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Testing Carbon Fibers for 3D Printing

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Abstract. This paper is focused on innovative method of the tensile testing of the carbon fibers in 3D printing. Carbon fibers have good mechanical properties especially high strength and Young modulus. 3D printing of carbon composites is progressive method which give new design and production possibilities. This material is used in automotive and aerospace industry. Composites in the design have good properties mainly in the mass reduction which follow trend decreasing of emissions.

Introduction

Carbon fibers belong to progressive materials, which are used in design of modern mechanical parts. Main advantages of carbon fibers are high stiffness and strength while maintaining a low weight. This material has some disadvantages mainly low ductility and fracture resistance. In this work, the carbon fiber used in 3D printing of composite in 3D printer type Markforged X7 is examined [1].

3D printing of composites is an innovative method of design of mechanical parts which cannot be produced using conventional technologies. Testing of mechanical properties of carbon fiber is important for the design of mechanical parts and for the prediction of material behaviour under loading.

Mechanical properties of the fiber is an important parameter for the prediction of mechanical properties of composites under different mixing ratio. This paper describes the method of fibers testing inspirited by standard ASTM D4018-17 [1].

Description of Test

The testing of fibers has some difficulties, especially when the small cross-sections are tested where the specimen can be damaged by the compression force and high stress concentration in clamping area.

This problem is solved in ASTM D4018-17 standard [2] where both ends of fiber are filled by resin which creates the clamping area. Another standard for fiber testing is ASTM D3379. However, this method is not suitable for large fiber diameters and high forces.

For clamping of fibers the new type of clamping zone has been designed. This can minimize the concentration of stress in the transition area between the fiber and resin. The form is made of aluminium.

Design of Aluminium Form

The form is made of two parts - form to be filled and base plate. Both parts are connected using bolts. Material of the form is aluminium plate 3 mm thick, machined by electro-spark machining technology or by laser cutting for the comparison of machining methods used. The middle part of the form is milled so that the carbon fiber is in the center of the form.

The removal force depends on the surface roughness of the specimen. Thus, it is necessary to minimize the grain size on vertical surfaces of the form. The optimal surface roughness is between Ra 0.4 and Ra 0.8. Another possibility is to incline vertical surfaces of the form by 2-3°. Base plate is only milled on its outer sides, the frontal surfaces did not need to be machined due to the sufficient roughness produced by the production technology of the plate. In the corners of the form and the base plate threaded holes for their mutual connection are drilled.

The form and the base plate must not be distorted and surfaces must abut without clearances. In the Fig. 1 the technical drawing of the form is presented.

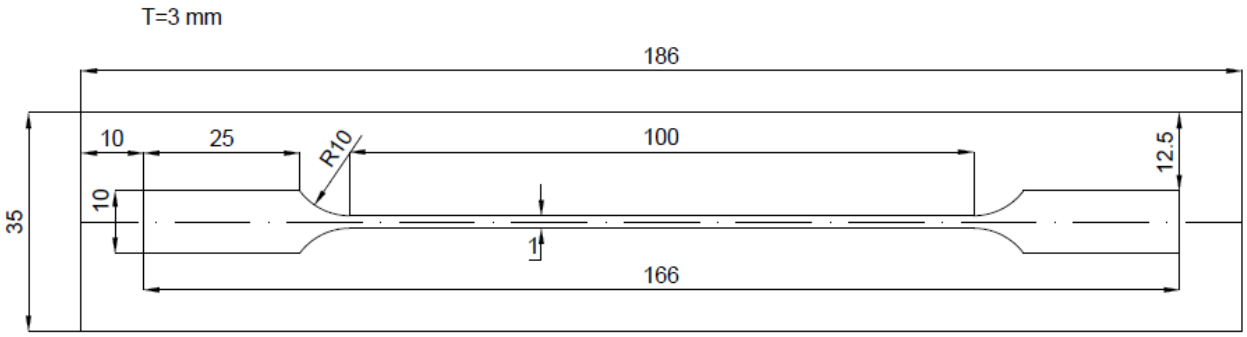


Fig 1: Drawing of form

Preparation of Specimen

The form and the fiber must be cleaned with isopropyl alcohol before the bonding, then it is necessary to connect the form and the base plate by bolted joints. After the connection, surfaces of the form are covered by the separator which prevents the bonding of the resin with the form. For this purpose, hot paraffin or wax is used. ¨

The separator must be removed from the middle part of the form. For the correct alignment of the fibre into the form, ends of the middle part of the fibre need to pressed using toothpick or wax. Polyurethane resin is mixed in the recommended mixing ratio. After the mixing, it is important to wait some time until the chemical reaction starts. After this step both ends are filled by resin.

The curing acceleration using higher temperature is not recommended because higher temperature can cause the change of mechanical properties of the fiber and resin is more fragile. This property was observed during specimen preparation in authors´ laboratory.

