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THE STUDY ON THE MODEL ORIENTATION ANGLE FOR ACCURACY OF ELEMENTS MADE WITH RAPID PROTOTYPING FDM METHOD

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Abstract: This paper presents the results of the research aimed at determining the influence of angle of model orientation in the working chamber on the accuracy of elements made with the FDM rapid prototyping method. Test samples were prepared to allow the measurement and analysis of printing accuracy at different angles of inclination of model surface walls. Surface finish precision has also been taken into account through the analysis of the influence of the surface inclination angle on the surface roughness degree. The research showed that the linear manufacturing errors do not exceed 0.13 mm, while the angular errors are lower than 0.77 degrees. The influence of the angle of the walls on the roughness is also important. Changing the angle can increase the roughness from Ra 12 to even more than Ra 100. The summary contains comments and recommendations concerning the orientation of models in FDM printing. They are helpful in choosing the printing parameters and arrangement of elements for optimal surface quality.
Key words: rapid prototyping, geometric accuracy, FDM.

1. INTRODUCTION

Rapid prototyping comprises a set of methods that allow creating physical geometry layer by layer. The created geometry is taken directly from 3D CAD (Computer Aided Design) models. These techniques are also referred to as incremental forming or additive methods and are not limited only to production of prototypes, as the name could suggest. They are also used for production of working tools, then we talk about RT (Rapid Tooling) techniques, and also for manufacturing of end products, in that case they are called RM (Rapid Manufacturing) techniques. All these methods are quite modern and undergo continuous development. In today's industry significant emphasis is put to accelerating the design and manufacturing processes, to reduce the turnaround time from the idea to the actual product. The changes that occurred in the typical design process are illustrated in Figure 1 [5].

The reason why RP methods are gaining popularity is actually the fact that they allow significant reduction of the time of preparation and production of products or their prototypes. Rapid prototyping methods allow quick production of individual elements to analyse their physical form, which previously often involved relying only on computer analyses. Traditionally, items are manufactured using the so-called removal machining techniques, usually involving machine cutting of material from the prefabricated part using machining tools. It includes milling, grinding, rolling, drilling and spark erosion processing. Additive techniques are quite different, as the product is built up layer by layer.

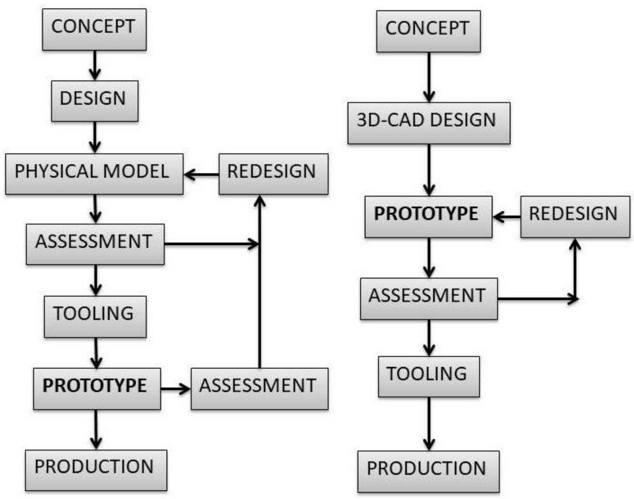

Fig. 1. On the left – traditional approach; on the right – construction using RP techniques, [5]

The advantages of that approach include the possibility of producing items with complex geometries and those considered impossible until the development of the RP technology, e.g. hollow sphere. In comparison with removal techniques, rapid prototyping is not as effective and refined, therefore it development is very important. Additionally, when compared to removal methods, additive production techniques allow to save material, [10-11]. Certain results of accuracy tests are described in the literature, e.g. [8,9], the presented tests concern professional printers, in contrast to many other publications. In some researches [3] were made tests for dimensional deviation in 3-axis, in this test dimensional accuracy among this axis was measured, no rotation was performed. In [14] the main aspect of researches is accuracy, the paper present among others results the accuracy of rotated planes but the researches are made for printed parts without support material. In this case the printed parts are greatly distorted, which is not happening in the presented research, thanks to the use of support structures during model printing. As of today, there is a lot of research on FDM printing and part manufacturing with this technology, but there is little regarding the accuracy [1-4, 6, 7, 9, 12, 13, 15] and almost no research on the influence of the part orientation angle in working chamber on the accuracy of printed models. In this paper different angle of model surface simulate rotation of the model in building area. As you can see on the finished elements, the roughness of surfaces made with a different arrangement of the walls differs significantly. Determining the theoretical influence of the angle on the roughness is troublesome. Therefore, an attempt was made to determine the effect of this angle on the surface roughness in practice. The research is important for elements printed on professional printers, e.g. Stratasys.

