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A COMPARISON OF THE TENSILE STRENGTH OF PLASTIC PARTS PRODUCED BY A FUSED DEPOSITION MODELING DEVICE

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Abstract. Rapid Prototyping systems are nowadays increasingly used in many areas of industry, not only for producing design models but also for producing parts for final use. We need to know the properties of these parts. When we talk about the Fused Deposition Modeling (FDM) technique and FDM devices, there are many possible settings for devices and models which could influence the properties of a final part. In addition, devices based on the same principle may use different operational software for calculating the tool path, and this may have a major impact. The aim of this paper is to show the tensile strength value for parts produced from different materials on the Fused Deposition Modeling device when the horizontal orientation of the specimens is changed.

Keywords: Rapid Prototyping; FDM; Fused Deposition Modeling; 3D printer; additive manufacturing.

1. Introduction

Rapid Prototyping refers to a group of techniques used for rapid production of scaled models, real parts or assemblies based on a 3D model designed by a CAD system [1].

Rapid Prototyping systems and systems for producing prototypes rapidly are coming to the forefront at great speed. Although the name Rapid Prototyping suggests that prototype production is the primary aim, these devices are ever more frequently used directly in the manufacturing process. They are not able to operate in producing large series, but have their place in short-run or medium series production. These devices are still expensive, but we can now observe Fused Deposition Modeling technology spreading widely on the market, and they can produce items much more cheaply than primary producers can. This is because the validity of the patent protection for this technology has expired, and production has been able to expand in the global market. This has rapidly reduced the price of FDM devices.

Rapid prototyping devices are very widely applied not only in production, and not only inmechanical engineering industries. In addition, there are a wide range of technologies for creating prototypes. A feature of all of them is so-called additive manufacturing where, in contrast with classical conventional manufacturing methods, material is added to a workpiece, not removed from it. Conventional technologies are based on principle that material is removed from a predefined semi-product (raw material), until the final required shape and dimensions are achieved. In additive manufacturing, is the action is in the opposite direction. The material is added step-by-step and layer-by-layer, added and this way a totally new part, a prototype, is formed). Fig 1 illustrates how in most rapid prototyping technologies the parts built up layer-by-layer (Fig. 1).

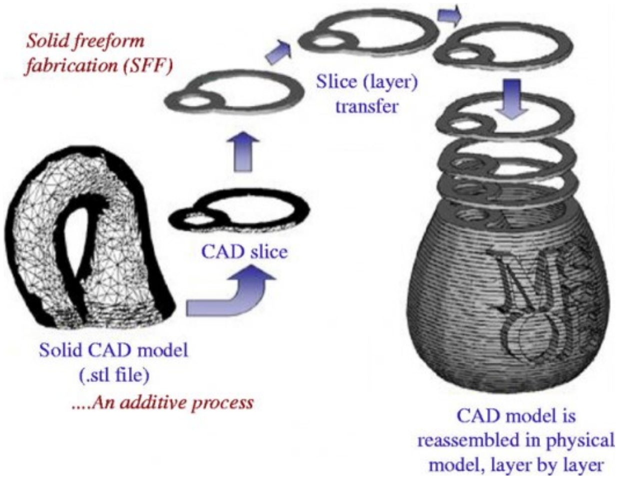

Figure 1. The additive manufacturing process – layer manufacturing [3].

2. FDM technology overview

In this paper, we will concentrate on Fused Deposition Modeling (FDM) technology. FDM is a technique that uses two types of materials, for modeling and for support [2]. First, the modeling material is used to build a model. Then, the support material is used to build a support structure on areas where the modeling material will overhang the rest of the model [5]. This technique works on a principle as similar to that of the fuse gun [4]. The material is unspooled from

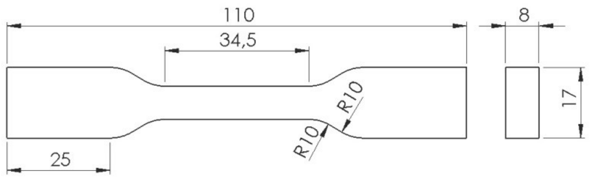

Figure 2. Dimensions of the specimen for tensile strength measurements.

