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INFLUENCE OF DETERMINATION ACCURACY OF THE BUILD STEP ON THE EFFICIENCY OF ADAPTIVE SLICING GROUP OF PRODUCTS FOR LAYERED MANUFACTURING

Abstract. *Research results on improving the efficiency of the developed algorithm for adaptive layer-by-layer dissection are presented on the example of 3D models group placed in the workspace of an additive setup. This algorithm for 3D model adaptive cutting allows you to increase the productivity of the process and adjust the accuracy of manufacturing products, taking into account their geometry, by setting a rational value of the variable building step for each individual lowering of the work platform. Building step is calculated taking into account the distribution of the direction of surfaces normal of products group (relative to the construction direction) that fall into the current layer. The developed algorithm provides for some truncation of this distribution, which makes it possible to further increase the building step and, accordingly, reduce the number of layers. Thus, conditions can be created for rational support and given reduction in building time. This achieves a reduction in building time compared to existing strategies for variable dissection. Estimate of efficiency of adaptive layer-by-layer dissection was carried out taking into account the accuracy of determining (setting) building step in relation to 5 options for placing 3D models of industrial products in workspace. Comparative analysis of dissection options was performed by the number of layers and assessment of deviations from of surfaces correct shape. Increase in the efficiency of layer-by-layer shaping process with increased accuracy in determining variable step of building a group of complex products placed in workspace of installation has been revealed. This research was developed at the Department of "Integrated Technologies of Mechanical Engineering" named after M. Semko of NTU "KhPI".*
Keywords: *technology planning; additive manufacturing; triangulated model; layered slicing, packing, shaping accuracy.*

Introduction. In planning the additive manufacturing processes, one of the main tasks is layer-by-layer slicing of 3D models of products placed in the installation workspace [1]. The task of slicing quite significantly determines the efficiency of implementing layer-by-layer building processes. For example, the number of layers affects the build time. According to layered building, the product surface has a “stepped” appearance. In this case, the error mainly depends on the layer thickness and the surface orientation relative to the coordinate axis O_Z, i.e. building direction [2].

The result of 3D model separation procedure is a set of section contours and layer thicknesses. A single slice of a polygonal 3D model is formed by crossing the *XY* plane. The solution of this task has two problems: the first is determination of layer thickness, and the second is associated with determination of closed contour geometry or several contours without self-intersections.

Usual cutting strategy is carried out at a given constant building step, i.e. with the same thickness of all layers [3]. This approach does not take into account the features of the product geometry and therefore leads to a decrease in the accuracy of resulting surfaces or manufacturing productivity. In some cases, ensuring a rational balance between the productivity of layered manufacturing and the accuracy of product surfaces is possible using adaptive slicing 3D models (with a variable building step). In this case, the step is determined based on the analysis of 3D model surface in the current layer according to the given criterion [4].

Literature analysis. In a scientific work [5], comparative analysis of known methods (two main groups: planar and nonplanar) of adaptive slicing 3D models placed in the workspace according to the surface quality, build time, support structure, and mechanical properties of 3D printed products was performed. Planar slicing methods create planar layers, non-planar algorithms create curved and non-planar layers, increasing build speed, eliminating support structures, smoothing the outer surface and improving mechanical properties. Planar algorithms are divided into single-axis and multi-axis (direction of building vector is changed for different layers). Conventional 3D printers provide uniaxial flat layering and are among the absolute majority in additive technology market.

To date, a large number of strategies have been developed for slicing: uniform slicing by set of planes [6], adaptive slicing with description of the section contour by piecewise linear curves [7, 8], piecewise linear approximation [9–12], curved lines [13-15].

Calculation of the adaptive step can be performed together with the correction of the layer contour to minimize the build error [16]. In [17] presents an adaptive slicing, which is based on the extracted amount of candidate feature points for the part model in different areas.

Often, the optimization task of determining the building step for adaptive slicing is performed together with the rational orientation of the product in a workspace [18, 19].

