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Research on Shape and Dimensional Accuracy of FDM Produced Parts

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Abstract. Production of technical parts for Mechanical Engineering field is very important. There are many conditions which the produced parts have to satisfy. Very important for functional parts are accuracy of final parts. This accuracy could be evaluated in different ways. For example it can be evaluated shape accuracy or dimensional accuracy. This paper is focused to Fused Deposition Modelling (FDM) technology which is used for Additive Manufacturing process. The parts in additive manufacturing are produced directly from virtual model and digital file which could be obtained by direct modelling with CAD software or by 3D scanning. Published paper deals realized research where the full factor experiment was prepared and measured shape and dimensional accuracy of produced specimens. There are designed two types of specimens with different shapes and dimensions. Digital models are processed with different different 3D printer settings. Measured values are evaluated by statistical methods.

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1. Introduction

For technical practice is very important question of production precision of the machine parts in view of their intended use. The use of additive production of additive manufacturing systems increase from year to year in the forefront also in the production of parts and components for final use. That is why in this area it is necessary to know the technology so much that it is possible to influence the preparation and process of production of components through additive manufacturing systems in order to ensure the required accuracy of the final part [1]. In the case of mechanical engineering practice there have to be taken into the consideration dimensional accuracy of produced parts, what is the most common, but it have to be counted with shape and positional tolerances. It is necessary to make sure that the produced shapes have defined positions between important entities.

There are presented in this this paper the experiments focused to dimensional and shape and positional precision measurement [8]. There are many ways how could be this precision measured. In this paper is presented the measuring process with use of optical measuring instrument combined with special software which is directly evaluate specified tolerance. It is new way how to make the measurement process more effective and make it easier.

This tolerance evaluation is also connected with the specified factors which are selected as possible factors which could influence accuracy of parts produced by additive production techniques. In this case is the production process focused to FDM (Fused Deposition Modeling) technology which work with semi melted thermoplastic material which is deposited layer by layer to build required 3D part.



2. Material and Devices

The main aim of this research is to specify what are the shape and positional tolerances and also dimensional accuracy produced specimens by FDM technology. First of all there were specified the factors which could be possible for influencing of produced parts. There are many factors which could work with tolerance influence during the 3D printing [2, 3]. After experiences and literature research we specified two main used factors.

Temperature necessary for plastic material melting and layer thickness. Each producer of filaments state just range of suitable temperatures, not the exact temperature. This is because different 3D printers work with different software and have different technical design, so there could be necessary different temperature setting, but also settings of many others parameters. The temperature affect the consistence or the flow of semi melted thermoplastic what will affect the difffluence of deposited fibres.

Layer thickness is affecting the dimensional accuracy, so we try to figure out if there is also influence to shape and positional tolerances [4]. Each 3D printer allows to set layer thickness and it is easy to change and affect the final quality of produced parts.

Each of this two factors have two levels. The specified values are set to marginal possible values. For PLA plastic, which have been selected as very easy used production material, the producer state the printing temperature from 180°C to 220°C. The layer thickness is set to 0,1 and 0,2mm.

Using of this selected factors and their specified levels, there have been prepared full factor experiment, so combination of each levels each factors together. Respecting Design of Experiment (DOE) there is prepared full factor experiment (Table 1).

From each of this combination are produced 5 specimens to ensure data samples for measurement and proper statistical evaluation. Each specimen or each measurement have been repeated 5 times on each specimen. So we collected 25 values for each measured parameter, what is really significant set of values.

Table 1. Design of Experiment (DOE)

Specimen (Experiment)	Layer Thickness (mm)	Printing Temperature (°C)
1	0,1	220
2	0,2	220
3	0,1	180
4	0,2	180

The specimens are presented on Figure 1. There are two types of designed models, just to measure the both rounded and angular shapes, to test the possibility of selected 3D printer. As it is visible, the objects have also the holes with appropriate shape. On the Figure 1 are also presented the dimensions of each model. The printed height of models is the same with value 40mm.

