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**НОВІ МАТЕРІАЛИ І ТЕХНОЛОГІЇ
В МЕТАЛУРГІЇ
ТА МАШИНОБУДУВАННІ**

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- механізація, автоматизація та роботизація. Вдосконалення методів дослідження та контролю якості металів. Моделювання процесів у металургії та машинобудуванні.

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СТРУКТУРОУТВОРЕННЯ. ОПІР РУЙНУВАННЮ ТА ФІЗИКО-МЕХАНІЧНІ ВЛАСТИВОСТІ

STRUCTURE FORMATION. RESISTANCE TO DESTRUCTION AND PHYSICAL-MECHANICAL PROPERTIES

UDC: 669.715:669.018.25:620.186

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STRUCTURAL AND PHASE FORMATION IN A MEDIUM-ENTROPY, HIGHALLOYED COMPOSITION OF THE AL-MG-SI-V-CR-MN-FE-NI-CU SYSTEM

Purpose. To obtain, in the simplest possible way, an alloy with a relatively low melting temperature for HEAs and MEAs, containing non-deficit components capable of dissolving in aluminum and exhibiting mutual solubility. The concentration of most components did not exceed 2.5–5 at.%, therefore the main was to increasing the mixing entropy was the number of elements included in the alloy composition.

Research methods. The melt was prepared using a laboratory resistance furnace. Pure components and concentrated master alloys were used as charge materials, added gradually in small amounts to prevent the formation of refractory intermetallics. Melting was carried out in an alumina crucible at 1000 °C, which ensured dissolution and assimilation of all components.

Results. Structural and phase characteristics of the experimental alloy were compared depending on the cristalization rate. When cooled with the furnace at a rate of 0.5 °C/s, a heterogeneous structure formed, represented mainly by three phases: an intermetallic of the Al_6Me type, based on Al_6Mn with dissolved Fe, Ni, Cr, and V; an intermetallic based on the Al_6Cu_2Ni -type phase, which by stoichiometry could be expressed as $(Al,Ni)_2Cu$; and the Mg_2Si phase. Rapid solidification at $5 \cdot 10^2$ °C/s resulted in some refinement of the structure and increased its homogeneity, but did not significantly change the phase composition. Notably, in the Al_6Me intermetallic, the higher-temperature compound $Al_{23}V_4$ became predominant. The formation of an intermetallic in the Al-Ni-Cu system under these conditions could correspond to a compound formation with the formula $Al_2(Ni,Cu)_3$. The Mg_2Si phase was observed as part of the eutectic (Mg_2Si+Si).

Scientific novelty. A new approach to producing medium-entropy multicomponent alloys by resistance furnace melting has been demonstrated. The influence of cooling rate on phase formation in the Al-Mg-Si-V-Cr-Mn-Fe-Ni-Cu alloy has been revealed.

Practical value. An approach has been developed for obtaining medium-entropy alloys from non-deficit components with a reduced melting temperature, which simplifies their synthesis. The results can be used for further studies of high-entropy and medium-entropy alloys.

Key words: Al-Mg-Si-V-Cr-Mn-Fe-Ni-Cu system, HEA, MEA, highly alloyed compositions, new materials, structure, phase formation.

Introduction

In recent decades, particular attention of materials scientists has been drawn to the development of high-entropy alloys (HEAs), medium-entropy alloys (MEAs), and multi-principal element alloys (MPEAs), which are distinguished by a set of extraordinary properties determined by their specific structural–phase state. HEAs were first mentioned in 1995, which subsequently stimulated the advancement of scientific research in this field, and since 2003 they have been regarded as one of the latest breakthroughs in the development of a new class of materials [1, 2].

Since the first publications in 2004 in independent studies by Jien-Wei Yeh and Brian Cantor, high-entropy alloys have opened new opportunities for the development of a wide range of novel materials [3, 4]. By the general definition, such alloys contain at least five principal elements, each with a concentration ranging from 5 to 35 at. % and may also include minor elements with concentrations below 5 at. %.

Over the past decade, the evolution of materials research has led to a modification of the definition of HEAs. The compositional constraints of 5–35 at. % for principal elements are now applied less frequently, thereby enabling the formation not only of single-phase solid-

solution structures but also dual-phase, eutectic, and multiphase structures, intermetallic compounds, as well as their combinations, which may exhibit either crystalline or amorphous configurations [5–7]. The microstructure and specific crystallographic features of HEAs account for their high strength and hardness, wear resistance, resistance to high-temperature oxidation, enhanced corrosion resistance, fatigue strength, and fracture toughness.

Analysis of research and publications

In the design of metallic alloys, the conventional approach typically involves a base metal with minor additions of one to four soluble elements, which act through mechanisms of solid-solution or dispersion strengthening. With the advent of high-entropy alloys, the paradigm of alloy design has shifted: all constituent elements, present in approximately equiatomic concentrations, exhibit such a high degree of energetic uncertainty regarding the formation of individual phases that this leads to the development of complex and distinctive crystalline structures. The key contributing factors include the high degree of configurational entropy, sluggish diffusion, lattice distortion, and the so-called «cocktail effect», which together give rise to the unique physical and mechanical properties of these materials [3].

The synthesis of high-entropy alloys is feasible only within a rather limited range of technologies. In many cases, these processes require a protective atmosphere and are associated with powder metallurgy methods, as well as several metallurgical and casting techniques. The latter two categories reveal significant limitations when the alloys contain low-melting elements, metals with high vapor pressure, or components with substantial differences in density.

Density is a critical characteristic of most materials; therefore, the development of HEAs and MEAs incorporating lightweight elements represents an important task. The most suitable constituents in this context are aluminum, magnesium, and silicon. To preserve technological feasibility, particularly castability, the concentration of these elements in the alloy should be predominant. For effective incorporation, it is desirable that the components exhibit high mutual solubility, a condition that is satisfied by the aforementioned three elements. To enhance the configurational entropy of mixing, while adhering to the criteria outlined above, it is necessary to increase the number of alloying components.

For improved processability, reduced melting temperatures, and enhanced solubility of the constituents, the aluminum content was raised to as much as 60 at.%. The concentrations of the other elements remained relatively low; however, both their presence and number contributed to achieving a mixing entropy level approaching that of conventional HEAs.

As a result, a high-alloy composition of 60Al-10Mg-10Si-2.5V-2.5Cr-2.5Mn-2.5Fe-5Ni-5Cu (at. %) was selected. Within this system, certain elements and groups of elements possess similar atomic radii, which is one of

the essential criteria for the formation of homogeneous solid solutions in HEAs. Copper and magnesium exhibit high solubility in aluminum, whereas silicon and manganese are less soluble. Copper can also dissolve nickel, which in turn, along with manganese, facilitates the dissolution of otherwise insoluble or poorly soluble elements such as iron, chromium, and vanadium.

It was initially assumed that the high configurational entropy of mixing (ΔS_{mix}) in HEAs would inherently promote the formation of homogeneous solid solutions based on simple crystal lattices. However, subsequent studies have demonstrated that other thermodynamic and geometric factors—such as the enthalpy of mixing (ΔH_{mix}), atomic size mismatches among the constituent elements, interaction parameters, and valence electron concentration—also play a decisive role in governing the phase stability of HEA solid solutions [8–11].

Atomic size mismatch (δ_r): The percentage deviation in atomic radii of the constituent elements within the system. Values within the range of 0–6.6% favor the formation of stable solid solutions, whereas larger deviations may lead to the formation of intermetallic phases. The atomic size mismatch is calculated according to the following equation:

$$\delta_r = \sqrt{\sum_{i=1}^n c_i \left(1 - \frac{r_i}{\bar{r}}\right)^2} \times 100\%, \quad (1)$$

where c_i is the atomic fraction of the i -th element; r_i is the atomic radius of the i -th element; and $\bar{r}$ is the average atomic radius of the system, defined as:

$$\bar{r} = \sum_{i=1}^n c_i \cdot r_i. \quad (2)$$

Table 1 – Atomic radii of elements

Chemical element	Al	Mg	Si	V	Cr	Mn	Fe	Ni	Cu
Atomic radius, (pm)	143	160	111	134	128	127	126	124	128

The average atomic radius ($\bar{r}$) was calculated as $\bar{r} = 138.375$ pm for the charge and $\bar{r} = 138.043$ pm for the final alloy. Substituting the atomic radii of the elements, the average atomic radius, and their atomic fractions into the formula yielded $\delta_r = 9.15\%$. This value is relatively high, since for the stability of solid solutions in high-entropy alloys it is generally desirable that $\delta_r < 6.6\%$. A deviation of 9.15% may cause lattice distortion and promote the formation of intermetallic phases.

The concentration of valence electrons (VEC) provides a useful criterion for predicting the type of crystal lattice that a system may form. A value of $\text{VEC} > 8$ indicates the formation of an FCC structure, whereas $\text{VEC} < 6.87$ points to the preferential formation of a BCC structure. For $6.87 < \text{VEC} < 8$, the formation of a mixed

FCC + BCC structure can be expected. The corresponding data for the selected system are presented in Table 2.

Table 2 – The concentration of valence electrons

Chemical element	Al	Mg	Si	V	Cr	Mn	Fe	Ni	Cu
VEC	3	2	4	2	1	2	2	2	1

The concentration of valence electrons determines the average number of valence electrons in an alloy and is calculated using the formula:

$$VEC = \sum_{i=1}^n c_i \times VEC_i, \tag{3}$$

where VEC_i is the number of valence electrons of the i -th element.

By substituting the data from Table 2 into equation (3), the valence electron concentration was calculated as $VEC = 2,7$, which indicates the predominant formation of a BCC structure.

Electronegativity difference ($\Delta\chi$): A small electronegativity difference ($\Delta\chi \leq 0,12$) promotes the formation of solid solutions, whereas larger differences may stimulate the formation of intermetallic (IM) phases. The electronegativity difference is calculated according to the following equation:

$$\Delta\chi = \sqrt{\sum_{i=1}^n c_i (\chi_i - \bar{\chi})^2}, \tag{4}$$

where χ_i is the electronegativity of the i -th element, and $\bar{\chi}$ is the average electronegativity of the alloy, calculated as:

$$\bar{\chi} = \sum_{i=1}^n c_i \chi_i, \tag{5}$$

The relevant data for the selected system are given in Table 3.

Table 3 – Electronegativity of components

Chemical element	Al	Mg	Si	V	Cr	Mn	Fe	Ni	Cu
Electronegativity, χ_i	1.61	1.31	1.9	1.63	1.66	1.55	1.83	1.91	1.9

By substituting the electronegativity values of the constituent elements and their atomic concentrations into equation (4), the electronegativity difference was calculated as $\Delta\chi = 0,162$. This value exceeds the optimal range (≤ 0.12), which may indicate structural instability.

The design and application of alloys based on simple solid solutions are sometimes justified by their superior processability, strength, and retention of ductility. At the same time, intermetallic phases are often regarded as detrimental, since they tend to embrittle alloys and

complicate their processing. However, many structural alloys with advanced properties, including superalloys – where IM phases frequently constitute the dominant volumetric fraction – can exhibit both high strength and ductility. These characteristics depend strongly on the type of intermetallic lattice, their interaction with other phases, as well as the size, morphology, and distribution of the intermetallic [12].

The formation of intermetallic in amounts exceeding several volume percent is characteristic of alloys which, similar to HEAs, contain significant concentrations of multiple elements. However, their composition is designed in such a way that the configurational entropy of mixing is noticeably lower, thereby favoring a partial manifestation of the “cocktail effect.” Such alloys are generally referred to as medium-entropy or high-alloy systems. Alloys developed through partial implementation of HEA design principles, but incorporating intermetallic phases, are now considered one of the key strategies for the development of new materials with tailored properties [13–15].

Purpose

The objective of the present study was to ascertain the particularities inherent in the process of obtaining a high-alloyed multicomponent alloy based on aluminum, in which the conditions for obtaining HEA and MEA could be realized.

Materials and methods

The alloy was prepared under conditions closely resembling simple industrial processes. Although this approach could complicate the achievement of the desired outcome, it allowed for the evaluation of component assimilation, their mutual interactions, and the overall potential of such a processing route. The alloy of the Al-Mg-Si-V-Cr-Mn-Fe-Ni-Cu system was produced in a resistance furnace using an alumina crucible. Initially, concentrated ligatures of Al-20Mg, Al-20Si, Al-16Mn-4Fe, Al-50Cu, Al-15V, Al-10Cr, and Al-8Ni were remelted in small quantities at a temperature of 800 °C. To obtain the planned chemical composition of the alloy, the lacking components were subsequently added into the melt in small portions. During this process, the melt was stirred and its temperature was gradually increased to 950–980 °C to ensure maximum assimilation of all components. The melt was held at the maximum temperature for 15 minutes.

Upon completion, a small volume of the molten alloy was withdrawn from the crucible at 950 °C using a ceramic sampler (2 cm³ volume) and immediately transferred into a copper cylindrical mold in order to achieve the highest possible cooling rate. The remaining portion of the melt was left in the furnace, solidifying as the furnace cooled down. The cooling rate of the melt was approximately 0.5 °C/s in one case, and about $5 \cdot 10^2$ °C/s in the other. The appearance of the charge and the obtained samples is presented in Figure 1.

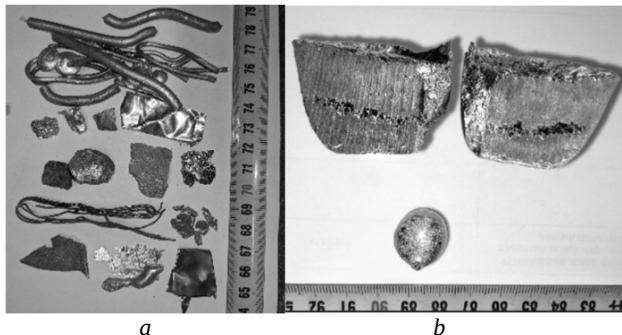


Figure 1. Appearance of charge materials (a) and obtained samples of experimental alloy (b)

Results and discussion

During alloy preparation, complete assimilation of all components was not achieved, as evidenced by the data in Table 4. Some constituents remained undissolved, while others were most likely lost due to evaporation or oxidation. The microstructural and phase analyses of the obtained samples revealed the presence of multiphase structures in both cases (Fig. 2). The corresponding local chemical compositions, in accordance with the designations in the figure, are summarized in Table 5.

In the case of slow solidification, a heterogeneous structure was formed, consisting predominantly of three phases. Based on the chemical composition of point 1, the formation of an intermetallic compound of the Al_6Me type, derived from Al_6Mn , can be assumed, in which Fe and Ni, as well as Cr and V, are dissolved.

Table 4 – Chemical composition of the experimental alloy charge and mixing entropy (ΔS) values

Chemical composition		Al	Mg	Si	V	Cr	Mn	Fe	Ni	Cu	ΔS
Alloy charge	at. %	60	10	10	2.5	2.5	2.5	2.5	5	5	1.44R
	wt.%	49.23	7.39	8.54	3.87	3.95	4.18	4.25	8.92	9.66	
Alloy in cast form	at. %	61.16	8.95	10.92	2.22	0.61	2.03	2.24	5.17	6.70	1.37R
	wt.%	49.97	6.59	9.29	3.42	0.96	3.37	3.79	9.18	12.9	

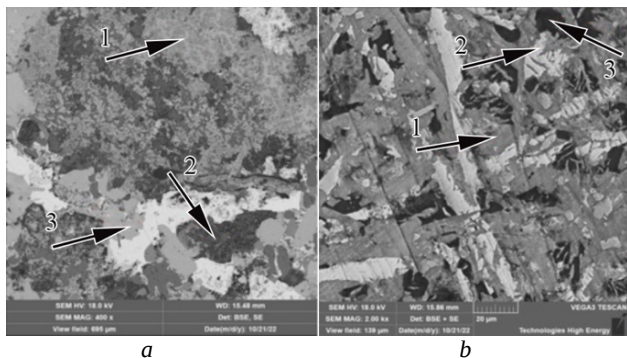


Figure 2. Microstructure of the experimental Al-Mg-Si-V-Cr-Mn-Fe-Ni-Cu alloy under slow (a) and rapid (b) cooling conditions

The second phase is also an intermetallic, but based on an Al_6Cu_2Ni -type structure, although its stoichiometry could alternatively be represented as $(Al,Ni)_2Cu$. The composition of point 2 clearly corresponds to the Mg_2Si compound.

Rapid solidification promoted partial refinement of the microstructure and an increase in its homogeneity, yet it did not lead to significant changes in the phase composition. It is noteworthy that in the Al_6Me -type intermetallic, a higher-temperature phase, likely $Al_{23}V_4$, may have become the dominant constituent. The formation of the Al-Ni-Cu intermetallic under these conditions could correspond to a compound approximating the formula $Al_2(Ni,Cu)_3$. The Mg_2Si phase in this sample was observed as part of a eutectic mixture ($Mg_2Si + Si$).

Table 5 – Local chemical composition of the alloy phases corresponding to the designations in Figure 2

Chemical composition, at. %		Al	Mg	Si	V	Cr	Mn	Fe	Ni	Cu
Slow cooling	point 1	56.98	5.65	2.29	1.7	1.72	9.25	7.98	9.42	4.86
	point 2	3.44	59.91	31.77	0.05	0.06	0.01	0.07	0.65	3.78
	point 3	42.41	0.45	0.27	0.06	0.18	0.14	0.47	36.21	19.68
Rapid cooling	point 1	60.57	0.97	3.38	7.47	1.22	6.72	5.83	9.84	3.96
	point 2	41.8	0.71	0.17	0.07	0.04	0.44	1.06	24.99	30.65
	point 3	11.8	37.66	47.86	0.16	0.04	0.23	0.38	0.36	0.51

Conclusions

Analyzing the obtained data, it can be concluded that the experimental Al-Mg-Si-V-Cr-Mn-Fe-Ni-Cu alloy, which falls into the category of medium-entropy alloys based on its mixing entropy, does not form solely solid solutions, regardless of the cooling rate of the melt. The phase composition of the obtained samples is characterized by the presence of three types of intermetallic compounds. In the rapidly solidified sample, a high-temperature eutectic reaction, $L \rightarrow \text{Mg}_2\text{Si} + \text{Si}$, is observed. The simultaneous presence of magnesium and silicon in the alloy and the formation of an intermetallic phase between them may reduce the likelihood of forming an aluminum-based solid solution.

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СТРУКТУРО- ТА ФАЗОУТВОРЕННЯ В СЕРЕДНЬОЕНТРОПІЙНОМУ ВИСОКОЛЕГОВАНОМУ СПЛАВІ СИСТЕМИ AL-MG-SI-V-CR-MN-FE-NI-CU

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Мета роботи. Одержати найбільш простим можливим способом сплав з відносно низькою для високоентропійного сплаву (BEC) та середньоентропійного сплаву (CEC) температурою плавлення, який би містив недефіцитні компоненти, здатні розчинятися в алюмінії та мати взаємну розчинність. Концентрація більшості компонентів не могла перевищувати значення 2,5–5 % ат., тому основним засобом підвищення ентропії змішування слугувала кількість елементів, що входили до складу сплаву.

Методи дослідження. Для приготування розплаву було використано лабораторну піч опору. В якості шихтових матеріалів використовували чисті компоненти і концентровані лігатурні добавки, які додавалися почергово і поступово у невеликих кількостях, щоб запобігти утворенню тугоплавких інтерметалідів. Плавлення відбувалось в алундовому тиглі при температурі 1000 °C, що дало можливість розплавитись і засвоїтись всім компонентам.

Отримані результати. Було проведено порівняння структурних та фазових характеристик експериментального сплаву в залежності від швидкості кристалізації. При охолодженні розплаву з піччю зі швидкістю 0,5 °C/c формується неоднорідна структура, представлена переважно трьома фазами – інтерметалідом типу Al_6Me , на основі Al_6Mn , в якій розчинені залізо, нікель, хром та ванадій, інтерметалідом на основі фази типу Al_6Cu_2Ni , яка за стехіометрією могла б бути виражена формулою $(Al,Ni)_2Cu$, та фазою Mg_2Si . Швидка кристалізація $5 \cdot 10^2$ °C/c сприяла певному подібненню структури та збільшенню її однорідності, проте не призвела до помітних змін фазового складу. При цьому, варто відзначити, що в інтерметаліди типу Al_6Me основою стала виступати більш високотемпературна сполука $Al_{23}V_4$. Формування інтерметаліду системи $Al-Ni-Cu$ за даних умов могло б відповідати утворенню сполуки з формулою $Al_2(Ni,Cu)_3$. Фаза Mg_2Si для даного зразку виділилась у складі евтектики (Mg_2Si+Si).

Наукова новизна. Показано підхід до виготовлення середньоентропійних багатокомпонентних сплавів методом плавки в печі опору. Показано вплив швидкості охолодження на фазоутворення в сплаві $Al-Mg-Si-V-Cr-Mn-Fe-Ni-Cu$.

Практична цінність. Розроблено підхід до отримання середньоентропійних сплавів із недефіцитних компонентів та зниженою температурою плавлення, що спрощує їх синтез. Отримані результати можуть бути використані для подальших досліджень високоентропійних та середньоентропійних сплавів.

Ключові слова: $Al-Mg-Si-V-Cr-Mn-Fe-Ni-Cu$, BEC, CEC, високолеговані сплави, нові матеріали, структура, фазоутворення.

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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 manufac-

ture 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.

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 $\alpha > 1$. 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.

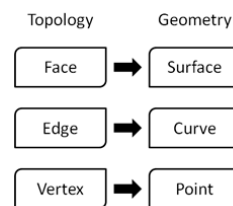


Figure 1. Relationship between topological and geometric elements

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

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]:

$$N_S = N_e - N_f + 1, \quad (3)$$

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).



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).

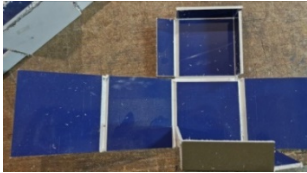


Figure 4. Appearance of the cube flat layout to determine the flow of material

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.

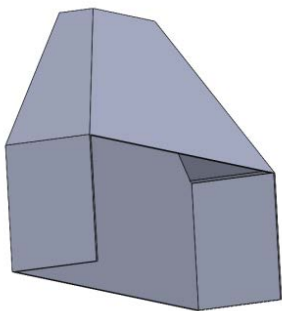


Figure 5. 3D model of the part

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.

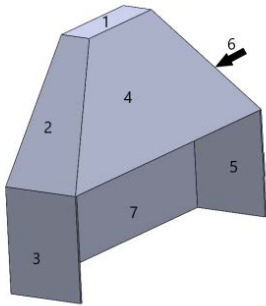


Figure 6. Numbering of part surfaces

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).

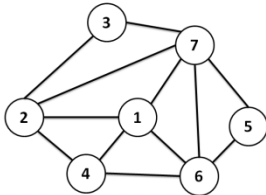


Figure 7. The graph obtained after topological analysis of the part

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).

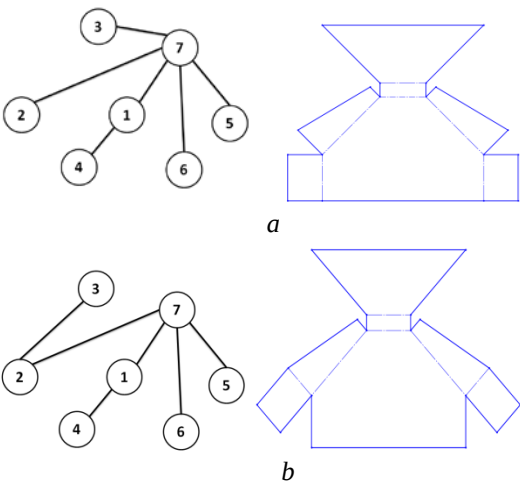


Figure 8. Calculated graphs and corresponding part layouts: a – first graph option and relevant layout, b – second graph option and relevant layout

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):

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

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):

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

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:

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

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. 8a, two groups of parallel bending grooves can be clearly identified. The second development, shown in Fig. 8b, 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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INVESTIGATION OF THE FABRICATION OF BN-REINFORCED PURE ALUMINUM COMPOSITES BY CASTING PROCESSES

Purpose. The main objective of this research was to evaluate the feasibility of producing aluminum matrix composites (AMC) based on pure aluminum reinforced with boron nitride using casting technologies, in particular the stir casting method. This approach was chosen due to its technological simplicity, relatively low cost, and potential scalability for industrial applications.

Research methods. To analyze the distribution and morphology of the reinforcing particles, microstructural metallographic analysis using optical microscopy was applied. The chemical composition of the composites was determined by X-ray fluorescence analysis and spark optical emission spectrometry. These methods provided reliable data on the content and incorporation of boron nitride particles into the aluminum matrix, as well as the influence of additional alloying elements (Ni, Sn, Zr) on the composite structure.

Results. Experimental AMC samples containing 1–3 wt.% BN were produced by stir casting, including variants with fluxes and alloying elements under different melting conditions. The composite structures contained BN particles evenly distributed in the matrix; however, their actual content was only 7–15 % of the amount initially introduced in the charge. It was found that the efficiency of BN incorporation strongly depends on the melt composition (amount of reinforcing particles, presence of fluxes and microalloying elements) and on the melting parameters (superheating temperature, stirring time). The porosity of the obtained composites was also studied: the addition of BN significantly increased porosity, whereas the presence of Sn reduced it due to eutectic formation.

