Mechanical properties of structures produced by 3D printing from composite materials

František Bárnik[1,*], *Milan* Vaško[1], *Milan* Sága[1], *Marián* Handrik[1], *Alžbeta* Sapietová[1]

[1]University of Zilina, Faculty of Mechanical Engineering, Univerzitná 1, 010 26, Žilina, Slovakia

Abstract. By 3D printing it is possible to create different structures with different fiber-laying directions. These structures can be created depending on the type of 3D printer and its software. The Mark Two printer allows printing Onyx, a material based on nylon in combination with microcarbon fibers. Onyx can be used alone or reinforced with kevlar, glass or carbon fibers. This article deals with 3D printing and evaluation of mechanical properties of printed samples.

Keywords: composite material, composite structures, 3D printing, mechanical properties, Onyx

1 Introduction

Modern 3D printers are currently able to print components from composite materials and create composite materials. Composite material consists of at least two materials having different properties. It is an artificially created heterogeneous material. One component is a reinforcement which is usually rigid (its role is to deliver the composite resistance to external load forces) and the second component is a jointing material (matrix) that can be metal, ceramic or polymer. The matrix must absorb the reinforcement phase; it is continuous and usually less rigid. The matrix protects the reinforcement, keeps it in the desired position and transfers loading to the fibers. By integrating materials with different properties into one unit, a material with improved properties called a composite material is created [1].

Characteristic properties of most composite materials are lower weight, high strength, stiffness, toughness and high fatigue strength. Some composites may have better corrosion resistance, refractoriness and heat resistance, heat insulating properties, chemical resistance, lower thermal expansion, less deformation, and other properties over traditional homogeneous materials. Composite materials can thus be defined as an useful and effective material that is made by the macroscopic combination of the two components - the reinforcement and the matrix so that the components do not dissolve or incompatible with one another and retain their individual properties but act together for better technical properties [2]. The weakness of composite materials is their higher price and worse recyclability. Some composite materials have different mechanical properties in different directions (anisotropy) and aging at raising humidity and temperature [1, 3].

* Corresponding author: frantisek.barnik@fstroj.uniza.sk

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2 Production of composite materials

Composites and components made of composite materials can be manufactured using multiple technologies. The choice of technology depends on the shape of the component being manufactured, the requirements for its mechanical properties, the structure and surface quality, the cost of manufacturing the product and the required productivity [4]. Methods for producing composite materials are [5, 6, 7]:
- applying the liquid matrix to the surface of the fibers,
- powder metallurgy (cold pressing and subsequent sintering),
- vacuum or pressure impregnation of the reinforcement by the liquid matrix,
- infiltration of the fibers with a liquid matrix from the bottom side, from the top side and combined (pouring, filling or immersion of the reinforcement),
- wetting of the reinforcement in the matrix and its subsequent shaping,
- hot pressing (the matrix melts during hot pressing and the reinforcement is distributed in its volume),
- hot rolling (during continuous lamination by inserting a reinforcement placed between the sheets of the matrix),
- spraying a matrix with discontinuous reinforcement,
- gas phase infiltration (foam composite materials),
- infiltration of liquid reinforcement (coating of porous materials),
- electrolytic metal deposition.

One of the most recent methods of producing composite materials is nowadays manufacturing through 3D printing.

3 3D printing technologies

The 3D digital model must exist at the beginning of each 3D print process. This model can be created in various 3D programs. The model is "sliced" on individual layers in these programs and it is thus ready to be sent to the 3D printer reader. The printer applies the material to individual layers depending on the shape of the model and the printing process. There are several different 3D printing technologies that use different materials and a way to create the final object.

The materials are mainly different types of plastic, metal, ceramics and sand powder (similar to artificial sandstone). Plastic is currently the most widely used material - mainly ABS or PLA, even though there are a number of alternative materials such as Nylon [8].

There is no single solution for 3D printing, but it involves using different methods, procedures, and materials to achieve the desired result. There are various 3D printing technologies such as stereolithography, digital light processing, laser sintering (laser melting), fused deposition modeling (freeform fabrication), inject, selective deposition lamination and others [9, 10]. Below we will introduce only technology Fused Deposition Modeling, because this technology uses the Mark Two printer.

