MECHANICAL PROPERTIES OF BIODEGRADABLE PLA PLASTIC PARTS PRODUCED BY 3D PRINTING

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The presented paper is focused on FDM (Fused Deposition Modeling) 3D printing technology, which works with thermoplastic materials that are gradually applied layer by layer to the work platform. As we knows, plastics are made from crude oil, and in general they are an environmental burden on our environment. However, there are also different plastics that are produced from renewable sources and are environmentally friendly materials that are degradable and does not pose a risk to the environment. Such plastic is, for example, PLA thermoplastic. To show what is the status of biodegradable PLA plastic it is necessary to make strength testing. Paper describes prepared and realized full factor experiment, focused to tensile strength measurement. The measurement is done on PLA plastic samples designed by standards. Experiment is statistically evaluated. The measured and evaluated values are compared also with production time for effectiveness comparison.

KEYWORDS

Additive Manufacturing, 3D printing, PLA plastic, Tensile strength, Rapid Prototyping, Measurement

1 INTRODUCTION

We can meet a lot of names which are suitable for presented technology. There can be used 3D printing, Rapid Prototyping, Additive Manufacturing and others [Nutz 2015]. There are small differences between these titles, it depend what is the purpose of use, what is the type of machine and others. Basically we can use such technology for producing of prototypes and also parts for final use. There are many types of materials suitable for models production [Svetlik 2013]. 3D printing is phenomenon of this age and we can hear about it almost everywhere. We knows more types of 3D printing technologies which could be used. Presented paper is focused to Fused Deposition Modeling (FDM) technology or it is also known as Fused Filament Fabrication (FFF) or Fused Layer Modeling (FLM) [Keller 2016]. Different companies and producers use different names. Mentioned Fused Deposition Modeling technology is probably the most used 3D printing technology and the devices of different level quality can by purchased from few hundred of euro to thousands of euro, depend on quality and potentialities of use and possible materials processing. This technology is popular because the principle is very simple, compare to other known rapid prototyping technologies [Mohamed 2016].

The basic principle FDM technology is fusion of plastic material, which is in the form of plastic wire [Chua 2003]. Material is melted in hot nozzle and deposited to the building bed one fiber beside to another when the one layer is done, the base move down and next layer will be deposited [Safka 2016, Safka 2017]. The graphical representation of FDM technology principle is on the Figure 1 [Gaynor 2014].

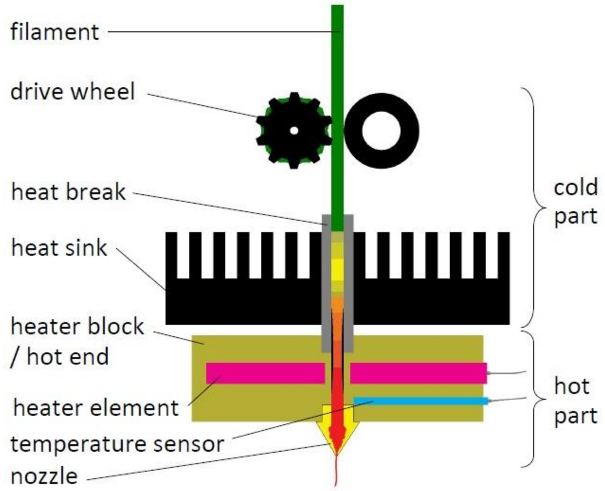

Figure 1. Principle of FDM 3D printing Technology [Gaynor 2014]

FDM technology is also the cheapest from all 3D printing systems. This devices are able process wide range of materials as for example ABS (Acrylonitrile Butadiene Styrene) and PLA (Polylactic Acid) plastic material as most used materials [BeniakJ 2014, Stanek 2012]. There are also others technical plastic materials which are suitable for producing final use parts, as Nylon, PC (Polycarbonate), PET (Polyethylene terephthalate glycol), ASA (Acrylonitrile Styrene Acrylate) and others [Phan 2014].

