ТЕХНОЛОГІЇ ОТРИМАННЯ ТА ОБРОБКИ КОНСТРУКЦІЙНИХ МАТЕРІАЛІВ

TECHNOLOGIES OF OBTAINING AND PROCESSING OF CONSTRUCTION MATERIALS

UDC 621.9.01: 51-74

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TECHNOLOGY FOR CREATING PRODUCTS FROM SHEET COMPOSITE MATERIAL USING TOPOLOGICAL ANALYSIS OF A 3D MODEL

Purpose. *Using a three-dimensional model of a part, propose an optimal part unfolding using graph modeling and topological analysis methods; develop additional criteria for optimizing flat layouts to reduce the milling labor intensity and assembly accuracy; test the developed criteria on a practical example.*

Research methods. *In the case under study, the research was conducted using graph modeling based on topological analysis of the product model. The research material was a 4 mm thick aluminum composite sheet with a 0.4 mm aluminum layer. Two variants of flat layouts were created based on the developed graphs. The final selection of the optimal flat layout variant was determined according to the developed optimality criteria.*

Results. *The experience of selecting technological parameters for mechanical processing of aluminum composite sheet, which provide high processing productivity and product quality, has been generalized. It has been shown that the use of graph theory based on topological analysis of the model formalizes the process of creating variants of flat layouts. New optimality criteria are proposed, namely the total length of mechanical processing and the minimum number of parallel machining trajectories of bending grooves. Optimization should be carried out according to a priority criterion, using the rest as references for choosing between comparable variants.*

Scientific novelty. *Criteria for optimising the flat layout when machining aluminium composites have been developed, such as: total cutting length to reduce the labour intensity of milling; minimum number of parallel trajectories for machining bending grooves.*

Practical value. *The use of the developed criteria ensures maximum productivity of mechanical processing and maximum accuracy of assembly of products made of aluminium composites. The method of using graph theory based on the analysis of model topology can be the basis for automating the process of creating flat layouts.*

Key words: *flat layout, bending groove, cut length reduction, accuracy of assembly, unfolding algorithms.*

Introduction

Modern mechanical engineering requires new approaches to the manufacture of products from sheet composite materials that combine economy, flexibility and manufacturability. Traditional methods, in particular stamping, are associated with high costs for the manufacture of moulds, significant energy consumption and limitations in design variability. In this context, the technology of milling composite sheets is a promising direction. It allows obtaining complex three-dimensional geometries from a single flat layout, which minimizes the number of components, reduces production costs and lowers the energy intensity of the process.

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A perspective way to develop possible options for layout of sheet composite parts is to use graph modeling based on topological analysis of the model. However, when analysing the geometry of a part, it may turn out that even for simple models there are several dozen possible layout variants, which raises the question of the final choice of layout geometry. This issue can be resolved by developing additional criteria for the optimality of the obtained flat layout that would take into account production indicators such as: labour intensity of cutting, number of connecting seams, orientation of fold grooves and the area of layout.

Existing criteria for optimising layouts are mainly focused on steel, plywood and textiles, but are practically not taken into account for aluminium composites. The relevance of optimising aluminium composite layouts is based on the fact that in modern mechanical engineering they are actively used for body structures, protective covers, transport vehicles, and in the future they may become the basis for lightweight and rigid load-bearing elements in electric transport and aviation due to their technological characteristics: relatively high rigidity at low weight, corrosion resistance, vibration and noise insulation, and machinability using various methods: mechanical, laser and hydrocutting [1, 2]. The main problems of milling aluminium composites include: large total length of the contour and bending grooves, which leads to an increase in milling time; inefficient arrangement of the unfolding elements and, as a result, an increase in the number of bends and seam grooves.

The development of an integrated optimisation model that takes into account the labour intensity of milling and the specifics of assembly is a pressing issue for ensuring the cost-effectiveness and accuracy of the manufacturing process for aluminium composite parts.

