

www.elsevier.com/locate/procedia

Structural Integrity and Reliability of Advanced Materials obtained through Additive Manufacturing (SIRAMM23)

Layer thickness influence on impact properties of FDM printed PLA material

Aleksa Milovanović[a]*, Sergiu-Valentin Galațanu[b], Aleksandar Sedmak[c], Liviu Marșavina[b], Isaak Trajković[a], Cosmin-Florin Popa[b], Miloš Milošević[a]

[a]University of Belgrade, Innovation Center of the Faculty of Mechanical Engineering, Kraljice Marije 16 Street, Belgrade 11120, Serbia
[b]Polytechnic University of Timişoara, Department of Mechanics and Strength of Materials, 1 Mihai Viteazu Avenue, Timişoara 300222, Romania
[c] University of Belgrade, Faculty of Mechanical Engineering, Department of Material Science, Kraljice Marije 16, Belgrade 11120, Serbia

Abstract

Polylactic Acid (PLA) is a widely used material in Fused Deposition Modeling (FDM) technology. Additive Manufacturing (AM) parameters are known to have an influence on the mechanical properties of final components. In FDM, the layer thickness is an influencing parameter providing overall better mechanical properties with lower layer thickness values. In that case, the air gaps created between layers and raster lines have a lower share in total volume. However, layer over-compression might be an issue when choosing the lowest layer thickness options. This research paper investigates the impact properties of PLA material with variations in layer thickness namely, 0.1, 0.2, and 0.3 mm are considered here. Charpy tests were used for the impact property assessment, and all specimens were prepared with 100% infill percentage and honeycomb infill structure. Worth mentioning is that specimens have AMed notches. The impact tests were carried out on 7 specimens per batch (a total of 21 specimens). Therefore, obtained impact results from an instrumented pendulum were observed between groups to have an insight into the beneficial influence of lower layer thickness on impact properties and lower result scatter that finer layer resolution should produce.

Keywords: PLA; FDM; Charpy; layer thickness; Instrumented pendulum.

---

* Corresponding author. Tel.: +381-64-614-8698.
E-mail address: amilovanovic@mas.bg.ac.rs

10.1016/j.prostr.2024.02.055

1. Introduction

At first, AM technology was used for rapid prototyping purposes, because of its faster and cheaper production compared to conventional (subtractive) methods. Over time, with the increase in available production methods and materials, the utilization of this technology in the production of functional components was also taken into consideration. Now, the importance of particular AM technology is not measured only by fabrication time, production energy consumed, and quantity of material used, but also by the potential of a particular AM technology to deliver components for functional applications.

For this estimation material's mechanical properties have to be obtained using standardized tests, and the most probable first choices are tensile, compressive, and flexural tests. Most used are the tensile tests, providing valuable information about the material, utilized in research works by Popović et al. (2023), Pandžić et al. (2019a), Pandžić et al. (2019b), Milovanović et al. (2022a). A comprehensive mechanical property assessment using all three test methods for AMed materials dedicated to dental aligners is shown in Milovanović et al. (2021). Also valuable are the tests from fracture mechanics aspects, as in Milovanović et al. (2022b), and Milovanović et al. (2022c).

For a better insight into the material's behaviour impact properties are also preferable. Standardized impact tests include Charpy and IZOD tests. These two methods differ in specimen geometry and placement on the impact machine, but they both evaluate the same material property, as stated by Popa et al. (2022) and Ailinei et al. (2022).

In FDM, the printing parameters and materials used dictate the mechanical properties of finished components. The proof of the significant influence of the raster angle on impact strength was investigated by Rajpurohit et al. (2020), and Patterson et al. (2021) also investigated build orientation with raster angle on seven different materials. As stated by Patterson et al. (2021), brittle materials (e.g., PLA) have more consistent impact properties. Build orientation influence on impact strength was also a subject in Stoia et al. (2022) research in the case of Polyamide material, used in SLS technology. Popa et al. (2022) investigated the dependence of specimen thickness on IZOD impact strength, for PLA and PETG materials. Here, PLA material has higher impact force values than PETG but has lower overall deflection. A particularly interesting research finding is that higher specimen thicknesses produce a higher value scatter of results. Our research matches the lowest specimen thickness used in the Popa et al. (2022) paper, namely 4 mm.

