Determination of the influence of infill pattern and fiberglass reinforcement on the tensile properties of additively manufactured material by FDM technology

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Abstract: FDM technology is among the most widely used additive manufacturing technologies. The most popular materials are ABS and PLA, but lately nylon has been used more often. The aim of the paper is to determine the impact of infill pattern and continuous fiberglass reinforcement on the tensile properties of additively manufactured composite material. The samples were made of onyx as matrix material on a Markforged Onyx Pro printer, without and with varying fiberglass volume fraction. In addition, five different infill patterns (solid, triangular, quadrilateral, hexagonal and gyroid) were investigated. The experimental results revealed that infill patterns have different effects on the tensile strength and elastic behavior of the material, but the consumption of material and time should also be considered. The use of continuous fiberglass reinforcement significantly improves the tensile characteristics of the material. Proper arrangement of fibers in multiple layers can give better tensile properties of the material.

1. Introduction

In modern industry, additive manufacturing (AM) occupies an important place, both in terms of classical technologies (repair surfacing [1,2]), and in the case of new technologies, in the application of rapid prototyping and tooling using AM techniques [5-6] .

Additive manufacturing enables high-quality and efficient production of customized products with sophisticated shapes and new materials, which are difficult to produce with traditional production. In addition, it is possible to analyze the functionality of the product within the assembly, check the design solution, carry out ergonomic and other functional tests. Currently, several industrial sectors (automotive, aerospace, biomedical, etc.) are adopting additive manufacturing principles and applying various AM methods and systems to increase flexibility and individualization of manufacturing processes.

In order to categorize various AM systems, the ISO DIS 17296-1 standard [7] was adopted, which provides definitions of AM terms and classifies all AM technologies into 7 groups: Binder jetting processes – BJT, Directed energy deposition – DED, Material extrusion – MEX, Material jetting – MJT, Powder bed fusion – PBF, Sheet lamination – SHL, and Vat photopolymerization – VPP. Fused deposition modeling (FDM) belongs to the category of MEX technologies.

Each of the mentioned AM categories is characterized by an appropriate selection of different types of materials: plastic, metal, ceramics and sand powder. The application of polymers in AM is the most common, and ABS, PLA, resins and nylon are leading in this [8].

In order to meet the requirements for the production of functional parts with satisfactory exploitation characteristics, composite materials, such as the commercially available Onyx [9], are increasingly being used. It is a specially tuned PA6 copolymer filament (polyamide, nylon) with a chopped carbon fiber blend, which is 1.4 times stronger and stiffer than ABS. Compared to nylon (PA11), it has even 2.5 times higher flexural strength and 3 times higher resistance to temperature deflection [9]. It can be used to print parts independently or combined with reinforcing fibers (carbon, glass, Kevlar) to obtain printed parts similar to aluminum ones.

Additive manufacturing is based on layer-by-layer production, so it is ideal for making parts of complex geometries from composite materials with appropriate topological optimization and adaptation of the composite structure to the operational loads of the part. The use of composite materials in additive manufacturing is the subject of numerous studies with the aim of determining the mechanical characteristics of the material and giving recommendations for various applications in production.

In the paper [10], research on the influence of reinforcing fibers on the tensile characteristics of the printed composite is presented. The samples were printed according to standard D638 with short carbon fibers (SCF), with a fiber content of 20% and continuous carbon fibers (CCF) with 5% fibers. The results showed that the tensile strength and elasticity modulus were significantly higher for nylon reinforced with continuous carbon fibers (145MRa, 13.45GPa) than with short once (78Mpa, 5.91GPa) even though the percentage of carbon was higher.

The mechanical characteristics of nylon 66 reinforced with chopped carbon fibers can be evaluated analytically using the rule of mixture [11]. Based on the values of the characteristics of the matrix material and reinforcing fibers, it is possible to estimate the tensile, compressive and flexural composite properties, as well as the value of the Poisson's coefficient. Prediction of elastic characteristics (elasticity modulus) of printed samples reinforced with fibers (carbon, glass, Kevlar) in different volume fractions using this analytical approach was also used in the study [12]. In addition, mechanical tests and microstructural analyzes of composite layers were performed, so in combination with analytical predictions, a mathematical model was recommended for determining the modulus of elasticity of printed composites.

The influence of printing orientation, filling density and temperature on the mechanical characteristics of samples made of onyx is the subject of the study [13]. The samples were printed with hexagonal, rectangular and triangular filling structure, and as a solid sample. In the experiments, the filling density (30% and 50%) as well as the printing orientation were varied. It has been shown that the best mechanical characteristics are achieved for the square structure of the infill, and that the thermal treatment of the samples leads to certain improvements of the basic printed material. Similar conclusions were reached by the authors of the paper [14], who, in addition to the analysis of the infill pattern (triangular, rectangular, hexagonal), and infill density (40%, 60% and 80%), also took into account the influence of the layer thickness. It has been shown that a smaller layer thickness gives improved material characteristics due to better adhesion.

