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Peculiarities of Abrasive Finishing of Surfaces of Parts Made of Aluminium Alloy of AMts Grade in Magnetic Field

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A B S T R A C T

The scientific article presents the results of research to identify the regularities arising from the abrasive finishing of the surfaces of parts made of aluminium alloy grade (AMts) in a magnetic field. As a result of conducted experiments the relations between variable factors of abrasive finishing in a magnetic field and quality indicators of surfaces of parts from aluminium alloy of mark AMts which have been expressed by means of physical and statistical model of graphic dependences of functions defined as $Ra = f(t, n)$ and $Ra = f(B, S)$. It has been established that abrasive finishing in a magnetic field allows for an insignificant amount of time t = 4...12 min to reduce surface roughness from initial Ra = 1.3...1.9 µm to Ra = 0.23...0.85 µm (depending on processing conditions). In addition, the optimization problem of determining the optimal conditions of abrasive finishing in a magnetic field, providing the achievement of the minimum value of roughness Ra_{min} = 0.23 µm of the surfaces of parts made of aluminium alloy grade AMts was solved.

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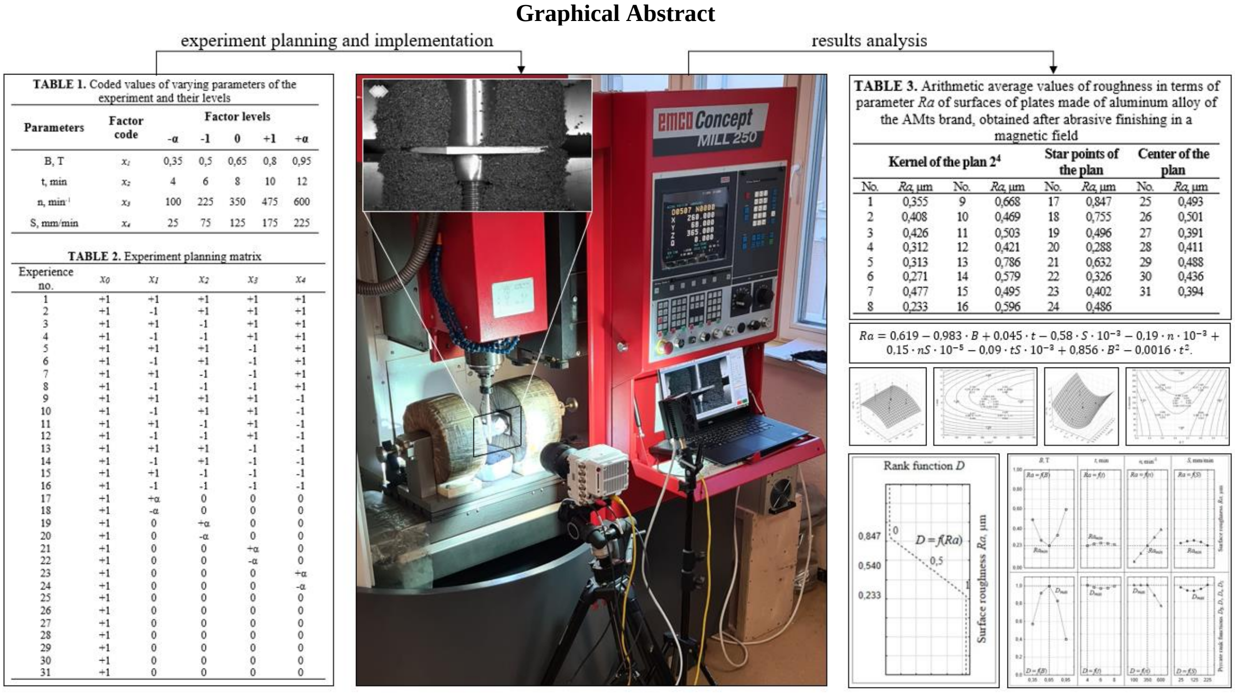
Graphical Abstract



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1. INTRODUCTION

Currently, there is a tendency to expand the scale of machine building industries (1, 2). This is primarily due to the need to provide oil and gas (3-5), energy (6, 7), mining (8, 9) and other industries with high-performance machinery and process equipment (10, 11).

Improvement of machine-building production in accordance with modern challenges cannot be realized without a deeper study of the issues of mechanical processing of materials (12, 13). It is connected first of all with the fact that the level of machine-building productions, the quality of products manufactured by them, as well as the rationality of decisions taken in the development of technological processes of machining largely depends on the degree of study of these issues (14).

