Improvement of Adaptive Slicing in Additive Manufacturing

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Abstract. The results of the study on the capabilities of adaptive slicing the original 3D model at layered product shaping are presented. The proposed method of adaptive slicing the 3D model allows to increase the process effectiveness and regulate the accuracy of manufacturing products by setting the building step for each lowering of the working platform of additive technologies installation. The building step is selected taking into account the density of the distribution of angles between the building direction vector and the normals of the product surfaces that are in the current layer. Evaluation of the effectiveness of adaptive slicing was carried out based on the comparative analysis of the number of layers and the predicted deviations from the regular surface shape as applied to 3D models of industrial products.

Keywords: Additive Manufacturing, Technological Preparation, Slicing, Accuracy of Shaping.

1 Introduction

One of the main problems in preparing a product for materialization by additive manufacturing is slicing the original 3D model [1]. The solution of this problem quite significantly determines the effectiveness of the use of additive manufacturing. The number of layers affects the product construction time. The accuracy of shaping when considering the resulting product in a cutting plane going through the O_Z coordinate axis (the building direction) is mainly determined by the thickness of the layers and the surface orientation [2].

The usual slicing strategy is carried out at the set constant building step, i.e. with the same thickness of all layers. This approach does not take into account the features of the product geometry and, therefore, leads to a decrease in the accuracy of the resulting surfaces or manufacturing performance. Adaptive strategies based on the use of a variable building step are developed to eliminate the above-mentioned drawback [3]. A variable construction step is determined to take into account a set criterion based on the analysis of the surface of the 3D model in the current layer.

2 Literature Review

In [4], a comparative analysis of the known methods of adaptive dissection of 3D-models of products based on construction time, volume error, and visual assessment of surface quality was performed.

Improvement of adaptive dissection is carried out by step-by-step correction concerning the surfaces parallel to XY plane [5], indicating heterogeneous requirements Ra for product surfaces [6]. In [7], an adaptive construction strategy is proposed based on tree-type cluster analysis (*k*-d Tree) with the determination of deviations from the regular shape and volume error.

The variable building step h_i with adaptive slicing is determined to take into account the following characteristics: protrusion height or the depth of the cavity formed on the product surface as a result of a step effect [3]; relative difference in the area of adjacent sections [8]; surface roughness parameter Ra [9]; the arithmetic mean error of the dissected surface [10], considering as the error, the minimum of the two components of the deviation of the product surfaces from the CAD model − vertical or horizontal; volume error in product construction [11]; structure of octree about the distribution of material in space [12].

In the process of evaluating the characteristics of the resulting surface, its profile is considered in the form of steps [3] or radius sections [13].

The main problem is that in existing works with the adaptive cutting of 3D-models, the construction step is selected based on the limit values of the selected parameter characterizing the manufacturing error or surface quality. This problem can be completely or partly eliminated by taking into account the nature of the distribution of the selected parameter values. Regardless of the parameter selected as a criterion, it will depend on the construction step and the angle between the construction direction vector and the normals of the surfaces φ_{NZ}, that fall into the cutting plane of the layer. Therefore, this problem should be considered based on the density distribution of the angles according to their relative area.

The paper considers a scientific hypothesis that the efficiency of adaptive dissection of a 3D model can be increased by using the statistical analysis of the distribution of angles φ_{NZ} taking into account the relative surface area, since this will allow determining scientifically the building step to ensure the set accuracy and reduce building time.

The paper aims at studying the capabilities of adaptive dissection of the initial 3D product model based on the statistical analysis of the distribution of angles between the building direction vector and surface normals φ_{NZ} to ensure the set accuracy of shaping with the minimum building time.

3 Research Methodology

Implementation of adaptive slicing the initial triangulated 3D-model of the product was carried out as a part of the technological preparation system for materializing complex products using additive manufacturing developed at the Department of Integrated Engineering Technologies of NTU "Kharkiv Polytechnic Institute". This system allows evaluating the manufacturability of the design and the effectiveness of solving the problems of technological preparation based on the statistical analysis of the studied features of polygonal, voxel and layered 3D model of the product. To solve the above-mentioned problem, a subsystem of statistical layered analysis has been developed. The screen form of the subsystem is shown in Fig.1.