The main problem is that in existing scientific works, the construction step optimization can be carried out according to various criteria. This is due to the multifactorial nature of processes occurring during layer-by-layer construction, which affect their output characteristics, such as productivity and quality of resulting surfaces. But this does not take into account the non-determinism of layer-by-layer construction processes. Hypothetically, this problem can be solved better by taking into account the nature of distribution of values of the selected parameter. In this case, the choice of a parameter as a criterion is not so important. The most important thing when solving the optimization problem is to ensure in the objective function the dependence of the selected criterion on building step and the angle between building direction vector and the surface normal φ_{NZ}, which fall into the cutting plane of layer. Therefore, this problem should be considered based on the distribution density of the angles φ_{NZ} over their relative area [4].

As a rule, to ensure higher efficiency of using additive installation, products are manufactured not individually, but in a group for one or more installation loadings. Therefore, it is interesting to consider the possibilities of an adaptive slicing products group in the workspace.

This article presents the results of an additional study of adaptive slicing effectiveness of 3D models group placed in the workspace based on a statistical analysis of distribution of the angles φ_{NZ}, taking into account the relative surface area, to reasonably determine the step to ensure the specified accuracy and reduce the building time for a batch of complex products.

Purpose and objectives. This article purpose to identify the possibilities of adaptive slicing products group, provided that specified accuracy of shaping is ensured, taking into account the step (discreteness) of setting the layer thickness (i.e., the rounding error of calculated value).

To achieve this goal, the following tasks were solved:

- adaptive slicing 3D models group depending on their orientation and packing in the workspace;
- comparative analysis of options for slicing 3D models group depending on orientation and placement in the workspace, and also the discreteness of setting the layer thickness (building step);
- statistical analysis of deviations distribution from the correct form for various slicing with constant and variable building steps.

Research methodology. The research was carried out using the system of technological preparation for materialization of complex products by additive manufacturing, developed at the Department of Integrated Mechanical Engineering Technologies of NTU "Kharkiv Polytechnic Institute" [4, 19]. This system allows you to evaluate the effectiveness of solving optimization problems of planning additive manufacturing processes based on statistical analysis of studied features of polygonal, voxel and layered 3D model of products placed in the workspace.

One of the most common approaches for determining the building step h_i is to perform a calculation based on given limit Δ_{Limit} for deviations from the correct shape of surfaces specified by 3D model (as a result of the formation of step effect on the surface from layer-by-layer building process) [20, 21]:

$$h_i = \frac{\Delta_{Limit}}{cos\,\varphi_{NZ\,min}},$$

where $\varphi_{NZ\,min}$ is the minimum value of the angles between Z-axis (construction direction) and the normals of faces included in current layer.

Research works [4, 19] presented and developed an adaptive strategy for slicing 3D models made individually and by joint group. This research of capabilities of developed algorithm for adaptive slicing was carried out using examples of loading group of sufficiently large number (more than 20 pcs.) of test 3D models of complex-shaped products, shown in Fig. 1.

