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Research Article

INFLUENCE OF PROCESS PARAMETERS ON DIMENSIONAL ACCURACY OF PARTS MANUFACTURED USING FUSED DEPOSITION MODELLING TECHNOLOGY

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ABSTRACT
The paper presents the results of experimental study – part of research of additive technology using thermoplastics as a build material, namely Fused Deposition Modelling (FDM). Aim of the study was to identify the relation between basic parameter of the FDM process – model orientation during manufacturing – and a dimensional accuracy and repeatability of obtained products. A set of samples was prepared – they were manufactured with variable process parameters and they were measured using 3D scanner. Significant differences in accuracy of products of the same geometry, but manufactured with different set of process parameters were observed.

Keywords: rapid prototyping, fused deposition modelling, 3D optical scanning, manufacturing accuracy.

INTRODUCTION

Rapid Prototyping (RP) and Additive Manufacturing (AM), also known as Layered Manufacturing is a group of technologies that allow to produce a physical prototype based only on the 3D CAD model, without need to prepare tooling of any kind. RP technologies have found their place among other, traditional manufacturing technologies – they are invaluable when there is a need of quick manufacturing of a physical prototype of a designed part [5].

Usability of prototypes manufactured with RP technologies is directly related to their parameters, among which accuracy is one of the most important, especially in case of functional prototypes. Manufacturing accuracy of any part is a degree of its compatibility with an ideal part [11]. Two types of accuracy in manufacturing can be distinguished. Dimensional accuracy is a degree of compatibility of linear or angular dimensions with dimensions of a perfectly produced part, dimension deviations being a direct measure of this accuracy. Shape accuracy is a degree of compatibility of specific shapes with the perfect part or with other shapes – direct measures of this type of accuracy are deviations from the ideal cylinder, sphere, straight line, plane etc. Just like all other technical and economic indexes of products manufactured in an additive manner, accuracy is strongly affected by parameters of manufacturing process – products of the same nominal geometry will have entirely different properties if they are manufactured using different sets of values of these parameters. The most important parameter is the model orientation – set of angles between basic planes of the object and the manufacturing direction.

Dependency between manufacturing orientation (and other parameters of additive manufacturing process) and technical and economic product indexes are of particular interest of research facilities all over the world dealing with the additive manufacturing technology. There are studies focused on identification and description of these relations [1, 2, 4] and their generalization and formulation of directives for the control of economic and technical indexes of products by optimal process parameter selection [3, 9]. This paper presents research belonging to this type of study – it presents the results of experimental testing of influence of the orientation on the accuracy and dimensional repeatability of products obtained using one of the most widespread AM technologies – Fused Deposition Modelling (FDM). The acquired results are shown together with the results of earlier work by the authors, regarding the relations between orientation and mechanical properties of additively manufactured products [6]. The authors have also worked on a similar problem in the past (influence of process parameters on accuracy of FDM parts), but the layer filling strategy was the parameter investigated instead of the orientation [10].

The research was performed in the Laboratory of Rapid Manufacturing of Chair of Production Engineering and Management, located in the Faculty of Mechanical Engineering of Poznan University of Technology. The Laboratory frequently cooperates with industry and there are often requests for prototypes of parts manufactured with high accuracy and strength. It is impossible to obtain a product with an optimal combination of these two properties without identifying the relations between them and process properties – and this is what this paper is about.

BASIC INFORMATION

Additive manufacturing using thermoplastics –Fused Deposition Modelling

Fused Deposition Modelling is a process consisting of layered deposition of plasticized build and support material supplied in a form of a wire by an extrusion head (see fig. 1 for process schema). Numerically controlled device deposits its build and support material on the model base, with data about head positioning coming from horizontal cross-sections of the part, prepared on the basis of the 3D CAD model. The ABS material is frequently used, other thermoplastics can be used too, depending on the machine and head type. Obtained models are considerably strong and can be subjected to further treatment by machining, gluing or painting, to obtain desired surface quality. The produced part is ready for use immediately after support material removal [8].