Scientific novelty. New data were obtained on the feasibility of producing AMCs based on pure aluminum with BN reinforcement by stir casting with the use of fluxes and microalloying additives, which improve BN incorporation.

Practical value. The results complement existing knowledge on AMC fabrication and explain the lack of studies using pure aluminum as the matrix. The findings may also be applied to optimize casting technologies for manufacturing aluminum matrix composites.

Key words: aluminum matrix composites, stir casting, aluminum, boron nitride, microstructure.

Introduction

Aluminum matrix composites (AMCs) based on pure aluminum are attracting increasing interest in materials science due to their unique combination of properties: low density, high electrical conductivity, and corrosion resistance, complemented by the strength, wear resistance, and thermal stability of the reinforcing phases. Despite the widespread use of powder metallurgy technologies in AMC production, one of the most economically feasible and technologically simple methods for obtaining such composites is stir casting, which ensures low cost and suitability for mass production [1].

However, the implementation of this method in case of pure aluminum ($Al \geq 99.7\%$) encounters a number of significant challenges, the main one being the insufficient wettability of ceramic, carbon, and other particles by the metallic matrix. The low interfacial energy between the reinforcement particles (e.g., SiC, Al_2O_3 , TiB₂, graphene) and the aluminum melt hinders their uniform distribution within the matrix and leads to aggregation, pore formation, or defective bonding at the phase interface [2, 3]. As a result, the obtained composite may exhibit a non-uniform microstructure, reduced mechanical strength, and lower wear resistance.

The main factors influencing the incorporation and distribution of reinforcing particles include wettability, particle shape and size, rheological properties of the melt, stirring rate, density of the reinforcing material, temperature regime, and others [4–7].

To ensure better wettability of reinforcing particles in the metallic matrix and their uniform distribution in the melt volume, fluxes and modifying additives are widely used. These components alter the surface energy of the system, contributing to the reduction of interfacial tension and minimizing the probability of particle agglomeration. Fluxes play an important role in improving wettability by promoting effective wetting of the particle surface with the melt and removing oxide films that hinder the formation of a strong matrix-particle interface. In the production of aluminum matrix composites (AMCs), chloride-fluoride fluxes have proven their efficiency, as they actively clean the melt surface from aluminum oxides, thereby facilitating the incorporation of reinforcing particles into the melt and ensuring their uniform inclusion in the matrix [8].

The use of hexagonal boron nitride (BN) as the primary reinforcing phase in aluminum-based composites is attracting increasing attention due to its unique combination of structural and functional efficiency [1, 9, 10]. BN has a low density (2200 kg/m³), a layered hexagonal crystal structure similar to graphite, which provides a low coefficient of friction and high thermal stability (~1000 °C). In the context of stir casting, these properties make BN a promising alternative to traditional ceramic fillers (SiC, Al₂O₃), especially for systems operating under intensive friction or thermal loading [11].

Despite these advantages, the use of BN for AMC fabrication by stir casting is associated with several technological challenges, the most critical being the poor wettability of BN surfaces by molten aluminum, which arises from its chemical inertness and energetically stable surface structure.

Existing studies on the use of BN in AMC fabrication by casting technologies have demonstrated significant improvements in the mechanical and tribological properties of the composites. However, aluminum alloys such as AA3003 [12] and AA7075 [13] have been used as matrix materials. Investigations of similar AMCs based on pure aluminum may allow a better evaluation of the influence of individual melting conditions on the reinforcement efficiency of boron nitride.

Purpose

The aim of this study is to produce aluminum matrix composites based on pure aluminum with boron nitride by melt stirring followed by casting, and to evaluate the incorporation of reinforcing particles into the matrix as well as the factors affecting this process.

Materials and methods

The material of study was aluminum matrix composites based on high-purity aluminum grade A95

(≥ 99.7 % Al, analogous to AA1350). Hexagonal boron nitride with an average particle size of ~5 μm was used as the reinforcing phase. The BN content in the charge ranged from 1 to 3 wt.% under different conditions of AMC fabrication (Table 1).

Melting was carried out in a laboratory resistance furnace using an alumina crucible. To improve particle incorporation, the melt was mechanically stirred with a titanium impeller (Fig. 1a) at a rate of 10 s⁻¹. Stirring time prior to casting varied depending on the experiment. Reinforcing particles were preheated to 200 °C. The casting temperature was 750–850 °C. The melt was poured into thick-walled steel molds to produce cylindrical samples with diameters of 10 and 15 mm. Cooling occurred under normal air conditions directly in the mold (Fig. 1b).

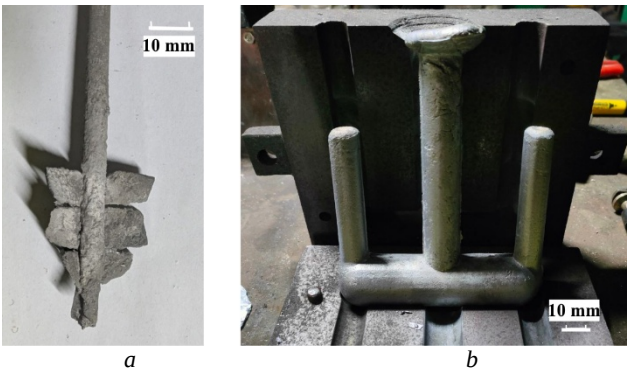


Figure 1. Features of the technology for producing AMCs: *a* – titanium stirrer; *b* – mold with an experimental aluminum matrix composite sample

Some experimental melts included fluoride fluxes [8], as indicated in Table 1. The flux consisted of a mixture of KCl, NaCl, and NaF in an amount equivalent to the mass of BN particles.

Table 1 – Chemical composition of experimental samples

AMC	Element content in the charge, wt.%				
	Al	BN	Sn	Ni	Zr
Al-BN	97,7	2,3 ¹	-	-	-
	98,2	1,8	-	-	-
	97,7	2,3	-	-	-
	97,0	3,0	-	-	-
Al-(Sn+BN)	99,0	0,5	0,5	-	-
	98,0	1,0	1,0	-	-
Al-(Ni+BN)	97,2	1,8	-	1,0	-
	96,7	2,3	-	1,0	-
	96,0	3,0	-	1,0	-
Al-(Ni+Zr+BN)	97,5	1,5	-	0,5	0,5
	97,0	2,0	-	0,5	0,5

Note. 1. In this AMC no flux was used.

Additional melts were conducted with the addition of tin (Sn) to improve BN incorporation (Table 1). According to the Al-Sn phase diagram, under normal conditions, Sn may exist in solid solution in small amounts [14]. Sn can act as a surface energy modifier, thereby enhancing BN

wettability by molten aluminum [15]. Tin also improves plasticity and wear resistance of the composite [16], and in synergy with BN, this may yield improved performance. The drawback of Sn is reduced thermal stability [14, 17]. At the microstructural level, Sn may localize at grain boundaries or BN-matrix interfaces, forming interlayers that affect grain growth, hinder BN coalescence, and reduce agglomeration [18].

Nickel additions exert a fundamentally different effect. Ni exhibits high solubility in liquid Al and strong reactivity, forming intermetallic phases, improving interfacial adhesion, generating eutectics, and enhancing thermal stability. At the casting temperature (750–800 °C), Ni actively interacts with Al, forming Al_3Ni , which may distribute at grain boundaries or around BN particles [19, 20]. The formation of reaction interlayers such as Ni-BN or Al-Ni-BN at the matrix-particle interface can further improve adhesion. Corresponding data on the chemical composition of Al-Ni-BN composites are given in Table 1.

The addition of zirconium to Al-Ni-BN systems further modifies the microstructure. During solidification, stable Al_3Zr intermetallics form, refining grains and strengthening the matrix. Due to Zr's high affinity for nitrogen and boron, interfacial reactions may produce ZrN or ZrB_2 , enhancing BN-matrix bonding [21]. The composition of Al-(Ni+Zr+BN) composites is shown in Table 1.

Metallographic specimens were prepared from the samples and etched with Keller's reagent (aqueous solution of HNO_3 , HCl , and HF) [22] for microstructural analysis under an optical microscope. Chemical composition was analyzed using an Expert 3L X-ray fluorescence spectrometer. The BN content was determined using a SPECTRO-MAXx spark optical emission spectrometer.

Composite density was both theoretically calculated and experimentally measured to evaluate porosity. Experimental density was determined by mass measurement in air and water according to ASTM C135-2003 [23]. Theoretical density was calculated by the rule of mixtures (Eq. 1).

$$\rho_{th} = \rho_{Al}\varphi_{Al} + \rho_x\varphi_x, \quad (1)$$

where ρ_{th} , ρ_{Al} , ρ_x are the theoretical densities of the AMC, aluminum, and reinforcing particles, respectively, kg/m^3 ;

φ_{Al} , φ_x are the mass fractions of aluminum and reinforcing particles, respectively, %.

For the investigated samples, porosity was determined according to equation (2):

$$\%porosity = \frac{\rho_{th} - \rho_{exp}}{\rho_{th}}, \quad (2)$$

where ρ_{exp} is the experimental density of the AMC, kg/m^3 .

Results

Metallographic analysis revealed that the macrostructures contained only minor inclusions of BN particles, which became visible only after prolonged etching. In samples with 2.3 wt.% BN produced without flux, optical microscopy did not reveal BN inclusions.

Figure 2 presents a comparison of the microstructures of composites with 2.3 wt.% BN produced without and with flux. Chemical analysis likewise did not detect reinforcing BN particles in the sample cast without flux. In the other sample, the BN content was only 0.15 wt.%. This indicates poor wettability of boron nitride by aluminum, causing BN to agglomerate and float on the melt surface.

For AMC samples with BN and flux, a series of melting runs was conducted to establish the dependence of particle incorporation on the duration of mechanical stirring and on the melt temperature prior to pouring (Fig. 3). The obtained data indicate that the stirring duration may range from 30 to 90 s, as this parameter had only a minor effect on the BN content measured by chemical analysis. All melts were mechanically stirred not only before pouring but also during melting; otherwise, BN would float and be absent from the composite. The effect of melt superheating can be assessed more precisely: the optimal pouring temperature is 800–820 °C, above which the BN content changes negligibly. For subsequent runs, the following parameters were used: mechanical stirring for 60 s at a pouring temperature of ~ 800 °C.

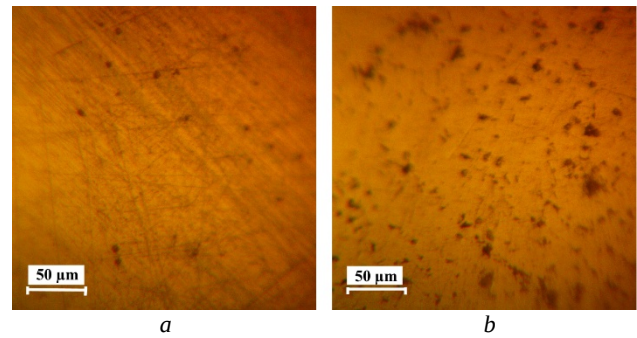


Figure 2. Microstructure of Al-2.3 wt.% BN samples: *a* – without flux; *b* – with flux

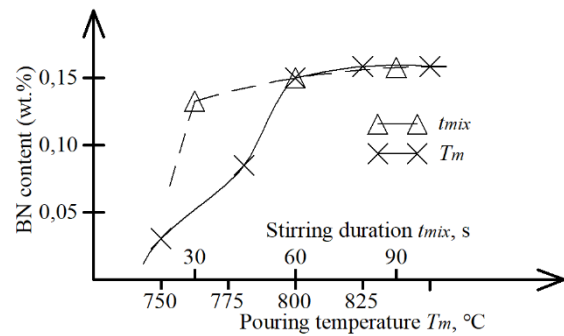


Figure 3. Dependence of BN content in AMCs on melting parameters at 2.3 wt.% BN in the charge

To assess the effect of the amount of BN reinforcing particles, several experimental melts were carried out with a BN mass fraction in the charge from 1.5 to 4 wt.%. The results of chemical analysis (Fig. 4a) indicate inefficient reinforcement with BN above 2.5 wt.%, which is explained by the poor wettability of BN by pure aluminum and more pronounced reverse sedimentation.

Tin additions to BN-containing composites improve the wettability of the reinforcing particles and increase their retained amount in the samples (Fig. 4b). However, the incorporated amount is only about 10 % of the BN mass charged. Moreover, increasing the joint content of Sn and BN to 1 wt.% worsens particle incorporation. The microstructure of the Sn-containing composite exhibits eutectic regions and dark BN inclusions within a fine-grained aluminum matrix (Fig. 5a).

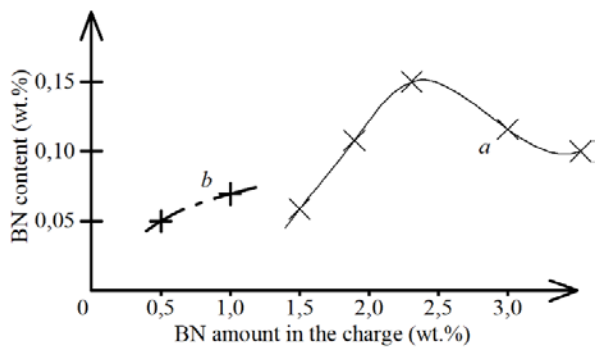


Figure 4. Dependence of BN content in AMCs on its amount in the charge for composites: *a* – Al-BN; *b* – Al-(*x*%Sn+*x*%BN)

As expected, samples containing nickel showed better BN incorporation. The microstructure of the alloy with 2.3 wt.% BN and 1 wt.% Ni indicates the presence of intermetallic phases (Fig. 5b). According to chemical analysis, the sample contains reinforcing BN particles up to 0.3 wt.%.

Replacing half of the nickel in the charge with zirconium led to an even larger amount of intermetallic phases. The microstructures (Figs. 5c, 5d) show dark inclusions up to 20 μm that may be clusters of Al_3Ni , Al_3Zr intermetallics and boron nitride.

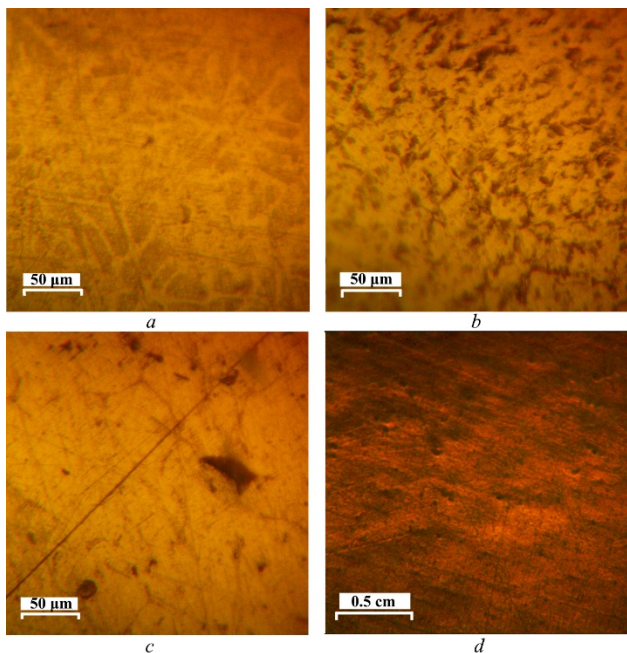


Figure 5. Microstructures of AMC samples (wt.%):
a – Al-(0,5Sn+0,5BN); *b* – Al-(1,0Ni+2,3BN);
c, d – Al-(0,5Ni+0,5Zr+1,5BN)

Composites with nickel (including those with zirconium) exhibit better BN incorporation (Fig. 6). At the same time, the dependence of BN incorporation on its amount in the charge is similar to that in AMCs without Ni and Zr (Fig. 4a).

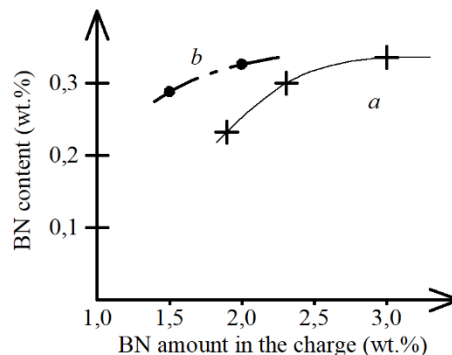


Figure 6. Dependence of BN content in AMCs on its amount in the charge for composites: *a* – Al-(1%Ni+BN); *b* – Al-(0,5%Ni+0,5%Zr+BN)

A summary of BN incorporation in the obtained composites is presented in Fig. 7. After measuring the sample masses and performing the corresponding calculations, the porosity of each composite was determined. The porosity of the aluminum matrix composites is shown graphically in Fig. 7.

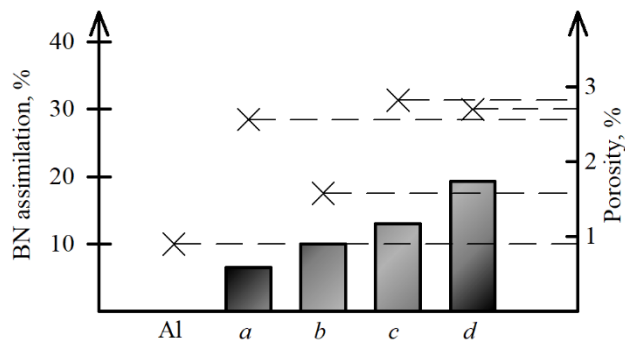


Figure 7. Assimilation of BN and porosity in Al-matrix composites: *a* – Al-2,3%BN; *b* – Al-(0,5%Sn+0,5%BN); *c* – Al-(1%Ni+2,3%BN); *d* – Al-(0,5%Ni+0,5%Zr+1,5%BN)

The porosity values of the AMCs were significantly higher than for pure aluminum, due to poor wettability and gas removal during melting. The formation of intermetallics in Ni- and Zr-containing composites hinders gas evolution from the melt; therefore, effective melt degassing should be employed for such AMCs. The presence of Sn reduces the concentration of gas voids and improves particle-matrix bonding, which favorably affects the porosity of these composites.

Conclusions

In this study, the feasibility of producing aluminum matrix composites (AMCs) based on pure aluminum with the addition of boron nitride by melt stirring and the use of agents to improve its incorporation was investigated. Tin,

nickel, and zirconium were also introduced into the composites. Based on the obtained results, the following conclusions were drawn:

- The wettability of BN by aluminum in the absence of magnesium or other metals capable of significantly reducing the melt surface tension is very poor. Sn improves wettability due to eutectic formation in the melt, while Ni and Zr enhance it through the formation of intermetallics and the strong affinity of Ni for BN. At best, during stir casting, about 19% of the charged BN was incorporated.

- For stir casting, the addition of fluxes or modifiers is essential, as is melt stirring for at least 60 s before pouring and superheating the melt to 800–830 °C.

- The presence of BN leads to a sharp increase in composite porosity. The lowest porosity was observed in samples containing Sn, whereas the presence of Ni and Zr intermetallics further increased porosity.

- Increasing the BN content in the charge to 3 wt.% or higher did not improve, and in some cases even reduced, the BN content in the composite. This was caused by severe particle agglomeration and flotation to the melt surface during melting. The optimal BN content was 1–2.5 wt.% depending on the alloying elements present. However, with the addition of magnesium or other modifiers, larger amounts of BN can be effectively incorporated due to the significantly improved wettability of BN by aluminum.

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ДОСЛІДЖЕННЯ ОДЕРЖАННЯ КОМПОЗИТІВ З НІТРИДОМ БОРУ НА ОСНОВІ ЧИСТОГО АЛЮМІНІЮ ЛИВАРНИМИ ТЕХНОЛОГІЯМИ

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Мета роботи. Основною метою дослідження було оцінити можливість одержання алюмоматричних композитів (АМК) на основі чистого алюмінію з армуванням нітридом бору за допомогою ливарних технологій, зокрема методу лиття з перемішуванням. Такий підхід обрано завдяки його технологічній простоті, відносно низькій вартості та потенційній масштабованості до промислових умов.

Методи дослідження. Для аналізу розподілу та морфології армуючих частинок застосовано мікроструктурний металографічний аналіз за допомогою оптичної мікроскопії. Хімічний склад композитів визначали методами рентгенофлуоресцентного аналізу та іскрової оптично-емісійної спектроскопії. Це дозволило отримати достовірні дані щодо вмісту та засвоєння частинок нітриду бору в алюмінієвій матриці, а також оцінити вплив додаткових легуючих елементів (Ni, Sn, Zr) на структуру композиту.

Отримані результати. Експериментальні зразки АМК з вмістом 1–3 % (мас.) BN були отримані методом лиття з перемішуванням, у тому числі із застосуванням флюсів і легуючих елементів за різних умов плавки. У структурах композитів виявлено частинки BN, рівномірно розподілені в матриці, проте їх фактичний вміст становив лише 7–15% від кількості, внесеної у шихту. Встановлено, що ефективність засвоєння BN суттєво залежить від складу розплаву (вмісту армуючих частинок, наявності флюсів і мікролегуючих елементів), а також від технологічних параметрів плавки (температура перегріву, тривалість перемішування). Досліджено пористість отриманих композитів: введення BN значно її збільшує, тоді як наявність Sn знижує пористість завдяки утворенню евтектики.

Наукова новизна. Одержано нові дані щодо можливості виплавки алюмоматричних композитів на основі чистого алюмінію з нітридом бору технологією перемішування розплаву з використанням флюсу та мікролегуючих добавок, які підвищують засвоєння нітриду бору.

Практична цінність. Результати роботи доповнюють наявні відомості про виплавку алюмоматричних

композитів та пояснюють відсутність досліджень саме з чистим алюмінієм як матрицею. Також отримані дані можуть бути використані для оптимізації ливарних технологій виготовлення таких композитів.

Ключові слова: алюмоматричні композити, лиття з перемішуванням, алюміній, нітрид бору, структура.

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RESEARCH ON THE INFLUENCE OF BALL TREATMENT IN THE MAGNETIC FIELD OF THE BLADES WITH OPERATIONAL DAMAGES ON FATIGUE STRENGTH

Purpose. Research the effect of ball treatment in a magnetic field on the blade tips, which have varying degrees of blade tip damage in operation, on their endurance limit.

Research methods. Mechanical method for studying residual stresses, experimental method for determining blade endurance, stepwise regression methods for building regression models.

Results. On engine blades that operated under different conditions and had different service life, the greatest wear was observed in the peripheral part of the blade (cross sections A7-A7 and A8-A8). Processing blades from various engines with operational damage with balls in a magnetic field significantly increases the resistance of the blades to fatigue, the endurance limit of the blades increases from 14 to 22 %. Regression models of natural oscillation frequencies and blade life were constructed. The obtained regression models showed that the greatest influence on the natural oscillation frequency of blades is not only the operating conditions and blade geometry, but also the amount of life, the hardness of the initial blade and the ultimate strength of the blades. Operation of helicopter engines in conditions of increased dustiness and abrasive wear requires the application of protective coatings with high erosion resistance to the upper section of the blade back. Additional application of surface hardening methods provides increased reliability, fatigue strength and extended service life of the gas turbine engine.

Scientific novelty. A method has been proposed that allows for effective processing of blade back with damage that occurred during operation, which ensures an increase in their durability and reliability. As a result, endurance indicators increase and the service life of parts is extended.

Practical value . The obtained experimental data provide grounds to recommend the method of treating blade tips with steel balls in a magnetic field as a technological operation for repairing compressor blades that have undergone operational damage such as potholes on the leading edges.

Key words: blade, erosion, damage, balls, magnetic field, endurance, performance, regression model.

Introduction

The extension of the service life of aircraft gas turbine engines is largely determined by the durability and operational reliability of the compressor and fan blades. A significant factor in this process is the reduction of their vulnerability to damage that occurs when foreign objects enter the flow part. One of the most effective ways to increase the strength characteristics of the blade profile is the technology of surface plastic deformation (SPD). This method is a complex of mechanical effects on the surface of the part, which result in a decrease in roughness

parameters, the formation of a layer with useful residual compressive stresses, leveling the metal structure and creating the necessary microrelief. The cumulative effect of these changes is a significant increase in the fatigue strength of the material and an increase in the service life of the part.

During the operation of aircraft gas turbine engines, one of the most vulnerable elements remains thin-walled parts, especially areas with small radii of curvature, which include thin edges of blades. Under the influence of aerodynamic loads, vibrations and ingress of foreign particles into the flow, microcracks, foci of plastic

deformation and local overheating zones are formed on the surface and in the subsurface layers of the metal. These factors, acting together, initiate subsurface fractures, which cause a noticeable decrease in the endurance limit of the part.

To prevent such defects in the practice of repair and modernization, surface plastic deformation (SPD) is widely used. However, for thin-walled elements with high sensitivity to overloads, it is necessary to use gentle processing modes with precise adjustment of parameters in each functional zone of the part. In some cases, it is advisable to combine different hardening technologies, which allows achieving the specified characteristics of roughness, residual stresses and material structure [1]. Special attention is paid to strengthening blades made of titanium alloys. The geometry of the blade back, which includes complex spatial curvature and the presence of thin edges, requires not only precise positioning of the cutting tool, but also an understanding of the distribution of mechanical stresses on the surface. Any excess of the permissible pressure during the PPD can lead to local deformation or the appearance of surface defects, which reduce the resource details.

