Mechanical properties and geometric accuracy of angle-shaped parts manufactured using the FFF method

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Abstract. The paper presents the results of research on the influence of the parameters of Fused Deposition Modelling (FDM) on the mechanical properties and geometric accuracy of angle-shaped parts. The samples were manufactured from acrylonitrile butadiene styrene (ABS) on a universal machine. A complete factorial experiment was conducted. The results indicated that the critical technological parameter was the angular orientation of the sample in the working chamber of the machine. The results were compared with the results of research performed on simple rectangular samples. A significant similarity was found in the relationships between the FDM parameters and properties for both sample types.

Key words: material extrusion; additive manufacturing; mechanical properties; angle-shaped parts.

1. Introduction

Additive manufacturing (AM), also known as 3D printing, allows the shaping of parts with a complex geometry without the need for additional technological equipment [1]. Moreover, a broad spectrum of additive manufacturing varieties makes it possible to manufacture parts from many types of materials [2]. However, concerning traditional technologies (casting, machining and plastics moulding), AM has significant constraints relating to its efficiency and the quality and, above all, the physical and chemical properties of the manufactured parts [3]. Therefore, the scope of AM applications in the industrial production of everyday products is still relatively limited [4]. For most types of AM methods, especially those in which metal alloys are not used, production is focused mainly on prototypes and visual supplies [5], some types of tooling [6] and simple parts which are not heavy-duty [7].

One of the most commonly used additive manufacturing methods is FFF (Fused Filament Fabrication), also known as FDM (Fused Deposition Modelling). In this method, the physical version of a part is made from thermoplastic material. The production itself consists of applying plasticized material extruded through a nozzle with a circular end section, moving along the X and Y axis, parallel to the print bed, which is often enclosed in a chamber (see Fig. 1). After applying the material within one layer, the print bed moves its position relative to the head along the Z axis, at a value corresponding to the defined thickness of a single layer.

The FDM technological parameters are related to the parts manufactured (product parameters) and to the process of material layering (process parameters) (Fig. 1). The product parameters are object position and orientation in the machine chamber, number of contours, infill percentage (air gap – offset of the internal material paths), number of top and bottom solid layers, and layer thickness. The process parameters include head speed
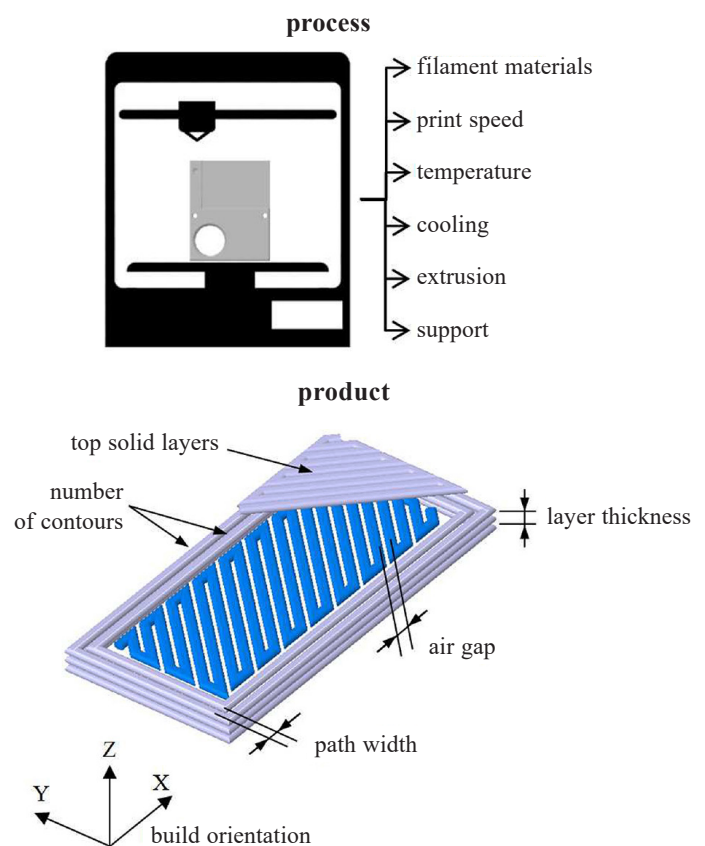

Fig. 1. Product and process parameters of FDM

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(plastic deposition speed), the temperature in the working chamber, the temperature of the plasticized material, and the type of thermoplastic material used. By selecting a suitable FDM machine, material that can be reinforced with, for example, additional filling particles [8], and setting appropriate technological parameters, it is possible to shape, to a vast extent, the properties of the parts manufactured.

