TENSILE TESTING AND FEA SIMULATION OF A 3D PRINTED ONYX SPECIMEN

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Abstract
Additive manufacturing is a relatively new process, so it needs many studies to be able to produce parts with the required properties. This is the reason why this domain has had a sustained development in recent decades. This paper is focused on the comparison between the mechanical properties of ONYX material determined by tensile testing and the results from a Finite Element Analysis (FEA). The use of simulation will allow a significant shortening of the design time of new structures. The application of FEA for the tensile testing of 3D printed specimens led to the results close to results obtained by the real tensile tests. Difference between the values obtained by real tensile tests and values obtained by simulation are up to 6.19%. The simulation was applied for the printed specimens from a single material. The results of applied FEA are close to results obtained by real testing.

Key words: *additive manufacturing, finite element analysis, tensile strength, nylon, simulation.*

INTRODUCTION

Nowadays additive manufacturing (AM) is used in many areas of production and development. The ASTM society defined AM as "the process of joining materials to produce objects from 3D model data, mostly layer by layer (*Kumar & Prasad, 2021*). AM originated in the 1980s. Initially, the use of AM was limited to the production of prototypes, due to the small choice of materials, mostly polymers. But today we can use AM for a wide range of materials from thermoplastics to metals, ceramics, composites and biocompatible materials. Recently mentioned materials include a composite material reinforced with a continuous fiber. With proper fiber distribution, objects can achieve the strength of aluminum castings (*Morgan, 2005; Kuncius, et al., 2021*). One of the main advantages of AM is the unlimited freedom of geometric shapes and the complexity of the created objects, which allows AM to match or even surpass conventional production technologies.

Fused deposition modeling (FDM) is the most commonly used AM technology (*Kuncius, et al., 2021*). FDM creates objects by extruding molten plastic layers. The material in the form of a thin fiber is fed to an extruder, where the material is melted and extruded through a nozzle onto the surface of the object (*Madaj & Kohár, 2020*). The mechanical properties of composites produced by FDM are worse than the mechanical properties produced by injection molding. The main reason is the insufficient bonding between individual layers and also; there is high porosity and residual stress (*Jain, et al., 2022*).

A large variation in the mechanical properties of 3D printed polymers has promoted designers to develop simulation strategies for the prediction of mechanical properties of 3D printed objects. Several testing techniques are generally used to determine the mechanical properties of a material. The most common mechanical tests include a uniaxial compression test, a plane-strain compression test, and a uniaxial tensile test. The uniaxial tensile test is the most commonly used mechanical test, providing accurate values of key mechanical parameters such as Young's modulus, yield strength, ultimate tensile strength, elongation at break and Poisson's ratio (*Kalova, et al., 2021; Majko, et al., 2019*). *Provaggi et al. (2019)* recently employed finite element analysis (FEA) to predict mechanical properties of 3D printed polymers under compression and concluded that inputs provided by FEA could be potentially useful for reducing product design and development time. The aim of the study was verification of material parameters by comparing simulation results and real experiment results.

MATERIALS AND METHODS

For our research we have used a Markforged Mark Two 3D printer. This 3D printer offers continuous fiber fabrication (CFF) process. Printer has two nozzles, first for plastic material called Onyx and second for continuous fiber. The printer builds the matrix from Onyx and irons down continuous strands of fibers into the part. The fibers are impregnated with nylon and are fused to the Onyx layer. Printing parameters are shown in Tab. 1.

Tab. 1 Printing parameters

Parameter	Value
Print temperature (°C)	275
Layer height (mm)	0.125
Nozzle size (mm)	0.4
Infill	solid
Number of perimeters	2

Markforged Onyx was used for manufacturing of specimens. Onyx is a micro carbon fiber filled nylon. It is 1.4 times stronger and stiffer than ABS and can be reinforced with any continuous fiber from Markforged. Mechanical properties of the Onyx material are shown in Tab. 2.

Tab. 2 Mechanical properties of Markforged Onyx

Property	Testing method (ASTM)	Typical value
Tensile Modulus (GPa)	D638	2.4
Tensile stress at Yield (MPa)	D638	40
Tensile stress at Break (MPa)	D638	37
Tensile strain at Break (%)	D638	25
Flexural Strength (MPa)	D790	71
Flexural Modulus (GPa)	D790	3.0
Heat Deflection Temp (°C)	D648 B	145
Izod Impact - notched ($J.m^{-2}$)	D256-10 A	330
Density ($g.cm^{-3}$)		1.2

Tensile tests were performed in accredited laboratory VÚSAPL, a.s., Nitra. For tensile tests we used a MTS Exceed E43.104 universal tensile testing machine with maximal force 10 kN. Tests were performed according to ISO 527-1 and ISO 527-2 standards. Total number of specimens was 5. Speed rate was set to $1 mm.min^{-1}$. Shape and dimensions of test specimens are shown in the Fig. 1.
For finite element analysis (FEA) we used Solidworks 2020 software. Despite on the fact infill value was 100%, in the FEA it was considered that the specimen was working like a single block and has the same properties in the entire volume. We have used an ONYX plasticity model for the simulation where a curvature-based mesh was applied. Mesh type was Solid Mesh and we used triangles (tetrahedrons) type of elements. The mesh consists of 13195 nodes with mesh size of 1.03714614 mm with a 1.4 ratio of a/b.

