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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, with and without varying fiberglass volume fraction. In addition, five different infill patterns (solid, triangular, rectangular, 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 a significant place, starting with classic production technologies in the repair of tool surfaces [1, 2], as well as in the application of new reverse and virtual engineering technologies [3, 4], and especially in rapid prototyping products and tools [5, 6]. 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. Each of the 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 [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 being increasingly used. In the study by Ali et al. [10], the influence of printing orientation, filling density and temperature on the mechanical characteristics of samples made of Onyx was examined. 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 varied. It was shown that the best mechanical properties were achieved for the rectangular in fill pattern, and that the thermal treatment of the samples led to certain improvements of the basic printed material. In the paper by Bárnika et al. [11], similar conclusions were reached by the authors, 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 was shown that a smaller layer thickness resulted in improved material characteristics due to better adhesion. The aim of this study was to investigate the effect of infill pattern variation on the tensile strength of the Onyx composite material. 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 study, the composite material Onyx was used, which has nylon as the basic material with added chopped micro carbon fibers, manufactured and trademarked by Markforged (MF). All samples were prepared from the same lot, from a 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. Tensile tests were performed according to the ASTM D638-14 (Type I) standard, using specimens with a thickness of 3.2 mm. The 3D model of the sample was modeled in CAD software CATIA, which was exported in STL format for printing. Three specimens were tested for each experiment in the research plan. A MF Onyx Pro 3D printer was used for printing the specimens, and the model setting and selection of printing parameters were defined using the Eiger software-as-service in the cloud. Selected specimen printing parameters for all the experiments in this study are shown in Table 1. For the first experimental set, the samples were prepared with predefined infill patterns in Eiger (triangular, hexagonal, rectangular, gyroid, solid). The 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 1.

Table 1. Specimen printing parameters and variations.

Specimen geometry variable	Value
Test specimen	ASTM D638-14 (type I)
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 (recommended as optimal by MF)	37 % - for triangular pattern 27 % - for hexagonal pattern 50 % - for rectangular pattern 40 % - for gyroid pattern
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

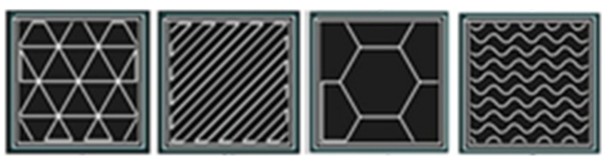
2.2 Infill pattern variance

The influence of the infill pattern as lattice structures within the specimens on the mechanical properties was examined with the variation of all infill types predefined in the Eiger software (triangular, hexagonal, rectangular, gyroid, and solid), as shown in Fig. 1. Taking into account that the shell, which is made of floor, roof and side wall layers, has higher impact on the tensile strength of the printed part than the increase of infill density, the variation of density is not analyzed in this paper. Hence, optimal recommended values of the producer were applied (37 %, 27 %, 50 % and 40 % for triangular, hexagonal, rectangular and gyroidal patterns, respectively). The influence of printing orientation can be analysed only for triangular and rectangular infill when print head mostly travels in straight lines across the specimen. However, when printing hexagonal and gyroidal filling, the printhead has to keep changing direction and rotate two-dimensional waves, so that the change in the print direction has no effect on these two patterns. Therefore, this influential factor was not considered in the paper. The specimens were printed with the same printing orientation, with the longer side of the specimen parallel to the x-axis of the table, and in a laid-down state. In order to compare the influence of applied infill patterns, specimens with maximum density, i.e. solid infill (100 %), were also tested. A total of 15 samples were prepared, three samples for each considered case.

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 and the mean value is shown. The printing time was also registered for further cost analysis and recommendations for the choice of infill pattern. The data are presented in Table 2.

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 0.3 mm



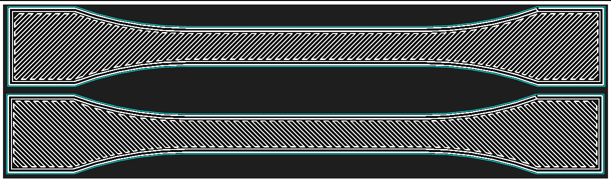
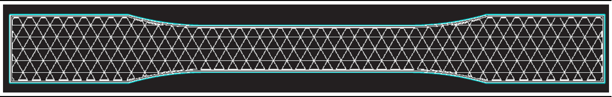
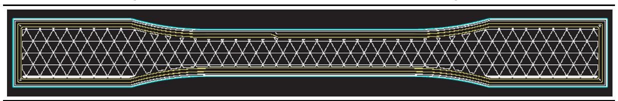
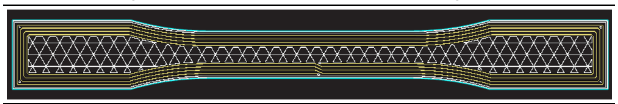
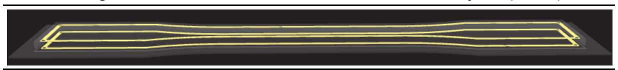
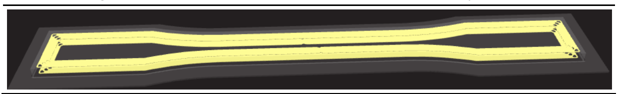
(a) (b) (c) (d)

Fig. 1. Tested variations of infill pattern: (a) triangular; (b) rectangular; (c) hexagonal; (d) gyroid.

