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INFLUENCE OF A DIRECTIONAL DEPENDENCEON MECHANICAL PROPERTIES OF COMPOSITES REINFORCED WITH CHOPPED CARBON FIBRE PRODUCED BY ADDITIVE MANUFACTURING

Progress in the industry is accompanied by the development of new materials and more efficient technological production processes. At present, additive production is becoming very attractive in all industries (research, development, production), which brings a number of advantages compared to subtractive methods (customization, production speed, control of material properties by users, etc.). The main advantage of 3D printing is the controlled deposition of material in defined places. Instead of demanding manual labour, fully automated production via computers leads to the manufacturing of complex components from materials whose production in conventional ways would be problematic or even impossible. Because these are new technologies, the main direction of research at present is to identify the basic physical properties of these materials under different types of loading.

The main goal of this article is to observe the dependence of the behaviour of the extruded material (thermoplastic reinforced with chopped carbon fibre) on the printing parameters (thickness of the lamina, the orientation of the fibres of the printed material, etc.). Based on published scientific works, it appears that these settings have a significant impact on the achieved physical properties. This is the reason why the authors decided to analyze the influence of these parameters on the basis of processed data from experimental measurements of mechanical properties in the MATLAB program. As this is FFF printing, an essential condition is to identify and specify the directional dependence of the behavior of the printed material. This physical phenomenon is a necessary condition for gradual knowledge for the purposes of a subsequent mathematical description of the material properties. According to the authors, for the purposes of modeling these materials in FEM-based programs, it is essential to define the directional dependence in the plane of the lamina.

Keywords: experimental measurement; physical properties; 3D printing; composite; fibre reinforcement; MATLAB

1. Introduction

Additive manufacturing has undergone many improvements in recent years, thanks to which this new production technology can currently compete with conventional production methods based on material subtraction. The most significant advantages of 3D printing are prototyping, customization and controlled production. These features lead to a fall in manufacturing costs [1,2]. Therefore this computer-controlled production method based on the addition of material is gradually applied in the branches of space and weaponry but even in the aerospace and automotive industries [3-5].

For a widespread extension of 3D printing to the practice, significant development of working principles is necessary. Implementation of many innovations in the branch of 3D printing is the expected requirement for subsequent raise of interest and possible application in the executive processes in all sectors, for example, industry, medicine and entertainment [6-9].

The development of additive production is a process, which began forty years ago and has continued to these days. The first 3D printers appeared in the 1980s what is connected with the submission of the first patents. These times are characteristic of development the first printing technologies such as SLA, SLS and FFF. The differentiation between the mentioned technologies lies in two essential parameters. The first is the usage of different materials according to relevance towards the respective method. The second is a technological aspect, which means the best possible processing method selection of particular materials into the product form. All of the mentioned technologies have undergone many essential improvements to this period in order to bring them into mass popularity in manufacturing or home use. In current time, the most commonly used method is the FFF (Fused Filament Fabrication) method based on the gradual deposition of material layer upon layer [10].

The working principle of the FFF method is following. In general, the material in the filament form is fed by an extruder

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into the printer head. The printer head moves in the X-Y plane and deposits molten material at predefined locations on the printer's working bed (Fig. 1). Subsequently, the deposited material cools and solidifies, which lead to forming a bond with the previously deposited material. After complete deposition of the material in the lamina, the printer continues to print the next layer. Until recently, the FFF method was limited solely to the printing of thermoplastic material [11,12]. Therefore, from the material point of view, a significant milestone in the current period is the possibility of printing objects made of composites, metals and other materials [13]. The development leads to the extended exploitation of 3D printing, mainly in the defence industry. The industry is typical of primary concern on the production of complex structures. The aspect present difficult requirement, which 3D printing fulfil sufficiently with the usage of lightweight materials.

