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Comparative analysis of printing parameters effect on mechanical properties of natural PLA and advanced PLA-X material

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Abstract

FDM is a commercially widespread 3D printing technology which uses thermoplastic materials for building prototypes and functional parts. Most used materials in this technology are PLA (PolyLactic Acid) and ABS (Acrylonitrile Butadiene Styrene) materials which contain dissimilar mechanical properties and printing abilities. PLA is considered as a good material for prototypes and parts that acquire higher dimensional accuracy, and is considered as a material that is easier to print than ABS. Advantages of ABS material, compared to standard PLA are better mechanical properties, sufficiently higher printing speeds and higher heat resistivity. Deficiency of ABS over PLA is shrinking of ABS material after 3D printing-resulting in poor dimensional accuracy or failure during printing. A newly available material PLA-X (''mcPP'', Mitsubishi Chemical, Japan) houses advantages of both mentioned materials and may lead to wider commercial and industrial use. Different printing parameters of the same material may lead to different mechanical properties of the finished part. The aim of this paper is to compare how different printing parameters effect on mechanical properties of standard PLA and PLA-X -which is a material that has similar dimensional accuracy of finished parts as PLA and possesses higher mechanical properties like ABS. Samples of PLA and PLA-X where printed in five different printing regimes, varying layer height, number of outline perimeters, infill density and sample humidity, with five samples each (according to ISO 527-2 international standard) and used for mechanical testing on standard tensile testing machine.

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Keywords: Additive Manufacturing; polymer materials; PLA

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1. Introduction

Fused Deposition Modeling (FDM) is an extrusion based Additive Manufacturing (AM) technology in which thermoplastic materials are melted and extruded through a nozzle onto a build platform in layer-by-layer manner. Thermoplastic material is usually in the form of filament, wrapped around a spool. Before AM process filament is pulled into the extruder mechanism, which uses stepper motor to rotate pulleys that feed the filament into radiator unit. Two pulleys represent feed mechanism of an extruder and in most FDM machines only one pulley is steered by stepper motor, while the other pulley follows the rotating motion of the steered pulley when the filament is inserted into the extruder. Radiator unit has a vital role in dispersing heat from the heater block, thus preventing filament clogging on the way from the feed mechanism to the heater block. Melting of the filament is performed in the heater block section, where resistors connected to the block increase the temperature to predefined value. In the heater block there is also a sensor unit, which is used for maintaining the constant temperature during the FDM process. Filament is then extruded through a nozzle onto a build platform, which is one layer height lower than the tip of the nozzle. After each performed layer platform lowers one step down, to allow creation of the next layer. Few more stepper motors in the FDM machine navigate the X-Y motion of the extruder unit to form a layer of material. Process is repeated until the part is finished. Some FDM machines have installed resistors beneath the build platform to enhance the temperature on the surface of the build platform, thus allowing for better adhesion of processed part on platform surface. FDM process is illustrated in Fig. 1.

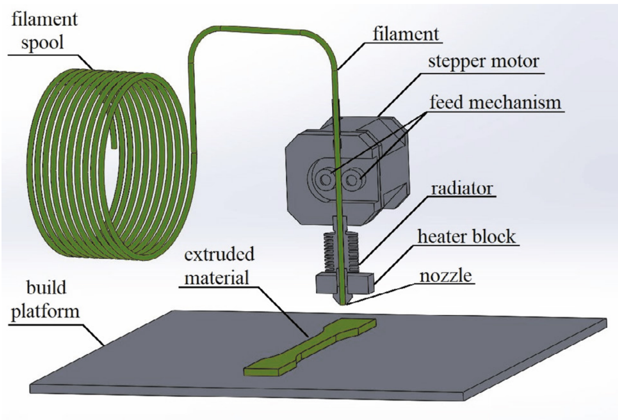

Fig. 1. FDM process schematic.

Most widespread FDM thermoplastic materials are PLA (polylactic acid) and ABS (acrylonitrile butadiene styrene) which own different mechanical properties and printing abilities. ABS material has a problem in the area of dimensional accuracy, specifically concerning material shrinking during the cooling process after extrusion. Previous research conducted by Milovanovic et al. (2019) proofs high dimensional accuracy of PLA material after cooling on selected benchmarking models. However ABS has better mechanical properties than PLA material. PLA is an environmentally friendly biodegradable material derived from renewable resources such as corn starch, cassava roots or sugarcane making it better solution for future application than ABS, which is a petroleum based polymer. Advanced PLA materials which have an addition of second-phase particles to a polymer matrix are already available on the market. Subject of this research is one such material, PLA-X (‘’mcPP’’, Mitsubishi Chemical, Japan) which is claimed to have better mechanical properties than natural PLA material retaining high dimensional accuracy and printing abilities.