Except for impact testing of individual materials current research papers cover the properties of composite FDM materials, either as fiber-reinforced or created by stacking layers of different materials. For example, a dual-extruder FDM machine allows for the creation of one layer from one material, and then the other material comes in the next layer. Ahmed et al. (2021) investigated the properties of composites that contain fiber-reinforced PLA in one layer and ABS material in the other. The conclusion here shows that more ABS layers create higher impact strength, and all PLA layers here have brittle fracture surfaces. Ferdinand et al. (2023) used PLA with added synthetic polymer fibers, such as PET and PVA, showing that PVA is a more efficient impact modifier among selected reinforcements. Research shows that fiber characteristics and its adhesion with the matrix material are the main factors for the composite material's impact properties. PLA is a bio-based material, and Tian et al. (2022) focused their research on incorporating nano-fibrillated cellulose into PLA resulting in a 2.3 times higher impact strength of such material.

The subject of this research paper is the influence of layer thickness on the impact properties of PLA material, i.e., impact force-deflection, impact energy-deflection response, maximum impact force value, deflection at the point of break, impact energy, and impact strength values.

Nomenclature

AM	Additive Manufacturing
FDM	Fused Deposition Modeling
PLA	Polylactic Acid
SLS	Selective Laser Sintering
PETG	Polyethylene Terephthalate Glycol
ABS	Acrylonitrile Butadiene Styrene
PET	Polyethylene Terephthalate

PVA	Polyvinyl alcohol

2. Materials and Methods

The research covers three different layer thickness values namely, 0.1 mm, 0.2 mm, and 0.3 mm. Specimens were prepared according to ISO 179 standard, with chosen type A notch (see Fig. 1, Left). Specimens' notches were AMed, not machined- as suggested by Valean et al. (2020). All specimens have two outlines and a honeycomb infill structure (see Fig. 1, Right). The honeycomb structure has proven to be the best choice regarding mechanical properties among all available infill patterns in the utilized Simplify3D slicer software (Simplify3D, Cincinnati, OH, USA), as stated by Milovanović et al. (2022d). The infill percentage is set to full (100%).

The tests are conducted on the instrumented pendulum, Instron CEAST 9050 machine (see Fig. 2) with hammer properties listed in Table 1. The sampling rate was set to 1000 Hz, adequate for the interpretation of results. The specimens were tested in an edgewise direction, with a 60 mm span between the anvils. The standard defines five specimens for sufficient repeatability, but just in case two additional specimens were prepared- giving a total of seven specimens per batch.

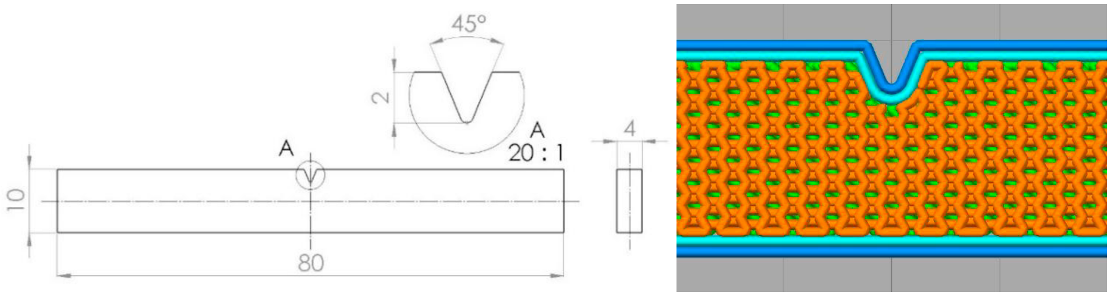


Fig. 1. (Left) Charpy specimen dimensions (in mm); (Right) Layer structure.

Fig. 2. Instron CEAST 9050 Charpy instrumented pendulum.

