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SIMULATION AND EXPERIMENTAL INVESTIGATION OF A 3D PRINTED COMPOSITE SPECIMEN´S MECHANICAL PROPERTIES

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Abstract
Nowadays, additive manufacturing is a very common manufacturing method which requires the use of several polymers reinforced with carbon fiber, Kevlar etc. This article focuses on the experimental investigation of 3D printed composite specimens made of PET-G Carbon material. Since these materials can replace several commercial materials, it is necessary to know their mechanical properties. The main goal of our research is to experimentally measure the tensile strength of the selected material according to ISO 527-1 and ISO 527-2 standards with two different layer heights. The measured data will be processed, and a Finite Element Analysis (FEA) simulation model will be created to compare the measured and simulated data. The results of the FEA simulation have shown that the difference between the values obtained by the tensile tests and simulation are 7.706 % for PET-G Carbon. The results of the applied FEA are close to the measured data for the PET-G Carbon material.

Key words: *additive manufacturing; finite element analysis; tensile strength; composite materials.*

INTRODUCTION

At present, additive manufacturing (AM) is used nearly in every field in industry. The growing requirements for the use of cheap and durable materials force the engineers to use polymer materials enhanced with different materials (Carbon fiber, Kevlar, Glass fiber etc.). The development and application of 3D printing technology in these enhanced fiber polymer-based materials (composites) have seen significant advancements in recent years. Recent studies have highlighted the potential of 3D printing technologies, such as fused deposition modeling (FDM) and selective laser sintering, to produce polymer composites with complex geometries and enhanced mechanical properties. The customization capabilities of 3D printing allow material properties to meet specific application requirements, including tensile strength and elasticity (*Ma et al., 2024; Wang et al., 2017; Chen et al., 2023).* Despite significant advancements, challenges remain in the long-term performance and degradation of 3D printed polymer composites, particularly under varying environmental conditions. Furthermore, since we are dealing with a layered final product, these materials pose a barrier to the broader adoption of 3D printed polymer composites in industrial applications (*Wang et al., 2017*). This is the reason why these materials need to have determined their mechanical properties by commonly used mechanical tests, providing accurate values of mechanical parameters such as Young´s modulus, yield strength, elongation at break and Poisson´s ratio (*Kalova, et al., 2021*; *Majko, et al., 2019*). The use of Finite Element Analysis (FEA) simulations in conjunction with 3D printing technologies enables the optimization of carbon fiber-reinforced composites by predicting their mechanical behavior under various loading conditions. To have an accurate FEA analysis, several real measurements should be made first. FEA provides valuable insights into the tensile performance and elasticity of these materials, guiding the design process to enhance durability and performance (*Wang et al., 2017*). This simulation-driven approach not only accelerates the development cycle but also reduces the costs associated with physical testing and (*Ma et al., 2024*). The aim of this article was to analyze the mechanical properties of 3D printed composite specimens with different 3D printing parameters and then compare them with a FEA simulation model.

MATERIALS AND METHODS

For our research we have used a Prusa I3 MK3s+ FDM 3D printer. As a material for the test specimens, we have used PET-G Carbon material with 10% addition of carbon fibers. This filament was produced by Spectrum, and its diameter is 1.75 mm. The mechanical properties of the used material are shown in Tab. 1.

Tab. 1 Mechanical properties and recommended 3D printer parameters of the composite filament used

Material	Density $g.cm^{-3}$	Tensile strength MPa	Modulus of elasticity MPa	Poisson´s ratio	Nozzle temperature °C	Heated bed temperature °C
PET-G Carbon	1.32	45	4250	0.385	230-255	60-80

Since we wanted to examine also the influence of the 3D printing parameters on the measurement, we had used rectilinear infill pattern with 0.15 mm and 0.3 mm layer height. The other printing parameters are described in Tab.2.

Tab. 2 Printing parameters

Parameter	Value
Nozzle temperature (°C)	245
Heated bed temperature (°C)	80
Nozzle diameter (mm)	0.4
Number of perimeters	2
Printing speed ($mm.s^{-1}$)	70
Infill density (%)	100

The tensile tests were done on a Testometric X350-10 universal testing machine with maximal force 10 kN. The tests were performed according to ISO 527-1 and ISO 527-2 standards. The number of specimens used was 10 for each measurement and the speed rate was set to 1 $mm.min^{-1}$. For finite element analysis we have used Solidworks 2020 software, where custom material with the described mechanical properties was used for the simulations. A curvature-based solid mesh with tetrahedrons as an element type was used. The mesh size was 6343 nodes with a mesh size of 1.03715 mm. The shape of the specimen was designed according to the ISO standard mentioned, and it is shown in Fig. 1.

