Available online at www.sciencedirect.com

ScienceDirect

Procedia Structural Integrity 31 (2021) 122–126

Structural Integrity Procedia

www.elsevier.com/locate/procedia

4th International Conference on Structural Integrity and Durability, ICSID 2020

Influence of second-phase particles on fracture behavior of PLA and advanced PLA-X material

Aleksa Milovanović[a]*, Aleksandar Sedmak[b], Aleksandar Grbović[b], Zorana Golubović[b], Miloš Milošević[a]

[a]*University of Belgrade, Innovation Centre of the Faculty of Mechanical Engineering, Kraljice Marije 16 street, Belgrade 11120, Serbia*
[b]*University of Belgrade, Faculty of Mechanical Engineering, Kraljice Marije 16 street, Belgrade 11120, Serbia*

Abstract

Most widespread materials in Additive Manufacturing are PLA (PolyLactic Acid) and ABS (Acrylonitrile Butadiene Styrene), which are dissimilar materials in terms of printing abilities and mechanical properties. PLA material originates from renewable resources making it better solution for environment in comparison with petroleum-based ABS material. Addition of second-phase particles to polymer matrix may have a substantial influence on mechanical properties of created material. Subject of this paper are natural PLA material and advanced PLA material with addition of second-phase particles ("PLA-X") which has similar mechanical properties as ABS material, making it a perfect PLA based substitute. Tensile tests are conducted according to ISO 527-2 standard. Subject of this paper is the analysis of fracture behaviour of PLA and advanced PLA-X material, which ranges from brittle to formation of large craze zones before fracture. Analysis is conducted for five batches of both materials, with variation in printing parameters. The main focus of this research was to evaluate the influence of second-phase particles on fracture behaviour of PLA and advanced PLA-X material.

Keywords: Additive manufacturing; polymer; PLA; fracture

---

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

10.1016/j.prostr.2021.03.020

1. Introduction

FDM (Fused Deposition Modeling) is a most used Additive Manufacturing technology due to low cost of device unit and fabrication materials. Mentioned technology uses thermoplastic materials in form of filament for model creation. FDM is an extrusion-based technology where thermoplastic filament is heated to temperature above glass transition temperature and then melted plastic is extruded through nozzle onto a build platform, creating a model in layer-by-layer manner. Most common materials in FDM are PLA and ABS, where PLA has good dimensional accuracy but lacks in mechanical properties, according to findings of Milovanović et al. (2019). Addition of second-phase particles to polymer matrix influences on mechanical properties of material. According to research conducted by Pandžić et al. (2019), particles used for pigment on commercial PLA material significantly change mechanical properties and that PLA materials of different color house noticeably different mechanical properties. Type and size of second-phase particles may affect in creation of material with dissimilar mechanical properties compared to original material. Examined PLA material with second-phase particles has a commercial name ''PLA-X'' (mcPP, Mitsubishi Chemical, Japan), and both PLA and PLA-X materials were a subject of previous research on printing parameters effect on mechanical properties of both materials, conducted by Milovanović et al. (2020).

Nomenclature

FDM	fused deposition modeling
PLA	polylactic acid
ABS	acrylonitrile butadiene styrene
PLA-X	polylactic acid material with added second-phase particles

2. Fracture behavior analysis

Fracture behavior in polymers may vary from brittle to ductile depending on strain rate, temperature and molecular structure, according to Anderson (2005). In this case five batches of PLA and advanced PLA-X material are tested according to ISO 527-2 standard for tensile testing, which defines 1mm/min strain rate. Main printing parameters are the same for all batches of both materials, shown in Table 1. Batches differ in layer height, printing orientation, infill type and density and sample humidity. All the specimens after fabrication were stored and tested at room temperature. Best mechanical properties were attained for samples with lowest layer height, i.e. highest number of layers, full infill and raster orientation in the direction of applied load on tensile testing machine, which is consistent with research of Pandžić et al. (2019), Valean et al. (2020), Sardinha et al. (2020) and Rigon et al. (2020). For further fracture behavior analysis those specimens will be considered.

Table 1. Main printing parameters for all specimens.

