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Determination of Mechanical Properties of Materials Used for 3D Printing

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The presented paper deals with determination of mechanical properties of materials used for 3D printing (ABS, nylon and PLA). The theoretical part of the paper characterizes the static tensile test by which selected mechanical properties of samples were evaluated. The practical part of the paper characterizes the additive technology Fused Deposition Modelling, by means of which standardized plastic samples were printed on the 3D printer. The practical part also deals with analysis of selected mechanical properties of samples made by Soft Tooling technology. SG 2000 and SG 145 polyurethane resins were used for the production of samples using Soft Tooling technology. Individual samples were analysed using selected tests (tensile test and hardness test). Surface integrity parameters were also determined for 3D printing test specimens. Parameters (tensile strength, tensile modulus, tensile strength and hardness) that were statistically processed were selected for each test. The paper is finished evaluating the results obtained, which were compared with those given in the material sheets.

Keywords: mechanical properties, 3D printing, test specimen, tensile test, material.

1 Introduction

The first experiments with 3D printing technology were attributed to Dr. Kodam, who in 1980 described the technology of single layer production today known as Rapid Prototyping. The first functional 3D printer, based on SLA technology, was made in 1987 by Charles Hull. The name of this printer was SLA-1 [1]. Other 3D printing technologies have been developed at the University of Texas in 1988. This was SLS technology, where individual grains of powder were bonded by lasers [2, 3].

The technology of 3D printing came to the attention of the general public only at the beginning of the 21st century when kidney was the first think to be printed. The first kidney transplantation into the human body was done after 13 years. [1] RepRap was created in 2004 and 3D printers have become available to the general public. After the expiration of the patent in 2009, Stratasys occurred to the great development of 3D printers and many new 3D printing companies have emerged. 3D printing technology has been implemented in production (e.g. the first car was printed in 2010). Another great advance came in 2014 when 3D printing technology was used outside our planet. It was done at the International Space Station [1, 3, 4].

3D printing is still in the research phase. There has been a great deal of interest in 3D metal printing, which is already present used, for example, to manufacture automotive parts. The materials used in this technology are also undergoing major development. There are new types of materials that are further applied in production.

2 Static tensile test

The static tensile test is one of the most widely used tests used to evaluate mechanical properties of construction materials. The principle of this test consists in loading the test specimen slowly increasing the tensile force until the fracture. The sample is clamped in the jaws of the test apparatus so that the sample axis is identical to the jaw axis. The goal of the tensile test is to determine the deformation and stress parameters. The test is most often performed at room temperature (23 °C) as prescribed in EN ISO 6892-1 [5, 6].

Test specimens used for tensile test are called test rods. We divide the test rods according to the cross-section as flat and circular [6, 7].

The breaking strength R_m is the value of the stress, see (1), just before the neck formation. After exceeding the yield limit value, the load force begins to decrease even though the real stress relative to the real cross-section at the neck is increasing. The neck is still narrowing when fracture occurs and the test is completed [7]. The strength limit value (1) is an essential material characteristic by which structural materials are classified and divided. The strength limit value (1) is less suitable for structural calculations [6, 8]:

$$R_m = \frac{F_m}{S_0} \; [MPa] \quad (1)$$

R_m – tensile strength [MPa],
F_m – breaking strength [N],
S_o – initial cross-section [mm^2] [7].

Hook's law expresses the relationship between stress and relative extension. The Hook relationship is shown as a straight line in the tensile diagram. The value of the modulus of elasticity E (2) is the direction of the Hook line. The mathematical representation of the modulus of elasticity is (2) [6, 8]:

$$E = \tan(\alpha) \; [\mathrm{GPa}] \quad (2)$$

E – tensile modulus of elasticity [GPa],
α – angle formed by the Hook line with horizontal axis [°] [7].

Elongation A is the percentage of elongation ε_u. The ductility value is given by (3) [6, 8]:

$$A=100\cdot\boldsymbol{\varepsilon_u}=100\cdot\frac{\Delta L_u}{L_0} \; [\%] \quad (3)$$

A – ductility [%],
ε_u – final elongation [-],
$\Delta L_u = (L_u - L_0)$ – absolute increment of initial length after breaking[mm],
L_u – final length [mm],
L_0 – initial length [mm] [7].