2. ANALYSED MODELS

Models used for the research purposes have been designed using the UNIGRAPHICS NX v.7.5 software, with the "Modeling" module for 3D components and assemblies. Two models have been produced, referred to as Model 1 and Model 2.
These models have been designed in such a way that the influence of the walls orientation angle on model accuracy could be determined. For that purpose, bodies with walls inclined at different angles in relation to the base have been used.

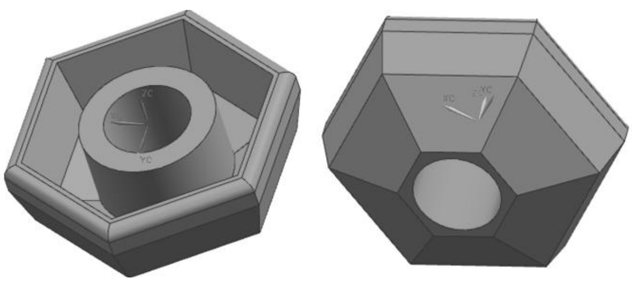

Fig. 2. Model 1

Their geometrical characteristics were as follows:
a) Model 1 – with external surfaces inclined at 30º and 75º and a 35 mm hole in-side. Upper edge radius of 5 mm. Overall dimensions: 103.9x120x47.5mm (Figures 2 and 3).
b) Model 2 – the second model designed for the research purposes, with external surfaces inclined at 60º and 45º and a 25 mm hole inside. Upper edge radius of 3mm. Overall dimensions are the same as in Model 1 are shown in Figure 5. Isometric views of Model 2 are presented in Figure 4.

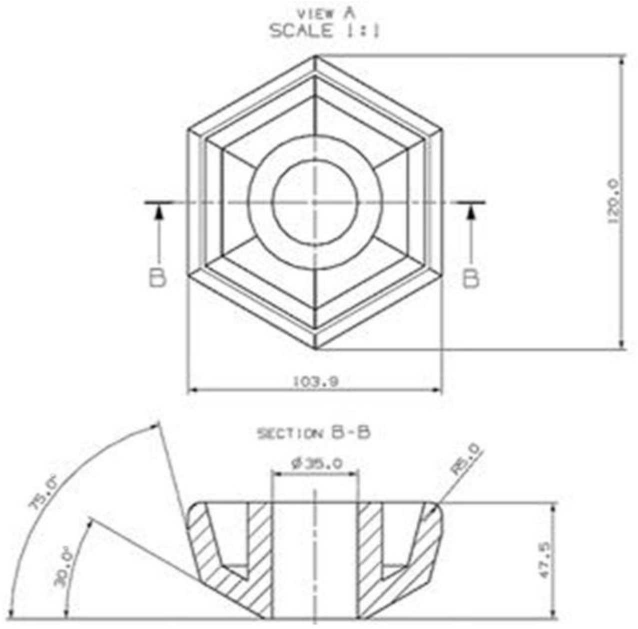

Fig. 3. Basic dimensions of Model 1

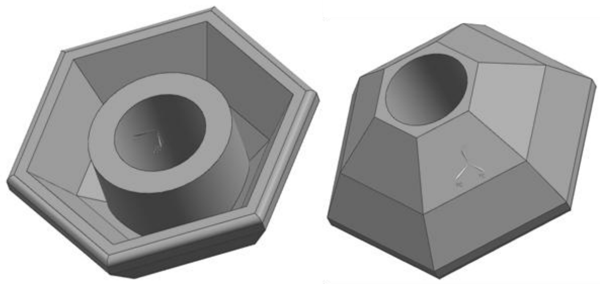

Fig. 4. Model 2

3. TECHNICAL MEASURES USED IN THE RESEARCH

The research has been performed at the Machine Construction Department of the Silesian University of Technology. The following equipment has been used in the course of the research:
• STRATASYS FDM Vantage machine, used for printing of previously designed models,
• Taylor Hobson SURTRONIC 3+, portable, self-contained instrument for the measurement of surface texture, used for determining roughness profiles and surface roughness parameters,
• ZEISS C400 coordinate measuring machine, used for determining basic angular and linear dimensions of previously printed models