A promising direction is the treatment of compressor blades with operational damage with steel balls in a magnetic field. This method is based on the phenomenon of magnetic retention and controlled movement of the strengthening element, which allows evenly distributing the dynamic impact of the complex surface of the blade. When steel balls come into contact with metal, local plastic crushing of micro-roughness occurs, the micro-relief is leveled, the surface layers are compacted and compressive residual stresses are formed. These stresses prevent the opening of microcracks under cyclic loads, which ultimately increases the fatigue life and improves the operational reliability of the blades. Thus, the use of the SPD method using steel balls in a magnetic field not only ensures the restoration of the operational characteristics of damaged elements, but also allows creating a surface structure that is more resistant to the effects of high-frequency vibrations, thermal fluctuations and shock loads. This makes the technology especially relevant for extending the service life of aircraft gas turbine engine blades.

Analysis of research and publications

When operating military helicopters and transport aircraft in conditions of soil and sandy runways, the intense air flow formed during takeoff and landing captures a significant amount of solid mineral particles. These particles, having high hardness and mass, when colliding with compressor blades and other elements of the flow part of the engine, cause local microplastic deformations, microcracks and tearing of material from the surface layer. The gradual accumulation of such damage changes the aerodynamic profile of the blades, reduces the efficiency of the compressor and can lead to a violation of the strength of the integrity of the structure, which as a result negatively affects the reliability of the

engine [2]. The work [3] presents the results of an experimental study of erosive wear of compressor blades in a gas-solid environment that simulates operation in an aero-turbine engine. To perform the experiments, a stand was developed and manufactured that allowed testing of the titanium alloy Ti-6Al-4V at various speeds of abrasive particles. The particle speeds were determined by the image velocimetry method, which provided high accuracy of measurements when varying the supplied air pressure. Analysis of worn samples showed that erosion damage is distributed extremely unevenly. The main destruction zones were on the pressure surface of the rotor blade and on the suction and pressure sides of the stator blades. The maximum wear intensity was observed in two characteristic areas: near the leading edge at 80 of the span and near the leading and trailing edges at 95 of the span. Such localization is explained by the features of the flow around the blade profile: at 80 of the span, the flow has the highest particle velocity relative to the blade surface, which increases the impact energy, and in the region of 95 % of the span, turbulent zones and changed angles of attack of particles appear, which cause their direct impact. A schematic distribution of the zones of maximum wear can be conditionally presented as two belts of increased erosion activity: the first is located along the leading edge in the middle part of the span; the second covers the leading and trailing edges closer to the periphery. Such a distribution must be taken into account when designing and choosing methods for protecting blades from erosion [3].

Operation of aircraft gas turbine engines in conditions of high dust content and the presence of abrasive particles in the atmosphere poses a serious threat to the durability of the compressor blades. Studies show that the intensity of erosive wear directly depends on the concentration of solid inclusions in the air flow: the more sand or dust, the faster microplastic deformations, the formation of notches and local destruction of the material occur. In this case, the blade profile gradually changes, its aerodynamic characteristics deteriorate and the efficiency of the compressor decreases. As a result, the real life between overhauls of the engine operating in high dust conditions is significantly less than the standard one established by the designer, and is largely determined by the degree of erosive damage. Analysis of statistical data on the operation of gas turbine units confirms the critical importance of this phenomenon. About a third of cases of premature engine retirement (30–35 %) are associated with erosive destruction of compressor blades. For comparison, damage caused by external objects from the runway is recorded in 25–30 % of cases. Thus, erosive wear is one of the leading causes of reduced engine reliability and service life. The mechanisms of erosive damage include particle impact, surface shear, and local crushing of the surface layer of metal. These processes cause the formation of microcracks and the loss of part of the material, which is especially critical for thin-walled blades with high requirements for the accuracy of the aerodynamic profile. Understanding the physical processes underlying erosion

allows not only to predict a reduction in service life, but also to develop protective measures: use more resistant alloys, optimize blade design, introduce coatings, and adjust engine operating modes in conditions of increased dustiness.

The working blades of the compressor of aircraft engines are subject to erosive and mechanical effects of solid particles entering with the air flow, especially in conditions of increased dustiness of the atmosphere [4]. The size, shape and concentration of abrasive inclusions determine the intensity of destructive processes on the blade surface. The main dangers for further operation are associated with fretting corrosion in the tail part of the blade and erosive wear of the blade. These defects cause local microplastic deformations, the formation of micro-notches and gradual thinning of the material, which reduces the reliability of the engine and increases the risk of surge. The physical mechanisms of erosive destruction include impact and shear effects of particles on the surface layer of the metal, which leads to local stress concentration and the formation of microcracks. At the same time, fretting corrosion initiates chemical destruction of the material in places of friction, enhancing the erosive effect. Together, these processes change the aerodynamic profile of the blade, impair its load-bearing capacity, and affect the distribution of mechanical loads along the length of the blade. Studies show that wear is distributed along the height of the blade nonlinearly: the highest intensity of damage is recorded at the base of the blade and on the leading and trailing edges, while the peripheral ends remain less susceptible to erosion. Potholes in critical zones have a much stronger effect on engine operation than similar defects in external areas, as they disrupt the balance and aerodynamics of the rotor, increasing local stresses. To maintain operational safety, an industry standard [5] is used, which regulates the permissible dimensions, shape and location of mechanical damage. The standard defines the zones in which defects are unacceptable, as well as the types of damage that require repair or replacement of parts. This allows you to systematize maintenance, prevent emergencies and extend the engine life.

A particular problem is caused by damage from external objects, which lead to accelerated wear of the blades, the need to overhaul and balance the rotor, as well as replace a large number of elements. A comprehensive approach to the study of erosion and mechanical processes, which includes the analysis of load distribution, microstructural changes and chemical action, allows developing methods for protecting the blades, optimizing alloys and structures, and adjusting operating modes to increase the service life and improve the reliability of aircraft gas turbine engines.

The rotor blades of the compressor of the TV3-117 helicopter engine are key loaded elements, on as well as simultaneously acting static, dynamic and cyclic loads. To ensure the necessary strength, heat resistance and resistance to thermomechanical influences, they are made of high-strength titanium alloys capable of withstanding

intensive working loads and temperatures, not inferior to other light structural materials. During operation, helicopter engines often encounter increased dustiness, characteristic of ground airfields, desert areas and unequipped sites. In such conditions, the working blades of the compressor are subjected to the abrasive effect of solid particles of soil and sand. When in contact with the surface of the blades, the particles create microdamage: scratches, risks and potholes. The nature and intensity of these damages depend on the size and mineralogical composition of the particles, their angle of attack and collision speed. Microscopic impacts of particles cause local plastic deformations and accumulation of microcracks, which gradually reduces the strength and aerodynamic efficiency of the blades [6].

The peripheral zones of the blade back are particularly vulnerable, especially at the leading and trailing edges, where the concentration of shock loads is maximal. Analysis of operational data has shown that the blades of the first stage of the compressor suffer the greatest amount of damage. The depth of potholes in the range of 0,3-0,5 mm occurs on the first stage approximately four times more often than on the following stages, which is associated with the high relative velocity of particles in the zone of first contact of the flow with the blade, as well as with the geometric features of the first stage profile, which enhance local stresses on the material [7]. Thus, the first stage of the compressor is critically vulnerable to abrasive wear, which requires special attention when developing protective coatings, selecting materials and planning preventive repairs. Understanding the physics of the interaction of particles with the blade surface allows us to predict the nature of damage and increase the durability of the power plant in operating conditions on dusty and sandy airfields.

Ensuring the durability and reliability of compressor blades is impossible without effective methods of restoration after operational damage. One of the promising technological solutions is surface plastic deformation with steel balls in a magnetic field, which modifies the structural state of the blade and improves its mechanical properties.

Purpose of work

This study is aimed at analyzing the possibilities of using magnetic field ball processing for the repair and restoration of compressor blades after operational damage.

The work investigates the geometry and natural frequencies of engine blades operated under different conditions, with different service life and different degrees of blade damage. Fatigue tests were conducted on blades with damage in the state of receipt from operation and blades treated with balls in a magnetic field. A comparative analysis of the stress state and fatigue strength of blades after repair and treated with balls in a magnetic field was conducted. Regression models were also constructed that describe the dependence of the natural oscillation frequencies and the operating life of

blades from engines that were in operation in different countries and, accordingly, the physical characteristics of the operational processes differ, which serves as the basis for the further development of methods for repairing and restoring compressor blades.

Research material and methodology

The object of research was the first-stage compressor blades of the TV3-117 engine, made of titanium alloys VT8 and VT8M, which have operational damage to the blade. Residual stresses were determined by mechanical method on PION-2 device - by measuring the deflection of a cantilevered specimen cut from the blade by the electroerosion method with sequential removal of metal layers by electrolytic polishing. The study of the blade profile geometry was carried out using the POMKL device. Measurements of the natural frequencies of the blades were carried out on the MIKAT-KM device. Measurements of the blade geometry were carried out with a caliper with a digital display with an accuracy of 0,01 mm. Determination of the blade endurance limits was carried out by an accelerated method on the basis of $N=2 \cdot 10^7$ cycles with subsequent recalculation using the coefficient $\alpha=0,8$ on the basis of $N=10^8$ cycles [8]. Stepwise regression methods were used to build regression models.

Research results

Operational damage to the blade not only forms stress concentrators, but also changes the original geometry of the blades [9–12]. The study was conducted on engine blades that were operated in different conditions, have different operating hours and, accordingly, different degrees of damage to the blade tip: engine D2 – 990 hours – (VT8, Yemen), and three engines that have damage to the tip during operation (potholes with a depth of 0,5 mm and more), which exceed the permissible standards, as a result of which the blades cannot be restored using repair technology: engine D18 – 975 hours (VT8M, Spain), engine D14 – 2048 hours - (VT8M, Algeria), engine D3 – 1652 hours (VT8M, India). The nature of damage to the blade tip is shown in Fig. 1.

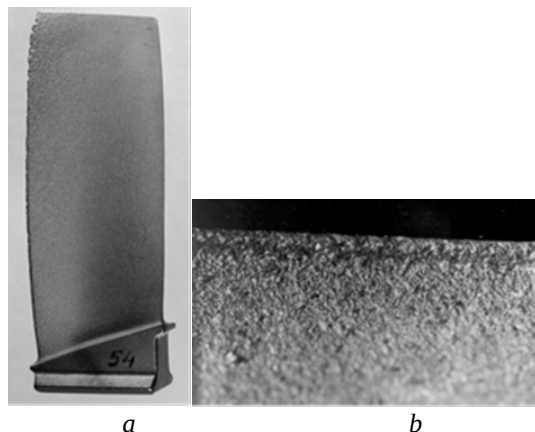


Figure 1. First-stage blade of the TV3-117 turbine with erosion damage to the blade (a) and leading edge (b)

The study of the geometry of the blades of the engines D3, D14, D18 consisted in measuring the chord in sections A2-A2 and A8-A8, i.e. in sections that clearly characterize the degree of blade wear. The measurement results are presented in Table 1. The results of measuring the natural oscillation frequencies of the blades of the engines D3, D14 and D18 correspond to the technical requirements of the drawing.

For further research, 12 blades were selected from each engine. Each batch of blades was processed according to the optimal option with steel balls in a magnetic field. The optimal scheme and processing mode were determined in previous studies [13]: the blade - $d_k = 1,6$ mm, $\tau = 30$ min and then additionally the zone near the inlet edge - $d_k = 0,35$ mm, $\tau = 30$ min.

Table 1 – Results of engine blade geometry measurements (chord, mm)

No. i/o	D18		D3		D14	
	A2- A2	A8- A8	A2- A2	A8- A8	A2- A2	A8- A8
1	26.67	28.09	26.70	28.20	26.72	27.90
2	26.72	28.12	26.55	28.22	26.85	28.02
3	27.03	27.93	26.73	28.10	26.75	27.89
4	26.56	28.03	26.75	28.09	26.7	27.92
5	27.05	28.00	26.59	28.12	26.83	28.01
6	26.82	27.92	26.56	28.22	26.87	27.91
7	27.05	28.13	26.60	28.13	26.90	27.99
8	26.55	28.10	26.53	28.00	26.73	27.94
9	26.53	26.11	26.83	28.20	26.77	27.95
10	26.98	28.03	26.30	28.28	26.79	27.87
11	27.10	27.80	26.70	28.39	26.69	27.92
12	26.53	27.85	26.72	28.40	26.58	27.95
13	26.77	28.10	26.74	28.20	26.72	28.01
14	26.80	28.00	27.05	28.12	26.67	28.00
15	26.74	27.92	27.70	28.00	26.64	27.87
16	26.81	27.80	26.36	28.01	26.69	27.80
17	26.90	28.89	26.39	28.05	26.72	28.05
18	27.59	28.23	26.50	28.07	26.77	27.79
19	26.56	27.98	26.59	28.15	26.59	27.83
20	26.92	28.15	26.42	28.22	26.70	27.93
21	26.52	28.15	26.50	28.13	26.65	27.89
22	26.83	28.10	26.73	28.21	26.80	28.03
23	26.75	28.12	26.50	28.05	26.73	27.85
24	26.66	28.19	26.65	28.17	26.69	27.89
25	26.81	28.21	26.40	28.15	26.73	27.95
26	26.52	28.03	26.72	28.03	26.65	27.83
27	26.73	28.09	26.49	28.12	26.71	27.83
28	26.90	27.90	26.60	28.10	26.77	28.00
29	26.77	27.95	26.43	28.00	26.67	27.98
30	26.53	28.05	26.70	28.03	26.80	27.89
31	26.91	28.07	26.68	28.07	26.64	28.00
32	26.68	28.09	26.81	28.17	26.69	27.97
33	26.72	28.10	26.90	28.20	26.72	27.95
34	26.83	28.08	26.73	28.17	26.67	27.92
35	26.74	28.13	26.51	28.16	26.70	28.00
36	26.55	28.10	26.45	28.11	26.72	28.01

Analysis of the data presented in Table 1 shows that the wear of the blades in the A8-A8 section is very significant compared to the theoretical profile of the blades, i.e. serial ones – the chord size l_{A8-A8} is 28,5 mm.

In the A2-A2 section, the wear is smaller (the theoretical chord size l_{A2-A2} is 26,5 mm). Thus, we can say: on the blades of engines that operated in different conditions and have different operating times, the greatest wear is observed in the peripheral part of the blade.

Fatigue tests were conducted on blades with damage in the condition of receipt from operation and blades treated with balls in a magnetic field. Endurance limit of the original blades (in operation): D3 - 448 MPa; D14 - 424 MPa; D18 - 400 MPa. The results of fatigue tests of blades treated with balls in a magnetic field under the optimal regime are presented in Table 2–4.

Table 2 – Results of fatigue tests of blades strengthened according to the optimal option (D3 engine)

No. i/o	Load level σ , MPa	Number of cycles, $N \times 10^6$	Test results	Note
1	670	20	not destr.	-
2	700	20	not destr.	-
3	730	11.87	destroyed	$l = 26$ mm, en. edge
4	700	18.6	destroyed	$l = 34$ mm, en. edge
5	700	10.99	destroyed	$l = 30$ mm, en. edge
6	670	1.46	destroyed	$l = 42$ mm, en. edge
7	640	20.0	not destr.	-
8	640	20.0	not destr.	-
9	640	20.0	not destr.	-
10	640	20.0	not destr.	-
11	640	20.0	not destr.	-
12	640	20.0	not destr.	-

According to the methodology, the endurance limit based on 10^8 cycles will be $640 \times 0,8 = 512$ MPa.

Table 3 – Results of fatigue tests of blades strengthened according to the optimal option (D18 type)

No. i/o	Load level σ , MPa	Keelnumber of cycles, $N \times 10^6$	Test results	Note
1	700	1.26	destroyed	$l = 25$ mm, en. edge
2	670	20.0	not destr.	-
3	670	6.73	destroyed	$l = 22$ mm, en. edge
4	640	20.0	not destr.	-
5	640	4.99	destroyed	$l = 22$ mm, en. edge
6	610	20.0	not destr.	-
7	610	20.0	not destr.	-
8	610	20.0	not destr.	-
9	610	20.0	not destr.	-
10	610	20.0	not destr.	-
11	610	20.0	not destr.	-

According to the methodology, the endurance limit based on 10^8 cycles will be $610 \times 0,8 = 488$ MPa.

Table 4 – Results of fatigue tests of blades strengthened according to the optimal option (D14 type)

No. i/o	Load level σ , MPa	Keelnumber of cycles, $N \times 10^6$	Test results	Note
1	700	20.0	not destr.	-
2	730	14.98	destroyed	$l = 30$ mm, en. edge
3	700	20.0	not destr.	-
4	700	20.0	not destr.	-
5	700	15.26	destroyed	$l = 26$ mm, en. edge
6	670	0.37	destroyed	$l = 24$ mm, en. edge
7	640	20.0	not destr.	-
8	640	20.0	not destr.	-
9	640	20.0	not destr.	-
10	640	20.0	not destr.	-
11	640	20.0	not destr.	-
12	640	20.0	not destr.	-

According to the methodology, the endurance limit based on 10^8 cycles will be $640 \times 0,8 = 512$ MPa.

The results of fatigue tests showed that the blade endurance limit increased from 14 to 22 %. That is, the treatment of blades from various engines with operational damage with balls in a magnetic field significantly increases the blades' fatigue resistance.

For further research, blades from the D2 engine were selected for processing using the repair technology. The repair technology involves: cleaning and polishing of damage on the surfaces of the blade profile from the back and trough sides; polishing of the inlet and outlet edges of the blade profile; vibropolishing; checking the natural oscillation frequencies; luminescent control. Blades with damage on the inlet and outlet edges, the cleaning of which will lead to a reduction in the chord size to the size $l_{\min A2-A2} = 25,64$ mm and $l_{\min A8-A8} = 27,76$ mm, are allowed for repair. The natural oscillation frequencies of the blades before and after repair were measured. The results of measuring the natural frequencies of the blades are in the range of 590-650 Hz, i.e., they meet the technical requirements of the drawing.

Also, residual stress measurements were carried out on 3 blades, both original and after repair. The residual stress plots, constructed using the average values, are presented in Fig. 2

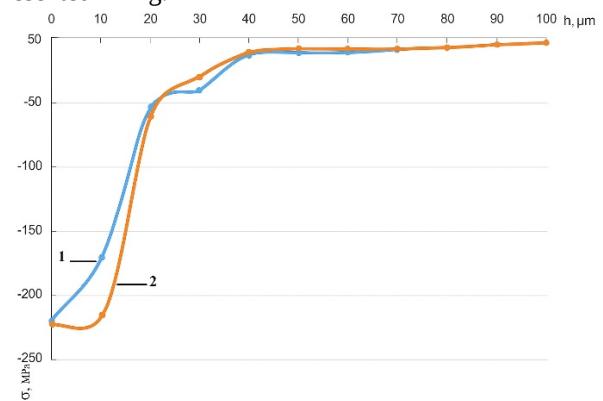


Figure 2. Residual stress distribution diagrams of the original blades (1) and after repair (2)

The figure shows that the repair technology does not lead to a change in the stress state. For comparison, a study of the stress state of the blade feather (engine D14) after treatment with balls in a magnetic field was conducted (Fig. 3).

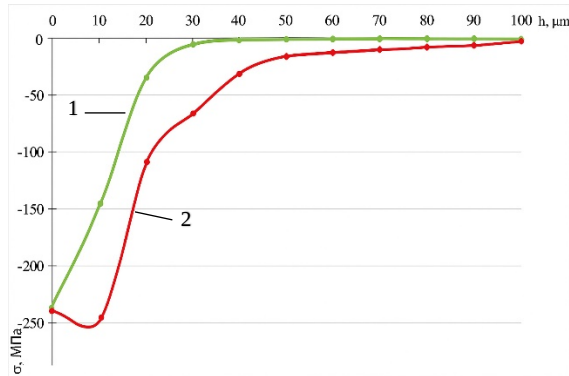


Figure 3. Residual stress distribution diagrams of the original blades (1) and those treated with balls in a magnetic field (2)

The figure shows that after ball processing we have a more favorable stress distribution diagram – on the surface, compressive stress up to 240 MPa and a greater depth of occurrence than in the original blades, which should lead to increased fatigue resistance.

The geometry of the blade profile in sections A2-A2, A8-A8 and the thicknesses of the leading and trailing edges of the output blades were also measured after repair (Table 5, 6).

Table 5 – Results of measurement of the geometry of the output blades (engine D2)

No. i/o	Chord original size , mm		C1 , original size, mm		C2 , original size, mm	
	A2- A2	A8- A8	A2- A2	A8- A8	A2- A2	A8- A8
1	26.44	27.85	1.3	0.5	0.60	0.21
2	26.65	27.72	1.31	0.5	0.58	0.22
3	26.66	28.03	1.31	0.57	0.62	0.23
4	26.97	27.88	1.31	0.58	0.62	0.21
5	26.58	27.90	1.12	0.47	0.60	0.20
6	26.83	27.94	1.27	0.55	0.61	0.23
7	26.65	27.60	1.3	0.50	0.60	0.22
8	26.54	28.15	1.29	0.47	0.62	0.24
9	26.59	28.14	1.39	0.52	0.68	0.23
10	26.53	27.58	1.2	0.56	0.59	0.21
11	26.71	28.43	1.41	0.50	0.61	0.22
12	26.88	28.11	1.23	0.60	0.59	0.21
13	26.71	27.99	1.4	0.50	0.61	0.21
14	26.70	28.17	1.34	0.48	0.62	0.22
15	26.55	27.95	1.41	0.55	0.61	0.22
16	26.40	28.08	1.42	0.56	0.60	0.21
17	26.60	28.02	1.45	0.49	0.59	0.20
19	26.39	27.65	1.52	0.58	0.60	0.22
20	26.63	28.00	1.2	0.57	0.59	0.21

Table 6 – Results of blade geometry measurements after repair (engine D2)

No. i/o	Chord after renovation, mm		C1 , after reno- vation, mm		C2 , after reno- vation, mm	
	A2- A2	A8- A8	A2- A2	A8- A8	A2- A2	A8- A8
1	26.38	27.69	1.3	0.49	0.60	0.25
2	26.47	27.57	1.35	0.50	0.60	0.24
3	26.60	27.84	1.3	0.55	0.62	0.22
4	26.92	27.55	1.3	0.52	0.63	0.24
5	26.60	27.68	1.12	0.47	0.60	0.22
6	26.74	27.76	1.27	0.55	0.62	0.25
7	26.48	27.47	1.3	0.50	0.62	0.25
8	26.60	27.96	1.29	0.45	0.63	0.25
9	26.49	27.90	1.35	0.50	0.62	0.22
10	26.56	27.39	1.22	0.55	0.59	0.23
11	26.70	28.15	1.41	0.50	0.60	0.25
12	26.72	27.86	1.25	0.47	0.61	0.23
13	26.61	27.81	1.41	0.53	0.62	0.21
14	26.64	27.86	1.35	0.48	0.63	0.22
15	26.51	27.92	1.42	0.57	0.60	0.23
16	26.32	27.85	1.44	0.55	0.65	0.22
17	26.63	27.82	1.47	0.47	0.60	0.21
19	26.30	27.57	1.53	0.57	0.61	0.23
20	26.60	27.95	1.22	0.59	0.58	0.19

According to the results of measuring the geometry of the blades before and after repair, it can be said that the dimensions do not change significantly. Fatigue tests of the blades in the state of receipt from operation (initial) and after repair (D2) were also carried out. The ultimate strength of the initial blades is 360 MPa. The test results are presented in Table 7.

Table 7 – Results of blade fatigue tests after repair

No. i/o	Load level σ , MPa	Number of cycles, $N \times 10^6$	Test results	Note
1	510	20	not destr.	-
2	540	14,13	destroyed	$l = 20$ mm, en. edge
3	510	20,0	not destr.	-
4	510	20,0	not destr.	-
5	510	16,79	destroyed	$l = 35$ mm, en. edge
6	480	20,0	not destr.	-
7	480	20,0	not destr.	-
8	480	20,0	not destr.	-
9	480	20,0	not destr.	-
10	480	20,0	not destr.	-
11	480	20,0	not destr.	-

According to the method, the endurance limit based on 10^8 cycles will be $480 \times 0,8 = 384$ MPa. We see that the endurance limit after repair increased insignificantly, by 6 %. While after treatment with balls in a magnetic field up to 22 %.

In this work, regression models of natural oscillation frequencies and blade life were also built. The blades of the first stage of the compressor of the TV3-117 engine,

made of titanium alloy VT8 and VT8M, which have operational damage to the blade feather, were selected as the object of research. The studies of observed engines that were in operation in different countries, respectively, the physical characteristics of the operational processes differed. The blades had different operating hours and, accordingly, different degrees of damage to the blade feather. The engines were operated in the following countries: Yemen, India, UAE, Peru, Cyprus, Algeria, Spain. Operational damage to the feather creates not only stress concentrators, but also leads to a change in the geometry of the blades. Initially, a selection of informatively significant features was carried out (for this, stepwise regression methods were used). Feature selection allows you to discard uninformative features that complicate the model, reduce its interpretability, and sometimes introduce erroneous (noisy) data that reduce the accuracy of the model. After that, using the selected feature groups, regression models were built. Linear regression models were chosen as regression models. Since feature selection was previously performed, the models were built much faster and are relatively simple.