For ecological production is suitable PLA plastic material. Conventional technical plastics are made from This material environmental friendly material is produced from corn, poratoes or sugar-beet (Figure 2) [Castro 2016].

Figure 2. Polylactic acid (PLA) plastic manufacturing and life cycle [Castro 2016]

This means that is biodegradable, and in the environment will degrade and decompose in a few years by contrast to other polymers. The PLA filament is a new, biodegradable material, which is environmental friendly. Also the advantage of this material is, that their use for 3D printers is more easy then ABS. Require lower heating temperature of nozzle, the parts are not so predisposed for deformation and do not require table heating [Krassenstein 2015, Fabian 2015].

The ABS filament as a constructional material is widely used in the industry, for example as an interior parts material. So it can be easy printed also parts for real use. It depends just what material properties or part surface is requires.

If we want to replace the PLA plastic material instead of others known non environmentally friendly plastics, we have to figure out if its properties are similar or comparable. For this we prepared full factor experiment to test and evaluate tensile strength of PLA samples [Jarosova 1997].

2 EXPERIMENT PREPARATION AND TESTING

Presented experimented is prepared and realized by standard STN EN ISO 527-1,2. Designed specimen is shown on Figure 3. All specimens are produced from PLA plastic material. As FDM device is used 3D Factories ProfiMaker.

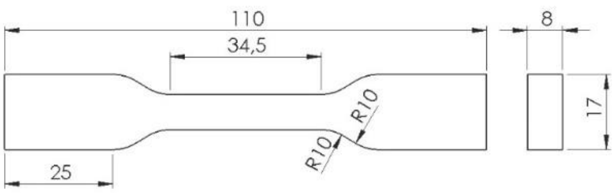

Figure 3. Shape and dimension of specimen for tensile strength testing

For experiment are chosen four factors (Table 1) which values are set within two levels. These factors and levels are chosen based on previous testing and experiences or from research from scientific papers [Lipina 2014, Safka 2016, Safka 2017].

Factor	Level 1	Level 2
A - Model infill	90%	50%
B – Infill shape	Linear	Honeycomb
C - Layer thickness	0,125mm	0,25mm
D - Orientation (X-Y)	0 deg	45 deg

Table 1. Factors and their levels selected for experiment

Factor A presenting interior model infill volume. Percentage of infill volume is illustrated on Figure 4. We have selected 90% and 50% infill. This is significant difference and logically it will have big influence to measured tensile strength values, because mass of material will influence model stiffness. There is recommendation in the practice to use at least 10% infill for produced model, to ensure model compactness.

Figure 4. Illustration of interior infill volume for 20% (left), 50% center) and 75% (right) [Cain 2012]

Factor B is shape of interior model infill. There is many possible shapes, which could be used in the practice. We have to also realize, that when is the infill shape too complicated, the production time will be much more longer, what can be big disadvantage. For our experiment we chose simple line infill and the second is more complex honeycomb shape (Figure 5). We are suppose that the honeycomb shape will have bigger influence to model stiffness in positive way. The linear shape is conventional infill which is often used in practice.

Factor C is layer thickness. It depend on the device and software if this factor is optional or not. We are able to select different layer thickness. On this device is usually used 0,25mm layer thickness so we select this primary value. As a second value is selected smaller thickness 0,125mm. When the thickness is big, the model is build fast, but the vertical shape precision is really rough, especially for surfaces with shallow slope. When the thickness is selected to small value, the building process is much slower but vertical shape is more precise. We selected 0,125mm and 0,25mm layer thickness, which are acceptable for good quality 3D model producing.

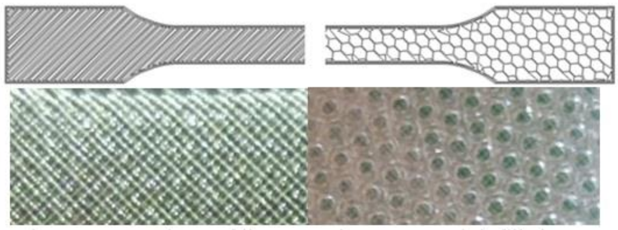

Figure 5. Linear and Honeycomb infill shape

The last factor C presents model orientation on the build platform of 3D printer. Orientation is on the horizontal plane X-Y (Figure 6). When the model is turned by specified angle, the deposited lines will have different orientation, so there should be also some influence to produced model stiffness.