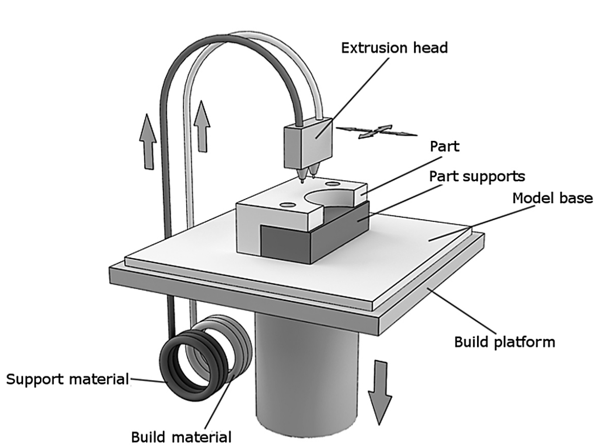

Fig. 1. Schema of the Fused Deposition Modelling process [8]

Influence of the FDM process parameters on features of obtained products

Finished product manufactured using Fused Deposition Modelling technology can be characterized by technical indexes – strength of certain kind (tensile, flexural strength or impact resistance), dimensional and shape accuracy, as well as economic indexes, such as manufacturing time and amount of support and build material used. Many factors have direct influence on these indexes [2]. A phenomenon specific for the described technology is relatively high significance of additive process parameters. Additive technologies make no use of any tooling, it is their most important advantage. The role of the tooling in the aspect of influencing technical and economic indexes is taken by the process parameters (more specifically, the sets of parameters), which may be directly or indirectly controlled by the process engineer (Fig. 2). The orientation of manufactured model during the process is the most important parameter of these which can be changed directly.

Orientation of the model in the working chamber during layered manufacturing process can be intuitively described as an angular difference between plane determining direction of the object division into layers and selected, basic plane of the manufactured object (Fig. 3). Orientation can be unequivocally defined by three angular values. One of them – rotation in the Z axis (around vertical direction) has no importance from the viewpoint of technical and economical indexes, as it has no influence on how the object is divided into layers.

The orientation directly affects the internal structure of the model [6], deciding, among other

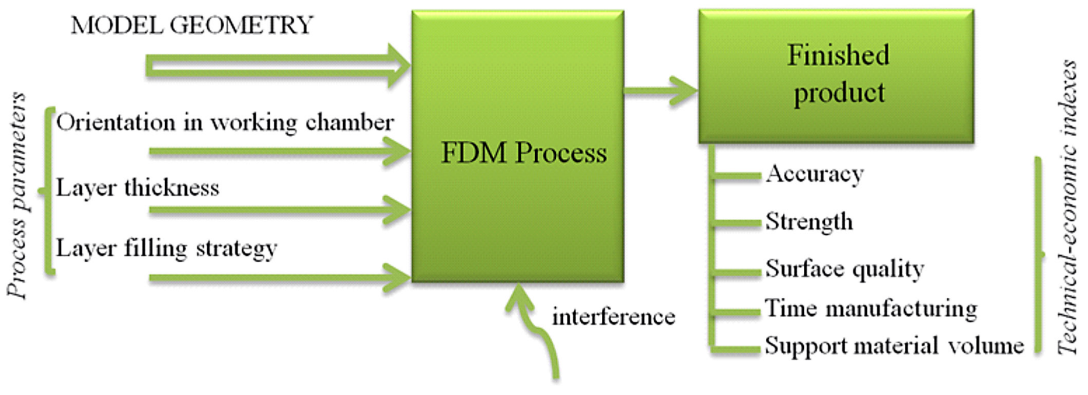

Fig. 2. Parameters of the FDM process and technical and economic indexes of the finished product

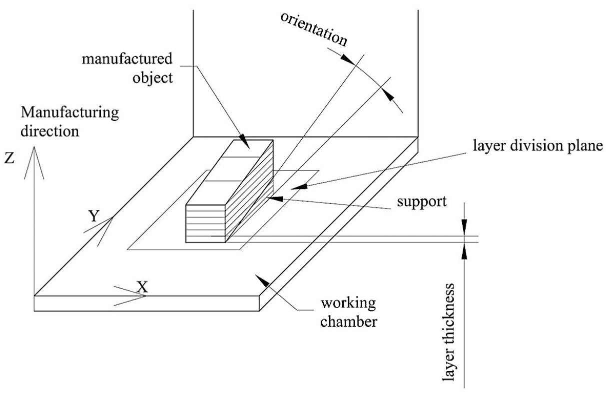

Fig. 3. Orientation of the model in the working chamber [6]

things, about strength, accuracy or surface quality. It is also a relevant parameter in terms of economic aspects of product manufacturing.