Planning technological processes for additive manufacturing is not simple a task [9]. The literature presents many studies on the impact of FDM technological parameters on the properties of the parts manufactured. These are mainly experimental studies, and mathematical modelling is only used to a limited extent to predict the properties of the part [10]. Most often, the parts tested are shaped in the form of simple cuboid samples (compare Fig. 3a). In [11], it was found that a significant anisotropy of strength properties characterized a cuboid part produced by FDM. The greatest capacity to transfer tensile loads was obtained along the paths on which the material was deposited. This indicated the significant importance of the parameters related to the orientation of the product in the working chamber. These parameters could also significantly affect the accuracy of the cuboid part. By using a negative value for the air gap parameter, both better strength and stiffness were achieved. This was also confirmed by [12], where the authors found that the joints of the material paths between the layers of the part were more resistant to shear stresses than combinations of paths within a single layer. According to the same authors, the width of the material path and the temperature of the extruded material had no significant effect on the strength properties. However, the width of the extruded material path had a significant impact on the time and accuracy of the product.

Changing the part's orientation in the working chamber, depending on its geometry, can dramatically affect production time. At the same time, minimizing production time by changing the orientation may result in a significant increase in material consumption due to the need to use supports for geometries overhanging the outline of the previous layer [13].

The orthotropic strength properties of cuboid parts produced by the FDM method were presented in [14]. Using the classic laminate theory, it was proven that, with a high probability, it was possible to use it to estimate the modulus of elasticity. The tests were carried out for both ABS and PLA (polylactic acid) material, with a variable orientation of the inside of the part layers. At the same time, it was confirmed that the orientation of the filling had a significant impact on the strength properties, and the manufacturing process itself caused significant increases in the brittleness of the input material (the produced parts had much less flexibility than the input material).

According to [15], the thickness of the layer, the number of contours and the offset of the material paths are of the most significant importance for the strength of the parts, which are subjected to dynamic and cyclic loads. The number of contours should be as high as possible, while the distance of the material paths should be as short as possible. Decreasing the thickness of the layer increases the probability that unfavourable material discontinuities (pinholes or voids) and delamination of the layers will occur, which weakens the overall strength. On the other hand, the authors of the study [16] note that a thinner layer may lead to the appearance of larger temperature gradients in the manufactured part and thus better diffusion between the layers. Furthermore, in [17], the use of layers with the minimum possible thickness and layer filling paths with the minimum width is recommended to obtain better tensile strength; however, it should be borne in mind that this increases production costs. Other studies [18] have shown that there is a certain minimum layer thickness in the case of PLA material, and all the processes should be planned using a value higher than this. The use of a lower value leads to over-compressed layers and a weakening of the strength properties. For the ABS material, applying a thicker layer while reducing the material extrusion speed allows for smaller deformations of the product geometry [19]. For thinner layers and low extrusion speeds, the force at which material flowing out of the nozzle is pressed against the substrate may be too weak to get its deposition in the planned location. In contrast, for thicker layers, an excessive increase in the extrusion speed leads to inadequate heating of the material so that it is extruded at too low a temperature or extrusion is not continuous [20].

In addition to the number of contours affecting tensile strength [21], their orientation in the direction of force is also essential. In [7], it was shown that the orientation of the direction of applying the contours with the direction of the load results in an increase in stiffness and tensile strength. An analytical model was prepared, which enabled the estimation of tensile stresses and Young's modulus based on the arrangement of contours. The authors of [22] also developed a mathematical model for the estimation of strength properties. In this case, the values used in the calculations were technological parameters relating to the direction of the division of the part into layers and its angle of rotation about the Z axis. Experimental studies have shown that the best properties can be obtained with a minimum number of layers (division into layers referred to as the X direction) and at a rotation of 45 degrees around the Z axis.

A strong dependence between the FDM geometry parameters and part strength was found by Kuznetsov [23]. Nozzles with different diameters for extruding PLA material were investigated. In all cases, it was shown that layer thickness was the most important parameter, and as its value increases, there is a decrease in part strength. Opposing conclusions were presented in the study [24], where it was shown that when manufacturing PLA parts, the most significant factors for the obtained strength properties, surface roughness and manufacturing time were also layer thickness and the diameter of the extrusion nozzle. However, by increasing the values of these parameters, greater strength and roughness were obtained, with a significant shortening of the processing time.

