Mechanical properties comparison of PLA, tough PLA and PC 3D printed materials with infill structure – Influence of infill pattern on tensile mechanical properties

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Abstract. One of the advantages provided by fused deposition modelling (FDM) 3D printing technology is the manufacturing of product materials with infill structure, which provides advantages such as reduced production time, product weight and even the final price. In this paper, the tensile mechanical properties, tensile strength and elastic modulus, of PLA, Tough PLA and PC FDM 3D printed materials with the infill structure were analysed and compared. Also, the influence of infill pattern on tensile properties was analysed. Material testing were performed according to ISO 527-2 standard. All results are statistically analysed and results showed that infill pattern have influence on tensile mechanical properties for all three materials.

1. Introduction
3D printing technology, also known as additive manufacturing, has developed rapidly in the manufacturing, engineering, automotive, civil, aerospace, medical and other fields. AM is a fast-growing technology that enables the production of products of both simple and complex geometries [1], [2]. Additive manufacturing is relatively new technology which uses a deposition of material layer by layer to produce parts using a CAD model. The additive manufacturing process is based on the generating of the virtual CAD model of product, then slicing this model into 2D cross-sections using “slicer” software and translating these 2D data to the 3D printers in order to manufacture the physical product layer by layer (Figure 1) [3].

Figure 1. Schematic representation of the additive manufacturing process

During the last decade, 3D printing has made significant developments in industrial products. One of the main advantages of 3D printing is converting industrial products from a proposal to an actual application in minimum time. On today's market, there are many different AM technologies, but one of
the widely used technology is Fused Deposition Modelling (FDM), and mostly due to relatively low cost and its user-friendliness [4], [5].

FDM as one of the most popular but also complex additive manufacturing (AM) technology that provides a number of advantages over conventional manufacturing processes. FDM process, also known as “Fused Filament Fabrication, FFF” and “Material Extrusion”, is based on the extrusion of molten material layer by layer on working bed and producing part on working print bed, showed on picture bellow [6], [7].

![Schematic representation of FDM process](image)

**Figure 2.** Schematic representation of FDM process [8]

The 3D printing parts fabrication with FDM technology begins with the material also known as a filament, most often the material is thermoplastic, that is conveyed into the extrusion head via a feeder. In the extrusion head, the filament is melted in a heating element and through the nozzle it is applied in the form of deposited lines on the printing bed, where the final geometry of the product is formed. The material is in the form of wire, known as filament, and usually materials for FDM are thermoplastics, but also materials can be different types of composites, ceramics and even metals. Some of the commonly used materials for producing parts with FDM technology are PLA (Polylactic Acid), PC (Polycarbonate), PET (Polyethylene terephthalate), PP (Polypropylene), ABS (Acrylonitrile Butadiene Styrene), TPU (thermoplastic polyurethane) and Nylon presented in the below (Figure 3) [7], [9], [10].

![Materials diagram](image)

**Figure 3.** Most commonly used materials in FDM technology
Product quality and mechanical properties of printed materials depend on a large number of parameters (Figure 4) that need to be analyzed in order to make the most of the advantages of this technology. Based on the literature analysis of previous research, the parameters that are most often examined and that have a significant impact on the mechanical properties of FDM printed materials are: layer thickness, infill density, infill pattern, infill angle, build orientation, raster angle, printing speed, printing temperature, airgap, and more [8], [11], [12].

![Figure 4. Parameters with significant impact on FDM printed materials mechanical properties](image)

As mentioned before, FDM printed material with an infill structure provides several advantages such as reduction of printing time and the amount of consumed material, which directly affects the reduction of the price, also lighter weight of final product. To make the most of this, we need to understand how infill design affects the mechanical properties of the printed material in order to provide required strength as well as other properties of the finished product.

The main influencing factors of infill design (Figure 5), also the most frequently examined are “Infill density”, “Infill pattern” and “Infill angle”, and through literature review it can be seen that all three have an impact on different mechanical properties of printed materials.

![Figure 5. The main influencing factors of infill design](image)
The importance of studying this topic is evidenced by previous research of infill design impact on the mechanical and other properties of FDM printed parts, such as that of Mustafa et al. [13], where effect of infill density on tensile and flexural properties of PLA material was analysed; that of Miguel and Rismalia et al. [14], [15], the influence of infill pattern and density on ABS and PLA FDM printed material tensile mechanical properties; that of Jaya [16], the impact of infill pattern, density and angle on the printing time and the filament length were analysed, that of Nuha et al. [17], the influence of infill density on the flexural properties of PLA printed material; and that of Pushpendra et al. [18], strength and surface characteristics analyse of FDM printed PLA parts for multiple infill patterns. In addition to this, master thesis on this topic were written, where impact of infill design on mechanical strength and production cost in FDM was researched [19] and observing the effects of infill shapes on tensile properties of 3D printed polymeric parts [20].