CONCEPT AND METHODOLOGY OF RESEARCH

Aim and plan of the study

An exact character of dependencies between the orientation and particular features of products obtained with FDM method has not been fully investigated yet. There were attempts at experimental determination of these relations [1], but it is still an open research problem. This paper is aimed at preliminary identification of the relation between model orientation and two basic characteristics related to accuracy of the obtained products:

- dimensional accuracy, understood as degree of compatibility of basic dimensions of the obtained product with dimensions of the ideal product (nominal dimensions),
- repeatability – degree of dimensional compatibility of two products of the same nominal geometry, manufactured in the same conditions, with identical values of the process parameters.

Obtained results – accuracy and repeatability coefficients for samples of variable orientation – were compared with simultaneously acquired results of tensile tests performed on the same samples. Simplified plan of the research (in chronological order) is shown in Figure 4. Samples were manufactured using FDM technology available in the Laboratory of Rapid Manufacturing. Then they were measured using 3D optical scanner. After measurements, they were subjected to tensile tests.

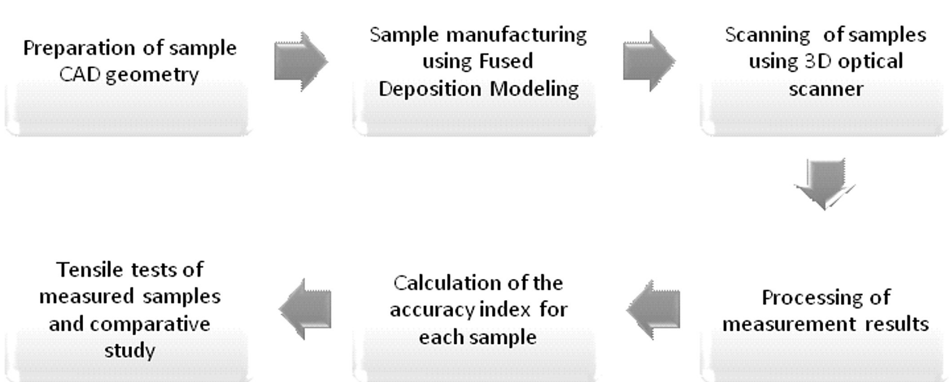

Fig. 4. Plan of the research

Preparation of samples for measurements

For the accuracy study of FDM made parts, tensile test samples were selected as a nominal geometry (they contain both straight and curved profiles, so it is also possible to evaluate shape accuracy). On the basis of the standards describing the strength tests (PN-EN ISO 527), CAD models of samples were prepared (Fig. 5). Then they were transformed to a triangle mesh and loaded into software CatalystEX, used for process control on the available machine – Dimension BST 1200 (Fig. 6).

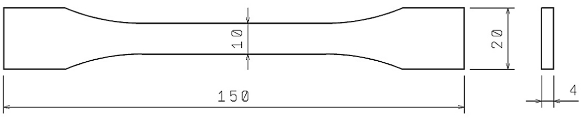

Fig. 5. Sample used in accuracy studies

Using the same geometry, five different samples were prepared by changing the orientation values – two possible values of X orientation were selected (flat and side) and for these, Y orientation was varied by 45 degrees. Samples of the following orientation were manufactured:

- 0° X, 0° Y (flat-orientation sample)
- 90° X, 0° Y (side-orientation sample)
- 0° X, 45° Y
- 90° X, 45° Y
- 90° Y (vertical orientation sample).