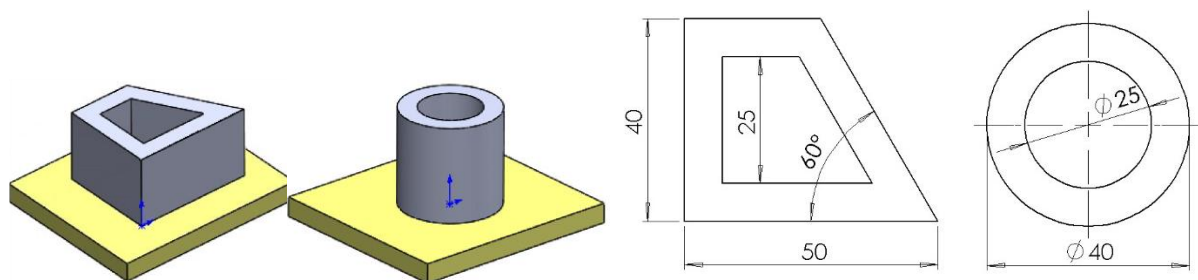


Figure 1. Designed 3D models selected for tolerance measurement.

Preparation of specimens are realized on FDM 3D printer Profi3DMaker (Figure 2 left) with following conditions:

- material of specimens – PLA
- printing speed – 50 mm.s^{-1}
- nozzle diameter – 0,3 mm
- number of bottom layers – 3
- density of bottom layers – 100%
- number of top layers – 3
- density of top layers – 100%
- number of wall contours – 2
- infill density – 5%
- infill structure – rectangular grid
- temperature of built platform - 50°C

Produced parts are subsequently measured. As is mentioned above, for measurement is selected sophisticated optical measuring device SmartScope MVP 200 (Figure 2 right).

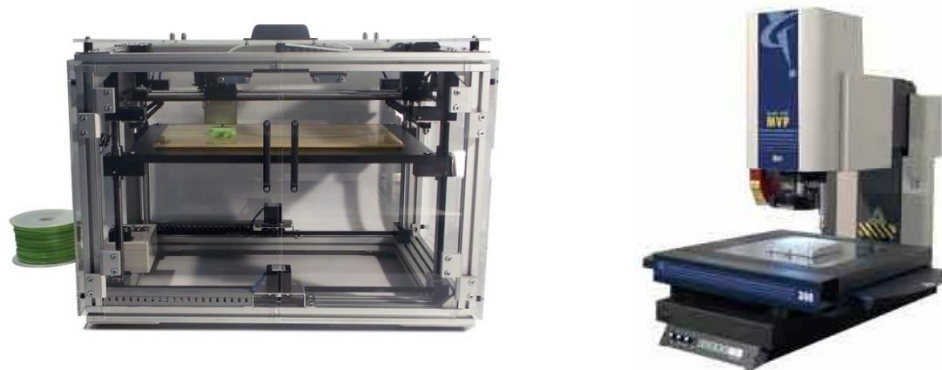


Figure 2. Profi3Dmaker 3D printer (left) [6] , Smartscope MVP 200 measuring instrument (right) [7],

Device MVP 200 work with measuring software Measure-X. This software automatically evaluate the final tolerance, it is just necessary to specify the appropriate lines or surfaces for correct measurement. The following Figure 3 and Figure 4 present labeling of measured tolerances. The dimension (for example “a” means the width of tolerance zone in which are the measured points.