Reinforcing fibers also have an influence on the flexural strength of the printed material, as shown in [15]. Nylon samples reinforced with carbon and glass fibers were investigated by bending test. The highest flexural strength and modulus of elasticity were achieved for glass fiber reinforced samples at 0˚ print orientation.

The results of determining the impact of reinforcement with chopped carbon fibers and the use of continuous fibers are presented in the paper [16]. Samples of nylon and onyx are made with triangular and rectangular filling structure and density of 10% and 70%. Experiments revealed that onyx has better mechanical characteristics than nylon, but also less ductility, which is all a consequence of the presence of chopped carbon fibers in this composite material. By using continuous carbon fibers, several times higher values of tensile strength and elasticity modulus are obtained, and it was concluded that an increase in the fraction of reinforcing fibers has a positive effect on the tensile characteristics of the material.

Reinforcement of the composite with fibers is possible in two ways, by placing concentric rings of continuous fibers in the desired proportion and arrangement, or by isotropic reinforcement of the selected zone of the sample. In order to evaluate the tensile characteristics of the samples reinforced in these two ways, and to monitor the influence of the fiber volume fraction, a study was conducted, the results of which are presented in the paper [17]. Experimental results prove that the application of concentric continuous reinforcing fibers provides greater flexural strength and energy absorption capacity than those with isotropic fiber distribution.

By reviewing the reference literature, it is evident that the effects of reinforcing the composite printed material with glass fibers have not been sufficiently investigated, considering the effects of different infill patterns with the recommended infill density. Therefore, the aim of this study is to investigate the effect of infill pattern variation on the tensile strength of the onyx composite material at a constant infill density of 37%. In the second part of the experimental research, the tensile characteristics of this material were determined by applying reinforcement with continuous fiberglass, with different volume fractions, obtained by varying the number of rings and layers.

2. Experimental procedures

2.1 Materials and specimen preparation

For this rstudy, the composite Onix material was used, which as the basic material has nylon with added chopped micro carbon fibers, manufactured and trademarked by Markforged. All samples were prepared from the same lot, from filament that was protected from moisture in a Dry Box. The printed samples were tested only a few days after printing, in order to eliminate the influence of moisture from the air on the characteristics of the material.

Markforged printers can, in addition to this basic composite as filament, which is extruded by the classic FDM process, use continuous fibers that the second printing head in the extrusion system places continuously along the positions selected in the Eiger software. The distribution of reinforcing fibers can be with concentric paths of continuous fibers, chosen by the user, or with a uni-directional arrangement of reinforcement of a certain zone in a model with a higher volume fraction of continuous fibers. Carbon, glass or Kevlar fibers can be used to reinforce additively manufactured parts. In Table 1, the characteristics of Onix and reinforcing fibers, reported by Markforged [18], are given.

Table 1. Material properties of Onix and continuous fibers [18]

	Onyx	Fiberglass	Carbon	Kevlar
Elasticity Modulus (GPa)	2.4	21	60	27
Tensile Strength (MPa)	40	590	800	610
Tensile Strain at Break (%)	25	3,8	1.5	2.7
Flexural Strenght (MPa)	71	200	540	240
Heat Deflection Temp (°C)	145	105	105	105
Density (g/cm3)	1.2	1.5	1.4	1.2

Tensile tests were performed according to the ASTM D638-14 (Type IV) standard, using specimens with a thickness of 3.2mm. The 3D model of the sample was modeled in CAD software CATIA, which was exported in STL format for printing, with the orientation shown in Fig.1. Three specimens were tested for each experiment in the research plan.

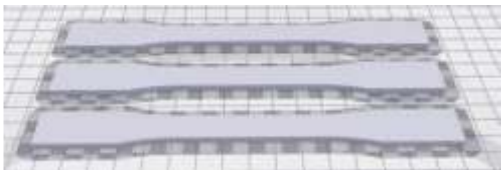


Fig. 1. Specimen model and printing orientation

A Markforged Onyx Pro 3D printer was used for printing the specimens, and the model setting and selection of printing parameters was realized using the Eiger software-as-service in the cloud. Eiger is not only slicing software but a comprehensive solution to support part design and optimization of printing conditions. Selected specimen printing parameters for all experiments in this study are shown in Table 2.

For the first experimental set, samples were prepared with all offered infill patterns in Eiger (triangular, hexagonal, rectangular, gyroid, solid). Samples for the second experimental set were prepared reinforced with continuous glass fibers, varying the number of concentric rings (R) and layers (L), as shown in Table 2. Fig. 2 shows printed onyx samples with a triangular infill.