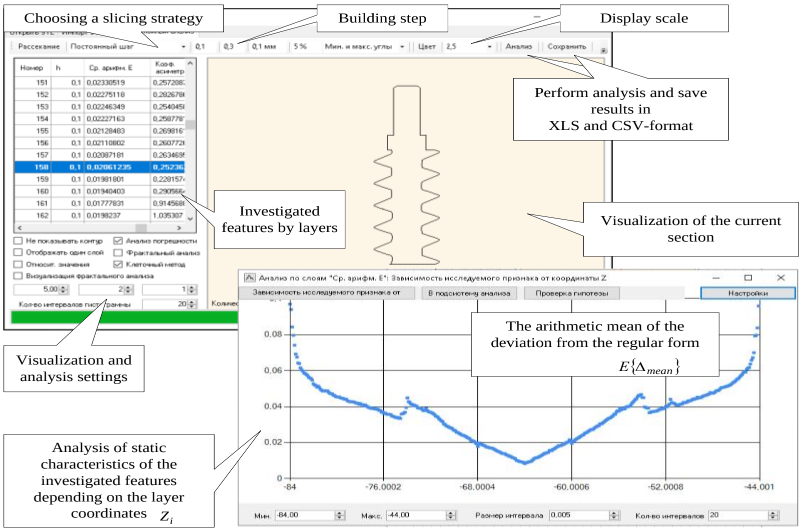

Fig.1. Subsystem of layered analysis 3D model of product.

The transition from the initial triangulation 3D-model of product to the set of layers was carried out according to the procedures developed taking into account the existing works [6] that implement strategies with a constant and variable construction step. When performing the dissection procedure at the first stage, a list of coordinates of Z_{Ci} layers is created. The second stage includes defining the outlines for each layer. The list of Z_{Ci} coordinates is formed according to the following dependence

$$Z_{Ci} = Z_{Ci} + h_i, \quad Z_{Ci} \in \left[Z_{min}, Z_{max}\right), \tag{1}$$

where Z_{min}, Z_{max} – the minimum and maximum coordinates of the vertices of the triangulation 3D model; h_i – building step, for a strategy with a constant step $h_i = const$, for an adaptive strategy $h_i \in \left[h_{min}, h_{max}\right]$; h_{min}, h_{max} – minimum and maximum values of the range of building steps allowed by the equipment used and the original material for the resulting product.

As a rule, in the methods of adaptive dissection of a 3D model, the building step h_i is set taking into account the set limit Δ_{Limit} on surface shape deviations (maximum permissible error in shaping) [14]:

$$h_i = \Delta_{Limit} / cos\,\varphi_{NZ\,min}\ ,\qquad (2)$$

where $\varphi_{NZ\,min}$ − is the minimum angle of an inclination concerning the *Z*-axis of the normal of the faces that fall into the current layer.

The problem of adaptive slicing of the 3D model of a complex product includes resolving the following issues: the need in taking into account the entire surface of the model, fallen between the planes that determine the current and next construction layer; uneven angular distribution of surface area φ_{NZ}.

The first problem arises due to the initial uncertainty of the current step h_i. In the proposed method of adaptive slicing of a 3D model, this problem is solved by initially dissecting the 3D model from the current plane coordinate to the plane determined by the largest allowable value of h_{max} with the step equal to the discreteness of setting the coordinates of the location of the layer along Z_i axis.

The second problem is connected with the materialization of 3D models of industrial products with complex geometry. The consequence of both problems is an unreasonable setting of the building step based on incomplete information about the surface which is formed by the current layer. Because of the existing uneven angle distribution φ_{NZ} of surface area for complex products, the building step set according to the known dependence (2) is understated. In practice, taking into account surfaces with normals having a minimum deviation from *Z*-axis (building directions) may be excessive if their relative area is less than 5–20%. This circumstance can be taken into account by relative area truncating the distribution density φ_{NZ} in the current layer by a permissible value. The permissible truncation value must be set from the condition of minimal influence on the resulting quality indicators and product surface accuracy. Such truncation will increase the angle $\varphi_{NZ\,min}$ and, therefore, taking into account dependence (2), it will increase the permissible value of the construction step h_i. As a result, it becomes possible to minimize the number of layers and therefore the construction time by increasing h_i and ensuring in practice the specified limit deviation of the surface shape.

