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Tensile testing of polymer composites reinforced with continuous fibers produced by CFF method

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1. Introduction

3D printing is a manufacturing technology based on the gradual deposition of material layer upon layer. The development of additive manufacturing in recent years has led to the possibility of printing not solely pure plastics but also other materials. For example, thermoplastics reinforced with long or chopped fibres. Generally, the presence of fibre limits the portfolio of applicable 3D printing methods. The most suitable are methods based on the extrusion of material (e.g. Fused Filament Fabrication - FFF). In the case of these methods, the nylon with chopped fibre passes through the printer nozzle without substantial modifications to the printer. The deposition of the long filament into the structure was allowed by the augmentation of the FFF printer by adding the second nozzle intended for continuous fibre (Continuous Filament Fabrication - CFF). Fibre-reinforced plastic composites printing came on the market a few years ago. Therefore, research into the mechanical properties of these materials is currently ongoing. In the case of tensile testing, several studies have been published evaluating the results of experimental measurements performed on variously shaped specimens. The reason is that there are currently no standards focused on mechanical testing methodology for additively manufactured composites. In general, the authors used standards ASTM D3039 or ASTM D638-14. The former is dedicated to tensile testing of long fibre reinforced composites, and the latter specifies tensile testing of pure plastics. Both shapes lead to the creation of stress concentrators, which results in premature failure of specimens at inappropriate locations. Therefore, the authors proposed a new specimen shape using finite element analysis. The primary aim is to verify the specimen shape suitability by the experimental measurements. In addition, the comparison of obtained tensile strength with results published in peer-reviewed journals by other authors will be performed.

2. Experiment preparations

2.1. Manufacturing process

The production of the specimens was performed using a Markforged MarkTwo printer. This printer works on the principles of FFF and CFF methods, which we classify as extrusion technologies. The FFF method comprises the following procedures:

1) The material wound on a spool is fed into the printer head.
2) The material is heated to a melting temperature.
3) The molten material is extruded and deposited at precisely specified locations.
4) Upon deposition, the material cools and solidifies. In addition, deposited material forms bonding with adjacent filaments.

2.2. Material

The experimental measurement was carried out on laminates made of polymer reinforced with long fibres. The matrix function was fulfilled by nylon reinforced with chopped carbon fibre (trademark onyx). The long carbon fibres fulfilled the reinforcement function.

Table 1. Mechanical properties of essential materials specified by printer manufacturer

	Young Modulus [GPa]	Tensile strength [MPa]	Strain at fracture [%]
Onyx	1.4	30	58
Carbon fiber	60	800	1.5

2.3. Specimens

The tensile test was realized on the specimens with modified dog bone shapes (Fig. 1). Based on the FE analysis published in [6], this shape type appears to be the most suitable for tensile testing purposes. The shapes according to standards ASTM D3039 and ASTM D638-14 are inappropriate. The reason is the premature breakage caused by the formation of stress concentrators.

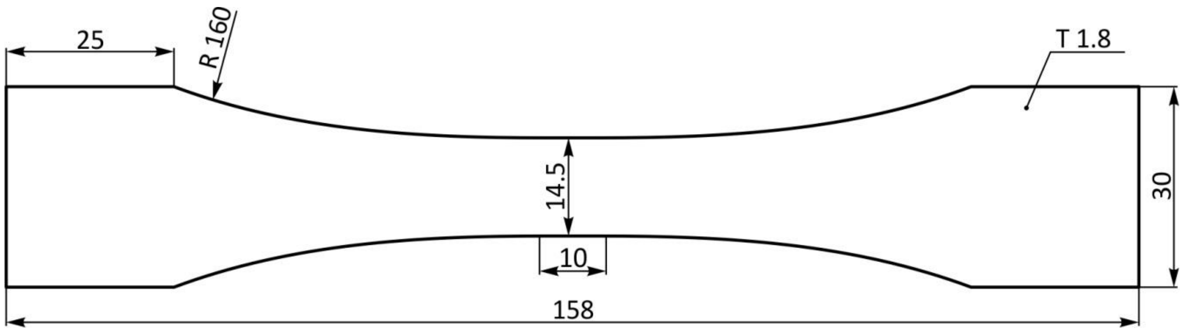

Fig. 1. Proposed specimen shape

2.4. Printing parameters

In the slicing software, the printer user can modify some parameters. Table 2 gives an overview of the print settings applied in this study.