Table 2. Specimen printing parameters and variations

Specimen geometry variable	Value
Test specimen	ASTM D638-14 (Type1)
Specimen height, mm	57
Specimen width, mm	13
Specimen thickness, mm	3.2
Stacking order direction	Z
Nozzle temperature (Onyx)	272 °C
Nozzle temperature (Glass fiber)	252 °C
Layer thickness, mm	0.1
Infill pattern	triangular, hexagonal, rectangular, gyroid and solid)
Infill density	37% (recommended by MF)
Raster angle	45° / -45°
Floor layers	4
Roof layers	4
Side wall layers	2
Total number of layers	32
Use of brim	Yes
Only for reinforced specimens with fiberglass	
Fiber fill type	Concentric
Infill layers	22, 20, 18
Fiber layers (L),	2, 4, 6
Concentric fiber rings (R)	2, 4

Fig. 2. Printed specimens

2.3 Infill patern variance

The influence of the infill pattern as lattice structures within the specimens on the mechanical characteristics was examined with the variation of all infill types offered by the Eiger software (triangular, hexagonal, rectangular, gyroid, and solid). An identical infill density of 37%, recommended by the manufacturer, was applied to all specimens, so that only the influence of the infill pattern on the behavior of the composite material with a lattice structure could be investigated. In order to compare the values of the applied patterns, specimens with maximum density, i.e. solid infill (100%), were also tested. Fig. 3 shows the four mentioned infill structures. The specimenss were printed with the same printing orientation, when the longer side of the specimen is parallel to the x-axis of the table, and in a laid-down state (as in Fig. 1.). A total of 12 samples were prepared, three samples for each considered case.

As for the infill pattern, triangular is recommended by the manufacturer as the strongest infill that offers fairly uniform properties of the parts in both horizontal directions of the model (X-Y plane). It is also one of the best infill choices when applying continuous fiber reinforcement (CFR).

Hexagonal infill structure has the highest strength-to-weight (S/W) ratio of any infill pattern, and has a positive impact on reduced part weight, and part printing cost and time.

Rectangular infill patern produces a grid-like pattern by alternating parallel and normal extrusion directions in the print layers. This filling gives good mechanical properties only at an infill density higher than 60%.

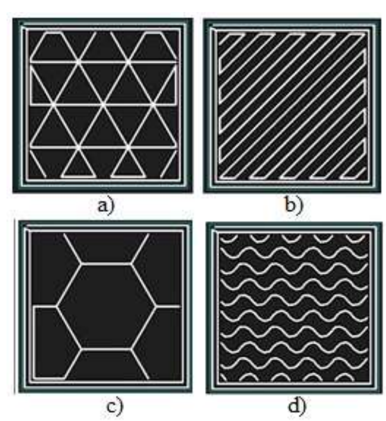


Fig. 3. Tested variations of infill pattern a) triangular b) rectangular c) hexagonal d) gyroid

The newest type of infill is the gyroid, which consists of rotating two-dimensional waves characterized by a high strength-to-mass ratio, especially when the part is subjected to shear loads. It has approximately isotropic properties and is suitable for parts exposed to bending because it has good shear resistance.

In order to establish the relationship between the tensile strength of the printed material and the total mass of the specimen (S/W), the mass of all printed specimens was measured. The printing time was also registered for further cost analysis and recommendations for the choice of infill pattern. The data are presented in Table 3.

Table 3. Specimen mass and printing time

Infill pattern	Mass (g)	Time (min)
Solid specimen	9,14	104
Triangular	5,81	77
Rectangular	6,69	83
Hexagonal	4,48	70
Gyroid	5,94	89

2.3 Fiberglass reinforcement variance

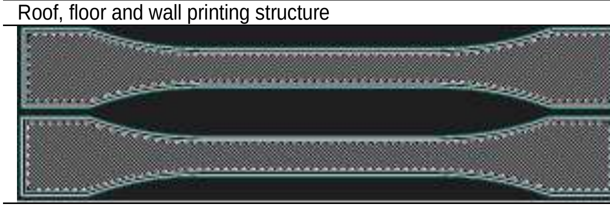
Reinforcement of printed materials with fibers implies the use of two materials in the 3D printing process, i.e. continuous reinforcing fibers and matrix polymer, which are joined during printing. In this study, glassfiber with a thickness of 0.3mm was used, which were printed simultaneously with onyx as matrix material using FDM technology.