4. PREPARATION OF ANALYSED MODELS

The first step in the preparation of the previously printed models was to convert them from the PRT file (UG NX software source file) into a format supported by the machine. In this case it was the STL format. The file has been converted using a proper functionality of the UG NX software. As it is known, when converting to stl format, the dimensions of the model may change due to triangulation errors. Therefore it was set during conversion the highest imaging resolution, to obtain the best possible quality of produced surfaces.

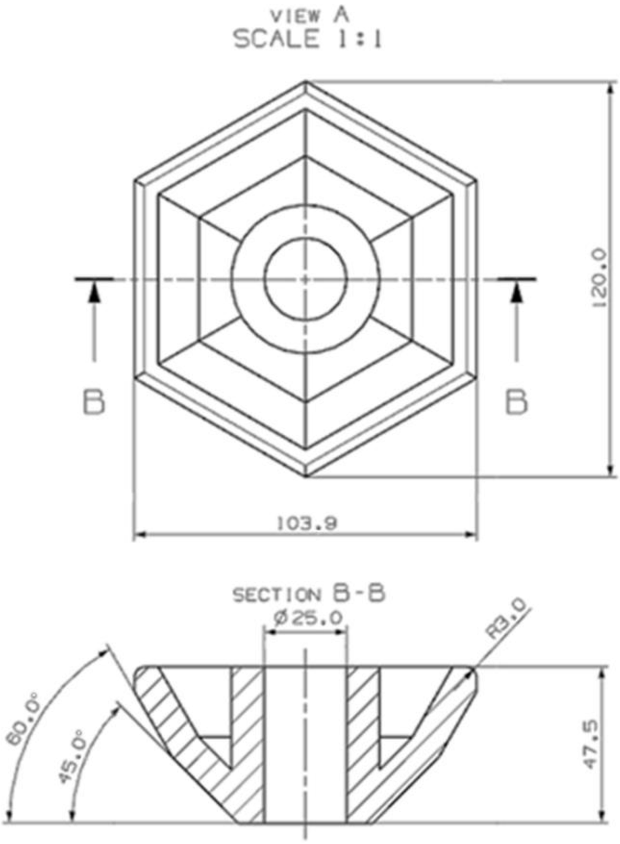

Fig. 5. Basic dimensions of Model 2

The following step was preparing the parts for production. That procedure has been performed using the software integrated with the VANTAGE SE machine, intended for setting FDM printout parameters. The first activity to do after running the INSIGHT program is the modeller configuration. The following parameters have to be set:
• machine type –Vantage SE in the described case,
• material used for production of components,
• type of printing nozzle.
When the material is selected, available nozzles are displayed. Then, after nozzle selection, single layer thickness is already determined. The material selected in the described case was ABS, due to good availability and affordability. As far as the printing nozzle is concerned, T16 has been chosen to ensure a good compromise between surface quality and printing time. For printing of support structures, T12 nozzle has been chosen by default. Layer thickness for the T16 printing nozzle is 0.254 mm.
The following step was setting the modeller appropriately for the selected filling type, quality of visible surfaces, type of supports and the production mode. The following parameters can be selected:
• inner surface style – sparse double dense,
• visible surfaces – surface raster,
• type of supports – sparse,
• production mode – normal.
The following step was proper models arrangement in the machine working chamber. It has been chosen with the assumption that part of the inclined surfaces of the designed models are attached to supports, while the other part is free. That should enable quality check of printed surfaces both attached to the supporting material and those having no contact with that material. Figure 6 presents the arrangement of the models.