In AM printing parameters, such as layer height, printing orientation, infill type and density, number of outline perimeters, have a high influence on mechanical properties of finished parts. Pandzic et al. (2019) examined the influence of infill type and density on tensile properties of PLA specimens and showed that with the increase of infill density PLA parts have better mechanical properties. Also, variation of infill type has significant influence and best results were attained with samples that have concentric infill pattern, due to alignment of deposited rasters with the loading direction. According to Akhoundi et al. (2018) dramatic increase in mechanical properties is shown in samples with 100 % infill, which is attributed to the promotion of strong bonding between rasters and layers.

According to Valean et al. (2020) orientation of printed parts on build platform has an influence on tensile properties, whereby it has higher influence on tensile strength and has less influence on Young's modulus of tested samples. Likewise, number of printed layers in prepared samples lead to a reduction of both the Young's modulus and tensile strength.

Addition of second-phase particles to a polymer matrix may result in better mechanical properties of AM parts. According to Caminero et al. (2019) addition of graphene nanoplatelets to PLA material enhances properties of material both in tensile and three-point bending tests, at a cost of reduced impact strength. Pandzic et al. (2019) also examined PLA materials of different colour. Results show that added second-phase particles that are used as a pigment have a significant influence on mechanical properties of PLA material. For some coloured samples it is evident that addition of particles influences in lowering of stiffness and tensile strength, with an increase of the toughness and overall strain. According to El Magri (2019) annealing of materials with added second-phase particles can influence on mechanical properties of material due to increased crystallinity attributed to orientation of polymer chains toward the second-phase particles.

In this paper a tensile testing of natural PLA and PLA material with added second-phase particles is conducted on samples with different AM printing parameters in order to see their influence on mechanical properties of two similar materials.

2. Materials and Methods

Five different printing regimes for PLA and PLA-X material were used, varying layer height, infill density, printing orientation and sample humidity. Both materials were used for manufacturing of specimens for tensile testing according to ISO 527-2 standard for tensile testing of extrusion plastics, with dimensions of specimen shown in Fig. 2. Five batches of both PLA and PLA-X material were prepared, with five specimens per batch according to tensile testing standard, in the following order:

- First batch: 0.1 mm layer height and 50 % infill density
- Second batch: 0.1 mm layer height, 100 % infill density with rectilinear orientation of printing
- Third batch: 0.1 mm layer height, 100 % infill density with circular orientation of printing
- Fourth batch: 0.2 mm layer height and 50 % infill density
- Fifth batch: 0.1 mm layer height and 50 % infill density with filament previously dried

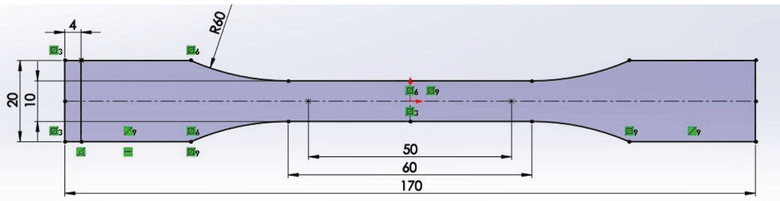

Fig. 2. Specimen dimensions according to ISO 527-2.

For all five batches of both materials few printing parameters were not changed, as nozzle diameter, printing speed, temperature of nozzle and build platform, with values shown in Table 1.

Table 1. Mutual printing parameters for all specimens.

Description	Value
Nozzle diameter	0.4 mm
Printing speed	60 mm/s
Printing temperature	200 °C
Build platform temperature	60 °C
Filament diameter	1.75 mm

Second and third batch differ in printing orientation of specimens, with rectilinear orientation which has raster under 45° relative to loading direction and circular orientation which has printed rasters aligned with the loading direction. Thus circular orientation is expected to have better mechanical properties than specimens with rectilinear orientation. Both printing orientations are shown in Fig. 3.

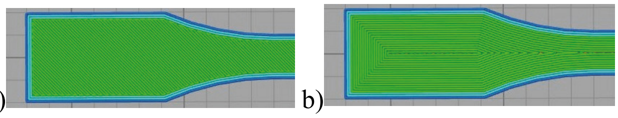
a) b)

Fig. 3. (a) Rectilinear orientation of printing; (b) circular orientation of printing.