In order to examine the influence of the application of continuous glassfiber reinforcement on the mechanical properties of the composite onyx material, all samples for this set of experiments were made according to the data given in Table 2, with a triangular shape infill patern and a recommended density of 37% [9]. The fiber volume fraction in the basic onyx material was varied by changing the number of concentric rings (2, 4) and layers (2, 4 and 6). The number of reinforcing concentric rings is limited by the geometry of the specimen (gauge section width is 13 mm), thus the maximum number of rings is four. There is a possibility of strengthening 28 layers ((two layers for the roof and two for the floor cannot be reinforced) but due to the optimization of the printing time and material consumption, the three specified values of the varied layers were chosen (2, 4 and 6). Due to the reproducibility of the results, three specimens were printed for each combination of parameters (RxLy). Roof, floor and wall printing structure for the Markforged printer is predefined and unchangeable, as a rectangular infill of 100% density (solid), with alternately changing raster angle ±45° in each of the layers. All other layers were printed with triangular infill, with the addition of continuous fiberglass according to the plan of the experiments, in the layers above the floor and below the roof. The presentation of the characteristic layers of the printed structure of those specimens is shown in Table 4.

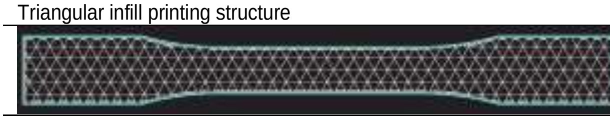
After printing, the mass of each sample was measured, which is denoted by RxLy, where x indicates the number of rings and y the number of reinforcement layers, and the values are shown in Table 5, in order to calculate the S/W ratio. Material consumption data (cm^3) for onyx and glassfiber used were taken from the Eiger software after printing. Fiber volume fraction in the specimens (FVF) was calculated for the entire specimen based on the Eiger consumption of fiberglass and onyx, expressed as a percentage. However, bearing in mind that for the tension test only the measurements on the gauge section of the specimen are relevant, for the analysis and final considerations the FVF calculation methodology presented in the paper [12] will be taken into account. Therefore, the FVF values shown in the last column of the Table 5 are calculated as the ratio of the volume of reinforcing fibers on the measuring section (57x13x3.2mm) and the total volume of that section. As for the previous set of experiments, the printing time was recorded for these specimens, shown in the table.

Table 4. Printing structure for continuous glassfiber reinforced specimen

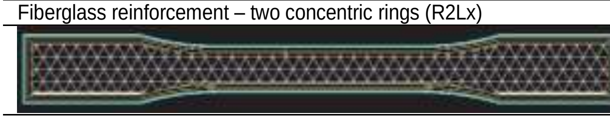
Roof, floor and wall printing structure



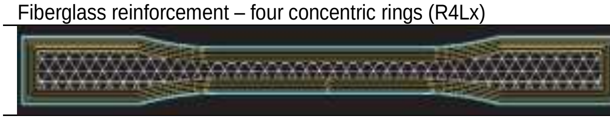
Triangular infill printing structure



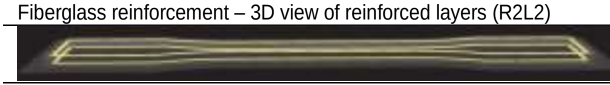
Fiberglass reinforcement – two concentric rings (R2Lx)



Fiberglass reinforcement – four concentric rings (R4Lx)



Fiberglass reinforcement – 3D view of reinforced layers (R2L2)



Fiberglass reinforcement – 3D view of reinforced layers (R4L6)

Table 5. Mass, consumption and FVF for reinforced specimens

Continuous fiberglass reinforcement	Mass (g)	Consumption, (cm3)		FVF, specimen (%)	FVF at gauge section, (%)	Time (min)
		onyx	fiber			
without reinforcement	6,69	5,26				77
R2L2	6,6	7,47	0,13	1,71	1,36	92
R2L4	6,71	7,43	0,26	3,38	2,72	93
R2L6	7,04	7,39	0,38	4,89	4,08	94
R4L2	6,93	7,70	0,25	3,14	2,72	92
R4L4	6,97	7,61	0,5	6,17	5,43	94
R4L6	7,35	7,52	0,75	9,07	8,15	97

2.4 Tensile testing equipment and conditions

Tensile tests were carried out on a universal material testing machine ZWICK/Roell Z100, with a displacement-controlled loading rate of 1.3 mm/min, according to the standard (Fig.4). Automatic data acquisition and processing is enabled by testXpert software, with a data acquisition speed of 500Hz. A ceramic extensometer in the range of 11-50mm is used to measure elongation, which facilitates direct measurement of change in the length of specimen. All tests were conducted at room temperature of 23℃. The testing machine enables pneumatic clamping of the specimen with adjustable clamping force (2-2,5 bar).

Fig. 4. Testing machine Zwick/Roell Z100

The test parameters and data on the used test equipment are given in Table 6.