Analysis of research and publications

The problem of creating 3D model flat layouts from sheet materials, in particular aluminium composite panels (ACP), remains one of the key issues in the production of complex geometric structures. It has two interrelated components:

- geometric: the complexity of the machining contour, the number of connecting seams and the number of bending grooves;
- technological: the labour intensity of manufacturing and the accuracy of assembly.

Currently, there is little information available on the machining of ACP using milling. The literature contains more extensive coverage of the machinability of composite sandwich panels [3–5].

A review of the literature [3, 6–10] showed that the technological parameters for machining ACP by milling are not systematised. All technological parameters for machining composite panels by milling are based entirely on the recommendations of the manufacturers of these panels.

The literature does not specify clear criteria for the optimality of milled ACP profiles. To evaluate them, it is recommended to use criteria for profiles made from other materials using other methods (bending on dies, laser cutting) [11, 12]. These criteria include:

1. Compactness, calculated using the formula (1) [13]:

$$C = \frac{A}{P^2}, \quad (1)$$

where C – the compactness index; A– the area of the layout; P– the perimeter of the layout.

2. Ease of assembly calculated using the formula (2) [12]:

$$A_{score} = N_{folds} + \alpha \cdot N_{seams} \;, \quad (2)$$

where A_{score} – ease of assembly score; N_{folds} – number of bending grooves; N_{seams} – number of seam grooves; α – weight coefficient (If the seams are technologically more expensive/critical than the bends, then α >1. If the seams are less critical than the bends, for example, in concealed installation, then $\alpha < 1$ is taken).

Topological analysis methods allow formalising the structure of a 3D model through its connectivity, cycles and local surface features, as well as using optimisation criteria even before production begins. This approach reduces the cost of finished products and unifies the production process [12].

Studies [14, 15] have shown that topological decomposition of complex surfaces allows for the correct selection of areas for further unfolding, while preserving the geometric integrity of the model.

There are two main methods of geometric representation of a 3D model that can be used in topological analysis of flat layouts:

- boundary representation (B-representation);
- solid representation.

In B-representation, the structure is modeled as a set of surfaces that are in contact with the construction material [15–17]. Also, for sheet metal assembly, the representation of boundaries is sufficient to describe all the necessary geometric and topological information, where geometric data convey the shape of the structure, while topological data describe the relationship between surfaces [15, 20].

The relationship between topological and geometric elements of a 3D model is presented in Quattawi’s work [11], and this relationship is shown in Fig. 1.

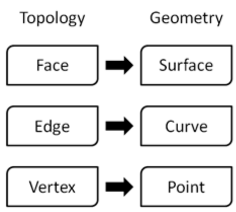

Figure 1. Relationship between topological and geometric elements

Qattawi notes, that topological characteristics, particularly the presence of cycles and nodes in a polygonal

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mesh, directly affect the ability to construct an flat layouts without overlaps. The author has demonstrated that analysing such structures allows for the prediction of ‘problematic’ areas at the design stage.

The use of simulation optimisation methods, such as the annealing algorithm, in combination with topological analysis deserves special attention. This approach allows simultaneously solving the problem of minimising overlaps in the flat layout and reducing the length of the tool trajectory during milling [19].

In combination with topological methods, graph theory tools are also actively used to formally describe the surface of the model. Sheffer and Hart [11, 20] proposed representing a polygonal mesh as a graph, where the vertices correspond to faces and the edges correspond to potential cut grooves.

In this case, constructing a projection boils down to finding a spanning tree that transforms the surface into a plane without overlaps.

The authors of [21] developed algorithms based on the minimum spanning tree (MST) for selecting optimal cuts with minimum total length, which is especially important when cutting sheet composites, where the length of the trajectory directly affects the thermal load and edge quality.

Mitani and Suzuki [22] showed that reducing the number of layout fragments by analysing strip structures allows for a reduction in the number of technological cuts and preserves the strength of the material. Shatz and Tal [23] proposed a method for selective cutting of meshes that takes into account both geometric and mechanical properties, which is critically important for composite materials [24].