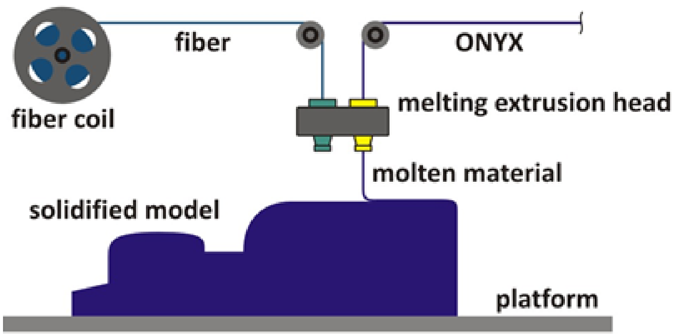

Fig. 1. Working principle of 3D printer

In the case of 3D printed composites, the primary group presents thermoplastics reinforced with various fibres. Generally, the customer has the number of fibre choice opportunities in fibre material and fibre length. In terms of fibre material selection, the essential division is into natural (glass) and artificial fibres (Kevlar); while in the case of fibre length, there is opportunity to select composites reinforced with short (e.g. chopped) or long fibre. In the former case, the fibre is usually part of the matrix. The main advantages of fibre-reinforced composites are better mechanical properties compared to a pure matrix [14].

Within fibre-reinforced composites, the distribution of the functions of the individual components predominates. The fibre serves primarily to transfer loads. On the other hand, the matrix has many significant purposes. Between them, we include the transmission of the loadings from a surface to the fibres and ability to keep the composite in the desired shape. Also, maintenance of the fibre location and orientation in the structure is a serious feature of the matrix [15].

In recent time, extensive research works are underway in various areas of fibre-reinforced printed composites. One of the main topics is the determination of the mechanical properties. In that field, several research articles have been published yet. The articles were primarily focused on the implementation, analysis and evaluation of tensile tests [16], bending tests [17], impact tests [18] and fatigue [19]. It is assumed that modelling of these materials with sufficient accuracy simulation in FEM programs in the future will lead to mass expansion of technology in practice. To achieve this goal are the following conditions necessary. The first condition is a precise specification of material behaviour under various types of loading [20]. The second condition relies on the suitable mathematical-physical models that will describe the selected material with sufficient accuracy [21].

Therefore authors decided to perform a series of tensile tests on specimens made of nylon reinforced with chopped carbon fibre (trademark Onyx) printed using Markforged MarkTwo printer. The printer working principle is based on the Fused Filament Fabrication method. The thickness of laminates was diverse with uniform thicknesses of laminas. The authors aimed to observe the effect of this factor on the tensile strength of the printed specimens. Subsequently, the authors attempted to specify the mechanical properties of the individual laminas in the laminate.

Therefore the reason why authors try to identify the properties of laminas is the fact that during printing, two adjacent printing filaments are joined, but the joints could be considered as cold joints. Although one material is cooled and just extruded filament is melted, the joint may not be of good quality. Therefore the strength of the material may not be achieved. The extruded filaments have a flattened ellipse-like shape. Thus the contact area of two adjacent filaments is less than the thickness of the printing layer. In the printing process, the short carbon fibres are preferably oriented in the filament printing direction. This is given by the dimensions of the extruded filaments 0.1×0.2 mm. The carbon fibre length is 0.2 mm [22]. Therefore when joining two adjacent laminas, the connection is only through the thermoplastic, since there is no connection of the adjacent laminas via short carbon fibres.

Based on these assumptions, we can expect the different mechanical properties of the material in particular laminas. Therefore the purpose was to determine whether the mechanical behaviour of printed laminates is directionally dependent. These pieces of knowledge could be later exploited to specify a suitable way of modelling the 3D printed laminates. When assessing the useful properties of a product from the point of view of the mechanical properties of the material, the main parameter is the yield strength. The yield strength of the material affects the shape stability of the structure. Exceeding the yield strength leads to the beginning of shape change, which is usually an undesirable condition. Therefore we assessed the yield strength of the material and not the tensile strength of the material.

2. Preparations of tensile testing

Specimens were designed corresponding to ASTM D638-14 [23] standard and printed by a Markforged MarkTwo whose printing principle is based on Fused Filament Fabrication method. The specimen's shape and dimensions are described in Fig. 2 and Fig. 3. Each series consisted of five specimens made of onyx. Onyx is a material composed of nylon filaments filled with chopped carbon fibre. The material properties specified by the manufacturer are defined in TABLE 1 [24].