3.1 Fused deposition modelling / freeform fabrication

3D printing using extrusion of thermoplastic material is a simple and perhaps the most famous 3D printing process. The name for this process is Fused Deposition Modeling (FDM) - melting applied modeling. The process is based on the melting of the plastic fiber by means of a heated extrusion head and its application in a single layer to the platform. Each additional layer is applied with the previous links (since it is melted) and after cooling, the material hardens (Fig.1).

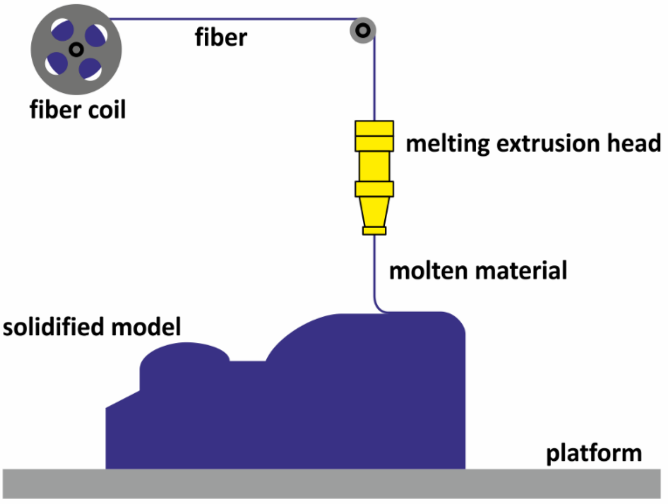

Fig. 1. FDM technology principle

The FDM process (or Freeform Fabrication - FFF process) also requires pushing the support structure to the 3D model if it contains protruding shapes. For FDM, this means using a second water-soluble material that forms a supporting structure, and after the 3D model is printed, it is easily washed it away from the model. An alternative is the use of material that is then simply separated from the model - it breaks off. Models printed by the FDM are accurate and the printing process is reliable. Printers using the FFF method print less accurate models, but their quality is constantly improving.

3.2 Mark Two printer

Mark Two printer is one of Markforged's desktop printers, which uses FDM technology when printing (Fig. 2). The printer is able to print from nylon and onyx separately, or at the same time they can be reinforced with a continuous fiber of carbon, kevlar, and glass. By selecting the reinforcement and the plastic matrix correctly, we can delete the time required for structural iterations, and the components can be used immediately after extrusion.

By reinforcing the parts with fibers in their 3D printing, the Mark Two printer in the printed part achieve unique strength, stiffness and durability. The 3D printing software comes with the printer, which makes printing simple and intuitive. Markforged Eiger software is powerful and easy to use in an internet browser. Mark Two printer also has a built-in touch screen that lets you manage your printer, easily connect to Wi-Fi and printing management [10]. Technical specifications for Mark Two printer are listed in Table 1.

Table 1. Technical specifications for Mark Two printer

Dimensions of the print [mm]	320×132×154
Plastic materials	Onyx, Nylon
Fiber materials	Carbon, Kevlar, Glass fiber
The minimum layer thickness [mm]	0.1