The combination of topological analysis with graph algorithms opens up new possibilities for automating the process of creating layouts:

- the topology of the model allows critical areas of the surface to be identified where overlaps or excessive deformations are possible;
- graph methods provide a formal selection of optimal cutting grooves and reduction of milling trajectories;
- integration with CAD/CAM systems allows for the automated creation of layouts, taking into account edge quality, material rigidity, and waste minimisation.

Therefore, modern research shows that the use of topological analysis in combination with graph methods is one of the most effective approaches to solving the problem of constructing layouts for products made of sheet composite materials.

Purpose

Using a three-dimensional model of a part, apply graph modelling and topological analysis methods to propose an optimal part layout; develop additional criteria for optimising layout to reduce the labour intensity of milling and assembly accuracy; test the developed criteria in a practical example.

Research material and methods

The graph method and topological analysis of the 3D model for creating an optimal flat layout were performed on a part made of ACP, with a sheet thickness of 4 mm: two layers of aluminium, each 0.4 mm thick, and a layer of polyethylene 3.2 mm thick. The 3D model of the part is developed using CAD software.

The research was conducted in the following sequence:

1. To use the graph method, a topological analysis of the model was performed [11,15,18]. The result of the analysis is the determination of the number of planes and edges of the detail.

2. When drawing the graph, it is assumed that the vertices of the graph correspond to the planes of the part, and the edges of the graph correspond to the edges of the part [11,18].

3. The base plane is selected based on the graph obtained. The selection of the base plane is based on which face has the largest number of mutual edges with other planes, which minimises the number of orientation operations during bending.

4. A graph is drawn to predict possible variations of the layouts of the part. To do this, the number of cuts in the part's edges is estimated, taking into account the integrity of the shell during unfolding. The number of edges that can be cut is calculated using formula (3) [11]:

$$N_S = N_e - N_f + 1, \tag{3}$$

де N_S – maximum number of edges that can be cut; N_e – number of edges of a part; N_f – number of faces of a part.

Combining the calculation results with the obtained graph makes it possible to predict possible variations of the flat layouts even before the start of modelling. To obtain different variants of flat layouts, the edges between the vertices are removed from the graph in the amount corresponding to the calculated one, which means that the removed edge will be cut on the part during unfolding. By combining the positions of the cuts, you can create a set of flat layouts that will then be analysed for optimality.

4. Milling was performed on a Woodpecker CAMARO CP-1208 CNC milling machine. A V-shaped milling cutter with an angle of 90°, ø14 mm, and a shelf length of 2 mm (Fig. 2). The cutter shelf allows you to obtain enough material on the uncut layer of aluminium for easy bending.

Figure 2. Appearance of the milling cutter for bending grooves

A double-tooth cylindrical milling cutter for machining aluminium with a diameter of 6 mm was used as a milling cutter for machining the contour of the flat layout (Fig. 3).

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Figure 3. Appearance of the milling cutter for machining the contour of the flat layout

To determine the material flow per bend of the bending groove during bending, a cube measuring 100x100x100 mm was milled and assembled (Fig. 4).

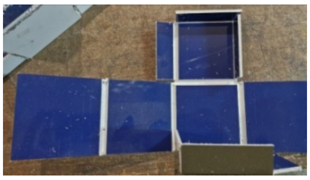

Figure 4. Appearance of the cube flat layout to determine the flow of material

Research results

Based on practical experience and recommendations from aluminium composite manufacturers, technological recommendations for ACP by milling were systematised (Table 1).

Table 1 – Systematisation of technological recommendations for machining ACP by milling

Groove type	V- or U-groove
Undercut groove	Depends on the type of ACP: 0.2–0.5 mm
V-groove angles	~ 90–105°
Minimum internal bending radius	2–3 × panel thickness
Feed rate	5–15 m/min

The study was performed for a part whose 3D model is shown in Fig. 5. The model was developed using SolidWorks software.