TABLE 1

Mechanical properties of materials

	Nylon	Nylon Reinforced with Chopped Carbon Fibre (Onyx)
Tensile Modulus (GPa)	1.7	1.4
Tensile Strength (MPa)	36	30
Tensile Strain at Break (%)	150	58
Flexural Strength (GPa)	50	81
Flexural Modulus (MPa)	1.4	3.6
Flexural Strain at Break (%)	—	—
Printing method	FFF	FFF

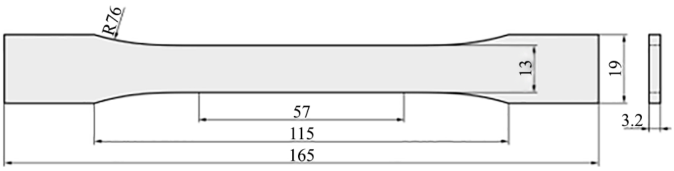

Fig. 2. Dimensions and shape of specimen according to standard ASTM D638-14

Fig. 3. Printed specimens divided into series according to adjusted printing parameters

TABLE 2 specify the printing parameters adjusted by authors in the printing process of mentioned specimens.

The specimens differed in the following parameters: filament deposition arrangement in the individual laminas and the laminate thickness. The selected material deposition strategy was solid fill. The thickness of the lamina was 0.1 mm. The filament orientations in individual laminas were at angles of 0 and 90

TABLE 2

Printing parameters

Parameter	Value
Layer thickness of matrix	0.1
Base plane of specimen	XY
Matrix filament orientation in lamina	0/90 (Fig. 4a and Fig. 4b respectively)
Number of walls	1
Fill density	100%
Infill type	Solid fill
Total number of laminas	5, 7, 9, 11

degrees, as shown in Fig. 4a and Fig. 4b. According to the preset parameters, the filament orientation in the successive laminas is alternately arranged in the sense of $[0/90/0/90]_x$. The authors aimed to monitor the influence of these parameters on the tensile strength of the specimens. In addition, the purpose of the work was to observe whether the direction of material deposition in the printing process affects the mechanical properties of the extruded object.

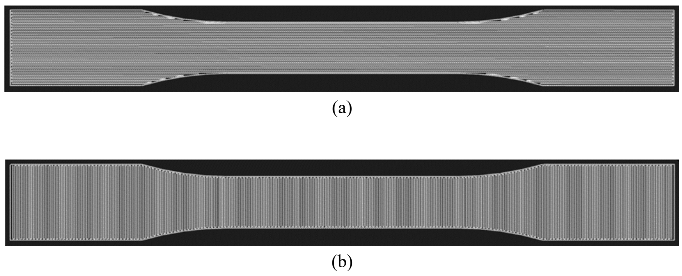

Fig. 4. Deposition of the material in lamina: (a) the material deposited in the direction of loading axis (0 degrees); (b) material deposited perpendicular to loading axis (90 degrees)

3. Tensile test results

The tensile test was performed on the INOVA testing machinewith a maximum tensile force of 100 kN for selected four types of specimens. The more detailed description of specimens is defined in TABLE 3.

For each specimen type are shown results in the form of graphs using the MATLAB program (Fig. 5). The results reveal that an increasing number of laminas lead to increase of specimens strength.

TABLE 3

Description of assessed specimen series and measured values obtained from tensile testing

Series	Lamina thickness [mm]	Number of laminas	Filament orientation	Yielding force [N]	Yield strength [MPa]	Ultimate strength [MPa]
A	0.1	9	[0/90/0/90/0/90/0/90/0]	262.0688	22.399	35.95
B	0.1	9	[90/0/90/0/90/0/90/0/90]	252.5555	21.586	34.49
C	0.1	11	[0/90/0/90/0/90/0/90/0/90/0]	350.9995	24.545	38.71
D	0.1	11	[90/0/90/0/90/0/90/0/90/0/90]	319.875	22.368	34.5