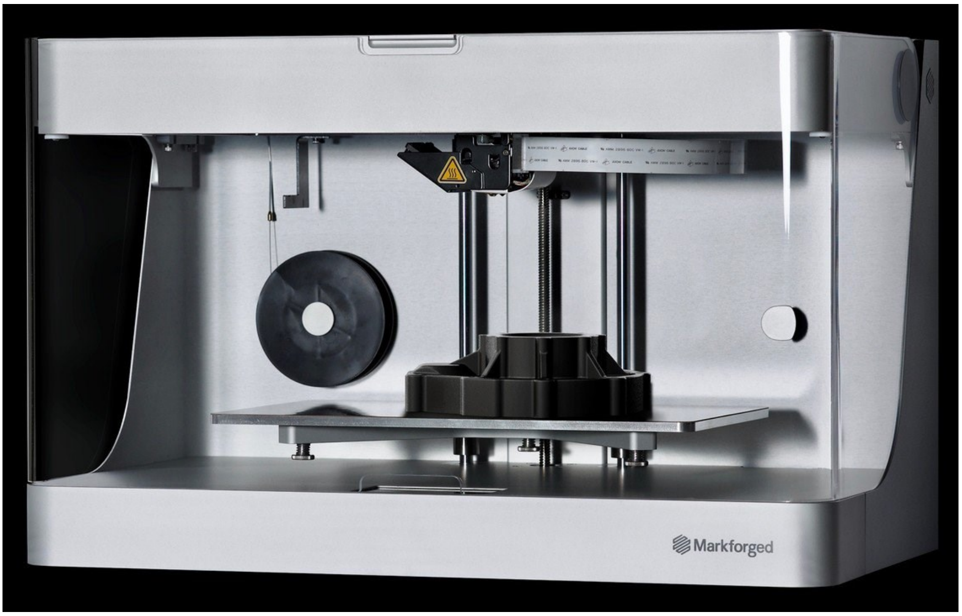

Fig. 2. Mark Two printer [10]

4 3D print structures and fills

Onyx is a material based on extremely rigid nylon in combination with micro-carbon fibers. It is stronger, harder and more resistant to heat than other plastic 3D printing materials. It is the ideal material for the production of parts that require good look in compliance with industry requirements. The material provides toughness of nylon with added stiffness of fiber reinforced plastic, heat resistance up to 145° C and a high resistance to adverse conditions. The final product does not require any post-processing because its smooth and matte surface does not look like a piece that was printed on a 3D printer.

Onyx can be used alone or reinforced with kevlar, glass or carbon fibers. The parts reinforced by these fibers extend beyond the boundaries of the normally 3D extruded plastic. According to Markforget, parts printed with Onyx are 30% stronger and stiffer than similar parts made in other 3D printers. All products printed with Onyx are ready for use right after printing. Material properties for Onyx reported by the manufacturer are shown in Table 2 [11].

Table 2. Mechanical properties of the Onyx

Young's modulus [GPa]	1.4
Yield stress [MPa]	36
Ultimate stress [MPa]	30
Flexural Strength [MPa]	81
Flexural Modulus [GPa]	2.9
Density [g/cm^3]	1.2

Mark Two is capable of printing different structures at different percentages filling of the printed components. However, the percentage fill must be less than 100% in order to print individual structures. The printer software allows you to choose from three types of filler structures: triangular, hexagonal and rectangular filler. Figure 3 shows the individual fill patterns displayed in the Mark Two printer software.

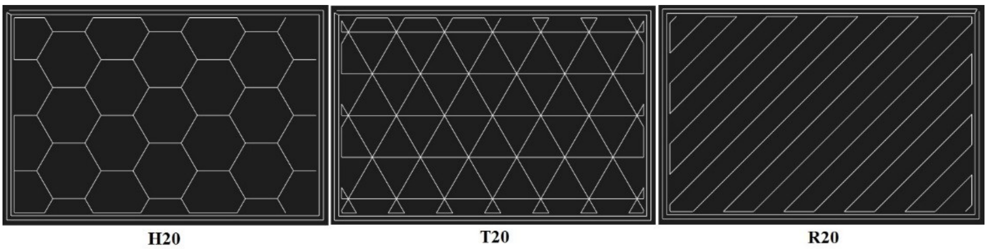

Fig. 3. Fill patterns displayed in the Mark Two printer software

The structure sampler at different percentages of the filler was made for illustration (Figs. 4-6). The triangular structure is denoted by the letter T, the hexagonal structure by the letter H and the rectangular fill by the letter R. Fill in % of the print is indicated by a number expressing the percentage fill (for example triangular filler of 60% = T60).