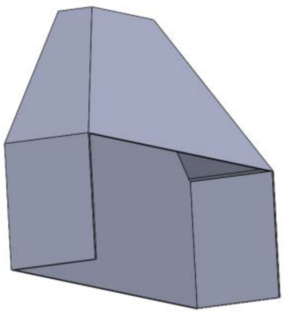

Figure 5. 3D model of the part

To use the graph method, a topological analysis of the model was performed. The result of the analysis is the determination of the number of surfaces and edges of the part. All faces were numbered to construct the graph (Fig. 6). In our case, the number of surfaces is 7, and the number of edges is 12.

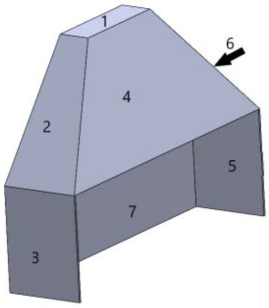

Figure 6. Numbering of part surfaces

Considering that the vertices of the graph correspond to the surfaces of the part, and the edges of the graph correspond to the edges of the part, a graph describing the topology of the part was drawn (Fig. 7).

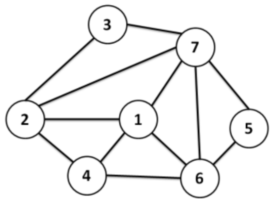

Figure 7. The graph obtained after topological analysis of the part

The graph shows that plane 7 has the maximum number of common edges, so it is designated as the base plane. The number of edges that are cut is calculated using formula (3):

$$N_S = 12 - 7 + 1 = 6.$$

Taking into account the calculation results, several graph options describing the model layout were developed (Fig. 8).

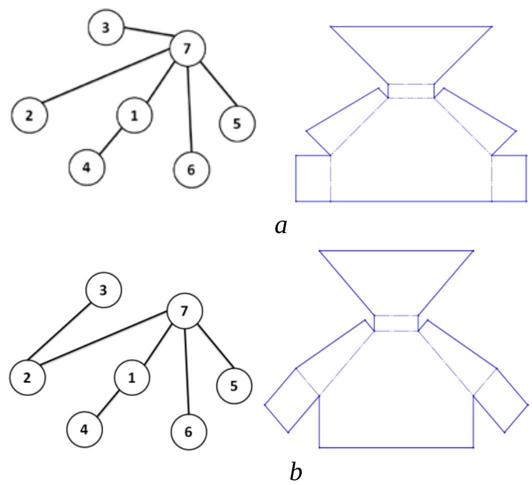

Figure 8. Calculated graphs and corresponding part layouts: *a* – first graph option and relevant layout, *b* – second graph option and relevant layout

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For the final selection of the optimal layout, optimisation criteria have been developed to complement those considered above:

1. The total cutting length should be minimised to reduce the labour intensity of milling. This criterion is expressed by formula (4):

$$L_{\Sigma} = P + \sum_{i=1}^{n} l_i \rightarrow \min, \qquad (4)$$

where L_{Σ} – total milling length; P – length of the perimeter of the layout; l_i – bending groove length; n– number of bending grooves.

2. The inaccuracy of assembly occurs due to the flow of material when turning along the bending groove. Control of the dimensions of the assembled cube 100x100x100 mm, showed that when the material is deformed when turning one bending groove, the size of the edge increases by approximately 0.7 mm (material run-up). The control was carried out for ACP with a thickness of 4 mm. Therefore, to ensure the accuracy of the assembly of the part from the layout, it is necessary to minimise the number of parallel bending grooves k on the layout, which is calculated using formula (5):

$$\max k_j \rightarrow 1 + \sum_{i=1}^{n_j} 1_{\{a_i \| a_{i+1}\}} \rightarrow \min. \qquad (5)$$

де k – bending number of grooves; j- number of parallel groups of bending grooves; n– number of grooves in a group; a- edge.

In this case, accuracy is improved by reducing the impact of material flow on complex parts, especially large ones with a large number of bending grooves. Using the developed optimisation criteria, the optimal unfolding was selected from among those calculated using graphs.

The total length of milling of the rollers has been calculated:

- L_{Σ} = 5182,96 mm for the layout shown in Fig. 8*a*;
- L_{Σ} = 5583,86 mm for the unfolding shown in Fig. 8*b*.

