Experimental Investigation on Influence of Infill Density on Tensile Mechanical Properties of Different FDM 3D Printed Materials

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Abstract – One of the advantages of FDM technology is the production of product materials with infill structure. In order to make the most of this advantage, the behaviour of FDM printed material with infill structure under different loads has to be analyzed and understood. Therefore, the goal of this experimental research is to analyze influence of infill density (100%, 80%, 60% and 20%) on tensile mechanical properties (tensile strength and elastic modulus) of PLA antibacterial nanocomposite, tough PLA and ABS-X 3D printed materials.

Keywords – FDM, infill density, PLA, ABSx.

1. Introduction

Today, in the world of advanced technologies, additive manufacturing (AM), also known as rapid prototyping (RP), is in the focus of various industries. When it comes to AM, there are several different technologies depending on how and in what way the finished product is made, so several techniques have been developed including fused deposition modeling (FDM), selective laser sintering (SLS) and stereolithography (SLA) [1].

FDM 3D printing (also known term “fused filament fabrication”, FFF) is one of the additive manufacturing (AM) technology, and today it is increasingly used in field of engineering applications such as customized products, automotive industry, aeronautic, medical engineering and more [1], [2]. FDM product manufacturing starts from designing a CAD 3D model of final product (in Solidworks, Catia et.), which is then exported in STL format. Further, slicer software (eg. “Cura” from Ultimaker) is used to prepare CAD 3D model in STL format for 3D printing and generate G-code with all printing parameters [3], [4].

The process of making a product by the FDM method could be described as a process in which the material is melted, applied layer by layer and solidified into the geometrical shape of the finished product [5], [6].

Figure 1. FDM 3D printing process [7]

Figure 1 shows a simplified scheme of an FDM 3D printer and product manufacturing process itself with this technology. The most used materials in FDM technology are thermoplastic, in form of a wire (filament) on a spool. The filament is delivered via drive wheels to the print head with heating chamber

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where it melts and is further delivered to the build plate through a nozzle, where final product was made. [8], [9].

For FDM technology, there are a large number of materials on the market, and new materials are being developed almost on a daily basis. As mentioned before, most popular FDM materials are thermoplastics as PLA (polylactic acid), ABS (acrylonitrile butadiene styrene), PC (polycarbonate), nylon, PP (polypropylene), PET (polyethylene), TPE (thermoplastic elastomer). In addition to thermoplastics, FDM technology also uses composite materials based on glass and carbon fibers, even ceramics, but also metal materials are used in FDM [10], [11], [12].

As for the mechanical and other properties of FDM 3D printed materials, they depend on many factors such as: layer thickness, raster angle, building direction, infill shape (pattern), infill density, infill angle, raster width, printing speed, printing temperature, nozzle diameter and many more. It can be seen through previous research that the focus is on examining the influence of various factors and parameters on the mechanical properties of printed materials, and the best possible understanding of them, in order to maximize the potential of these technologies [13], [14], [15].

Materials with infill structure, that can be produced with additive technologies, bring us a number of advantages which can be seen from the above mentioned literature, and some of the key advantages are reducing amount of material and time of 3D printing, which results a lower price of final product (Figure 2.).

Figure 2. Benefits of FDM printed material with infill structure

The aim of this research is to investigate the influence of infill density on tensile mechanical properties of three different FDM printed materials

with infill structure: antibacterial nanocomposite PLA (cPLA), Tough PLA (tPLA) and ABS-X. The experimental tests of tensile strength and elastic modulus were performed for different infill densities: 100%, 80%, 60% and 20%. All results were statistically analyzed and presented in further text.

2. Materials

As mentioned earlier, there are many different materials for FDM 3D printing technology today, and new materials are constantly being developed and improved. Also, one of the most commonly used and among the most popular materials for both “ordinary” users and researchers are PLA and ABS materials. In this research, PLA and ABS materials with “improved” characteristics were tested, while still having good printability, which is important when making a finished functional product. The brand names of the materials as well as their characteristics given by the manufacturer are presented in the text below, also mechanical properties by manufacturer are presented in Table 1.

Table 1. Tested materials properties by manufacturer

Material properties	cPLA	tPLA	ABS-X
Tensile strength [MPa]	60	37	23,8
Yield strength [MPa]	53	37	-
Elastic modulus [GPa]	3,6	1,8	4,5
Elongation at break [%]	6	3,1	13,3
Flexural strength [%]	83	78	63,6

PLACTIVE AN1, by Copper3D company, is high quality PLA nano-copper composite, which is biocompatible, non-cytotoxic and skin contact approved material by the ISO 10993 standard. Also, it is antibacterial material, in which antimicrobial action has been scientifically validated eliminating more than 99,99% of bacteria, viruses and fungi and wide range of microorganisms. Clinically tested in prosthesis for amputees and great for manufacture of other medical applications where avoiding bacterial contamination is required.

