ANALYSIS OF TEST PLASTIC SAMPLES PRINTED BY THE ADDITIVE METHOD FUSED FILAMENT FABRICATION

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ABSTRACT

The presented paper deals with the influence of coloring additives and the setting of process parameters of 3D printing on the mechanical and surface properties of samples made of PLA material. The paper characterizes the process of filament production, as well as the printing of normalized samples on a 3D printer using the additive method Fused Filament Fabrication (FFF). The effect of 3 types of coloring additives is evaluated on the basis of tensile test, hardness test and surface analysis. The evaluated quantities are especially loading force, yield stress, hardness, surface texture, roughness and waviness. The influence of the percentage of sample filling with respect to the mechanical properties of the material is also evaluated. The paper is completed assessing achievements of the results achieved and an overall recommendation for filament manufacturers and users of 3D printers.

KEYWORDS

3D printing, PLA, filament production, coloring additive, tensile test, hardness test, surface texture

1 INTRODUCTION

3D printing technology is experiencing one of the sharpest growths in the technological world of the 21st century. It became known especially in 2004 thanks to the project of self-replicating printers RepRap. Stratasys' Fused Deposition Modeling (FDM) patent expired in 2009 and 3D printing has become more accessible to the wider public [KLOSKI 2017] [Stratasys 2019].

3D printing is one of the additive methods of production, when the gradual addition of material creates the desired three-dimensional object. The field of application of this additive technology is constantly growing. It meets the requirements of a modern customer, such as high accuracy, speed of piece production, and due to minimal waste also environmental friendliness. The technology allows the creation of a large number of similar prototypes without the need for special molds or tools. The potential of 3D printing is constantly evolving in healthcare, where it is used in the production of implants or the printing of living cells. The technology is applicable to a wide range of materials, such as plastics, special concrete, metals, etc. [KLOSKI 2017] [PALERMO 2013] [SEDLAK 2016] [SEDLAK 2020] [SEDLAK 2020] [ZEMCIK 2019].

Due to the above-mentioned reasons, higher demands are placed on mechanical and surface properties, health safety and other parameters of used materials. Additive manufacturing is nowadays widely used for producing end-user products thus technical properties and thermal behavior of final products must be well known in advance, during design stage [ATTARAN 2017]. Many authors have dealt with evaluation of the most often used 3D printing materials in terms of their mechanical and thermal behavior [ALSSABBAGH 2017] [CANTRELL 2017] [DIZON 2017] [RANEY 2017] [ZALDIVAR 2017]. Based on these researches, we are able to find the most suitable basic materials for special reasons. Polylactic Acid (PLA) is one of the most popular materials for 3D printing despite some shortcomings such as its natural brittleness [KOH 2018].

The basic properties of the printing materials are not the only parameter that affects the quality of outputs. Setting of printing process parameters influence the mechanical properties of printed products just as significantly. Tontowi et al. [TONTOWI 2017] tested tree printing process parameters (layer thickness, temperatures and raster angles) using Taguchi and Response Surface Methods for PLA as a filament material. Fernandes et al. [FERNANDES 2018] add the fourth process parameter, which is infill density, and studied the influence of each on mechanical properties of printed PLA products using analysis of variance. Fernandes et al. [FERNANDES 2018] and some other authors [HUYNH 2019] [LANYOTTI 2015] [TYMRAK 2014] agree on the similar values of the above mentioned process parameters, combination of which ensures the best values of individual mechanical properties of tested PLA materials. Namely temperature equal to 220 °C, raster angle equal to 0° or 90°, layer thickness equal to 0.1mm – 0.15 mm and infill of 60%.