Table 2. Specimen mass and printing time.

Infill pattern	Infill density	Mass (g)	Time (min)
Solid specimen	100 %	9.14	104
Triangular	37 %	5.81	77
Rectangular	50 %	6.69	83
Hexagonal	27 %	4.48	70
Gyroid	40 %	5.94	89

Table 3. 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)


was used, which was 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 material Onyx, all samples for this set of experiments were made according to the data given in Table 2, with a triangular shape infill pattern 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). 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 MF printer was predefined and unchangeable, as a rectangular infill of 100 % density (solid), with alternately changing raster angle ±45° in each of the layers. The presentation of the characteristic layers of the printed structure of those specimens is shown in Table 3.

Table 4. Mass, consumption and FVF for reinforced specimens.

Continuous fiberglass reinforcement	Mass (g)	Consumption, (cm^3)		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

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 4, in order to calculate the S/W ratio (MPa/g). 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] was taken into account. Therefore, the FVF values shown in the last column of Table 4 were calculated as the ratio of the volume of reinforcing fibers on the measuring section (57×13×3.2 mm) 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.

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. A ceramic extensometer in the range of 11-50 mm was used to measure elongation, which facilitated direct measurement of the change in the length of specimen. The test parameters and data on the used test equipment are given in Table 5.

3. Results and discussion

3.1 Influence of infill patterns

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 was also noticeable. In Fig. 2, two separated parts of the broken specimen in the machine grips and the distance between them can be seen, caused by

Table 5. Testing equipment and parameters.

Testing machine	Zwick/roell Z100
Nominal load	100 kN
Force measurement accuracy	1 N
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	500 Hz
Positioning accuracy	±2 µm
Testing temperature	23 °C

Fig. 2. Broken specimen in the machine grips (left) and three specimens after tensile test (right).

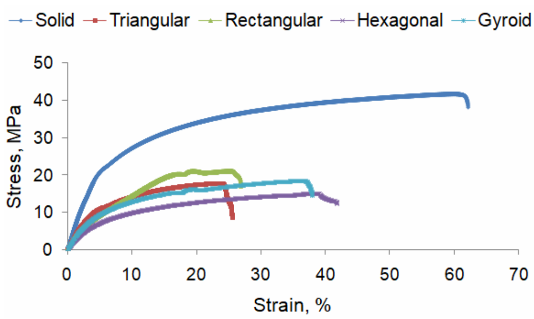


Fig. 3. Stress-strain curves for solid Onyx specimen and specimens with different infill patterns.

the large elastic recovery after breaking. The same picture shows three samples with triangular infill after breaking by tensile test. The failure mechanism was similar for all infill patterns, as gradual destruction occurs, i.e. formation of the so-called crocodile jaws. Fig. 3 shows the stress-strain curves for five types of the infill pattern, where the first one refers to a solid structure (100 % density). Table 6 shows the results of this set of experiments with relevant values for the characterization of the printed material.

Experimental results reveal that printing parts with solid infill have the best mechanical properties (ultimate strength is 40.96 MPa), and the highest ductility since the strain at break is

Table 6. Experimental results for infill pattern variance.

Infill pattern	Yield stress (MPa)	Ultimate strength (MPa)	S/W ratio (MPa/g)	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

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 the samples with 100 % infill density. Rectangular pattern gives the highest strength (21.25 MPa), but, compared to the triangular and hexagonal patters, it has a significantly higher consumption of material and requires more time for printing.

The choice of hexagonal infill pattern is reasonable when taking into account the printing costs and if the parts are not subjected to heavy exploitation, because the tensile strength is the lowest (14.19 MPa). 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 MF, gyroid, also has increased ductility and slightly higher strength than hexagonal, but requires the longest printing time. Triangular infill has the lowest S/W ratio, the lowest stress at yield (8.48 MPa) and the lowest strain at break (25.67 %), for the applied infill density. However, this type of infill pattern is recommended by MF, because it gives almost isotropic material characteristics in the printing plane, as the triangles are more compact compared to all other types of lattice.

3.2 Influence of fiberglass reinforcement

Fig. 4 shows the stress-strain curves for the tested specimens that were reinforced with continuous fiberglass in 2, 4 and 6 layers, with 2 (a) and 4 concentric rings (b). In addition to these curves, the stress-strain curve for a specimen printed from Onyx (without reinforcement), with a triangular infill and a density of 37 % is shown in the diagrams. The mechanical properties for those specimens (RxLy) are shown in Table 7. 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, it is impossible to explicitly introduce strain at break data into the experimental

Table 7. Experimental results for reinforcement variance.

