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EXPERIMENTAL INVESTIGATION OF THE IMPACT TOUGHNESS OF POLYLACTIC ACID- PLA SPECIMENS FABRICATED BY FFF 3D PRINTING USING THE CHARPY METHOD

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Abstract: This paper presents an experimental investigation of the impact toughness of 3D-printed specimens made of polylactic acid (PLA) using the Fused Filament Fabrication (FFF) process, tested by the Charpy method. One of the main disadvantages of 3D printing is that the parts often have significantly lower mechanical properties, making mechanical testing necessary to determine their functional suitability. The testing of impact toughness for plastic materials was carried out in accordance with the standard EN ISO 179-1: 2023 Plastics- Determination of Charpy impact properties- Part 1: Non-instrumented impact test. Among the most important adjustable 3D printing parameters in the FFF process are the layer height and infill pattern. This research specifically investigates how different layer heights and infill types (linear, zig-zag, and concentric) affect the impact toughness of PLA specimens. The results confirm that higher layer heights and concentric infill patterns result in greater impact toughness, due to better interlayer bonding and more effective stress distribution under impact load.

Key words: Impact toughness testing, Charpy method, Additive manufacturing, Fused Filament Fabrication (FFF), Polylactic acid (PLA).

INTRODUCTION

Parts produced by 3D printing exhibit weaker mechanical properties and lower surface finish quality, which makes it necessary to determine their mechanical characteristics: toughness, hardness, tensile strength, as well as impact strength, compressive strength, flexural strength, and fatigue strength. Additionally, it is important to assess creep, aging, coefficient of friction, shear resistance, and crack propagation resistance in accordance with EN ISO 17296-3: Additive manufacturing – General principles – Part 3: Main characteristics and corresponding test methods.

This standard also defines categories of testing for metal, plastic, and ceramic parts, grouping them into three categories: group H: Testing of functional parts that are highly safety-critical, group M: Testing of functional parts that are not safety-critical, and group L: Testing of parts during the design phase or prototype parts [1].

The testing of toughness for plastic materials is defined by the EN ISO 179-1 standard: Plastics – Determination of Charpy impact properties – Part 1: Non-instrumented impact [2].

Previous research has shown that the impact energy of PLA specimens without notches produced by the FFF 3D printing process is 0.55 J. In that case, the layer orientation angle relative to the direction of applied force during testing was between 15° and 75°, while for layer angles between 30° and 60°, the impact energy was 0.54 J [3].

Similar results were found in a study where the Charpy impact strength of PLA specimens produced by 3D printing was 5 kJ/m², which is equivalent to a impact energy of 0.2 J [4].

On the other hand, research using carbon fiber reinforced PLA-CF with a 15% carbon fiber content, which provides high stiffness and bending resistance, showed that the toughness of PLA specimens produced via the FFF method significantly increases, reaching values of 13,4 kJ/m², 14 kJ/m², and 16,5 kJ/m² [5, 6, 7].

The aim of this study is to determine the impact toughness of PLA plastic specimens using the Charpy method, depending on the layer height in the shell and infill. Additionally, it is necessary to determine the toughness for different infill patterns (linear, zig-zag, and concentric) at the same layer height.

The research hypotheses are that the highest impact toughness of PLA plastic specimens is achieved at the highest layer height in both the shell and the infill, and that the impact toughness differs for various infill patterns, even at the same layer height.

ADDITIVE MANUFACTURING

Additive manufacturing can be divided according to ISO 17296-2: Additive technologies- General principles- Part 2: Overview of process categories and filling, into: Vat photopolymerization- laser stereolithography (SLA) and full-layer illumination-based stereolithography (DLP-SLA, LCD-SLA); Material extrusion (FFF- Fused filament fabrication); Binder jetting; Material jetting; Powder bed fusion- procedures using laser (SLS, SLM, DMLS) and procedures using electron beam (EBM); Directed energy deposition (DED- Deposition of materials using directed energy) and Sheet lamination (LOM- Laminated object manufacturing, PSL) [8].