The study of the blade geometry consisted of measuring the chord in sections A2-A2 and A8-A8. x_1 is the average temperature in the region where the operational process took place; x_2 and x_3 are the chord values in sections A2-A2 and A8-A8; x_4 is the total operating time, hours; x_5 is the operating time before the first repair, hours; x_6 is the hardness of the original blade, HRC; x_7 is the yield strength of the original material, MPa; x_8 is the tensile strength, MPa; y is the frequency of natural oscillations of the blades, Hz.

Linear regression model for the full data set ($x_1 - x_8$)

$$y = -0.2800 x_1 - 0.0791 x_2 - 0.0812 x_3 + 0.5604 x_4 - 0.1232 x_5 - 0.2217 x_6 - 0.3890 x_8$$

Model accuracy: 0,0003.

The obtained regression model shows that the greatest influence on the frequency of natural oscillations of the blades is not only the operating conditions and blade geometry, but also the amount of service life, the hardness of the original blade, and the ultimate strength of the blades.

Second-order linear regression model with a first-order component:

$$y = 0.8079 + 0.2148 x_1 - 0.2214 x_3 + 0.0310 x_4 + 0.3649 x_8 - 0.3694 x_1 : x_3 + 0.0352 x_3 : x_4 - 0.1712 x_3 : x_5 - 0.4127 x_3 : x_8 - 0.9691 x_4 : x_8 - 0.5155 x_1^2 + 0.0123 x_3^2 + 0.2760 x_4^2.$$

Model accuracy: 0,00065.

The regression model shows that the natural frequency is affected by a significant relationship between wear and operating conditions, wear and service life, and wear and ultimate strength.

Thus, in the operating conditions of helicopter engines, the use of erosion-resistant coatings in the upper part of the blade blade is of particular importance. This

solution reduces the intensity of edge destruction under the influence of abrasive particles and, in combination with the strengthening treatment of the blade, ensures an increase in the engine's service life (Table 8).

Table 8 – Neural network model for the combination for the full data set ($x_1 - x_8$)

Layer number	Number of neuron in the layer	The input number of the neuron			
		0	1	2	3
1	1	3.6311	-4.6286	17.2227	-3.9438
	2	1.0208	0.4336	-11.2933	7.2829
	3	4.8576	3.1807	-50.3267	28.6725
	4	1.2853	-4.7502	-11.1495	1.7869
	5	0.9485	5.0594	10.1262	-2.3578
	6	-0.1418	0.0050	-5.1386	-5.0073
	7	-0.3975	0.7221	-6.3940	-4.0722
	8	-1.2545	0.0242	-5.7687	-4.2826
2	1	-4.6557	-3.7127	-13.5488	0.5368

Conclusions

A study was conducted of the geometry and natural frequencies of the compressor blade blades made of titanium alloy VT8M, which were operated under various conditions. and have damage to the blade that exceeds the permissible standards and does not allow the blades to be restored using repair technology.

Fatigue tests were conducted on the blades in service and after treatment with steel balls in a magnetic field in the optimal mode. The results of the fatigue tests showed that the endurance limit of the blades increased from 14 to 22 %.

The blades were restored using repair technology, the geometry of the blade profile was measured in sections A2-A2, A8-A8 and the thicknesses of the leading and trailing edges of the output blades and after repair, and the stress state and natural frequencies of the blades were studied.

Fatigue testing of the original blades was conducted and after repair, the endurance limit increased by 6 %.

Regression models of natural oscillation frequencies and blade life were constructed. The obtained regression models show that the greatest influence on the natural oscillation frequency of blades is not only the operating conditions and blade geometry, but also the amount of life, the hardness of the original blade, and the ultimate strength of the blades.

6. Based on the obtained results of experimental research, the feasibility of introducing the method of ball treatment in a magnetic field of the blade feather as a technological operation in the process of repairing compressor blades, which allows significantly increasing fatigue resistance, is substantiated.

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ДОСЛІДЖЕННЯ ВПЛИВУ ОБРОБКИ КУЛЬКАМИ В МАГНІТНОМУ ПОЛІ ПЕРА ЛОПАТОК З ЕКСПЛУАТАЦІЙНИМИ ПОШКОДЖЕННЯМИ НА ВТОМНУ МІЦНІСТЬ

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Мета роботи. Дослідження впливу обробки кульками в магнітному полі пера лопаток, які мають різний ступінь ушкодження пера лопаток в експлуатації, на їх границю витривалості.

Методи дослідження. Механічний метод для дослідження залишкових напруг, експериментальний метод для визначення витривалості лопаток, методи покрокової регресії для побудови регресійних моделей.

Отримані результати. На лопатках двигунів, які працювали в різних умовах та мають різне напрацювання, найбільший знос спостерігається у периферійній частині пера (перетини А7-А7 і А8-А8). Обробка лопаток з різних двигунів, що мають експлуатаційні ушкодження, кульками в магнітному полі суттєво підвищує опір лопаток втомі, границя витривалості лопаток збільшується від 14 до 22 %. Побудовані регресійні моделі частот власних коливань і напрацювання лопаток. Отримані регресійні моделі показали, що найбільший вплив на частоту власних коливань лопаток мають не тільки умови експлуатації та геометрія лопатки, а також величина напрацювання, твердість вихідної лопатки та границя міцності лопаток. Експлуатація гелікоптерних двигунів в умовах підвищеної запиленості та абразивного зношування вимагає нанесення на верхню ділянку пера лопатки захисних покриттів з високою ерозійною стійкістю. Додаткове застосування методів поверхневого зміцнення забезпечує підвищення надійності, втомної міцності та подовження ресурсу роботи газотурбінного двигуна.

Наукова новизна. Запропоновано метод, який дозволяє ефективно обробляти перо лопатки із пошкодженнями, що виникли під час роботи, що забезпечує зростання їх довговічності та надійності. В результаті підвищуються показники витривалості та подовжується термін служби деталей.

Практична цінність. Отримані експериментальні дані дають підстави рекомендувати метод обробки пера лопаток сталевими кульками в магнітному полі як технологічну операцію для ремонту компресорних лопаток, що зазнали експлуатаційних ушкоджень типу вибоїн на вхідних кромках.

Ключові слова: лопатка, ерозія, ушкодження, кульки, магнітне поле, витривалість, напрацювання, регресійна модель.

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FINISHING METHODS FOR GTE BLADES TO INCREASE THEIR SERVICE LIFE

Purpose. The purpose of the work is to analyze modern approaches and methods, extend the service life of compressor blades of gas turbine engines through the use of various individual and complex methods of surface treatment of parts. The final result of this analysis is a summary of data on the effectiveness of the individual use of each method separately and the effectiveness of the combined use of two or more methods simultaneously or sequentially. Based on the results of the summary, conclusions were made on the rationality of using complex approaches and directions for new research in the future were identified.

Research methods. Literary sources were selected using the Google Scholar and Scopus bibliographic databases. The keywords for the search were «methods for strengthening blades», «complex technologies», «thermal methods», «chemical methods», «nitriding», «total resource», and «GTE compressor» in Ukrainian and English.

Results. The main result of the work is a clear and detailed generalization and comparative analysis of the main methods of strengthening the blades of gas turbine engines. This generalization clearly demonstrates the advantages of using integrated approaches. The synergy effect of the simultaneous use of several technologies is considered in detail and confirmed by the results of reports on practical use and laboratory studies published by domestic and foreign scientists.

Scientific novelty. A comprehensive systematization and comparative analysis of the effectiveness of individual and combined methods of surface treatment of gas turbine engine (GTE) blades has been performed, taking into account the depth of strengthening, resource increase, technological compatibility, and practical feasibility. A structured approach to assessing the synergistic effect of combinations of different methods (mechanical, chemical-thermal, thermal, ion-plasma) has been proposed, with the most effective technological combinations being identified. It is substantiated that the use of such combinations provides an increase in resource by 400–500% without changing the geometry of the part or base material, which opens up new opportunities for their implementation in serial production and repair of aviation equipment.

Practical value. The results of the work can be used by engineers and researchers to familiarize themselves with modern diverse methods of increasing the resource of GTE scrap, the effectiveness of these methods, and the advantages of comprehensive approaches to the use of these methods in GTE production.

Key words: methods for strengthening blades, complex technologies, thermal methods, chemical methods, nitriding, total resource, gas turbine engine.

Introduction

The working blades of a gas turbine engine (GTE) operate in harsh conditions: high temperatures, loads, contact with aggressive environments. As a result, damage occurs on their surfaces over time—fatigue cracks, erosion, wear, which limits their service life and increases the risk of accidents. To extend the service life of the blades, it is necessary to increase their fatigue strength and wear resistance. In modern conditions, when using aircraft engines, it is critical to reduce their cost, operating costs, and maximize their efficiency. One way to achieve this is to increase the service life of gas turbine engine blades. At the same time, in order to reduce the cost of such modernization, it is necessary to avoid significant changes in the design and materials of the blades as much as possible.

The above issues dictate the need for an in-depth study of the effectiveness of existing methods of surface treatment of gas turbine engine blades.

Purpose of the work

The purpose of this review is to analyze modern approaches and methods for increasing the service life of gas turbine blades with various individual and comprehensive methods of their surface treatment. The result of this analysis is a summary of data on the effectiveness of the individual use of each method separately and the effectiveness of the combined use of two or more methods simultaneously or sequentially. Based on the results of the summary, conclusions were made on the rationality of using complex approaches and directions for new research in the future were identified.

Material and methods of research

The selection of literature sources was carried out using the bibliographic databases Google Scholar and Scopus. Keywords for the search were: “methods of strengthening the blades”, “complex technologies”, “thermal methods”, “chemical methods”, “nitriding”, “general resource of service”, “GTE compressor” in Ukrainian and in English.

Discussion

Conventionally, all existing methods that are used for treating the surfaces of the blades of the GTE for increasing the service resource can be divided into several groups according to the methods of influencing the material of the blade surface.

Mechanical treatment using plastic deformation of the material of the surface: Table 1 summarizes the main mechanical methods of surface treatment of the GTE blades using plastic deformation. The data was obtained by analyzing scientific publications and technical reports. The greatest hardening depth and service life extension are demonstrated by hardening method known as the Laser Shock Peening (LSP). This is a method of creating residual compressive stresses in the surface layer, which is deformed by a micro-blast wave from a micro-explosion of plasma on the surface of the part. Plasma is created as a result of a short, high-energy laser impulse. This creates internal compressive residual stresses in a layer of material up to 1.0 mm deep. These stresses slow down the development of fatigue cracks and significantly increase cyclic durability [15].

Shot peening and ultrasonic treatment are less effective but widely used methods due to their ease of implementation. The choice of method depends on operating conditions and durability requirements.

Chemical-thermal treatment. In the course of further analysis, chemical-thermal treatment methods were analyzed. Since this analysis concerns GTE blades, boriding can be selected for titanium alloys as the most effective among conventional chemical-thermal surface treatment technologies.

Boriding can provide the highest hardness up to 2000 HV, forming a thick layer (up to 0.8 mm) that is resistant to erosion and abrasive wear.

Table 1 – Main mechanical methods of compressor blade surface treatment using plastic deformation

Treatment method	Hardening layer depth, mm	Increase of general resource of service, %
Shot (Peening)	0.1–0,3	30–50 [4]
Deep rolling	0.5–1.0	Up to 100 [1],[17]
Laser Shock Peening	0.6–1.2	Up to 150 [3],[15]
Low plasticity Burnishing	0,6-1,0	200+ (Depending on the alloy) [5]
UIT	0,3-0,8	200+ [6] (Depending on the material)

Table 2 – Increase of the general resource depending on the depth of the reinforced layer after boriding.

Method	Depth of the reinforced layer, mm	General resource increase, %
Boriding [8]	Up to 0,07	80–150

Thermal and thermomechanical treatment. To ensure high reliability and durability of gas turbine engine (GTE) blades, one of the critically important areas is the use of thermal and thermomechanical treatment methods. Table 3 summarizes the results of the analysis of thermal and thermomechanical treatment methods for GTE blades and the selection of the three most commonly used methods that have demonstrated the greatest effectiveness in aviation engine manufacturing, particularly during serial production and blade repair.

Analysis of the main existing methods and selection of the most common and most effective ones: hot isostatic pressing (HIP) is one of the most effective methods for strengthening blades manufactured by casting or additive technologies. This method eliminates internal porosity, microcracks, and defects characteristic of the initial state of the blank. HIP provides volumetric strengthening of the part, as evidenced by an increase in overall service life of up to 90 % [10]. The method is widely used in practice by manufacturers such as Rolls-Royce, GE Aviation, and Motor Sich JSC.

Aging after preliminary hardening is a thermal method that ensures the formation of dispersed strengthening phases in the alloy structure (in particular, in β -titanium alloys such as VT22 and Ti-6Al-4V). This approach gives a significant increase in fatigue strength, allows stabilization of material properties during long-term usage, and reduction of the rate of damage accumulation [13, 16]. The increase in general resource due to a properly selected aging regime reaches 100%, which is one of the highest indicators among classical thermal processes.

Thermomechanical aging combines plastic deformation of the material of the surface (up to 5–10 %) with subsequent thermal aging at the aging temperature. This approach not only allows the formation of strengthening phases, but also additionally increases compaction of the surface layer and reduces the grain size. The method is particularly effective in strengthening areas working under concentrated loads, such as the root of the blade. The increase in service life under such conditions is up to 50 %, and the depth of strengthening is 0.8–1.5 mm [13].

Vacuum annealing [10] allows effective reduction of internal stresses after mechanical treatment while maintaining the chemical purity of the surface, which is particularly important for subsequent ion-plasma coating.

Isothermal tempering [14] is used for thermal stabilization of the structure in heat-resistant alloys. This improves creep resistance and preserves mechanical properties at continuous operating temperatures, which is relevant for GTE blades.

Thus, the most effective and practically significant methods for increasing the service life of GTE blades are hot isostatic pressing, aging after hardening, and thermomechanical aging. These technologies combine high service life increase, availability for implementation in production, and compatibility with modern materials –titanium, nickel, and heat-resistant steels.

Table 3 – Generalized results of the analysis of methods of thermal and thermomechanical treatment of GTE blades

Method	Layer depth, mm	General resource growth, %
Hot isostatic pressing (HIP)	Full volume	Up to 90 (depending on the alloy) [9],[10]
Aging after hardening	Full volume	Up to 100 (depending on the alloy) [11],[12]
Thermomechanical aging	0.8–1.5	Up to 100 (Depending on the alloy) [13],[14]

Laser and ion-plasma methods: this group of processing methods is one of the ways to increase the durability of blades using laser and ion-plasma technologies, which allow improving performance characteristics without changing the geometry of the product or the structure of the base material.

The most effective methods in this group include:

Ion-plasma nitriding is a process of saturating the surface layer with nitrogen in an electric plasma environment. This promotes the formation of solid nitride phases with high wear resistance and hardness (up to 1200 HV). As shown in [7, 16], the service life of blades after nitriding increased by an average of 50–80 % depending on the engine operating mode.

Ion-plasma coating (PVD, CVD) – unlike previous methods, this method involves the application of thin functional coatings (TiN, AlTiN, CrN) with high adhesion to the substrate. The method provides increased erosion resistance when operating at high temperatures. [2]

Table 4 – Results of analysis of laser and ion-plasma processing methods

Method	Layer depth, mm	Resource increase, %
Ion-plasma nitriding	0,01–0,05	Up to 80
Ion-plasma coating (PVD)	0,002–0,010	Up to 50 (depending on the coating)

Analysis of the effectiveness of the complex use of methods for treating the surfaces of the blades of the GTE

The first part of the article was devoted to the analysis of existing methods of surface treatment of GTE blades to increase their service life. The effectiveness of these methods under individual use conditions was analyzed. Today, one of the main promising areas of development of blade

production technology is the study of the effectiveness of complex use of these technologies. This approach makes it possible not only to combine several methods, but also to achieve a synergistic effect through the sequential or simultaneous application of several physical and chemical processes to the surface of the part, resulting in multiple times increase in general effectiveness.

Below are graphs showing the effectiveness of the complex use of the methods described in the article in various combinations. Further study of the technological experience that exists today was aimed directly to finding the most effective combinations. Eleven existing technologies were analyzed, classified in the previous part of the article by direction: mechanical processing using plastic deformation of the surface material of the part, chemical-thermal processing, thermal and thermomechanical processing, laser and ion-plasma methods. Based on a multifactorial analysis of efficiency, hardening depth, technological compatibility, and practical implementation, five most promising combinations were formed:

1. LSP (Laser Shock Peening) + PVD – laser shock peening combined with ion-plasma spraying of thin hard coatings (Fig. 1). When these treatment methods are used in combination, a synergistic effect is observed and the overall service life of the GTE compressor blade increases by up to 300 %, depending on the blade material.

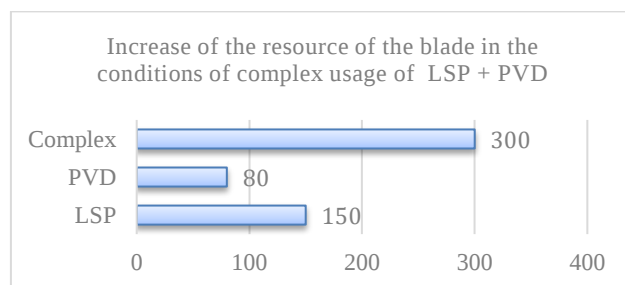


Figure 1. Resource increase when using LSP + PVD

2. LSP (Laser Shock Peening) + Ion-Plasma Nitriding – mechanical strengthening and diffusion saturation of the surface with nitrogen (Fig. 2). When these treatment methods are used in combination, a synergistic effect can also be observed, resulting in an increase in the service life of the GTE blade up to 300 %

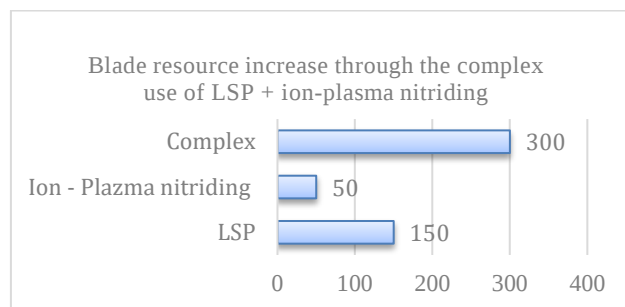


Figure 2. Blade resource increase through the complex use of LSP + ion-plasma nitriding

3. HIP (Hot Isostatic Pressing) + Ion-Plasma Nitriding – hydrostatic compaction of the internal structure and increased hardness of the surface layer of the blade material (Fig. 3). This combination of methods implements a structurally complex approach to increasing the service life of GTE blades. HIP eliminates internal defects (pores, cracks) that can become centers of fatigue failure, while nitriding creates a hard protective layer that is highly resistant to wear, erosion, and oxidation. This is especially relevant in the production of blades by casting or 3D printing, as well as in blade restoration.

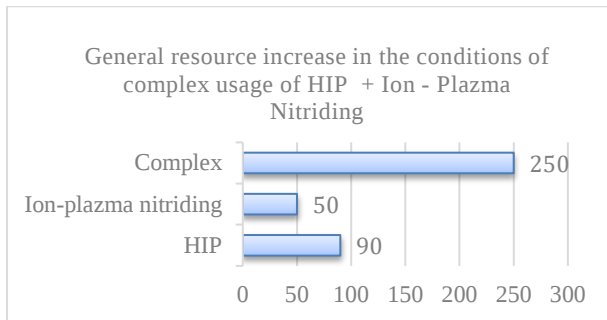


Figure 3. General resource increase in the conditions of complex usage of HIP + Ion -Plazma Nitriding

4. HIP (Hot Isostatic Pressing) + Thermomechanical Aging (TMA) – structural stabilization and reduction of internal stresses (Fig. 4). The combinat of HIP + thermomechanical aging is an effective strategy for improving the internal structure and increasing the fatigue strength of blades. Unlike surface methods, this technique works at a deeper level, strengthening the entire part. This is particularly effective for cast or additively manufactured blades made of titanium and nickel alloys.

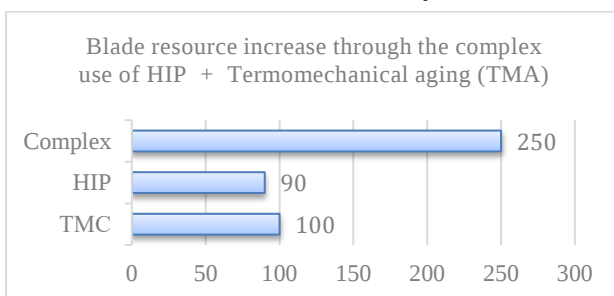


Figure 4. Resource increase through complex usage of HIP + TMA

5. LSP (Laser Shock Peening) + PVD (Ion-Plasma Deposition) + Ion-Plasma Nitriding – a three-component combination that provides comprehensive strengthening (Fig. 5). This combination is the most effective in terms of increasing the service life of GTE blades. There is a powerful synergistic effect. Synergy mechanism: LSP creates deep residual compressive stresses (~1 mm deep), which inhibits the growth of fatigue cracks, nitriding forms a chemically stable and superhard layer with a hardness of up to 1200 HV, PVD applies a wear-resistant coating (TiN, CrN, AlTiN, etc.), which increases resistance to erosion, oxidation, and corrosion.

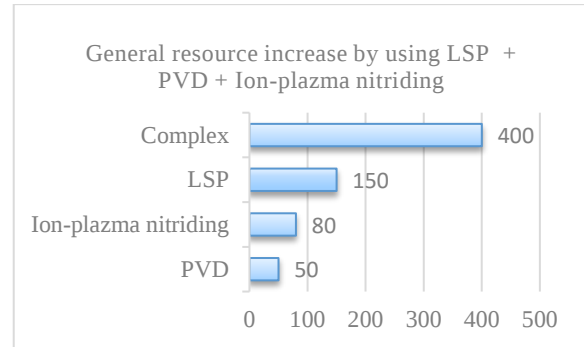


Figure 5. General resource increase by using LSP + PVD + Ion plasma Nitriding

Conclusions

As a result of this research, 13 modern technological methods for strengthening gas turbine engine (GTE) blades were analyzed. Mechanical, chemical-technical, chemical-thermal, thermal, laser, ion-plasma methods, as well as coating application methods were evaluated.

All selected processing methods act at different levels: from submicrostructure (LSP) to the chemical composition of the surface layer (nitriding, coating). Methods that create surface deformation of the blade material form compressive stresses up to 0.3 mm deep. This strengthens the surface layer due to work hardening and orientation of the material structure, which increases strength and prevents the initiation and development of fatigue cracks. Changing the chemical composition of the surface layer of the material, for example, diffusion nitriding, increases the surface hardness to 1000–1100 HV. PVD coatings with TiN or CrN act as a barrier against wear and oxidation. The blade surface is subject to diverse influences. This diversity and sequence creates synergy effects.

Of the five processing methods, three with the highest potential for application in the aviation industry were selected:

LSP + Nitriding – demonstrated effectiveness in increasing fatigue strength. Published studies have shown an increase in cycles to failure from 8×10^3 to 2×10^5 at a load of 450 MPa.

LSP + PVD + Nitriding – combines mechanical strengthening, chemical-thermal saturation and the application of a hard wear-resistant layer. The increase in total resource is up to 400% (depending on the material) compared to raw samples

HIP + Nitriding – Provides compaction of cast or printed structure and formation of a solid surface layer. This method increases the resource by up to 300 % and has proven itself in the production of large GTE blades.

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ФІНІШНІ МЕТОДИ ОБРОБКИ ЛОПАТОК ГТД ДЛЯ ПІДВИЩЕННЯ ЇХ РЕСУРСУ

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Мета роботи. Метою роботи є проведення аналізу сучасних підходів та методів, збільшення ресурсу компресорних лопаток ГТД через використання різних індивідуальних і комплексних методів обробки поверхні деталей. Кінцевим результатом цього аналізу є узагальнення даних по ефективності індивідуального використання кожного з методів окремо і ефективності комбінованого використання двох і більше методів одночасно або послідовно. По результатах узагальнення зроблені висновки по раціональності використання комплексних підходів та означені напрямки нових досліджень в майбутньому.

Методи дослідження. Підбір літературних джерел здійснювався з використанням бібліографічних баз Google Scholar та Scopus. Ключові слова для пошуку були «методи зміцнення лопаток», «комплексні технології», «термічні методи», «хімічні методи», «азотування», «загальний ресурс», «компресор ГТД» українською та англійською мовами.

Отримані результати. Основним результатом роботи є чітке і детальне узагальнення і порівнювальний аналіз основних методів зміцнюючої обробки лопаток ГТД. Вказане узагальнення обґрунтовано показує перевагу

використання комплексних підходів. Детально розглянуто ефект синергії при одночасному використанні декількох технологій і підтверджується це результатами звітів по практичному використанню і лабораторних досліджень, які опубліковані вітчизняними та іноземними науковцями.