Specimen Clamping

Clamping specimen into the test machine must be done parallel with the axis of the deformation. Clamping the specimen is realized using jagged jaws with minimal clamping force. Too high force causes the failure of the bonded joint and the pramature failure of the specimen. This property was observed during test realization in authors´ laboratory.

Carbon Fiber Testing

The fiber has been measured by pasameter and digital-optical microscope before the testing. The fiber has the eliptical cross-section with the difference of halfaxis length of 0.03 mm. Due to this small value, the elipsis can be considered as the circle with diameter of 0.437 mm and cross-sectional area of 0.150 mm^2.

Carbon fiber is tested using the Testometric M500-50CT machine with 50000 N force sensor. For testing, ten specimens have been prepared. The loading velocity was set from 0.5 - 10 mm/min with the minimal initial preload. Values $0.5, 1$ and 10 mm/min are infromative values only.

Deformation of the specimen is overtaken from the displacement of the crossbar sincethe usa of the extensometer was not possible due to the missaligment of jaws causing the initial deformation of the specimen.. The deformation of the specimen could be measured by the optical extensometer. However, this device was not availabe at the time of the experiment. After the exceeding the strength limit, the fiber broke at multiple locations into the fragments around 3-4 cm long.

For the calculation of mechanical properties equations from Table 1 are used [3]. In Table 2, the nomenclature for Table 1 is described. In Fig 2., the secant modulus is decribed.

Table 1: Used Equation

Stress	$\sigma_1 = \frac{F}{A}$	[MPa]	(1.1)
Strain	$\epsilon_1 = \frac{\Delta L}{L_o}$	[-]	(1.2)
Secant modulus	$E_t = \frac{\sigma_{\epsilon_{0.25}} - \sigma_{\epsilon_{0.005}}}{\epsilon_{0.25} - \epsilon_{0.005}}$	[GPa]	(1.3)

Table 2: Nomenclature used

σ_1	First principal stress	[MPa]
F	Force	[N]
A	Area	[mm^2]
ΔL	Change of length	[mm]
L_o	Initial length	[mm]
E_t	Secant modulus	[MPa]
ϵ_1	First principal strain	[-]
$\sigma_{\epsilon_{0.25}}$	Stress at 0.25 strain	[MPa]
$\sigma_{\epsilon_{0.005}}$	Stress at 0.005 strain	[MPa]
$\epsilon_{0.25}$	0.25 strain	[-]
$\epsilon_{0.005}$	0.005 strain	[-]

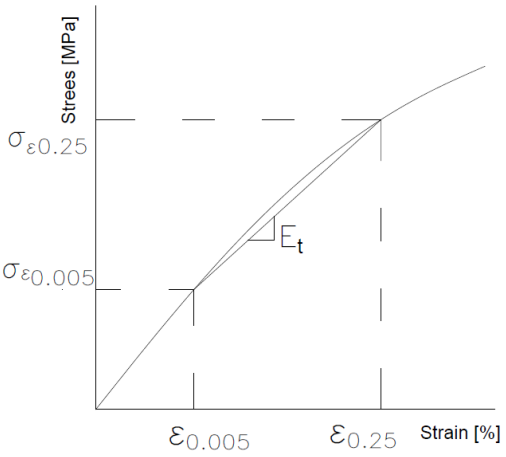


Fig. 2: Secant Modulus

For calculation of the Secant modulus the equation (1.3) is used. Optionally, the least squares method can be used.

Analysis Results

Results of tensile testing were evaluated acording to ISO-2602 [4] where monitored prameters are Young modulus, ultimate strength and ultimate strain.

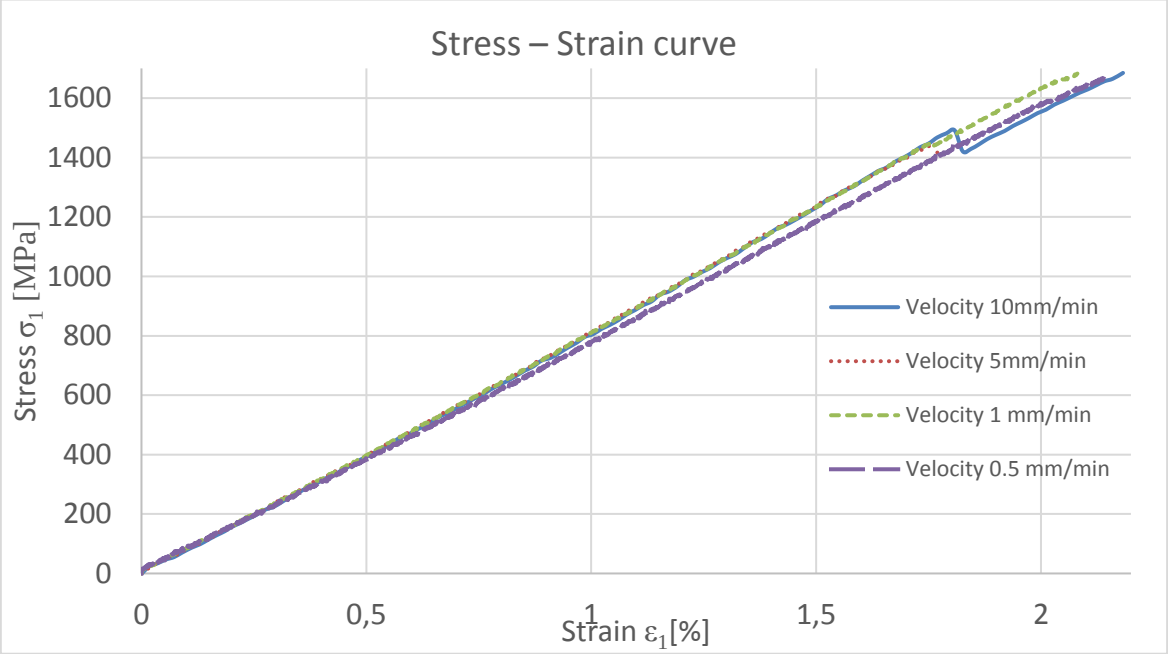
Data from tensile test has been statisticaly evaluated for loading velocity 5 mm/min, so results can be considered asaverage values with 95 percent confidence interval.