Some examples of angle distributions φ_{NZ} for the surfaces falling into the *i*-th layer are shown in Fig. 2. The example given in Fig.2 a refers to unsuitable cases because it does not allow to change substantially the threshold value $\varphi_{NZ\,min}$, necessary for calculating the current construction step h_i from dependence (2). An example of angle φ_{NZ} distribution that allows truncation to be performed more efficiently (to change substantially the limit values of the angle φ_{NZ}) is shown in Fig. 2 b. This type of distribution is one of the most common among the layers of construction for complex geometry products. For this example (Fig. 3 b), when the distribution density φ_{NZ} is area truncated by 5%, it is possible to reduce the range of values $\Delta\varphi_{NZ}$ by 4 times and choose the angle $\varphi_{NZ\,min} \approx 58°$ instead of $\varphi_{NZ\,min} \approx 46°$. In this case, taking into account dependence (2), construction step h_i will be chosen equal to 0.19 mm instead of 0.14 mm (at the maximum permissible deviation from the regular surface shape $\Delta_{Limit} = 0.1$ mm). However, with such a significant increase in the construction step for a particular *i*-th layer 5% of the resulting product surface is ignored. Such ignoring does not lead to a noticeable increase in the arithmetic mean of deviations from the regular shape (statistics of deviations for specific 3D models of products is given below).

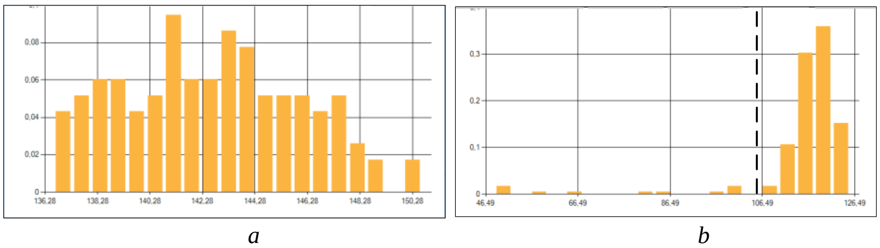

Fig. 2. Angle distribution options φ_{NZ} for the surfaces in the layer: a) without the possibility of a significant change in the angle φ_{NZmin}; b) with the possibility of enough reduction in the range φ_{NZ} when truncating 5% of the area (probability of being outside the confidence range – 0.05).

4 Results

The study of the capabilities of the proposed adaptive dissection of the 3D model was carried out by determining the number of construction layers using test models of simple and complex products shown in Fig. 3.

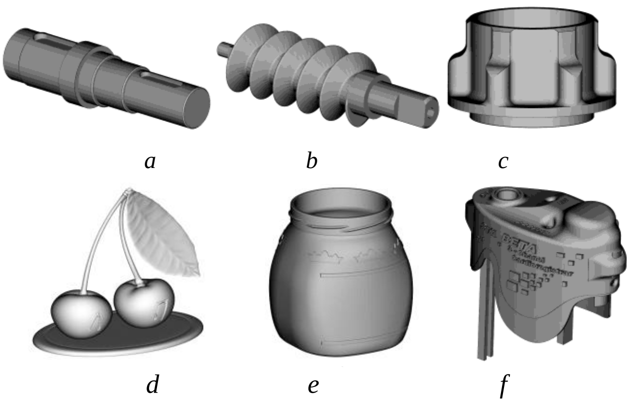

Fig. 3. Test 3D models: *a*) shaft; *b*) auger; *c*) case; *d*) souvenir; *e*) container; *f*) lid.

The dissection of test models was carried out according to strategies with a constant and variable building step to provide comparative analysis.