Table 6. Testing equipment and parameters

Testing machine	Zwick/Roell Z100
Nominal load	100kN
Force measurement accuracy	1N
Test speed (this study)	1.3 mm/min
Clamping pressure	2-2.5 bar
Initial measurement length of extensometer	11-50 mm
Testing software	testXpert
Data acquisition speed	500Hz
Positioning accuracy	±2 µm
Testing temperature	23°C

3. Results and disscusion

3.1 Influence of infill paterns

In the case of specimens printed only from onyx, with varying infill patterns, but without reinforcement, a significant elongation of the specimen was achieved until the moment of breaking, but high elastic recovery is also noticeable. In Fig. 5, two separated parts of the broken specimen in the machine grips and the distance between them can be seen, caused by the large elastic recovery after breaking. The same picture shows three samples with triangular infill after breaking by tensile test.

The computer-controlled ZWICK/Roell testing machine enables automatic data acquisition, in this case forming load and displacement values. Based on the collected test data, the engineering stress (MPa) and strain (%) are calculated. Fig. 6 shows the stress-strain curves for five variants of the infill pattern, where the first one refers to a solid structure (100% density). TestXpert software determines tensile stress at yield by fitting the curve to a parallel line with offset 0.2% strain. The maximum value of the calculated engineering stress represents the ultimate tensile strength, for which the strain at maximum tensile stress is taken from pairs of experimental data values. In the same way, strain at break values were also taken for all tested specimens, which serve to evaluate the ductility of the printed material. The modulus of elasticity is calculated as the ratio of stress and strain in two selected points of the linear part of the curve, but in which the stress is lower than the tensile stress at yield. Table 7 shows the results of this set of experiments with relevant values for the characterization of the printed material.

Fig. 5. Broken specimen in the machine grips (left) and three specimens after tensile test (right)

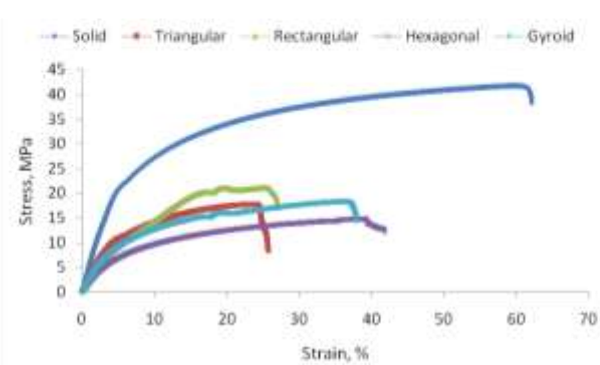


Fig. 6. Strees-straing curves for solid onyx specimen and specimens with different infill paterns

Table 7. Experimental results for infill patern variance

Infill pattern	Yield stress (MPa)	Ultimate Strenght (MPa)	S/W ratio	Strain at maximum stress (%)	Strain at break, %	E, MPa
Solid	16,7	40,96	4,48	60,23	62,11	516,47
Triangular	8,48	17,66	3,04	23,17	25,67	289,13
Rectangular	13,83	21,25	3,18	25,11	26,94	254,72
Hexagonal	13,48	14,19	3,17	38,34	41,85	185,79
Gyroid	13,81	18,22	3,07	35,25	37,91	223,63

Experimental results reveal that printing parts with solid infill have the best mechanical characteristics (ultimate strength is 40.96MPa), and the highest ductility since the strain at break is 62.11%. Although this infill has the highest material consumption and specimen mass, even twice as much as the hexagonal infill, and in addition the printing time is 48% longer, the S/W ratio is the highest for samples with this 100% infill density (Fig.7). Due to the printing costs, it is reasonable to apply this infill in cases where good strength of the part is required and when subsequent processing by cutting is necessary, without fear that the lattice structure of the infill can be reached.

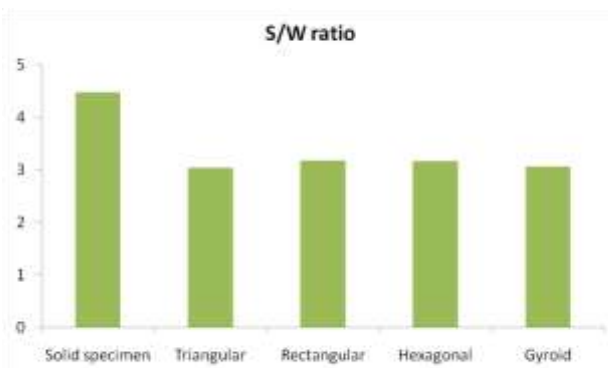


Fig. 7. S/W ration for different infill paterns

After this infill patern, the rectangular type gives the best strength (21.25 MPa), but compared to the triangular and hexagonal filling (Table 3), it has a significantly higher consumption of material and time for printing, at the same infill density of 37%.