Today, special attention is paid to the machining of materials with special physical and mechanical properties (15, 16), including aluminium-based alloys (17-19). The machining of aluminium and its alloys is a rather labour-intensive process. For example, the high thermal conductivity of aluminium and its alloys causes oxidation during heating, which is accompanied by the formation of cold cracks in the material (20); increased temperature during machining of aluminium products causes structural changes in the surface of the machined material.

An effective solution to this problem is the use of finishing methods with low temperature in the cutting zone when machining aluminium material. The most promising finishing methods include abrasive finishing in a magnetic field (21), at which the temperature in the micro-cutting zone is of the order of $T = 30 \div 40^{o}$C. This type of finishing consists in the creation of a technological tool, consisting of a magnetic field and abrasive powder, and its subsequent use for impact during a certain period of time on the machined surfaces of parts. In this case, to implement magnetic and abrasive impacts, the machined part, pole tips or the part and pole tips together are given different combinations of movements (rotational, oscillating, reciprocating) (22).

Studies of abrasive finishing of aluminium and its alloys in a magnetic field have received considerable attention in literature (23, 24). For example, in the work of Khomich (23) the influence of technological tool on the number of inclusions, micro-sharpening and removal of oxide film from the flanks of sheets from aluminium alloy of *Al-Mg* system (grades 1560 (AMg-6)) was studied. It is noted that rational selection of mode parameters and type of technological tool allows to perform defect-free abrasive finishing of sheet edges in a magnetic field. The criteria of surface roughness and its morphology after abrasive finishing in a magnetic field of surfaces of parts made of aluminium alloy of *Al-Cu-Mg* system (grades 2024 (D16)) has been analyzed in the work of Anjaneuli and Venkatesh (24). It was revealed that the following factors have the main influence on the quality of parts surfaces: stress, allowing to change the stiffness of the technological tool; feed rate, providing the process of micro-cutting. The influence of rotation speed and abrasive material composition on the quality of machined surfaces of parts made of aluminium alloy of *Al-Mg-Si* system (grades 6061 (AD33)) was studied by Li et al. (25). It was experimentally established that as a result of abrasive finishing in a magnetic field, the roughness value of parts surfaces by *Ra* parameter can be improved by 97%.

The conducted researches were focused on finishing of aluminium alloy systems: *Al-Mg* (grades 1560 (AMg-6)), which belongs to deformable alloys and used in the manufacture of hull parts and transport tanks; *Al-Cu-Mg* (grades 2024 (D16)), which is most commonly used in sub-zero and cryogenic temperatures in aircraft and aerospace applications; *Al-Mg-Si* (grades 6061 (AD33)), which is a corrosion-resistant alloy and is used for the manufacture of pipes and profiles of various cross-sections. However, the parts made of aluminium alloy of Al-Mn system (grades 3003 (AMts)), which are used in gas-insulated transformers and sensitive elements of electric tachometers (26), were not subjected to abrasive finishing in a magnetic field, despite the high surfaces quality requirements ($Ra = 0.25 \div 0.63$ μm) for these parts.

In this connection, the research presented in the scientific article is aimed at studying the peculiarities of abrasive finishing in the magnetic field of surfaces of parts made of aluminium alloy of *Al-Mn* system (grades 3003 (AMts)).

2. MATERIALS AND METHODS

Studies on abrasive finishing of AMts aluminium alloy parts surfaces in a magnetic field were carried out on a specially designed complex. The developed experimental complex included a technological system of abrasive finishing in a magnetic field (27-29), created on the basis of an upgraded machining centre *Emco Concept Mill* 250 with CNC (Figure 1) and a mobile computerized information-measuring system (Figure 2), consisting of an optical bench, profilometer *Mitutoyo* SJ-210 and a laptop with the appropriate software.

As experimental samples plates from aluminium alloy of AMts grade with dimensional parameters 30x30x2mm with initial surface roughness $Ra_{inital} = 1{,}3...1{,}9$ μm were used. Fixing of plates was made by means of a fixture (Figure 1), which was installed in the mandrel of an upgraded machining centre *Emco Concept Mill* 250 with CNC.