Printing parameter	Value
Printing speed, mm/s	60
Printing temperature, °C	200
Build platform temperature, °C	60

All the PLA samples in all five batches of material faced brittle fracture (Fig.1a), whereas with PLA material with added second-phase particles samples created crazing before fracture (Fig.1b). Brittle behavior of regular PLA material may pose a limitation in engineering applications, according to Valean et al. (2020). One should keep in mind that failure mechanisms in polymers are completely different from those in metals, compare with description in Tuma et al. (2004). Crazing is a yielding mechanism in polymer materials, which can be identified with white stripes on tested specimens. Some polymer materials before fracture create aligned packets of polymer chains, with microvoids around them. During that yielding mechanism remaining fibrils carry the applied load, and snap when the stress is sufficiently high to break all the polymer chains. Those macrovoids at macroscale appear as so-called ''stress-whitened regions'' perpendicular to direction of the applied load, according to Anderson (2005).

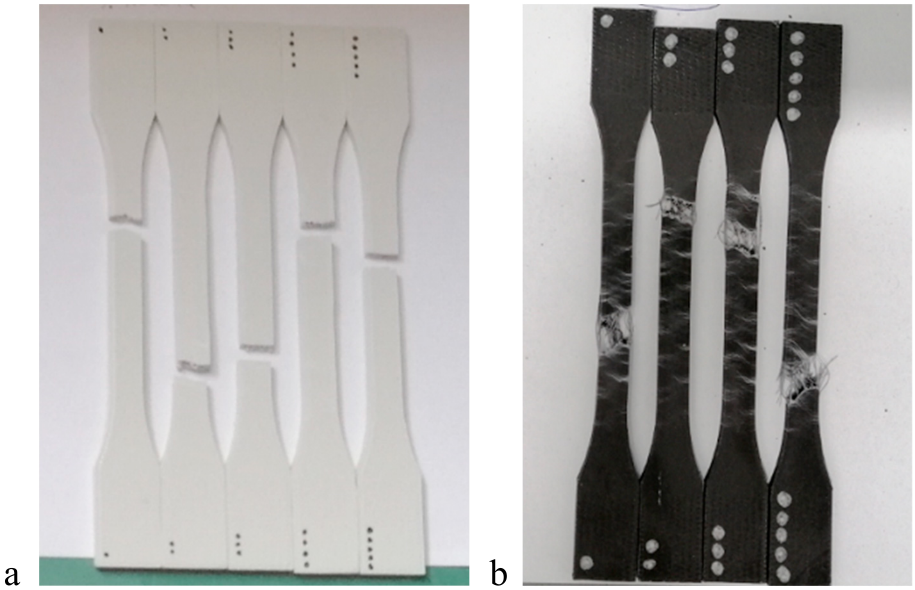

Fig. 1. Fractured ISO 527-2 samples of: a) PLA; b) PLA-X material.

Concerning mechanical properties, addition of second-phase particles may increase toughness of original material, by making craze initiation easier. Added second-phase particles are locations for microvoid initiation, thereby lowering the required stress for craze formation. This process is called ‘’rubber toughening’’, according to Anderson (2005). Increase in toughness and ductility, i.e. higher overall strain, comes at an expense of yield and ultimate tensile strength, according to Anderson (2005).

Fig. 2 contains stress-strain diagram for the batch of PLA material shown in Fig. 1a. Brittle fracture of all PLA specimens in Fig.1a is clearly noticeable on stress-strain diagram (Fig.2). Average Ultimate tensile strength is 54.35 MPa, with standard deviation of only 0.59 MPa. Specimens strain 2.06 % on average, with standard deviation of 0.04 %. Elastic modulus of PLA material is 3.42 GPa on average, with standard deviation of only 83 MPa. Low standard deviation for all mentioned mechanical properties shows good repeatability of tested samples, which is visually verifiable in the Fig. 2. Average value of tensile toughness for PLA material, i.e. surface area underneath stress-strain curve, is 67.64 J·cm^{-3}.