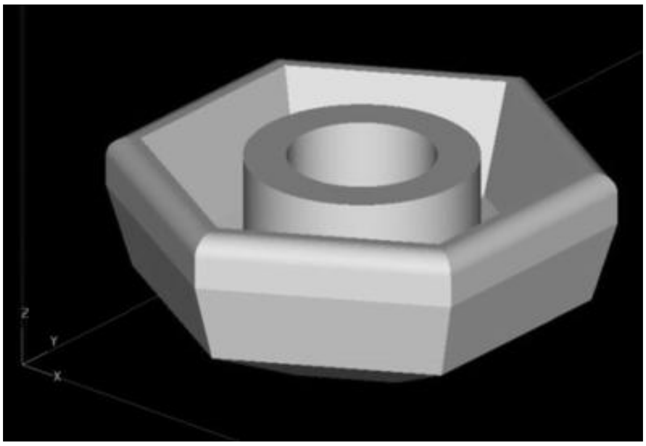

Fig. 6. Model arrangement in the working area

5. MEASUREMENT STRATEGY

The purpose of measurements made using the coordinate machine and the profilegraphometer was to determine the basic dimensions and roughness parameters for selected surfaces of previously produced models. The following model dimensions have been checked:

a) Model 1
• linear measurements: overall dimensions 103.9 mm and 47.5 mm; diameter D=35 mm (measured on both sides);
• angular measurements: side walls inclination angles 30º, 75º, 90º;
• roughness measurement of faces and one of the inclined side walls.

b) Model 2
• linear measurements: overall dimensions 103.9 mm and 47.5 mm; diameter D=25 mm (measured on both sides);
• angular measurements: side walls inclination angles 45º, 60º, 90º;
• roughness measurement of faces and one of the inclined side walls.

6. RESEARCH RESULTS

6.1 Surface roughness measurement results

All roughness measurements of the surface have been performed at a distance of 12.5 mm, as specified in the PN-ISO 4288:1997 standard. Each measurement has been repeated three times. The average results for individual measurements are specified below. The following major roughness parameters of the surface have been determined:

- Rp – maximum profile peak height,
- Rʋ – maximum profile valley depth,
- Rc – mean height of profile elements,
- Ra – arithmetic mean deviation of the assessed profile.

The markings of walls of the models used during roughness measurements are specified on Figures 7 and 8.

- Model 1

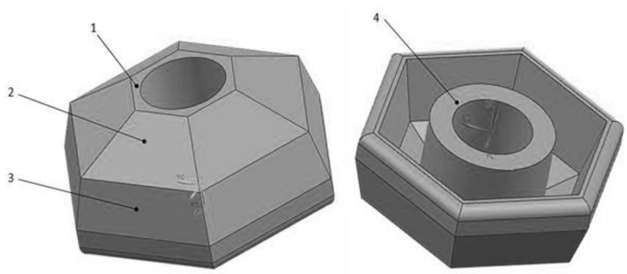

Fig. 7. Marking of measured faces on Model 1

- Model 2

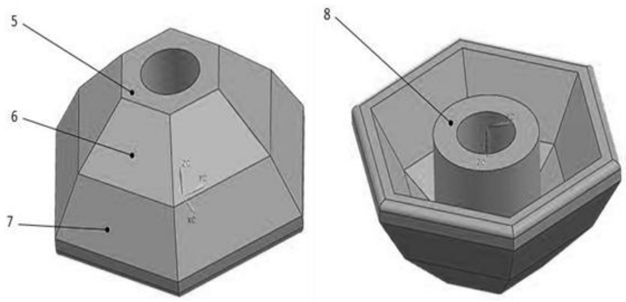

Fig. 8. Marking of measured faces on Model 2

The results of roughness measurements for the analyzed models are presented in Table 1.