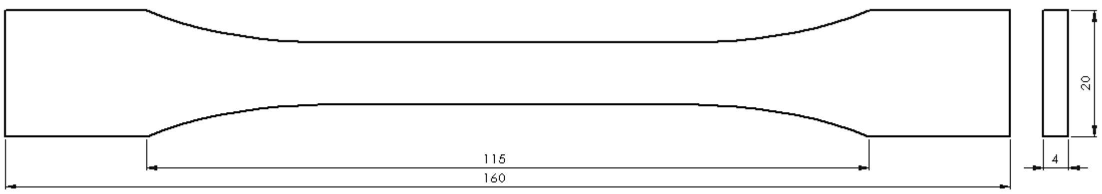

Fig. 1 Dimensions of the PET-G Carbon specimen

RESULTS AND DISCUSSION

The printing process began with the preparation of the G-code for the printer used. We have created 2 types of G-code for each variation (rectilinear infill with 0.15 mm and 0.3 mm layer height). After a series of 10 pieces was printed, the tensile test was done. The results of the measurements for specimens made with rectilinear infill pattern are shown in Fig. 2 and Fig. 3.

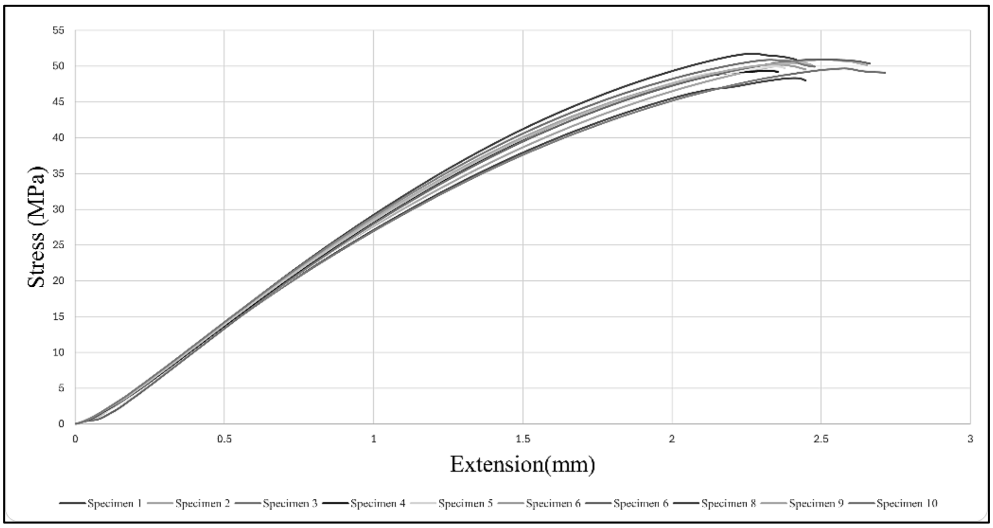

Fig. 2 Measured data from specimens made with 0.15 mm layer height

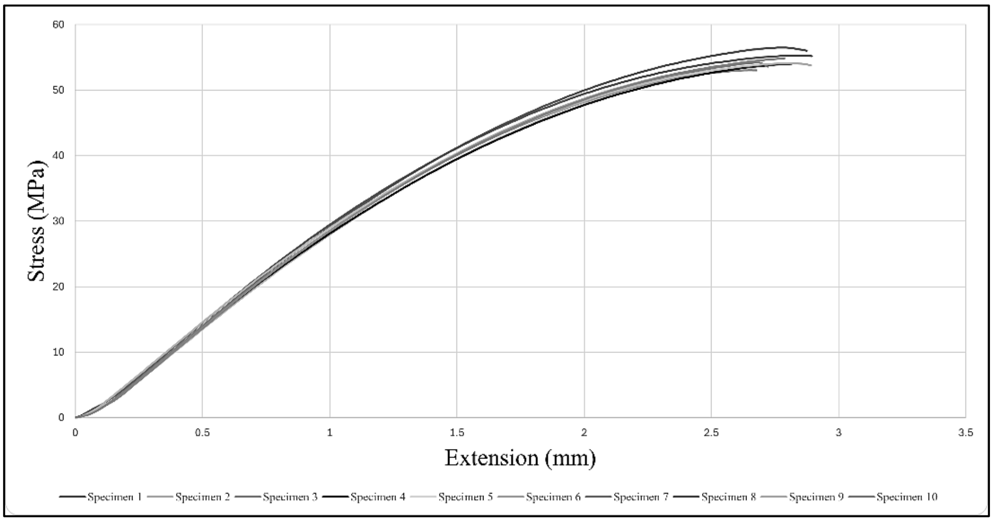

Fig. 3 Measured data from specimens made with 0.3 mm layer height

In Fig. 2 and Fig. 3 we can see the Stress – Extension dependence of the specimens made with rectilinear infill pattern. In both cases we can see that the maximal stress is below 55 MPa (50.247 MPa average for 0.15mm layer height and 54.309 MPa average for the 0.3 mm layer height). That means, the mechanical properties have been affected by the 3D printing process. In terms of numbers, the results are listed in Tab. 3.