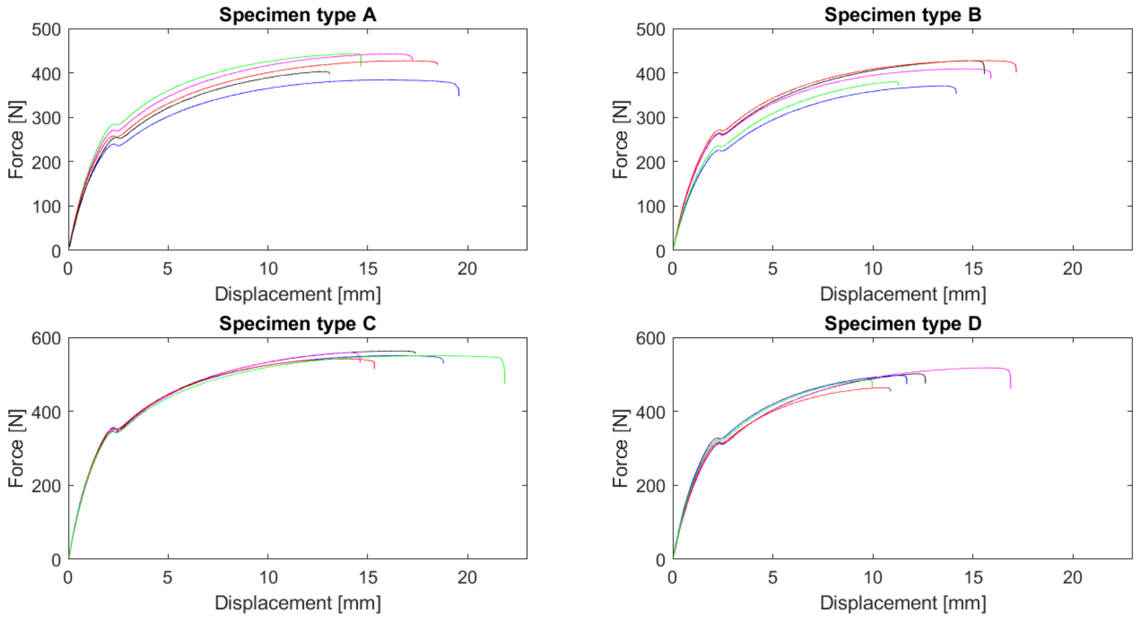

Fig. 5. Graphs of performed tensile tests

The observation of results in the graphic form (Fig. 5) leads to the question of measurement accuracy. The authors analyze each measurement to identify two parameters: the average value of the ultimate force and the deviation between measured results. The results of this analysis are shown in Fig. 6.

From the results, we can observe acceptable differences, based on which we can consider the measurement as accurate and continue the analysis of the strength of individual laminas. The best results have been achieved in the case of C type specimens. The measured values differed by only 1.5%. In the case of A and