Factor	Level 1	Level 2	Level 3
A	0 deg	45 deg	90 deg
B	PC	ABS	PLA

Table 1. Factor specification for the experiments.

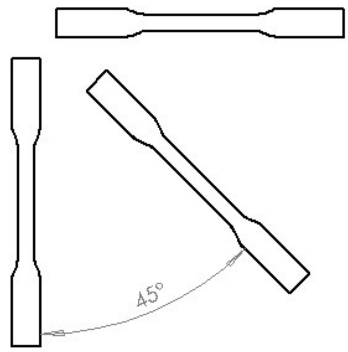

Figure 3. Orientation of the samples in the workspace of the FDM device.

the spool to the fuse head, where it is melted and deposited on the working table. After the model has been completed, the support material is broken away or dissolved in a special bath. Using this technique, the prototype is built up layer by layer (Fig. 1).

A range of materials are used for making prototypes. The most widely used materials are ABS plastics and polycarbonate (PC).More recently, a broad spectrum PLA plastic modifications and composite materials have been introduced, consisting of PLA polymer and others material particles (wood, ceramic, metal, and others). Each type of plastic has certain advantages and disadvantages [6]. From the point of view of the designer, the mechanical properties of the selected material are very important, e.g. its tensile strength.

3. Tensile test of FDM samples

If we want to use prototypes or real parts in practical applications, or if need to test them under a load, it is necessary to know their material properties and to be able to compare the properties of a prototype with parts manufactured in the conventional way. If we know the ratio between the table values of the material properties of conventionally produced parts and the real values of the material properties of prototype samples produced by by FDM technology. Conversely, if we test the prototype and find its properties, we can make a reverse estimate of the properties of the real part.

We will measure the tensile strength of tested samples (Fig. 2), working only with parts produced by /FDM. The tensile test specimens were made on different devices, because each device is suitable for processing a single material type. Three material types were chosen, Polycarbonate (PC), Acrylonitrile Butadiene Styrene (ABS) and Polylactic Acid (PLA), which is environment-friendly polymer sourced from corn, a renewable material. These materials were selected on the basis of the availability of FDM devices for processing the materials, and also the availability of materials.

All of the selected devices were set up in the same way, in order to make the experiment suitable for comparng the measured values. The Polycarbonate plastic specimens are produced on the FORTUS 360mc professional device [7]. The ABS plastic parts are made on Dimension SST, andthe PLA plastic parts from are made on the 3D ProfiMaker device. The PC and ABS plastic samples are pre-processed using Catalyst software, and the PLA samples are pre-processed with G3DMaker software.

Each of the selected materials has a different preferred processing temperature for this technology, it is not possible use the same temperature for all the materials for experimental purposes. The other settings are the same for all device settings. The interior space of the model is filled with plastic fibers to provide the maximum possible material content (the maximum relative specimen density). The model layer thickness is set to 0.25 mm. The specimens lie in flat position in the horizontal plane. The only driven factor is the orientation of the specimen in the horizontal plane, which is in three levels: 0°, 45° and 90° (Fig. 3, Table 1).

The aim of this experiment is to find the tensile strength of the FDM specimens, with reference to the orientation of the model in the workspace of the device. This data is important for users of FDM devices, for proper production of parts, and also for preparing further experiments involving other factors. It is also important for correct selection of the testing device for tensile tests and for defining the dimensions and the parameters of test samples, because all tensile test devices are limited by their maximum possible load.

Basically we have a two-factor experiment in which each factor has three levels, and we are able to prepare complete experiment (Table 2). The specimens are tested on the Inspekt Desk 5 kN universal testing device (Fig. 4), which enables a maximum load of 5 kN to be applied ot the specimen.