Besides the material properties and process parameters, various additives also influence the material behavior significantly. Color pigments added to the PLA filament cause produced parts are often out of the defined features. Wittbrodt and Pearce [WITTBRODT 2015] tested several samples of the same material and discovered that their tensile strengths fluctuated. After a deeper analysis, a strong relationship between tensile strength and percent crystallinity of samples of different colors was proven. Other researchers [KOH 2018] [SOARES 2008] [SCHWARTZ 2020] [SPINA 2019] [VALERGA 2017] also confirm that different PLA colors lead to different quality of 3D printed products under the same process conditions. Color additive as well as the coloring process itself can cause mentioned deviations. Therefore, it is necessary to consider both when evaluating the expected quality of printed products.

The paper examines the properties of samples produced by the additive method Fused Filament Fabrication (FFF), which, thanks to affordability, a wide range of mechanical properties and low printing intensity, has gained a leading application among domestic users and industrial enterprises [KLOSKI 2017]. The main goal of this study is to evaluate the influence of coloring additives and printing process parameters on the mechanical and surface properties of parts produced from PLA material. The study brings a complex view that enables better estimation of final part properties already at design stage. The achieved results can be also used for completing some of the missing technical specifications of individual types of filaments and will help users choose the most suitable material for specific purposes.

2 DESCRIPTION OF THE FUSED FILAMENT FABRICATION ADDITIVE METHOD

The principle of the method is the application of thin layers of molten thermoplastic wire (filament) over a printing head (extruder), which has a heated nozzle at the end. Shifting and precise dosing of the filament is realized by a stepper motor. The molten material is applied layer by layer to the substrate, where it solidifies rapidly. For optimal setting of the nozzle temperature, it is necessary to take into account not only the type of material, but also the printing speed or the diameter of the filament fiber. During printing, the extruder moves in a horizontal plane. After finishing the layer, it rises by the height of the newly formed layer, the printing is repeated until the model is created. Alternatively, the vertical movement is realized by lowering the base plate [GUPTA 2019] [PISKA 2009] [SEDLAK 2016] [SEDLAK 2020] [SEDLAK 2020] [ZEMCIK 2019].

The additive FFF method requires the use of supporting material. Depending on the material used, the supports are removed either mechanically or chemically, e.g. by immersion in a special solution. The FFF additive method uses non-toxic materials for the construction of models, which enables its safe placement in households, schools or offices. Frequently used additive materials are e.g. PLA and ABS [GUPTA 2019] [PISKA 2009].

3 STATIC TENSILE TEST OF PLA

The aim of the static tensile test is to evaluate the mechanical properties of the materials. The principle is to load the test bar with a slowly increasing tensile force up to the breaking moment. During the test, the force load applied to the test piece and the distance between the jaws of the loading device shall be measured. The result is determined deformation and stress characteristics, usually shown by a deformation curve or a working diagram [BEHALEK 2016] [MACHEK 2014] [MORAVCIK 2015].

The test material passes through four phases during the tensile test. The stress shown on the deformation curve is usually defined as the ratio of the loading force F and the undeformed cross-sectional area S_0. It is therefore an agreed stress σ (see relationship 1). The actual stress is higher because the cross-sectional area decreases by deformation [BĚHÁLEK 2016].

$$\sigma = F / S_0 \qquad [\mathrm{MPa}] \qquad (1)$$

Other parameters used to evaluate the mechanical properties of test materials include the relative elongation ε (see relation 2), or nominal relative elongation εt (see relation 3).

$$\varepsilon = (\Delta L_0 / L_0) \cdot 100 \qquad [\%] \qquad (2)$$

$$\varepsilon_t = (L_t / L) \cdot 100 \qquad [\%] \qquad (3)$$

Where L_0 is the initial measured length of the test piece [mm], ΔL_0 is the increase in the initial length of the specimen [mm], L is the clamping distance between the jaws [mm], and L_t represents the increase in the clamping distance between the jaws [BEHALEK 2016].