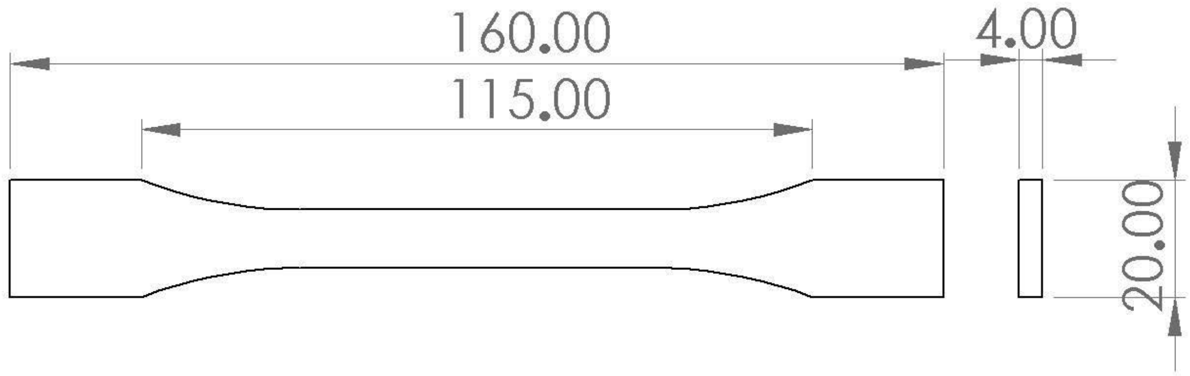

Fig. 1 Specimen shape and dimensions

RESULTS AND DISCUSSION

All specimens were printed at the same time, so ambient conditions were the same. Nylon is hygroscopic and it can absorb moisture from air. Humidity absorbed in nylon can influence mechanical properties of material (*Zhou, et al., 2001*). Due to this fact tensile tests were performed in short time after specimens were printed. Tensile tests allowed us to obtain values of tensile strength and values of maximal force. In the next step, the FEA analysis was performed. Specimens were loaded by forces from 1000 N to 2000 N with 100 N steps. From results obtained from FEA analysis we created a dependence of von Mises stress on force (see Fig. 2.). As we can see this dependence is linear. Based on this fact equation (1) was used to calculate von Mises stress of specimen loaded by maximal force reached during the test.

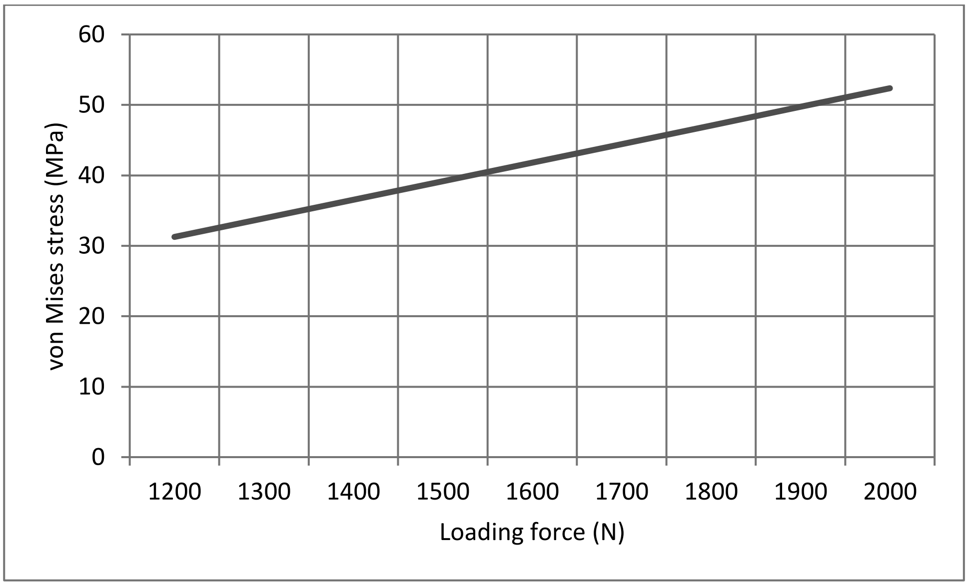

Fig. 2 Dependence of von Mises stress on force

$$VM_{F_M} = \frac{F_L}{VM} \cdot F_M \quad (1)$$

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_{F_M} is the von Misses stress in specimen loaded by F_M (N).