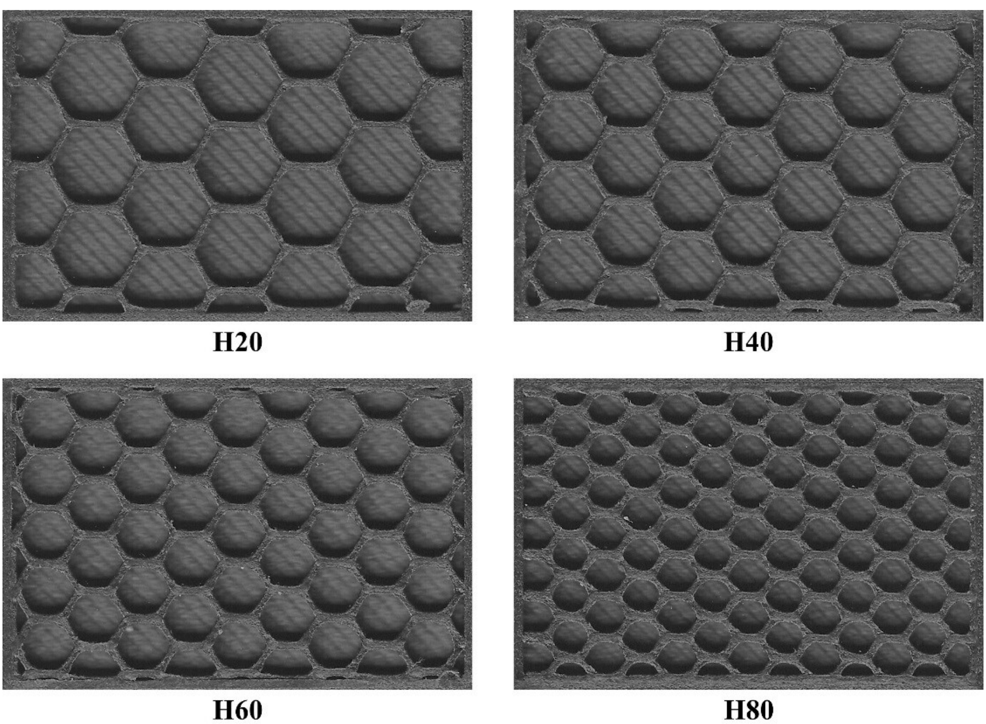

Fig. 4. Hexagonal structure

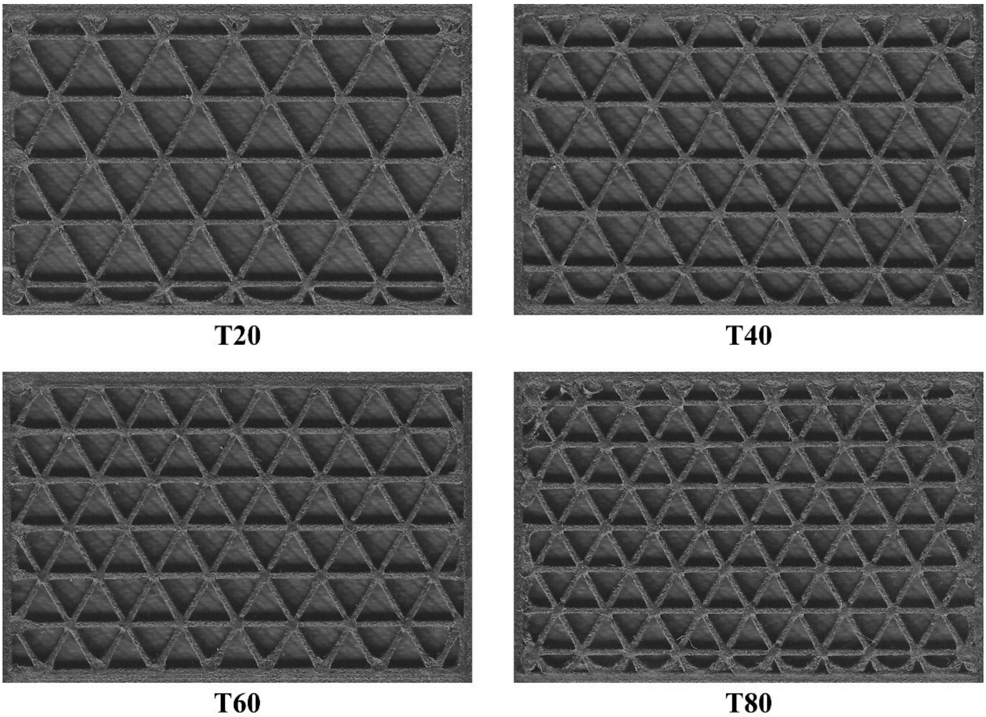

Fig. 5. Triangular structure

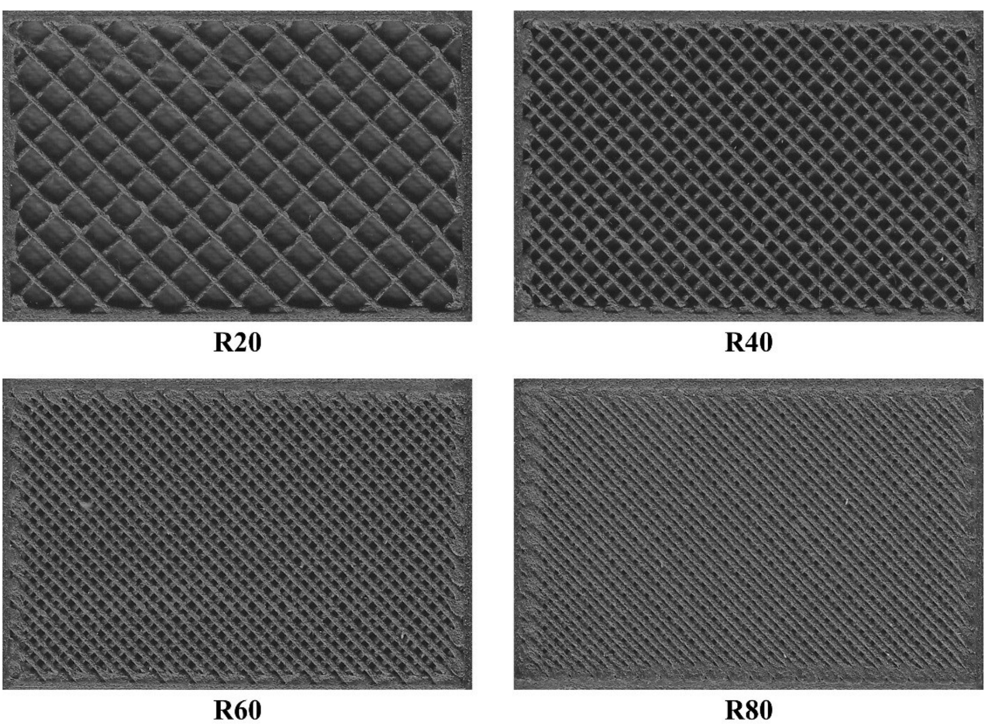

Fig. 6. Rectangular structure

For 100% filler and for the first and last layers of printing, the individual layers are placed at a 45° angle to the horizontal axis. The individual layers of the fillers alternate with each other. The directions of the individual layers placing schematically show Fig. 7.

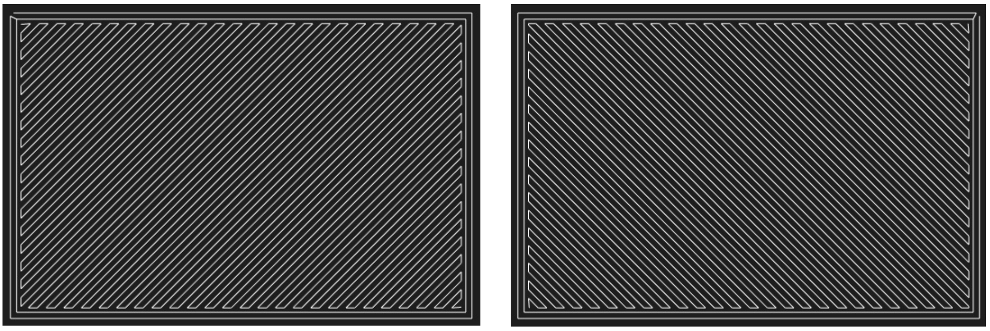

Fig. 7. Direction of placing of the individual layers; first layer (left) and second layer (right)

5 Experimental measurements

The influence of height and number of layers to the mechanical properties of the material was verified experimentally. Specimens for tensile tests were made on the basis of standard EN ISO 527-5 to verify the mechanical properties of the material Onyx. A series of tensile tests on specimens created by 3D printing were performed at 100% filled material [12-14]. Two types of layers were used to perform the tests (layer thickness 0.1 mm and 0.2 mm) and different layers were used (even and odd). The results of experimental measurements are reported in Table 3 and shown in Fig. 8. Figure 8 is defined as the stress-displacement dependence for the purpose of verifying the mechanical properties presented by the manufacturer.