4 EXPERIMENTAL PART – PRODUCTION OF FILAMENTS AND 3D PRINTING OF SAMPLES BY FUSED FILANENT FABRICATION METHOD

The filament production process consists of three phases, which are filament extrusion, cooling in water and winding on a spool. For the production of test filament was used experimental line Chemosvit Fibrochem, s.r.o. company based in Svit. The core of their production is the production of polypropylene fibers called Prolen for various applications. The production process of polypropylene fibers and 3D filaments has a common basic principle. Thanks to this, it was possible to use the experimental line for the production of filaments after adjusting the parameters and minor modifications to the equipment of the experimental line. PLA filaments are available in a variety of shades, which is especially useful when printing multi-color decorative prints. For this reason, the effect of coloring additives on the mechanical and surface properties of the prints was tested. Red organic pigment, black inorganic carbon black and gold organic granular dye were tested. The proportion of dye in the granulate of the PLA base material was 2%. A filament with a diameter of approximately 1.75 mm was produced. The filaments produced in this way were subsequently used for 3D printing using the PRUSA i3 MK3 device. It is an open, popular and affordable 3D printer among users. "Rectilinear" with a fiber orientation at an angle of +/- 45° was chosen as the filling pattern. The printing temperature was 225 ° C and the heating pad temperature was 60 ° C [SEDLAK 2015] [SEDLAK 2016] [SEDLAK 2017] [SEDLAK 2020] [Stratasys 2019] [WOHLERS 2016] [ZEMCIK 2019].

4.1 *Parameters of test specimens*

The shapes and dimensions of the tested samples were determined on the basis of the EN ISO 527-2: 2012 standard. This standard specifies conditions for testing plastic materials to determine their tensile properties. EN ISO 527-2: 2012 is primarily intended for testing specimens made by injection molding, extrusion, casting and compression molding, and since there is no direct standard defining tensile testing for specimens made by additive technology, this standard has been chosen. A type 1BA sample was selected for testing (see Fig. 1). The main reason for selecting a sample with smaller dimensions is the saving of material and the associated reduction of costs. Another reason is the saving of time required for the production of samples [CSN EN ISO 527-1 2012] [CSN EN ISO 527-2 2012].

Each series of samples subjected to the tensile test consists of 8 samples. Their number was chosen in an effort to achieve the most relevant results in terms of cost and time. A total of 128 samples (Tab. 1) were evaluated in the experiment investigating the effect of the percentage of sample filling and coloring additive.

Filament	Infill percentage [N]	No. of samples [-]
100 % PLA	25 / 50 / 70 / 100	8 / 8 / 8 / 8
Red	25 / 50 / 70 / 100	8 / 8 / 8 / 8
Black	25 / 50 / 70 / 100	8 / 8 / 8 / 8
Gold	25 / 50 / 70 / 100	8 / 8 / 8 / 8

Table 1. Number of samples

The input material used for our study is 100% PLA, specifically PLA3D-173-MK. Some samples were coloured by the following organic and inorganic pigments:

- organic gold pigment in form of pellets marked STAPA Mastersafe Gold 10103 RG
- organic red pigment in form of pellets marked Cromophtal red 3890
- inorganic black pigment in form of soot marked PRINTEX ALPHA

Input material is purchased form external supplier in form of dried pellets. Pellets are stored in airtight containers. No additional drying was applied. All tested samples were flatwise oriented (Fig. 1).

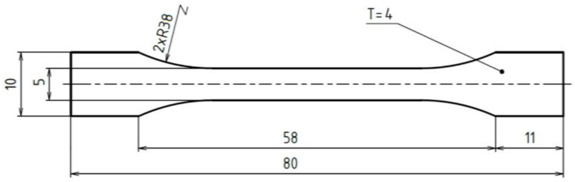

Figure 1. Type 1BA test specimen

Tab. 2 includes process parameters of 3D printing that were used for printing all 128 tested samples.

Infill pattern	Rectilinear (± 45°)
Infill percentage	25 / 50 / 70 / 100 %
Printing temperature	225 °C
Templerature of heating pad	60 °C
Bottom layer thickness	0.20 mm
Other layers thickness	0,15 mm
No. of solid infill layers (top / bottom)	7 / 5
3D printing speed	45 mm/s
Number of perimeters	4
Cooling	100 %

Table 2. Process parameters of printing all samples

5 EXECUTION OF TENSILE TEST

The tensile test was performed on a Zwick Z100 tester. The maximum allowable value of the machine load reaches 100 kN, which meets the requirements for this experiment. The device is connected to a computer with testXpert from Zwick via a data cable.