The strategy with a constant step was carried out at $h_i = 0.06$ mm. The strategy with a variable step was performed at $\{h_i\}_{min} = 0.06$ mm, $\{h_i\}_{max} = 0.20$ mm and acceptable (maximum) surface formation error $\Delta_{Limit} = 0.06$ and 0.1 mm. The selected range of building steps is recommended for Ultimaker 3D-printers with the simultaneous use of AA 0.4 mm extruder. The proposed adaptive dissection strategy was carried out at 0−20% truncation of the distribution of angles φ_{NZ}. The calculation results are given in Table 1.

Table 1. The results of slicing test models of industrial products by the layers number.

Model (overall dimensions, mm)	Constant step, h_i = 0.06 mm	Variable trimming step $\Delta\varphi_{NZ}$, %				
		0	5	10	15	20
	Number of layers, N_L					
Permissible deviation from the regular surface shape Δ_{Limit} = 0.06 mm						
Shaft (60×216×60)	1000	717	716	715	713	708
Auger (40×40×144)	667	576	530	456	407	392
Case (210×210×125)	2084	949	921	898	876	853
Souvenir (73×51×70)	1169	873	736	695	670	649
Container (102x94x125)	2092	969	901	874	858	829
Lid (84×101×43)	721	676	610	592	577	565
Permissible deviation from the regular surface shape Δ_{Limit} = 0.1 mm						
Shaft (60×216×60)	1000	456	454	452	450	448
Auger (40×40×144)	667	338	317	281	257	249
Case (210×210×125)	2084	729	720	709	703	696
Souvenir (73×51×70)	1169	525	455	441	434	427
Container (102x94x125)	2092	734	704	693	688	679
Lid (84×101×43)	721	406	370	358	351	344

Comparative analysis of the number of dissection layers for specific 3D-models (Tabl. 1) shows the advantage of variable step strategies over constant step ones. This advantage is common for variable step strategies, regardless of the approach chosen in determining the construction step. Adaptive slicing performed at $\Delta\varphi_{NZ}$ =0% made it possible to reduce the number of layers by 43.7−65.0% concerning the slicing with constant step $h_i = 0.06$ mm for the considered 3D test models. The truncation of the distribution density of angles φ_{NZ} made it possible to further reduce the building layers number for all the considered 3D-models. When truncated by 5% − by 48.7−66.3% (in relation to dissection at $\Delta\varphi_{NZ}$ =0% by 0.4−13.3%). When truncated by 10% − by 50.3−66.9% (concerning the slicing of 3D models at $\Delta\varphi_{NZ}$ =0% by 0.9−16.9%). The results of model calculations using 3D models of products differing in the geometric complexity of surfaces revealed a tendency. On the example of the shaft model, there are no significant differences between the options for cross-section with variable step. This difference in the number of N_L layers increases with the geometric complexity of the products. The data obtained (Table 1) allow us to conclude that the strategy is effective with truncating the distribution of the angle φ_{NZ} for products that are quite complex in geometry. In this study, such 3D-models of the lid, souvenir and screw are presented (in order of increasing efficiency, as shown in Fig. 4).

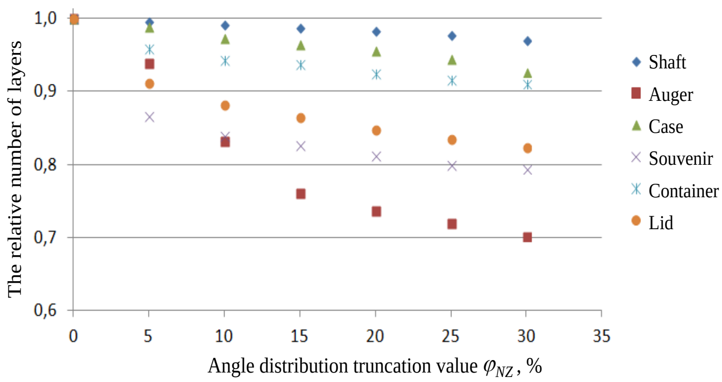

Fig. 4. Correlation of the relative number of layers for building test 3D models from the value of truncation of the angle distribution φ_{NZ} .