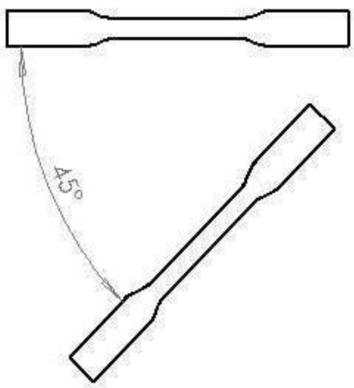

Figure 6. Specimen orientation in horizontal plane (X-Y) on the built platform

For this mentioned factors and their levels is prepared full factor experiment. The design of experiment (DOE) is presented later in the paper also with measured values of tensile strength.

Own measurement was realized on Universal measurement device Inspect Desk 5kN (Figure 7). The maximum possible loading of specimens is 5kN. Depends on this maximum possible testing device loading force we had to also check the specimen dimensions to be able break the designed cross-section. This selected measurement device automatically record all necessary data and also evaluate them. Measured data can be after exporting to graphical editor analysed and illustrated by graphs.

Each combination from design of experiment is measured and repeated 5 times to be able make statistical evaluation. All samples are made from the same package of material to ensure the same properties for all specimens and eliminate some errors which could result from different material production. Also the 3D printer is precise set before the production of specimens starts. This is also necessary to ensure the same conditions within whole production of specimens. The set conditions are not changed during the printing process.

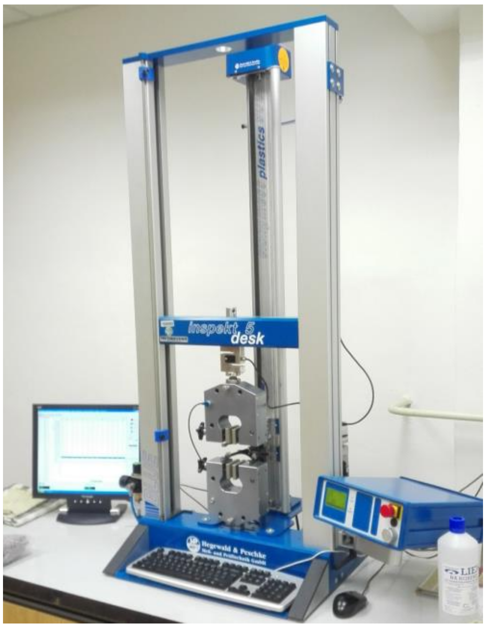

Figure 7. Universal testing device Inspekt Desk 5 kN

3 EVALUATION OF MEASURED VALUES

By the prepared full factor experiment (Table 2) there are make ale measurements. As is mentioned above each combination, each experiment is repeated five times with five specimens. Table 2 shows also average value from five measurements for each experiment.

Exp. No.	A (x_1)	B (x_2)	C (x_3)	D (x_4)	R_m (MPa)
1	1	1	1	1	**41,19**
2	2	1	1	1	**24,37**
3	1	2	1	1	**48,63**
4	2	2	1	1	**26,80**
5	1	1	2	1	**45,81**
6	2	1	2	1	**29,00**
7	1	2	2	1	**46,46**
8	2	2	2	1	**32,28**
9	1	1	1	2	**43,38**
10	2	1	1	2	**24,36**
11	1	2	1	2	**45,94**
12	2	2	1	2	**28,13**
13	1	1	2	2	**45,31**
14	2	1	2	2	**33,37**
15	1	2	2	2	**46,79**
16	2	2	2	2	**33,37**

Table 2. Prepared plan of experiment – Full factor experiment with measured values of Tensile strength

Measured values are also presented graphically on the Figure 8. From the table and from the Figure we can easy recognize some regularity. All the odd experiments are presented with bigger measured values compare to even experiments with noticeable lower values.