The literature review shows that relatively few studies describe the impact of FDM technology parameters on the properties of parts with a more complex shape than cuboid parts. If such tests have been carried out at all, the influence of the parameters and properties related to the specific use of the manufactured part has been examined [25–27]. These studies also show that FDM technology is still limited in its ability

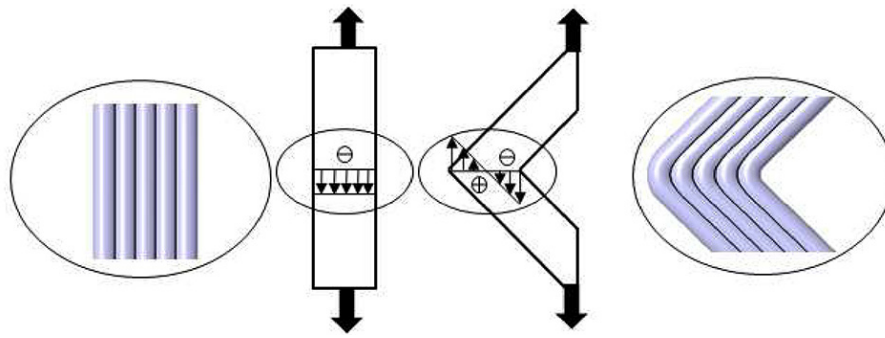2

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Fig. 2. State of stress in simple and angle-shape samples

to manufacture parts of any geometry. The most important constraints are the need to use additional supports, the limited value of the diameter of the hole in the extrusion nozzle and the limited strength of the layer boundary join. For some part shapes, removing supports (even those that can be dissolved) may not be possible or may involve the considerable risk of geometric deformation in the part. Reducing the nozzle diameter and reducing the thickness of the layer (to obtain greater thinness and shape accuracy) is limited by the viscosity of the extruded thermoplastic.

Furthermore, as the way that each successive layer of material is laid significantly affects the properties of the part, research is needed on the impact of technological parameters on the strength and geometric properties of parts with shapes more complex than simple cuboid parts, and to formulate general conclusions based on these. This need has been highlighted in previous studies, for example, in [10, 24]. The results of the research presented in this article are an attempt to fill this gap partially.

2. Material and methods

2.1. Goals and assumptions. The research aimed to compare the strength and geometrical accuracy of angle-shaped parts (hereafter referred to as angle-shaped samples or samples, for short) and simple cuboid parts manufactured under comparable conditions using the FDM method. The selection of angle-shaped samples and the properties indicated above was based on the following premises:

- The form of the angle-shaped sample applied affects its strength properties. Loading such a sample with force as in Fig. 2 leads to creating a complex state of stress in its middle section. Compressive, tensile and shear stresses occur. For comparison, in most studies, only tensile stresses have been measured on simple cuboid samples.
- The layers of the material used in the angle-shaped sample are located at an angle to the load direction (in the straight sample, they are parallel to the direction of force).
- The form of an angle-shaped sample limits the attainable geometrical accuracy. In an angle-shaped sample, some curvature is present, which can cause the so-called "staircase effect". This effect may have a significant impact on the

geometrical accuracy of the product (volume error). Moreover, the misalignment of the holes means that some part of this feature geometry overhangs; thus, it may be necessary to use some support in any possible orientation. Although it is also possible to produce the sample without supports, during production, a segment of it may not have complete support in the previous layer, thereby negatively affecting the accuracy of the obtained shape.

The geometry of the part and its loading while testing is shown in Fig. 3.
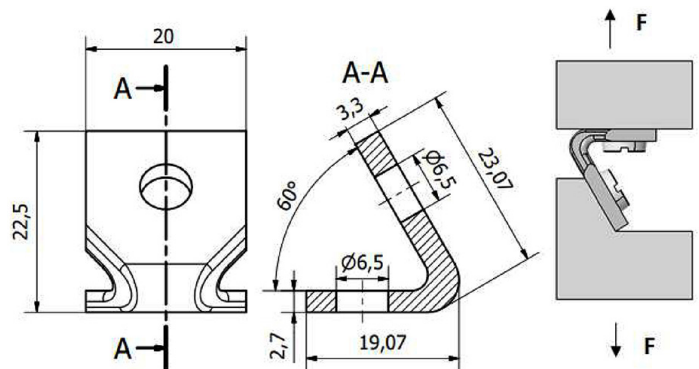

Fig. 3. V-shaped part, geometric and strength values included in the research

The following mechanical and geometrical properties of the samples were measured:

- strength (STR), resistance to loading force F, as shown in Fig. 3c,
- wall thickness deviation (WTD), Tnom = 3,30 mm,
- hole diameter deviation (HDD), Dnom = 6,50 mm.

The geometry of the sample is a result of its practical application – it is a part that connects two other parts. As can be observed, wall thicknesses differ in the two arms of the sample due to a lack of space between the connected parts. The wall thickness deviation was analyzed only for the thicker wall. That was related to the experimental setup (see Fig. 4); as for the thickness of 2,70 mm, neither of the two selected manufacturing orientations allow investigating the layer division influence on the dimension deviation.