In this paper, the focus is on the analysis of the influence of infill pattern on the mechanical properties of three different FDM 3D printed materials: PLA, Tough PLA and PC. For every material, seven different infill patterns were examined, all results are statistically analysed and presented in further text.

2. Materials

For this study, three FDM printing material types, PLA, Tough PLA and PC were used (Figure 6). All materials were from same manufacturer “Ultimaker” and same colour (black). This is important because in research [5] and [10] has concluded that mechanical properties differ from one material manufacturer to another, but also colour affects mechanical properties even though the material is from the same manufacturer.

Ultimaker PLA material is a polymer named polylactic acid, made from renewable and organic resources. It is biocompatible thermoplastic that provides easy printing and good surface quality. It is safe and nontoxic material and is used in a wide range of applications for novice and advanced users. It has relatively good tensile and flexural strength, higher than ABS, easy to work with at high printing speeds, user-friendly for home and office environments with a wide range of colour options available. It has a low coefficient of thermal expansion, which limits its applications in which the printed part is exposed to temperatures higher than 50 °C [7], [21].

Ultimaker Tough PLA material is a technical PLA material with better toughness comparable to ABS. It is material good for printing a “large” sizes technical models, and also offers the same safe and easy use as regular Ultimaker PLA material. It has stronger impact resistance than PLA and similar to ABS, also with higher stiffness compared to ABS. Tough PLA bends before it breaks, which makes it well suitable for many engineering applications, especially where high-wear and impact resistance are required. It is less brittle than regular PLA and gives a more matte surface finish quality. With heat resistance similar to standard PLA materials, so printed products should not be exposed to temperatures above 60 °C [7], [22], [23].
PC material is polycarbonate thermoplastic material for manufacturing strong and tough products. In general, PC material has high thermal stability, up to 100 °C. Ultimaker PC material is engineered to be printed at moderate temperatures compared to other PC filaments and shows minimized warping and good printability. Mechanical properties differ from the colour of the material, so that the transparent colour gives the higher tensile and flexural properties compared to black and white colour. In general, material is with high toughness, flame retardant characteristics, temperature resistance, strong interlayer bonding, dimensionally stable (up to 100 °C) and with good bed adhesion. It is used for molds, engineering parts, tools, functional prototyping and short-run manufacturing [24], [25].

The mechanical properties of these materials defined by the manufacturer are presented in Table below. What should be noted is that the values of these mechanical properties from the Table below may differ because they depend on the 3D printing parameters and other factors, as shown by many studies [1], [2], [3], [11]. Also, the method of material testing can affect, because one of the influencing factors on tensile mechanical properties is strain rate during material testing [26].

**Table 1.** Material specification of PLA, Tough PLA and PC materials defined by manufacturer

| Material properties          | Standard | PLA   | Tough PLA | PC  |
|-----------------------------|----------|-------|-----------|-----|
| Colour                      | -        | Black | Black     | Black |
| Diameter [mm]               | -        | 2,85  | 2,85      | 2,85 |
| Tensile modulus [GPa]       | ISO 527  | 2,35  | 1,8       | 1,9  |
| Yield stress [MPa]          | ISO 527  | 49,5  | 37        | -    |
| Tensile at break [MPa]      | ISO 527  | 45,6  | 37        | 53,7 |
| Elongation at brake [%]     | ISO 527  | 5,2   | 3,1       | 5,9  |
| Flexural strength [MPa]     | ISO 178  | 103   | 78        | 95,5 |
| Hardness [Shore D]          | Durometer| 83    | 79        | 80   |

3. Methodology

In this study, three different FDM printed materials with infill structure were tested. The aim was to analyse influence of infill pattern on tensile mechanical properties. Experiment methodology is presented on diagram below (Figure 7), and details are presented in further text.

![Figure 7. Experiment methodology](image-url)

CAD 3D model of testing specimens are designed in Solidworks, according to ISO 527-2 in dog-bone shape, and prepared in “stl.” format. Specimen geometrical characteristics and dimensions are presented on Figure 8.
Figure 8. Tensile testing specimen dimensions according to ISO 527-2

Cura slicer software was used to prepare specimens for 3D printing and defining printing parameters. All specimens are printed with predefined printing parameters for Ultimaker materials in black colour and with “Normal 0.15 mm” printing profile. Main printing parameters for every material are presented in Table 2.