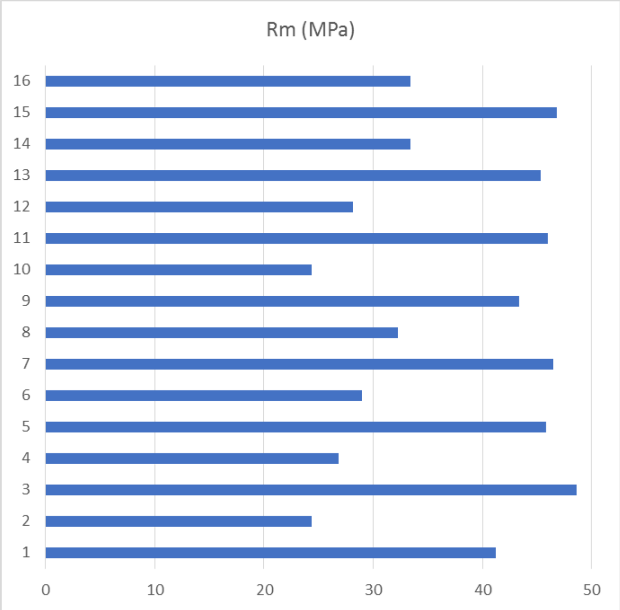

Figure 8. Illustration of measured tensile strength values

The higher measured value of tensile strength is on experiment number 3 (48,63 MPa). Opposite the lower value is measured in experiment number 10 (24,36 MPa) what is just about half of highest measured value. The difference is in the mass of applied material. It is natural when we use much more material for model production the model will be more stronger.

When we looks on measured values which are influenced only by shape of internal infill, there is also visible difference. Compare the experiment number one and experiment number 3, there is difference about 18% between measured values, what we can consider as significant. In others experiments it is about 10% what is also important.

3.1 Linear Regression Model

For processing of measured data we used also linear regression analysis. This is suitable for exact specification of coefficients, which presents the weight of investigated factors. For this we selected empirical model of experiment:

$$\hat{y} = \varphi(\boldsymbol{x}, \boldsymbol{\beta}) + \boldsymbol{s} \qquad (1)$$

where $\boldsymbol{x}$ is vector of selected factors, $\boldsymbol{\beta}$ is vector of unknown parameters and $\boldsymbol{s}$ is vector of errors. Its parameters are estimated from empirical data by regression analysis methods. The model (1) can be replaced by power law series [10]:

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum\sum \beta_{ij} x_i x_j + \ldots + \beta_{12\ldots k} x_1 x_2 \ldots x_k \qquad (2)$$

where βi parameter is estimated from empirical data and where β_{12} to $\beta_{12\ldots k}$ present correspondent interactions between two to k factors.

For simplicity we take linear regression:

$$T = b_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 + b_4 x_4 + b_{1,2} x_1 x_2 + b_{1,3} x_1 x_3 + b_{1,4} x_1 x_4 + b_{2,3} x_2 x_3 + b_{2,4} x_2 x_4 + b_{3,4} x_3 x_4 + b_{1,2,3} x_1 x_2 x_3 + b_{1,2,4} x_1 x_2 x_4 + b_{2,3,4} x_2 x_3 x_4 + b_{1,2,3,4} x_1 x_2 x_3 x_4 \qquad (3)$$

In formula (3) are b_0, b_1, b_2, b_3 ..., point estimation β_0, β_1, β_2, β_3 , ...

Verification of each coefficient is made independently. For this verification can be used Student criterion. When using the full factors experiment or repeated measurements, the determining intervals are the same for all coefficients.

The coefficient b_0 can be calculated as follows :

$$b_0 = \frac{\sum_{i=1}^{k} \bar{y}_i}{k_c} \qquad (4)$$

where k_c is number of experiments, y_i is arithmetic average of measured values.