Tab. 3 Average values of the measured mechanical properties for rectilinear infill pattern

Layer height mm	Stress during maximal force MPa	Tensile strength MPa	Yield strength MPa	Maximal force N
0.15	50.247	49.253	50.225	2105.41
0.3	54.309	52.981	54.286	2405.54

The measured data in Tab. 3 showed that the mechanical properties of the PET-G Carbon filament had been affected by the 3D printing process. Since the tensile strength of the material used is according to the material information provided by the producer only 45 MPa, it means that the 3D printing process had improved its mechanical properties. The amount of its change is listed in Tab. 4.

Tab. 4 Comparison of the average measured tensile strength with the basic value from the material properties

Infill pattern	Layer height mm	Tensile strength - measured MPa	Tensile strength - basic MPa	Difference %
Rectilinear	0.15 0.3	49.253 52.981	45	+9.45 +17.73

After the tensile tests were done, we started to focus on the FEA simulation. The experimental measurements had shown that the linear deformation area ends near 1000 N force according to the data in Tab. 3, the maximal force has reached approximately 2400 N. According to this data, the FEA simulation was done with forces between 1000 N and 2400 N with a 200 N step. The measured data from the FEA simulation is shown on Fig 4.

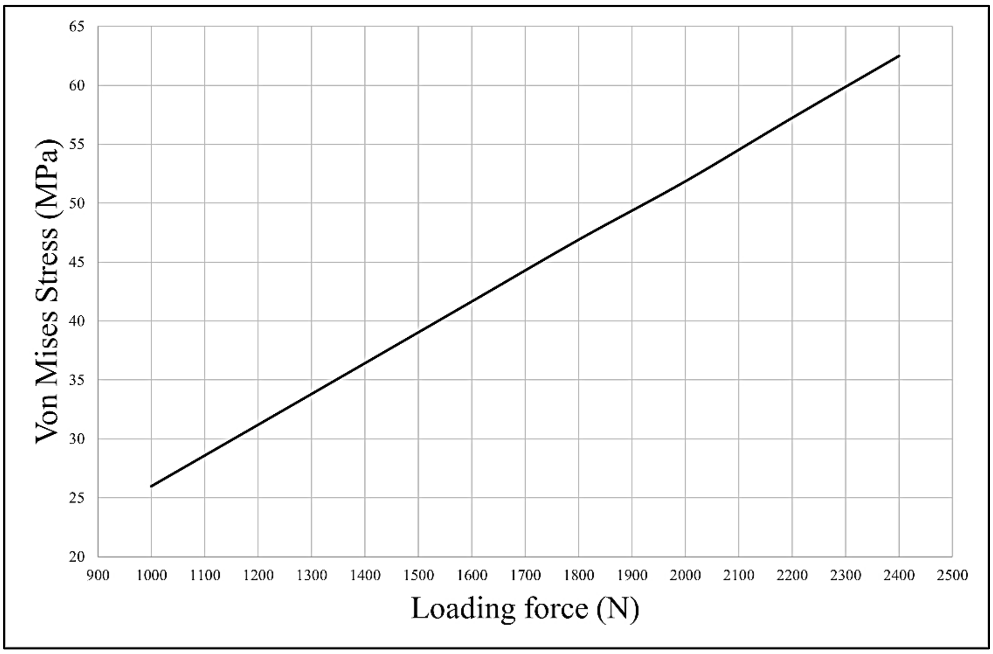

Fig. 4 Dependence of von Mises stress on force

From the results obtained from the FEA analysis (von Mises stress), we had to calculate von Mises stress of specimen loaded by maximal force during the real tensile test (equation 1).

$$VM_{F_M} = \frac{VM}{FL} \, . F_M \qquad (1)$$

where F_M is the maximal force reached during test (N), F_L is the loading force during the FEA analysis (N), VM is the von Mises stress in specimen loaded by F_L (MPa), VM_{FM} is the von Misses stress in specimen loaded by F_M (N).