For the specified part, it is difficult to assess the criteria for minimising the number of parallel bending grooves. In the development shown in Fig. 8*a*, two groups of parallel bending grooves can be clearly identified. The second development, shown in Fig. 8*b*, has only one group of such grooves, so according to this criterion of optimality, it is more optimal, but the location of the ribs that were cut along the graph leads to an increase in the length of machining.

In accordance with the principle of uniqueness in solving optimisation problems, optimisation according to all existing and proposed criteria is impossible, since there can only be one criterion of optimality. In this case, several criteria can be combined into one by normalisation, i.e. by reducing them to a dimensionless form and convolving them using weighting coefficients that determine the degree of importance of each criterion. This approach is a compromise and does not provide the best results for individual indicators. Therefore, for the formation of layouts, it is considered more rational to determine the rating of criteria depending on the purpose of the product (for example, accuracy, labour intensity or cost-effectiveness) with the optimisation of the layout according to the criterion of optimality that has the highest rating. The remaining criteria will be used as references for choosing between comparable options based on the main criterion.

Conclusions

The experience of selecting technological indicators for machining of ACP, which ensure high machining productivity and product quality, has been summarised. It has been shown that the use of graph theory based on topological analysis of the model formalises the process of creating different variants of unfoldings, which are the object of optimisation. This approach can be the basis for automating the process of creating layouts.

New optimality criteria are proposed, namely the total length of machining and the minimum number of parallel machining trajectories of bending grooves. Such criteria ensure maximum machining productivity and maximum product assembly accuracy, respectively.

It is recognised that a rational approach to optimisation is to compile a rating of optimality indicators without determining their weighting coefficients. Optimisation should be based on a priority criterion, with the rest being used as references for choosing between comparable options.

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ТЕХНОЛОГІЯ СТВОРЕННЯ ВИРОБІВ З ЛИСТОВОГО КОМПОЗИТНОГО МАТЕРІАЛУ З ВИКОРИСТАННЯМ ТОПОЛОГІЧНОГО АНАЛІЗУ 3D-МОДЕЛІ

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Мета роботи. *На прикладі тривимірної моделі деталі, використовуючи методи графового моделювання та топологічного аналізу запропонувати оптимальну розгортку деталі; розробити додаткові критерії оптимізації розгортки для зменшення трудомісткості фрезерування та точності збірки; перевірити розроблені критерії на практичному прикладі.*

Методи дослідження. *Дослідження, що розглядається, проводилось методом графового моделювання на основі топологічного аналізу моделі виробу. Матеріал дослідження – лист алюмінієвого композиту товщиною 4мм, з шаром алюмінію 0,4мм. Було створено два варіанти розгорток основуючись на розроблених графах. Остаточний вибір оптимального варіанту розгортки було визначено за розробленими критеріями оптимальності.*

Отримані результати. *Узагальнено досвід вибору технологічних показників механічної обробки алюмінієвого композиту, що забезпечують високу продуктивність обробки та якість виробу. Показано, що використання теорії графів на основі топологічного аналізу моделі формалізує процес створення варіантів розгорток. Запропоновані нові критерії оптимальності, а саме сумарна довжина механічної обробки та мінімальна кількість паралельних траєкторій обробки ліній згину. Оптимізація має відбуватися за пріоритетним критерієм з використанням решти як референтних для вибору між співставними варіантами.*

Наукова новизна. *Розроблені критерії оптимізації розгортки при обробці алюмінієвих композитів, такі як: сумарна довжини різу для зменшення трудомісткості фрезерування; мінімальна кількість паралельних траєкторій обробки ліній згину.*

Практична цінність. *Використання розроблених критеріїв забезпечує максимальну продуктивність механічної обробки та максимальну точність збірки виробу з алюмінієвих композитів. Методика використання теорії графів на основі аналізу топології моделей може бути основою для автоматизації процесу створення розгорток.*

Ключові слова: *розгортка, згинальні канавки, зменшення довжини різу, точність складання, алгоритми розгортання.*

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