After selecting the EN ISO 527-1: 2012 standard in this program, certain input parameters were automatically filled in. Subsequently, the initial distance of the clamping jaws was set to 60 mm. Also, the preload value of each sample was zeroed before the test. Each test bar was measured with a digital caliper before loading. The dimensions in the narrowed, i.e. specific part of the sample were measured. The sample thickness values in millimeters are described in the interval (3.91; 4.11) and the sample width values in millimeters are the interval (4.97; 5.26). After setting the test parameters, a test rod was inserted into the test device.

When clamping the specimens to the jaws of the test rig, it shall always be ensured that the longitudinal axis of the test bar coincides with the axis of the test rig. During the clamping itself, the sample is first inserted between the lower jaws, which are then pressed against the surface of the sample using a lever mechanism. After checking the parallelism of the axes, the upper clamping jaws will also be pressed. The loading speed of 30 mm.min^{-1} according to the CSN EN ISO 527-1: 2012 standard was chosen for testing.

During the test, the testXpert program records the dependence of the jaw distance on the applied force. The evaluated quantities include e.g. ultimate stress, tensile modulus or maximum loading force, which was considered during our experiment. To successfully complete the test, it is essential that there is a break in the measuring part of the test bar. Only data from such broken samples are further evaluated.

5.1 *Tensile test results*

This section evaluates the results of examining the effect of the coloring additive and the percentage of filler on the mechanical properties of the test bars. A total of 128 tensile tests in 16 series of samples are evaluated. For the most accurate results, each series includes 8 samples. The value of the maximum force of the individual columns in Fig. 2 and Fig. 3 is calculated as the mean value $\bar{x}$ with the corresponding standard deviation *s*.

The magnitude of the maximum loading force that the test specimens reached before breaking is described in Tab. 3. The strength is evaluated for filaments with gold, red, black coloring additives and for filaments made of 100% PLA. Data for samples with 25, 50, 70 and 100% fill percentages are shown.

Filament	**Loading force [N]**			
Gold	398.2	401.9	426.2	555.2
100 % PLA	349.1	466.7	391.9	504.7
Red	475.7	457.8	523.6	642.1
Black	262.2	229.6	287.6	344.5
Fill rate	**25 %**	**50 %**	**70 %**	**100 %**

Table 3. Values of the loading force acting on the sample

Table 3 shows that the values of the force load are affected by the percentage of filling, but also by the coloring additive. As the volume of material in the test specimen increases, so does the maximum loading force. This effect is described in more detail in the following Fig. 2. From Tab. 3 is also clear that by adding a coloring additive to the base material, it is possible to increase or decrease the value of the loading force. The effect of additives on the loading force is described in more detail in Fig. 3.

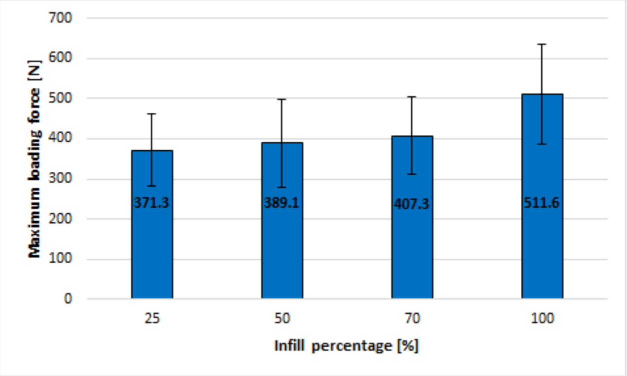

Figure 2. Dependence of the loading force on the percentage of the sample filling

As shown in Fig. 2, with increasing percentage of filling, the maximum tensile force with which it is possible to load the test specimen also increases. The maximum loading force is achieved by a completely filled sample. The values of the loading forces of the individual columns in Fig. 2 and Fig. 3 are mean values from Tab. 3. From Fig. 2 shows that the most significant increase in loading force occurs between 70% of the fill and the full sample. The difference against the completely filled sample in this case is 20.5%. Conversely, in the case of samples with a fill percentage of 25, 50 and 70%, the increase in strength is not so significant.