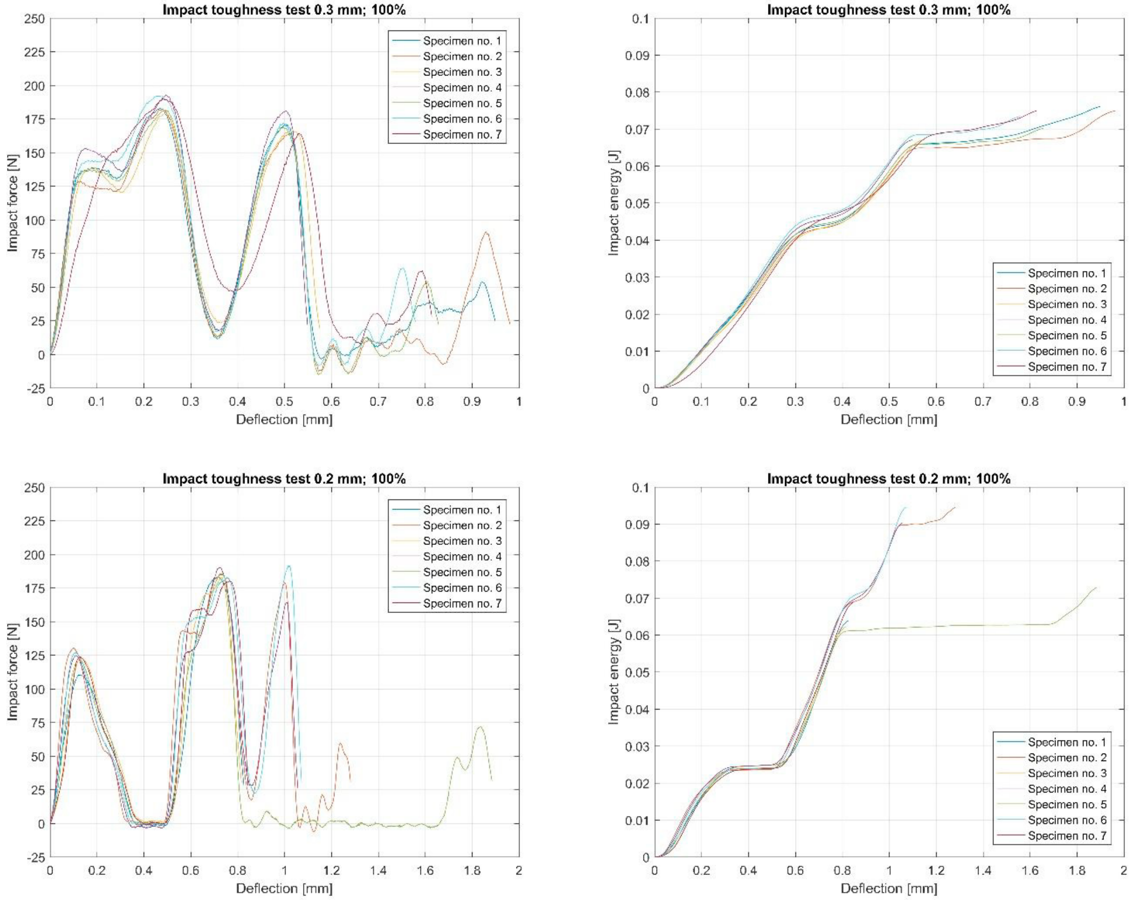
Table 1. Charpy hammer properties.

Parameters	Values
Potential energy	5 J
Impact speed	2.9 m/s

Starting angle	150°
Weight	1.186 kg
Length	229.7 mm

3. Results and Discussion

The impact force and impact energy dependence from deflection are shown for all three chosen layer thicknesses in Fig. 3. Each chart contains seven curves, for all individual specimens.