3 Technology description of Fused Deposition Modelling

The default material for this 3D printing method is a wire spooled on a spool. The essence of this technology is the application of thin layers of material to each other [1, 9]. The wire is pushed into the preheated nozzle by means of pulleys, which causes it to shrink. The nozzle dispenses molten material to form a single layer. Upon completion of one layer, the pad is dropped by a predetermined value and the process of applying the next layer is repeated [9, 10].

This technology requires the construction of supports. The supports serve as a support for the building material in the formation of cavities and overhangs. The print head may be provided with two nozzles, one nozzle serving for dispensing the building material and the other for supporting material [10, 11, 12].

When the product is finished, it is removed from the pad. The next step is to remove the spots that occurred during the printing process. They are removed either mechanically or using soluble supports by dissolving in a special solution [11, 13].

4 Experimental part – mechanical tests.

The following materials (ABS, PLA, nylon, SG 2000, S G145 and SG 2000 + Al binder) were used for the tensile test. Because aging plays an important role in ABS, it has been decided that the mechanical properties of the material will be determined for both the material from 2013 (the material cartridge was supplied by the manufacturer) and material from 2018 (the cartridge was also supplied by the manufacturer). Materials ABS, PLA and nylon were made by 3D printing, materials SG 2000, S G145 and SG 2000 + Al are among the group of polyurethane resins used in Soft Tooling technology.

4.1 Making test samples

The test specimen shapes and dimensions were determined according to EN ISO 527-2: 2012. This standard specifies conditions for testing plastic materials and determining their tensile properties [14]. EN ISO 527-2: 2012 standard Czech Standard ČSN EN ISO 527-2 from 1996. The standard EN ISO 527-2: 2012 is prescribed for testing of samples made by injection molding, pressing, extrusion and casting. Since there is no standard for tensile samples for additive technology, this standard has been used.

For the tensile test, a test sample of type 1BA was selected, see Fig. 1. The main reason for selecting this sample was to save material and the associated cost of one sample. Another reason was the saving of time needed to make individual samples.

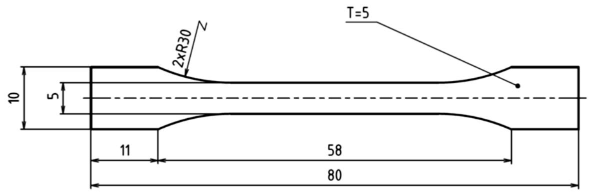

Fig. 1 *Test sample type 1BA*

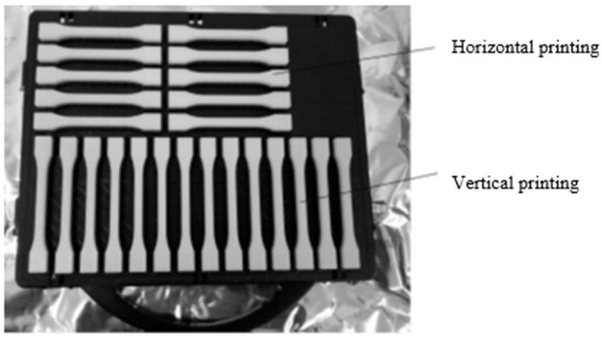

Fig. 2 *Samples printed vertically and horizontally*

In order to improve the statistical evaluation, 30 pcs of samples were manufactured from these materials (ABS with production year 2013, ABS with production year 2018, PLA, nylon). For ABS and nylon materials, these 30 samples were divided into two groups (horizontal printing and vertical printing).

The ABS samples, see Fig. 2, were made on an uPrint 3D printer from Stratasys. This 3D printer creates models using FDM technology. The printer is equipped with two nozzles, with the main nozzle providing the main building material and the other for support [15, 16, 17, 18].

According to the above, ABS and nylon materials were printed in two ways - horizontal printing and vertical printing. The main reason why the specimens were printed horizontally or vertically was to determine the strength characteristics with the different arrangement of layers against the load direction. The samples printed vertically, see Fig. 2, have the fibres perpendicular to the load-bearing direction and the samples printed horizontally, see Fig. 2, have the fibres parallel to the load force direction [15, 16, 17, 18].

The test pieces made by Soft Tooling technology were cast into a silicone mold. The silicone meld was made according to a model made on a 3D printer. It has been chosen as the material for making the silicone mold silicone RTV-4234-T4 Base. In order to remove the pores from the resulting meld, the molding material was placed in a vacuum chamber and depressurized as shown in Fig. 3.