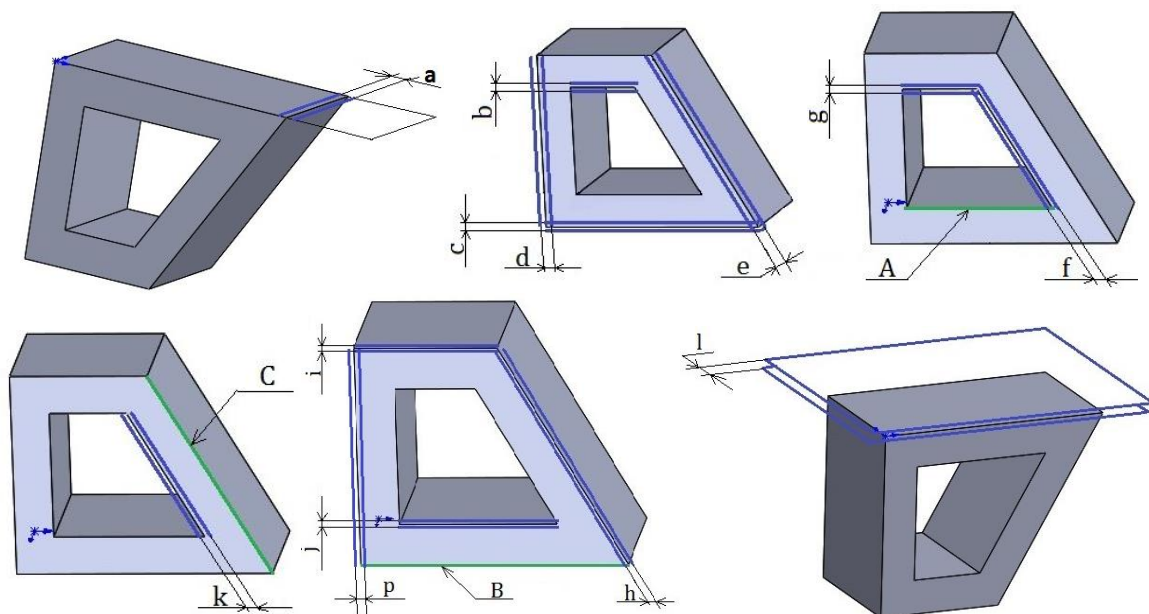


Figure 3. Measured precision for trapezium.

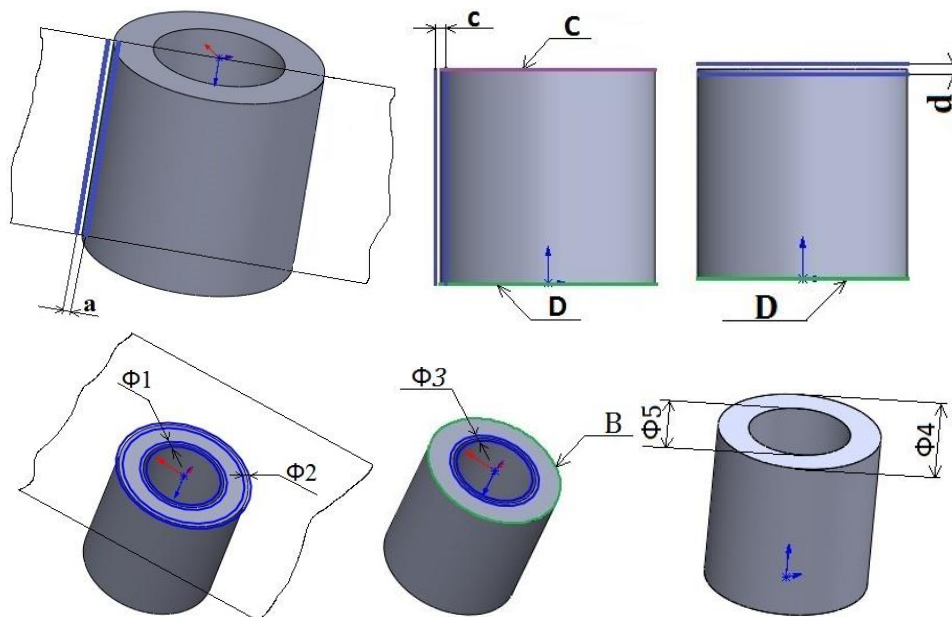


Figure 4. Measured precision for cylinder.

3. Measurement and evaluation of dimensional precision

The whole measurement is divided to measurement of dimensional precision and shape precision. In the case of trapezium there are measured dimension “*m*” and dimension “*n*” Measured values are presented in Table 2. Average values are calculated based on the equation (1). For statistical evaluation are also necessary at least standard deviation calculated by equation (2). Difference between theoretical designed value and average measured value are presented also on the Figure 5.