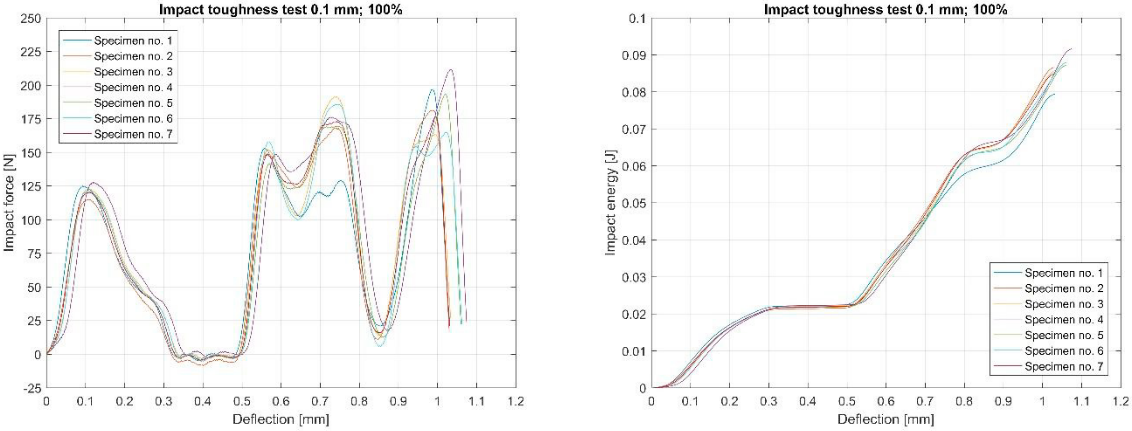


Fig. 3. (Top-Left) Force-deflection for 0.3 mm; (Top-Right) Energy-deflection for 0.3 mm; (Middle-Left) Force-deflection for 0.2 mm; (Middle-Right) Energy-deflection for 0.2 mm; (Bottom-Left) Force-deflection for 0.1 mm; (Bottom-Right) Energy-deflection for 0.1 mm.

The repeatability of impact force and energy response relative to deflection is notable, as can be seen from all the charts in Fig. 3. Especially good repeatability is apparent in the first elastic impact domain (i.e., force increase from zero value until the first peak) and first damage event (i.e., decrease in force after the first peak until the first gradual increase in force). Unlike the batches with lower layer thickness, the 0.3 mm batch contains a distinctive plateau before reaching the first peak (also visible on the average curve chart, Fig. 4- Left).

The similarity in response for the 0.1 mm and 0.2 mm batches can also be seen in Fig. 4, Right (average impact energy-deflection curves). The effect of plastic deformation can be derived from the displacement increase at a constant energy level, as stated by Krausz et al. (2021). The plastic deformation is visible from 0.3 mm until 0.5 mm deflection for 0.1 mm and 0.2 mm layer thickness batches. Unlike these two batches, the 0.3 mm batch has a significantly smaller plateau here. Also, the impact energy value is higher for both lower thickness batches (values are about 0.09 J), and the impact energy value for the 0.3 mm batch is around 0.07 J (see Fig. 4, Right).

In FDM, higher layer thicknesses have lower adhesion between layers and a larger portion of air gaps in the cross-section. For these stated reasons, the 0.3 mm batch differs so much from the other two higher-resolution batches.

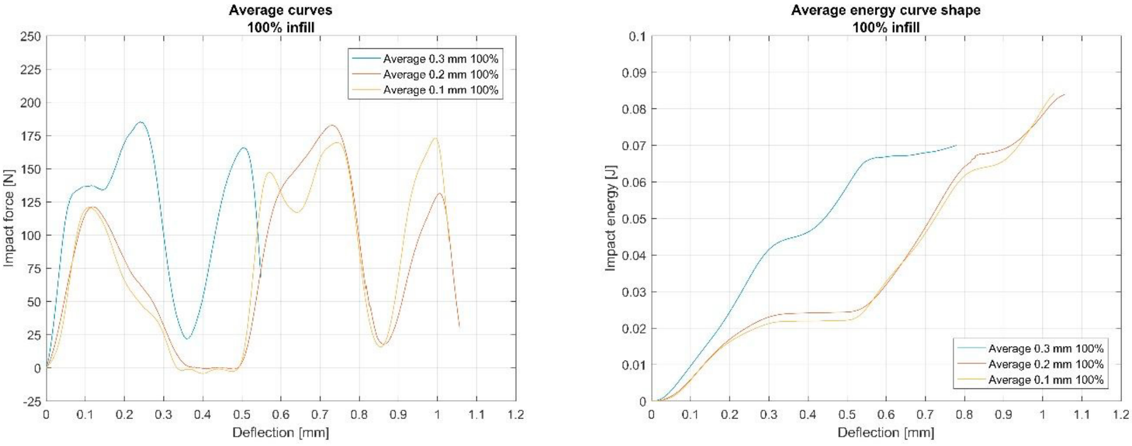


Fig. 4. (Left) Average force-deflection curves; (Right) Average energy-deflection curves.