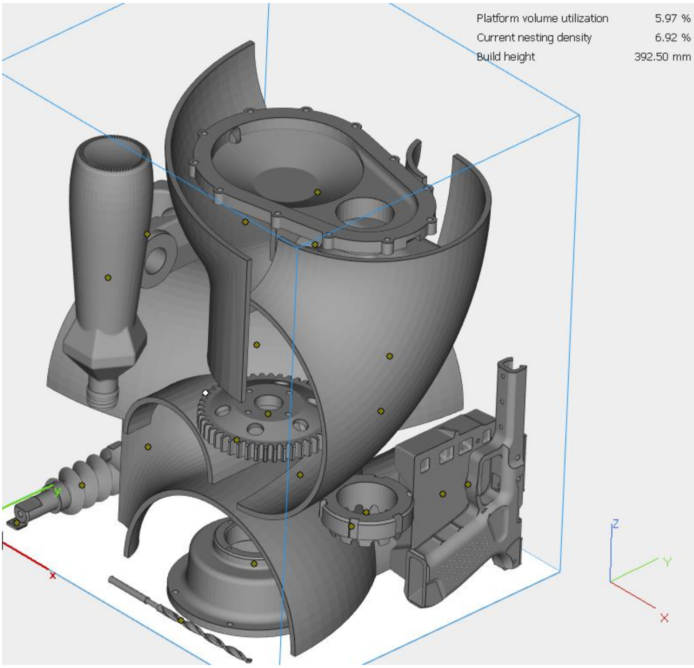

Figure 1 – A group of test 3D models placed in the workspace

Research of the influence of step discreteness of setting the layer thickness on efficiency of using adaptive slicing. In the research, to provide a comparative analysis, a group of test 3D models was dissected for 5 options for their orientation and placement in the workspace according to strategies with constant and variable construction steps. Placement options for 3D models were created in the Materialize Magics system using the EOSPACE automatic placement module. Strategy with constant step was carried out at $h_i = \{0.05;\ 0.1\}$ mm. Strategy with variable step at $\{h_i\}_{\min} = \{0.05;\ 0.1\}$ mm, $\{h_i\}_{\max} = 0.3$ mm, and allowable (maximum) error of surface formation $\Delta_{Limit} = \{0.05;\ 0.1;\ 0.2\}$ mm. The selected build steps range is wide enough for recommended steps when using SLA setups. The proposed adaptive cutting strategy was performed with a 5% truncation of the angle distribution (this truncation is the optimal value [4, 19]). Based on the results of model calculations, the range diagrams are in Fig. 2.

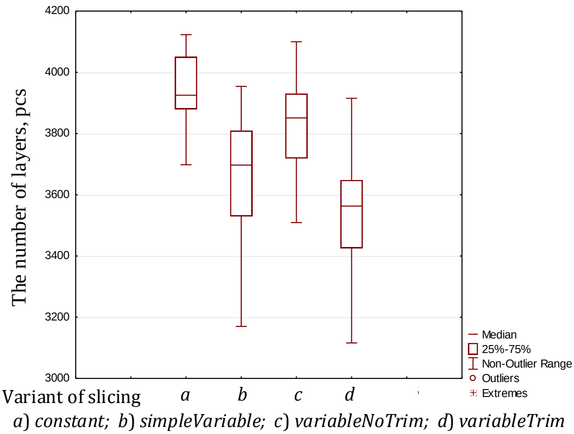

Figure 2 – Statistical comparative analysis of variants of layer-by-layer slicing with the following parameters: $\{h_i\}_{\min}$ = 0.1 mm, $\{h_i\}_{\max}$ = 0.3 mm and Δ_{Limit} = 0.1 mm

Fig. 2 shows the distribution of layers number with the same load of large batch of products that differ in orientation and packing in the workspace for four cutting strategies: *a* – uniform with a constant step; *b* – adaptive slicing according to analysis in the cutting plane; *c*, *d* – adaptive slicing with preliminary analysis of the surface by microsections (with 0 and 5% truncation of the shaping error distribution, accordingly). The variants of slicing in Fig. 2*a* and Fig. 2*c*. Other variants (Fig. 2*b*, Fig. 2*d*) of adaptive slicing are more demanding on allotting of orientation and packing strategy. But at the same time, the last option related to the developed strategy can provide the least number of layers (accordingly, the building time is minimal). This becomes possible with the rational selection of orientation and products packing in the workspace.

Comparative analysis of the number of layers for all studied options for packing 3D models (Fig. 2) confirms the previously justified [4] advantage of strategies with a variable step (Fig. 2*b*-*d*) compared to constant step (Fig. 2*a*) by 0.1-19.2%.

Adaptive slicing performed without preliminary analysis of the surface by microsection (such adaptive strategy is known from publications [22]) is shown in Fig. 2*b*. It makes it possible to reduce the number of layers relative to dissection with a constant step h_i = 0.1 mm by 19% at best. The developed strategy of dissection (Fig. 2*d*) allows to reduce in different cases from 1.8% to 15.7%, which indicates the importance of joint solution of several tasks of technological preparation. If we compare the number of layers of "VariableTrim" strategy (Fig. 2*d*) concerning "simpleVariable" (Fig. 2*b*), then it is from -11.6% to 11.7%.

