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COMPRESSIVE PROPERTIES OF COMMONLY USED POLYMERS IN ADDITIVE MANUFACTURING PROCESSES

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Abstract: Production methods based on additive manufacturing technologies represent a powerful approach to the rapid and efficient production of complex prototypes and functional parts from different materials. This paper presents the procedure of development and production of a holder using a fusing deposition modeling process. Since compression is the dominant load on the holder in exploitation, mechanical testing was carried out and the results obtained can contribute to adequate material selection.
Keywords: Additive manufacturing, mechanical properties, polymers: ABS plus, ABS, PLA

INTRODUCTION

Modern, unconventional production processes are mainly used today for fabrication of prototypes and functional elements of extremely complex geometric configurations. Their implementation is based on the principle of joining material layer by layer in order to obtain a physical model that is identical to the virtual model, without using the tools and accessories. This production concept is known as Additive Manufacturing – AM in scientific and professional community. In the last thirty years, a number of procedures of additive manufacturing has been developed and successfully applied, whose main features are reported in [1-3].

In general, for the realization of any AM process the following are needed: material, energy and a CAD model. Taking into account quality and functionality of the obtained product, the correct choice of materials to be used for the fabrication is of great importance. Therefore, it is necessary to know the mechanical properties because they enable a preliminary assessment of the behavior of materials during exploitation.

The paper [4] presents the results related to the tensile strength of test samples produced by using different additive processes. Also, the same paper reports recommendations for the selection of AM procedure depending on the required strength of the product. Results from the study [5] clearly show that the mechanical properties of the 3D-printed polyether-ether-ketone (PEEK) sample were superior to the 3D-printed pattern of the ABS polymer. Fragassa and Minak in the work [6] announced the results of the mechanical properties of four photopolymer resins known under their commercial names as FullCure720, PA, MK3 and VeroBlu. On the basis of various mechanical tests similarities and differences were found in the behavior of materials in quasi-static loads. Influence of processing conditions on the tensile strength of 3D-printed models has been published in [7].

Previous studies of mechanical properties have been done regardless of the fact that manufacturers of material must provide information related to the physical and mechanical properties. However, as stated in [6], secondary experimental verification is required in terms of the increased reliability of the final components, which are obtained by using innovative and insufficiently known technologies.

Since polymeric materials are predominantly used in the AM procedures today, the paper presents the results of experimental research related to characterization of compressive properties of the three most commonly used polymers: Polylactic Acid – PLA, Acrylonitrile Butadiene Styrene - ABS and an enhanced version of ABSplus. Also, the paper presents the development and production of functional parts of the tested polymers using the AM process which is based on the technology of material extrusion.

THE PROCESS OF MATERIAL EXTRUSION

Material extrusion is an additive manufacturing process for fabrication of prototypes and final parts based on the principle shown in Figure 1.

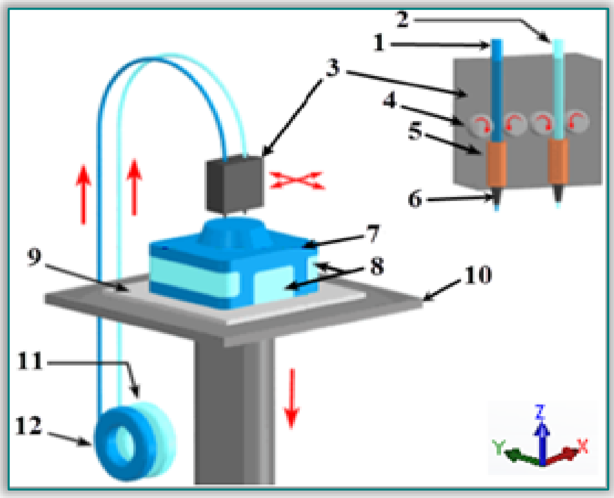


Figure 1. Schematic view of material extrusion process: 1-Build material filament, 2-Support material filament, 3-Extrusion head, 4-Drive wheels, 5-Liquifiers, 6-Extrusion nozzles, 7-Part, 8-Part supports, 9-Foam base, 10-Build platform, 11-Support material spool, 12-Build material spool [8]

The material in the form of a wire is fed into the nozzle around which electrical resistant heaters are located. Due to the heating and maintaining the temperature above the melting point, the material in viscous state is applied to the platform in the form of layers, wherein it rapidly solidifies. When a layer has been formed, the platform lowers, and the nozzle starts making the next layer. The thickness of the layer and vertical accuracy depend on the diameter of the nozzle opening. Various types of materials are used including ABS plastics, polyamides, polycarbonates, polyethylene and polypropylene.

EXPERIMENTAL RESEARCH

Experimental research consists of two parts. The first part refers to the development and fabrication of functional parts (the holder) and test samples for mechanical tests using material extrusion, and the second part is focused on the characterization of the compressive properties of used materials.