***Fig. 3** The process of vacuuming the molding material*

4.2 Tensile test

The tensile test was performed on a Zwick Z100 tester. This device allows sample testing up to 100 kN. The test device is connected to a computer with a program via a data cable testXpert from Zwick. With this program, the input test parameters are set as speed loading, loading, starting sample dimensions and initial distance of clamping jaws. This program also serves to evaluate the progress of the test and the individual parameters such as strength, ductility, yield strength, modulus of elasticity and more.

In the testXpert program from Zwick, input data was set at the beginning of the experiment EN ISO 527-1: 2012. The clamping jaw spacing was set to 60 mm, and the initial thickness and width of the tapered section were also entered.

The test is automatically terminated at the time the sample breaks. TestXpert evaluates the required parameters and displays the results. Each sample has an assigned test number in its group named by material type.

The process is repeated until all sample types are measured. When the test is completed, the individual data is exported to excel, where further data can be processed.

4.3 Hardness test

The hardness test was performed for the following types of materials: ABS, PLA, nylon, SG 2000, SG 145, SG 2000+AL. The Shore D method was used to measure hardness. This method allows hardness measurements ranging from 10 to 90 units.

For the hardness test, cylindrical samples with a diameter of 40 mm and a height of 10 mm were prepared. Two samples were prepared for each material. The sample size was selected with respect to EN ISO 7619. The minimum indentation distance and the sample edge distance were observed. A total of 16 hardness values were determined for each material (16 values were equally divided between two samples).

4.4 Surface roughness measurement

Surface roughness was evaluated for materials made with 3D printing technology. For roughness measurements, samples of the same shape as for hardness measurements were made. Surface specimens were taken on an OLYMPUS MVX10 workshop microscope.

Spatial measurement and surface profile evaluation was performed with a Talysurf CLI 1000 instrument. The touch method of measurement was chosen for the surfaces to be analysed.

5 Evaluation of results achieved

The experimental part deals with the evaluation of achieved results from individual mechanical tests. The experimentally obtained parameter values are compared with the values given by the manufacturer. The breaking strength, the tensile modulus, the ductility, the surface roughness and the hardness are among the evaluated parameters.

The normal distribution was chosen for the evaluation of the measured quantities. Normal distribution was used in consultation with a statistician and optimization mathematician who performed data checking based on normal distribution criteria. Since the measured data fit the normal distribution criteria, it was used to generate a Gaussian curve and a confidence interval.

Individual quantities were statistically processed in the statistical program STATGRAPHICS, which allows evaluation of measured data by normal distribution.

Individual statistical parameters (arithmetic mean, variance, standard deviation and coefficient of variation) evaluated for individual mechanical properties were calculated according to the relations (4) to (8). The calculation was performed for all sample types in the same way:

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n} \tag{4}$$

$$s^2 = \frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1} \tag{5}$$

$$s = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}} \tag{6}$$

$$s_{\bar{x}} = \frac{s}{\sqrt{n}} \tag{7}$$

$$V = 100 \cdot \frac{s}{\bar{x}}\ [\%] \tag{8}$$

$\bar{x}$ – arithmetic mean,
n – number of elements of the statistical file,
x_i – index file element i,
s^2 – scattering,
s – Standard deviation,
V – coefficient of variation [%],
s_x – mean diameter error

5.1 Results evaluation for ABS material

ABS samples were divided into four groups (ABS Horizontal Printing 2013, ABS Vertical Printing 2013, ABS Horizontal Printing 2018, ABS Vertical Printing 2018), which were subsequently subjected to tensile testing. According to the above, the strength limit, tensile modulus, ductility, surface roughness parameters were evaluated for each material and hardness. In the following, tab. 1 shows the basic statistical parameters and their values for ABS vertical printing material 2013.

***Tab. 1** Basic Statistical Parameters of ABS Vertical Printing Material 2013*

Parameters	Tensile strength values	Module values of tensile elasticity	Elongation values
Diameter	25.40 MPa	1.13 GPa	4.06 %
Median	25.32 MPa	1.19 GPa	4.17 %
Scattering	2.31	0.04	0.19
Standard deviation	1.52	0.19	0.44
Variation coefficient	5.99 %	17.06 %	10.83 %
Mean diameter error	0.39	0.05	0.11
Minimal value	22.63 MPa	0.72 GPa	3.01 %
Maximal value	29.19 MPa	1.41 GPa	4.77 %

5.2 Surface texture evaluation for ABS material

Two different surfaces were selected for surface roughness evaluation. The first surface was upper (perpendicular to the nozzle) and the second was lateral (parallel to the nozzle).