The maximum impact force and the value of deflection at the break for the observed layer thicknesses are shown in Fig. 5. The maximum impact force is higher in lower layer thicknesses (see trendline, Fig. 5- Left). Unfortunately, the highest value scatter is present in the 0.1 mm batch, due to the presence of the highest peaks later in the propagation phase (see Fig. 3, Bottom-Left). In the 0.3 mm batch, the highest values are located at the first peak, in the 0.2 mm batch the maximum values are mostly placed at the second peak. The maximum impact force value range is 11.489 N and 13.123 N for the 0.2 and 0.3 mm batches, respectively. In the 0.1 mm layer thickness batch the value range is much higher, i.e., 35.24 N. The 0.1 mm batch is unique because it has a considerable number of maximum impact force values located at the last peak. On the one hand, this is an advantage for this layer thickness because it can withstand high forces later in the propagation phase. Unfortunately, this may produce a high scatter of the force values.

The same applies to the deflection at break values (see Fig. 5, Right): the trendline shows higher values for lower layer thicknesses. The highest value scatter is present in the 0.2 mm batch, mostly due to specimens no. 2 and 5 reaching a much higher deflection than the other specimens from the batch (see Fig. 3, Middle-Left). Here, five specimens experienced a break at around 1 mm, the other two failed at around 1.3 mm and 2 mm. Because of that, the deflection at the break range for the 0.2 mm batch is the highest, i.e., 1.068 mm. In the 0.3 mm batch, there were deflection recordings after the last peak, resulting in a 0.432 mm range in break deflection values. In contrast to the mentioned batches, all of the 0.1 mm specimens experienced a break at almost the same location, resulting in a deflection value range of just 0.044 mm.

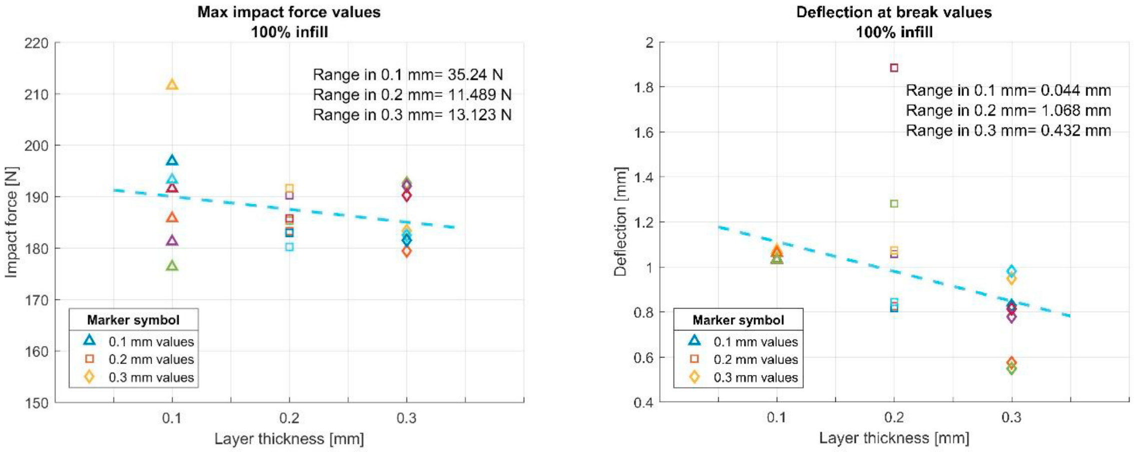


Fig. 5. (Left) Maximum impact force values; (Right) Deflection at break values.

The impact energy and impact strength values are shown in Fig. 6. From both charts the trendline shows that lower layer thicknesses produce higher values. The highest value range is present in the 0.2 mm batch, due to the large difference in deflection at the point of specimen break. Namely, two of the 0.2 mm specimens accumulated more energy because they experienced break much after 1 mm, where almost all of the tested specimens failed. That is the reason why two of the 0.2 mm specimens had much higher values than the rest of the batch. The range in impact energy values is shown in Fig.6- Left. The range in impact strength values is also the highest in the 0.2 mm batch. The impact strength values (Fig. 6- Right) have a similar trendline and range as impact energy due to the impact energy value being a constituent of the impact strength equation from ISO 179. The average impact strength values for all three chosen layer thicknesses are shown in Table 2.