Based on these findings, it is possible to recommend that in the case of lightly loaded prints, it is best to set the print to a fill percentage of 25%. This reduces the cost of the filament used and at the same time shortens the printing time. For printing of components subjected to tensile stress, it is suitable to use a printout with 100% filling, which will enable the achievement of the highest values of the loading force for a given material.

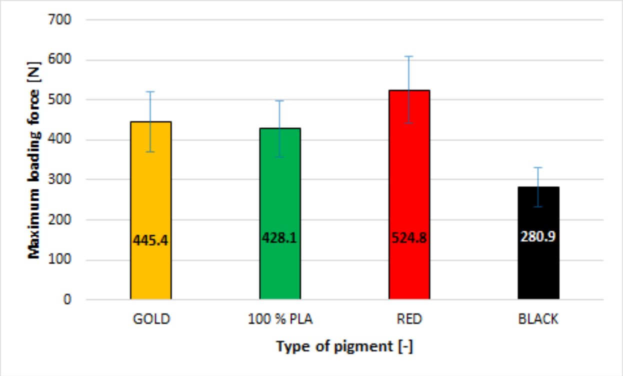

Figure 3. Influence of coloring additives on the loading force acting on the sample

From Fig. 3 shows that the coloring additive has a significant effect on the mechanical properties of the prints. The highest values of force loading were achieved by samples from the filament with a red additive, while the force increased by up to 22.5% compared to the base material. There was a less significant increase in the load due to the gold additive, by approximately 4%. While the addition of black additive reduced the load by up to 34.5%. Samples with a black additive thus perform significantly worse in the tensile test than samples from 100% PLA.

A tensile diagram is used to plot the dependence of the agreed voltage on the nominal relative elongation. This diagram is one of the basic outputs of the tensile test and for selected prints with a 100% fill share is shown on Fig. 4.

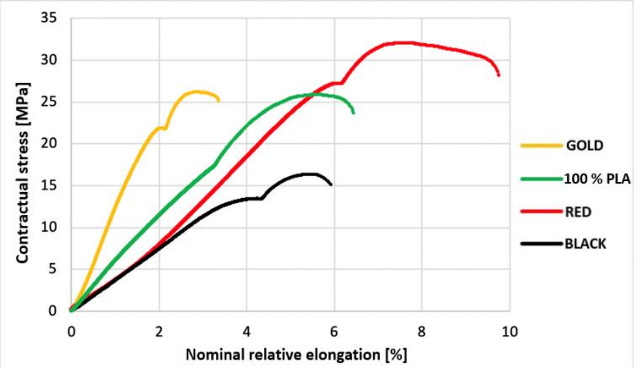

Figure 4. Tensile diagram

It is clear from the tensile diagram that the highest values of the yield strength, as well as the nominal elongation, were reached by the red filament sample. The gold color sample reaches the second highest value of the yield strength, but at the same time the lowest nominal relative elongation. Based on Fig. 4, therefore, there is no dependence between the agreed voltage and the nominal elongation.

This shape of the curve is unusual for PLA material, but in the tensile test we cannot determine with certainty what caused the change in the slope of the curve. Due to many factors such as setting the printing parameters (printing direction, adhesion of individual layers, setting the thickness of individual layers, blow setting, nozzle speed), possible influence of individual additives on chemical homogeneity of material, we can not assess and clearly determine the cause of change. However, since this change occurs in all curves, it can be said that this anomaly is caused by the possible inhomogeneity of the individual layers in the test body with the influence of the amount and shape of the filling in the sample. To prove this phenomenon, additional tests would be needed, where the individual print parameters will change and test the effect of the change on the course of the tensile test.