Table 1. Roughness measurement results

Parameter	Face 1	Face 2	Face 3	Face 4	Face 5	Face 6	Face 7	Face 8
Rp[μm]	50.6	49.6	29.5	18.6	42.8	43.4	46.9	12.7
Rʋ[μm]	43	49.5	48.5	46.3	37.9	52.5	68.2	35.4
Rc[μm]	77.1	80.5	68.1	58.1	74.2	65.4	107.3	38.9
Ra[μm]	24.7	23.9	18.6	14.2	17.6	18.2	28.9	11.5

The analysis of the results brings to a conclusion that the lowest roughness has been measured on faces 4 and 8 that had no contact with the working table and the supports and also were oriented in the normal layer forming direction. The highest roughness has been measured on face 7. It is the wall with the inclination angle of 60º, having no contact with the supports. Other faces (marked 1, 2, 3, 5 and 6) had similar roughness parameters. All of them, except wall No. 3, touched the supports or the working table in the course of production. Those walls were also inclined to the working table at different angles. Surface No. 3 had no contact with the supports in the course of production, but was inclined against the base at the angle of 75º, which has apparently improved its quality in comparison with wall No. 7.

6.2 Results of linear and angular measurements

Each basic geometrical shape has been determined by 8 measurement points. All measurements have been repeated three times. The average values are presented below. The linear and angular dimensions measured using the coordinate machine are presented in Figure 9:

- Model 1

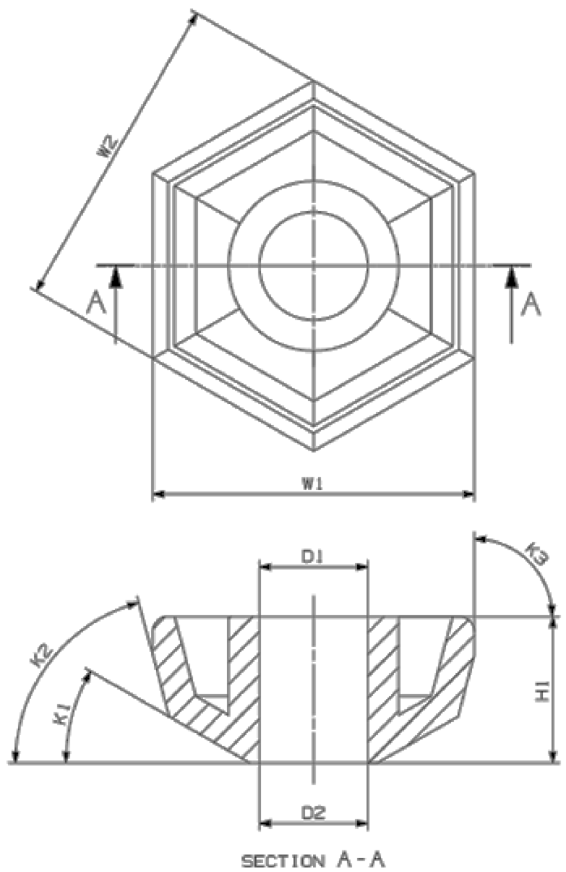

Fig.9. Marking of dimensions measured in Model 1

The results of linear and angular measurements are presented in Tables 2 and 3.

Table 2. Measured linear dimensions of Model 1 in mm

Dim.	Nominal value	Measured value
W1	103.9	103.85
W2	103.9	103.82
H1	47.5	47.58
D1	ϕ35	ϕ35.11
D2	ϕ35	ϕ35.08

Table 3. Measured angular dimensions of Model 1 in deg

Dim.	Nominal value	Measured value
K1	30	29.87
K2	75	74.72
K3	90	90.39

The analysis of the presented results leads to a conclusion that all linear measurements fall within the tolerance range given by the manufacturer of the Stratasys FDM machine, which is +/- 0.13mm. It has also been noticed that the D1 hole diameter measured at the end having no contact with the supports was less accurate than at the end attached to the table in the course of production.

Table 4. Measured linear dimensions of Model 2 in mm

Dim.	Nominal value	Measured value
W1	103.9	103.84
W2	103.9	103.79
H1	47.5	47.50
D1	ϕ25	ϕ25.13
D2	ϕ25	ϕ25.08

Table 5. Measured angular dimensions of model 2 in deg

Dim.	Nominal value	Measured value
K1	45	44.87
K2	60	60.23
K3	90	90.77

Having compared both these results of angular measurements it has been found that small deviations are present in all dimensions and they increase with the value of measured angles. The highest inaccuracy has been obtained for K3, that is the angle between two surfaces not touching the supports. The smallest inaccuracy has been obtained for K1, that is the angle between the base of the model and the wall attached to the supports.