To measure the 3D surface (spatial parameters of surface texture), the basic amplitude parameters Sa, Sq, St and Sz were selected for evaluation, see Tab. 2, which represent a group of spatial evaluation parameters and are based on the distribution of the surface coordinates coordinates.

From the 2D roughness parameters, the amplitude (height) parameters Ra, Rq, Rt and Rz were selected, see Tab. 2. The waviness was evaluated by the amplitude parameters Wa, Wq, Wt and Wz see Tab. 2. The values given here are for the surface without any adjustments (as the sample was pulled out of the 3D printer). Of course, the resulting roughness and waviness can be improved by, for example, grinding, polishing and flowering.

***Tab. 2** Measured 2D and 3D surface texture parameters for ABS material*

Parameters [μm]	S_a	S_q	S_t	S_z	R_a	R_q	R_t	R_z	W_a	Wq	W_t	W_z
Top surface	10.6	13.8	67.1	66.7	8.2	10.7	51.1	43.5	3.6	4.0	13.6	10.7
Side surface	18.7	22.1	85.3	85.1	18.7	21.9	76.6	73.6	1.7	2.0	9.0	4.4

Fig. 4 shows the 2D surface profile of the side printed surface. It can be seen from Fig. 4 that the resulting surface has a certain periodicity. This periodicity is due to the height of the individual layers. The printer on which this sample was made has a preset layer height of 0.254 mm. In a closer look at Fig. 4, it can be seen that the individual sinks are approximately repeated according to this value (0.254 mm).

The resulting surface roughness is significantly influenced by the printing parameters. The values reported herein can only be used for parameters (layer height 0.254 mm, print head temperature 293 °C, chamber temperature 75 °C and print speed 20 cm^3/hr) used in the manufacture of this sample.

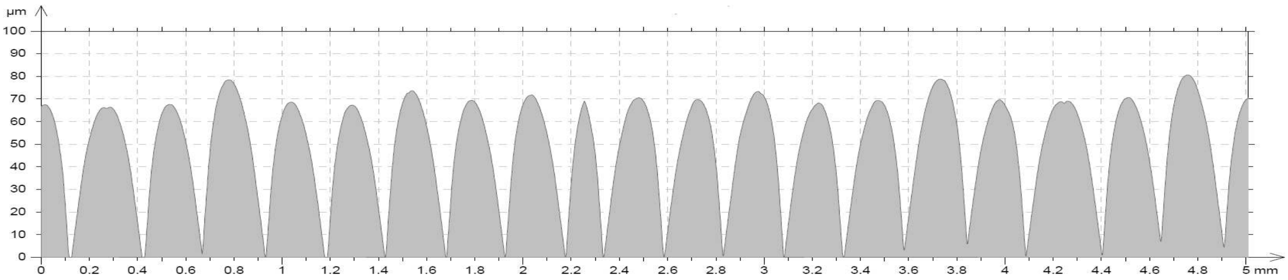

Fig. 4 *Surface profile of the measured area of the side surface*

Fig. 5 *3D surface representation of the upper surface*

Fig. 6 *3D surface representation of the side surface*

Figs. 5 and 6 show the 3D surface profile of the ABS material. It can be seen from Figs. 5 and 6 that the surface to be measured has a certain periodicity. This periodicity is caused by placing individual fibres side by side.

5.3 Evaluation of other materials tested

The evaluation of other types of materials was carried out in a similar manner to that of ABS. For SG 2000, only the tensile strength was known as the reference value given by the manufacturer, and therefore only the strength characteristics (tensile strength) were compared with the measured data. For other quantities (ductility, modulus of elasticity, hardness), basic statistical parameters were determined.

The surface texture was evaluated only for materials used for 3D printing such as ABS, PLA and nylon. Similar conclusions apply to PLA and nylon materials as for ABS.

6 Discussion to achieved results

Tab. 3 shows the lower 95% confidence intervals. Thus, if a value for a given material is selected from Tab. 3, 95 % will be fair value.

Tab. 3 *Measured 2D and 3D surface texture parameters*

Material	Rm [MPa]	E [GPa]	At [%]	Hardness [HShD]
ABS_H_2013	26.54	1.27	3.77	72.48
ABS_V_2013	24.56	1.03	3.82	
ABS_H_2018	23.34	0.79	4.48	
ABS_V_2018	23.28	1.16	4.49	
Nylon_V	40.43	0.92	14.76	71.96
Nylon_H	40.97	0.94	30.25	
PLA	52.07	1.37	4.19	80.38
SG 2000	28.28	0.82	5.10	70.04
SG 2000 + AL	18.67	1.30	1.35	70.74
SG 145	15.99	0.56	3.67	65.94

The overall assessment shows that the material with the highest strength value is PLA. At the same time, it is also apparent that the ductile material is nylon printed horizontally.