6 PERFORMING A HARDNESS TEST

An apparatus from Bareiss Digi test II was used for the hardness test. For measurement, the method Shore D was used. Load force was 4536 g, dwell time 15 s. When measuring with the Shore D method, this instrument uses a different measuring principle, which allows the measurement of variously curved surfaces. This device uses measurements according to these standards (DIN ISO 7619 / DIN ISO 48, ISO 48-2 / 3/4 / ASTM D 2240 / ASTM D 1415 / NF T 51-174 / NF T46-003-4 / DIN ISO 48- 4 / NF T51-174 JISK 6253, DIN ISO 27588). Unlike conventional hardness testers, which are limited to measuring flat surface samples only, the Bareiss digi test II allows hardness testing even on complex surfaces with automatic surface detection technology.

Based on an expert consultation with an employee of the company providing the test equipment, it was decided that, in order to reduce costs, the same samples would be used as in the tensile test. Samples of 100% PLA and with mixed red, black and gold coloring additives were tested. The percentage of sample filling was 25, 50, 70 and 100%. Each series contains 6 samples with two measuring points on the sample located in the middle of the extended parts of the samples.

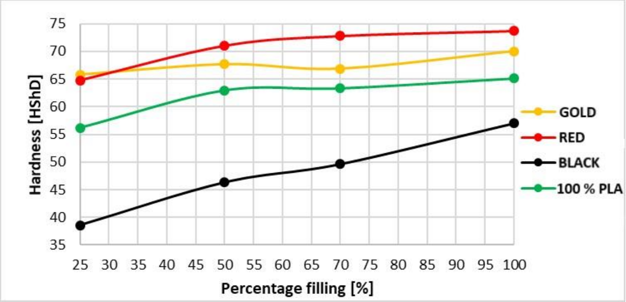

Figure 5. Influence of the percentage of filler and coloring additives on the hardness of the sample

The dependence of the hardness on the percentage of filler, for different coloring additives, is described in Fig. 5. The values plotted in this graph represent the mean values of each of the 12 measurements in the series. The graph shows a clear increasing trend of hardness values with increasing percentage of sample filling.

The highest hardness values are achieved by samples completely filled with material. Overall, the highest hardness of 74±2 HShD is achieved by the red sample with a 100% filler content. The least significant increase in hardness was recorded by the sample with the gold coloring additive. With an increase in the percentage of filling from 25% to 100%, the hardness increased by only 5 HShD. On the contrary, the most significant increase in hardness from 39±1 HShD to 57±2 HShD at 100% fill was recorded by a sample with a black coloring additive.

Under the given conditions, the addition of red and gold coloring additives increased the values of the measured hardness. On the contrary, by adding a black additive, the hardness values were significantly reduced.

7 SURFACE TEXTURE ANALYSIS

The surface texture was determined using a Talysurf CLI 1000 instrument, and the results were evaluated using TalyMap Platinum software. The tactile measurement method was chosen for the analyzed surfaces. Four samples made on a 3D printer were analyzed, their dimensions were the same as in the tensile test. All samples had a fill percentage of 100%, but differed by an additional coloring additive. Samples with red, black and gold coloring additives were evaluated, as well as a sample of 100 % PLA.

Each material was represented by one test sample. The measured points were on the top and bottom of the sample when the sample was oriented flat. One measurement was performed on each surface, which was always in the middle of the clamping part of the sample. The last measuring point was located on the side surface in the measuring part of the sample.

As part of the 3D surface measurement (spatial parameters of the surface texture), the basic amplitude parameters Sa, Sq, St and Sz were evaluated, which represent a group of spatial evaluation parameters and are based on the distribution of heights of the surface profile coordinates. Amplitude (height) parameters Ra, Rq, Rt and Rz were determined from 2D roughness parameters. The undulation was evaluated by the amplitude parameters Wa, Wq, Wt and Wz [CSN EN ISO 4287 2012] [CSN EN ISO 25178-2 2012].