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2.2. Equipment. The samples for testing were manufactured using a da Vinci 1.0 Pro machine produced by XYZ Printing. This low-cost device has a closed (but not heated) working chamber and an open material system, enabling the change of basic process parameters. The machine was not further modified, but it was equipped with an additional overlay for the print bed, increasing the adhesion of the produced element during the manufacturing process – COROPad.

The material used was grey ABS sold under the trade name 3DGO. The material came from a new batch, which was hermetically sealed before production, and did not show any signs of excessive dampness during production.

In order to prepare the NC codes for the FDM machine, it was decided that different software should be used rather than that originally provided with the machine since it offered the possibility of more flexible control of the technological process parameters. The program, Simplify3D version 4.0, was used with the standard profile settings made available by the creator of the software and designed specifically for the FDM machine used in the research.

Table 1 presents the most important technological parameters that were identical in the production of all the test samples.

Table 1
Constant values of parameters of the manufacturing process

Parameter	Value
solid top layers	2
solid bottom layers	2
internal infill percentage	20%
internal infill type	fast honeycomb
external infill type	rectilinear 45°/−45°
bed temperature	90°C
extrusion temperature	230°C
cooling	disabled
perimeter extrusion speed	20 mm/s
external infill extrusion speed	25 mm/s
default extrusion speed	30 mm/s
perimeter overlap	10%
seam	optimized for fastest printing speed

Strength tests were carried out on a universal measuring machine, SUNPOC model WDW-5D-HS. An additional fixture was prepared in order to fix the samples on the machine properly. The tested product was not a standardized test sample, and the stress state during loading was complex. For this reason, durability tests were carried out following the ISO 527–2: 2012 standard, although not adhering to its exact requirements. A measurement of the samples' mass was carried out with the help of an OHAUS laboratory scale, model PA 512/1. A Mahr Micromar 40 ER micrometre was used to measure the wall thickness of the samples. Due to their size and form deviations, the diameter of the holes was only measured along one axis consistent with the long edge of the angle bar. A Mitutoyo calliper, model CD-15CPX, was used as a measuring tool. In this particular case, the calliper is an acceptable measuring tool, as the average dimensional error (resulting from the staircase effect of layer division and machine tool accuracy) is higher than the measuring resolution of the applied tool.

2.3. Design of experiments. To determine the impact of the FDM parameters on the strength and geometric accuracy of each sample, a full factorial two-level experiment (2^k) was applied. Three main factors were selected for the experiment: the setting angle of the sample in the working chamber (factor A), the thickness of the layer (factor B) and the number of contours (factor C). The choice of these factors was based on the availability in the literature of well-documented results of experimental studies on strength and geometric accuracy, which were carried out on simple cuboid samples under conditions comparable to those used in this research.

The factors A, B, and C, are later referred to in the analysis as "input variables" while the product properties, strength (STR), thickness deviation (WTD) and hole diameter deviation (HDD), are referred to as "output variables". The levels of the input variables are presented in Table 2.

Table 2
Levels of process input variables

Input variable	Level	
	−1	+1
A	0°	90°
B	0.1 mm	0.3 mm
C	1	3

A graphic interpretation of the orientation angle setting is presented in Fig. 4.

For variable A (angle), levels −1 and +1 indicate the orientation of the applied material layers (X direction) in relation to the direction of the loading force or the direction of thickness measurement. The value (−1) corresponds to the compatibility of the directions of layer application and the action of the
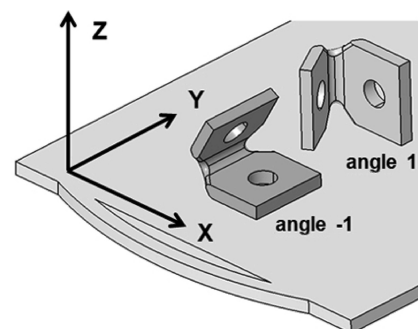

Fig. 4. Building orientation determined by angle value

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loading force (direction Z), with value (+1) corresponding to their perpendicularity.

The design of the experiment is shown in Table 3. Each stage of the experiment was replicated five times. The average value and the range of results in each stage are also presented in Table 3.