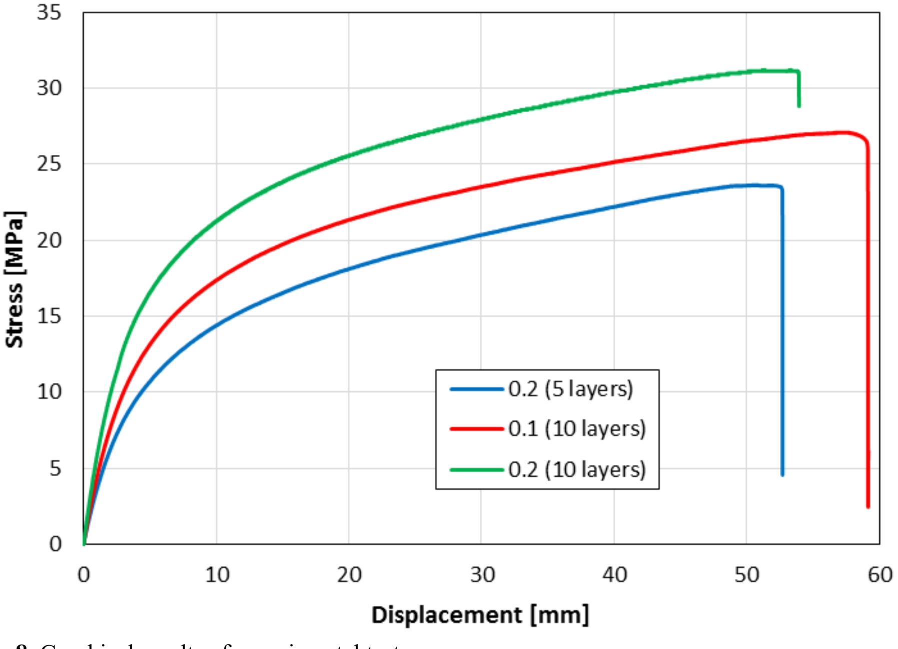

Fig. 8. Graphical results of experimental tests

Table 3. The results of experimental tests

Ultimate stress [MPa]	Layer thickness [mm]	Number of layers	Specimens dimensions [mm]
22.8	0.2	5	15×1×250
27	0.1	10	15×1×250
33.4	0.2	10	25×2×250

Ruptured specimens after tensile tests are shown in Figures 9 and 10.