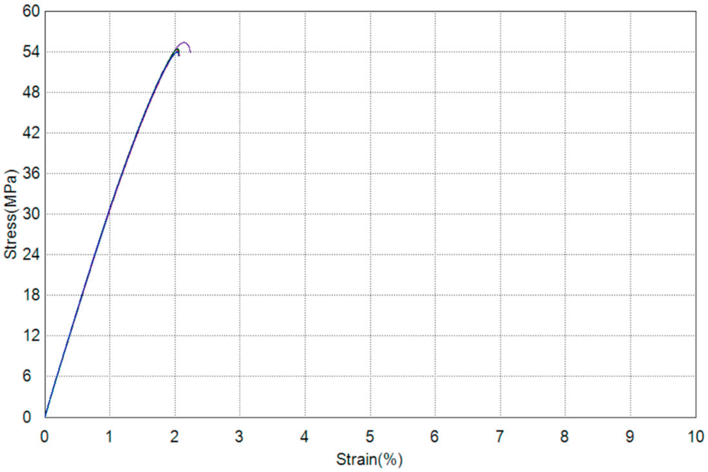

Fig. 2. Stress-strain diagram of PLA material batch.

Due to great repeatability of all five samples of PLA material shown in stress-strain diagram (Fig. 2), offset was applied on Fig. 3 for the best representation of all five curves.

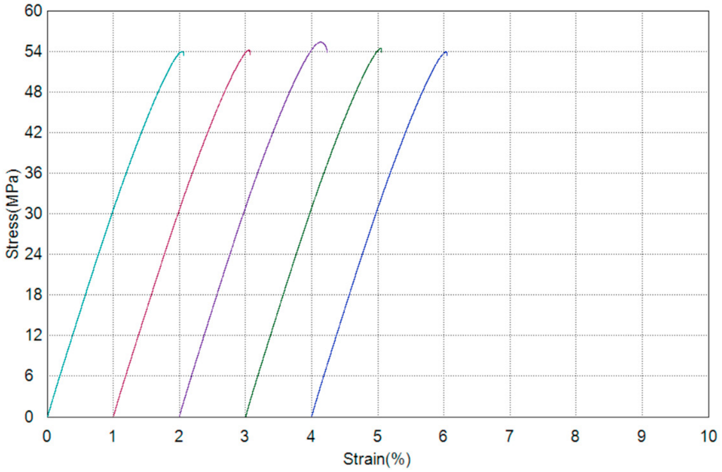

Fig. 3. Offset curves in stress-strain diagram of PLA material batch.

Stress-strain diagram of advanced PLA material with identical printing parameters as with observed PLA material, is shown in Fig. 4. In comparison with brittle PLA material, PLA-X material shows ductile behavior in all tested samples (Fig. 1b). Ductile behavior of PLA-X specimens is verified on their stress-strain diagram from Fig. 4. PLA-X specimens show great repeatability until achieved Ultimate tensile strength (in this case equal to Yield strength), which is 34.75 MPa on average and with standard deviation of only 0.25 MPa. Ultimate tensile strength is noticeably lower in PLA-X than in PLA material. Average Elastic modulus is 3.9 GPa, with standard deviation of 82 MPa. Elastic modulus of PLA and PLA-X specimens show similar values, both with very low standard deviation. There is a noticeable difference in strain values on PLA-X specimens. Overall strain of PLA-X specimens ranges from 4.77 % up to 17.21 %. Unequal strain values between samples are due to amorphous nature of PLA plastics and to uneven distribution of added second-phase particles. Tensile toughness for PLA-X material specimens ranges from 99.67 J·cm^{-3} to 357.4 J·cm^{-3}, for the specimen which strained the most. Even the lowest values of tensile toughness for PLA-X material are considerably larger than any value for tensile toughness for PLA material.