Table 2. Average values of trapezium dimensions

Exp.	Dimension <i>m</i> (mm)	Difference <i>m</i> (mm)	SD (mm)	Dimension <i>n</i> (mm)	Difference <i>n</i> (mm)	SD (mm)
1	49,86	-0,14	0,0749	39,87	-0,27	0,01573
2	49,955	-0,045	0,3991	39,96	-0,039	0,06515
3	49,8	-0,2	0,0618	39,85	-0,35	0,03554
4	49,96	-0,04	0,03977	39,83	-0,021	0,02344

The following is the formal mathematical formula for the arithmetic mean (a fancy name for the average).

$$\bar{X} = \frac{1}{n} * \sum_{i=1}^n x_i \quad (1)$$

\bar{X} = average (or arithmetic mean)

n = the number of terms (e.g., the number of items or numbers being averaged)

x_i = the value of each individual item in the list of numbers being averaged

Standard deviation values are calculated based on following equation:

$$SD = \sqrt{\frac{\sum (x_i - \bar{X})^2}{n-1}} \quad (2)$$

Measured values are also evaluated by ANOVA statistical method [5]. The results from ANOVA analysis are as follow:

Dimension “m”

Thickness	$F(1,96) = 6,75$	$p < 0,010847$	$SS=0,02$ $MSe=0,01$
Temperature	$F(1,96) = 119$	$p < 0,000001$	$SS=0,38$ $MSe=0,01$
Thickness*Temperature	$F(1,96) = 6,48$	$p < 0,012475$	$SS=0,02$ $MSe=0,01$

Dimension “n”

Thickness	$F(1,96) = 24,1$	$p < 0,000004$	$SS=0,04$ $MSe=0,01$
Temperature	$F(1,96) = 85,2$	$p < 0,000001$	$SS=0,13$ $MSe=0,01$
Thickness*Temperature	$F(1,96) = 51,4$	$p < 0,000001$	$SS=0,08$ $MSe=0,01$

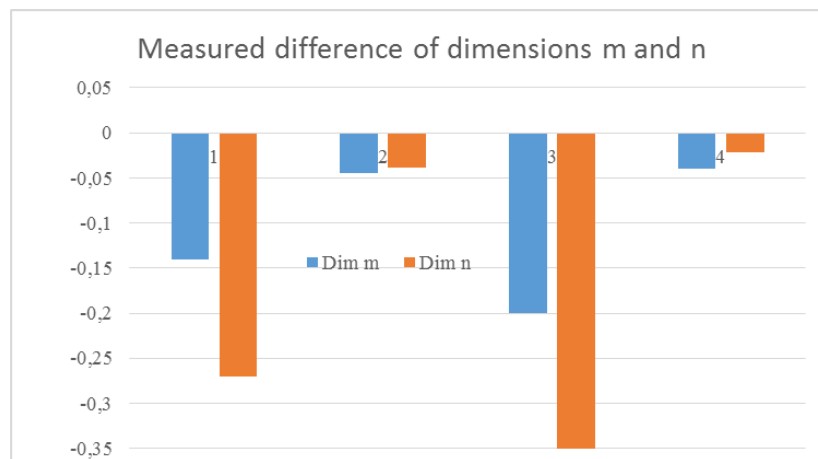


Figure 5. Measured difference of dimensions m and n.

Measured values from cylindrical specimens are presented in Table 3. Difference between theoretical designed value and average measured value are presented also on the Figure 6.

Table 3. Average values of cylinder dimensions

Exp.	Diameter $\phi 4$ (mm)	Difference $\phi 4$ (mm)	SD (mm)	Diameter $\phi 5$ (mm)	Difference $\phi 5$ (mm)	SD (mm)
1	40,27	+0,27	0,1675	24,44	-0,44	0,1363
2	40,25	+0,25	0,1336	24,5	-0,5	0,1841
3	39,85	-0,15	0,0433	24,82	-0,18	0,0209
4	39,84	-0,16	0,0265	24,87	-0,13	0,0263

Measured values are also evaluated by ANOVA statistical method. The results from ANOVA analysis are as follow:

Dimension “ $\phi 4$ ”

Thickness	$F(1,96) = 0,020$;	$p < 0,888327$;	$SS=0,01$; $MSe=0,01$
Temperature	$F(1,96) = 364$	$p < 0,000001$;	$SS=4,41$; $MSe=0,01$
Thickness*Temperature	$F(1,96) = 0,286$;	$p < 0,593873$;	$SS=0,01$; $MSe=0,01$

Dimension “ $\phi 5$ ”

Thickness	$F(1,96) = 0,002$	$p < 0,965637$;	$SS=0,01$; $MSe=0,01$
Temperature	$F(1,96) = 264$	$p < 0,000001$;	$SS=3,54$; $MSe=0,01$
Thickness*Temperature	$F(1,96) = 5,69$	$p < 0,018994$;	$SS=0,08$; $MSe=0,01$