The technological tool for abrasive finishing in a magnetic field of AMts aluminium alloy plate surfaces was a combination of magnetic field, abrasive powder and coolant (30-32). The magnetic field was constant and

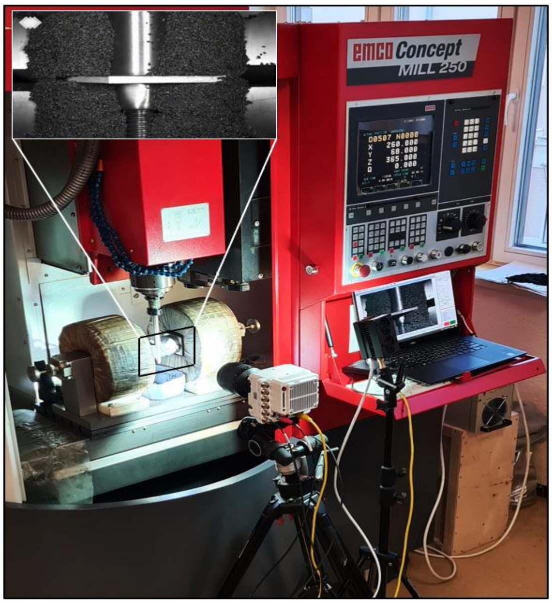

Figure 1. Experimental complex for abrasive finishing in a magnetic field

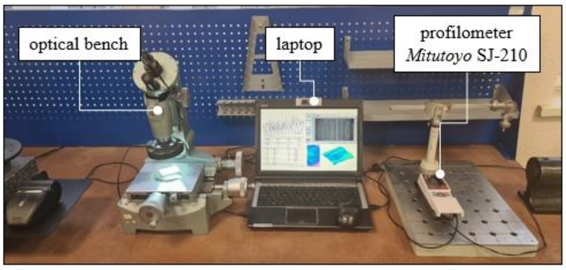

Figure 2. Mobile computerised information and measurement system

was generated by electromagnetic coils of the abrasive finishing in a magnetic field system (33-35). A homogeneous abrasive of PR10P6M5 grade with fraction $\Delta = 0.25 \div 0.16$ µm, consisting of high-speed steel P6M5 particles with increased carbon content of rounded splinter shape, was used as an abrasive powder. Cooling lubricant Global was used to ensure clean surfaces of plates made of aluminium alloy of AMts grade and to prevent abrasive material inclusions in the processed samples.

Abrasive finishing in the magnetic field of the surfaces of plates made of aluminium alloy of AMts grade was carried out according to the central composite rotatable plan (Tables 1 and 2). This plan consisted of 31 experiments: 16 experiments were the core of the plan and corresponded to the planning matrix of the full-factorial experiment 2^4; 8 experiments were the «star» points; 7 experiments were the centre of the plan.

The variable factors during abrasive finishing in a magnetic field of the surfaces of plates made of

TABLE 1. Coded values of varying parameters of the experiment and their levels

Parameters	Factor code	Factor levels				
		-α	**-1**	**0**	**+1**	**+α**
B, T	x_1	0,35	0,5	0,65	0,8	0,95
t, min	x_2	4	6	8	10	12
n, min^{-1}	x_3	100	225	350	475	600
S, mm/min	x_4	25	75	125	175	225

TABLE 2. Experiment planning matrix

Experience no.	x_0	x_1	x_2	x_3	x_4
1	+1	+1	+1	+1	+1
2	+1	-1	+1	+1	+1
3	+1	+1	-1	+1	+1
4	+1	-1	-1	+1	+1
5	+1	+1	+1	-1	+1
6	+1	-1	+1	-1	+1
7	+1	+1	-1	-1	+1
8	+1	-1	-1	-1	+1
9	+1	+1	+1	+1	-1
10	+1	-1	+1	+1	-1
11	+1	+1	-1	+1	-1
12	+1	-1	-1	+1	-1
13	+1	+1	+1	-1	-1
14	+1	-1	+1	-1	-1
15	+1	+1	-1	-1	-1
16	+1	-1	-1	-1	-1
17	+1	+α	0	0	0
18	+1	-α	0	0	0
19	+1	0	+α	0	0
20	+1	0	-α	0	0
21	+1	0	0	+α	0
22	+1	0	0	-α	0
23	+1	0	0	0	+α
24	+1	0	0	0	-α
25	+1	0	0	0	0
26	+1	0	0	0	0
27	+1	0	0	0	0
28	+1	0	0	0	0
29	+1	0	0	0	0
30	+1	0	0	0	0
31	+1	0	0	0	0

aluminum alloy of the AMts brand were: the value of magnetic induction $B = 0.35 \div 0.95$ T; finishing time $t = 4 \div 12$ min; plate rotation speed $n = 100 \div 600$ min^{-1}; plate feed along the pole pieces $S = 25 \div 225$ mm/min (Table 1). The controlled parameter was the surface roughness of the plates according to the *Ra* parameter, which was monitored using a *Mitutoyo SJ-210* profilometer (Figure 2).