Total of fifty specimens were manufactured and tested on universal tensile testing machine Shimadzu AGS-X (Shimadzu Corp., Kyoto, Japan) equipped with load cell of 100 kN capacity, with loaded specimen just before testing shown in Fig. 4. Particular machine has a sampling rate of 1msec and measurement accuracy of +/-0.5N, ensuring high accuracy of received values. Tensile testing was performed with testing speed of 1 mm/min. Results were obtained and displayed using ''Trapezium-X'' software (Shimadzu Corp, Kyoto, Japan).

Fig. 4. ISO 527-2 specimen on universal tensile testing machine.

3. Results and Discussion

Mechanical properties of printed PLA and PLA-X samples, obtained from tensile testing according to ISO 527-2 standard are displayed in charts. Average values of elastic modulus, ultimate tensile strength (UTS), strain and toughness for all ten batches of tested material are presented in Figs. 5-8, respectively. Below each column for all materials are labeled exact average values for every batch of both materials. Elastic modulus of PLA and PLA-X material have similar values, with clear distinction in values for samples of 100 % infill, as seen in Fig. 5. Thus, infill density has the highest influence on stiffness regardless of the material. Lowest values of elastic modulus are present in PLA-X samples with 0.2 mm layer height. Samples with higher layer height have larger air gaps in-between layers, resulting in lower mechanical properties of tested material. Comparing first and fifth batch of both materials, filament drying doesn't show any effect on stiffness of the tested samples on both materials.

Average values of UTS are overall higher in PLA samples than in PLA-X, depicted in Fig. 6. As with stiffness, highest values of UTS are present in 100 % infill samples, with slightly higher value with circular orientation, i.e. 54.35 MPa compared to 51.36 MPa in rectilinear orientation for PLA material and 34.81 MPa compared to 29.76 MPa for PLA-X material. PLA-X samples with 0.2 mm layer height hold the lowest values in this segment as well, with average value of 12.08 MPa. Filament drying shows a slight increase for PLA-X samples, i.e. 20.36 MPa compared to 17.94 MPa for non-treated samples, while PLA samples show insignificant difference. This is mostly due to heat influence on increased crystallinity credited to orientation of polymer chains toward second-phase particles in PLA-X material.

However, PLA-X samples have significantly higher straining for all selected batches, as seen in Fig. 7. PLA material's third batch is the most brittle, straining only 2.09 % on average. Highest straining is present in the fourth batch of PLA-X material, i.e. the samples with highest layer height. Samples with greater layer height have thicker filament diameter, thus having more material to resist straining.

Toughness values of PLA and PLA-X samples are displayed in Fig. 8. Highest average value for toughness of PLA material has the second batch with 100 % infill and rectilinear orientation, with average value of 5.82 J. Surprisingly, PLA samples with circular orientation average only 2.83 J. In PLA-X material highest average value is obtained for the batch with circular raster and 100 % infill-namely third batch. For particular PLA-X material batch average value is 10.36 J, which is slightly more than twice the value for rectilinear orientation, and almost twice the value for the highest result for natural PLA material. Filament drying doesn't have a clear influence on toughness values for both PLA and PLA-X material.

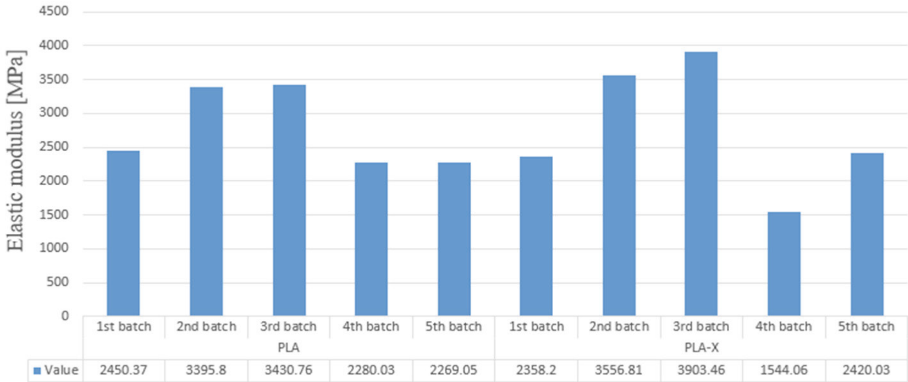

Fig. 5. Average values of elastic modulus for all specimens.