Tough PLA, by Ultimaker company, is technical PLA material with great toughness comparable to ABS. It is safe, non-toxic and with great printability as regular PLA material. With an impact strength similar and higher stiffness compared to ABS, also Tough PLA is less brittle than regular PLA. It can be used for functional prototyping, tooling, manufacturing aids etc.

ABS-X, by 3D Republika company, belongs to the latest generation of ABS filaments. It is strong, with minimal warping and is characterized by excellent layer adhesion. It is a great solution for all standard ABS problems, such as warping and poor build plate adhesion. Compared to regular ABS filaments, ABS-

X cracks much less and has excellent mechanical properties. Also, thanks to its properties, ABS-X is material that perfectly matches prints that require high impact resistance.

3. Methodology

For this experimental research, dog bone type tensile specimens are designed in Solidworks CAD software according to ISO 527-2 (Figure 3.), and STL format of specimen 3D model was created for slicer Cura.

Figure 3. 3D model of tensile testing specimen according to ISO 527-2, designed in Solidworks

Using slicer Cura, 3D models of testing specimens were prepared for 3D printing. Printing parameters for cPLA and tPLA materials were chosen by default PLA printing profile (normal 0,15mm profile) with predefined printing parameters from Cura. For ABS-X material, default ABS printing profile (normal 0,15mm profile) from Cura was chosen. It should be noted that a CC red printing core, specially designed to print with composite materials, with nozzle diameter of 0,6mm was used for printing cPLA material, because this material contains nanoparticles of copper that create abrasion on the nozzle. While for tPLA and ABS-X material, a standard AA core with a 0,4mm diameter nozzle was used. Main printing parameters for every material are presented in Table 2.

Table 2. Main printing parameters

Printing parameters	cPLA	tPLA	ABS-X
Filament diameter [mm]	2,85	2,85	2,85
Cura printing profile	Normal 0,15mm	Normal 0,15mm	Normal 0,15mm
Nozzle diameter [mm]	0,6	0,4	0,4
Layer height [mm]	0,15	0,15	0,15
Wall thickness [mm]	1	1,23	1,3
Printing speed [mm/s]	70	45	60
Printing temp. [°C]	200	215	245

In slicer Cura user have option to select 13 different infill patterns. For this test, on all specimens, “Triangle” pattern with 45° infill angle

was used with four different densities: 20%, 60%, 80% and 100%. It should be noted that for 100% infill density, the specimen volume is filled on the same way for any selected infill pattern (Figure 4.).

Figure 4. Test specimens with “Triangle” infill pattern and different infill density

All specimens were manufactured on Ultimaker S3 desktop 3D printer, where five replicas were made for each infill density (Figure 5.).

Figure 5. Test specimens manufacturing on Ultimaker S3

After 3D printing, all specimens were tensile tested on Shimadzu AGS-X (10 kN) universal testing machine, according to ISO 527-2 with strain rate of 5 mm/min (Figure 6.).

Figure 6. Tensile testing on Shimadzu AGS-X machine

Trapezium-X software, from Shimadzu, was used for monitoring and collecting data, where Stress-Strain curves are presented on diagram below (Figure 7).

Figure 7. Stress-Strain curves for all materials

All collected data were transferred to Excel where statistical analysis was done and the results are presented in further text.

4. Results and Discussion

For this experimental research, total of 60 specimens of three different materials (cPLA, tPLA and ABS-X) were tested. The results of the twelve combinations were collected and presented in Table 3, where all values are average of five specimens.

Table 3. Tensile properties of tested specimens

Material	Infill density	Tensile strength, Rm [MPa]	Elastic modulus, E [GPa]
cPLA	100%	61.4	3.1
cPLA	80%	37.5	2.5
cPLA	60%	32.7	2.1
cPLA	20%	26.7	1.8
tPLA	100%	49.5	2.5
tPLA	80%	41.6	2.2
tPLA	60%	38.9	2.1
tPLA	20%	35.4	1.9
ABS-X	100%	38.6	1.8
ABS-X	80%	30.9	1.6
ABS-X	60%	29	1.5
ABS-X	20%	26.9	1.3

Analysis of tensile strength for the case where the samples are with 100% infill density is presented on diagram in Figure 8, and it shows that cPLA material have the tensile strength 21% higher than tPLA and 45,6% than ABS-X material.

Figure 8. Tensile strength for cPLA, tPLA and ABS-X printed materials with 100% infill density

Stress-Strain curves of all three materials with 100% infill density are presented in Figure 9. What can also be seen is that the tPLA material shows the greatest strain compared to cPLA and ABS-X materials.

Figure 9. Stress-Strain curves for cPLA, tPLA and ABS-X printed materials with 100% infill density

Analyzing the elastic modulus for samples with 100% infill density, cPLA material showed the largest elastic modulus of 3,1 GPa. When comparing elastic modulus of cPLA with other materials, cPLA showed higher elastic modulus by 21,4% than tPLA and 53% than ABS-X materials, which can also be seen from the diagram below (Figure 10).