Наукова новизна. Виконано комплексну систематизацію та порівняльний аналіз ефективності індивідуальних і комбінованих методів поверхневої обробки лопаток газотурбінних двигунів (ГТД) з урахуванням глибини зміцнення, приросту ресурсу, технологічної сумісності та практичної реалізованості. Запропоновано структурований підхід до оцінки синергетичного ефекту від комбінацій різних методів (механічних, хіміко-термічних, термічних, іонно-плазмових) з відокремлення найбільш результативних технологічних поєднань. Обґрунтовано, що використання таких комбінацій забезпечує підвищення ресурсу до 400–500% без зміни геометрії деталі чи матеріалу основи, що відкриває нові можливості для їхнього впровадження у серійне виробництво та ремонт авіаційної техніки.

Практична цінність. Результати роботи можуть використовуватись інженерами та науковими співробітниками для ознайомлення із сучасними різноплановими методами підвищення ресурсу лопаток ГТД, ефективністю цих методів та з перевагами комплексних підходів до використання цих методів у виробництві ГТД.

Ключові слова: методи зміцнення лопаток, комплексні технології, термічні методи, хімічні методи, азотування, загальний ресурс, газотурбінний двигун.

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RESEARCH ON THE INFLUENCE OF TECHNOLOGICAL FACTORS ON THE QUALITY OF COMPOSITE MATERIALS

Purpose. The purpose of this study is to analyze the impact of the main stages of manufacturing composite products on the probability of various defects. Special attention is paid to finding and justifying practical ways to eliminate them at the early stages of the production process. The work is aimed at identifying the relationship between technological parameters, such as temperature, pressure and polymerization time, and the final quality, strength and reliability of the finished product. In addition, the goal is to develop methodological recommendations for manufacturers to minimize defects and increase production efficiency.

Research methods. The work uses an analytical method and a detailed consideration of factors that directly affect the quality of composite materials. An analysis of scientific and technical literature was conducted, as well as systematization of production practice data. To detect hidden defects and assess their impact on the structure of the material, modern methods of non-destructive testing were used. This allowed obtaining objective data on the condition of the material without its destruction, which is critically important for preserving the integrity of products.

Results. Based on literary data and production practice, attention is paid to the production factors that most affect the quality of manufacturing composite materials and parts made from them. Analysis and comparison of existing destructive testing methods to preserve the structure of products, as well as the use of various control methods to detect defects in the complex structure of composite materials, which can ensure high quality of the manufactured products.

Practical value. The work examines the factors that affect the quality of the product during its operation, as well as technological factors and methods of their control. For the study, practical work was carried out to determine the influence of technological factors on the quality of the product, and methods for eliminating defects in ing of the part.

Key words: vacuum, grinded fabric, prepreg, polymerization, venture, composite materials.

Introduction

The modern use of composite materials extends to all fields of engineering, ranging from the most prominent such as aerospace, shipbuilding, mechanical engineering, or other industrial sectors, to our everyday life. The field of synthesized materials offers new solutions to complex engineering problems without the mandatory presence of high-tech equipment or additional mechanical processing for high-quality surface formation.

Composite materials are combined (the combination of the reinforcing component and the matrix is adjusted) to better utilize their advantages while minimizing their disadvantages. This intensification process allows designers to overcome the limitations associated with the selection and manufacture of traditional materials, simultaneously expanding possibilities in selection, as well as reducing unnecessary steps (such as surface oxidation or

galvanizing), or reducing the weight of structural elements. It is also possible to use stronger and lighter materials, whose properties are tailored to specific requirements. Thanks to the ease of manufacturing complex shapes and the reusability of existing structures, the use of composites leads to more economical and technological improvements in selected industries.

At the same time, the manufacture of composite materials is a complex process due to the large number of technological factors that affect product quality: the choice of materials, their bonding with each other, temperature regimes, process duration, as well as mechanical and chemical influences. Managing these factors allows for controlling and significantly improving the properties of the final product, obtaining materials with the necessary characteristics for various purposes of their use.

Purpose

Investigate the technological modes of manufacturing and various deviations that can lead to serious defects in the composite structure: such as porosity, delamination, uneven distribution of the reinforcing material, which ultimately reduces its mechanical strength, durability, and reliability.

Results and discussion

The main factors affecting the technological process of manufacturing composite materials have been analyzed, their characteristics, conditions, types, and areas of application are presented.

Temperature factor. Temperature is one of the main factors influencing the process of manufacturing composite materials. High temperatures can accelerate the polymerization process, which is important for the production of composites based on thermosetting polymers, such as epoxy resins. At the same time, excessively high temperatures can lead to the decomposition of the material, significantly deteriorating its mechanical properties.

In the process of manufacturing composites based on thermoplastic polymers, the "fusion" of fibers with the matrix is controlled by temperature. The choice of the optimal temperature is critical to ensuring the strength and durability of the composite material. If the temperature is too low, it may lead to insufficient integration of the fibers and matrix, which will affect the material's strength [1].

At every stage of product manufacturing (during cutting of composite material, milling or drilling, or during its polymerization in the oven), temperature can affect the quality of mechanical and chemical factors, the deterioration of which may lead to a reduction in the subsequent service life [2].

Effect of pressure. Pressure is a factor that influences the quality of composite materials, especially during the forming process: vacuuming (compression and removal of excess air) or pressing in a mold in thermal presses. Increased pressure helps achieve better impregnation of the fibers by the matrix, which improves the mechanical properties of the composite. High pressure also allows the creation of a denser structure, reducing the number of pores or voids, which enhances the tensile strength of the material.

In vacuum composite manufacturing processes, where low pressure is used to remove air from the inter-fiber space, the pressure is controlled to ensure uniform distribution of the matrix and to achieve the required material consistency, thickness, and surface replication of the mold or mandrel (it is possible to use a repair-type forming where this product will be applied, on the surface of which the composite material will be laid).

Pressure should be monitored periodically and possibly more regularly than temperature, due to the presence of "cold polymerization" (without high temperatures, properly selected pressure ensures the quality of the for-

mation and bonding of composite layers or parts).

There are several types and modes of pressure in the manufacturing of these parts:

- pressing, used for creating composites from thermoplastic materials, especially in the manufacture of structures in the form of plates, pipes, blades, spars, and skins, where there are certain requirements and the need to control pressure;

- autoclave method, this method is important in the production of critical components where it is necessary to achieve a minimum of pores and defects. During the autoclave forming process, composites are subjected to high pressure and temperature in a sealed environment, which ensures thorough impregnation of the fibers with the matrix and minimizes air pores. Thanks to a reliable pressure and temperature control system, this method guarantees excellent quality of the final material with high mechanical and physical properties. Compared to pressing, the autoclave method allows working with large sizes and complex parts, making it versatile for the manufacture of high-precision, reliable, and durable products;

- the vacuum forming method is one of the simplest and most effective methods for manufacturing composites, widely used for creating products from thermoplastic materials, particularly in small-batch and medium-batch production. This method is based on the use of vacuum to deform the material on a mold, or as previously mentioned, it is possible to use existing parts or products as a form. Vacuum forming is used for manufacturing lightweight or combined structures, such as components for the automotive industry, household appliances, decorative elements, or ship hulls (side, bottom, keel hull), which are assembled in large facilities (hangars) and consist of a frame covered with prepreg shaped according to a specified form and assembled from a large number of vacuum bags, as well as a large number of vacuum pumps [3]. That is, the method is limited by the pressure conditions in the system, as well as the cleanliness and quality of the manufactured products when increasing the vacuum size. There may also be a deterioration in the quality of the prepreg, such as wrinkles when there is a large bend in the part, where the angle between two vacuumed surfaces becomes more acute than obtuse;

- the hydrostatic pressure method allows for an even distribution of pressure from all sides, which is especially important for complex shapes or large products that require high precision and density. It helps to avoid local defects and ensures uniformity of the structure, having a significant difference from its counterpart (vacuum method) - the possibility of using higher pressure on the part.

Effect of time. Time is an important factor in the processes of polymerization and material curing, as all changes in the structure can only be recorded with the presence of time variation and its control.

Insufficient polymerization time can lead to the material not gaining sufficient strength, while excessively long time can result in the loss of properties such as elasticity. When manufacturing certain composites, materials for the mold are used in which the operating temperature

is lower than the polymerization temperature of the binder in the composite; therefore, preliminary polymerization is performed at lower settings (then the part is removed and final polymerization is carried out without the mold) or with increased time but reduced temperature.

The time required for the curing of composite materials also depends on temperature and pressure, as they can accelerate or slow down the processes of polymerization and curing. Considering and regulating these factors helps maintain the quality of the material and its stability at all stages of manufacturing depending on various factors [4–6].

The influence of moisture and other extraneous inclusions. Moisture is another important factor that can affect the quality of composite materials, especially during the stages of fiber storage and processing. High humidity can lead to water penetration into the material's structure, which worsens its physicochemical properties. This can cause corrosion or degradation of the material, as well as reduce its strength and resistance to loads.

Moisture control is an important stage at all phases of composite production, particularly during fiber storage, matrix processing, as well as during material forming and curing. Accordingly, air cleanliness is regulated by the state standard ДСТУ ISO 14644-1:2009, there are 4 classes of cleanliness and more, but under more responsible production conditions or the creation of composite material itself, it is necessary to use a higher cleanliness class due to the need to meet high quality requirements, as well as safety in production, where the air may contain ether, formaldehyde, and other resins and substances.

Moisture can occur as condensation when storing prepreg at subzero temperatures in freezers, or in the binder mixture and other consumables, as well as in cut pieces before the next molding of the material on mandrels or layups on the mold. Moisture also appears on glass fiber rovings stored in rooms near resin impregnation areas or layup workstations. In the case of mass production and the inability to store materials elsewhere, the aforementioned materials should be placed in foam inserts or cores that simulate voids and lighten the subsequent structure, due to their high porosity and good ability to absorb moisture and other unwanted substances.

To ensure product quality and avoid further defects related to poor storage and storage conditions, drying of the products is carried out, which depends on their type, structure, and accordingly volume, since in addition to moisture, there may be wax present in fiberglass fabrics or possible gasoline or acetylene inclusions on parts during storage or manufacturing.

Manufacturers producing fiberglass fabric impregnate it with paraffin emulsion or other types of oil for preservation purposes, but the presence of such components in the fabric composition can significantly affect the subsequent quality of the manufactured prepreg, so it is necessary to perform an annealing operation. It is simultaneously used as a substitute for drying for fabrics that have been oiled, but it should be taken into account that not all fabrics have prior impregnation.

Drying from moisture has better performance in process technology due to lower requirements for time and temperature, as well as necessary equipment, so it is better to use fiberglass without adding various preservatives, which will save time and energy, which will increase hundreds of times with large production volumes. It is recommended to perform drying and annealing for as large volumes of fabric as possible to save resources and necessary time [7].

Influence of chemical additives. Chemical additives, such as plasticizers, stabilizers, polymerization accelerators, and other modifying agents, are important components of the composite material manufacturing process. They are used to improve the properties of the material, particularly strength, flexibility, load resistance, and thermal stability. However, unlike the effects of moisture or other unwanted inclusions, additives are controlled elements of the technological process, and their impact directly depends on the accuracy of dosing and usage conditions.

One of the key problems is that incorrect selection or overdosing of chemical additives can cause defects in the material, such as reduced stability, formation of pores, cracks, or uneven polymerization of the binder, which can lead to defects in parts of the component or product in critical areas or where a continuous surface is required. As a result, the part will be defective without any possibility of repair. For example, using plasticizers in excessive amounts can reduce the stiffness of the composite, and stabilizers in high concentrations can worsen its adhesive properties, affecting the delamination of prepreg layers or detachment from the bonded part.

Additional risks are associated with the use of additives prone to the release of volatile substances, such as ethers or formaldehyde resins. This requires adherence to strict cleanliness standards in production. To prevent the release of chemical residues into the air of production premises, especially in cases of mass production, it is necessary to use exhaust systems and regular cleaning of work areas, which should be monitored by recorders and other control devices.

Chemical additives also affect the storage of materials. For example, polymerization accelerators included in prepreps, binders, or other pre-treated materials can change their properties under improper storage conditions. High humidity or inappropriate temperature can cause undesirable chemical reactions, leading to a deterioration in the quality of the finished product. During the manufacturing of products, it is necessary to control the conditions of forming, creating, and processing composites at all stages to avoid the formation of unwanted inclusions or residual stresses, as is the case with extraneous inclusions (humidity, dust, oily materials). Implementing these measures will help preserve the mechanical and physicochemical properties of the composite material and ensure the stability of its operational characteristics [8, 9].

Preparation of the binder (matrix). The process of manufacturing composite materials begins with the

preparation of raw materials. This aspect includes the preparation of epoxy resin, which is the main protective component of the reinforcing element and the “form holder”, since in the production of prepregs, the binder is responsible for maintaining the shape of the fabric. These include many types of adhesives with various physical and chemical characteristics, as well as different modes and components.

For example, polyurethane adhesives can be either cold-curing or hot-curing. Their composition includes polyesters, polyisocyanates, and fillers (including cement). The chemical reaction that occurs when the components are mixed ensures the adhesive hardens. They have universal adhesion due to polar groups (NHCO), good vibration resistance, strength under uneven tearing, and resistance to the effects of petroleum fuels and lubricants. Well-known brands of such adhesives – ПУ-2, BK-5, BK-II, leukonate. It is important to note the toxicity of adhesives and their various fields of application, where in one case they may serve as a sublayer for laying impregnated fabric, and in another – for bonding composite-metal, metal-metal.

Also, adhesives modified with carbon-containing compounds are characterized by high heat resistance. For example, the BK-20 adhesive can withstand prolonged heating up to 350–400°C and short-term heating up to 800°C, maintaining high strength or altering adhesion with small doses of “alloying”.

Cyanoacrylate-based adhesives, including brands EO №87 і EO №170, are not prone to aging, and their strength increases during storage.

To improve the adhesive properties, silicone adhesives are often combined with other resins. Many adhesives also use mineral fillers to improve the properties [10, 11].

Fabric preparation (reinforcing component). When preparing fabric for impregnation, it is recommended to use methods or instructions for the production of composites, in accordance with the materials used in their manufacture, due to the structurally different processing and operating modes.

Fabric treatment involves annealing, or drying. Annealing may involve higher temperatures than drying, and may require more space to remove wax or oils. Drying has a simpler purpose - it is used to remove moisture, volatile compounds, oils, and wax from the fabric.

Cleaning the fabric is necessary before applying the resin to the fiberglass and impregnating it to remove preservatives or moisture. If more specific components such as dirt or grease are present, the fabric should be cut and excluded from further use, especially when making critical structures. This will ensure better adhesion between the fibers and the resin.

Pre-cutting is performed after heat treatment or after, depending on the technological process. The fiberglass should be cut into blanks of the required shape and size, with minimal material consumption. This is done both manually and with the use of special equipment. It is important to avoid twisting or pulling the fibers when

cutting. But it is not possible to completely avoid this due to the fact that often reinforcing materials have a high threshold for shear and tension. In such cases, a larger specified allowance for this material or preliminary impregnation is used, when it already becomes a prepreg.

When cutting is performed manually, the quality and accuracy of the manufactured blanks, and accordingly their subsequent efficiency in the layout, are worse. There is an imposition of one tolerance on another, especially when the cutting was designed for a high material consumption coefficient, as well as a large number of threads and delamination of the fabric blank layer. This phenomenon occurs more often with dense material and small blanks. Material stretching is also possible.

Cutting using special equipment (plotters and their various types) is more aimed at optimizing production, improving the quality of cutting, its accuracy, high material consumption coefficient and the need for only one person when performing large volumes of production. This method allows you to ensure high requirements for cutting with an accuracy of up to 0.1 mm, strong pressing, and technological efficiency.

Impregnation with a binder (resin) must be carried out in designated areas (equipped areas or rooms). The binder must be applied evenly to ensure complete impregnation of the fabric, the cleanliness of its application and the avoidance of dirt or unnecessary impurities. Particular attention must be paid to various degreasing agents or oils. For impregnation, the method of manual application, vacuum infusion, as well as equipment in the form of impregnation machines is used, which allow removing part of the air and achieving the required ratio of fiber to resin. Rollers or spatulas are used to evenly distribute the resin and remove air pockets during the manual method and vacuum infusion. One of the impregnation machines is shown in Figure 1.



Figure 1. Modular impregnation line for the production of fabric or tow prepregs

On one line, solvents from hot-melt resins (binders) are used, as well as reverse roller coating for the production of polymer film using hot-melt resins, which will improve the quality of the applied resin layer and ensure the proper condition after rolling with rollers.

In such machines, there is precise control of the thermal process: the speed of heating and cooling, which will increase the quality of the manufactured products and reduce the number of scrap with the number of

unimpregnated zones.

Improving the quality of polymerization, which determines the mechanical strength, chemical resistance and durability of future structures and products.

It is necessary to control the temperature and ensure uniform heating throughout the product. Insufficient heating can lead to incomplete polymerization, while overheating can lead to thermal degradation of the resin. It is also necessary to take into account the materials and volumes of the matrices and mandrels on which the prepreg was laid out.

The polymerization time must be optimized and adjusted according to the temperature, as an excessively short cycle can leave the resin uncured, while too long a time can affect the mechanical properties of the composite material, or damage the matrix or mandrel.

It is also necessary to use vacuuming, which allows you to remove air and minimize the formation of pores in the material structure, reducing the possibility of delamination. The use of pressing for critical and especially critical parts and assemblies performs better compared to vacuuming, but reduces the amount of resin. This is especially important when manufacturing large parts, such as ship hulls or aircraft or aerospace components.

Ensuring uniform impregnation of the fibers with resin is important to avoid local defects and weak zones in the material. The use of infusion methods, such as vacuum infusion or the use of pre-impregnated prepreps on rolling machines, can significantly improve the quality of impregnation and save time.

Modern monitoring systems, such as fiber optic sensors, thermal sensors, recorders and others, allow you to monitor the polymerization process in real time and adjust parameters in case of deviations [12-15].

It is also necessary to avoid critical moments such as:

- overheating of the material during molding. The exothermic reaction of the resin can cause local overheating, especially with large masses. This can cause cracks or changes in physicochemical properties;
- poor compaction during pressing or incorrect vacuum mode can leave free zones that will be filled with binder and crumpled fabric, causing defects in the structure;
- improper preparation of the surface of the matrix or mandrel, or preparation of the reinforcing part (fiber-glass, carbon fiber) can lead to reduced adhesion between components and cause delamination of the material.

Forming is carried out by various methods, depending on the size, shape and functional requirements of the product. As the material is laid out in layers on the mold (matrix) manually or automatically, the orientation of the fibers is controlled to achieve the required mechanical properties, depending on the inclination: 45°, 90°,

45°×45°, 90°×90° (most frequent).

Conclusions

An analysis of technological factors that affect the quality of the manufactured composite material and parts has been conducted. The possibility of the occurrence and detection of defects in the complex structure of composite materials, cost reduction with appropriate selection of the necessary control methods, has been considered.

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ДОСЛІДЖЕННЯ ВПЛИВУ ТЕХНОЛОГІЧНИХ ФАКТОРІВ НА ЯКІСТЬ КОМПОЗИЦІЙНИХ МАТЕРІАЛІВ

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Мета роботи. Метою даного дослідження є аналіз впливу основних етапів виготовлення композитних виробів на ймовірність виникнення різноманітних дефектів. Особлива увага приділяється пошуку та обґрунтуванню практичних шляхів їх усунення на ранніх стадіях виробничого процесу. Робота спрямована на виявлення взаємозв'язку між технологічними параметрами, такими як температура, тиск та час полімеризації, і кінцевою якістю, міцністю та надійністю готової продукції. Окрім того, метою є розробка методичних рекомендацій для виробників з метою мінімізації браку та підвищення ефективності виробництва.

Методи дослідження. У роботі використано аналітичний метод та детальний розгляд факторів, які безпосередньо впливають на якість композитних матеріалів. Проведено аналіз наукової та технічної літератури, а також систематизація даних виробничої практики. Для виявлення прихованих дефектів та оцінки їхнього впливу на структуру матеріалу застосовано сучасні методи неруйнівного контролю. Це дозволило отримати об'єктивні дані про стан матеріалу без його руйнування, що є критично важливим для збереження цілісності виробів.

Отримані результати. На підставі літературних даних і виробничої практики приділено увагу факторам виробництва, які найбільше впливають на якість виготовлення композиційних матеріалів та деталей із них. Аналіз та порівняння наявних методів неруйнівного контролю для збереження структури виробів, а також використання різних методів контролю для виявлення дефектів у складній структурі композиційних матеріалів, що може забезпечити високу якість виготовленої продукції.

Практична цінність. В роботі розглянуті чинники, які впливають на якість виробу при його експлуатації, а також технологічні фактори і методи їх контролю. Для дослідження було виконано практичну роботу по визначенню впливу технологічних факторів на якість виробу, і методи усунення дефектів при виготовленні деталі.

Ключові слова: вакуум, склотканина, препрег, полімеризація, зв'язувальне, композиційні матеріали.

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МОДЕЛЮВАННЯ ПРОЦЕСІВ В МЕТАЛУРГІЇ ТА МАШИНОБУДУВАННІ

MODELING OF PROCESSES IN METALLURGY AND MECHANICAL ENGINEERING

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MODELING THE ANGLE OF THE DIRECTION OF THE RESULTING DISPLACEMENT OF THE CUTTING EDGE OF THE CUTTER-OSCILLATOR

Purpose. Establishing the dependence of the angle of the direction of the resulting displacement of the cutting edge of the cutter-oscillator on the geometric parameters of the holder using various methods and substantiating the feasibility of using cutter-oscillators with single degree of freedom for targeted modeling of the influence of individual factors, such as the regenerative effect or a change in the instantaneous cutting speed.

Research methods. The analytical method involved obtaining calculation formulas for determining the angle of the direction of the resulting displacement of the cutter-oscillator. For numerical modeling of the bending of the cutter-oscillator during turning, the SolidWorks and Unigraphics NX programs were used. The research was also conducted by an experimental method, in which oscillograms of the oscillations of the cutting edge were recorded, from which the static bending of the cutter-oscillator was determined.

Results. Methods for determining the direction of the resulting displacement of the cutting edge of the cutter-oscillator have been developed based on analytical calculation, computer modeling, and experimental methods. Computer modeling of the bends of the cutters-oscillator has been carried out in the SolidWorks program, which made it possible to determine with high accuracy the angle of the direction of the resulting displacement of the cutting edge at different ratios of the cutter-oscillator holder dimensions. It has been shown that the optimal ratio of the height to the width of the holder ($h/b > 3.3$ for the oscillator X; $h/b < 0.3$ for the oscillator Z) provides the direction of movement with a deviation of no more than 5° from the X and Z axes, respectively. The accuracy of the computer modeling method has been experimentally confirmed, which allows it to be used for designing cutters-oscillators with specified dynamic properties.

Scientific novelty. The optimal dependence of the angle of the direction of displacement of the cutting edge of the cutter-oscillator on the geometric parameters of the holder has been established, which allows controlling the orientation of oscillations during cutting.

Practical value. The results of the work can be used in the design of cutters-oscillators to study the dynamics of the turning process. The developed methodology allows reducing the costs of manufacturing prototypes of cutters-oscillators due to preliminary modeling of their characteristics in the CAD/CAM environment.

Key words: oscillogram, self-oscillations, degree of freedom, regenerative self-oscillations, cutting speed.

Introduction

Turning is one of the key metalworking methods, widely used for the manufacture of parts of varying complexity. However, this process is often accompanied by self-oscillation, known as chatter [1], the nature of which

has not yet been fully elucidated due to its multifactorial nature and complexity. Chatter negatively affects the stability of the cutting process, worsens the quality of the machined surface, reduces dimensional accuracy, accelerates tool wear and can lead to equipment damage [2].

Despite a significant amount of scientific research in this area, there is still no single theory that would fully explain the physical mechanism of self-oscillations during turning. The main sources of vibration are considered to be the regenerative effect [3] and coordinate (modal) coupling [4, 5].

For a deeper understanding of the mechanism of self-oscillations and the development of effective methods for their suppression, specialized experimental approaches are necessary. One of such approaches is the use of cutters-oscillators with single degree of freedom along the X or Z axis [6, 7]. This allows us to exclude the influence of the coordinate connection and separately investigate the influence of the regenerative effect (with oscillations along the axis of change of the cut thickness - the X axis) or the influence of instantaneous changes in the cutting speed (with oscillations along the Z axis). This is the basis for building a reliable experimental base and testing analytical models of the dynamics of the turning process.

Analysis of research and publications

In the field of vibration research, which occurs during turning, a large number of scientific works have been carried out, the main attention of which is paid to the prediction and prevention of self-oscillations [8, 9]. In order to detect and analyze vibration processes, various experimental and analytical methods are used.

One of the widely used approaches is the analysis of acoustic emission signals [10, 11]. However, the reliability of such studies significantly depends on a number of factors, including the accuracy of the sensor location and the level of external noise, which can distort the results. A more reliable alternative is the use of dynamometers [12], since cutting forces are more sensitive to vibrations compared to acoustic signals. At the same time, due to the inertial properties and design limitations of the dynamometers themselves, distortion of the measured values is possible.