The roughness values obtained in the course of experimental studies in terms of the *Ra* parameter of the surfaces of plates made of aluminum alloy of the AMts brand were subjected to statistical processing in order to construct a physical-statistical model, which can be generally represented by means of a response function in the form of a complete polynomial of the second degree espressed in Equation 1:

$$y_i = b_0 + \sum_{1\le i\le k} b_i x_i + \sum_{1\le i\le j\le k} b_{ij} x_i x_j + \sum_{1\le i\le k} b_{ii} x_i^2. \quad (1)$$

where y_i is *i*-th quality parameter (roughness according to the *Ra* parameter) of the surfaces of the part after finishing; x_i is *i*-th factor of abrasive finishing in a magnetic field; b_0, b_i, b_{ij} are values of model coefficients.

The construction of a physical-statistical model 1 of the influence of varying factors of abrasive finishing in a magnetic field on the roughness in terms of the parameter *Ra* of plate surfaces was carried out in accordance with the calculation algorithm, which is described in detail. The main stages of the calculation algorithm were: coding the levels of factors x_i, calculating the coefficients b_0, b_i, b_{ij} model, estimating the dispersion of the reproducibility of the experiment S_y^2, estimating the dispersion of the model coefficients S_b^2 and their root-mean-square errors S_b, calculating confidence intervals Δb_i and determining the statistical significance of the coefficients b_0, b_i, b_{ij} models, calculation of the variance of model inadequacy $SS^2{}_{inad}$, calculation of the F_{calc} calculation model criterion and testing the hypothesis about the adequacy of the model $F_{calc} < F_{table}$, decoding the levels of factors x_i.

The physical-statistical model 1 of the influence of abrasive finishing factors in a magnetic field on the roughness in the *Ra* parameter of the surfaces of plates made of aluminum alloy of the AMts brand will make it possible to predict quality indicators with sufficient accuracy depending on the processing conditions. This is especially important when the complexity of the occurrence of physical phenomena in processes creates significant difficulties in creating analytical models.

All mathematical calculations necessary to construct a physical and statistical model 1 of the influence of abrasive finishing factors in a magnetic field on the quality indicators of plate surfaces, and the subsequent conversion of the obtained data into graphical form, were carried out in an automated mode using *Microsoft Office Excel* and *Statistica 12* programs.

3. RESULTS AND DISCUSSION

As a result of experimental studies on abrasive finishing in a magnetic field of the surfaces of plates made of aluminum alloy of the AMts brand, the roughness values for the parameter *Ra* were obtained. The calculated arithmetic average roughness values are summarized in Table 3 and divided according to the 3 parts of the central compositional rotatable plan.

Based on the mathematical calculations performed following the calculation algorithm previously summarized, a physical-statistical model was built in the form of a response function, which makes it possible to predict the roughness values in terms of the *Ra* parameter of the surfaces of plates made of aluminum alloy of the AMts brand, depending on the conditions of abrasive finishing in a magnetic field stated in Equation 2:

$$Ra = 0{,}619 - 0{,}983 \cdot B + 0{,}045 \cdot t - 0{,}58 \cdot S \cdot 10^{-3} - 0{,}19 \cdot n \cdot 10^{-3} + 0{,}15 \cdot nS \cdot 10^{-5} - 0{,}09 \cdot tS \cdot 10^{-3} + 0{,}856 \cdot B^2 - 0{,}0016 \cdot t^2. \quad (2)$$

A more visual representation of the response function 2 can be presented using its geometric analogue - the response surface. However, a geometric representation is only appropriate when there are no more than two factors influencing the output parameter. Taking this fact into account, the response surface was geometrically depicted in three-dimensional and two-dimensional spaces in two combinations: the influence of finishing time and rotation speed on the roughness parameter *Ra* (Figure 3, *a*, *c*); the influence of magnetic induction and feed on the roughness in terms of the *Ra* parameter (Figure 3, *b*, *d*).