Table 3
Experiment design and results

	Input variables			Output variables					
				STR Strength [N]		WTD Thickness Deviation [mm]		HDD Hole Diameter Deviation [mm]	
Run	A – Angle	B – Layer thickness	C – Number of contours	Average	Range	Average	Range	Average	Range
1	−1	−1	−1	6.53	0.8	0.50	0.24	0.06	0.00
2	+1	−1	−1	81.80	43.3	0.10	0.12	0.30	–
3	−1	+1	−1	9.53	4.4	0.22	0.12	0.10	0.09
4	+1	+1	−1	66.03	33.1	0.12	0.04	0.18	0.19
5	−1	−1	+1	11.80	4.9	0.46	0.30	0.08	0.19
6	+1	−1	+1	185.27	27.0	0.35	0.35	0.28	0.68
7	−1	+1	+1	8.10	2.9	0.28	0.03	0.06	0.12
8	+1	+1	+1	119.67	5.3	0.41	0.20	0.28	0.37

3. Results

3.1. Results presentation overview. The results of the experiments performed are illustrated graphically in Figs. 5, 6 and 7 according to the following scheme:

a) the impact of input variables on an output variable (main effects plot),
b) the mutual influence of input variables on an output variable (interactions plot),
c) significance of main effects (A, B and C) and interactions (AB, BC, AC and ABC) (Pareto plot for effects and interactions),
d) average results for input variable level combination in the so-called "cube".

3.2. Strength. The graphs depicting the influence of the factors A, B and C on the strength of the sample (measured by the braking force) are shown in Fig. 5. The analysis of the results showed that the factor which had a decisive influence was the setting angle of the sample (factor A). A change in the angle between the product and the print bed from 0 degrees to 90 resulted in an increase of 104 N in the average breaking force. Taking all the factors into account, their interactions had a statistically significant effect on the analyzed variable. The strength was at a maximum when the following set of values
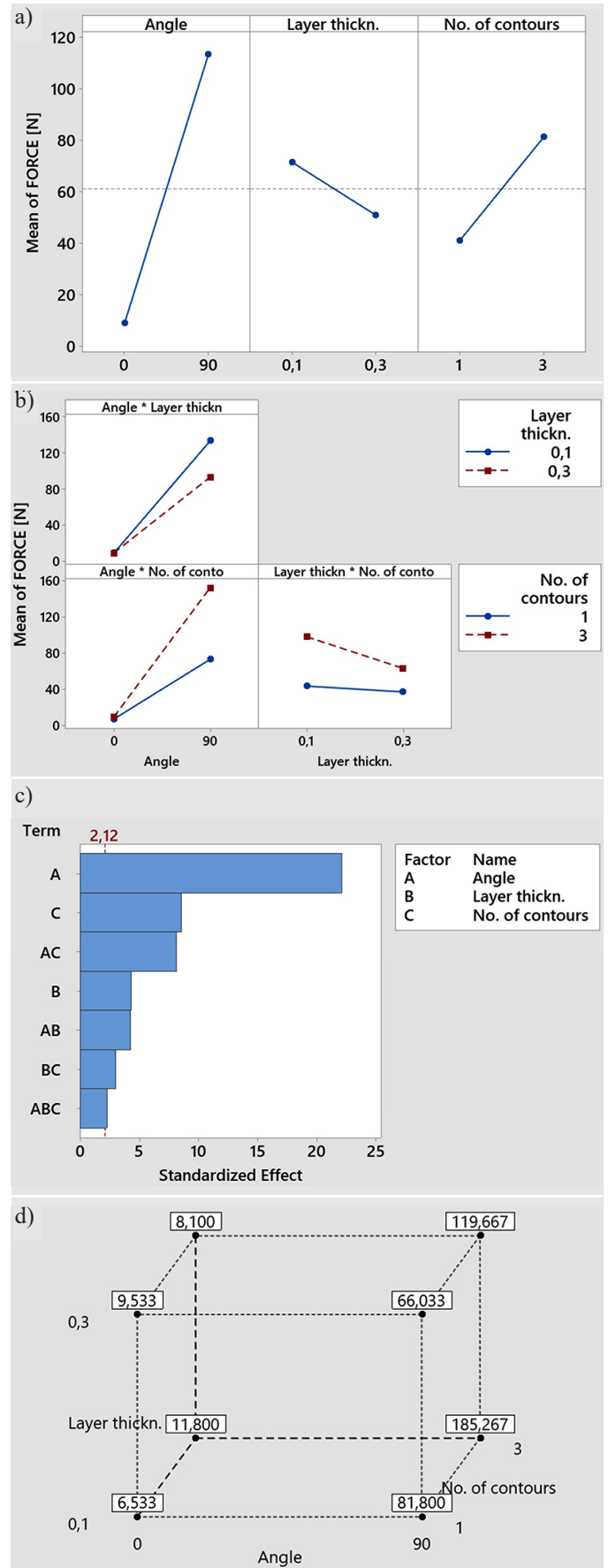

Fig. 5. Influence of process parameters on the strength of the sample

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were set: a 90 degree angle, three contour paths and a layer thickness equal to 0.1 mm.

The results presented confirm the dependencies described in the literature in the tests performed on typical cuboid samples in a static tensile test.