4. Measured tensile strength values

From each combination introduced in the Design of theExperiment (Table 2), we produced five specimens

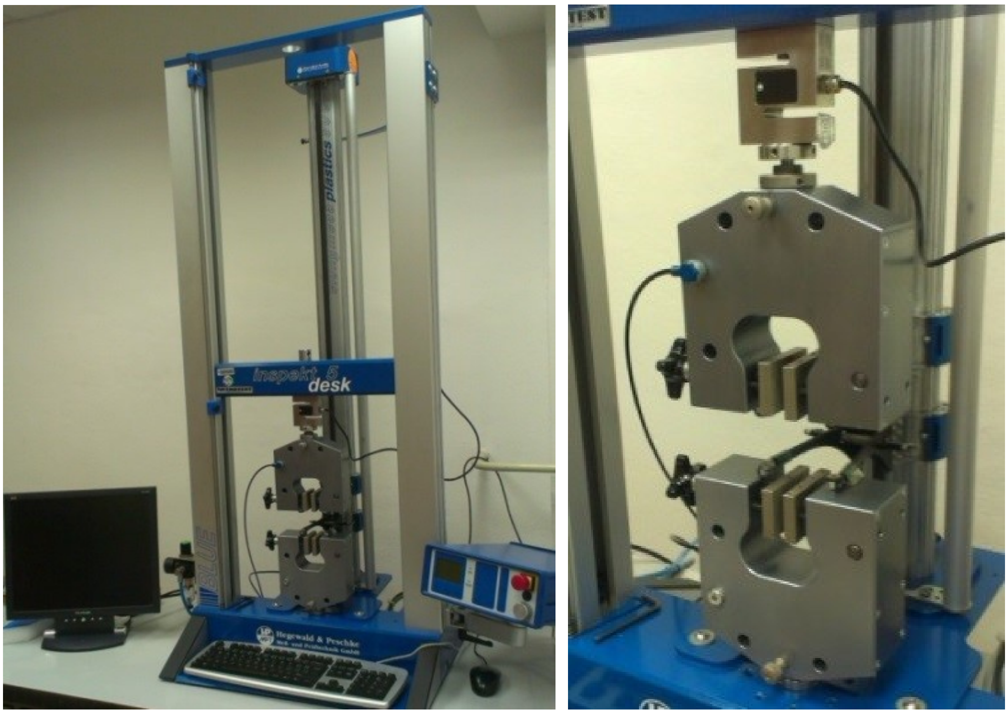

FIGURE 4. The Inspekt Desk 5 kN universal testing device.

Exp. No.	A	B
1	1	1
2	1	2
3	1	3
4	2	1
5	2	2
6	2	3
7	3	1
8	3	2
9	3	3

TABLE 2. Design of the experiment.

to make a statistical evaluation of the measured values possible. The measured values are the maximum tensile force F_m (N) and tensile strength R_m (MPa), which is given by the control software and is calculated by the following mathematical formulas (3). The situation is the same for the values of elongation ε (%), which are displayed by the control software but are calculated based on by the known formulas (1) and (2). Table 3 shows the spread of the reviewed Tensile strength values $s^2_{R_\mathrm{m}}$.

The tensile strength was measured on the Universal Tensile testing machine, controlled by a microprocessor with automatic value recording and scoring of the measured values. All samples were tested under the same conditions, except where there were changes due to the design of the experiment (Table 2 and Table 3). The measured values are displayed in Table 3. As was mentioned above, the tensile testing machine and its control software is able to calculate all necessary data, but the basic relations need to be known The revised Young modulus of elasticity E (1) and Tensile Strength R_m (3) were calculated by means of formulas (1) and (3), which will be introduced below.

Young's modulus E can be calculated by dividing the tensile stress by the extensional strain in the elastic (initial, linear) portion of the stress–strain curve:

$$E = \frac{\text{tensile strength}}{\text{extensional strain}} = \frac{R_\mathrm{m}}{\varepsilon} = \frac{F_\mathrm{max}/A_0}{\Delta L/L_0} = \frac{F_\mathrm{max} L_0}{A_0 \Delta L}, \tag{1}$$

where E is the Young's modulus (modulus of elasticity); F_max is the force exerted on an object under tension; A_0 is the original cross-sectional area through which the force is applied; ΔL is the amount by which the length of the object changes; L_0 is the original length of the object; R_m is tensile strength; ΔR_m is the percentage deviation from the table values for tensile strength.