The material extrusion process (FFF – Fused Filament Fabrication or FDM – Fused Deposition Modeling, the trademark of the company Stratasys) uses a solid thermoplastic material – filament – which is pushed through a heated nozzle. The temperature of the nozzle depends on the type of polymer, and the material is deposited in a molten or semi-molten state onto a heated or unheated build platform. After deposition, the material solidifies and forms the desired part layer by layer [9].

The most important adjustable parameters in the FFF (Fused Filament Fabrication) 3D printing process include: print speed, extrusion speed, layer height in the shell and infill, nozzle temperature, and build plate temperature.

The main limitations of the material extrusion process are related to the anisotropic nature of the printed parts. Layer-by-layer extrusion results in parts that are inherently weaker in one direction. The orientation of the part during the printing process significantly affects its strength in each direction. Infill percentage also impacts the part's strength. Most parts and prototypes produced by 3D printing have around 20% infill, which greatly reduces production cost and time. However, in areas where structural strength is required, 100% infill is used, which increases both the time and cost of fabrication [10].

POLYLACTIC ACID (PLA)

There is a wide variety of polymers with different mechanical, physical, chemical, electrical, thermal, and other properties, which makes them suitable for a broad range of applications.

PLA (Polylactic Acid) is a thermoplastic, biodegradable plastic derived from organic sources (such as corn starch, sugarcane, or sugar beet) – produced through fermentation of plant starch. It has similar properties to polypropylene (PP), polyethylene (PE), or polystyrene (PS). It is commonly used for manufacturing food containers, films, and medical implants, and it has a high surface energy, making it ideal for 3D printing.

The main disadvantages of PLA are its low heat resistance and relatively low strength. The properties of PLA are shown in Table 1 [11].

Table 1. *Properties of Polylactic Acid (PLA)*

The parameters	Values
Heat Deflection Temparature, EN ISO 75	52 °C
Density	1,24 g/cm³
Tensile Strength, EN ISO 527-1	50 MPa
Bend Strength, EN ISO 178	80 MPa
Impact Toughness IZOD Method, EN ISO 180	96,1 (J/m)
Shrinkage rates	0,37-0,41%

The chemical formula of polylactic acid (PLA) is $H\text{-}[OCH(CH_3)CO]_n\text{-}OH$, and the PLA polymer used for this type of 3D printing is in the form of a filament.

EXPERIMENT

The test specimens were produced using the FFF method on a Creality Ender 5 Pro 3D printer with Creality PLA polymer filament, 1.75 mm in diameter. The properties of the Creality PLA filament are shown in Table 2.

Table 2. *Properties of Creality PLA Filament*

The parameters	Values
Filament type	CR PLA black
Diameter (mm)	1,75
Melting point (°C)	190-210
Build plate temperature (°C)	0-60
Tensile Strength	≥60MPa

The 3D printing parameters were as follows: extrusion speed of 80 mm/s, layer heights of 0.1 mm and 0.2 mm in both the shell and infill, nozzle temperature of 200 °C, build plate temperature of 60 °C, and 100% infill. The Creality Ender 5 Pro 3D printer used for the fabrication is shown in Figure 1 [12].

Fig. 1. *3D printer Creality 5 pro*

The technical specifications of the Creality Ender 5 Pro 3D printer are shown in Table 3.

Table 3. *Creality 5 Pro 3D Printer Technical Features*

The parameters	Values
Materials	PLA, ABS, PETG, TPU
Max. part dimensions (mm)	300 x 225 x 380
Filament diameter (mm)	1.75
Nozzle outlet diameter (mm)	0.4
Working temperature (°C)	300
Build plate temperature (°C)	110

Charpy impact toughness testing was performed on notched specimens, type A1, produced using the FFF (Fused Filament Fabrication) 3D printing process with polylactic acid (PLA) polymer filament.

The specimen shape and dimensions were defined according to the EN ISO 179-1:2023 standard: Plastics – Determination of Charpy impact properties – Part 1: Non-instrumented impact test, and are shown in Figure 2.

The layers were oriented in such a way that, when observing the impact direction relative to the laminate plane, the impact was applied parallel- edgewise.