The choice of hexagonal filling is rational when taking into account the printing costs and if the parts are not subjected to heavy exploitation, because the tensile strength is the lowest (14.19MPa). On the other hand, this type of infill has the highest ductility if the solid specimen is excluded (strain at break is 41.85%).

The new type of infill offered by Markforged, gyroid, also has increased ductility and slightly higher strength than hexagonal, but requires the longest printing time compared to other infill patterns with a density of 37%.

Triangular infill has the lowest S/W ratio, the lowest stress at yield (8.48MPa) and the lowest strain at break (25.67%), for the applied infill density. However, this type of infill patern is recommended by Markforged, because it gives almost isotropic material characteristics in the printing plane, as the triangles are more compact than all other types of lattice. In addition, the printing time is less compared to rectangular and gyroid paterns. It is ideal as a infill when reinforcing the material with continuous fibers, which improves the mechanical characteristics, at optimal printing costs. In addition, this patern gives the material with the highest modulus of elasticity (289.13MPa), if the solid filling is excluded from comparison (516.47MPa) (Fig. 8).

3.2 Influence of fiberglass reinforcement

The procedure of acquisition and processing of experimental data is the same as in the first experimental set, described previously. Fig. 9 shows the stress-strain curves for the tested specimens that were reinforced with continuous fiberglass in 2, 4 and 6 layers, with 2 concentric rings (a) and four concentric rings (b). In addition to these curves, the stress-strain curve for a specimen printed from onyx with a triangular infill and a density of 37% is shown in the diagrams for comparison.

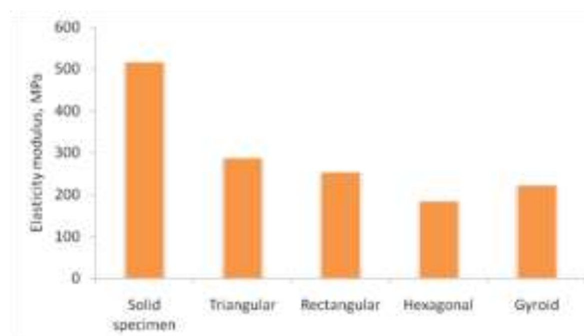


Fig. 8. Elasticity modulus for different infill patterns

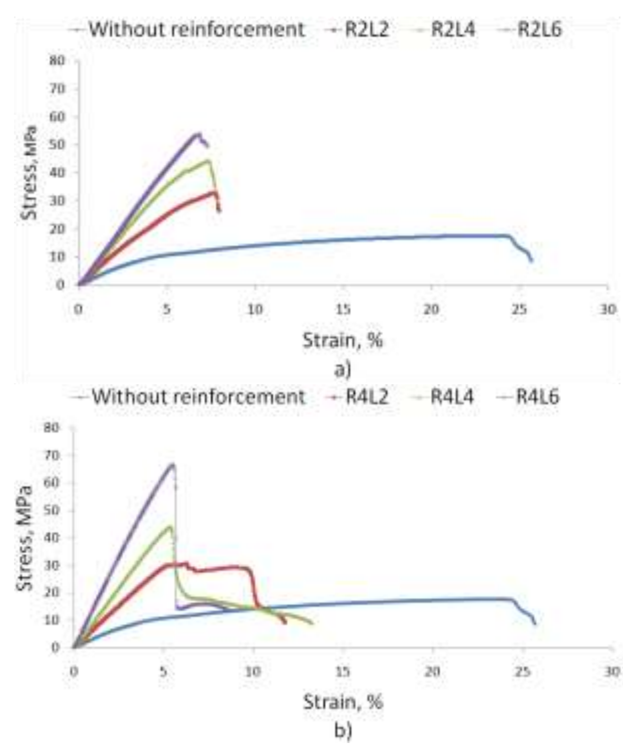


Fig.9. Stress-strain curves for reinforced specimens with a) 2 rings и b) 4 rings, compared to onyx specimen withot reinforcement

The mechanical characteristics for those specimens (RxLy) are shown in Table 8. Determination of the value of strain at break in specimens reinforced with fiberglass is not simple, and there is no rule to reach a general conclusion about the trend of these values according to the fiber volume fraction of glass fibers in matrix material. The reason for this is that the glass fibers break during tension successively, in different rings or layers. Unlike metal or non-fiber-reinforced composite polymer, the course of the curve and the moment of failure after reaching the maximum stress of the material are predictable and repeatable. This is not the case with glass fibers. Therefore, this makes it impossible to explicitly introduce strain at break data into the experimental results. In this set of experiments, only the strain at the moment of reaching the maximum stress, before fracture, will be monitored.

