EVALUATION OF GEOMETRICAL COMPLEXITY OF PRODUCTS BASED ON THE ANALYSIS OF TRIANGULATED MODELS

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Abstract: *The results of study evaluation possibilities of geometric complexity of industrial products are presented in this article by analyzing of functional dependence of number of triangular faces on triangulation parameters. As the main parameter of the triangulation was considered maximum size of edges. The dependence study was carried out for basic geometric bodies, which revealed the general regression equation. Test of the regression equation on models of industrial products has confirmed put forward a scientific hypothesis on the evaluation possibility of geometric complexity of industrial products based on the analysis of this functional dependence.*

Keywords: Additive manufacturing; DFAM; triangulated model; geometric complexity of product.

1. INTRODUCTION

At the present time there is a need to develop a scientifically sound methodology for determination of manufacturability and choice of strategy for manufacturing of product on the basis of 3D model analysis [1].

Some authors [1, 2] determined by manufacturability indexes based on CAD-models of products without evaluating the level of its complexity. But the practice shows a significant role of product complexity to design for additive manufacturing (DFAM) [3] and select effective strategies for making, which includes rational build orientation, build step (variable or constant), slicing strategy and product decomposition for packing on build platform [4].

With respect to additive manufacturing basic geometric information for production is a triangulated model of industrial product [5]. The triangulated model unifies the representation of the product surface, which creates prerequisites for the analysis of faces system. Analysis of the 3D model has to represent the definition of dimensionless characteristics to measure the geometric complexity of product and to predict workability of its manufacture [2, 6].

In known works, the evaluation of geometric complexity of products, prepared for additive manufacturing, produced on the basis of parameters determined by topological and morphometric analysis of CAD or triangulated models [1, 7-10]. The obtained characteristics did not take into account features of CAD-system for setting parameters of triangulation. Their values set constraints when solving the optimization of transition to triangulated model. The parameters of triangulation, given product design, determine the number and geometric (statistical) characteristics of triangular faces. Therefore, the existing characteristics are not sufficiently representative for the subsequent adoption of technological solutions during the preparation phase to additive manufacturing.

In this article, scientific hypothesis that analysis of triangulation parameters influences on number of triangular faces can be used to determine geometric complexity of products and, consequently, workability of their production with additive manufacturing.

The purpose of article is to consider estimation of geometrical complexity of individual products on the basis of analysis of triangular faces number dependence from triangulation parameter (maximum allowable size of edges).

2. STATEMENT OF BASIC MATERIAL

The study used Autodesk PowerShape CAD-system offering enough flexible settings of triangulation [11]. In PowerShape is provided to set two of parameters defining the triangulation of model surfaces: allowable error Δ_{max} and maximum allowable size of edges l_{max}. The main parameter is Δ_{max}, that given complexity of surface geometry (surface type and its bounding contours) determines number of triangular faces. An additional parameter l_{max} sets the limit on maximum edges size of triangular faces that in some cases (especially for flat surfaces) increases number of faces when triangulation. The feature of parameter l_{max} in "boundary" effect on sites of a surface close to contours, which leads with regard to their complexity additional increase in the number of faces. Settings in Autodesk PowerShape allow to set the value of Δ_{max} is large enough, as a result of l_{max} becomes main parameter that specifies the limitations when triangulation. Therefore, l_{max} is of special interest to the analysis of functional dependence of triangular faces number N_{face} from triangulation parameters.

Functional regression analysis of the dependence $N_{face} = f(l_{max})$ were performed in a professional statistical package of StatSoft Statistica and MS Excel. Analysis of $N_{face} = f(l_{max})$ for a set of simple geometric shapes and several test models of industrial products (shown in Fig. 1) will identify characteristics to measure the geometric complexity of the model.

Absolute numbers of triangular faces for the studied models differ significantly, therefore, to provide a comparative analysis of the results and their joint assessment was carried out normalization of N_{face} and l_{max} [12, 13].