| Table 2. Main 3D printing parameters for PLA, Tough PLA and PC materials |
|-------------------------------------------------|-------------------------------|--------------------------|--------------------------|
| 3D printing parameter                  | PLA                           | Tough PLA               | PC                        |
| Cura printing profile                 | Normal, 0.15mm                | Normal, 0.15mm          | Normal, 0.15mm           |
| Nozzle diameter, [mm]                 | 0.4                           | 0.4                     | 0.4                       |
| Layer height, [mm]                    | 0.15                          | 0.15                    | 0.15                      |
| Printing temperature, [°C]            | 200                           | 215                     | 280                       |
| Build plate temperature [°C]          | 60                            | 60                      | 110                       |
| Printing speed, [mm/s]                | 70                            | 45                      | 50                        |
| Infill print speed, [mm/s]            | 50                            | 50                      | 50                        |
| Fan speed, [%]                        | 100                           | 100                     | 0                         |
| Infill density, [%]                   | 60                            | 60                      | 60                        |
| Infill angle, [°]                     | 45                            | 45                      | 45                        |

For every material 7 different infill patterns were analysed. In 4.8 version of Cura slicer, there are 13 types of infill available for use, but for this research, only patterns that were named as “strong” by the manufacturer Ultimaker were selected, and these are: Cubic Subdivision (CS), Cubic (CU), Grid (G), Octet (OC), Quarter Cubic (QC), Triangles (T) and Tri-Hexagon (TH), presented on Figure 9.

Figure 9. Examined infill patterns from slicer Cura 4.8

Tensile specimens were manufactured on Ultimaker S5 and S3 desktop FDM 3D printers (Figure 10). Three replicas of tensile specimens were printed for each infill pattern. In order to reduce the influence of external “negative” factors on the results, the same 3D printer was always used and the specimens were printed in the same position on the build plate. Also, as already mentioned, material from the same manufacturer and the same colour was used.
A total of 63 specimens were printed and tensile tested using Shimadzu AGS-X tensile testing machine (max. force 10kN). The tensile test was performed according to the ISO 527-2 standard, where the strain rate was 5 mm/min, at room temperature. Figure 11 shows tensile testing process.

Monitoring and recording of mechanical properties of the tested materials during test were done using the program Trapezium X (Shimadzu). All results were statistically analysed in Excel and presented in the next chapter.

4. Results and discussion
Tensile testing of PLA, Tough PLA and PC printed materials with infill structure was carried out for all specimens at the same loading conditions. In general, from Stress-Strain diagrams it can be seen that infill pattern have influence on mechanical properties of FDM printed materials with infill structure. Also, Stress-Strain diagrams with all and average results for all three tested materials are presented on Figure 12.
Figure 12. Stress-Strain diagrams for all three tested FDM printed materials with infill structure

In the following text, the results of tensile strength (Rm) and elastic modulus (E) for tested materials are presented and commented, which are also presented through diagrams. Also, all results with average values of Rm and E are presented in Table 3.

Table 2. Tensile strength and elastic modulus results, with average values, for PLA, Tough PLA and PC materials with infill structure

| Infill design | PLA | Tough PLA | PC |
|---------------|-----|-----------|----|
| Pattern       | Angle| Density | Rm  [MPa] | E  [GPa] | Rm  [MPa] | E  [GPa] | Rm  [MPa] | E  [GPa] |
| CS            | 45°  | 60 %    | 42.50  | 2.20    | 38.13    | 2.1     | 47.20    | 1.8     |
| CU            | 45°  | 60 %    | 39.47  | 2.20    | 38.33    | 2.1     | 49.67    | 1.9     |
| G             | 45°  | 60 %    | 45.53  | 2.30    | 40.10    | 2.1     | 49.17    | 1.9     |
| OC            | 45°  | 60 %    | 45.57  | 2.40    | 37.77    | 2.1     | 50.03    | 1.9     |
| QC            | 45°  | 60 %    | 38.40  | 2.10    | 36.40    | 2.1     | 49.50    | 1.9     |
| T             | 45°  | 60 %    | 39.90  | 2.20    | 38.40    | 2.1     | 48.60    | 1.9     |
| TH            | 45°  | 60 %    | 43.57  | 2.30    | 38.23    | 2.1     | 48.97    | 1.9     |

Full name of infill pattern according to Cura slicer: Cubic Subdivision (CS), Cubic (CU), Grid (G), Octet (OC), Quarter Cubic (QC), Triangles (T) and Tri-Hexagon (TH).
Analysing the tensile strength of printed PLA material with infill structure, it can be seen that the value of tensile strength is from 45.57 MPa to 38.40 MPa, depending on the infill pattern (Figure 13). The highest tensile strength is shown by “Octet” and “Grid” patterns with 45.5 MPa, and the lowest tensile strength is shown by “Quarter Cubic” pattern with 38.40 MPa.