The strain ε can be measured by integrating the change in unit current length. This measure of strain is called the true strain, or the logarithmic strain [8]:

$$\varepsilon = \int_{L_0}^{L} \frac{1}{L} \mathrm{d}L = \ln \frac{L}{L_0}. \tag{2}$$

The ultimate tensile strength is calculated as follows:

$$R_\mathrm{m} = \frac{F_\mathrm{max}}{A_0}. \tag{3}$$

Average Tensile strength values R_m (MPa) are displayed in Fig. 5. The first three columns are for polycarbonate material, the next three are for ABS plastic, and the last three columns present average tensile strength values for PLA plastic. Fig. 5 also

Exp. No.	**A**	**B**	R_m (MPa)	$s^2_{(R_\mathrm{m})}$ (MPa)	F_m (N)	ε (%)
1	1	1	56.12	160	3591.7	5.19
2	1	2	43.53	1	2785.9	2.88
3	1	3	57.21	198	3661.4	5.78
4	2	1	35.47	152	2270.1	3.37
5	2	2	37.88	101	2424.3	3.44
6	2	3	35.78	200	2289.9	3.15
7	3	1	45.81	562	2931.8	3.17
8	3	2	45.31	294	2899.8	3.03
9	3	3	43.25	354	2768.0	3.29

Table 3. Measured tensile strength values.

Factor	F (calculated)	p (signification)	SS	MSe	$F_{\mathrm{tab}\,0.95}$
A	$F(2.18) = 70.4$	$< 10^{-6}$	68.74	0.49	3.56
B	$F(2.18) = 1107$	$< 10^{-6}$	1140.51	0.49	3.56
A*B	$F(4.18) = 153$	$< 10^{-6}$	299.28	0.49	2.93

Table 4. Results of an Analysis of Variances (ANOVA).

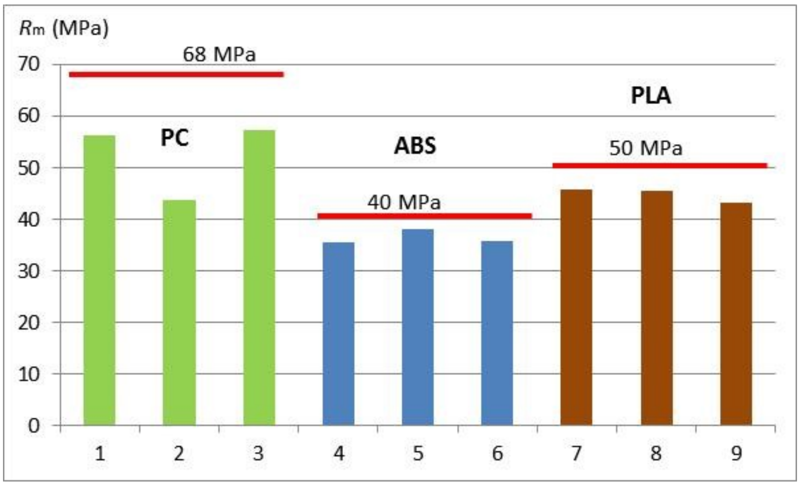

Figure 5. Measured tensile strength values.

show horizontal lines indicating the tensile strength measured for conventionally-produced samples, for comparison.

5. Discussion

We prepared an exact statistical evaluation by Analysis of Variances (ANOVA), and the results are presented in Table 4.

The ANOVA analysis results show that all the factors and the interaction are significant on a level of $p = 0.05$. The most significant result is for factor B (material type). This makes sense, because these polymers also have differences in tensile strength like those observed in specimens produced by conventional technologies. The maximum tensile strength values of specimens produced by conventional technologies are shown as a horizontal line in Fig. 5. Polycarbonate has a tensile Strength value of 68 MPa. The value for ABS plastic is 40 MPa, while PLA eco-plastic material has a value of 50 MPa. For each of the materials, our measured tensile strength value is lower. For polycarbonate, the measured value is 84 % of conventional tensile strength value. For ABS plastic, the measured value is 94.7 % of the value for a conventional material, and for PLA plastic the measured value is 91.6 % of the conventional material value.