7.1 *Results of 100% PLA sample surface texture analysis*

The 3D areas of the evaluated areas of the sample from 100% PLA are shown in Fig. 6. The upper surface (left) has a smooth, periodic surface formed by protrusions of circular cross-section having the same diameter (same microgeometry). Furthermore, relatively deep depressions are visible between the protrusions. In the left part of the evaluated upper area there is a clear dominant protrusion with a different orientation and a sharp top. In this case, it is an incorrectly placed filament on the surface of the print.

The lower surface (in the middle) in Fig. 6 is characterized by oriented microgeometry of protrusions and depressions, but with a pronounced morphology of protrusions that have sharp peaks. Larger depressions can be observed in the lower right part of the evaluated area. The directions of the protrusions of the top and bottom surfaces are identical.

The 3D representation of the side surface of the sample shows a different microgeometry of the surface, which is formed by dominant, oriented protrusions, on the surfaces of which other smaller protrusions oriented in the shape of a helix are visible. The morphology shows a certain periodicity, resp. repetition of protrusions and depressions.

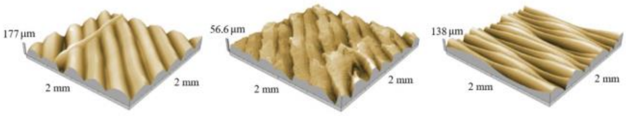

Figure 6. 3D areas of the measured area - top area (left), bottom area (center), side (right)

The surface roughness profile of the upper surface see Fig. 7 is characterized by higher protrusions with rounded peaks and deep depressions. These significant depressions are caused by imperfect stacking of the filament layers side by side. The height of the protrusions, in turn, is directly related to the height of the individual layers of the filament.

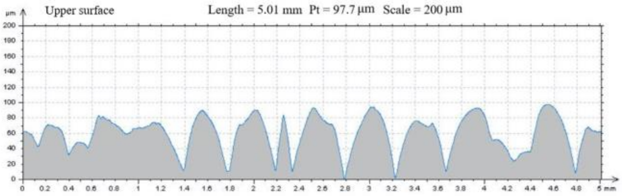

Figure 7. Surface roughness profile measured on the top surface of the sample

Measured 2D and 3D parameters of the texture of the evaluated area, samples from 100% PLA, describes Tab. 4.

Parametre [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	26.40	32.60	177.00	163.00	15.60	18.70	85.60	71.60	4.15	4.77	23.80	14.00
Bottom surface	7.90	10.10	56.60	54.60	5.23	6.51	35.20	29.10	1.00	1.13	4.84	3.22
Side surface	24.50	30.10	138.00	137.00	15.50	19.40	96.50	85.60	4.08	4.68	18.50	14.20

Table 4. Measured values of 2D and 3D parameters of the surface texture of the sample from 100% PLA

The determined results of the 2D and 3D parameters indicate similar values of the surface parameters in the case of the top and side surfaces of the sample. The bottom surface shows significantly lower values of all measured parameters.0% PLA.

7.2 *Evaluation of all tested filaments*

The evaluation of the other filaments was performed in the same way as for the 100% PLA materials. Surface analyzes of samples with a 100% filler content show that coloring additives have a significant effect on the surface quality of the prints. Different surface properties were also recorded between the individual surfaces of the same sample.

The 3D structures of the upper surfaces were characterized by an oriented and periodic structure with smooth protrusions and sharp depressions, and a constant shape of the laid fibers was also observed. Unwanted depressions were probably caused by imperfect stacking of the fibers next to each other. The 3D structures of the lower surfaces generally showed an indistinctly oriented structure with unevenly distributed sharp protrusions. Undesirable deformations of the structure caused by heat from the heating pad of the 3D printer were often observed. Also as a result of the action of this heat, significantly lower values of the monitored surface parameters were recorded on the lower surfaces. The side surfaces were usually formed by a number of smaller protrusions oriented in the same direction, possibly in the shape of a helix.