Additive manufacturing of the holder using material extrusion

Fabrication of the holder from the tested polymer was performed in the Laboratory for Technology of Plasticity at the Faculty of Mechanical Engineering in Banja Luka. In order to do so, 3D Printers Dimension Elite (left on Figure 2) and LeapFrog Creatr XL (right on Figure 2) were used. The physical model was based on material extrusion technology.

Figure 2. 3D printers: Dimension Elite (left) and LeapFrog Creatr XL (right)

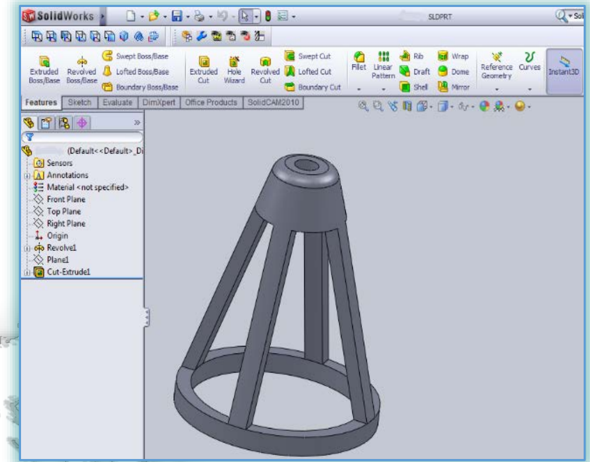


Figure 3. Holder design in SolidWorks software

The development of functional parts using material extrusion technology consisted of the following procedures:

- Product design in a CAD software package,
- Conversion of CAD models in STL format recognized by 3D printers,
- Transfer of STL files to the computer that controls the three-dimensional printer,
- Processing of STL files within the CatalystEX and Simplify3D in which all the parameters for the required model are set and adjusted,
- Creating a three-dimensional model using additive technology,
- Further processing of created prototypes and
- Post-processing techniques.

The above procedure was applied in its entirety for the development of the holder. The holder was designed in SolidWorks software package, Figure 3. After transferring STL files to a computer that controls the operation of the 3D printer and loading the generated model, the adjustment of operating parameters within the CatalystEX and Simplify3D software package, Figure 4, was performed.

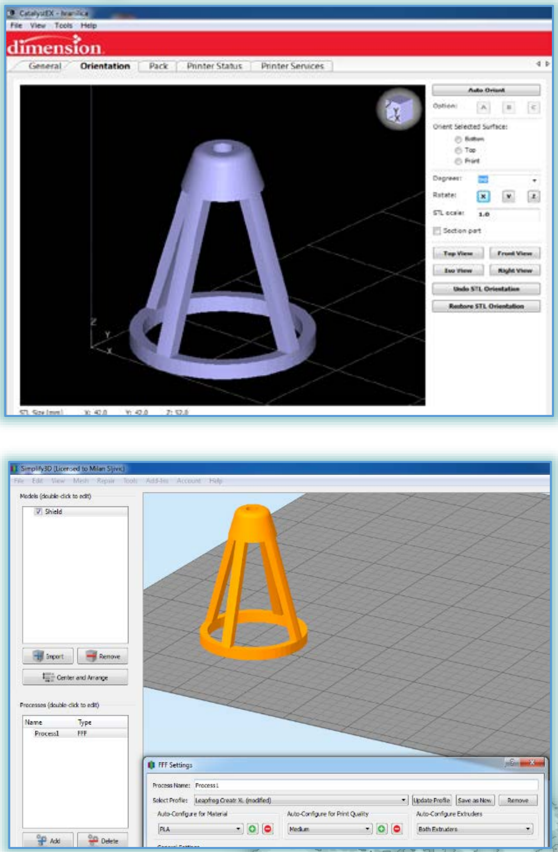


Figure 4. Preprocessing and adjusting operating parameters in software packages: a) CatalystEX i b) Simplify 3D