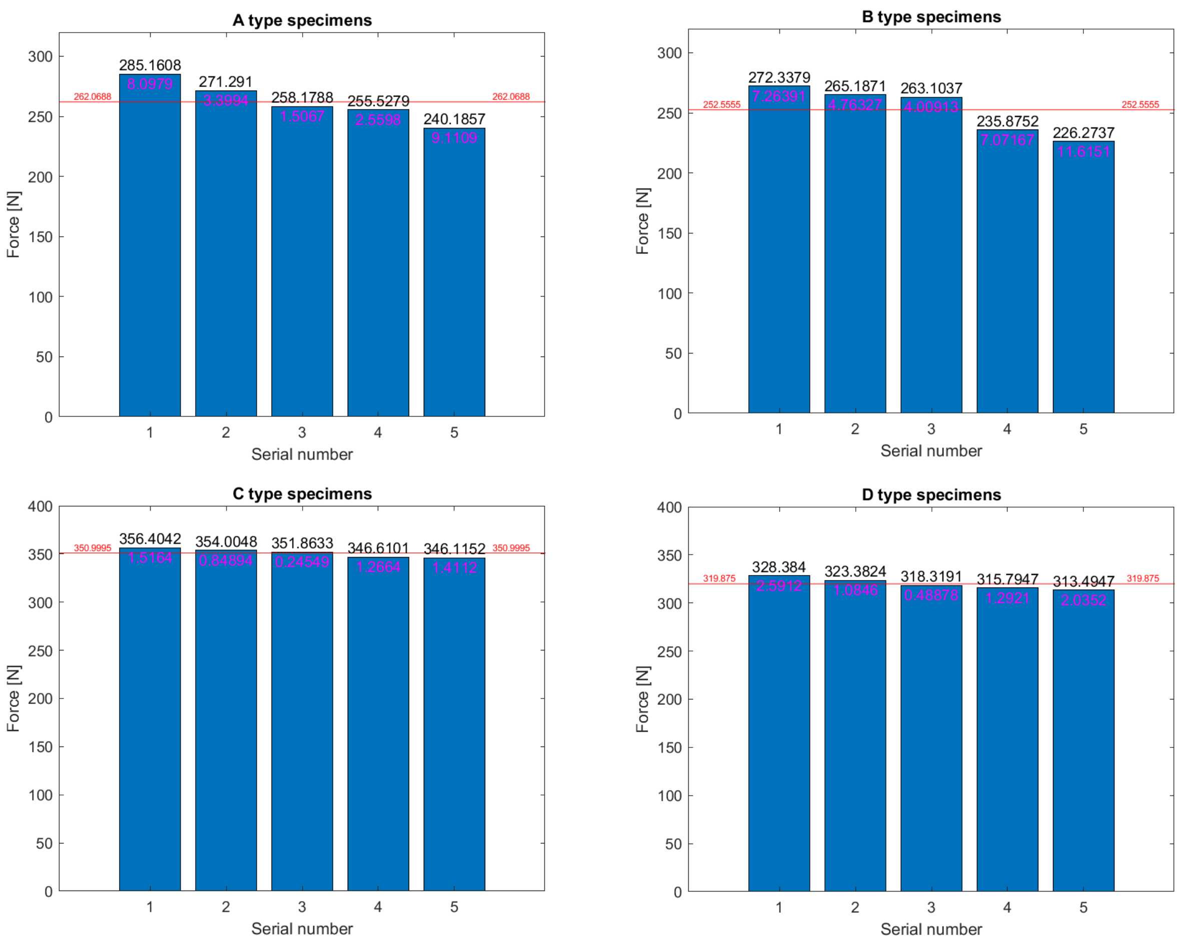

Fig. 6. Comparison of measured results within each series. Determination of mean value (red) and specification of the standard deviation (purple)

B type specimens, we observed the highest differences, but the difference was approximately 10%, therefore authors consider them as appropriate.

4. Analysis of lamina strength

For a better comparison of the tensile tests results was proposed a script in the MATLAB in the GUIDE environment, thanks to which it was possible to compare graphs obtained from the tensile test (Fig. 7).

Based on the above analysis, different strength can be observed concerning the proportion of individual types of laminas. Comparison of A and B specimen types lead to the conclusion that the differences are insignificant. However, in the case, C and D specimens, the effect of filament orientation on the strength of the specimens can be observed. In both cases, specimens with a higher proportion of layers oriented perpendicular to the loading direction have lower strength.

Subsequently, from these observations, a requirement arose to specify the strength of individual laminas. In the beginning, the strength of the laminate composed of two laminas with angle raster 0/90 could be expressed by the following formula:

$$P_{laminate} = P_0 + P_{90} \tag{1}$$

Then, if the laminate consists of more than two laminas, we can modify the equation 1 into the following form:

$$P_{laminate} = x * P_0 + y * P_{90} \tag{2}$$

Where x and y correspond to number of particular laminas with along and perpendicular orientation of infill respectively.

The printer deposition material strategy is based on a regular alternation of laminas in the laminate. In general it is possible to set the printing in a manner that the following rule will apply in the given laminate

$$x = y + 1 \tag{3}$$

Or

$$y = x + 1 \tag{4}$$

This rule is better described in the following table (TABLE 4). The = character represents the filament in the lamina oriented at an angle of 0 degrees to the loading direction. The || character in a similar principle represents a filament at an angle of 90 degrees to the loading direction.

TABLE 4

Composition of assessed specimen series

Series	=	||	Yielding force [N]
A	5	4	262.07
B	4	5	252.56
C	6	5	350.99
D	5	6	319.86

Subsequently, the appropriate parameters were substituted into Equation 2. This lead to two equations with two unknowns for the case of A and B specimens.