Each sample type was manufactured in 3 copies, to perform repeatability study. To refer to each sample type in an easy way, they were assigned IDs, based on their orientation in X and Y axes. Summary of manufactured samples is presented in Table 1. Some of the specimens are shown in Figure 7.

Sample measurement – 3D optical scanning

Three-dimensional scanners use light (mostly white, blue is also used) of a known structural pattern – usually it is a fringe sequence of known, variable width and density. Light is projected on an object and fringe pattern image is registered by cameras. Deformation of the pattern is then analyzed by the software to map each point from the camera matrix with an appropriate point coordinates in space. A single measurement (up to 20 seconds), also named scan, gives as many measured points as the camera matrix has – in case

Table 1. Summary of manufactured samples for measurements

No.	Orient. X [°]	Orient. Y [°]	ID	Manufacturing time [s]	Support material [cm^3]	Build material [cm^3]
1.	0 (flat)	0	0F	1320	1.96	8.81
2.	90 (side)	0	0S	2760	2.28	8.71
3.	0	45	45F	11520	16.71	8.60
4.	90	45	45S	13080	26.68	8.67
5.	n/a (vertical)	90	90	13320	11.69	8.51

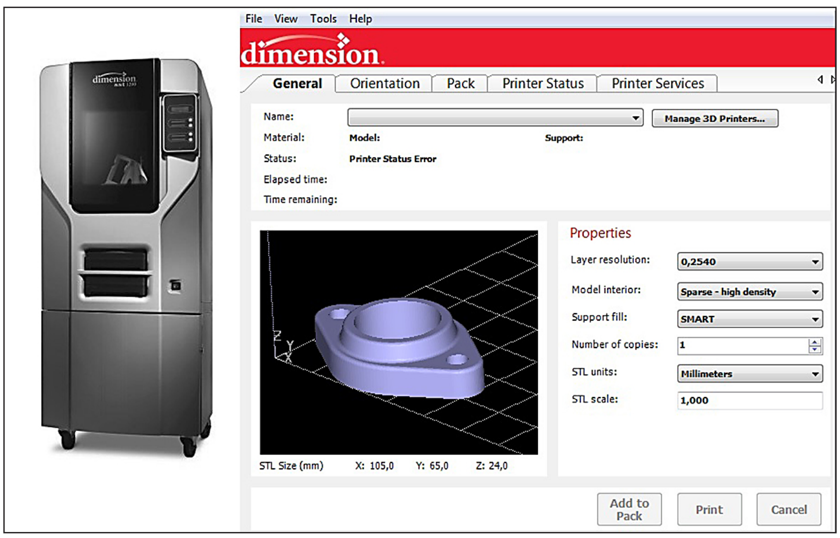

Fig. 6. Dimension BST 1200 machine used for sample manufacturing and main window of the CatalystEX software

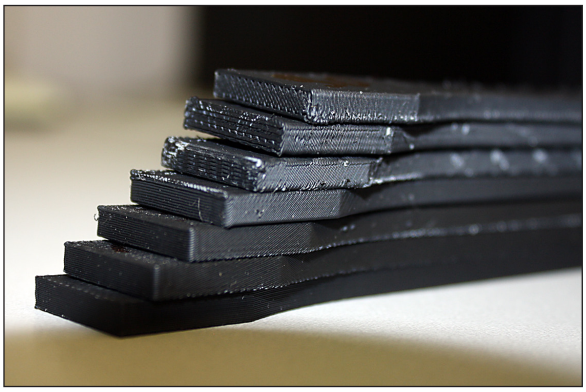

Fig. 7. Samples manufactured using FDM technology – same geometry, different orientation

of the scanner used in the research it is a value of 0,8 MPix, so it is 800 000 points, practically representing the whole measured surface. Measurement accuracy can be as high as 0,02 mm [7].

For research discussed in the paper, an ATOS I optical scanner by GOM was used (Fig. 8). To accurately measure small objects – tensile test samples – the smallest possible measurement field available for this scanner was used, with scanning volume of 125 mm per 100 mm per 90 mm. The objects were covered in non-coded targets, used for auto-orientation of the subsequent scans [7], placed in a fixed position (Fig. 9) and measured (Fig. 10).