It is worth noting that when produced at an orientation of 0 degrees, the other parameters tested did not affect the strength of the product. However, when producing a product at an orientation of 90 degrees, the strength was maximized by increasing the number of contours rather than changing the thickness of the layer. In addition, the production time for two different contours was much shorter than the time required to create two additional layers with a lower thickness. The mutually positive effect of a larger number of contours with thinner layers confirmed the theory of the occurrence of larger temperature gradients [16], and thus the diffusion between the material threads being contours responsible for transferring the vast majority of loads.

3.3. Thickness deviation. The results in Fig. 6 show that the factors having a decisive influence on the thickness deviation were: the number of contour paths (C) and the setting angle of the sample produced (A), as well as their interaction with other factors (AB and AC). The significance of the layer thickness factor (B) cannot be ruled out since, although it was at the limit of statistical significance, there was still a significant interaction with factor A. The factor setting that minimized the value of the thickness deviation was: an angle of 90 degrees, a single contour path and a layer thickness of 0.1 mm.

The thickness of the measured arm was 3.3 mm, which was a multiple of the thickness of the layer at both levels. Theoretically, the layer thickness factor should not have been significant. However, due to the problems with extrusion visible to the naked eye and the joining of material paths in the closing layers, for the 0-degree orientation, one of the surfaces of the measured arm was significantly deformed, which had an impact on the results. This is confirmed by the interaction of the layer thickness and orientation of the product: when manufactured at the 90-degree setting, the measurement was not performed on the deformed surface, and the differences in thickness were much smaller. Interpretation of the interaction of the orientation factor and the number of contours made it possible to conclude that adding additional contours within a single layer caused a significant reduction in the accuracy of the external dimensions (the convex constructional features) the plane of the layer.

3.4. Deviation in hole diameter. Graphs depicting the dependence of the production parameters on the deviation in hole diameter are shown in Fig. 7.

The most important factor from the point of view of the deviation in hole diameter was the setting angle of the sample produced. A change in the angle between the product and the print bed from 90 degrees to 0 resulted in a deviation of, on average, approximately 0.18 mm. The setting of factors that minimized the deviation in hole diameter was: an angle of 0 degrees, three contour paths and a layer thickness equal to 0.3 mm, or an angle of 0 degrees, single contour paths and
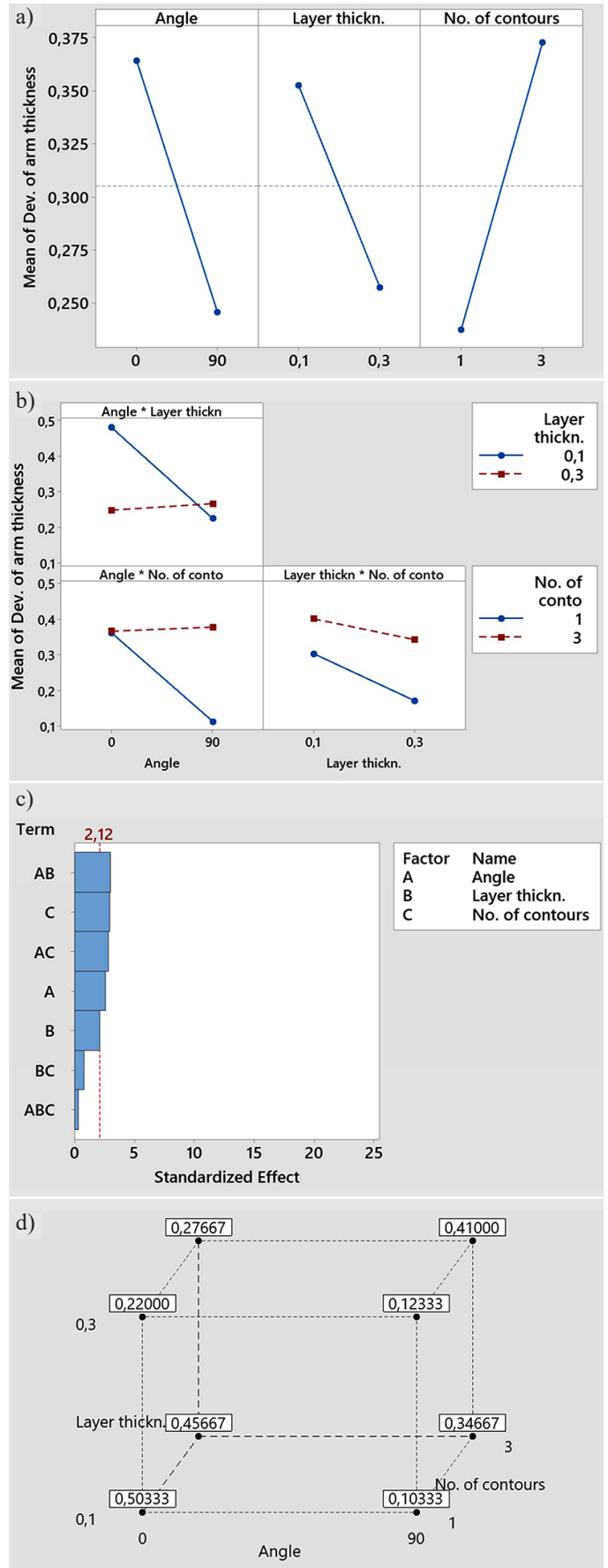