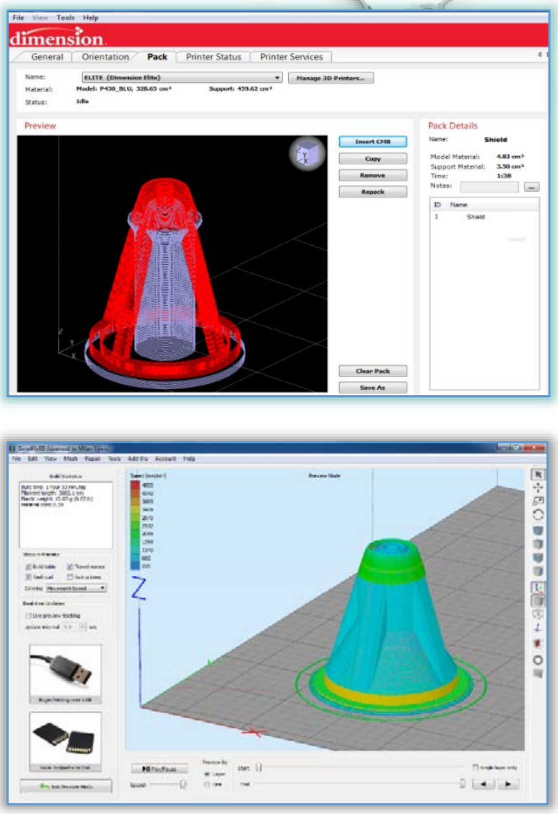


Figure 5. Positioning of a model on the printing platform and preparation of the 3D printing process of a holder in software packages: a) CatalystEX (Dimension Elite) and b) Simplify3D (LeapFrog 3D štampač)

The selection of the model orientation and the best position, processing of support and layers, as well as the arrangement of the model on the 3D printer platform are shown in Figure 5. Figure 6 shows a finished, i.e. printed element.

In the process of additive manufacturing of holders from the ABSplus polymer the Dimension Elite 3D Printer by manufacturer Stratasys from the United States has been used. The fact that the manufacturer patented the ABSplus polymer represents a limiting factor in terms of application of other types of 3D printers.

The making of holders from ABS and PLA polymers was carried out on the LeapFrog Creatr XL 3D printer. In this case a broader range of materials can be used because by using universal software different process parameters can be defined, such as the temperature of the nozzle, the speed of 3D printing, platform temperature, etc. The final result is the optimization of the additive manufacturing process of functional parts, depending on the material being used.

The parameters of holder fabrication on different 3D printers are shown in Table 1.

Table 1. The parameters of holder fabrication

Parameter	3D Printer	
	Dimension Elite	LeapFrog
Production time	98 minutes	113 minutes
Volume of the base material	4.83 cm^3	10.83 g
Volume of the support material	3.50 cm^3	4.65 g
Material price	7.46 €	5.43 €

Figure 6. The holders produced using additive manufacturing technology

The holders produced using additive manufacturing technology are shown in Figure 6.

Compressive testing

Experimental research of compressive properties was carried out on cylindrical polymer samples of original dimensions D_0 = 10 mm and H_0 = 20 mm, Figure 6.3. All samples were built on Dimension Elite and LeapFrog 3D printers in the Laboratory for Technology of Plasticity at the Faculty of Mechanical Engineering Banja Luka. Compressive testing of material was performed at the Laboratory for Welding and Material Testing at the

Faculty of Mechanical Engineering in East Sarajevo. The samples were deformed by using the universal testing machine "Shimnadzu", type AGS-20 kN NXD (Figure 7), and Trapezium X software was used for processing and graphical display of compression test results.

Figure 7. Testing machine with compressive module

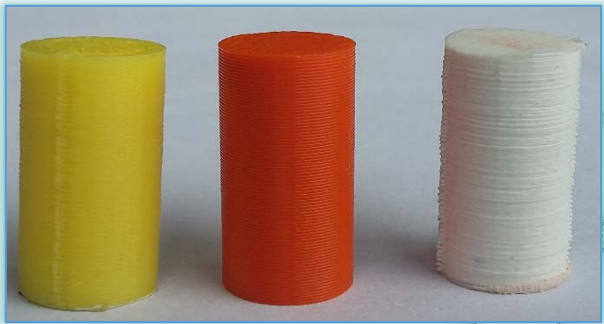


Figure 8. Samples for compressive testing:
a) ABS, b) ABSplus, c) PLA

a)

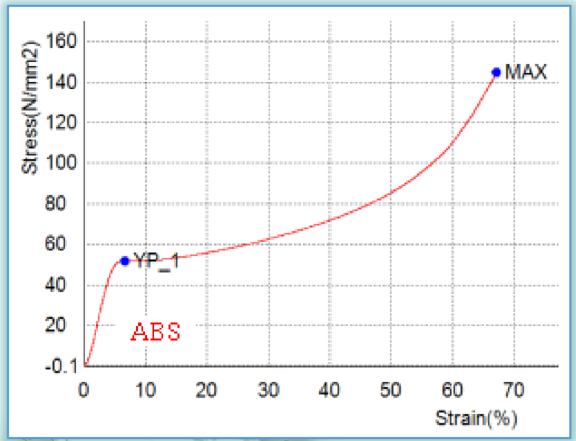
b)

c)