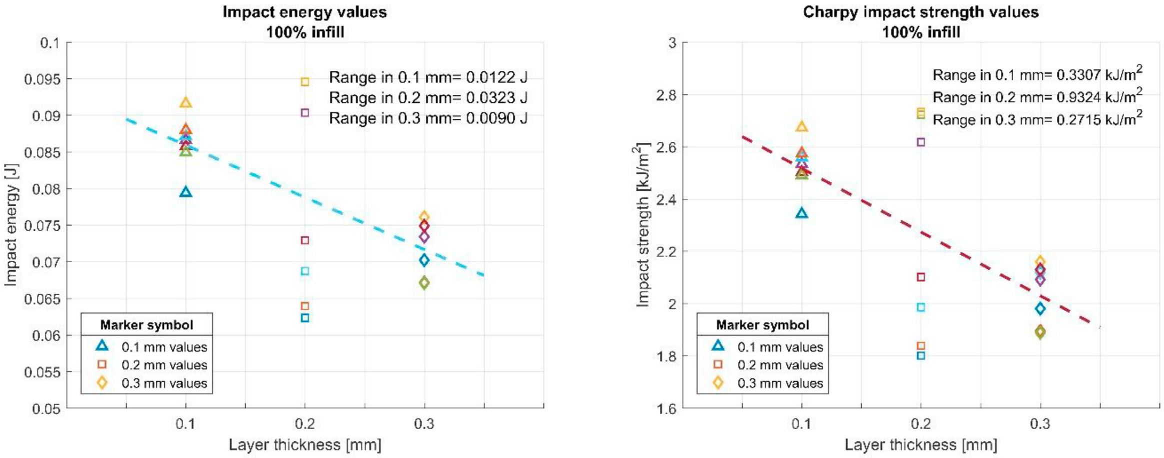


Fig. 6. (Left) Impact energy values; (Right) Charpy impact strength values.

Table 2. Average impact strength values for all three chosen layer thicknesses.

Layer thickness (mm)	0.3	0.2	0.1
Average impact strength (kJ/m^2)	2.0378	2.2572	2.5248

4. Conclusions

The Charpy impact tests were conducted on full infill specimens with different layer thicknesses namely, 0.3 mm, 0.2 mm, and 0.1 mm. All specimens were prepared according to ISO 179 standard, with a type A notch. The notch was directly AMed, not machined. The results are interpreted on impact force/energy-deflection charts and maximal impact force, deflection at the point of break, impact energy, and impact strength value charts relative to specimen thickness. Some conclusions are imposed here:

- High repeatability of results is present concerning impact force/energy response, relative to deflection.
- From average curves the matching between 0.2 mm and 0.1 mm batch is visible.
- Overall, higher impact force, energy, deflection at the point of break, and impact strength are achieved with lower layer thicknesses.
- Average impact strength values here are in the range between 2.0378 and 2.5248 kJ/m^2.
- The highest overall impact property value range is present in the 0.2 mm layer thickness batch, due to some of the specimens there failing much after the rest of the batch (see the impact force-deflection chart- Fig. 3, Middle-Left).

Acknowledgments

The authors would like to thank the support from the European Union's Horizon 2020 research and innovation program (H2020-WIDESPREAD2018, SIRAMM) under grant agreement No. 857124.

References

Popović, M., Pjević, M., Milovanović, A., Mladenović, G., Milošević, M., 2023. Printing parameter optimization of PLA material concerning geometrical accuracy and tensile properties relative to FDM process productivity. Journal of Mechanical Science and Technology 37(1), pp. 1-10. DOI: 10.1007/s12206-023-0113-6.

Pandžić, A., Hodžić, D., Milovanović, A., 2019a. Effect of Infill Type and Density on Tensile Properties of PLA Material for FDM Process. Proceedings of the 30th DAAAM International Symposium, DAAAM International. DOI: 10.2507/30th.daaam.proceedings.074.

Pandžić, A., Hodžić, D., Milovanović, A., 2019b. Influence of Material Colour on Mechanical Properties of PLA Material in FDM Technology. Proceedings of the 30th DAAAM International Symposium, DAAAM International. DOI: 10.2507/30th.daaam.proceedings.075.

Milovanović, A., Golubović, Z., Babinský, T., Šulák, I., Mitrović, A., 2022a. Tensile properties of polypropylene additively manufactured by FDM. Structural Integrity and Life 22(3), pp. 305-308.