The constructed physical-statistical model and graphical dependences of the functions $Ra = f(t, n)$ and $Ra = f(B, S)$ make it possible to determine the main tendency of the influence of varying factors of abrasive finishing in a magnetic field on the quality, in particular

TABLE 3. Arithmetic average values of roughness in terms of parameter *Ra* of surfaces of plates made of aluminum alloy of the AMts brand, obtained after abrasive finishing in a magnetic field

Kernel of the plan 24				Star points of the plan		Center of the plan	
No.	*Ra*, μm	No.	*Ra*, μm	No.	*Ra*, μm	No.	*Ra*, μm
1	0,355	9	0,668	17	0,847	25	0,493
2	0,408	10	0,469	18	0,755	26	0,501
3	0,426	11	0,503	19	0,496	27	0,391
4	0,312	12	0,421	20	0,288	28	0,411
5	0,313	13	0,786	21	0,632	29	0,488
6	0,271	14	0,579	22	0,326	30	0,436
7	0,477	15	0,495	23	0,402	31	0,394
8	0,233	16	0,596	24	0,486		

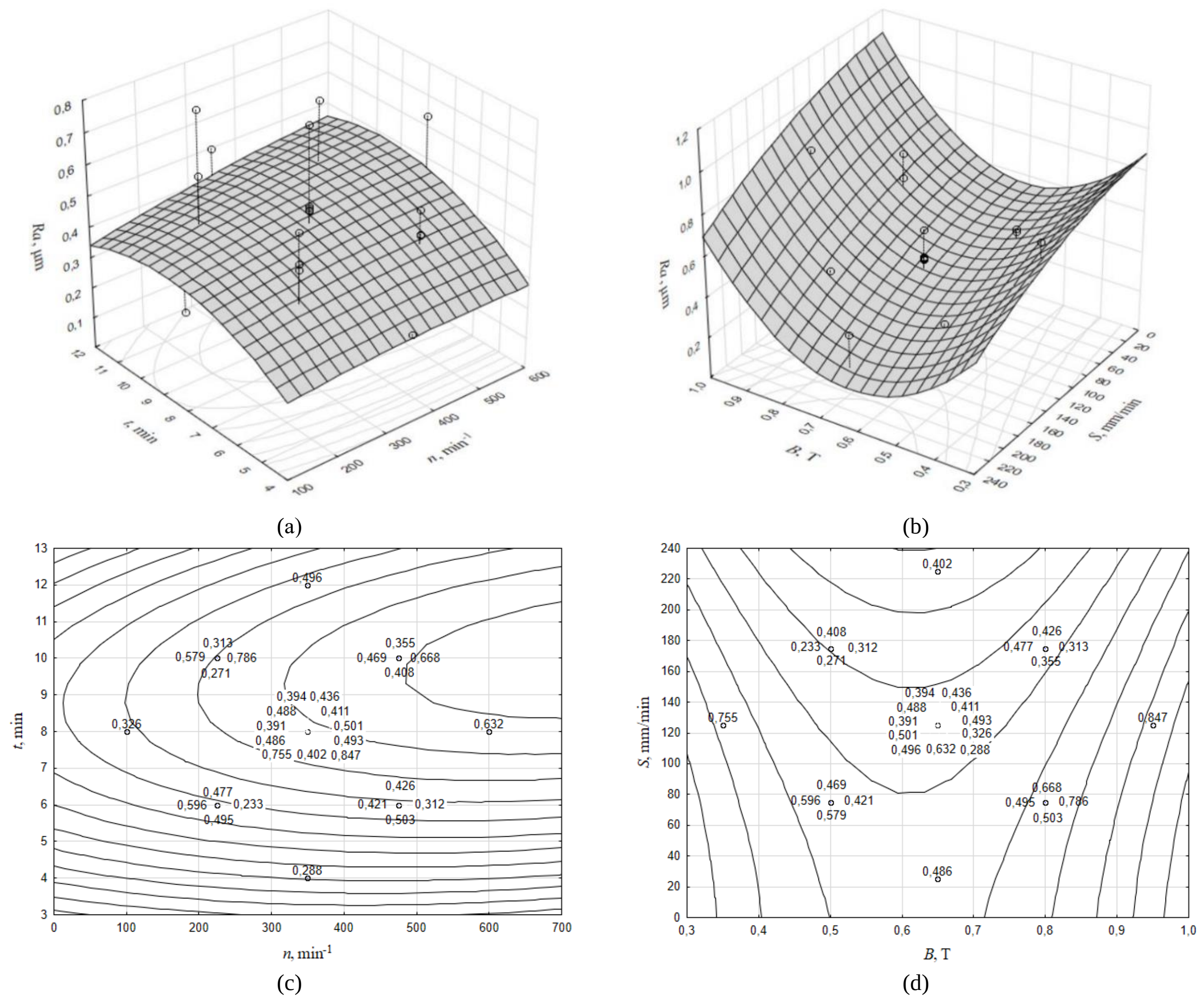

Figure 3. Graphic dependences of the influence of abrasive finishing factors in a magnetic field on the roughness in terms of the *Ra* parameter of the surfaces of plates made of aluminum alloy grade AMts