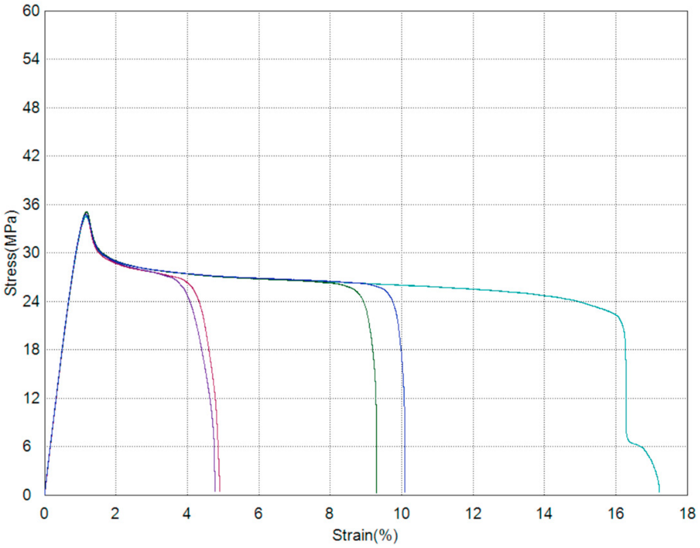

Fig. 4. Stress-strain diagram of PLA-X material batch.

Lower Ultimate tensile strength and higher overall deformation of PLA-X material relative to brittle PLA suggests how crazing mechanism effects on mechanical properties of originally brittle material. For real-life applications substantial increase in toughness values for PLA-X in regard to PLA suggests that such brittle material with added second-phase particles can have substantially increased longevity of any additively manufactured component in comparison with original PLA material.

3. Conclusions

Fracture behavior of regular PLA material and PLA material with added second-phase particles has been analyzed. Regular PLA material tends to fracture in brittle manner, while PLA material with added particles shows ductile behavior and forms large craze zones before fracture. Addition of second-phase particles in PLA material increases overall strain and calculated tensile toughness at the expense of maximal stress. Uneven distribution of second-phase particles in PLA material results in unequal strain values for PLA-X material.

Acknowledgements

This research is financially supported by European Union's Horizon 2020 program ''SIRAMM'', under grant agreement No.857124 and Ministry of Education, Science and Technological Development of the Republic of Serbia under project TR35006. Also, we are thankful to ''3D Republika'', private company based in Belgrade, Serbia, for support in materials used in the research.

References

Milovanović, A., Milošević, M., Mladenović, G., Likozar, B., Čolić, K., Mitrović, N., 2019. Experimental Dimensional Accuracy Analysis of Reformer Prototype Models Produced by FDM and SLA 3D Printing Technology. Experimental and Numerical Investigations in Materials Science and Engineering, in: Mitrović, N., Milošević, M., Mladenović, G. (Ed.). Springer, Cham; 84-95.

Pandžić, A., Hodžić, D., Milovanović, A., 2019. Influence of Material Colour on Mechanical Properties of PLA Material in FDM Technology. 30th DAAAM International Symposium on Intelligent Manufacturing and Automation, Vienna, Austria; Paper #075: 555–561.

Milovanović, A., Sedmak, A., Grbović, A., Golubović, Z., Mladenović, G., Čolić, K., Milošević, M., 2020. Comparative analysis of printing parameters effect on mechanical properties of natural PLA and advanced PLA-X material. Procedia Structural Integrity 28, 1963-1968.

Anderson, T.L., 2005. Fracture Mechanics: Fundamentals and Applications, Third Edition, Taylor & Francis Group, 265-270.

Pandzić, A., Hodžić, D., Milovanović, A., 2019. Effect of Infill Type and Density on Tensile Properties of PLA Material for FDM Process. 30th DAAAM International Symposium on Intelligent Manufacturing and Automation. Vienna, Austria; paper #074: 545-554.

Valean, C., Marsavina, L., Marghitas, M., Linul, E., Razavi, J., Berto, F., 2020. Effect of manufacturing parameters on tensile properties of FDM printed specimens. Procedia Structural Integrity 26, 313-320.

Sardinha, M., Frutuoso, N., Vicente, C., Ribeiro, R., Leite, M., Reis, L., 2020. Influence of seams in the mechanical properties of PLA produced with multiple extrusion modules. Procedia Structural Integrity 28, 358-363.

Rigon, D., Ricotta, M., Meneghetti, G., 2020. A literature survey on structural integrity of 3D printed virgin and recycled ABS and PP compounds. Procedia Structural Integrity 28, 1655-1663.

Valean, C., Marsavina, L., Marghitas, 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, 1134-1139.

Vojvodic Tuma, J., Sedmak, A., 2004. Analysis of the unstable fracture behaviour of a high strength low alloy steel weldment. Engineering Fracture Mechanics, Volume 71, Issue 9-10, Pages 1435-1451.