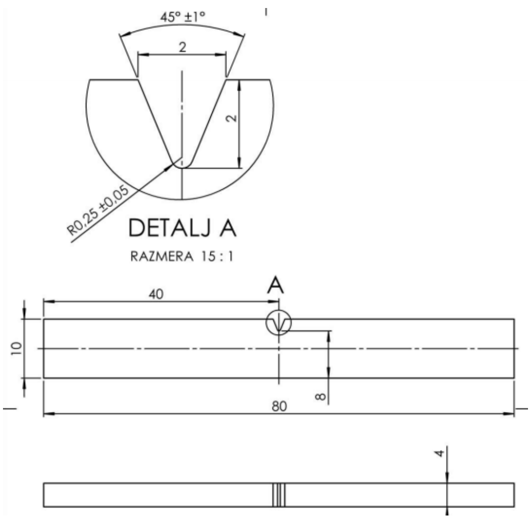


Fig 2. *Notched specimen*

The 3D CAD model of the specimen for Charpy impact toughness testing is shown in Figure 3.

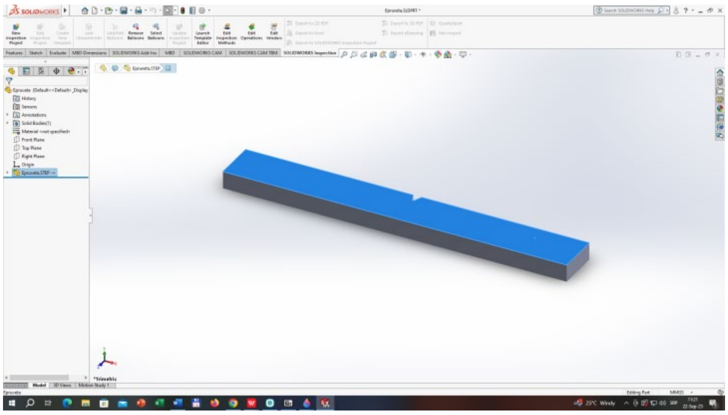


Fig. 3. *3D CAD model*

The STL file of the specimen for Charpy impact toughness testing is shown in Figure 4.

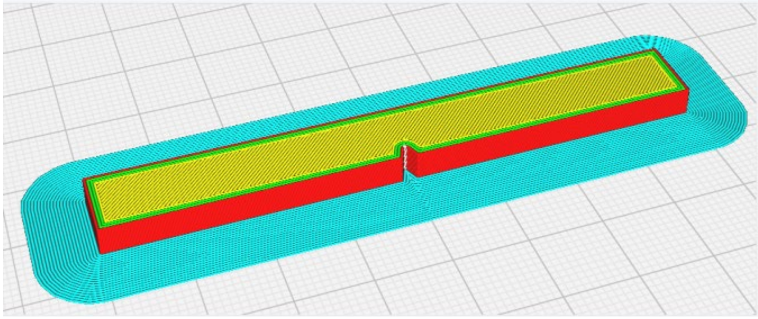


Fig.4. *The STL file*

The appearance of the specimens for Charpy impact toughness testing is shown in Figure 5. Specimen No. 1: PLA specimen with 100% zig-zag infill and 0.1 mm layer height. Specimen No. 2: PLA specimen with 100% concentric infill and 0.1 mm layer height. Specimen No. 3: PLA specimen with 100% linear infill and 0.2 mm layer height. Specimen No. 4: PLA specimen with 100% linear infill and 0.1 mm layer height.

Fig. 5. *The appearance of the specimens*

A Charpy impact testing device was used as the measuring instrument for determining impact toughness (Figure 6). Orientation of the samples: flat on the mat and in a horizontal position.