Table 3: Mechanical properties

Velocity [mm/min]	Secant modulus E_t [GPa]	Strength σ_1 [MPa]	Fracture Strain ϵ_1[-]
0.5	72938	1666	0.021
1	82925	1717	0.020
5	75918±933	1479±81	0.182±0.002
10	75342	1737	0.021

In the Table 3, mechanical properties for four loading velocities from 0.5 -10 mm/min are presented. Results show the small difference between individual strain rates. Maximum strength measured is 1479±81 MPa where this value exceeds 1.85 times the value guaranteed by producer of the 3D printer but the producer uses the different tensile test method D3039 [4].

In the Graph 1, stress-strain curves from testing are shown.



Graph 1: Stress – Strain curve σ_1 vs ϵ_1

In the Graph 1, the linear character of the material response on loading is shown. This corresponds to the behaviour of the brittle material with negligible plasticity effect. This fact is confirmed by the microscope image when the fracture inclination is approximately 45°.

The image of the fracture and the single diameter of the fiber are shown in Fig.3,4.

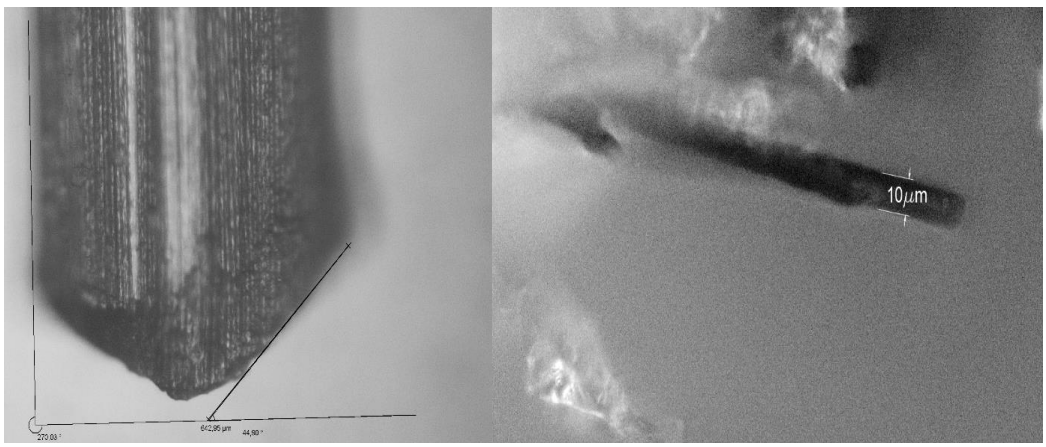


Fig 3,4: Fracture angle and Diameter of single Fiber

The fibre with the diameter of 10 μm is commonly used in industry and others applications According to ASTM D4018-99, the type of fracture is XGU where: X stands for eXplosive failure, G stands for location of failure near to the Grip and U stands for Unknown reason of the fracture.

Fracture into small fragments can be explained with the stress wave propagating along the length of the fiber. This could cause the cause fracture of the fiber on multiple locations.

Conclusion

This paper describes the tensile test of the carbon fibre for 3D printing. Resarch has shown that the method is apliccabe and gives good results with low scatering of values. This method describes newest trends in testing of materials.

Big advantage of this method is the simlipicity of specimen producution specimen. The form is applicable for other materials as well.

Microscopy images gave interesting values of fracture of carbon fibers when 45° correspond to a brittle fracture.

Next research is focused onto the prediction of fibers fracture using the acoustic emmisions and further on theeffect of fibre pre-heating on mechanical properties.

Additionaly, the effect of different clamping shape on mechanical properties of the fiber and the type of failure will be evaluated. This parameters are imporant for determination of mechanical properties of 3D printed composites.

Acknowledgement

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