$$5 * P_0 + 4 * P_{90} = = 262.07 \tag{5}$$

$$4 * P_0 + 5 * P_{90} = 252.56 \tag{6}$$

The solution of the equations 5 and 6 is

$$P_{90} = 23.84 \tag{7}$$

$$P_0 = 33.35 \tag{8}$$

A similar analysis was performed for 11-layer specimens

$$6 * P_0 + 5 * P_{90} = 350.99 \tag{9}$$

$$5 * P_0 + 6 * P_{90} = 319.86 \tag{10}$$

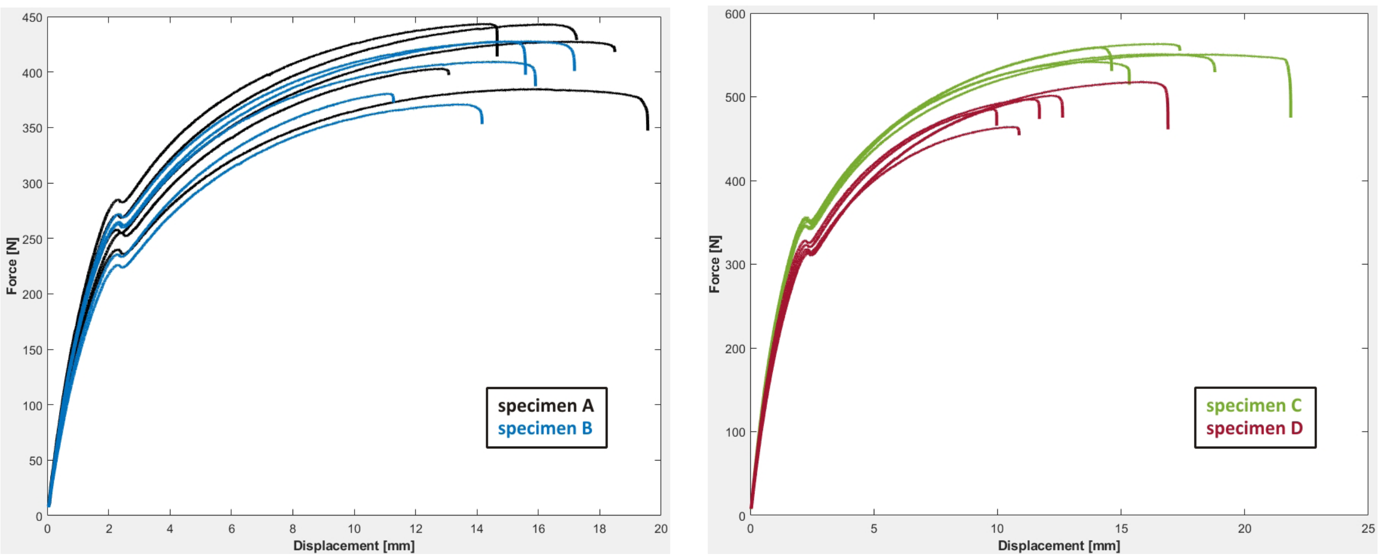

Fig. 7. Comparison of the results of individual series in MATLAB in GUIDE environment

And we obtain the following result

$$P_{90} = 14.93 \quad (11)$$

$$P_0 = 46.06 \quad (12)$$

Then, the arithmetic mean was calculated from the above results:

$$P_{90} = 19.38 \quad (13)$$

$$P_0 = 39.7 \quad (14)$$

By the subsequent substitution of the results back into the equations, it is possible to compare the difference between the calculation and the experiment (TABLE 5).

TABLE 5

Comparison of experimental results and numerical estimation

Series	Numerical estimation [N]	Experimental measurement [N]	Difference [%]
A	276.02	262.07	5.32
B	255.7	252.56	1.24
C	335.1	350.99	4.53
D	314.78	319.86	1.58

The results show that the differences are acceptable. Based on this, we can determine the yield strength of individual laminas (TABLE 6).

TABLE 6

Numerical estimation of yield strength of laminas

Yield strength$_0$ [MPa]	30.54
Yield strength$_{90}$ [MPa]	14.91

It means that a lamina with a filament oriented perpendicular to the loading direction has 51% less strength than a lamina with a filament oriented parallel to the loading direction.

5. Conclusions

The work aimed to continue on the already performed research work in the field of mechanical testing of 3D printed thermoplastics reinforced with chopped fibre. The article is focused on the tensile test analysis of onyx material printed by FFF printer. It has been shown that increasing the number of laminas affects the tensile strength of the samples. Subsequently, a different strength of the laminates was observed depending on the orientation of the individual layers. It has been shown that specimens which contain a larger proportion of layers oriented perpendicular to the direction of loading in the structure show less strength. For this reason, the strength analysis of the individual laminates was performed. The analysis identifies that strength of the lamina oriented perpendicular to the direction of the loading is 51% lower than the strength of the lamina oriented in the direction of the loading. The presented research results confirmed that the properties of the printed structure depend on the printing orientation. The assessment at the level of individual laminas leads to the conclusion that material behaviour orthotopically. With proper orientation of the layers, we can increase the resulting yield strength of the extruded structure. The result is the increase in the useful properties of the printed structure.