In the Tab. 3 are shown the results of the tensile tests, but also the results obtained by the simulation. The results consist of the maximal force reached during tensile test for each specimen, of the tensile strength for each specimen and of the von Mises stress under load with maximal force. We can clearly see that the difference between experiment result and simulation is low. Results of the simulation are up to 6.19% higher than results of tests. This fact indicates that model is designed in the right way and material parameters are right too.

Tab. 3 Results of tensile tests and FEA analysis

Speci-men number	Maxi-mum force N	Tensile strength MPa	von Mises stress MPa
1	1377.03	34.50	35.92
2	1427.60	35.07	37.24
3	1390.57	34.72	36.27
4	1454.76	36.16	37.94
5	1429.52	35.56	37.29

In the Fig. 3 is shown the result of the simulation under 1400 N load. Specimens after tensile tests are shown in the Fig. 4. If we look closer to both figures, it can be clearly seen that area with maximal von Mises stress and area of real break corresponds. Even every specimen was broken at the same area. This indicates that we can use 3D printing for manufacturing series of parts with the almost the same properties.

Fig. 3 Result of the simulation with load force 1400 N

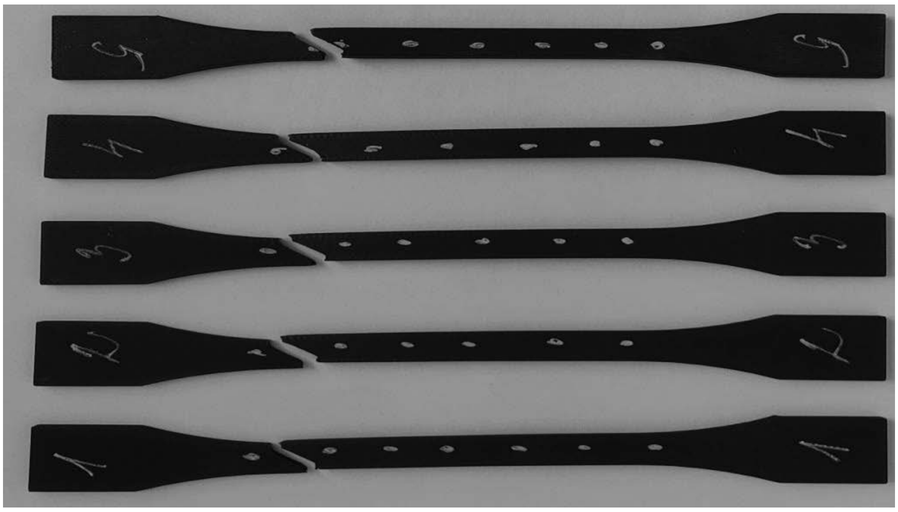

Fig. 4 Specimens after tensile tests

Some authors have done similar researches but they used other material, mostly PLA. We focused on Markforged Onyx material. For example (*Catana & Mihai, 2020*) were comparing results of experiment with results obtained by simulation. They had similar results and the deviation was between 4.7% and 7.2%. *Catana et al. (2021)* also studied the differences between simulation and experimental result but in this case they did bending tests. Despite this fact, differences between simulation and experiment were also up to 10 %. *Alhabri et al. (2020)* studied tensile strength of PLA. They used specimens with different dimensions, but they used the same software Solidworks as we used. They also had similar results, where the deviation of tensile strength was up to 6.7%. Also authors like *Mouti et al. (2011)* or *López et al. (2017)*, who used different testing methods in their researches, had similar differences between experiment and simulation results. All these authors used material properties for simulation obtained from experimental tests of 3D prints. Material properties we used for simulation were from the datasheet of Onyx material. Nevertheless our results almost correspond to results from authors mentioned above. This can be caused by fact that Markforged has closed system. Also, in a Markforged printer you can use material only from Markforged and the printer does not have option to change key printing parameter like printing temperature. Marforged has printing parameters set exactly to their materials, so quality of 3D prints is on high level and properties of 3D prints almost reach properties of filament.

CONCLUSIONS

We can conclude that the simulation process can be applied to 3D printed objects with good results. The results obtained from the simulation are in a line with the results obtained from real tensile tests, but it should be emphasized that their accuracy depends on the model used in the simulation process and how accurately it describes the 3D-printed structure. In this research were used specimens with 100% infill. They had the same properties in whole volume and they work like single block. Tensile tests results were consistent and the standard deviation was 0.67. This corresponds with fact that the technology of 3D printing has potential to repeatedly manufacture parts with the same mechanical properties. Results obtained by the FEA analysis in comparison to the real tests have only small deviation from 4.12% to 6.19% from results obtained by experiment.

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