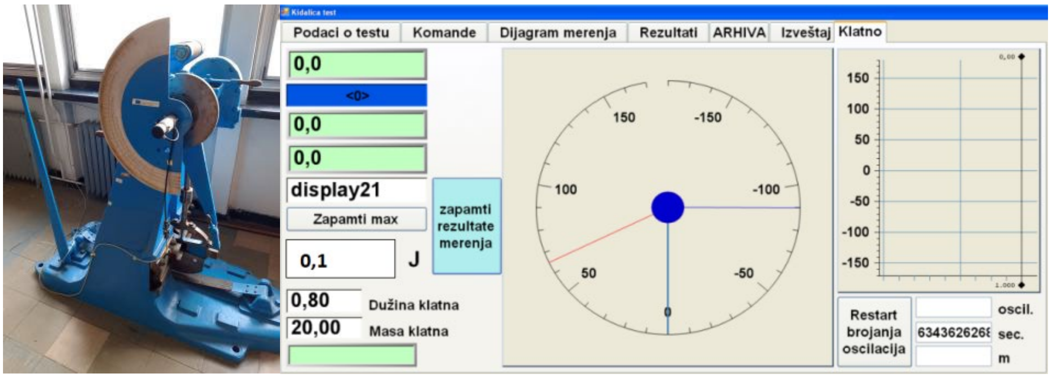


Fig.6. *Measurement of Impact Toughness of PLA Specimens*

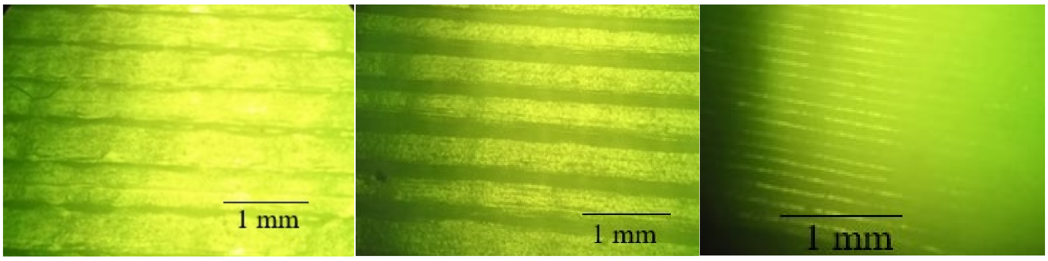
RESEARCH RESULTS

The surface quality of a workpiece made of PLA plastic depends on the layer height applied in the shell and infill. The lower the layer height, the higher the surface quality and greater the ability to produce fine details however, the printing time increases linearly.
The values of Impact energy and Charpy impact strength of notched specimens for different infill patterns and layer heights are presented in Table 4.

Table 4. *Values of Impact Energy and Charpy Impact Strength for Different infill patterns and layer heights*

Pattern	Build plate temerature (°C)	Layer height (mm)	Impact energy- W (J)	Charpy impact strength- a_{cN} (kJ/m^2)
Zig Zag	60	0,1	0,1	3,13
Concentric			0,2	6,25
Lines			0,1	3,13
Lines		0,2	0,2	6,25

Microscopic images of PLA specimens with layer heights of 100 and 200 microns, at 5x magnification, along with a cross-sectional view of the 4 mm thick layers, are shown in Figure 7.



a) b) c)

***Fig. 7**. Microscopic images of PLA samples with a) layer heights of 100, b) layer heights of 200 microns at 5x magnification and c) a cross-section of layers with a layer height of 100 microns.*

In Figure 7, the darker lines represent the grooves between the layers, which are locations of stress concentration. The wider these grooves, the rougher the surface. Microscopic examination revealed that the layer width is greatest at the highest applied layer height.

Figure 7c shows the cross-section of the specimen and the number of layers for a layer height of 0.1 mm.

The Charpy impact strength of PLA samples produced by FFF 3D printing technology depends on the layer height, being higher for larger layer heights. The Impact energy is 0.2 J for a layer height of 0.2 mm and 0.1 J for a layer height of 0.1 mm.

CONCLUSION

3D printing using the FFF material extrusion method results in low surface quality. From the standpoint of impact toughness, the hypothesis was confirmed that the highest impact toughness of PLA specimens is achieved with a larger layer height of 0.2 mm at full infill in both the shell and infill. The impact toughness is twice as low for half the layer thickness when using linear infill. This is because a greater layer height reduces the number of layers in the specimen, leading to better interlayer bonding and fewer sites for crack initiation, thereby increasing impact resistance.

The second hypothesis was also confirmed: impact toughness varies depending on the infill pattern, with all other parameters and layer height kept constant. It is twice as high with concentric infill, which better distributes stress during impact, compared to linear and zig-zag infills, which have more fractures at joints, reducing overall toughness.

These results highlight the importance of optimizing FDM printing parameters to improve the mechanical properties of finished products.

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