The transition from absolute values of N_{face} and l_{max} to relative was performed by comparison with a reference value [12]. The values of characteristics of most accurate model (with smallest l_{max}) of studied series of triangulated models were taken as a reference. Such a model (the most accurate) is called the base. As result of studied characteristics of triangulated models obtained on the basis of triangulation of original CAD-model and, accordingly, have model similarity, are relative to the relevant characteristic values of the basic model. Therefore, regression analysis was carried out for normalized values:

$$x_l = l_{max0} / l_{max}, \; y_N = N_{face} / N_{face0}, \tag{1}$$

where l_{max0}, N_{face0} — study characteristics of the basic model (reference values).

The proposed normalization (1) allows to obtain the following value ranges $x_\Delta \in (0,1]$ and $y_N \in (0,1]$ for whole range of triangulation models derived from the original CAD-model.

The analysis of $y_N = f(x_l)$ was performed for models obtained with triangulation of the CAD-model at maximum allowable size of edges l_{max} = 0.2÷4 mm. The range of values l_{max} determined the required accuracy of triangulated model for existing equipment of additive manufacturing and a large enough interval that allows to identify the features of $y_N = f(x_l)$ for the test models.

The study of $y_N = f(x_l)$ for the test models are executed when sample size $n = 5$ (number of models obtained by triangulation of test CAD-model). Critical value of correlation coefficient was $R_{cr} = 0.991$ for number of freedom degrees $d_f = (r - 2) = 3$ at significance level $\alpha = 0.001$ [14].