We see that factor A (orientation of the model in the X-Y horizontal plane) is also significant, but less significant than factor B. The measured values (Table 3, Fig. 5) point to a big difference between the different sample orientations for the polycarbonate material. For the other two materials (ABS and PLA polymers) the gap is smaller, but in each case the distribution between 0 degree orientation, 45 degree orientation and 90 degree orientation is also different.

These results may be due to the calculation and the distribution of the tool path. As we have pointed out, the different material specimens were produced on different FDM devices. Each device has its own

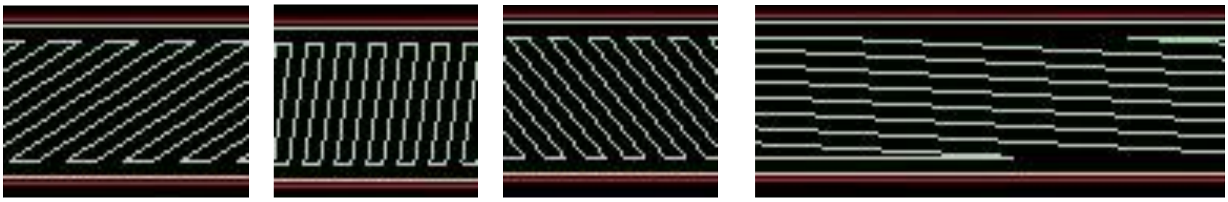

Figure 6. Direction of the fibers on different layers of PC specimens – 0 degrees and 90 degrees.

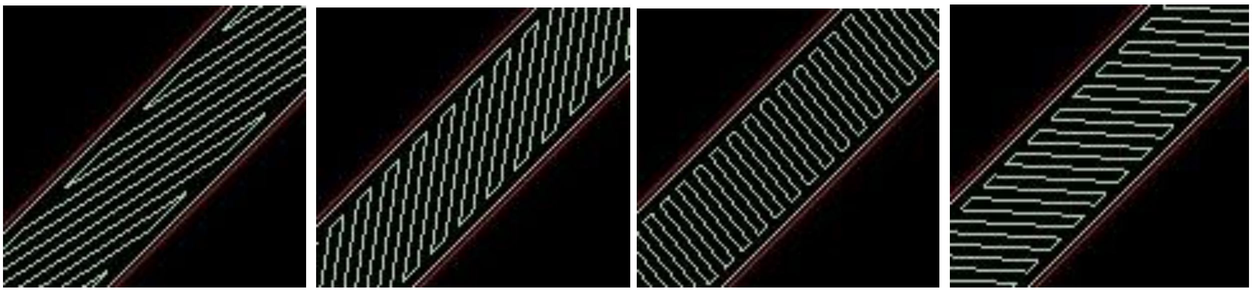

Figure 7. Direction of the fibers on different layers of PC specimens – 45 degrees.

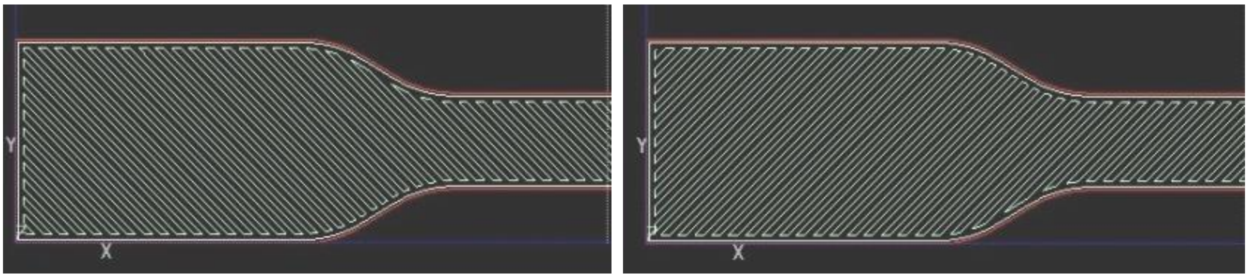

Figure 8. Direction of the fibers on different layers of PLA and ABS specimens – 0 degrees and 90 degrees

software for generating the control program and for setting the basic parameters for the device. Each software has its own logic for generating the tool part and the direction of the fibers in each layer of the model.