For methodological reasons, the capabilities of the developed 3D-model dissection strategy were evaluated based on the comparison with the adaptive slicing capabilities offered in Ultimaker Cura (free software) on 3D test models (see Fig. 3).

In the study of adaptive dissection in Ultimaker Cura, various combinations of the following parameters were considered: adaptive layers minimum variation (range of the construction step), $R_h = 0.14$ mm; adaptive layers variation step size (difference in h_i for adjacent layers), $\Delta_h = 0.01 - 0.10$ mm; adaptive layers threshold (probability of setting h_i of a smaller value), $p_h = 50 - 300$.

Table 2 shows the data obtained as a result of dissecting test 3D-models (see Fig. 3) using strategies with constant and variable building steps.

Table 2. The results of slicing 3D-models in Ultimaker Cura.

Model (overall dimensions, mm)	Constant step, h_i = 0.06 mm		Variable step	
	number of layers N_L	build time t_b, h	number of layers N_L	build time t_b, h
Shaft (60×216×60)	996	47,22	433÷624	31,1÷37,1
Auger (40×40×144)	663	20,23	307÷472	13,5÷17,1
Case (210×210×125)	2080	132,32	694÷759	58,2÷62,3
Souvenir (73×51×70)	1165	12,13	457÷666	6,7÷8,1
Container (102x94x125)	2088	80,77	701÷823	36,3÷41,9
Lid (84×101×43)	717	31,77	399÷645	21,8÷29,3

The analysis of the data obtained (Table 2) revealed a certain advantage of the proposed adaptive slicing with truncation φ_{NZ} over that used in Ultimaker Cura as applied to some 3D-models of products that are characterized by complex surface geometry. The adaptive slicing method used in [14] (corresponds to the developed method at $\Delta\varphi_{NZ}$ =0) is inferior in the number of layers for all models, but in the case of the lid, the difference is insignificant (less than 2%). As far as the lid model is concerned, it is possible to obtain a smaller number of building layers all over the considered range of values $\Delta\varphi_{NZ}$ =0−30%. The shaft model does not allow to obtain an advantage for the developed adaptive slicing, regardless of the set value $\Delta\varphi_{NZ}$. Adaptive slicing at $\Delta\varphi_{NZ} = \geq 5\%$ allows you to get closer in the number of layers and even get lower values for the models of augers, souvenirs and containers. For the case model, it is possible only at $\Delta\varphi_{NZ} = \geq 20\%$.

The use of adaptive slicing guarantees the set quality level and accuracy of the obtained product surfaces. Therefore, the layered estimation of deviations from the regular shape Δ_S was also performed according to the arithmetic mean value $\overline{\Delta_S}$. The protrusion height or the trench depth formed on the surface as a result of the stepwise effect was taken as the predicted deviations from the regular shape [14].

Statistical analysis of the results of the layered calculation of deviations from the regular shape $\overline{\Delta_S}$ for various variants of slicing test 3D models using Box Whiskers span diagrams is presented in Fig.5 (distribution diagrams $\overline{\Delta_S}$ to compare strategies with a constant construction step h_i = 0.06, 0.10, 0.15, 0.20 mm, a variable step at $\Delta\varphi_{NZ}$ =5−20 and the set restriction $\Delta_{Limit} = 0.1$ mm).

For most 3D-models, slicing with a variable step does not result in significant differences, i.e. the truncation value $\Delta\varphi_{NZ}$ does not strongly affect the distribution $\overline{\Delta_S}$. The resulting distribution $\overline{\Delta_S}$ for variable step dissections corresponds approximately to the dissection with a constant construction step h_i = 0.10–0.15 mm. This can be explained by the set limit value $\Delta_{Limit} = 0.1$ mm as the most characteristic for h_i = 0.10–0.15 mm.

For 3D-models of a screw, a souvenir and a container the choice of dissection parameters has the biggest influence on the distribution of values $\overline{\Delta_S}$, that is quite expected since for these models it was possible to reduce most significantly the number of construction layers, and thus reduce the time for their production.