Processing of the measurement results

After the measurements are finished, a preliminary data processing must be carried out. It consists of the following stages:

- joining the data from all scans together – performed automatically, with some corrections able to be performed manually;
- removal of useless points (representing fixtures or other objects present in the measurement volume), manually or automatically;
- assignment of a coordinate system to the object (basing) by the “plane, line, point” method – definition of Z plane, X axis and point 0 by indication of points forming these geometries (3 points for plane, 2 for line, 1 for coordinate system beginning);
- generation of triangular mesh on the basis of the processed point cloud and export of the generated mesh to an STL format.

Data processing is performed using the software supplied with the 3D scanner by GOM company. Further processing consists of preparation of measuring reports. The following reports have been prepared:

- accuracy report for each sample – comparison with an ideal part geometry (deviations between nominal CAD model and a triangle mesh),
- repeatability report for each pair of the same type of samples – comparison of the two samples (deviations between two triangle meshes).

Fig. 9. Non-coded reference targets placed on measured object

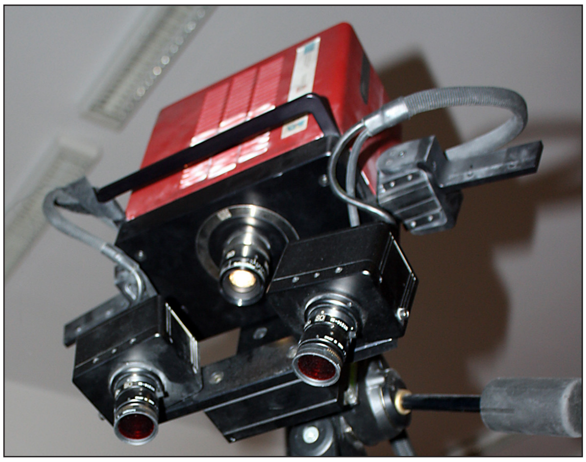

Fig. 8. ATOS I scanner used in the research

Fig. 10. Measurement of the samples using 3D scanner

The digital data that was compared (namely, triangle mesh with nominal model in 1 and two triangle meshes in 2) was put together using the “best fit” algorithm provided in the GOM software. Reports contained the following information in the visual form:

- coloured deviation map (examples in the Figure 11).
- deviations along the outlines of selected cross-sections,
- deviations from specified dimensions, checked dimensions are shown in the Figure 12a, with exemplary page from the report in the Figure 12b. Each dimension was inspected in several locations – 4 for widths, 2 for length, 7 for thickness.

For repeatability reports, only coloured deviation map and deviations in cross-sections were generated. Each sample type was characterized by two coefficients, a dimensional accuracy coefficient and a dimensional repeatability coefficient. Both were calculated using average deviation values from the reports.