Table 8. Experimental results for reinforcement variance

Specimen	Yield stress (MPa)	Ultimate strength (MPa)	S/W ratio	Strain at maximum stress (%)	E, MPa
without reinforcement	8,48	17,66	2,64	23,17	289,13
R2L2	24,46	32,69	4,95	7,74	555,86
R2L4	27,37	42,63	6,35	7,31	731,43
R2L6	32,48	52,81	7,50	6,61	823,57
R4L2	28,56	31,49	4,54	6,28	613,41
R4L4	39,60	48,10	6,90	5,43	875,35
R4L6	51,04	69,23	9,42	5,47	1376,58

It is evident that tensile strength and ductility depend on the level of reinforcement, that is, the concentration of fiberglass, expressed through FVF. A trend of increasing strength and decreasing ductility was observed when the fiberglass volume fraction increased.

In relation to the specimen of onyx material that was printed with triangular infill and density of 37%, where the tensile strength value is 17.66MRa, the maximum value of 69.23MRa was achieved for the reinforced specimen R4L6, where the FVF is 8.15 %. If the S/W ratio is observed, there is a multiple increase of that value compared to the unreinforced specimen (2.64), up to a maximum value of 9.42 for R4L6.

Many times higher values of yield stress and ultimate strength using continuous fiberglass are an indication that parts printed with fiber reinforcement can withstand significantly higher loads during exploitation and functional testing without deformation, even with such a small FVF. However, it should be borne in mind that such reinforced parts reach the maximum allowable stress at significantly lower strains and after that brittle fracture occurs very quickly, because they have very little ductility. Strain at maximum stress in the reinforced sample was in the range from 5.43% to 7.74%, while in the sample without fiber reinforcement, the strain was 23.17%.

The increase in the value of the modulus of elasticity, with the increase in the fiber volume fraction in the composite, just confirms the above, that at relatively small strains, a higher stress value is quickly reached (Fig. 10). There is very little room for plastic deformation from the yielding stage to failure.

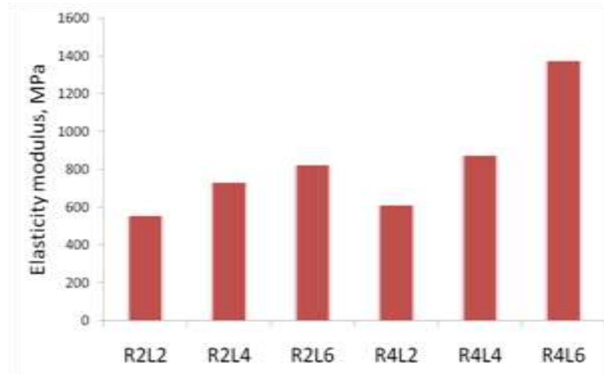


Fig. 10. Modulus of elasticity for various glassfiber reinforcements

By comparing specimens R2L4 and R4L2, which have an identical fiber volume fraction (FVF= 2.72%), it is noticeable that the tensile strength value in the first case is 42.63MRa and in the second 31.49MRa, and thus the S/W ratio is more favorable for R2L4 specimen. This means that with the same consumption of fiberglass, that are arranged in more layers and less concentric rings, better strength is achieved, and at the same time, a higher strain at break also, which means better ductility. If the values of the modulus of elasticity for these two cases are analyzed, the value of the modulus of elasticity is again higher for R2L4 (731.43MPa instead of 613.41MPa for R4L2). Such trends can be shown graphically as in Fig. 11.

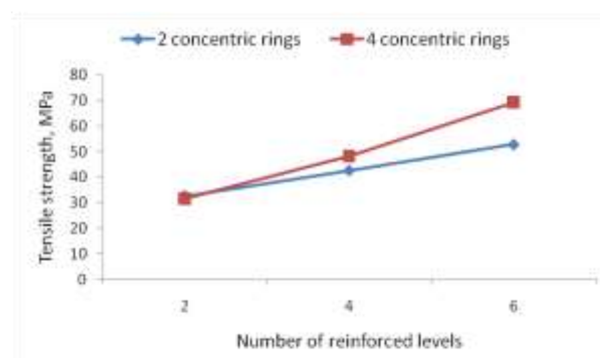


Fig. 11. The influence of the arrangement of fiberglass on the tensile strength

In order to establish more precise dependences of the mechanical characteristics of composite material reinforced with fiberglass, and in this way to choose the optimal layouts and amounts of fiberglass during the printing of reinforced composite parts with onyx as matrix material, the influence of fiberglass volume fraction (FVF) on tensile strength is shown in Fig. 12. Tensile strength values for a specimens with 2 or 4 reinforcing rings lie on a straight line, with a high correlation factor. Linear equations are given in Table 9, and can be used to estimate the value of tensile strength for further increasing the number of reinforcement layers, if the geometry of the part allows it.