In Tab. 5 the results from the simulation are shown compared to the results from the tensile tests. The results show that the difference between the measured tensile strength and the von Mises stress is relatively low. Results of the simulations are higher by 11.185 % in comparison to the 0.15 mm layer height and higher by 18.188 % in comparison to the 0.3 mm layer height.

Tab. 5 Comparison of the average tensile strength and the results from the simulations

Layer height mm	Tensile strength Mpa	Von Mises Stress Mpa	Difference %
0.15	49.253	54.762	+11.185
0.3	52.981	62.617	+18.188

Another parameter that was compared is the position of the break point. On the 3D printed specimens, the average measured distances were 43.73 mm for 0.15 mm layer height and 61.14 mm for 0.3 mm layer height. The distance was measured from the closed end of the specimen. A selection of the broken specimens are shown in Fig. 5.

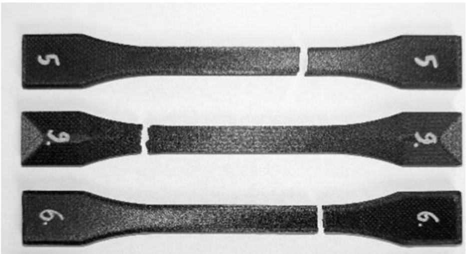

Fig. 5 Specimens broken after the tensile test

The result of the simulation at 2400 N loading force had shown that the maximum von Mises stress is 32.9 mm far from the center of the designed object. When we recalculate this distance, the simulation shows that the breaking point is 47.1 mm far from the closest end of the specimen. The percentual difference between the breaking point´s position in comparison to the tensile test is shown in Tab. 6.

Tab. 6 The percentual difference between the breaking point´s position in comparison to the tensile test

Layer height mm	Breaking point distance Mm	Breaking point distance – simulation mm	Difference %
0.15	43.73	47.1	+7.706
0.3	61.14		-22.964

The results in Tab. 6 have shown that the percentual differences are +7.706 % for the simulation compared to 0.15 mm layer height specimen and -22.964% for the simulation compared to 0.3 mm layer height specimen. The position of the breaking point in the FEA analysis is shown in Fig. 6.

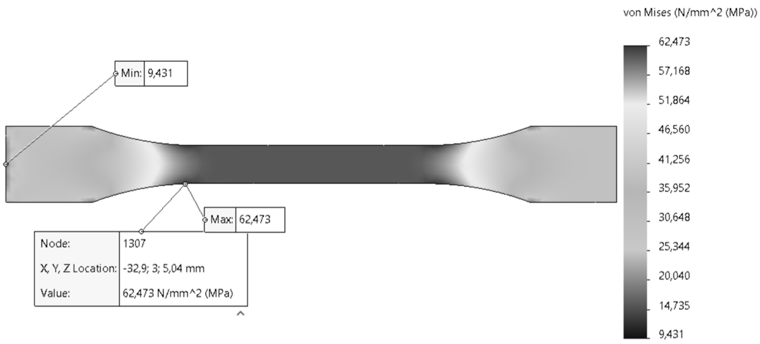

Fig. 5 The position of the breaking point in the FEA analysis

According to similar articles, where the authors have analyzed the mechanical properties of 3D printed specimens, there were similar results as we had. For example, *Bachhav et al. (2023*), in their article describe experimental properties of 3D printed parts made of ABS (Acrylonitrile butadiene styrene) material. Their results have shown that the difference between the FEA results and the tensile tests were between 21.22 % to 25.42%. *Catana et al. (2021)* also did research into the differences between simulation and experimental results but in this case, they did bend tests. According to their results, differences between simulation and experiment were also up to 10 %. Another research article written by *Taresh, Mezher & Daway (2023)*, describes that the mechanical properties of the 3D printed specimen had changed during the 3D printing process and it was most likely affected by the infill pattern and the infill density.

CONCLUSIONS

Our goal was to analyze and compare the tensile tests of a 3D printed PET-G Carbon specimen printed with different layer heights with the FEA analysis. The results showed that there is an increase in the tensile strength after the 3D printing process by +9.45 % for 0.15 mm layer height and +17.73% for 0.3 mm layer height. All the specimens were printed by 100 % infill density with rectilinear infill pattern. After tensile tests we created an FEA simulation, where the results showed very similar results. The deviation between the measured tensile strength and the tensile strength from the FEA simulation was only +11.185 % for the 0.15 mm layer height and +18.188 % for the 0.3 mm layer height. The last parameter that was compared is the distance of the breaking point. The results showed that FEA simulation results are nearly identical with the measured breaking point distance on specimens with 0.15 mm layer height. The lowest deviation was only +7.706 %. Finally, these results showed that the data from the FEA simulation can be used to analyze composite materials like PETG Carbon with relatively low deviation.

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