Fig. 6 shows the the structure of the fibers in successive layers of the model. In each layer there is a different orientation of thefibers. These four orientations change from the bottom to the top of the specimen. The direction of fibers in the 0-degree orientation is same as for the 90-degree orientation in the horizontal X-Y plane.

Fig. 7 shows successive layers and their fibes orientation if the specimen is oriented at 45 degrees within the horizontal X – Y plane. We see mostly short fibers, which are closer to the normal direction of the specimen. This causes the tensile strength to be lower in a 45-degree orientation than in a 0-degree or 90-degree orientation.

Fig. 8 and Fig. 9 show the orientation of the fibers for the devices that produced the PLA and ABS material specimens. It is clear that there are just two possible orientations, which change across the layers of the specimen. This basic difference between the structure of the PC specimen and the structure of the ABS/PLA specimen also causes a significant difference between the measured tensile strength values.

Fig. 10 compares the development of the tensile test for three different materials. There are measurements where tensile strength values are reached that similar to the average values presented in Table 3.

The development of the tensile tests presented in Fig. 10 shows that the yield point is almost completely missing, and the sample only breaks. This provides evidence of the fragility and the brittleness of the solidified extruded plastic material. By contrast, the samples formed by conventional technology display marked plastic deformation, a neck is formed, and then the sample breaks. According to the material properties list forABS plastic, the elongation-at-break about 30 %, whereas for our samples the elongation-at-break only about 3.44 %. This again points to the brittleness of the model produced from ABS plastic material using FDM technology. There is a similar situation for the other materials, and the calculated elongation of the FDM samples is also lower than to the elongation of samples produced conventionally from the same material (Table 5).

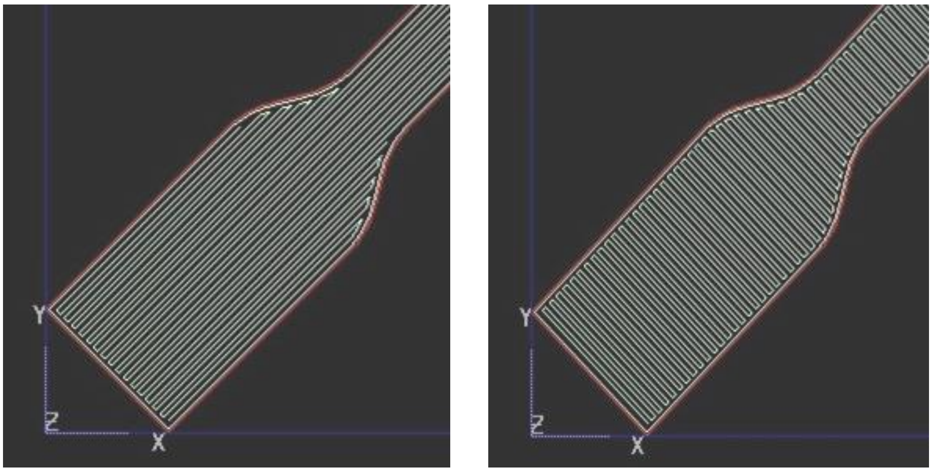

FIGURE 9. Direction of the fibers on different layers of the PLA and ABS specimens – 45 degrees.

Material	PC	ABS	PLA
FDM sample max. elongation $\varepsilon_{\mathrm{FDM}}$ (%)	5.78	3.44	3.29
Conventional sample average elongation $\varepsilon_{\mathrm{con}}$ (%)	95	24.3	28.5

TABLE 5. Elongation-at-break for plastic materials [9].