Fig. 6. Influence of process parameters on thickness deviation

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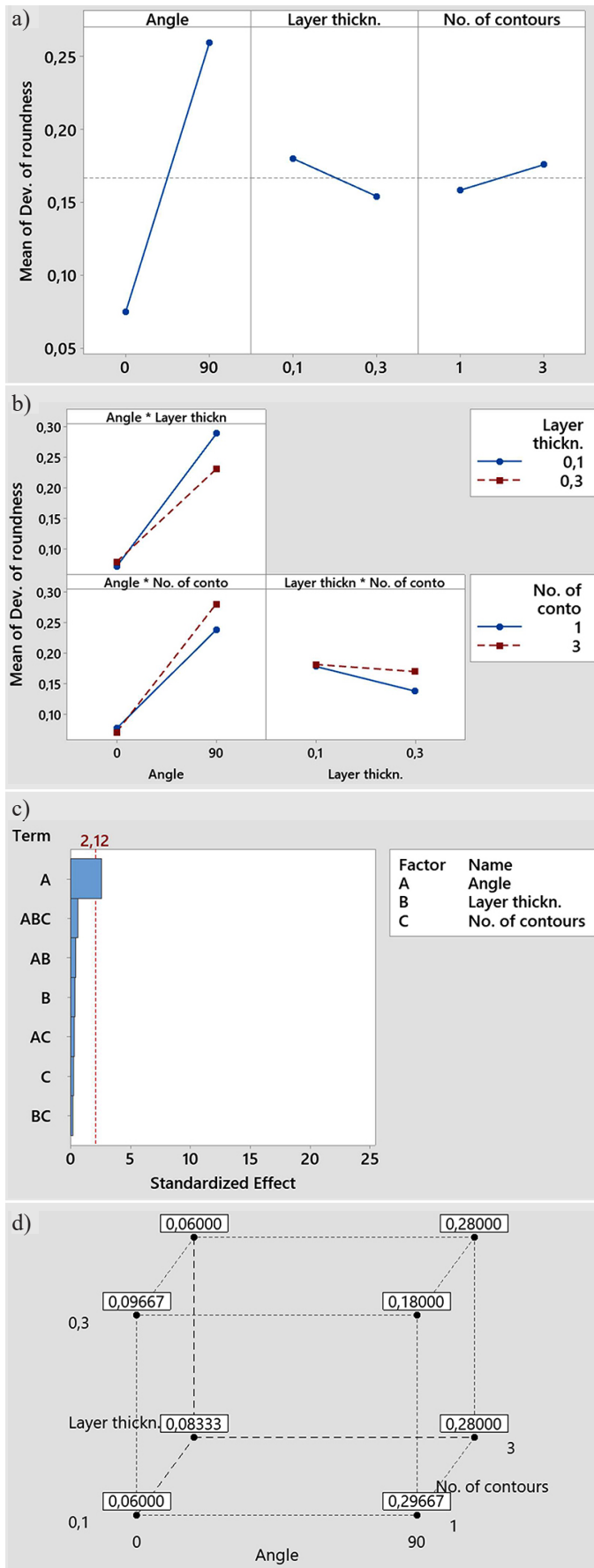Bull. Pol. Acad. Sci. Tech. Sci. 69(3) 2021, e137387

Fig. 7. Influence of process parameters on hole diameter deviation

a layer thickness equal to 0.1 mm. It is worth remembering that only factor A was statistically significant. Therefore the remaining ones can be set at levels that ensure cost-effectiveness.

The results obtained are in line with expectations since the hole produced at an orientation of 90 degrees was along the axis of the division into layers. Thus, its size was influenced by two important issues encountered in incremental production: the "staircase effect" and thread deflection at bridging. Moreover, the aforementioned problem of surface deformation in manufacturing a product with a thickness of 0.1 mm also impacted the upper surface of the hole.

4. Discussion

The experiment results showed that of the tested FDM technological parameters, the angle at which the sample in the working chamber (variable A) was placed had the greatest impact on the geometric and mechanical properties of the angle-shaped sample. Concerning sample strength (STR), a clear interaction between the angle and the number of contours (variable C) was also found.