The difference with respect to its production date is apparent on the ABS material, see Fig. 7. ABS material with a newer date shows higher ductility values than the older material see Tab. 3. With regard to mechanical properties (especially ductility), it is recommended to use the most recent material (see date of manufacture) if the plastic model is intended. However, the older material has higher strength limits at the expense of ductility.

Tab. 3 also shows that the materials printed horizontally show higher values of mechanical properties, see Fig. 8. Generally, it is recommended to print models so that the direction of loading is the same as the laying direction of the layers (horizontal print).

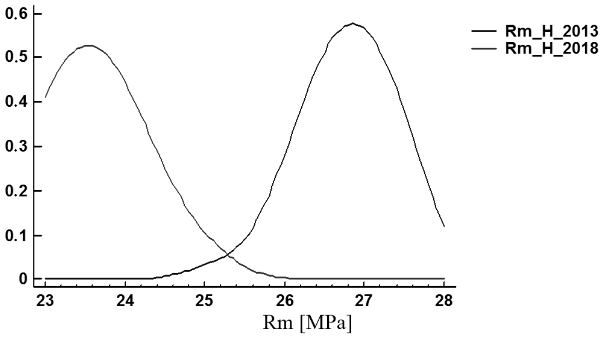

Fig. 7 *Comparison of the graphical dependencies of normal density tensile strength distribution for horizontal printing from material produced in 2013 and 2018*

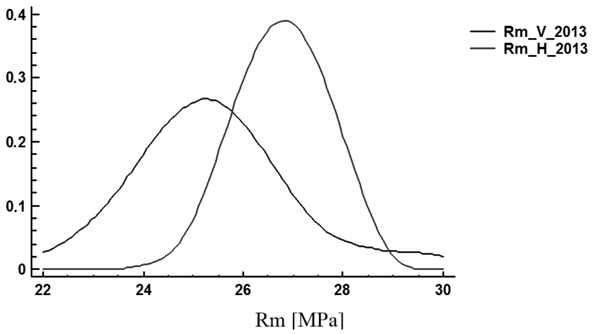

Fig. 8 *Comparison of the graphical dependencies of normal density tensile strength distribution for horizontal printing from material produced in 2013*

Tab. 4 *Percentage comparison of measured values and manufacturer's values*

Material	Rm [%]	E [%]	At [%]
ABS_H_2013	-17.1	-43.0	-46.1
ABS_V_2013	-5.5	-52.8	91.0
ABS_H_2018	-27.1	-64.6	-36.0
ABS_V_2018	-10.5	-46.8	124.5
Nylon_V	-15.8	-19.2	173.3
Nylon_H	-22.7	-28.2	218.4
SG 2000	-29.3	X	X

Tab. 4 shows the percentage comparison of the measured values and the values given by the manufacturer. Negative values indicate a decrease with respect to the values given by the manufacturer (the manufacturer's declared value is calculated as 100 %), while positive values show an increase. The comparison was made for materials and parameters for which the reference value was known.

7 Conclusion

The aim of the experiment was to determine and verify selected mechanical properties of materials (ABS, PLA, nylon, SG 2000, SG145 and SG 2000 + Al binder). For some materials, material characteristics have not been specified by the manufacturer. It is clear from the results of this experiment that the material characteristics of the tensile strength and tensile modulus show a decrease in values relative to the values given by the manufacturer in the material sheets. In contrast, the ductility of materials (ABS and nylon) printed vertically shows an increase in value.

At the same time, the relationship between the surface profile and the parameters used in 3D printing technology by the Fused Deposition Modeling method was also confirmed. The values obtained when evaluating the surface profile can only be used for the given technology and given conditions. When changing the print parameters (nozzle diameter, layering height, and laying speed), the individual roughness parameters would be different.

In the experiment, it was confirmed that the ABS material showed a change in properties depending on its production date. The change in properties is favourable due to its strength properties, but older material exhibits a decrease in ductility.

From the measured data it was proved that the difference between individual types of printing (horizontal and vertical printing) is not negligible in terms of mechanical properties. In view of the more advantageous material characteristics, it is better to use the printing method in the direction of stress, what is horizontal printing.

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