Overall, the lowest parameters of surface texture, waviness and roughness were recorded by the sample with the red additive. Its surface is therefore the best based on the evaluated parameters. However, undesirable deformations due to heat from the heating pad were apparent on the bottom surface of the sample. The black additive had a significant negative effect, as the sample from this material contained a significantly higher number of surface defects than the other samples.

8 DISCUSSION – EVALUATION OF ARCHIVED RESULTS

Research into the effect of the percentage of the sample filling on its mechanical properties turned out to be as expected. The highest values of the loading force were achieved by completely filled samples, but the difference between the filling share of 25% to 70% was surprisingly small. As expected, the hardness tests also turned out, where the value of hardness increased with increasing percentage of filling, and thus with increasing total density of samples.

The influence of coloring additives on the mechanical and surface properties of the samples was surprisingly significant. Species-different staining additives were tested, which affected the properties of the samples to varying degrees. In particular, it was unexpected to find that the addition of red and gold dyeing additives improved the mechanical and surface properties of the samples, compared to samples from filaments without coloring additives.

Using surface analyzes, different properties were determined on the top, bottom and side surfaces of the samples. The recorded 3D structures of the bottom surfaces mostly showed an indistinctly oriented structure with unevenly distributed sharp protrusions. Undesirable deformations of the structure caused by heat from the heating pad of the 3D printer were also observable in some samples. For this reason, an additional study determining the effect of the heating pad temperature on the surface properties of the bottom surface of the printout could lead to a higher quality of the printout surface.

9 CONCLUSION

3D printing technologies offer many benefits for multinational companies as well as home users. The paper examined prints made by the additive method Fused Filament Fabrication, which is characterized by low complexity, affordability and a number of usable materials.

The paper evaluated the influence of red, black and gold coloring additives on the mechanical and surface properties of the samples. A 3D filament of base material (100% PLA) and the appropriate dyeing additive was produced on an experimental line and subsequently used for 3D printing of prints on a PRUSA i3 MK3 machine. The samples thus prepared were subjected to tensile tests, Shore D hardness tests and surface texture, roughness and waviness analyzes. The test results showed that the coloring additive has a significant effect on the mechanical and surface properties of the prints. The highest values of loading force 642.1 N and hardness at the level of 74±2 HShD were reached by samples with red additive. The mechanical properties were improved and the hardness to the base material was increased by the addition of a gold additive. On the contrary, due to the black additive, there was a significant degradation of the mechanical properties of the material, to the level of 65.5% compared to the values of the force acting on the samples from 100% PLA. The sample with the black additive also achieved the worst surface quality. Overall, the lowest values of the parameters of the surface texture, waviness and roughness were recorded by the sample with the red additive (its surface is therefore of the highest quality). Based on the results, the filament manufacturer is recommended to use organic pigments as coloring additives, which have been represented by a red additive. On the contrary, the use of inorganic carbon black is strongly discouraged, as the black additive worsened the mechanical and surface properties of the prints.

The second purpose of the article was to provide users of 3D printing with recommendations on the basis of which their prints will achieve the desired properties. It was found that the individual surfaces of the prints are characterized by different surface quality. The highest quality surface was achieved by prints on the bottom surface, which was in direct contact with the heating pad.

Furthermore, the influence of the percentage of sample filling on the values of loading force and hardness was evaluated. It has been proven that with increasing percentage of filling, the maximum value of the force load increases and at the same time the hardness of the samples. The most significant increase in the loading force occurred between the proportion of the filling of 70% to 100%. Samples with a fill content of 25% to 70% showed only a small difference in the loading force, reaching 72.5% to 79.5% of the values of the samples with a fill content of 100%. For this reason, in the case of lightly mechanically loaded prints, it is advantageous to set the percentage of filling to 25% and thus save time and money. However, the best mechanical properties and the highest hardness are achieved by prints completely filled with filament.

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