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REFERENCES

[1] G.D. Goh, V. Dikshit, A.P. Nagalingam, G.L. Goh, S. Agarwala, S.L. Sing, J. Wei, W.Y. Yeong, Materials & Design **137**, 79-89 (2018). DOI: https://doi.org/10.1016/j.matdes.2017.10.021
[2] S.M.F. Kabir, K. Mathur, A.M. Seyam, Composite Structures **232**. DOI: https://doi.org/10.1016/j.compstruct.2019.111476
[3] G.D. Goh, W. Toh, Y.L. Yap, T.Y. Ng, W.Y. Yeong, Composites Part B: Engineering. DOI: https://doi.org/10.1016/j.compositesb.2021.108840 (in press)
[4] E.C. Botelho, R.A. Silva, L.C. Pardini, M.C. Rezende, Mat. Res. **9** (3), 247-256 (2006). DOI: https://doi.org/10.1590/S1516-14392006000300002
[5] P. Dunaj, S. Berczyński, K. Miądlicki, I. Irska, B. Niesterowicz, Materials **13**. DOI: https://doi.org/10.3390/ma13092125
[6] J.C. André, From additive manufacturing to 3D/4D printing 1, ISTE Ltd., London (2017).
[7] P. Krawiec, D. Czarnecka-Komorowska, Ł. Warguła, S. Wojciechowski, Materials **14**. DOI: https://doi.org/10.3390/ma14071682
[8] A. Unkovskiy, F. Schmidt, F. Beuer, P. Li, S. Spintzyk, P. Kraemer Fernandez, J. Clin. Med. DOI: https://doi.org/10.3390/jcm10051070
[9] I. Rojek, D. Mikołajewski, E. Dostatni, M. Macko, Materials **13**. DOI: https://doi.org/10.3390/ma13235437
[10] S.S. Crump, Apparatus and method for creating three-dimensional objects, United States patent, US5121329A, 1989.
[11] G. Mark, et al. Three dimensional printer with composite filament fabrication, United States patent, US9156205B2.
[12] J.R.C. Dizon, A.H. Espera, Q. Chen, R.C. Advincula, Additive Manufacturing **20**, 44-67 (2018). DOI: https://doi.org/10.1016/j.addma.2017.12.002
[13] S.L. Sing, S. Huang, G.D. Goh, G.L. Goh, C.F. Tey, J.H.K. Tan, W.Y. Yeong, Progress in Materials Science. DOI: https://doi.org/10.1016/j.pmatsci.2021.100795 (in press)

[14] M. Šofer, J. Cienciala, M. Fusek, P. Pavlíček, R. Moravec, Materials **14**. DOI: https://doi.org/10.3390/ma14040786

[15] D.D.L. Chung, Composite materials – Science and applications, 2nd ed., Springer Science & Business Media, New York (2010).

[16] G.W. Melenka, B.K.O. Cheung, J.S. Schofield, M.R. Dawson, J.P. Carey, Composite Structures **153**, 866-875 (2016). DOI: https://doi.org/10.1016/j.compstruct.2016.07.018

[17] M. Araya-Calvo, I. López-Gómez, N. Chamberlain-Simon, J.L. León-Salazar, T. Guillén-Girón, J.S. Corrales-Cordero, O. Sánchez-Brenes, Additive Manufacturing **22**. 157-164 (2018). DOI: https://doi.org/10.1016/j.addma.2018.05.007

[18] M. Vaško, M. Sága, J. Majko, A. Vaško, M. Handrik, Materials **13**. DOI: https://doi.org/10.3390/ma13245654

[19] A.D. Pertuz, S. Díaz-Cardona, O. Andrés González-Estrada, Int. J. of Fatigue **130**. DOI: https://doi.org/10.1016/j.ijfatigue.2019.105275

[20] P. Pavlíček, F. Fojtík, M. Fusek, Testing Carbon Fibers for 3D Printing. Proceedings of 58th International Scientific conference on Experimental Stress Analysis 2020, VSB-Technical University of Ostrava, Czech Republic, October 19 October 22, 2020. 382-386. ISBN978-80-248-4451-0

[21] P. Marsalek, M. Sotola, D. Rybansky, V. Repa, R. Halama, M. Fusek, J. Prokop, Materials **14**. DOI: https://doi.org/10.3390/ma14010140

[22] S.H. Sanei, A. Arndt, R. Doles, Journal of Composite Materials **54** (20), 2687-2695 (2020). DOI: https://doi.org/10.1177/0021998320902510

[23] ASTM D638-14, Standard Test Method for Tensile Properties of Plastics, ASTM International, West Conshohocken, PA, 2014. Available at: www.astm.org

[24] Markforged. Available online: https://markforged.com/ (accessed on 5 November 2020).