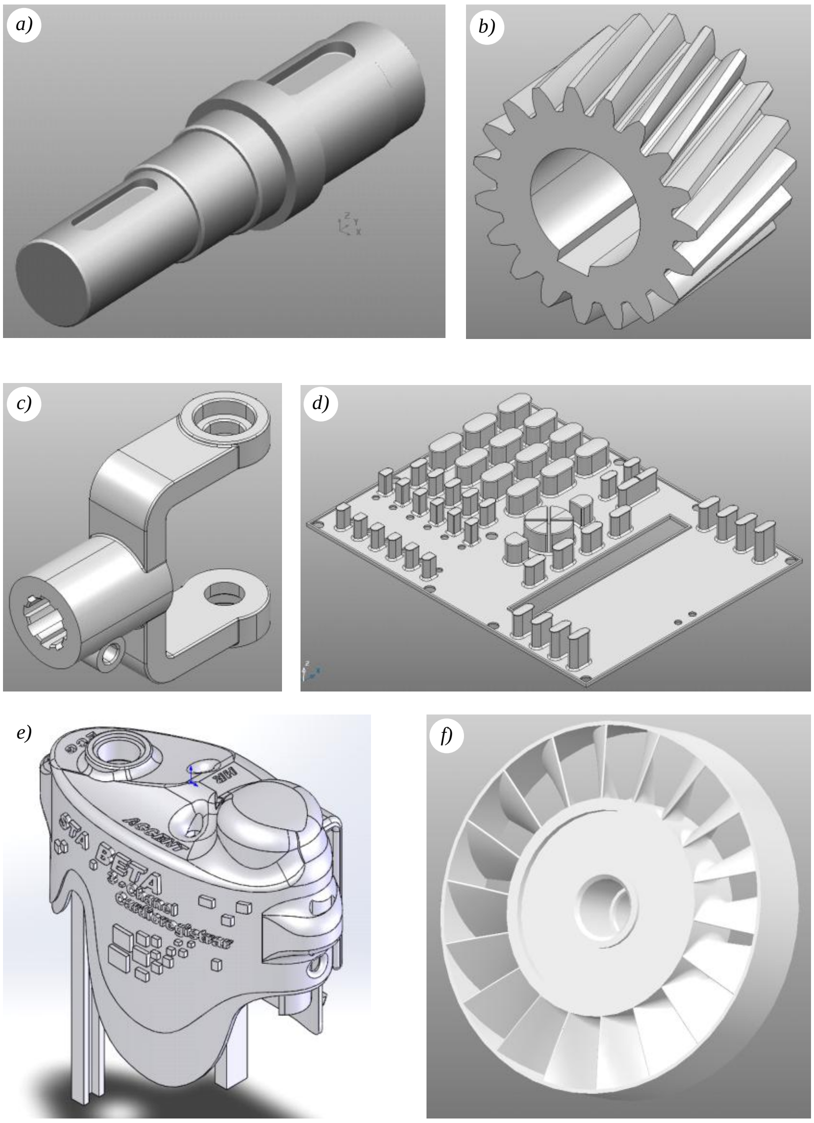

***Fig. 1**. 3D Models of industrial products for the regression analysis:*
a) shaft with keyways; b) gearwheel; c) driveshaft; d) panel; e) cover; f) fan

By results of the regression analysis of $y_N = f(x_l)$ based on using a set of equations from [14] and their combinations, the following regression equation with one coefficient provides the smallest values of maximum relative deviation from model data:

$$y_N = x_l^a, \qquad (2)$$

where *a* – the coefficient of the regression equation.

The results of the regression analysis with equation (2) are presented in table. 1. Fig. 2 shows the curve graphics for investigated 3D-models. For simple surfaces, no significant differences between the curves is not observed, but there is decreasing trend of exponent *a* (coefficient of the equation (2)) with increase of contour perimeter. Models with combination of surfaces have a relatively smaller *a*. Increasing the number of surfaces in the model leads to decrease in *a*.

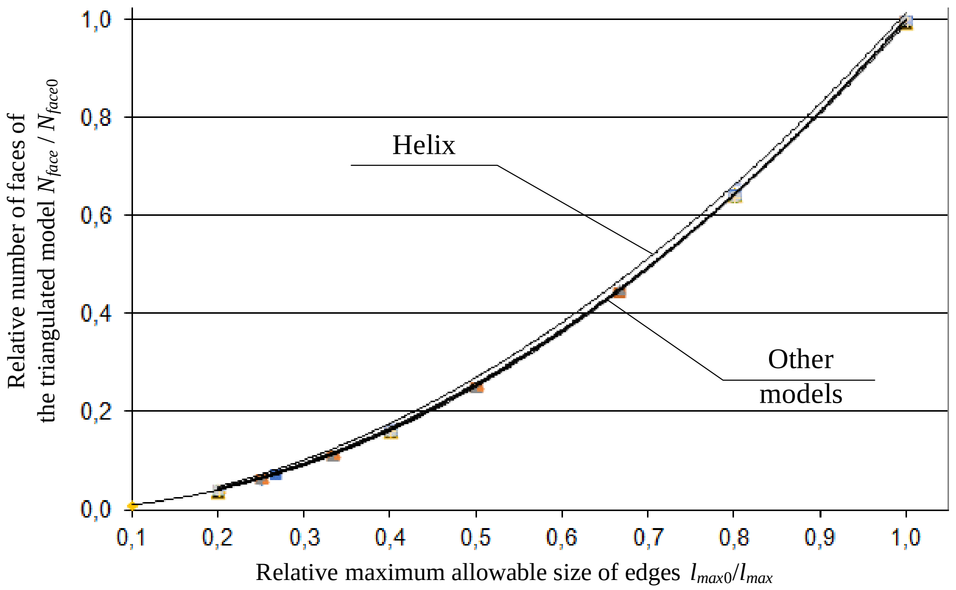

Fig. 2. *Influence of relative maximum allowable size of edges on relative number of faces of the triangulated model (for basic model l_{max0}, N_{face0} in table 1)*

With significantly small sizes of edges of triangular faces relative to the size of 3D model, as shown by the model data (table 1), there is a quadratic dependence for $y_N = f(x_l)$ (coefficient $a = 2$ in equation (2)).

With the increase in edge size increases the deviation of exponent of equation (2) from value of $a = 2$, which is partly explained by the peculiarities of triangulation close to surface contours. Such deviation is more evident with increase of perimeter of surface contours of the model. Models with curvilinear contours than with straight-line contours at the same parameter of triangulation l_{max} have a larger number of triangular faces. Therefore, the coefficient *a* of equation (2) can characterize the degree of model complexity, as value of *a* depends on perimeter and curved contours of surfaces.