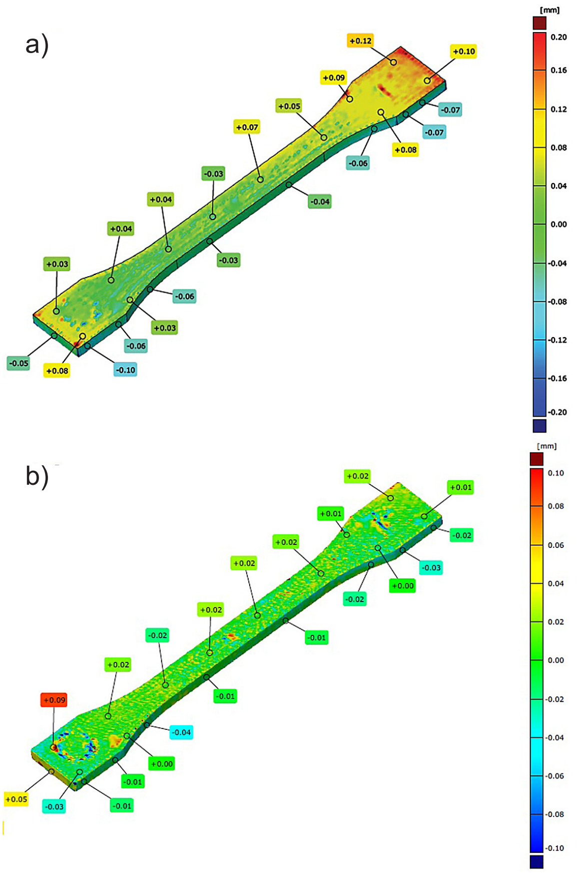

Fig. 11. Examples of deviation maps obtained during the study for sample type 0F: a) deviation from the nominal shape, b) deviation of sample 1 from sample 2

The dimensional accuracy coefficient is basically calculated as an average of deviation from all inspected dimensions, which is why it must be treated only as a general index. The formula for the accuracy coefficient is the following:

$$k_d = \frac{k_{len} + k_{w1} + k_{w2} + k_h}{4} \tag{1}$$

where: k_d – coefficient of dimensional accuracy of the specific sample type,

k_{len}, k_{w1}, k_{w2}, k_{th} – coefficients of accuracy of 4 checked dimensions (length, two widths and thickness), with a single coefficient formula as following:

$$k_x = \frac{\sum_{i=1}^{n} \frac{d_{x_i}}{x_{nom}}}{n} \cdot 100 \tag{2}$$

where: x – dimension (x stands for length, widths and thickness, formula (2) was used for all four coefficients),

n – number of samples taken into account (n=3 in this paper),

d_{xi} – average from deviation from the dimension x in sample number i [mm], absolute value

x_{nom} – nominal value of the dimension x (see fig. 5 for all nominal dimension values).

The higher the accuracy coefficient, the lower the accuracy. Ideal part would have an accuracy coefficient of 0. The value ofaccuracy coefficient equal 1 means that average deviation from the nominal dimensions is 1%.

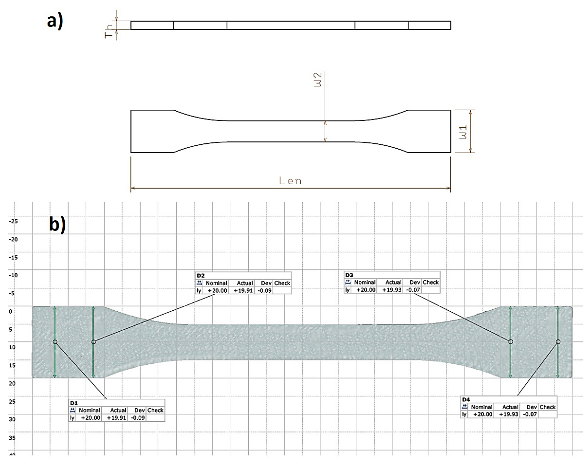

Fig. 12. Dimensions taken into consideration in accuracy analysis, a) indication of dimensions, Len – length, W1 – broad area width, W2 – narrow area width, Th – thickness; b) example of deviation report for W1 dimension, sample ID 0F

The repeatability coefficient is calculated as an average difference in dimensional accuracy coefficients calculated for each sample separately. The formula is as following:

$$k_r = \frac{|k_1 - k_2| + |k_2 - k_3| + |k_1 - k_3|}{3} \quad (3)$$

where: k_r – repeatability coefficient of the specific sample type,
k_1, k_2, k_3 – accuracy coefficients calculated as in formulas (1) and (2), but separately for each of the three samples.

The higher the repeatability coefficient, the lower the repeatability can be achieved for the sample – perfectly repeatable process would result in coefficient equal to 0.

Both coefficients are dimensionless, although they could be treated as a percentage.

RESEARCH RESULTS

Dimensional accuracy and repeatability measurement results

Using formulas (1), (2) and (3), the accuracy and repeatability coefficients were determined for each sample. Table 2 contains the most generalized form of actual research results – coefficients k_d and k_r for each sample type. The coefficients are illustrated in Figure 13. Table 3 contains the components of accuracy coefficient – average coefficients of each checked dimension – their analysis brings some interesting conclusions.