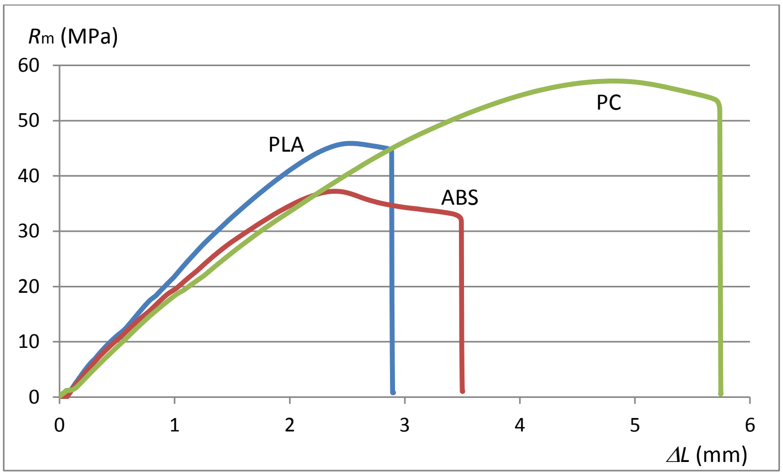

FIGURE 10. Development of the tensile test on different samples.

6. CONCLUSIONS

The measured tensile strength values shown in Table 3 and Fig. 5 show that the materials tested here achieve lower values than conventionally-produced specimens of PC, ABS and PLA plastic materials. This is primarily due to the way in which the tested samples were formed. The values for the material sheet properties are for injected parts. By contrast, the samples produced byFDM technology were formed by depositing thin semi-melted fibers side by side. If the fibers are deposited closely side-by-side for maximum density, we are also not able using this technology to achive such density of part as is achieved using conventional production methods, which produce a material with a homogeneous structure. We can also see, based on outputs (Table 3), that there are in some cases bigger differences in Tensile Strength values between single samples. This is caused by different fibers orientation and also different layers structure of each specimen. The result of presented experiment is that also the specimen orientation within horizontal X–Y plane affect measured values. The reason, why the proportions of measured values for each material are different, have to be investigated in separate experiment, where will be more close examined layer structure and its effect to measured values.

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References

[1] Rapid Prototyping & Manufacturing Technologies, IC LEARNING SERIES, Hong Kong Polytechnic University, Industrial Centre

[2] Williams, C., Rapid Prototyping with Metals: A Review of Technology and Associated Material Properties, Georgia Institute of Technology, Systems Realization Laboratory, November 2003,

[3] Sigler, Dean; Additive Manufacturing for Electric Motors, In: http://blog.cafefoundation.org/additive-manufacturing-for-electric-motors/ [2014-04-04].

[4] Pham, Duc-Truong; Dimov, Stefan: Rapid Prototyping, A time compression tool, Manufacturing Engineering Centre, Cardiff University.

[5] Chua, C. K., Leong, K. F., Lim, C. S., Rapid Prototyping, Principles and Applications, Nanyang Technological University, Singapore, World Scientific Co. Pte. Ltd, 2003, doi:10.1142/5064

[6] Beniak, J.; Rapid prototyping and accuracy of created models, In: ERIN, 5, č. 6 (2012), s. 2-9

[7] Lipina, J., Kopec, P., Marek, J., Krys, V.; Thread variants and their load capacity in components made by rapid prototyping technology, In: ERIN (6)11, 2013, p. 11-15.

[8] Persson, H., Adan K.; Modeling and experimental studies of PC/ABS at large deformations, Div. of Solid Mechanics, Sony Ericson, Lund, Sweden, 2004.

[9] Letcher, T., Waytashek, M.; Material property testing of 3d-printed specimen in PLA on an entry-level 3d printer; Proceedings of the ASME 2014 International Mechanical Engineering Congress & Exposition; IMECE2014; November 14-20, 2014, Montreal, Quebec, Canada, doi:10.1115/imece2014-39379