Modeling results (table 1) showed a significant effect of parameter of the basic model on the exponent *a*, so l_{max0} needs to be constant to compare CAD-models. Investigated dependencies $y_N = f(x_l)$ for $l_{max0} \in [0.8, 2]$ provide minimal deviation from model data. For adequate evaluation of geometric complexity of test products is shown in Fig. 1, results of analysis of $y_N = f(x_l)$ dependence, l_{max0} chosen the minimum value of rational range — 0.8 mm. Evaluation results of geometric complexity of test models of industrial products on basis of the regression analysis are presented in table 2.

The obtained *a* coefficients (table 2) allow to quantify the geometrical complexity of product. Among comparable the models (shown in Fig. 2), largest value of the coefficient obtained for the shaft, as for the most simple of test products. Fan model has least value of the coefficient, respectively, that specifies how the part having relatively complex geometry. Visual evaluation of geometric complexity of products confirms the results of the analysis (table 2).

Table 1. The results of regression analysis between number of triangular faces N_{face} and maximum allowable size of edges l_{max}

3D-model (dimensions, mm)	Basic model		Coefficient of equation (2)
	l_{max0}, мм	N_{face0}	
Cube (L = 100)	0.8	380 424	1.952
Cube with chamfers (L = 100, c = 5)	0.8	366 809	1.927
Cube with rounded edges (L = 100, r = 5)	0.8	379 653	1.957
Cylinder (R = 50, H = 100)	0.8	298 556	1.961
Cylinder with chamfers (R = 50, H = 100, c = 5)	0.8	281 512	1.961
Cylinder with rounded edges (R = 50, H = 100, r = 5)	0.8	283 072	1.939
Cone (R = 50, H = 100)	0.8	205 938	1,979
Sphere (R = 50)	0.8	217 722	2.001
Sphere (R = 100)	0.8	872 460	1.999
Sphere with a hole (R = 100, r = 15)	0.8	1 493 549	1.974
Sphere with a hole (R = 100, r = 25)	0.8	1 551 541	1.971
Sphere with two holes (R = 100, r = 25)	0.8	1 720 679	1.962
Torus (R = 50, r = 5)	0.8	75 264	1.942
Torus (R = 50, r = 10)	0.8	156 480	1.959
Helicoid (R = 50, H = 100)	0.8	258 338	1.906
Spring (R = 50, r = 5, H = 100)	0.8	362 232	1.939

Table 2. *The results of regression analysis between number of triangular faces N_{face} and maximum allowable size of edges l_{max} for test models of products*

Test models of products (dimensions, mm)	Number of triangular faces of basic model (l_{max0} = 0.8 mm), N_{face0}	Coefficient of equation (2)
1. Shaft (60.0 x 60.0 x 216.5)	252 360	1.868
2. Gearwheel (85.8 x 85.8 x 60.0)	321 468	1.844
3. Driveshaft (147.5 x 50.0 x 124.0)	330 292	1.822
4. Panel (151.5 x 195.5 x 20.1)	575 914	1.699
5. Cover (83,9 x 101,3 x 43,2)	237 362	1.610
6. Fan (92,0 x 92,0 x 26,0)	251 400	1.577

Presented in table 2, the values of coefficient of equation (2) allow a relative assessment of geometric complexity of product. This possibility is of interest for DFAM.

To determine index of geometric complexity of products it is necessary to further study the effect of parameters of triangulation on number and geometric (statistical) characteristics of faces of triangulated models for various types of surfaces, used in mechanical engineering.

3. CONCLUSIONS

1. Analysis of the impact of triangulation parameter (the maximum allowable size of edges l_{max}) on number of faces of triangulated model allows to estimate the geometric complexity of products, and eventually — the manufacturability of their production with additive technologies.

2. The transition from absolute values of studied characteristics to relative by comparison with reference values provides the opportunity for joint evaluation of research results, regardless of geometric complexity of model. The values of characteristics of most accurate model (with least value of l_{max}) of studied series of triangulated models are taken as references.

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