Comparison of accuracy coefficients with tensile strength

To compare the accuracy with the strength of the same FDM made samples, tensile tests were performed, described in greater detail in [6]. Their results, in juxtaposition with accuracy and repeatability coefficients, are contained in Table 4 and the values are presented in the graphical form in Figure 14. The table contains additional data about manufacturing time (from Table 1), for informational purpose. The best values in each category are bolded and worst are shown in a different colour. To make visual comparison easier, k_d and k_r coefficients were inversed – value used for graphs is equal to 100 – k_d/k_r. Thanks to the inversion, greater height of all the columns in the graph in the Figure 14 represents more beneficial value of a property, so it is easier to compare the values.

CONCLUSIONS

After analysis of the obtained data, the following conclusions can be drawn:

1. It is confirmed that the orientation directly influences both the accuracy and repeatability of FDM parts. Character of the $A = f(O)$ func-

Table 2. Coefficients of accuracy of samples made using Fused Deposition Modelling technology (k_d – accuracy, k_r – repeatability, lower value = better)

Sample ID \ Coefficient	k_d	k_r
0F	0.976	0.090
0S	1.403	0.409
45F	0.665	0.080
45S	0.852	0.603
90	1.046	0.668

Table 3. Coefficients of accuracy of each inspected dimension (lower value = better)

Sample ID \ Coefficient	k_{len}	k_{w1}	k_{w2}	k_{th}
0F	0.021	0.508	0.625	2.750
0S	0.031	0.600	2.817	2.167
45F	0.034	0.354	0.675	1.595
45S	0.038	0.300	0.583	2.488
90	0.193	0.092	0.933	2.964
on average:	0.064	0.370	1.127	2.393

Table 4. Comparison of accuracy with the tensile strength and elongation at break of FDM samples (higher value = better), with manufacturing time included (t_m)

Sample \ Property	100 - k_d	100 - k_r	σ_m [MPa]	ε_b	t_m [s]
0F	99.024	99.940	19	4.6%	**1320**
0S	98.560	99.727	**22.9**	**7.0%**	2760
45F	**99.335**	**99.947**	12.9	1.5%	11520
45S	99.148	99.598	14.9	1.2%	13080
90	98.954	99.555	11	1.0%	13320

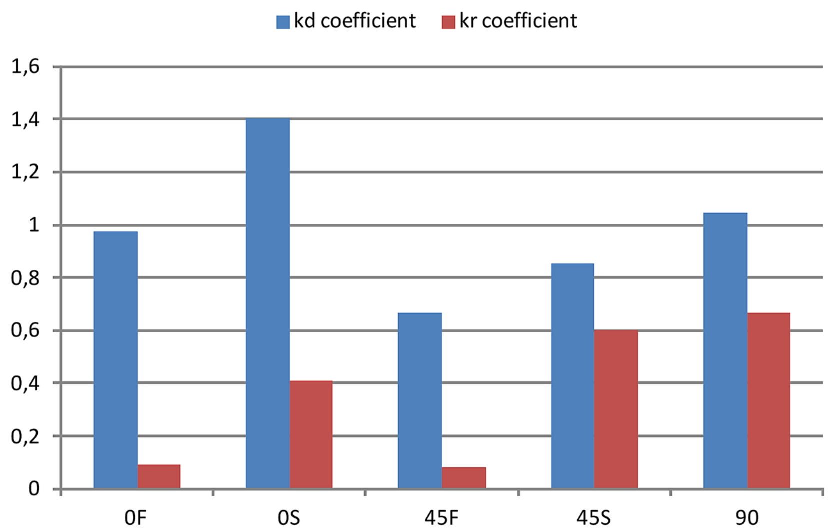

Fig. 13. Coefficients of accuracy and repeatability for FDM samples (lower = better)