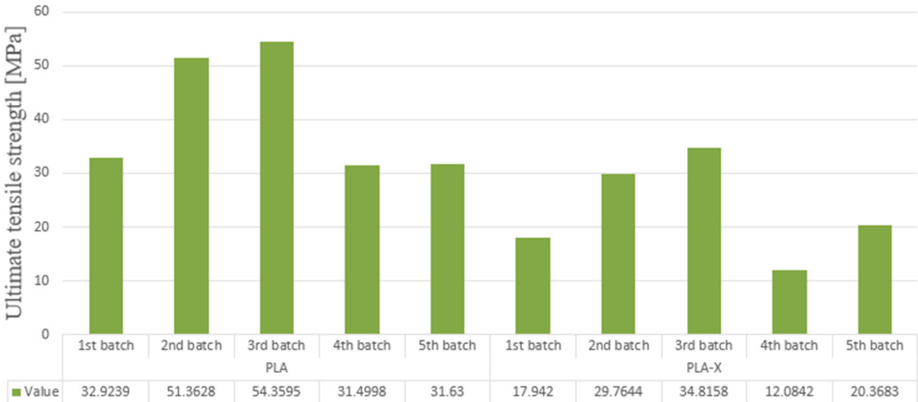

Fig. 6. Average values of UTS for all specimens.

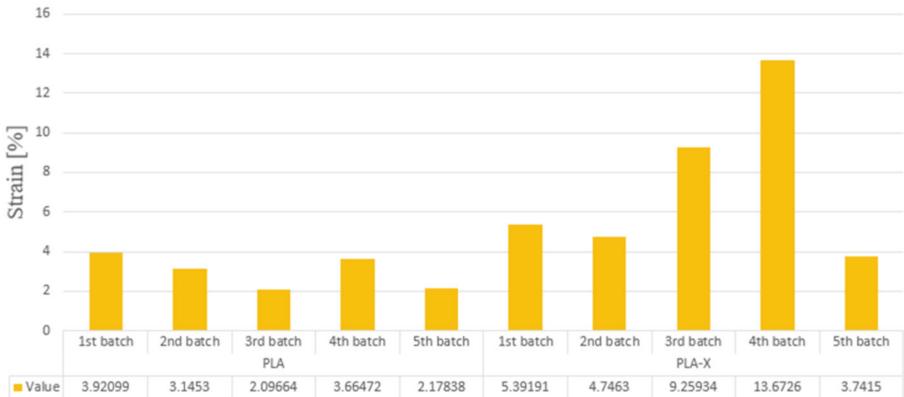

Fig. 7. Average values of strain for all specimens.

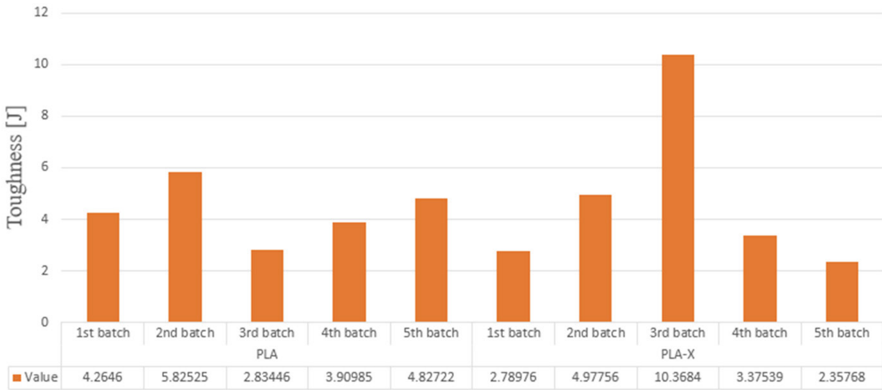

Fig. 8. Average values of toughness for all specimens.

4. Conclusions

Most used FDM technology materials are ABS and PLA which have different printing abilities and mechanical properties. Most important quality of PLA material in comparison to ABS is the fact that PLA is of natural origin, and not a petroleum based material like ABS. Concern toward environmental protection clearly separates PLA from ABS material for future use plans. Likewise, another feature of PLA material is biodegradability making it an only candidate in FDM technology for biomedical use. Only drawback of PLA material are low mechanical properties which can be changed by addition of second-phase particles in polymer matrix to enhance targeted properties of material.

Aim of this paper is to investigate mechanical properties of PLA based material with added second-phase particles, PLA-X (''mcPP'', Mitsubishi Chemical, Japan) and to compare it with the natural PLA material..

Results show that PLA-X material has similar mechanical behavior as regular ABS material, i.e. PLA-X material can strain more and with certain printing parameters has significantly higher toughness values that natural PLA material. Addition of second-phase particles comes at a cost of UTS values, which are lower for any combination of printing parameters compared to PLA material. No major difference was observed in elastic modulus values between PLA and PLA-X material.

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