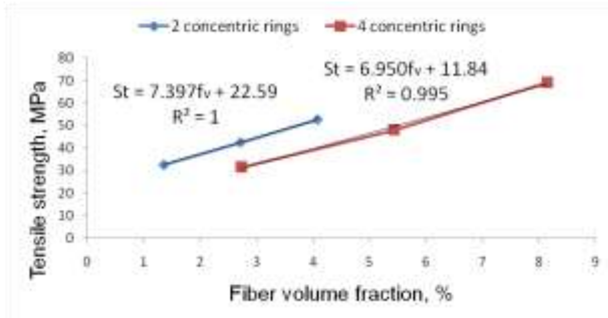


Fig. 12. Tensile strength versus fiber volume fraction

Table 9. Linear dependence of tensile strength on FVF

Reinforcement with 2,4 and 6 layers	Equation	Correlation factor
2 concentric rings	St = 7.397 f_v + 22.59	1
4 concentric rings	St = 6.950 f_v + 11.84	0,995

4. Conclusions

The influence of five different infill patterns and fiberglass reinforcement in the composite material onyx, which represents micro carbon fiber filled nylon, on the mechanical properties of additively manufactured materials was investigated in this study. Conclusions can be drawn as presented below:

I) Each of the five tested infill patterns has its own specificities that can give comparative advantages in certain applications of FDM technology, therefore knowing their influence on the mechanical properties of the printed material is of crucial importance for designers, scientists and practitioners in the industry. It has been shown that solid infill, which is basically a rectangular pattern with 100% infill density, gives the highest tensile strength of components printed from onyx composite material, but with higher consumption of material and time. On the other hand, at the examined density of 37%, it was shown that the smallest S/W ratio is with the triangular infill pattern, but in terms of isotropic characteristics in the printing plane, and thus of the printed parts, it is the most superior infill, which as such is recommended for application with reinforcing fibers, in order to bridge the lack of the smallest S/W ratio. The hexagonal infill structure is the most economical in terms of material and time consumption, but with the lowest tensile strength. A rectangular infill pattern with a lower infill density (37%) has a less favorable S/W ratio, and requires more consumption and printing time. The new gyroid infill pattern gives better tensile strength but requires more material and time. The sample with solid infill and density of 100% has the highest value of the modulus of elasticity.

II) The results of the second experimental set reveal that the reinforcing fibers have a positive effect on the mechanical characteristics of the printed parts. The value of the tensile strength of the specimen with a triangular infil and density of 37% is 17.66MPa, while with the addition of a small amount of continuous fiberglass (0.13cm^3, in the case of sample R2L2, i.e. converted to FVF only 1.36% volume fraction) it reaches a value of 32.69MRa (R2L2), and with a fiber volume of 0.75cm3 (R4L6 specimen, for which the FVF is 8.15%), has a value of 69.23MRa. Comparing specimens with the same amount of reinforcing fibers (FVF 2.72%) arranged in a different way, for example R2L4 and R4L2, there are large differences in tensile strength values in favor of the sample having fibers in 4 layers (42MRa for R2L4 vs. 31MPa for R4L2 specimen). This leads to the conclusion that from the aspect of mechanical characteristics, it is better to increase the number of reinforced layers than to increase the amount of reinforcing fibers in one layer (concentric rings). An increase in tensile strength on the one hand leads to a decrease in ductility for fiber-reinforced specimens. It is necessary to investigate the optimal balance area for these two opposing criteria of increasing strength and decreasing ductility. The linear dependence of the tensile strength on the fiber volume fraction was determined for the selected number of concentric rings of continuous fiberglass, which can be used to evaluate the tensile characteristics of the printed material in the target areas, and accordingly to model the reinforcement zones of the composite.

III) The values of the modulus of elasticity are relatively small for specimens without fibers and range from 185MPa to 516MRa, while in the case of using reinforcing fiberglass they range from 555MPa to 1376MRa. These values show that it is necessary to use reinforcing fibers for the printing of loaded parts from Onyx, for example soft gaskets or forming tools. The same conclusion is drawn in the case of the modulus of elasticity, the increase of fiber volume fraction leads to an increase of the modulus of elasticity, which is not linear and its value is more affected by the number of reinforced layers than by the amount of reinforcement in one layer.

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Nomenclature

St : Tensile strength, MPa
E : Elasticity modulus, MPa
R : Number of concentric fiber rings
L : Number of fiber layers
f_v : Fiber volume fraction
S/W : Strenght to weight ratio

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