Calculation of coefficients b_1, b_2, b_3, b_4:

$$b_u = \frac{\sum_{i=1}^{k} x_{ui} \bar{y}_i}{k_c} \qquad (5)$$

where u = 1, 2, 3, 4 is number of factors

i = 1, 2, ...k_c is number of experiments (k_c=16)

For coefficients b_{12}, b_{13}, b_{14}, b_{23}, b_{24}, b_{34}, for interactions of two factors is:

$$b_{uv} = \frac{\sum_{i=1}^{k} x_{ui} x_{vi} \bar{y}_i}{k_c} \qquad (6)$$

For coefficients b_{123}, b_{124}, b_{234}, for interactions of three factors is:

$$b_{uvw} = \frac{\sum_{i=1}^{k} x_{ui} x_{vi} x_w \bar{y}_i}{k_c} \qquad (7)$$

where w = 1, 2, 3 is number of factors, $w \neq u \neq v$.

For coefficients b_{1234}, for interactions of four factors is:

$$b_{uvwz} = \frac{\sum_{i=1}^{k} x_{ui} x_{vi} x_{wi} x_{zi} \bar{y}_i}{k} \qquad (8)$$

z = 1, 2, 3, 4 is number of factors, $z \neq w \neq u \neq v$

Following the mentioned result we can present reached mathematic formula (9). By determination of above mentioned coefficients and by substitution to linear regression mode (3) we reach mathematical formula which describe the behavior of our system in the frame of experiments.

$$R_m = 37{,}2 - 8{,}241\, x_1 + 1{,}3504\, x_2 + 1{,}8498\, x_3 + 0{,}3812\, x_4 + 1{,}1964\, x_1 x_3 + 0{,}4649\, x_1 x_4 - 0{,}675\, x_2 x_3 - 0{,}375\, x_2 x_4 + 0{,}2788\, x_3 x_4 + 0{,}3093\, x_1 x_2 x_3 - 0{,}645\, x_1 x_2 x_3 x_4 \quad \text{(MPa)} \qquad (9)$$

This is mathematical formula, what can be used for modeling of our system within the options specified for this described experiment.

By using of statistical method ANOVA (Analysis of Variance) and also with simple graphical evaluation of each factor we figured out that the most significant factor is Factor A – model infill volume (figure 9). the Factors B and C are almost on the same level when we talk about influence to measured tensile strength. Factor D have minimum influence and we can state that this factor is not significant in this experiment.

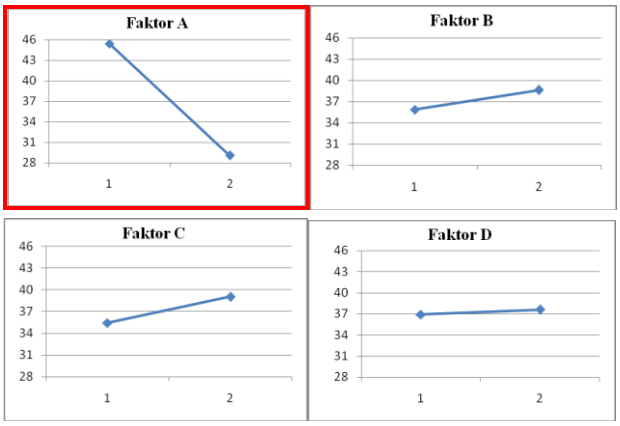

Figure 9. Graphical evaluation of each factor significancy

4 CONCLUSION

The results of this research is useful for all researchers who deals with FDM 3D printing technology. This give the frame what are the tensile strength values for different device setting. We can see that by using of PLA plastic material for 3D printing can be reached the models with really good tensile strength values, also compare to others technical plastics as for example ABS.

As the result from evaluated experiment can be stated that the most significant factor from selected is volume of used interior infill. This was even predicted. The next interesting thing is that shape of interior infill also influence the measured tensile strength in the frame about 10%, so we can say that honeycomb infill shape improve strength properties of produced parts.

The last interesting factor is layer thickness of deposited fibers. If we use 0,25mm layer instead of 0,125mm, the measured tensile strength values increase in range 11% - 19%.

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