The explanation for this result is a more detailed analysis of the geometry of the product surface, which in some cases requires a larger number of layers. Ancillary ambiguity in the results obtained gives the influence of orientation and relative position of the products. In the vast majority of cases (this is 84%), it is possible to obtain better results in terms of the number of layers.

Relative change in the number of layers for different building strategies changes strongly when lower accuracy requirements are set, i.e., when the permissible error doubles (corresponding range diagrams are shown in Fig. 3).

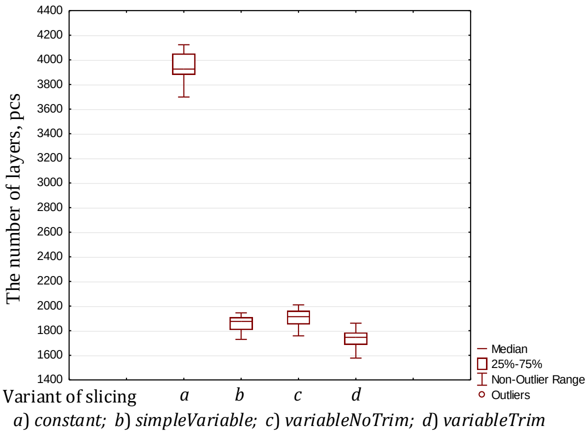

Figure 3 – Statistical comparative analysis of options for layered slicing with the following parameters $\{h_i\}_{\min}$ = 0.1 mm, $\{h_i\}_{\max}$ = 0.3 mm and Δ_{Limit} = 0.2 mm

Setting the limit of deviations value Δ_{Limit} = 0.2 mm (Fig. 3) makes it possible to reduce the number of building layers by 50-58%. At the same time, the differences between strategies of adaptive slicing are not so significant - 3.9-9.4%. It is also reasonable (according to the results in Fig. 3 in ratio to the data presented in Fig. 2), we can conclude that when requirements for building accuracy are lowered, the problem of orientation and packing problems is leveled.

In addition, the individual parameters influence on the efficiency of adaptive slicing was considered. With a strong decrease in the minimum building step to $\{h_i\}_{min}$ = 0.05 mm, no fundamental change in the number of layers was observed (within the range from -2.6% to +7.1%). While a decrease in the allowable value of deviations from the correct surface shape Δ_{Limit} = 0.05 mm leads to a change in the number of layers in the range from +62.6% to +108.1%. Therefore, we can conclude that it is necessary to rationally select two parameters $\{h_i\}_{min}$ and Δ_{Limit}.

Concerning the group of test 3D models taken in this study, the rational ratio of these parameters is their equality $\{h_i\}_{min} = \Delta_{Limit}$.

Statistical layered analysis of deviations from the correct surface shape. The use of adaptive slicing implies the provision of a given deviation from the correct shape of resulting product surfaces. Therefore, a layered assessment of deviations from the correct form Δ_S was also carried out according to the arithmetic mean value $\overline{\Delta_S}$. Predicted deviation from the correct shape was taken from the surface asperity formed on the surface as a result of the step effect by layered building [22].

Fig. 4 shows the box-whiskers distributions $\overline{\Delta_S}$ for comparing strategies with a constant step $h_i = 0.10$ mm, and with variable step $\{h_i\}_{min} = 0.1$ mm, $\{h_i\}_{max} = 0.3$ mm and allowable error $\Delta_{Limit} = \{0.1; 0.2\}$ mm at $\Delta\varphi_{NZ} = 5\%$.