- Model 2

The results of linear and angular measurements are presented in Tables 4 and 5.

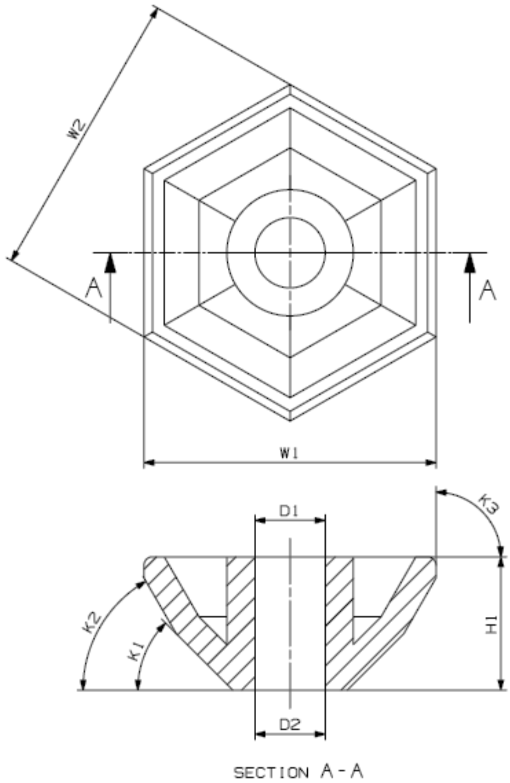

Fig. 10. Marking of dimensions measured in Model 2

Just as in the first model, the overall dimensions of the second model, marked W1, W2 and H3 (Figure 10) fall within the range of tolerance specified by the machine manufacturer. The difference occurred in dimension D1, that reached the limit of the acceptable tolerance. The analysis of both dimensions of the measured hole indicated that also in this model the opening at the bottom, touching the working table in the course of production, was more accurate.

For these angular dimensions very small angular deviations have been reached, smaller than in the first model. Additionally, angular deviations in this model increase with the angular dimension value.

7. CONCLUSIONS

Surfaces that are printed on a support matrix or directly on the table surface have a similar roughness profile.

Printing on support material reduces the step effect that is clearly visible for angled walls.

Qualitatively the best surfaces are obtained on walls perpendicular to or parallel to the table.

Analysing the effect of the angle of arrangement on roughness, the worst surface roughness is obtained for small wall inclination angles to the table. This is significantly affected by the stepped arrangement of the model layers.

According to manufacturer's data, the accuracy of the used FDM machine is ±0.13mm. All linear dimensions were within this range. Additionally, it can be concluded that:

-The largest deviation occurred in the diameter of

Model 2, measured at the end not touching the supports. It was 0.13 mm.
-A dependence has been found consisted in the fact that the dimensions of hole at the bottom of the model are more accurate than those at the top of the model. It was caused by the fact that layers in the bottom area were applied first and were stabilised by the supports. Certain inaccuracies occurred with each consecutive layer, thus the same dimension at the top of the model is somehow a sum of inaccuracies of all previous layers.
-The largest deviation occurred in angular dimension K3 of Model 2, reaching 0.77º.
-It has been noticed that its deviation increases along with the increase in the angle value. This situation occurred in both models. As in the case of linear dimensions, it was due to the model walls printing sequence. Surfaces inclined at smaller angles against the model base were printed first. Small inaccuracies always occur when printing a layer of the model and they accumulate with every consecutive layer.
In general, the described research might be useful for proper arrangement of items in working chambers of rapid prototyping machines. If there is a need to produce a specific element, we often focus on better quality of only certain surfaces or fragments of a given component. Considering that, proper arrangement may reduce the cost of production, as there is no need to use smaller printing nozzles or to increase the print quality parameters. The major problem in production of models using rapid prototyping methods is the stair-stepping effect. Certainly, the development of this technology will lead to reduction in the thickness of single layers, which will minimise the impact of the stair-stepping effect on the quality of printed surfaces, and most importantly, ensure better quality of produced models.

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