Experimental studies of vibration during turning are often carried out using oscillators [7, 12], which allow recording the movement of the cutting edge during machining. Of particular note is the use of cutters-oscillators [13, 14] with single or two degrees of freedom, which, due to their low rigidity, are able to perform oscillatory movements under the action of cutting forces, which are recorded using displacement sensors [13] and accelerometers [15]. However, despite the prevalence of such devices, in most studies insufficient attention is paid to the coordination of the direction of oscillations of the oscillator with the direction of the sources of the acting vibration disturbances, which is critically important for the correct analysis of the dynamics of the cutting process. In this regard, there is a need to develop a method for calculating the direction of the resulting movement of the cutting edge of the cutter-oscillator. This technique allows to ensure coordinated oscillation along a given axis, which, in turn, increases the accuracy and reliability of measurements. The use of modern 3D modeling tools in CAD/CAM environments for designing cutters-oscillators and comparing the results of numerical modeling with experimental data opens up new op-

portunities for analyzing vibration processes and improving the design of experimental devices.

Purpose of work

The aim of the work was to compare different methods for determining the direction of movement of the cutting edge of a cutter-oscillator during oscillations and to determine the conditions that allow for the constructive implementation of oscillations along a certain axis.

Research material and methodology

Analytical method for determining the angle of direction of the resulting cutting edge movement

The simplest design of a cutter-oscillator is a cantilevered rectangular rod of length l with a cross-section $h \times b$ (Fig. 1a). When placing the cutting edge on the central axis of rigidity of the cutter-oscillator holder, it is easy to provide two degrees of freedom, eliminating torsional vibrations. The cutting force F is applied at point O on the free end of the cutter-oscillator. The direction of action of the cutting force (DAF) is located at an angle α to the Z axis. The direction of the resulting displacement (DRD) of the cutting edge does not coincide with any of the main axes of inertia of the state. The deformation of the cutter-oscillator that occurs in this case is known as "oblique" bending.

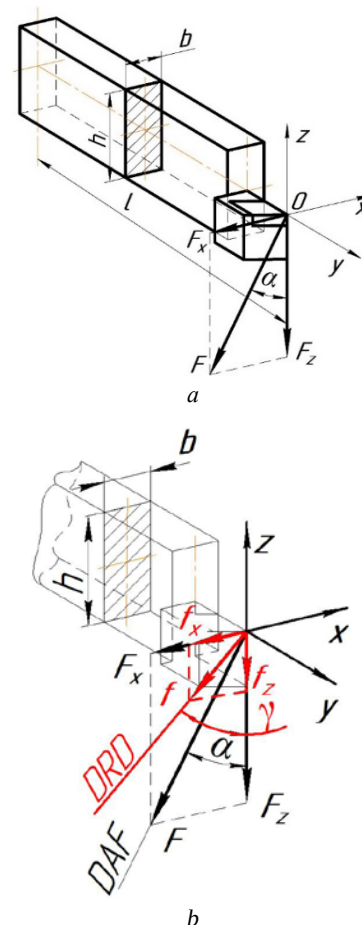


Figure 1. Design of a cutter-oscillator with two degrees of freedom (a) and a scheme for determining the DRD of the cutting edge of a cutter-oscillator (b)

For cutters-oscillators with two degrees of freedom, the “oblique” bend can be represented as the joint action of two axial bends f_x and f_z in two main mutually perpendicular planes of inertia (Fig. 1b). The magnitude of the “oblique” bend of the cutter-oscillator is calculated by the formula [13]:

$$f = \sqrt{f_x^2 + f_z^2}. \quad (1)$$

The plane in which the “oblique” bending of the cutter-oscillator occurs is inclined at an angle γ to the Z axis, the value of which can be found by equation [13]:

$$\operatorname{tg}(\gamma) = \frac{f_x}{f_z} = \frac{F_x}{F_z} \cdot \frac{l_x}{l_z} = \operatorname{tg}(\alpha) \cdot \frac{l_x}{l_z} \quad (2)$$

$$\gamma = \arctg \left[\operatorname{tg}(\alpha) \cdot \frac{l_x}{l_z} \right] = \arctg \left[\operatorname{tg}(\alpha) \cdot \left(\frac{h}{b} \right)^2 \right]. \quad (3)$$

To study vibration during turning, it is necessary to provide the possibility of oscillations of the cutter-oscillator in a certain direction, which may coincide:

- 1) With the direction of change in the thickness of the layer being cut (X axis).
- 2) With the direction of cutting speed (Z axis).

In the case of a cutter-oscillator with a rectangular cross-section of the holder, it is possible to artificially limit the bending only along one axis (X or Z), thereby realizing single degree of freedom. This is achieved by selecting the dimensions of the cross-section of the holder according to equation (3) in such a way that the angle of the DRD γ coincides with the X or Z axis. The cross-section diagrams of the cutter-oscillator holder for these cases are presented in Fig. 2.

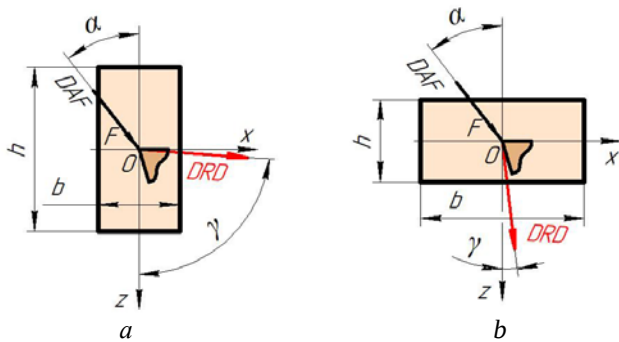


Figure 2. DRD for a cutter-oscillator with single degree of freedom along the X axis (a) and along the Z axis (b)

Modeling the angle of direction of the resulting cutting edge displacement

To model the DRD of the cutting edge due to the action of the cutting force components, the Unigraphics NX and SolidWorks programs were used. In the Unigraphics NX program, six solid-state models of cutter-oscillators with different ratios of the holder cross-section $h \times b$ were constructed (Fig. 3):

- for the cutter-oscillator with oscillations along the X axis (cutter-oscillator X): 60 mm $\times$ 8 mm, 60 mm $\times$ 15 mm, 60 mm $\times$ 30 mm;

- for the cutter-oscillator with oscillations along the Z axis (cutter-oscillator Z): 8 mm $\times$ 60 mm, 10 mm $\times$ 60 mm, 15 mm $\times$ 60 mm.

Next, the models were exported to the SolidWorks program for further calculations. The stages of the DRD modeling were the determination of:

- material parameters of the cutter-oscillator (steel 65G);
- fixation surfaces, depending on the toolholder overhang;
- components of the cutting forces acting on the cutting edge of the cutter-oscillator.

Using the SolidWorks program, a static analysis was performed, which allowed obtaining the axial deflections f_x and f_z of cutters-oscillators of all types under the action of the components of the cutting forces. Next, the DRD angle of the cutting edge γ was determined by formula (2).

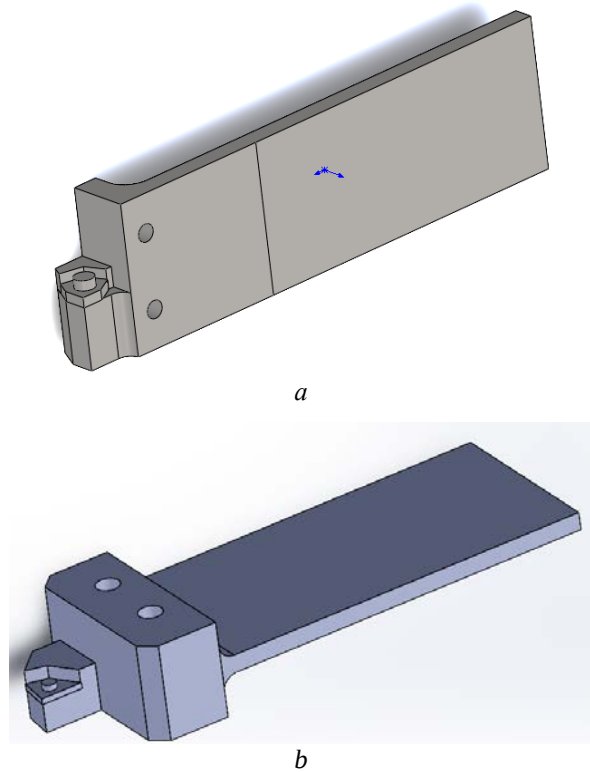


Figure 3. Models of cutters-oscillators:
a – cutter-oscillator X, 60 mm $\times$ 8 mm;
b – cutter-oscillator Z, 8 mm $\times$ 60 mm

Components of the cutting force were calculated by the formula [16]:

$$F_{z,x} = 10C_p t^x S^y v^n K_p, \quad (4)$$

where C_p – a constant that takes into account the processing conditions;

x, y, n – power indices;

t – cutting depth, mm;

S – feed, mm/rev;

v – cutting speed, m/min;

K_p – a generalized correction factor that takes into account changes in processing conditions relative to the tabular values.

$$K_p = K_{Mp} K_{\varphi p} K_{\gamma p} K_{\lambda p} K_{rp}, \quad (5)$$

where K_{Mp} – correction factor that takes into account the properties of the material being processed

$K_{\varphi p}$, $K_{\gamma p}$, $K_{\lambda p}$, K_{rp} – coefficients that take into account the geometric parameters of the cutting insert.

Since the cutting insert had principal approach angle $\varphi = 90^\circ$, the component of the cutting force along the X axis was absent.

The following cutting modes were adopted for the calculation: $t = 1$ mm, $S = 0.2$ mm/rev, $v = 150$ m/min, workpiece material – Steel 45 ($\sigma_B = 600$ MPa), without a cooling liquid.

Cutting insert parameters: material – hard alloy T15K6, $\gamma = 0^\circ$, $\alpha = 10^\circ$, $\varphi = 90^\circ$, $\lambda = 0^\circ$, $r = 0.5$ mm. According to equations (4), (5), the values of the components of the cutting forces were determined: $F_x = 279.9$ N $F_z = 304.6$ N. The angle of inclination of the cutting force was $-\alpha = F_x/F_z = 279.9/304.6 = 46.2^\circ$.

Experimental method for determining the angle of the resultant displacement direction

For the experimental study, a cutter-oscillator X was manufactured with the dimensions of the cross-sectional holder $h \times b = 60$ mm $\times$ 8 mm and a cutter-oscillator Z with the dimensions of the cross-sectional holder $h \times b = 8$ mm $\times$ 60 mm. A special device was used to install the cutters-oscillators in the tool holder of the lathe [14]. The cutter-oscillator was placed inside the device housing between two guide inserts. To adjust the departure of the cutter-oscillator, the inserts could move along the Y axis until they were fixed. Two inductive displacement sensors (mod. Schneider Electric XS4-P12AB110) were installed on the housing, with the help of which the oscillations of the cutting edge of the cutter-oscillator along the X and Z axes were monitored during turning (Fig. 4).



Figure 4. Image of the experimental setup

The study used round-section workpieces that had sufficient rigidity, which allowed us to neglect their own

vibrations during cutting.

When performing the experiments, the following cutting modes were used: $t = 1$ mm, $S = 0.2$ mm/rev, $v = 150$ m/min, workpiece material – Steel 45, without cooling liquid. Cutting insert parameters – alloy T15K6, $\gamma = 0^\circ$, $\alpha = 10^\circ$, $\varphi = 90^\circ$, $\lambda = 0^\circ$, $r = 0.5$ mm.

Signals from the displacement sensors were fed to a multi-channel analog-to-digital converter (mod. L-Card E140) and transmitted to a personal computer in the form of oscillograms. On the obtained oscillograms, the static deviation B_x , B_z of the cutting edge along the X and Z axes during turning was measured (Fig. 5). Before conducting the research, the cutters-oscillators were calibrated using a dynamometer DOSM-3-0.2 and a clock-type indicator ICH10B.

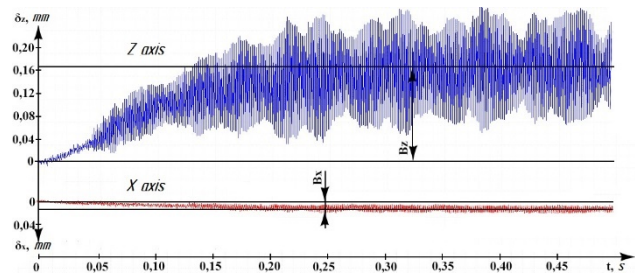


Figure 5. Example of an oscillogram for a cutter-oscillator Z

Research results and discussion

Fig. 6, 7 present the results of static analysis of cutter-oscillators in the SolidWorks environment. The toolholder overhang was $l = 100$ mm.

Table 1 shows the results of calculating the angle of the cutting edge DRD γ depending on the ratio of the cross-sectional dimensions of the cutter-oscillator holder, obtained by the analytical method, according to formula (3), and using computer modeling, formula (2).

The values of static deflections of the cutters-oscillators obtained from the oscillograms were:

1) for the cutter-oscillator X: $B_x = f_x = 0.175$ mm; $B_z = f_z = 0.011$ mm;

2) for the cutter-oscillator Z: $B_x = f_x = 0.013$ mm; $B_z = f_z = 0.166$ mm. Accordingly, according to formula (3), the experimentally obtained and calculated angle of the DRD for the cutter-oscillator X was $\gamma = 86.4^\circ$, and for the cutter-oscillator Z – $\gamma = 4.5^\circ$.

Based on the results of analytical calculations, computer modeling, and experiments, histograms were constructed (Fig. 8).

The obtained results showed that the analytical method of calculating the angle of the DRD does not take into account the geometric features of the real design of the cutter-oscillator. At the same time, the method of computer modeling using the SolidWorks analysis module allows you to obtain more accurate results, close to the characteristics of the actually manufactured cutter-oscillators. This emphasizes the advantage of static computer analysis in comparison with analytical and experimental methods, especially given the complexity of the design and the high cost of manufacturing cutters-oscillators.

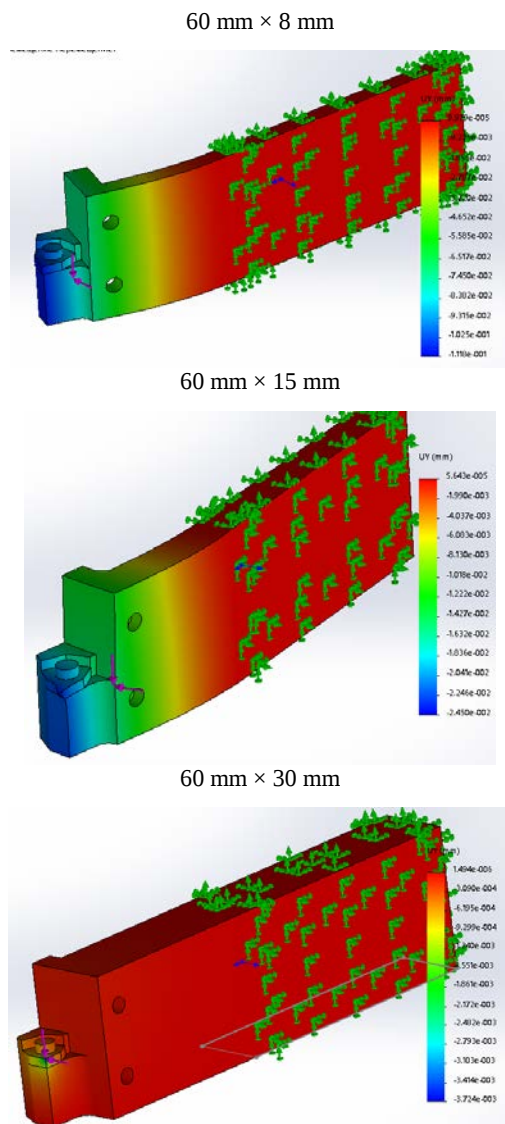
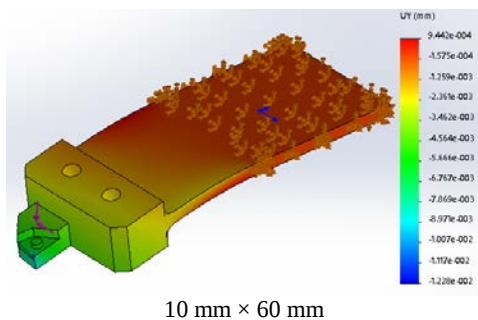


Figure 6. Results of static analysis in SolidWorks (cutter-oscillator X)
8 mm × 60 mm



10 mm × 60 mm

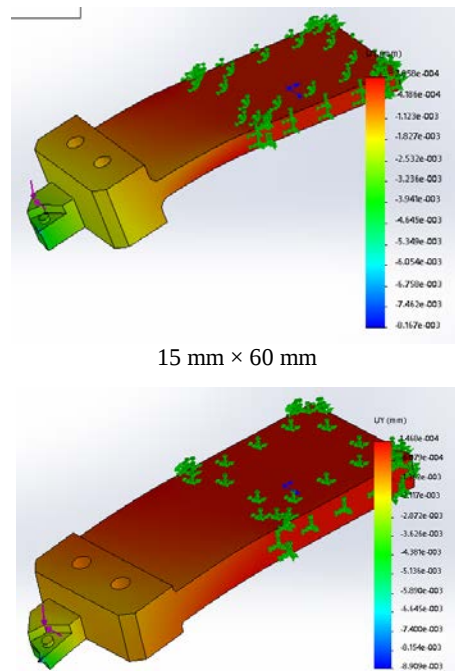


Figure 7. Results of static analysis in SolidWorks (cutter-oscillator Z)

Table 1 – Results of calculation of the cutting edge angle of the DRD γ , deg

Parameters	Analytical method					
	Cutter-oscillator X			Cutter-oscillator Z		
h , mm	60	60	60	8	10	15
b , mm	8	15	30	60	60	60
h/b	7.5	4	2	0.13	0.16	0.25
γ , deg	89.0°	86.6°	76.5°	1.0°	1.6°	3.7°
Parameters	Computer modeling method					
	Cutter-oscillator X			Cutter-oscillator Z		
h , mm	60	60	60	8	10	15
b , mm	8	15	30	60	60	60
f_x , mm	0.108	0.033	0.009	0.013	0.008	0.008
f_z , mm	0.007	0.007	0.006	0.426	0.090	0.036
γ , deg	86.0°	78.0°	56.3°	1.7	5.2	12.6

The modeling results are in high agreement with experimental data, which confirms the feasibility of using computer modeling in the design of cutter-oscillators.

Additionally, calculations have shown that to ensure the optimal angle of deflection of the DRD γ (no more than 5° relative to the X or Z axis), it is necessary to adhere to the ratio of the dimensions of the holder cross section:

- for the cutter-oscillator X: $h/b > 3.3$;
- for the cutter-oscillator Z: $h/b < 0.3$.

Such a minimum deflection of the angle γ from the axis gives grounds to assert that the cutter-oscillator performs oscillatory movements mostly along one X or Z axis, i.e. has single degree of freedom. Thus, the results of the study confirm that the cutter-oscillator with oscillations along the X axis allows for an isolated study of the influence of the regenerative effect on the excitation of self-oscillations. In turn, the oscillations of the cutter-oscillator

along the Z axis make it possible to analyze the occurrence of self-oscillations when the instantaneous cutting speed changes and in the absence of a regenerative effect.

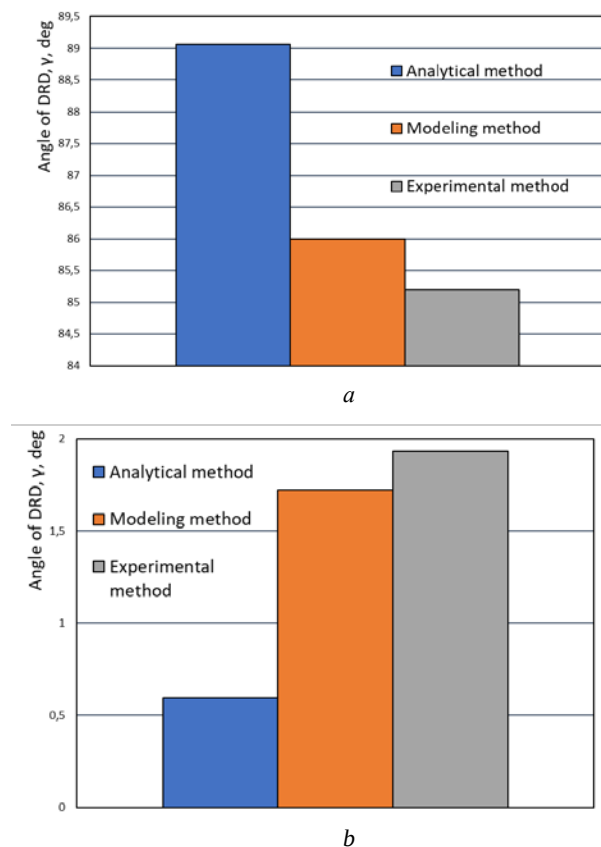


Figure 8. Results of the calculation of the DRD:
a - cutter-oscillator X, $h \times b = 60 \text{ mm} \times 8 \text{ mm}$,
b - cutter-oscillator Z, $h \times b = 8 \text{ mm} \times 60 \text{ mm}$

Conclusions

The dynamic characteristics of the turning process should be investigated using cutters-oscillators with single degree of freedom, which provide the possibility of accurate measurement of both static and dynamic components of cutting forces. This approach allows to eliminate the coordinate coupling and to study individual mechanisms of self-oscillations.

The proposed methods for determining the direction of the resulting movement of the cutting edge of the cutter-oscillators demonstrate similar results, which indicates their consistency and practical applicability. The results of the study confirmed the possibility of effective use of the computer modeling method. The choice of a specific method may depend on the available equipment and the convenience of its implementation in the conditions of a specific experiment.

The optimal ratios of the dimensions of the holder section were obtained: for the cutter-oscillator X: $h/b > 3.3$; for the cutter-oscillator Z: $h/b < 0.3$, which provide the minimum values of the direction angle of the resulting movement - γ (no more than 5°), i.e. single degree of freedom.

Analysis of the obtained data showed sufficient accuracy of calculations and reproducibility of results, which allows us to recommend this approach for the development and optimization of the design of cutters-oscillators with one-dimensional oscillations.

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МОДЕЛЮВАННЯ КУТА НАПРЯМКУ РЕЗУЛЬТУЮЧОГО ПЕРЕМІЩЕННЯ РІЗАЛЬНОЇ КРОМКИ РІЗЦЯ-ОСЦИЛЯТОРА

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Мета роботи. Встановлення залежності кута напрямку результуючого переміщення різальної кромки різця-осцилятора від геометричних параметрів державки різними методами та обґрунтування доцільності використання різців з одним ступенем свободи для цілеспрямованого моделювання впливу окремих факторів, таких як регенеративний ефект або зміна миттєвої швидкості різання.

Методи дослідження. Аналітичний метод передбачав отримання розрахункових формул для визначення кута напрямку результуючого переміщення різця-осцилятора. Для чисельного моделювання вигинів різця-осцилятора при точінні використовувалися програми SolidWorks та Unigraphics NX. Дослідження також проводили експериментальним методом, при якому записували осцилограми коливань різальної кромки, по яких визначали статичні вигини різця-осцилятора.

Отримані результати. Розроблено методики визначення напрямку результуючого переміщення різальної кромки різця-осцилятора на основі аналітичного розрахунку, комп'ютерного моделювання та експериментального методу. Проведено комп'ютерне моделювання вигинів різців-осциляторів у програмі SolidWorks, що дозволило з високою точністю визначити кут напрямку результуючого переміщення різальної кромки при різних співвідношеннях розмірів державки різця. Показано, що оптимальне співвідношення висоти до ширини державки ($h/b > 3,3$ для осцилятора X; $h/b < 0,3$ для осцилятора Z) забезпечує напрямок переміщення з відхиленням не більше 5° від осі X та Z, відповідно. Експериментально підтверджено точність методу комп'ютерного моделювання, що дозволяє застосовувати його для проєктування різців-осциляторів із заданими динамічними властивостями.

Наукова новизна. Встановлено оптимальну залежність кута напрямку переміщення різальної кромки різця-осцилятора від геометричних параметрів державки, що дозволяє керувати орієнтацією коливань під час різання.

Практична цінність. Результати роботи можуть бути використані при проєктуванні різців-осциляторів для дослідження динаміки процесу точіння. Розроблена методика дозволяє знизити витрати на виготовлення дослідних зразків різців-осциляторів за рахунок попереднього моделювання їх характеристик у CAD/CAM середовищі.

Ключові слова: осцилограма, автоколивання, ступінь свободи, регенеративні автоколивання, швидкість різання.

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TAKING FRICTION INTO ACCOUNT IN KINETOSTATIC ANALYSIS OF MECHANISMS

Purpose. Study the dynamics and characteristics of friction using the example of translational kinematic pairs.

Research methods. The theoretical aspects of friction research in translational kinematic pairs are examined in detail. The introduction of friction forces into the equations of kinematics leads to an increase in the number of unknown reaction components in kinematic pairs, while the number of equations remains unchanged. The force calculation of mechanisms taking into account friction comes down to a joint solution of kinematics equations containing friction forces as additional unknowns and relations obtained while considering the corresponding models of kinematic pairs of friction.

Results. As a result, analytical dependencies were obtained for determining the speed, acceleration and reaction from the magnitude of the slider displacement, and changes in the power parameters of the piston pump due to wear of the parts of the reciprocating slider-guide pair were analyzed.