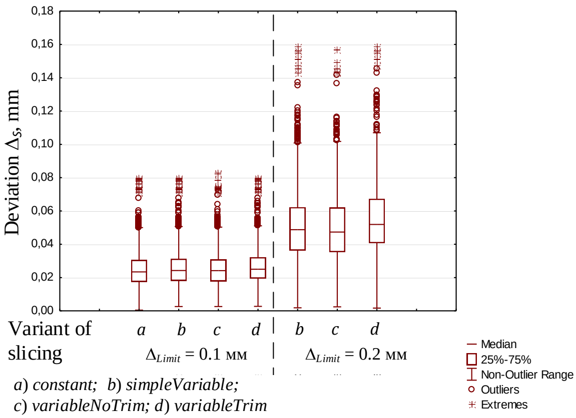

Figure 4 – Results of statistical layer-by-layer analysis of the arithmetic mean deviation from correct surface shape Δ_S

Comparative analysis of statistical layer-by-layer analysis (the result is shown in Fig. 4) was performed on the example of one variant of test 3D models placement. This analysis showed that there were no significant differences in the slicing with variable step, i.e. slicing strategy does not greatly affect the nature of distribution. For most packing options, resulting distribution for a slicing with variable step approximately corresponds to a slicing with constant step $h_i = \{h_i\}_{min}$. Statistical characteristics for Δ_S are mainly determined by the set limit value Δ_{Limit}.

Conclusions. Adaptive slicing 3D models using a statistical analysis of the distribution of angles between the *Z*-axis and the normals of surfaces that fall into the layer section, taking into account their relative area, taking into account rational orientation and packing can significantly increase the performance of layer-by-layer building.

Adaptive slicing, taking into account an insignificant reduction in the distribution of angles between the *Z*-axis and surface normals by $\Delta\varphi_{NZ}$ = 5%, with high requirements for construction accuracy, it is rational to set the minimum building step equal to the required maximum deviation from the correct shape of resulting product surfaces.

Further research should be directed to the joint solution of technological preparation problems: orientation, packing of products in the workspace, and their adaptive slicing.

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ВПЛИВ ТОЧНОСТІ ВИЗНАЧЕННЯ КРОКУ ПОБУДОВИ НА ЕФЕКТИВНІСТЬ АДАПТИВНОГО РОЗСІЧЕННЯ ГРУПИ ВИРОБІВ ДЛЯ АДИТИВНИХ ТЕХНОЛОГІЙ

Анотація. *Представлено результати дослідження щодо підвищення ефективності розробленого алгоритму для адаптивного пошарового розсічення на прикладі групи 3D моделей, розміщених у робочому просторі адитивної установки. Даний алгоритм адаптивного розсічення 3D моделі дозволяє підвищити продуктивність процесу та регулювати точність виготовлення виробів, з урахуванням їхньої геометрії, за допомогою завдання раціональної величини змінного кроку побудови для кожного окремого опускання робочої платформи. Крок побудови розраховується з урахуванням розподілу напрямку нормалі поверхонь групи виробів, що потрапили до поточного шару. Розроблений алгоритм передбачає деяке усічення даного розподілу, що дозволяє додатково збільшити крок побудови, а відповідно зменшити кількість шарів. Таким чином створюються умови для раціонального забезпечення та заданого зниження часу побудови. При цьому зазвичай одержуючи зменшення часу побудови у порівнянні з традиційною стратегією з постійним кроком побудови та існуючими стратегіями адаптивного розсічення з змінним кроком. Оцінка ефективності адаптивного пошарового розсічення виконувалась з урахуванням точності визначення (завдання) кроку побудови стосовно 5 варіантів розміщення 3D-моделей промислових виробів у робочому просторі. Порівняльний аналіз варіантів розсічення виконувався за кількістю шарів та оцінкою відхилень від правильної форми поверхонь. Виявлено покращення ефективності процесу пошарового формоутворення з підвищенням точності визначення змінного кроку побудови групи складних виробів, розміщених у робочому просторі установки Vanguard SLS (виробництва 3D Systems). Розроблений алгоритм адаптивного розсічення при раціональних параметрах дозволив зменшити кількість шарів побудови при забезпеченні заданих вимог щодо допустимих відхилень від правильної форми поверхонь. Дослідження виконувалося з використанням системи "Технологічна підготовка матеріалізації складних виробів адитивними методами" розробленої на кафедрі «Інтегровані технології машинобудування» НТУ «ХПІ».*

Ключові слова: *технологічна підготовка; адитивні технології; тріангуляційна модель; пошарове розсічення; розміщення групи виробів; точність формоутворення.*