Figure 13. Tensile strength of PLA FDM printed material with different infill pattern

Results of elastic modulus for PLA material with infill structure are presented on diagram below (Figure 14). Elastic modulus varies from 2.40 GPa to 2.10 GPa, depending on the infill pattern, where “Octet” pattern is showing highest value, and “Quarter Cubic” pattern the lowest value of elastic modulus.

For Tough PLA printed material with infill structure, tensile strength varies from 40.10 MPa to 36.40 MPa, depending on infill pattern (Figure 15). Highest tensile strength was achieved by “Grid” and the lowest by “Quarter Cubic” infill pattern. In general, the results are showing lower tensile strength for Tough PLA compared to PLA material.

Elastic modulus for Tough PLA material with infill structure compared with PLA material is slightly lower. What is noticeable is that for all infill patterns, value of the elastic modulus is the same and amounts to 2.10 GPa, except for “Quarter Cubic” pattern where it is 2.00 GPa. Elastic modulus results for Tough PLA material are presented on diagram below (Figure 16).
As expected, based on the data from Table 1, PC FDM printed material with infill structure showing highest tensile strength, where values are in range from 50 MPa to 47 MPa. Infill pattern “Octet” is showing highest, and “Cubic Subdivision” the lowest values of tensile strength. Tensile strength results for PC material are presented on diagram below (Figure 17).

Elastic modulus results for PC material are presented on Figure 18. Overall, FDM printed PC material with infill structure showed lowest elastic modulus values, compared to PLA and Tough PLA materials.
All infill patterns have 1,90 GPa elastic modulus, while only “Cubic Subdivision” pattern showed a slightly lower value of 1,80 GPa.

![Figure 18. Elastic modulus of PC FDM printed material with different infill pattern](image)

From the diagram below (Figure 19), it is evident that when looking at the results for all infill patterns, it can be seen that the highest tensile strength was achieved by PC, than PLA and Tough PLA FDM printed material with infill structure. Also, the highest values of elastic modulus were achieved by PLA, than Tough PLA and PC material (Figure 20).

![Figure 19. Tensile strength of all tested FDM printed materials with different infill pattern](image)

![Figure 20. Elastic modulus of all tested FDM printed materials with different infill pattern](image)

5. Conclusion
The literature review has shown the advantages of materials with infill structure that can be applied to products manufactured by additive technologies such as FDM. Infill design is defined by several factors that affect the mechanical properties of the printed material with infill structure, and one of them is the infill pattern, which through this research has been shown to affect tensile mechanical properties. In this research, influence of infill pattern on PLA, Tough PLA and PC FDM printed materials with infill...
structure were experimentally analysed. The obtained experimental results were statistically analysed, presented through diagrams, compared and based on those results conclusions are:

- Overall, infill pattern have an influence on tensile mechanical properties such as tensile strength and elastic modulus.
- For PLA material with infill structure tensile strength varies up to 17%, depending on the infill pattern, where maximum value is showed by “Octet” and “Grid” and minimum with “Quarter Cubic” infill pattern. Also, for elastic modulus, the influence of the infill pattern can be seen, where the results varies up to 9%. The “Octet” pattern showed the highest elastic modulus of 2,40 GPa, while “Quarter Cubic” had the lowest value of 2,10 GPa.
- For Tough PLA material with infill structure tensile strength varies up to 10%, depending on the infill pattern, where maximum value is showed by “Grid” and minimum with “Quarter Cubic” infill pattern. For all patterns the elastic modulus was the same with the value of 2,10 GPa, except for “Quarter Cubic” pattern which have up to 5% lower value in the amount of 2,0 GPa.
- For PC material with infill structure tensile strength varies up to 6%, depending on the infill pattern, where maximum value is showed by “Octet”, and minimum with “Cubic Subdivision” infill pattern. Similar to Tough PLA material, elastic modulus for PC material was the same for all patterns, except “Cubic Subdivision”, which have up to 5% lower elastic modulus.
- In general, when all three materials are analysed together, the highest tensile strength is shown by PC, while the lowest by Tough PLA material. Also, when the elastic modulus is observed, the highest values is shown by PLA, while PC material is showing lowest value of elastic modulus.

Analysis of other infill design parameters such as infill density and infill angle for these seven patterns is recommended for future research. In addition to this, it is necessary to do deeper analysis of all infill design parameters together, in order to determine the most influential factors on the mechanical properties, and also the interactions between them. Also, connect all this with the production time and the amount of material, so that a techno-economic analysis can be done. Of course, in addition to mechanical tensile properties, analyse both compressive and flexural properties, to better understand the behaviour at different loads and to make the most of the advantages of the printed materials with infill structure.

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