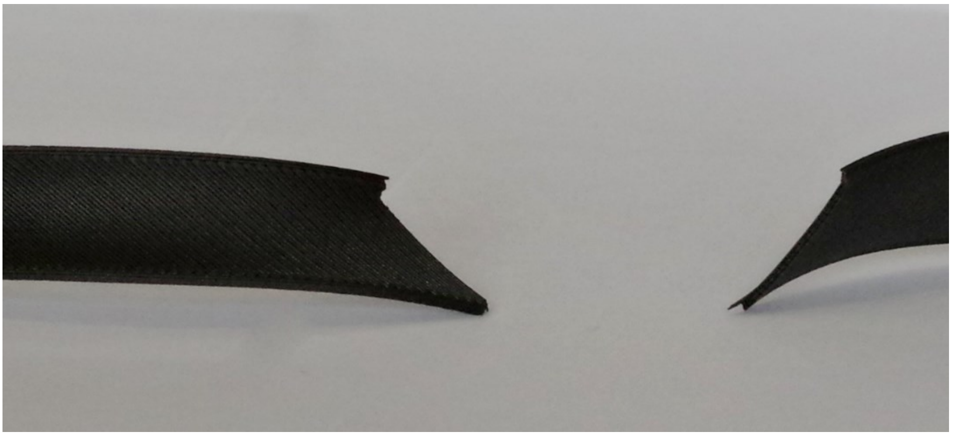

Fig. 9. Ruptured specimen made from 5 layers

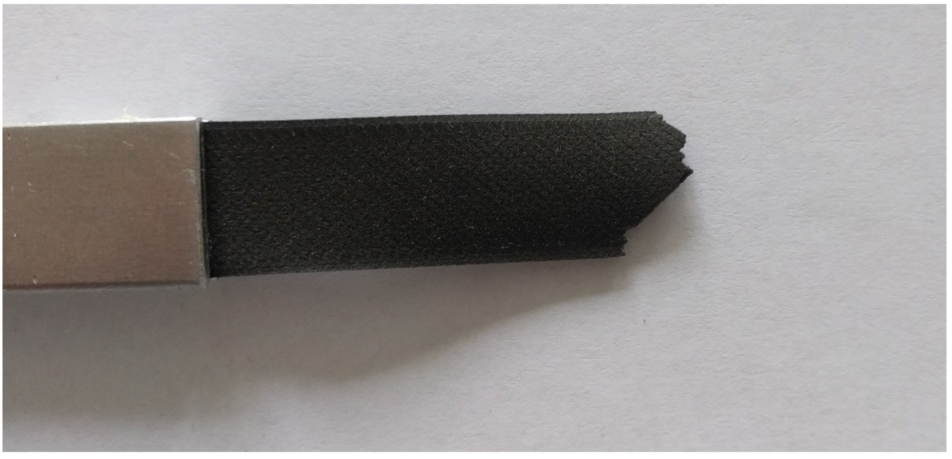

Fig. 10. Ruptured specimen made from 10 layers

A set of specimens of structures H20, T20 and R20 was also prepared to perform experimental measurements [15, 16]. Tensile tests were performed on these samples and the results were reported into Table 4. The graphical dependence (force-displacement) for individual fills is shown in Fig. 11. All specimens were made with the same external dimension (35×8 mm). Because the specimens were printed with a 20% fill and do not have a constant cross section, only the force needed to rupture them was evaluated.

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Table 4. The results of tests for 20% fillings

Structure type	Rupture loading [kN]
H20	1.9
T20	1.8
R20	2.1

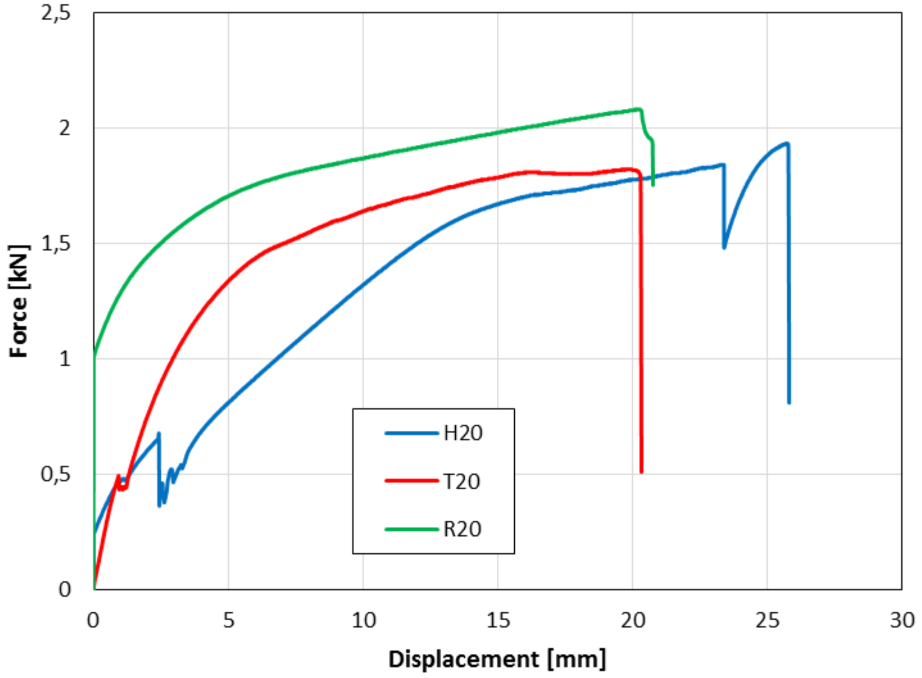

Fig. 11. The graphical dependence of the force on displacement for individual fills

The experimental results from the tensile tests show that the largest load at 20% of the filler takes specimens with a rectangular fill structure and the smallest load endures samples with a triangular fill structure.

6 Conclusion

Through a series of experimental tests, the mechanical properties reported by the manufacturer were verified. Based on the test results, it can be argued that the thickness of the layer has no significant effect on the mechanical properties of the material, but this does not apply when the number of layers is changing.

The mechanical properties of the material are lower in an odd number of layers than in the even number of layers. The specimen breaks along a plane in which a smaller number of layers are stored when the odd number of layers is used.

Based on experimental measurements, we recommend using the even number of layers when printing to maintain the best mechanical properties of the printed parts. Further experimental measurements should be performed on specimens with different fillings (40%, 60% and 80%) and structures (triangular, hexagonal and rectangular). The authors also plan to perform simulation of the tensile tests of the above specimens using FE analyzes in the ADINA software [17-25].

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