Scientific novelty. The current level of technological progress requires constant improvement of product quality and productivity to make it competitive. This leads to increased requirements for the performance characteristics of moving joints in mechanisms and machines operating under extreme conditions of friction and wear. Friction forces arise in the kinematic pairs of mechanisms, and in many cases these forces significantly affect the movement of the mechanism links and must be taken into account in force calculations. The energy costs associated with overcoming harmful resistance forces are irreversible, and the reduction of irreversible energy costs is achieved by limiting friction forces.

Practical value. The results of the research showed that the wear of the parts of the translational kinematic pair of the slider and the pump guides leads to an insignificant change in both the speed, and acceleration of the slider, at the same time, the maximum reaction in this kinematic pair changes more significantly.

Key words: kinetostatics, kinematic pair, friction, wear, resistance reactions, equilibrium equations.

Introduction

Every new step in the development of machines, mechanisms and devices is associated with a deep study of the phenomena occurring on the contact surfaces of parts, taking into account their strength, material properties and the peculiarities of destruction processes. In the context of combating wear, the development of a general theory of material wear becomes particularly relevant, which allows not only to predict the resource of parts, but also to increase the reliability and efficiency of modern technical systems. [1].

The general problem of reliability, accuracy and durability of machines, mechanisms and devices is mainly related to issues of friction, lubrication, wear of surfaces of parts and working bodies that interact with each other in complex conditions.

It has been established that today approximately one-third to one-half of the world's energy resources are spent in one form or another on friction. In translational kinematic pairs, friction has a complex nature, which changes dynamically depending on the speed, load, surface condition and lubrication. This directly affects the efficiency, durability and reliability of aircraft pumps, engines, hydraulic

drives. Therefore, the importance of the problem of friction and wear of machine parts in today's highly mechanised world cannot be overestimated [1]. Since the wear of moving joints under the influence of friction forces leads to premature failure of machines and unjustifiably high repair costs, special attention is paid to preventing wear in machines and mechanisms.

Most problems are solved using analytical calculation methods. Analytical methods can be divided into: simplified (classical (Coulomb friction), energy method) – for educational and approximate problems and advanced (Dahl model, LuGre friction model) – for accurate modelling in real mechanisms.

However, the obtained results often differ from the actual loads in the mechanisms. In addition, these calculations do not take into account the influence of aggressive factors of corrosive and abrasive environments, in which the equipment often operates [2].

It should be noted that the problem of determining friction coefficients and corresponding losses of parts and mechanisms has not been fully resolved. Determination of friction coefficients and corresponding energy losses in parts and mechanisms is one of the key and not yet fully solved problems of modern tribology and the theory of mechanisms. The problem of determining friction coefficients and energy losses in mechanisms remains open, since: the friction coefficient is not a constant value, its value depends on a complex set of factors, calculation models require experimental confirmation. Today, hybrid methods are used (a combination of theoretical models, computer simulations and experimental measurement).

Therefore, considering the abovementioned, the aim is to study tools and methods for analysing friction processes in kinematic pairs, which will enable the development of proposals for structural improvements, taking into account energy consumption in the system.

Analysis of research and publications

It is known that the forces counteracting displacement in any system are represented by useful and harmful resistance forces. The ratio of these forces determines the efficiency and durability of the system. The designer's task is to minimize harmful resistance (through lubrication, selection of materials, balancing of mechanisms). Useful or technological resistance is determined by the characteristics of the mechanism itself and, for given conditions, in most cases cannot be varied [3, 4]. In contrast, it is possible to limit harmful resistance within certain limits.

Equipment efficiency, with all other things being equal, is linked to a bunch of kinematic parameters in the chain from the engine to the working body, as well as the ability to create parallel or branched flows for specific purposes [3]. In the solution of problems of synthesis of technological machines, it is precisely the kinematic part that plays a decisive role. This is especially true for machines with periodic (cyclical) action, since the set of transient processes associated with their start and stop is supplemented by transient processes caused by reciprocating movements of

links. In addition to these, in many cases, kinematic or dynamic disturbances are added, which are a consequence of the structural features of the machines themselves.

Today, the development of automatic machine theory is mainly driven by the need to improve control system design methods that ensure the coordination of executive bodies. This is because the energy costs associated with overcoming harmful resistance forces (friction forces) are irreversible and are accompanied by the conversion of mechanical energy of motion into thermal energy [5].

Irreversible energy losses are reduced by limiting friction forces, which are mainly determined by the force interaction between moving and stationary parts and the values of friction coefficients [4]. The former depend on the condition and materials of contact surfaces, friction modes, relative sliding speeds, preliminary contact time, etc.

The necessity to study the wear resistance of machine parts is caused by significant economic costs of repairs and upgrades. High costs for repair and replacement of parts: in industry, up to 70 % of machine downtime is due to friction and wear. Reduced efficiency and productivity: wear increases energy losses due to friction, increases fuel and electricity consumption. Extending the life of parts directly reduces maintenance costs.

According to tribologists, in highly developed countries, losses in mechanical engineering associated with friction and wear reach about 8 % of national income. These losses are formed due to increased costs for fuel and energy (due to increased friction forces); repairs and replacement of parts that wear out quickly; a decrease in the efficiency of machines and mechanisms; forced downtime of production. Thus, even a 1% reduction in friction on the scale of the national economy can provide a colossal economic effect, namely billions of savings on repairs and energy resources; an increase in the resource of machines and mechanisms; a decrease in the cost of production; an increase in the competitiveness of the industry [6].

With the development of scientific and technological progress, the need for complex calculations of resistance forces in loaded, automatic and particularly precise friction units has become relevant, and the need to ensure their anti-friction properties under operating conditions has also arisen. Today, many industries require the creation of special devices and braking systems, where the work is directly based on the laws of friction. For example, aviation and transport – wheel and disc brakes, aircraft landing brake systems; mechanical engineering – brake clutches, clamping devices, friction gears; energy – turbine and generator braking systems; robotics and mechatronics – precision control systems, where the use of friction provides positioning and stabilization.

Thus, the study of the interaction of surfaces in relative motion, as well as the consequences associated with this phenomenon, and the determination of the possibility of influencing friction coefficients in the direction of their reduction, is a relevant scientific task today, which has significant theoretical and practical significance. The study of friction between moving surfaces and methods for its re-

duction is an urgent task of modern science and technology. This research is important both from a theoretical point of view - for a better understanding of the processes of interaction of materials, and from a practical point of view - for increasing the reliability, energy efficiency and durability of machines and mechanisms.

Nowadays, the effectiveness of friction research in kinematic pairs, which affects moving joint systems during mechanical testing, has been demonstrated in several scientific studies [7–9]. A structural-energy theory of friction and wear in machines has also been developed, which is widely known throughout the world and became the basis for modern methods of calculating the service life of machine parts, selecting materials and lubricants. It is actively used in aviation, mechanical engineering, transport and energy, where the problem of wear is particularly relevant [10].

At the same time, despite the significant scientific heritage that exists today, questions remain regarding the justification of optimal design solutions, as well as the correct choice of materials and the determination of rational technological methods for manufacturing and strengthening machine parts.

Purpose

The aim of the study is to identify the patterns of dynamics and characteristics of friction processes in translational kinematic pairs, determine their impact on the force and kinematic parameters of mechanisms, and develop approaches to account for friction (including the influence of wear and changes in friction coefficients) in kineto-static analysis to improve the accuracy of calculations, reliability and durability of machines and devices.

Therefore, taking into account the abovementioned, the purpose of this article is to study the dynamics and characteristics of friction using the example of translational kinematic pairs.

Material and research methods

Friction is the resistance that arises when one body moves relative to another. The surfaces that come into contact with each other are called friction surfaces. There are two main types of friction: sliding friction and rolling friction [2].

In lower kinematic pairs, sliding friction prevails, while in higher pairs, rolling friction or a combination of rolling and sliding friction may occur.

First, let us consider in detail the theoretical aspects of friction research in translational kinematic pairs. Therefore, friction occurs when the slider slides along a horizontal plane.

Fig. 1 shows a moving kinematic pair consisting of a horizontal guide 2 and a slider 1.

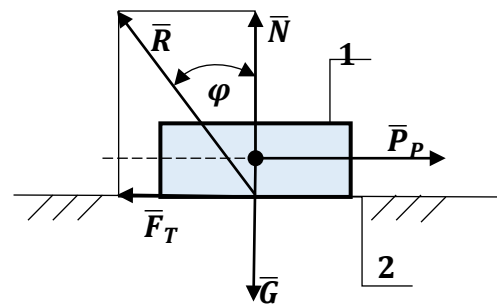


Figure 1. Kinematic pair with translational motion

Let the following forces act on slider 1: $\bar{P}_P$ – translational force, $\bar{G}$ – weight of the load or load acting on the slider, $\bar{N}$ – normal reaction, $\bar{F}_{T_0}$ – friction force (tangential reaction) at rest. When the slider moves, instead of the friction force at rest, the friction force of motion $\bar{F}_T$ acts, where $N = -G$ and the total reaction

$$R = F_T + N.$$

The angle φ of deviation of the total reaction from the normal in the direction opposite to the movement of the slider is called the friction angle. Therefore:

$$F_{T_0} = N \cdot \operatorname{tg} \varphi_0; \quad F_{T_0} = f_0 \cdot G; \quad \text{where } f_0 = \operatorname{tg} \varphi_0.$$

Considering that

$$F_T = N \cdot \operatorname{tg} \varphi = G \cdot \operatorname{tg} \varphi; \quad F_T = f \cdot G,$$

we will have

$$f = \operatorname{tg} \varphi.$$

Therefore, the coefficient of friction is equal to the tangent of the angle of friction. If the direction of the slider's movement is changed, the total reaction will deviate accordingly. The geometric locus of total reactions is the lateral surface of a straight cone (Fig. 2).

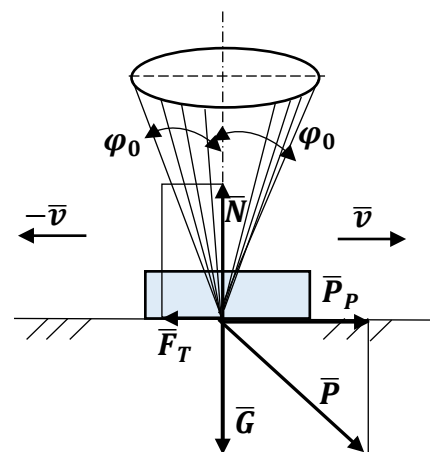


Figure 2. Friction cone

The friction cone has the following features:

- if the resultant $\mathbf{P}$ of the driving force $\mathbf{P}_P$ and the gravitational force $\mathbf{G}$ passes inside the friction cone, then $\mathbf{P}_P < \mathbf{F}$. Therefore, the body will not move from its place;
- if the resultant $\mathbf{P}$ of the driving force $\mathbf{P}_P$ and the force of gravity $\mathbf{G}$ passes outside the friction cone, then $\mathbf{P}_P > \mathbf{F}$ and the body will move from its place.

Obviously, when starting from rest $\mathbf{P}_P > \mathbf{f}_0 \cdot \mathbf{G}$; under equilibrium conditions, $\mathbf{P}_P < \mathbf{f}_0 \cdot \mathbf{G}$; in the case of uniform motion, $\mathbf{P}_P = \mathbf{f} \cdot \mathbf{G}$; in the case of accelerated motion, $\mathbf{P}_P > \mathbf{f} \cdot \mathbf{G}$.

Fig.3 shows the dependence of the friction force $\mathbf{F}_T$ on the driving force $\mathbf{P}_P$, ($\mathbf{F}_T = \mathbf{f}(\mathbf{P}_P)$).

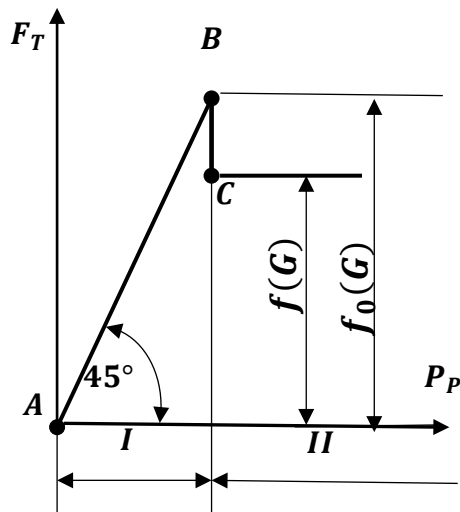


Figure 3. The graph of the dependence of $\mathbf{F}_T$ on $\mathbf{P}_P$.

Point A corresponds to the state of rest $\mathbf{P}_P = \mathbf{0}$ and $\mathbf{P} = \mathbf{0}$; section I corresponds to the state of equilibrium $\mathbf{P}_P \neq \mathbf{0}$, but $\mathbf{v}_k = \mathbf{0}$; section II corresponds to the state of motion $\mathbf{P}_P \neq \mathbf{0}$ and $\mathbf{v}_k \neq \mathbf{0}$; the limiting friction force $\mathbf{F}_{T0} = \mathbf{f}_0 \cdot \mathbf{G}$. In this case, friction force is understood as the force of adhesion. The values of the coefficients of sliding friction are given in Table 1. It should be remembered that these values are approximate and may vary depending on surface quality, temperature and other factors.

Table 1 – Friction coefficients in various kinematic pairs

Material of the pair	f_0		f	
	dry surfaces	lubricated	dry surfaces	lubricated
Steel on steel	0.15	0.11	0.13	0.09
Steel on bronze	0.11	0.10	0.10	0.09
Copper on steel	0.53	0.36	0.36	0.18
Brass on steel	0.51	0.19	0.35	0.16

In addition to the design, technological and operational factors discussed above, the shape and location of the elements of the kinematic pair also affect the friction coefficient [10–12]. For different types of pairs, reduced friction coefficients are determined [9].

Now let's take a closer look at how the characteristics of the friction process are determined in practice.

For example, piston pumps are widely used in oil and gas production, as well as in oil refining, since other types of pumps are unsuitable due to the intensive wear of hydraulic parts. There are studies that examined wear and considered various methods of increasing the durability of parts of the hydraulic part of piston pumps, but without taking into account the wear of parts of the mechanical drive part [13, 14]. There are also works [15] in which data for the kinematic and force calculation of the crank-slider mechanism of the pump was obtained. However, the authors did not take into account the wear of the reciprocating pair 'crosshead (slider) – guides'.

Let us analyse the changes in the kinematic and force parameters of a piston pump due to wear of the reciprocating pair of parts: the crosshead (slider) and the pump frame guides.

In the drive of piston pumps for converting rotary motion into reciprocating motion, a crank-slider mechanism with one degree of freedom is used (Fig. 4).

To study the effect of slider displacement due to wear of the kinematic pair parts of the crosshead (slider) – guide rails of a horizontal type piston pump, two-cylinder, double-acting (cranks are positioned at an angle of 90° in the direction of rotation) on its kinematic and power parameters, equations of closed vector contours $OABCO$ and OA_1B_1CO were compiled. To simplify, we assume that the displacement of the slider does not lead to a skew of the rod axis, and we give formulas only for one contour $OABCO$. Let us write down the vector equation:

$$\ell_1 + \ell_2 = \bar{e} + \bar{x}_B.$$

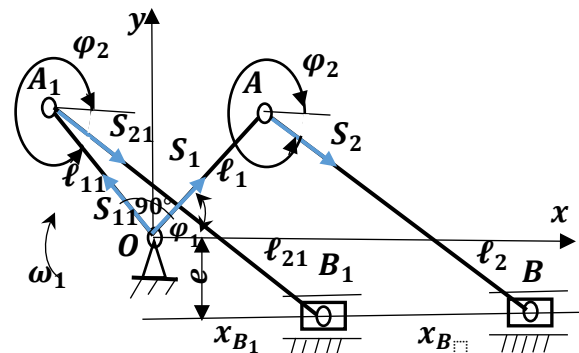


Figure 4. Kinematic scheme of the drilling pump mechanism

After performing the appropriate transformations, we obtain the following ratios:

$$x_A = \ell_1 \cos \varphi_1;$$

$$y_{S_1} = \ell_{S_1} \sin \varphi_1;$$

$$x_{B_1} = \ell_1 \cos \varphi_1 + \sqrt{\ell_2^2 - (\ell_1 \sin \varphi_1 + e)^2};$$

$$y_A = \ell_1 \sin \varphi_1; \quad x_{S_2} = \ell_1 \cos \varphi_1 + \ell_{S_2} \cos \varphi_2; \quad y_B = e;$$

$$x_{S_1} = \ell_{S_1} \cos \varphi_1; \quad y_{S_1} = \ell_{S_1} \sin \varphi_1 + \ell_{S_2} \sin \varphi_2.$$

Here e - s the displacement of the slider due to wear of the crosshead pads and pump frame guides.

As a result of differentiation of the aforementioned equations by the generalised coordinate φ_1 we obtain the dependencies of the change in projections of the analogues of the velocities of point A , centres of mass S_1 of crank OA , S_2 of connecting rod AB and slider B on the angle of rotation of the crank and the displacement e of slider B respectively:

$$x'_A = -\ell_1 \sin \varphi_1; \quad y'_{S_1} = \ell_{S_1} \cos \varphi_1;$$

$$x'_B = \ell_1 \tan \varphi_2 \cdot \cos \varphi_1 - \ell_1 \sin \varphi_1;$$

$$y'_A = \ell_1 \cos \varphi_1;$$

$$x'_{S_2} = -\ell_1 \sin \varphi_1 - \ell_{S_2} \sin \varphi_2 \cdot \varphi_2'; \quad y'_B = 0;$$

$$x'_{S_1} = -\ell_{S_1} \sin \varphi_1; \quad y'_{S_1} = \ell_1 \cos \varphi_1 + \ell_{S_2} \cos \varphi_2 \cdot \varphi_2'.$$

where $x'_A; y'_A; x'_{S_1}; y'_{S_1}; x'_{S_2}; y'_{S_2}; x'_B; y'_B$ - projections of the analogues of the velocities of points A and B , centres of mass S_1 and S_2 from the crank rotation angle φ_1 and the displacement value e of slider B respectively. The rotation angle of connecting rod AB :

$$\varphi_2 = \arcsin \left(-\frac{\ell_1 \sin \varphi_1 + e}{\ell_2} \right).$$

Having differentiated the above dependencies of projection changes in a similar way, we obtain the dependencies of projection changes of analogues of accelerations of point A , centres of mass S_1 of crank OA , S_2 of the connecting rod AB and slider B from the crank rotation angle φ_1 and the displacement value e of slider B .

We use the obtained results of the kinematic calculation to perform a force analysis of the pump mechanism and study the effect of the slider displacement on the reactions in the translational kinematic pair of the crosshead and the pump frame guides. To do this, we analyse the structural group of the connecting rod and slider using the principle of kinematics (Fig. 5).

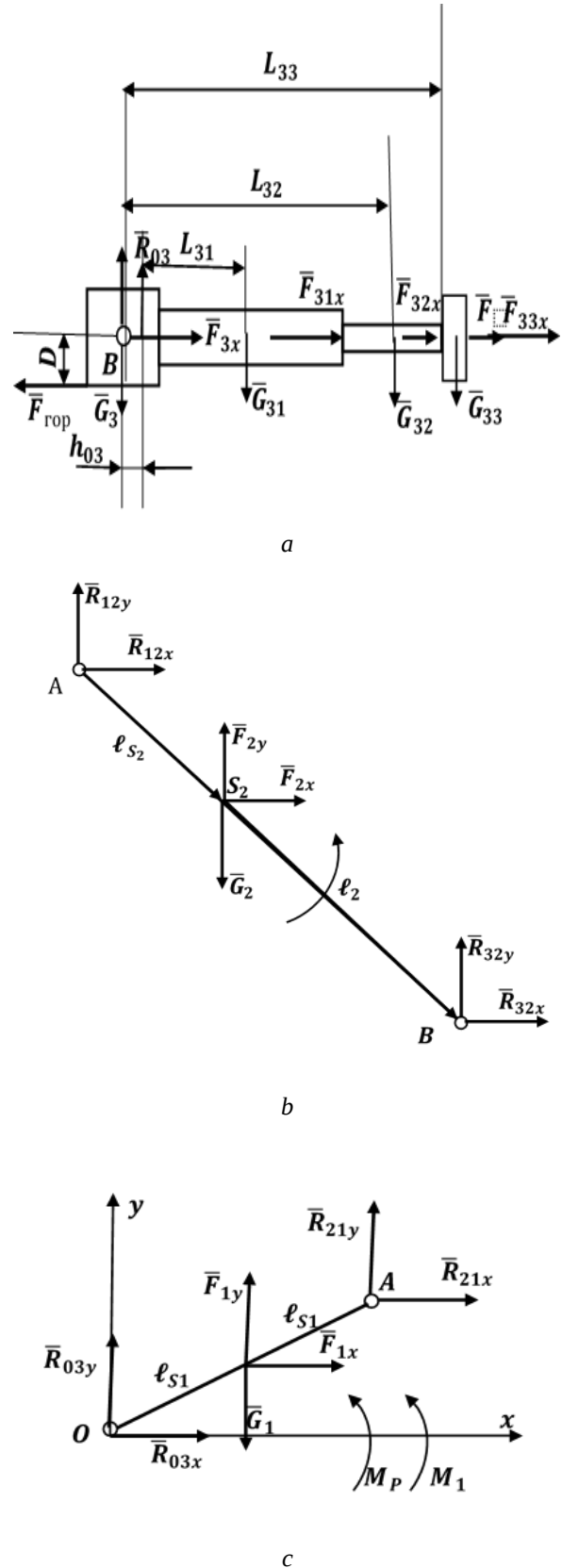


Figure 5. Force analysis of the pump mechanism:
a – slider B ; b – connecting rod AB ; c – crank OA

The kinematic equations for each link of the pump mechanism are as follows:
for connecting rod AB :

$$\begin{cases} R_{12x} + F_{2x} + R_{32x} = 0 \\ R_{12y} + F_{2y} + R_{32y} - G_2 = 0 \\ M_B R_{12} + M_B F_2 + M_B G_2 + M_2 = 0; \end{cases}$$

for slider B :

$$\begin{cases} R_{23x} + F_{3x} + R_{31x} + F_{32x} + F_{33x} + \\ F - \mu_1(v_B)R_{03} = 0 \\ R_{23y} + R_{01} - G_3 + G_{31} - G_{32} - G_{33} = 0 \\ R_{03} \cdot h_{03} + \mu_1(v_B)R_{03}^{0.5}D - G_{31}l_{31} - \\ G_{32}l_{32} - G_{33}l_{33} = 0; \end{cases}$$

for crank OA :

$$\begin{cases} R_{01x} + R'_{21x} + R_{21x} + F_{1x} + F_{11x} = 0 \\ R_{01y} + R_{21y} + R'_{21y} - G_1 + G_{11} + F_{1y} \\ + F_{11y} = 0 \\ M_O R_{21} + M_O R'_{21} + M_O F_1 + M_O F_{11} + \\ M_O G_1 + M_O G_{11} + M_1 + M_P = 0; \end{cases}$$

where R_{ijx} , R_{ijy} – are projections of the force (reaction) acting on the i -th link;

$F_{ijy} = -a_{ixy}m_i$ – is the projection of the inertia force of the i -th link;

F – is the resistance force applied to the slider, taking into account the friction forces in the pairs: seal – rod and piston – sleeve;

G_i – is the gravitational force of the i -th link;

D – is the diameter of the slider ('crosshead');

$M_i = -E_i J_i$ – is the moment of inertia forces of the i -th link;

μ_1 – friction coefficient in the translational kinematic pair of the crosshead and the pump guide rails.

Research results and their discussion

The solutions of the systems of equations are used to determine the reactions in the kinematic pairs of the pump mechanism for different values of the crank rotation angle φ_1 and different displacements e of the slider B . Based on the obtained data, it is possible to construct graphical dependencies $R_{03max} = f(S_B)$ for the maximum – 25 MPa (piston diameter $D_n = 130$ mm) and minimum – 10 MPa (piston diameter $D_n = 200$ mm) values of pump pressure at $e = 0$, for direct (piston movement into the rodless chamber of the pump) and reverse (piston movement into the rod chamber of the pump) pump strokes. The stroke of the pump piston is $s = 0,4$ m.

For the range $e = \pm 5$ mm, the dependence of the maximum reaction in the reciprocating pair for both forward and reverse pump strokes is linear. For the forward stroke of the pump, the maximum reaction increases with an increase in the displacement of the slider (direct relation-

ship), and for the reverse stroke, the maximum reaction decreases with an increase in the displacement of the slider (reverse relationship). That is, for forward stroke, an increase in the slider displacement (vertically down) leads to an increase in the maximum reaction in the reciprocating pair, which in turn leads to increased wear of the slider linings and pump guide rails.

The results of the research showed that the wear of the parts of the translational kinematic pair of the crosshead (slider) and the pump guides leads to an insignificant change in both the speed (0.07 %), and acceleration (0.0014 %) of the slider B . At the same time, the maximum reaction in this kinematic pair changes more significantly. During the forward stroke of the piston, it increases by 2.5 %, and during the reverse stroke of the piston, it decreases by 2.4 %.