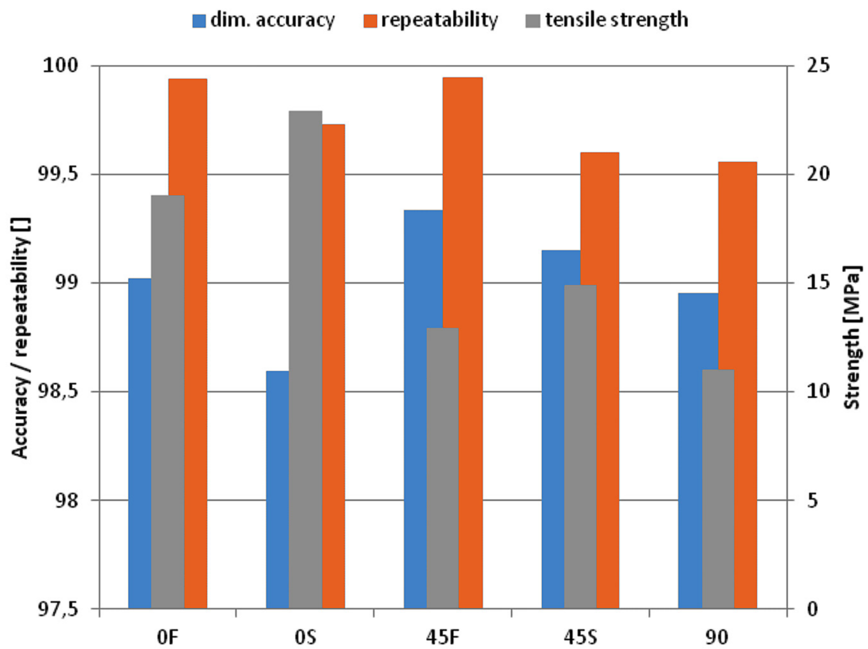

Fig. 14. Juxtaposition of strength and accuracy of FDM samples (higher = better)

tional relation (*A* – accuracy, *O* – orientation) is non-linear and rather hard to describe mathematically with such small number of sample types.

2. Relation between calculated accuracy and repeatability coefficients can also be described as non-linear, at least for coefficients calculated only on the basis of deviations from specific dimensions.
3. Accuracy of FDM made parts should be considered as low in comparison with other plastic forming technologies, with deviations of meaningful dimensions above 2% in some cases.
4. Analysis of deviations of particular dimensions brings an interesting conclusion – deviations are relatively smaller for higher dimensions, i.e. the greater the object size is, the more accurately it will be manufactured. This only applies to relative deviations (i.e. deviation/nominal dimension ratio), as absolute deviation values remain on more or less the same level, regardless of the nominal dimension value.
5. Strength of FDM made parts is not particularly related to the accuracy, although some minor positive coupling can be observed in some cases.

6. The most beneficial sample out of the manufactured 5 types, regarding all the possible criteria (accuracy, repeatability, strength, cost, time, surface quality) with assumption that all criteria are equally significant, is the 0F sample, as a combination of both technical and economic indexes is optimal for this product, although its strength, accuracy and repeatability are not the best.

General conclusion can be drawn that it is not easy to select a proper orientation to meet all the requirements regarding accuracy and strength of the part – there is no perfect combination, therefore, it is fully justified to use artificial intelligence tools to determine optimal orientation, as some authors suggest [3, 9]. For parts with simple geometry, it is usually the best way to focus on the economic effectiveness, because short manufacturing time is usually related to higher strength and in some cases – higher accuracy and better surface quality. It can be explained in a simple way – the more layers the product has, the longer it takes to manufacture it and there are more weak spots which lower the strength in certain tests (bond between layers is based only on adhesion, so each product has lower strength if the load direction is equal to manufacturing direction), so aiming at orientation with the lowest number of layers allows to rise at least two important product parameters, with high chance to rise accuracy and sometimes surface quality as well.

To fully identify the relation between orientation and accuracy, a higher number of sample types is required – for the start, with variation of orientation in Y axis equal to least 15 degrees, which would give 7 samples per one X orientation (14 samples in total for two X orientations) – it would allow to define at least an approximate character of the $A = \mathrm{f}(O)$ function. Further experimental studies should be conducted to explore the possibility of controlling all the product technical and economic indexes using orientation value, not only for products of simple geometry, but also for more complex shapes.

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