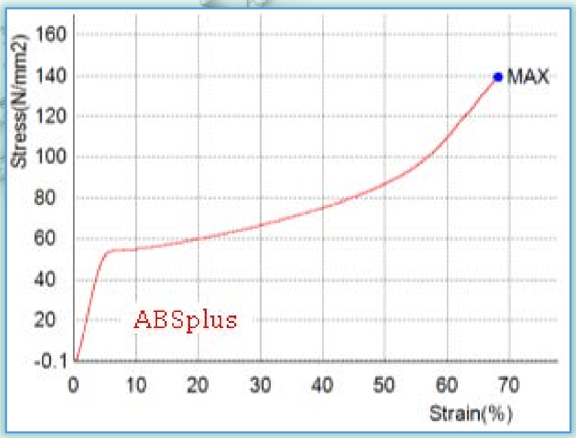
Figure 9. The appearance of samples after testing:
a) ABS, b) ABSplus, c) PLA

The total of 15 samples were used for compressive tests, wherein the characterization of the particular polymer was based on the results of five individual tests. A set of undeformed samples and those after testing is shown in Figures 8 and 9, respectively.

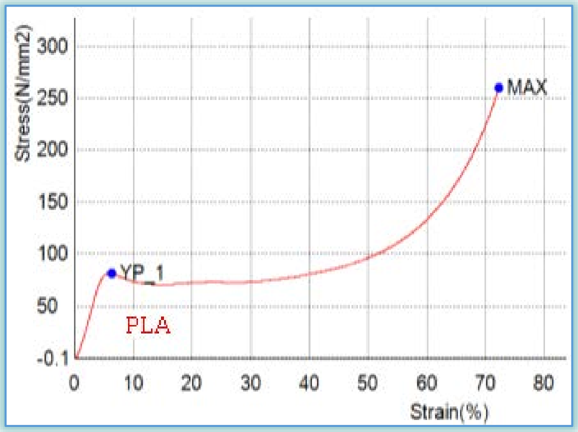
Typical behavior of the ABS, PLA and ABSplus polymer in compression for one of the five test samples is presented in Figure 10 (a), (b) and (c). The diagrams of Engineering stress (σ) / Engineering strain (ε) were automatically generated in the course of tests. In doing so, data relating to the initial tube size and test conditions were used.



a)



b)



c)

Figure 10. The curves σ-ε in compressive testing of different materials

The compression of all samples was conducted at the 5 mm/min speed of deformation. The mean values of yield stress R_{PT}, compressive strength r_{pM}, the maximum relative deformation ε_M and modulus of elasticity E_P were determined based on the results of five tests for the ABS and ABSplus polymer.

In compressive testing the PLA polymer demonstrated high plastic properties and because there were not any cracks it was not possible to determine the compressive strength. Therefore, only yield stress and R_{PT} and compaction module E_P were determined for this polymer. Comparative presentation of the results is given in Table 2.

Table 2. Mean values of compressive properties

Material	Yield stress R_{pT} [N/mm^2]	Compressive strength R_{pM} [N/mm^2]	Max. strain ε_M [%]	Modulus of elasticity E_P [GPa]
ABS	50,74	144,27	68,38	1,52
ABSplus	54,76	142,85	69,08	1,64
PLA	86,54	---	---	2,20

The analysis of the results

Analysis of fabrication of functional parts showed strong influence of material and 3D printer type on product quality. The best holder quality was achieved on the Dimension Elite – Stratasys professional printer using ABSplus polymers. Therefore, it is recommended to use the mentioned printer for the fabrication of finished parts, but in this case higher production costs must be taken into account.

The flows of curves σ-ε and the numerical values in Table 2 show that during mechanical compressive testing, ABSplus and ABS polymers behave similarly. The PLA polymer showed the greatest resistance to the turn to a plastic area. Numerically speaking, samples from the PLA polymer have 70% higher yield strength in comparison to the ABS polymer, or by 58% compared to the ABSplus polymer. However, after moving to the plastic area, the PLA polymer samples acted as perfectly plastic material in the initial stages of deformation, with no indications of strain hardening. However, with increasing level of deformation, especially for $\varepsilon > 50\%$, there was a pronounced strain hardening, which was still not enough to determine the compressive strength of the PLA polymers, because even with high loads there were no cracks on the free surface of samples.

CONCLUSIONS

The process of Additive Manufacturing based on material extrusion technology is suitable for the fabrication of functional components, but the quality and the production costs depend on the type of material and the type of the 3D printer being used.

Overall results of mechanical compressive tests showed that the PLA polymer has the highest yield strength, but its ductile properties are significantly variable and depend on the level of deformation. The resistance and ductility properties of ABSplus and ABS polymers are quite similar.

As the results presented in this study may contribute to the adequate selection of polymer materials for additive manufacturing processes, the following recommendations can be generally given:

- Due to the reduced toughness at higher levels of plastic deformation, PLA polymers are to be preferably used for parts which are mainly axially loaded;
- ABSplus and ABS polymers are advantageous for producing parts that work in varying operating conditions due to which complex stress states occur.

Acknowledgment

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Note

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