Conclusions

The theoretical and practical aspects of friction research in translational kinematic pairs and models for determining velocity, acceleration, and reaction from slider displacement using the example of a piston pump described in this article make it possible to more accurately determine their numerical values during the wear of certain parts of machines and mechanisms, in particular the slider and the pump guide rails. These results should be used to select modes during testing for wear of materials for parts of translational kinematic pairs.

External friction in braking systems and special devices acts not only as a resistance factor, but as a controlled technological element that requires accurate mathematical description, prediction, and effective use.

Thus, in conclusion, it can be noted that the theoretical analysis of the friction process in translational kinematic pairs conducted during the study makes it possible to accurately assess the level of losses from wear and tear of parts, taking into account the values of the design parameters of mechanisms, and can be used to predict the effective performance of the designed technological equipment.

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УРАХУВАННЯ ТЕРТЯ ПРИ КІНЕТОСТАТИЧНОМУ АНАЛІЗІ МЕХАНІЗМІВ

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Мета роботи. Дослідження динаміки та особливості процесів тертя на прикладі поступальних кінематичних пар.

Методи дослідження. Детально розглянуті теоретичні аспекти дослідження тертя в поступальних кінематичних парах. Введення сил тертя в рівняння кінетостатики призводить до збільшення числа невідомих компонент реакцій в кінематичних парах, а кількість рівнянь при цьому залишається незмінною. Силовий розрахунок механізмів з урахуванням тертя зводиться до сумісного рішення рівнянь кінетостатики, що містять сили тертя в якості додаткових невідомих, та співвідношень, отриманих при розгляданні відповідних моделей кінематичних пар із тертям.

Отримані результати. Отримані аналітичні залежності для визначення швидкості, пришвидження і реа-

кції від величини зміщення повзуна, проаналізовано зміни силових параметрів поршневого насоса внаслідок зношування деталей зворотньо-поступальної пари повзун – напрямні.

Наукова новизна. Сучасний рівень технічного прогресу потребує постійного вдосконалення продукції за якістю та продуктивністю, роблячи її конкурентною. Це призводить до підвищення вимог щодо експлуатаційних характеристик рухомих з'єднань в механізмах і машинах, які працюють в екстремальних умовах тертя та зношування. В кінематичних парах механізмів виникають сили тертя і в багатьох випадках ці сили істотно впливають на рух ланок механізмів і повинні враховуватись при силових розрахунках. Енерговитрати, пов'язані з подоланням сил шкідливого опору, є незворотними, а зменшення незворотних енергетичних витрат здійснюється завдяки обмеженню сил тертя.

Практична цінність. Дослідження показали, що зношування деталей поступальної кінематичної пари повзун – напрямні насоса призводить до несуттєвої зміни як швидкості, так і прискорення повзуна, при цьому величина максимальної реакції в цій кінематичній парі змінюється істотніше.

Ключові слова: кінестатика, кінематична пара, тертя, зношування, реакції опор, рівняння рівноваги.

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ANALYSIS OF METHODS FOR MAKING HOLES IN METAL WITH A THICKNESS OF MORE THAN 10 mm

Purpose. The aim of this study is to review and comparatively analyze modern methods for creating holes in metal workpieces with a thickness of over 10 mm, evaluate their efficiency, and investigate the influence of processing parameters on the quality of the resulting holes. Attention is given to conventional methods, such as drilling and punching with specialized tools, as well as non-traditional methods, including waterjet abrasive cutting, laser cutting, and electrical discharge machining (EDM).

Research methods. The study employed a literature review and experimental investigations. Experimental methods included step drilling, reaming, milling, hydro-abrasive cutting, laser cutting, EDM drilling, and cold stamping. Hole quality was assessed using geometric measurements, surface roughness analysis, and examination of deformation zones. Experimental setups included variable punch and die designs to study the influence of tool geometry, punch-die clearance, and cutting forces on hole quality.

Results. It was determined that each method has distinct advantages and limitations. Punching is most effective for high-speed, mass production with consistent geometry but requires precise tooling and rigid press equipment. Drilling and laser cutting are suitable for single or small-series production, offering high accuracy but slower speed. Hydro-abrasive cutting provides smooth edges and minimal thermal impact, though it is expensive and slower for small holes. EDM ensures exceptional precision for hard or high-alloy materials but has low productivity. Comparative analysis highlighted the influence of process parameters, such as punch-die clearance, cutting force, feed rate, and tool design, on the quality and accuracy of holes.

Scientific novelty. The study provides a systematic comparison of multiple hole-making methods for thick metal workpieces, integrating experimental results with process parameter analysis. The novelty lies in identifying optimal parameters and tool designs that minimize edge defects and deformation, offering guidance for high-precision hole formation in thick metals, which has not been comprehensively addressed in previous research.

Practical value. The findings can guide the selection of appropriate hole-making technologies in industrial metal-working, optimize productivity, improve surface quality and dimensional accuracy, reduce material waste, and inform the design of tooling and press equipment for mass and small-series production.

Key words: hole-making methods, thick metal workpieces, punching, drilling, laser cutting, hydro-abrasive cutting, EDM, cold stamping, process optimization, surface quality.

Introduction

In modern mechanical engineering, aviation, energy and construction industries, there is often a need to create high-quality holes in metal blanks of considerable thickness - over 10 mm, where the holes must have high precision, even edges and minimal material deformation. Drilling holes in metal with a thickness of more than 10 mm is

a technically difficult task, as it requires the optimal choice of processing method, taking into account the type of material, its properties, the geometry of the holes, the surface roughness, the required accuracy, the processing productivity and the economic feasibility of the chosen method, as well as technological limitations.

Purpose of the work

The purpose of this work is to review and compare modern methods of making holes in metal with a thickness of more than 10 mm, compare their effectiveness, and study the effect of processing parameters on the quality of the holes obtained. Given the constant improvement of technologies and growing demands for productivity and accuracy, attention will be paid to methods of punching in dies with special tools and drilling, as well as non-traditional methods such as waterjet cutting, laser cutting, and electrical discharge machining (EDM for drilling holes). Each method has its own advantages and limitations, making it more or less suitable for specific production conditions.

Research results

Drilling is the most common method of making holes, performed with a drilling tool. For thick metals, step drilling or pre-reducing the load on the tool is used.

Boring and milling operations are also used to enlarge or form non-standard holes, ensuring high precision and surface cleanliness, but requiring powerful equipment and experienced personnel (figure 1).



Figure 1. Step drill 8-30 mm

The advantages of this method are its simplicity of implementation, availability of equipment, and high precision when properly equipped.

The disadvantages include high tool wear, limitations on hole geometry, and the need for cooling.

Hydroabrasive cutting (Figure 2) combines water pressure and abrasive material. It is used to form complex contours in thick metal. Instead of cutters, the cutting tool is water enriched with abrasive additives, which is supplied under high pressure to the nozzle and destroys the integrity of the metal at high speed. This method allows cutting corrosion-resistant alloys and stainless steel grades. Hydroabrasive cutting outperforms laser cutting by tens of times with a cutting depth of up to 250 mm.

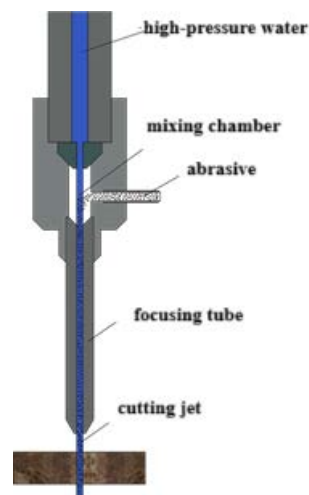


Figure 2. Hydroabrasive cutting scheme



Figure 3. Photo of hydroabrasive cutting

This method provides smooth and flawless edges (figure 4), free from structural defects, micro-scratches or thermal damage. Waterjet cutting also allows complex shapes and patterns to be processed thanks to a multi-axis cutting head.

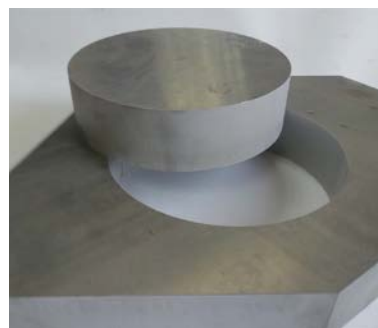


Figure 4. Photo showing the quality of the cut after hydroabrasive cutting

As an example of the results of hydroabrasive cutting, the results of a study of the cut surface for 30XGSA steel with a thickness of 30 mm [*] are given. The experiment was carried out on a Flow hydroabrasive cutting machine on samples of three materials at a constant pressure of 400 MPa. Garnet abrasive with a grain size of 80 μm was used. During the experiment, the cutting jet feed range was varied from 5 to 120 mm/min. The quality of the resulting surface (figure 5).

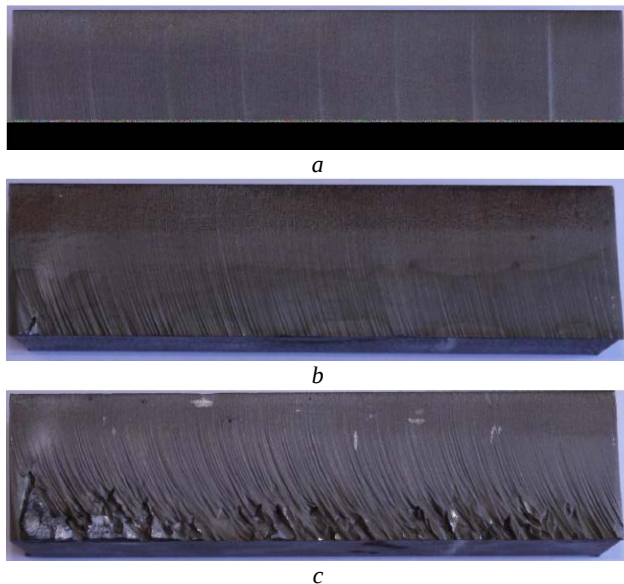


Figure 5. The quality of the surface obtained with different cutting jet feed ranges in hydroabrasive cutting: *a* – cutting jet feed range from 5 to 40 mm/min, *b* – cutting jet feed range from 45 to 80 mm/min, *c* – cutting jet feed range from 85 to 120 mm/min

The results of the research show that as the feed increases, the surface roughness increases. The roughness value also changes across the cut cross-section: the surface is uniform at the top of the cut, and a wavy surface is formed at the bottom of the cut. This phenomenon is due to the fact that the jet loses its cutting ability and deviates from its initial trajectory in the direction opposite to the feed direction.

The advantages of this method are the absence of thermal impact (the material in the working area does not heat up) and versatility (it allows cutting any materials).

The main disadvantages of this method are that defects arise during the cutting process, the nature of which is related to the loss of energy of the cutting jet passing through the material. The cutting ability of the jet is determined by kinetic energy – the speed of the cutting jet, as well as the shape and mass of the abrasive. During the cutting process, the abrasive is destroyed, losing its original shape. The flow, passing through the material layer, slows down, and the jet deviates in the direction opposite to the direction of the cutting jet. This deviation results in defects. The main one is the unevenness of the cut roughness. Analysis of research shows that the surface roughness after waterjet cutting in the range: $R_{(A)} = 2.05\text{--}10.4\ \mu\text{m}$, $R_{(Z)} = 12.6\text{--}42.3\ \mu\text{m}$ does not meet the requirements for

parts with a cut surface roughness of up to class 8. Other disadvantages include the high cost of equipment and the difficulty of creating small-diameter holes.

Promising material separation processes include laser cutting of metals, based on the processes of heating, melting, evaporation, chemical combustion reactions and removal of molten material from the cutting zone. Laser cutting (figure 6) is performed by locally heating the metal with laser radiation focused on its surface. A small portion of the incident radiation is absorbed by the surface layer and causes it to heat up. An oxide film is formed, which increases the proportion of energy absorbed, and the temperature of the metals rises to the melting point.

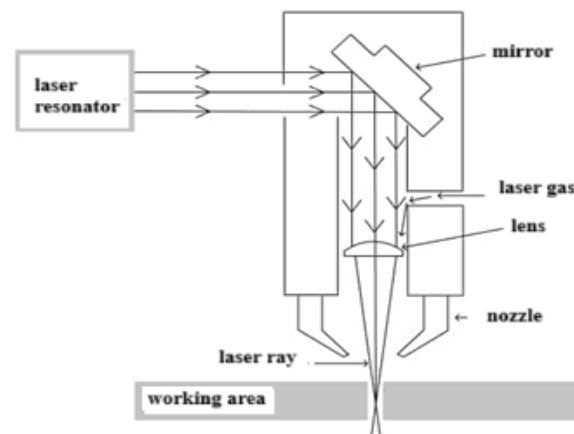


Figure 6. Laser cutting scheme

Analysis of the literature and research results on laser cutting has shown the following:

- the greater the thickness of the sheet, the greater the roughness at comparable laser cutting modes;
- increasing the speed reduces roughness and increases the power and pressure range in order to obtain a cut with minimum roughness;
- increasing pressure increases roughness; reduces the required power and increases the required speed for a given roughness value.
- increasing the focal length increases roughness but reduces the required power and increases the required speed to achieve a given roughness value to a lesser extent than pressure.
- increasing the power increases roughness, reducing the required pressure for a given roughness value.

Figure 7 shows the most common surface defects that occur when cutting certain metals of varying thicknesses [*]. You can see changes in the roughness structure depending on the thickness of the material (Fig. 7a, b, e). Residues of solidified melt of irregular shape (Fig. 5 (a, c)) or appear as rounded particles that adhere firmly to the lower edge after cooling (Fig. 5d, e). The surface of some samples may have a clearly defined smoother strip (Fig. 5b, c). The stainless steel sample (Fig. 5e) 5 mm thick has an irregularly shaped welded structure at the bottom, which differs in colour from the upper, smoother part.

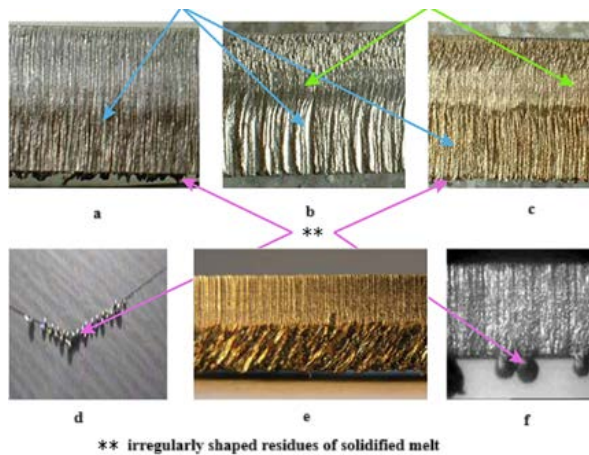


Figure 7. Laser cutting defects: *a* – stainless steel with a thickness of 5 mm, *b* – stainless steel with a thickness of 16 mm, *c* – titanium 30 mm; *d* – electrical steel 0.5 mm; *e* – stainless steel, oxidised at the bottom of the cut due to air mixing 5 mm, *f* – 1 mm stainless steel

The most common surface defects that occur when cutting certain metals of different thicknesses [*]. You can see changes in the roughness structure depending on the thickness of the material (figure 7*a, b, c, e*). Residues of solidified melt of irregular shape (figure 7*a, c*) or appear as rounded particles that adhere firmly to the lower edge after cooling (figure 7*d, f*). The surface of some samples may have a clearly defined smoother strip (figure 7*b, c*). The stainless steel sample (figure 7*e*) 5 mm thick has an irregularly shaped welded structure at the bottom, which differs in colour from the upper, smoother part.

With a material thickness of 10 mm and above, the surface roughness $R_z = 36.42\text{--}58.79\text{ }\mu\text{m}$, which does not meet the requirements for parts with a surface roughness of up to class 8. For thick materials (10 mm and more) with a large ratio of plate thickness to cut width, the quality of the cut is greatly reduced.

The advantages of this method are high precision, the ability to process hard-to-reach areas, and the absence of mechanical contact.

The disadvantages include the high cost of equipment, thickness limitations (over 20 mm is difficult), and thermal impact on the edge of the cut hole.

The electroerosion method is effective for high-alloy and hard metals. Processing occurs through an electrical discharge between the electrode and the workpiece (figure 8). This production method uses electrical pulses to generate sparks in a special liquid medium. These sparks create an electrical erosion effect, which is used to selectively remove metal material from the workpiece, ensuring high-precision machining. This innovative process efficiently converts electrical energy into heat and is widely used in the manufacture of precision components that require exceptional accuracy and surface quality [sales@hlc-metalparts.com].

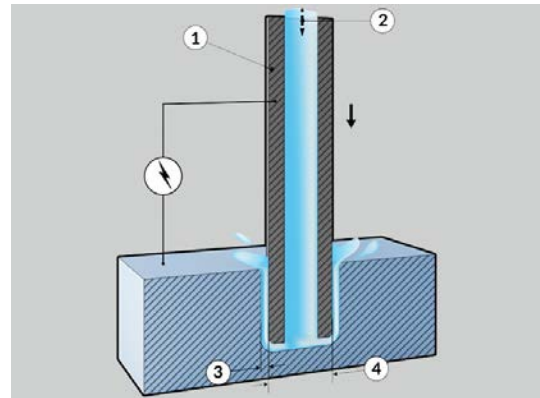


Figure 8. Electrical discharge machining (EDM for drilling holes) scheme

Electrical discharge machining (EDM for drilling holes) is specifically designed to create small holes or micro-pores. A rotating lead tube acts as an electrode, and the tool is advanced into the workpiece, creating a hole through a series of repeated electrical discharges. It is typically used for parts such as nozzles, injectors, filters, and other components that require precise hole diameter and shape.

The advantages of this method are high precision, namely, wire EDM can achieve incredibly tight tolerances, making it ideal for manufacturing complex parts with a high level of precision. Unlike traditional machining methods, electrical discharge machining works without direct contact between the workpiece and the cutting tool, making it faster and less prone to wear. This method allows you to cut a wide range of materials, from metals to alloys and composites, and is suitable for creating complex shapes with complex geometries.

The disadvantages include the slow process and the need for a special dielectric fluid.

Cold stamping is useful for serial or mass production when you need to make a bunch of similar holes in relatively thick blanks. But for single or small-batch production, this method isn't really worth it financially.

The cold stamping method involves making holes by punching metal with stamping equipment, either without preheating the workpiece or with preheating. It is mainly used for mass production with metal thicknesses of up to 12–15 mm, although options are also available for thicker sheets under conditions of increased force.

To conduct research on thick-sheet hole punching, the Department of Metal Forming designed and manufactured an experimental punch for punching holes (figure 9, 10).

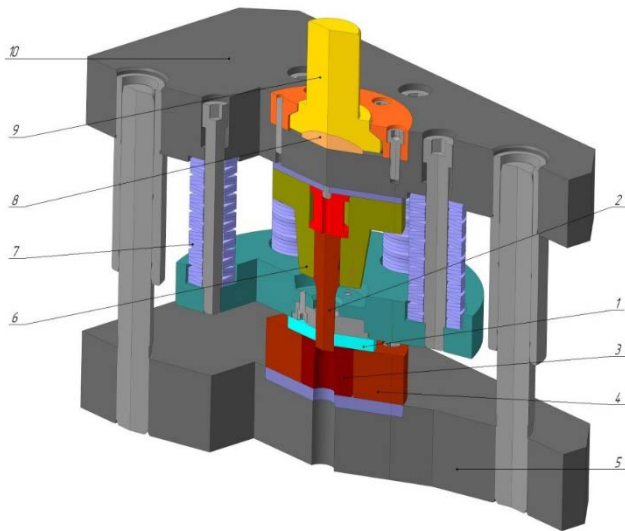


Figure 9. Model of an experimental stamp for punching a hole: 1 – blank; 2 – punch; 3 – matrix; 4 – matrix holder; 5 – lower plate; 6 – punch holder; 7 – disc spring; 8 – support; 9 – shank; 10 – upper plate



Figure 10. Photo of an experimental stamp for punching a hole

For research on thick-sheet hole punching, interchangeable punches and dies were designed and manufactured with different sizes and shapes of the working surface, from flat to stepped.

The advantages of this method are extremely high productivity, excellent repeatability of geometry, the possibility of process automation, and low cost in serial production.

The disadvantages include limitations on the shape and thickness of the hole, the relatively high cost of manufacturing the stamp, the increased need for rigidity of the press equipment, and the possible periodic formation of burrs and deformations of the hole edge.

Conclusions

The results of the analysis showed that the most effective method for making holes in metal with a thickness of more than 10 mm, the most effective method is punching, with each method having its own specific advantages and limitations (table 1).

Table 1 – Comparative table of methods for making holes (thickness 10 mm, Ø 20 mm)

Method	Accuracy (mm)	Speed	Cost	Limitations
Drilling	±0.2–0.5	~0.2–1 holes/min	Low	Drill wear, need for lubrication, low accuracy with high thickness
Hydroabrasive cutting	±0.1–0.2	~50–100 mm/min	High	Expensive equipment, lengthy preparation, complex contour processing
Laser cutting (fibre)	±0.05–0.2	~300–800 mm/min	High	Limitations on heat exposure, may cause scaling and structural changes
Electrical discharge machining (EDM)	±0.01–0.05	~5–15 mm/min	Very high	Only for conductive materials, low productivity
Cold stamping (punching)	±0.1–0.3	~30–60 holes/min	Low (for series production)	Requires dies, initial costs, possible defects on the edges of the hole

Selecting the optimal punching parameters is very important for achieving high-quality holes. In particular, important factors include the force, the geometry of the working surfaces of the punch, and the choice of clearance between the punch and the die. Failure to comply with the

recommended parameters can lead to defects on the edges of the hole and reduced accuracy and quality of processing.

For single and small-batch production, drilling and laser processing are the optimal methods, while for mass production, punching and stamping are the most effective methods.

The analytical review considers various methods of cutting and punching holes in thick-sheet materials. None of these methods allows for a high-quality cut surface across the entire thickness of the metal at a thickness of 10 mm and above.

It is necessary to investigate the gaps between the die and the punch in order to obtain the accuracy of the punched hole and the quality of the punched hole surface. It is necessary to investigate the influence of different designs of clamping devices on the quality of the cut surface. The force required to remove the bar from the punch with a rigid and movable remover. Investigate the factors that determine the stability of the tool when punching holes in thick sheet material. It is also necessary to investigate the influence of speed parameters on the quality of the holes.

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АНАЛІЗ МЕТОДІВ ОТРИМАННЯ ОТВОРІВ У МЕТАЛІ ТОВЩИНОЮ ПОНАД 10 мм

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Мета роботи. Метою цього дослідження є огляд та порівняльний аналіз сучасних методів створення отворів у металевих заготовках товщиною понад 10 мм, оцінка їхньої ефективності та дослідження впливу параметрів обробки на якість отриманих отворів. Увага приділяється традиційним методам, таким як свердління та штампування спеціалізованими інструментами, а також нетрадиційним методам, включаючи гідроабразивне різання, лазерне різання та електроерозійну обробку (EDM).

Методи дослідження. У дослідженні використовувався огляд літератури та експериментальні дослідження. Експериментальні методи включали ступінчасте свердління, розсвердлювання, фрезерування, гідроабразивне різання, лазерне різання, електроерозійне свердління та холодне штампування. Якість отворів оцінювалася за допомогою геометричних вимірювань, аналізу шорсткості поверхні та дослідження зон деформації. Експериментальні установки включали змінні конструкції пуансона та штампів для вивчення впливу геометрії інструменту, зазору між пуансоном та штампом, а також сил різання на якість отвору.

Отримані результати. Було визначено, що кожен метод має різні переваги та обмеження. Штампування є найефективнішим для високошвидкісного масового виробництва з послідовною геометрією, але вимагає точного оснащення та жорсткого пресового обладнання. Свердління та лазерне різання підходять для одиничного або дрібносерійного виробництва, пропонуючи високу точність, але меншу швидкість. Гідроабразивне різання забезпечує гладкі краї та мінімальний термічний вплив, хоча воно є дорогим та повільнішим для невеликих отворів. Електроерозійне різання забезпечує виняткову точність для твердих або високолегованих матеріалів, але має низьку продуктивність. Порівняльний аналіз підкреслив вплив параметрів процесу, таких як зазор штампів, сила різання, швидкість подачі та конструкція інструменту, на якість та точність отворів.

Наукова новизна. Дослідження забезпечує систематичне порівняння кількох методів виготовлення отворів для товстих металевих заготовок, інтегруючи експериментальні результати з аналізом параметрів процесу. Новизна полягає у визначенні оптимальних параметрів та конструкцій інструментів, які мінімізують дефекти крайок та деформацію, пропонуючи рекомендації щодо високоточного формування отворів у товстих металах, що не було всебічно розглянуто в попередніх дослідженнях.

Практична цінність. Результати можуть допомогти у виборі відповідних технологій виготовлення отворів у промисловій металообробці, оптимізувати продуктивність, покращити якість поверхні та точність розмірів, зменшити відходи матеріалу та врахувати проектування інструментів та пресового обладнання для масового та дрібносерійного виробництва.

Ключові слова: методи виготовлення отворів, товсті металеві заготовки, штампування, свердління, лазерне різання, гідроабразивне різання, електроерозійна обробка, холодне штампування, оптимізація процесу, якість поверхні.

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