Table 2. Printing parameters

Parameter	Value
Lamina thickness [mm]	0.125
Base plane	XY
Orientation of matrix filaments [degrees]	45/-45
Infill density [%]	100
Infill pattern	Solid infill
Number of roof and floor layers	4
Total number of laminas	14
Reinforcement type	Carbon
Reinforcement orientation	Unidirectional (0°)
Number of reinforced layers	6

The infill pattern was solid with 100% density and 45/-45 orientation. Also, the number of walls and roof/floor layers was 2 and 4, respectively. A previous study focused on nylon with chopped carbon fibres showed that all these parameters affect the strength of the laminates [8].

In the case of laminates reinforced with continuous fibre, there is no expectation of a significant effect of the matrix on the strength of the specimens since the strength of the fibres significantly exceeds the matrix strength.

3. Results

The results of the tensile test of the continuous fibre-reinforced thermoplastic composites performed using INSTRON 5985 are shown in Table 3.

Table 3. Tensile test results

Fibre type	Fibre orientation	Number of rings	Maximum force [N]	Ultimate strength [MPa]
Carbon	0°	0	8311.2	318.42

Subsequently, it was necessary to perform the comparison of the achieved tensile strength with results published by other research institutes. The comparison is in tabular form (Table 4) and also plotted using program Matlab (Fig. 2). The fibre volume fracture (FVF) was determined as the ratio between the number of reinforcing layers to the total number of laminas in the narrowest part of the specimens.

Table 4. Overview of the results of carbon fibre reinforced thermoplastic composite specimens published in scientific journals

Authors	Specimen shape	FVF [%]	Ultimate strength [MPa]	Fiber deposition
Majko	custom	42	318.42	0
Goh [5]	638-14	92	600	0
Lozada [9]	638-14	69	304.3	concentric
Al-Abadi [1]	3039	50	320	concentric
Dickson [3]	3039	30.7	216	concentric
Ghebretinse [4]	3039	71	560	0
		6.25	96.6	
Chacon [2]	3039	50	239.8	0
		87.5	436.7	
Iragi [7]	3039	88.8	779	0

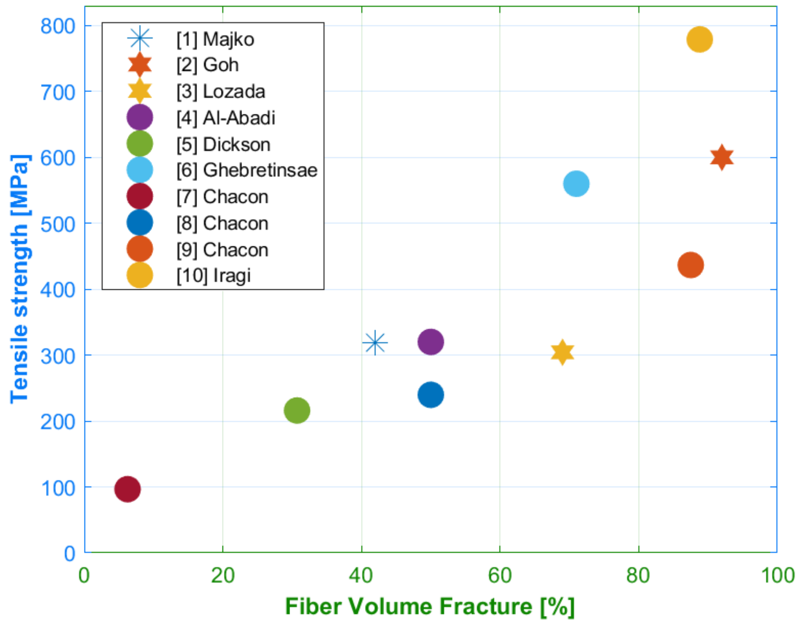

Fig. 2. Plot of results comparison

The specimen proposed by the authors achieved a tensile strength of 318.42 MPa at FVF of 42%. Comparable results obtained only specimens with shape according to ASTM D3039 in a study published by Al-Abadi et al. [1]. The tensile strength was 320 MPa at 50% FVF. Chacon et al. [2] realized the tensile test on identical specimens and achieved significantly lower tensile strength. The difference could lie in various fibre deposition arrangements. According to the results, the fibres deposited in rings around specimen circumference lead to higher tensile strength than unidirectionally deposited fibres.

For the ASTM D638-14 specimens, even a significantly higher FVF did not lead to tensile strength higher than 300 MPa.

4. Conclusion

The assessment of the results confirmed the suitability of the proposed shape for tensile testing of additively manufactured composite specimens. Therefore, in the future, the authors will follow up these results with further measurements to determine:

- the effect of FVF on the tensile strength,
- the influence of the reinforcement type and its arrangement on the tensile strength.

Acknowledgements

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