Specimen	Yield stress (MPa)	Ultimate strength (MPa)	S/W ratio (MPa/g)	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

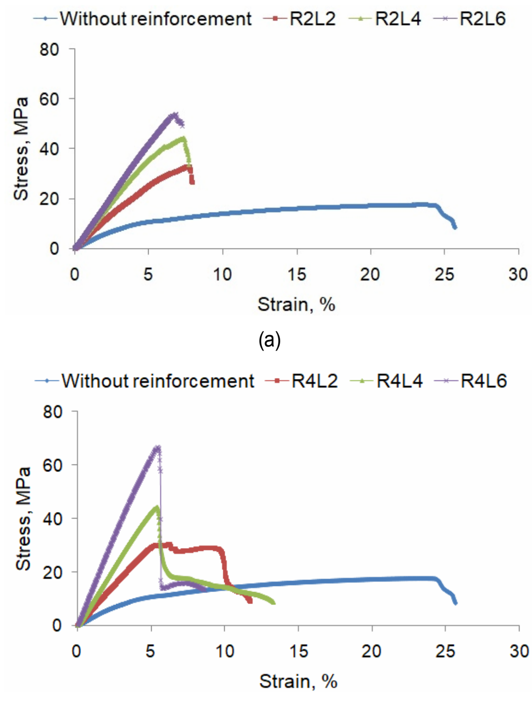


Fig. 4. Stress-strain curves for reinforced specimens with (a) 2 rings; (b) 4 rings, compared to Onyx specimen without reinforcement.

results. In this set of experiments, only the strain at the moment of reaching the maximum stress, before fracture, was monitored.

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 was 17.66 MPa, the maximum value of 69.23 MPa was achieved for the reinforced specimen R4L6, where the FVF was 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

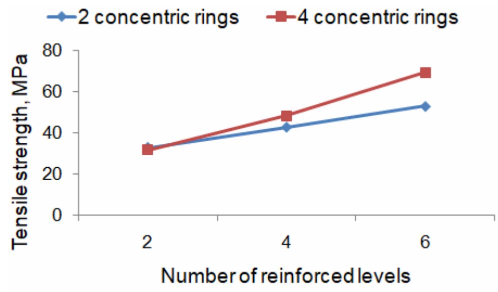


Fig. 5. The influence of the arrangement of fiberglass on the tensile strength.

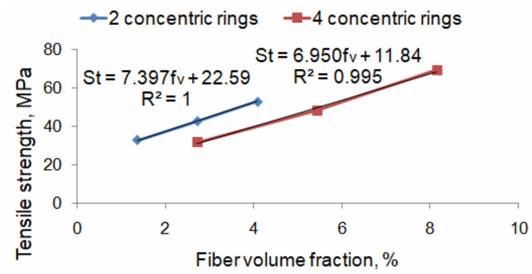


Fig. 6. Tensile strength versus fiber volume fraction.

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. There is very little room for plastic deformation from the yielding stage to failure.

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 42.63 MPa and in the second 31.49 MPa, and thus the S/W ratio is more favorable for R2L4 specimen. This means that, with the same consumption of fiberglass, that is 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 (731.43 MPa instead of 613.41 MPa for R4L2). Such trends can be shown graphically as in Fig. 5.

In order to establish more precise dependences of the mechanical properties of a composite material reinforced with fiberglass, and consequently 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. 6. Tensile strength values for specimens with 2 or 4 reinforcing rings lie on a straight line, with a high correlation factor. Linear equations are shown in Fig. 6, and can be used to estimate the value of tensile strength for further increase of the number of reinforcement layers, if the geometry of the part allows it.

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:

1) Each of the five tested infill patterns has its own specificities that can give comparative advantages in certain applications of FDM technology. Therefore, the knowledge of their influence on the mechanical properties of the printed material is of crucial importance for designers, scientists and practitioners in the industry. It was 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. 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 has a less favorable S/W ratio, and requires more material 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.

2) 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 infill and density of 37 % is 17.66 MPa, while with the addition of a small amount of continuous fiberglass (0.13 cm^3, in the case of sample R2L2, i.e. converted to FVF only 1.36 % volume fraction), it reaches a value of 32.69 MPa (R2L2), and with a fiber volume of 0.75 cm^3 (R4L6 specimen, for which the FVF is 8.15 %), has a value of 69.23 MPa. 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 (42 MPa for R2L4 vs. 31 MPa 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.

3) The values of the modulus of elasticity are relatively small for specimens without fibers and range from 185 MPa to 516 MPa, while in the case of using reinforcing fiberglass they range from 555 MPa to 1376 MPa. 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.

By increasing the infill density, the surface of contact between the layers increases, which makes the bonding better and the impact of possible errors during printing will be reduced. The influence of the infill density is different for different infill patterns, but the determination of the influence will be the subject of our future experimental research.

Acknowledgments

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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 : Strength to weight ratio, MPa/g

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