Milovanović, A., Sedmak, A., Golubović, Z., Zelić Mihajlović, K., Žurkić, A., Trajković, I., Milošević, M., 2021. The effect of time on mechanical properties of biocompatible photopolymer resins used for fabrication of clear dental aligners. Journal of the Mechanical Behavior of Biomedical Materials 119(104494), pp. 1-9. DOI: 10.1016/j.jmbbm.2021.104494.

Milovanović, A., Poduška, J., Trávníček, L., Nahlik, L., Sedmak, A., Milošević, M., Berto, F., 2022b. Side-groove effect on fracture mechanical fatigue testing of PLA material. Procedia Structural Integrity 42, pp. 847-856. DOI: 10.1016/j.prostr.2022.12.107.

Milovanović, A., Milošević, M., Trajković, I., Sedmak, A., Razavi, M.J., Berto, F., 2022c. Crack path direction in plane-strain fracture toughness assessment tests of quasi-brittle PLA polymer and ductile PLA-X composite. Procedia Structural Integrity 42, pp. 1376-1381. DOI: 10.1016/j.prostr.2022.12.175.

Popa, C.F., Mărghitaș, M.P., Galațanu, S.V., Marșavina, L., 2022. Influence of thickness on the IZOD impact strength of FDM printed specimens from PLA and PETG. Procedia Structural Integrity 41, pp. 557-563. DOI: 10.1016/j.prostr.2022.05.064.

Ailinei, I., Galațanu, S.V., Marșavina, L., 2022. The effects of layers orientation on impact energy evaluation of FDM printed specimens. Material Design & Processing Communications 3(10). DOI: 10.1002/mdp2.267.

Rajpurohit, S., Dave, H.K., 2020. Impact strength of 3D printed PLA using open source FFF-based 3D printer. Progress in Additive Manufacturing 6, pp. 119-131. DOI: 10.1007/s40964-020-00150-6.

Patterson, A.E., Pereira, T.R., Allison, J.T., Messimer, S.L., 2021. IZOD impact properties of full-density FDM polymer materials with respect to raster angle and print orientation. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science 235(10), pp. 1891-1908. DOI: 10.1177/0954406219840385.

Stoia, D.I., Galațanu, S.V., Marșavina, L., 2022. Impact properties of laser sintered polyamide, according to building orientation. Journal of Mechanical Science and Technology 37(6), pp. 1-5. DOI: 10.1007/s12206-022-2108-0.

Ahmed, H., Hussain, G., Gohar, S., Ali, A., Alkahtani, M., 2021. Impact Toughness of Hybrid Carbon Fiber-PLA/ABS Laminar Composite Produced through Fused Filament Fabrication. Polymers 13, 3057. DOI: 10.3390/polym13183057.

Ferdinand, M., Várdai, R., Móczó, J., Pukánszky, B., 2023. A novel approach to the impact modification of PLA. Engineering Fracture Mechanics 277, 108950. DOI: 10.1016/j.engfracmech.2022.108950.

Tian, J., Cao, Z., Qian, S., Xia, Y., Zhang, J., Kong, Y., Sheng, K., Zhang, Y., Wan, Y., Takahashi, J., 2022. Improving tensile strength and impact toughness of plasticized poly(lactic acid) biocomposites by incorporating nanofibrillated cellulose. Nanotechnology Reviews 11, pp. 2469-2482. DOI: 10.1515/ntrev-2022-0142.

Valean, C., Marșavina, L., Mărghitaș, M., Linul, E., Razavi, J., Berto, F., Brighenti, R., 2020. The effect of crack insertion for FDM printed PLA materials on Mode I and Mode II fracture toughness. Procedia Structural Integrity 28(10), pp. 1134-1139. DOI: 10.1016/j.prostr.2020.11.128.

Milovanović, A., Golubović, Z., Trajković, I., Sedmak, A., Milošević, M., Valean, E., Marsavina, L., 2022d. Influence of printing parameters on the eligibility of plane-strain fracture toughness results for PLA polymer. Procedia Structural Integrity 41, pp. 290-297. DOI: 10.1016/j.prostr.2022.05.034.

Krausz, T., Ailinei, I., Galațanu, S.V., Marșavina, L., 2021. Charpy impact properties and numerical modeling of polycarbonate composites. Material Design & Processing Communications 3(5), pp. 1-9. DOI: 10.1002/mdp2.260.