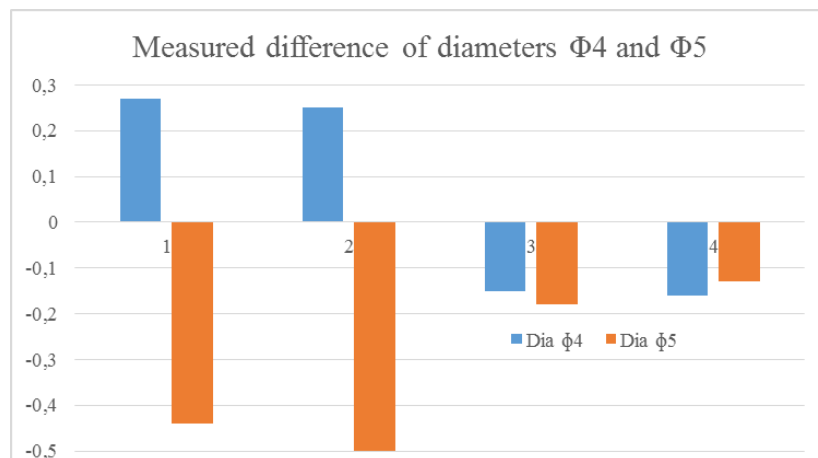


Figure 6. Measured difference of dimensions $\phi 4$ and $\phi 5$.

From this results we can see that the temperature as one of the factors is significant for dimensional precision. This is clear from the ANOVA analysis.

4. Measurement and evaluation of shape and positional tolerances

Based on the specified shape and positional tolerances from Figures 3 and 4, there was measured this tolerances. In the Table 4 are average values of tolerances specified on trapezium specimens. Average values of tolerances specified on trapezium specimens are in the Table 5.

Table 4. Average values of tolerances for trapezium specimens

(Exp)	Straight a (mm)	Straight c (mm)	Paralell i(B) (mm)	Paralell j(B) (mm)	Inclin f(A) (mm)	Inclin h(B) (mm)	Perpend p(B) (mm)	Flatness l (mm)
1	0,042	0,022	0,047	0,037	0,071	0,12	0,062	0,021
2	0,062	0,039	0,051	0,063	0,076	0,12	0,061	0,038
3	0,041	0,022	0,023	0,037	0,029	0,077	0,028	0,025
4	0,062	0,027	0,029	0,036	0,054	0,11	0,045	0,049

Table 5. Average values of tolerances for cylindrical specimens

(Exp)	Straight a (mm)	Paralell b(A) (mm)	Paralell d(A) (mm)	Perpend c(D) (mm)	Perpend c(C) (mm)	Round $\phi 1$ (mm)	Round $\phi 2$ (mm)	Concentric $\phi 3(B)$ (mm)
1	0,065	0,11	0,19	0,13	0,11	0,29	0,21	0,15
2	0,084	0,096	0,19	0,21	0,14	0,15	0,24	0,14
3	0,05	0,1	0,22	0,14	0,13	0,16	0,074	0,11
4	0,084	0,13	0,2	0,2	0,14	0,092	0,094	0,058

From this measured values stated in Table 4 and Table 5 we can see that statistically the worst results are reached from the combination of factors temperature and layer thickness for experiment number 2 (0,2mm layer thickness and 220°C printing temperature) for trapezium specimens. We can also see that the main change of tolerance is caused by change of temperature. It is possible to explain that the

deposited material is diffuent more to the sides and this cause bigger inaccuracy. This statement is also based on ANOVA statistical analysis, which had similar results as in case of dimensional accuracy measurement.

5. Conclusion

Based on the presented average vales from tolerance and dimension measurement and based on the ANOVA analysis it is possible to state that the printing temperature have the significant influence for shape and dimensional tolerance of FDM produced parts. This is because with higher temperature the melted material is more liquid with easy flow. So the material flow to the side caused by higher liquid and gravity, so the dimensions and tolerances are more inaccurate compare to specimens produced by lower temperature. This statement is based also on the optical comparison of specimens. The specimens with high printing temperature have worst surface quality what also lead to the worst tolerances.

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