Figure 10. Elastic modulus for cPLA, tPLA and ABS-X printed materials with 100% infill density

When tensile strength of all three materials with infill structure is compared, linear decrease in tensile strength can be seen as the density of the infill structure decreases (Figure 11). When comparing the tensile strength of samples with 100% infill density and samples with 80% infill density, it can be seen the largest difference for cPLA material, which is 48%, also 17% for tPLA and 22% for ABS-X material.

Figure 11. Tensile strength for cPLA, tPLA and ABS-X printed materials with different infill density

The results of the elastic modulus for all three tested materials with different infill densities are presented in Figure 12. The diagram shows a linear decrease of elastic modulus with a decrease of infill density for all three materials. As expected, the largest elastic modulus for all tested infill densities showed the cPLA material, while the lowest elastic modulus was showed by ABS-X material.

Figure 12. Elastic modulus for cPLA, tPLA and ABS-X printed materials with different infill density

Percent differences in tensile strength and elastic modulus for samples with different density of infill structure and those without infill structure (100% infill density) are presented in Table 4. When tensile strength is observed, it can be seen that depending on the infill density the strength decreases from 48% to 78% for cPLA, from 17% to 33% for tPLA and from 22% to 35% for ABS-X printed material. Also, analyzing the elastic modulus, depending on the infill

density, elastic modulus was also reduced from 21% to 53% for cPLA, from 12% to 27% for tPLA and from 11% to 32% for ABS-X printed material.

Table 4. Tensile strength and elastic modulus difference for different infill density compared with 100% infill density specimens

Material	Infill density	Difference in tensile strength	Difference in elastic modulus
cPLA	80%	48%	21%
cPLA	60%	61%	38%
cPLA	20%	78%	53%
tPLA	80%	17%	12%
tPLA	60%	24%	17%
tPLA	20%	33%	27%
ABS-X	80%	22%	11%
ABS-X	60%	28%	18%
ABS-X	20%	35%	32%

The diagrams below, presents the Stress-Strain curves for cPLA, tPLA and ABS-X FDM printed materials with different infill density. When analyzing all three diagrams (Figures 13, 14 and 15), generally no large scatter of results can be seen when considering that five replicas were examined for each case. Where scattering can be observed is with tPLA printed material when strain is analyzed.

Figure 13. Stress-Strain curves for cPLA FDM printed material with different infill density

Figure 14. Stress-Strain curve for tPLA FDM printed material with different infill density

Figure 15. Stress-Strain curve for ABS-X FDM printed material with different infill density

Tensile strength and elastic modulus comparison of all three tested printed materials with the infill structure are presented in the diagrams below (Figure 16, Figure 17). The results are grouped by infill density, in order to see the difference depending on the printed material.

Figure 16. Tensile strength comparison of all three tested printed materials with infill structure

Figure 17. Elastic modulus comparison of all three tested printed materials with infill structure

5. Conclusion

The aim of this study was to experimentally analyze the influence of infill density on the tensile mechanical properties of various FDM 3D printed materials: antibacterial PLA nano-copper composite (cPLA), Tough PLA (tPLA) and ABS-X. After

examining and analyzing the results, some of the conclusions are presented below.

- For samples with 100% infill density, the cPLA material shows the highest tensile strength, 21,5% higher than tPLA and 45,6% than ABS-X material. Also, for elastic modulus, cPLA showed highest elastic modulus, where it is 21,4% higher than tPLA and 53% than ABS-X material.
- For all three printed materials, the influence of the infill density on the tensile strength and elastic modulus can be seen. By decreasing the infill density, a linear decrease in the tensile strength value as well as the elastic modulus can be seen for all materials.
- The largest decrease in the tensile strength and elastic modulus is seen for cPLA material, when the samples are printed with infill structure and compared with specimens printed with 100% infill density (no infill structure).
- Analyzing only specimens with infill structure, tPLA material is showing greatest tensile strength for all infill densities (20%, 60% and 80%). If the elastic modulus is observed, for infill density of 80% the highest value is shown by cPLA, for infill density of 60% the same value is shown by cPLA and tPLA materials, the same as for infill density of 20%.
- From the Stress-Strain diagrams, in general, the tPLA material showed the greatest plasticity for specimens with and without infill structure.
- Also, the Stress-Strain diagrams do not show a pronounced scattering of results, based on this it can be concluded that Ultimaker 3D Printers provide good repeatability when 3D is printing a large number of pieces.

It is very important to understand influence of infill design in 3D printed materials, in order to maximize the benefits of making printed products with infill structure. In this study, only the influence of infill density was analyzed, and when it comes to the infill design, in addition to the density, infill pattern and infill angle in relation to the direction of loads should be examined. Also, orientation of the infill pattern in relation to loads is also important to be examined. Further, creating a model of materials for FEM/FEA analyzes will describe printed materials with an infill structure for the elastic and plastic deformation.

The above mentioned problems, which need to be explored, like many others, only tell us that this technology is still relatively new, and that it requires us to explore it as much as possible in order to be able to take advantage of its benefits.

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