According to the results of the study, the following conditions for the rational use of the proposed adaptive dissection of a 3D-model have been formulated: a product containing a sufficiently large number of surfaces with complex geometry or with rather large range of angle distribution between the surface normals and the *Z*-axis (the direction of construction); selection of the truncation value $\Delta\varphi_{NZ} \in [0; 0,2]$ taking into account the allowable increase in local deviation from the regular shape; possibility to reduce distribution truncation value $\Delta\varphi_{NZ}$ for more complex geometry products.

The developed algorithm of 3D model adaptive slicing is based on the statistical analysis of the distribution of angles between the *Z*-axis and surface normal φ_{NZ}. The revealed range of rational distribution truncation $\Delta\varphi_{NZ}$ makes it possible to reduce further building time by 0.7–30.1% in comparison with the existing strategies of variable dissection [14]. The approach proposed also allows to evaluate the effectiveness of adaptive slicing with sufficient reliability. It can be assumed based on the increasing efficiency of the proposed adaptive slicing with an increase in the geometric complexity of the product, that its use for a group of products placed on the installation platform will provide a more significant decrease in the building layers number.

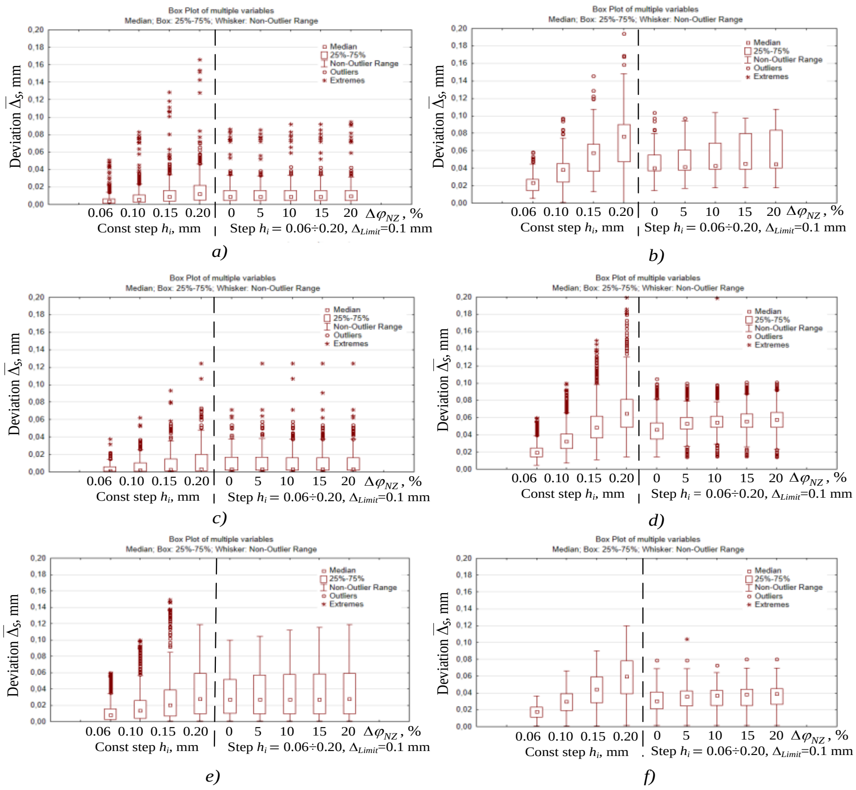

Fig.5. Statistical analysis of the arithmetic mean deviation from the correct shape of the surface Δ_S: *a*) shaft; *b*) auger; *c*) case; *d*) souvenir; *e*) container; *f*) lid.

5 Conclusions

Statistical analysis of the distribution of angles between the Z-axis and the normals of the surfaces, that fall into the section of the layer, which takes into account relative area of the surfaces, makes it possible to scientifically determine the construction step to ensure the set accuracy and reduce the product building time by means of the adaptive slicing 3D model.

An insignificant reduction in the distribution of angles between Z axis and surface normals $\Delta\varphi_{NZ}$ = 5−20% allows to reduce their building time by 0.7–30.1% for 3D-models of complex products.

The results of the work create the prerequisites for a comprehensive solution to the problems of technological preparation of additive manufacturing.

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