Since the purpose of this research was to compare the effect of FDM parameters on the properties of cuboid and angle-shaped samples, the dependencies between the input variables A, B and C, and the output variables STR, WTD and HDD of angle-shaped and simple samples are compared in Table 4. Data on the simple samples were derived from the literature [14, 16–21, 23] and the authors' own experience and research conducted previously [28].

Table 4
Dependence of strength and geometric accuracy on process parameters for cuboid and angle-shaped samples

		Input variable							
		A Angle		B Layer thickness		C Number of contours		AC Angle + Number of contours	
		Simple	Angle-shaped	Simple	Angle-shaped	Simple	Angle-shaped	Simple	Angle-shaped
Output variable	STR Strength [N]	3	3	−3	−3	3	2	3	3
	WTD Thickness deviation [mm]	3	2	3	−1	0	1	0	1
	HDD Hole diameter deviation [mm]	3	3	0	0	0	0	0	0

Two characteristics of the dependencies were analyzed:
- power of dependence (PD) on a three-point scale: (1 – low, 2 – medium, 3 – high),

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- direction (tendency) of the dependence, expressed as: (positive (+), negative (−) or neutral (0).

The numerical value of the dependence was determined based on the following ratio:

PD = (change of output variable) / (change of input variable).

The values in the table should be treated as relative a measure of the assessment (to some extent subjective) of the relationship between "input variable – output variable". The assessment was carried out independently for each pair of two samples, "cuboid sample – angle-shaped sample". Three cases may occur:

- there is a relationship for both types of samples: the dependence with the greater force is assigned the value +/−3, and the other dependence is assigned one of the values: +/−3 (an identical or slightly weaker dependence), +/−2 (a much weaker dependence) or +/−1 (a very weak relationship),
- in each pair, there is a relationship for only one type of sample: the sample in which the relationship occurs is assigned the value +/−1, while the second type of sample for which the relationship does not exist is assigned the value 0,
- in both types of samples, there is no relationship: both samples are assigned the value 0.

For example, if within the pair "WTD – HDD" the cuboid sample's PD = 3, and the angle-shaped sample's PD = −1, this means that the direction of interaction is inverse (positive for a straight sample and negative for an angle-shaped sample), and the impact strength is significantly higher for the straight sample.

The adoption of the above comparison method means that the information presented in the table should not be interpreted directly as the force of the impact of the "input variables" on the "output variables". They only have a comparative value. The value 3 in pair "A-STR" does not mean, for example, the same strength of dependence as the value 3 in pair "A-HDD". These values only mean that the influence of factor A on STR and WTD is stronger in the case of a simple sample. The pair of values (3,2), in the case of the dependence A and WTD, makes it possible to conclude that the effect of the factor is stronger in the case of the simple sample (3) than in the case of the angle-shaped sample (2).

An analysis of the data from Table 4 shows that the presented relationships are similar in relation to the sample strength and dimensional deviations.

Significant differences occurred only in the case of thickness deviation. For a simple-shaped sample, increasing the layer thickness led to a larger dimensional deviation. For the angle-shaped sample, the relationship was the reverse. This discrepancy can be explained by the poor quality of the upper solid layers at a layer thickness of up to 0.1 mm. This surface error affected the measured values, which can be confirmed by analyzing the mutual effect of layer thickness and orientation (Fig. 8). Orientation at an angle of 90 degrees meant that the surface affected by the error did not participate in the measurement, unlike the other orientations.

In the case of the mutual influence on the thickness deviation of the manufacturing angle and the number of contours,
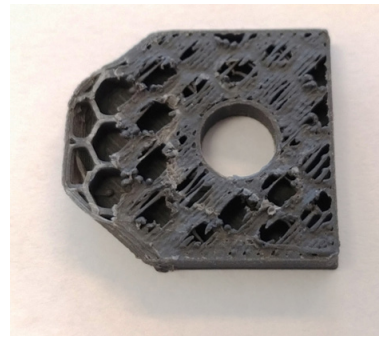

Fig. 8. Influence of process parameters on hole diameter deviation

a positive effect was observed for the angle-shaped samples. Similar relationships could not be confirmed in the literature data for simple shape samples. It could therefore be concluded that this is the result of the sample shape.

5. Conclusions

The results of the tests indicated that it is possible to estimate the mechanical properties of products with complex shapes produced by the FDM method based on tests using geometrically simple samples (such as the angle-shaped samples presented in the paper). An assessment of dimensional and shape accuracy should be approached with greater caution. In relation to these quantities in products with complex geometry, there could be a number of phenomena that do not occur when producing and testing simple geometry – incomplete support of the material path (bridging), thin-walledness, etc., that could generate errors, thereby heavily influencing accuracy and surface quality.

Therefore, it is worth conducting further research in this area, both into the use of other thermoplastic materials and into the variability of FDM process parameters not included in this study.

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