on the roughness in the parameter *Ra*, of plate surfaces made of aluminum alloy AMts brand. However, in this case, it is not possible to offer the most optimal conditions for abrasive finishing in a magnetic field for practice. For this reason, the obtained data were subjected to additional analysis in order to solve the optimization problem.

The criterion for optimal conditions for abrasive finishing in a magnetic field was the ability, under appropriate conditions, to form the minimum value of roughness Ra_{min} of the surfaces of plates made of aluminum alloy of the AMts brand. The process of searching for optimal conditions was carried out on the basis of a rank approach, in which a generalized rank function $D = f(Ra)$ (Figure 4), was initially constructed, subsequently converted into private rank functions of the levels of abrasive finishing factors in a magnetic field $D_B = f(B)$, $D_t = f(t)$, $D_n = f(n)$, $D_S = f(S)$ (Figure 5). Subsequently, these functions $D_B = f(B)$, $D_t = f(t)$, $D_n = f(n)$, $D_S = f(S)$ were compared with the profiles of the influence of abrasive finishing factors in a magnetic field on the roughness of plate surfaces $Ra = f(B)$, $Ra = f(t)$, $Ra = f(n)$, $Ra = f(S)$ and the optimal conditions for abrasive finishing in a magnetic field were determined (Figure 5).

When constructing the generalized rank function $D = f(Ra)$ three ranks «0», «0,5» and «1» were assigned experimental roughness values obtained during experimental studies (Table 3), Ra_{max}, Ra_{medium} and Ra_{min} respectively (Figure 4). The generalized rank function $D = f(Ra)$ shows the preference for minimum roughness values Ra_{min} of plate surfaces in comparison with values close to $Ra_{max.}$

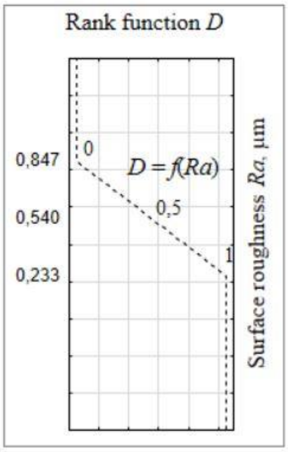

Figure 4. Generalized rank function plot $D = f(Ra)$

Based on the generalized rank function $D = f(Ra)$ partial rank functions were constructed from the levels of abrasive finishing factors in a magnetic field $D_B = f(B)$, $D_t = f(t)$, $D_n = f(n)$, $D_S = f(S)$ and compared with the profiles of the influence of abrasive finishing factors in a magnetic field on the surface roughness of plates $Ra = f(B)$, $Ra = f(t)$, $Ra = f(n)$, $Ra = f(S)$. This comparison showed that the minimum value of the surface roughness of the plates, within the studied range of changes in abrasive finishing factors in a magnetic field, is equal to Ra_{min} = 0,19 µm and is formed under the following conditions: B = 0,65 T, t = 12 min, n = 475 min^{-1}, S = 225 mm/min.

A more detailed study of the partial function $D_t = f(t)$ allowed to conclude that there are two preferred finishing times: t = 4 min and t = 12 min. In this regard, the range of values from t = 4÷12 min to t = 4÷8 min of the private rank function $D_t = f(t)$ was adjusted and the partial functions $D_B = f(B)$, $D_t = f(t)$, $D_n = f(n)$, $D_S = f(S)$ were again compared with profiles of the influence of abrasive finishing factors in a magnetic field on the roughness of plate surfaces $Ra = f(B)$, $Ra = f(t)$, $Ra = f(n)$, $Ra = f(S)$ (Figure 5). As a result, it was found that the minimum value of the surface roughness of the plates is Ra_{min} = 0,23 µm and is formed under the following conditions: B = 0,65 Тл, t = 4 min, n = 350 min^{-1}, S = 225 mm/min (Figure 5).

Despite the insignificant difference Δ = 0,04 µm in the minimum values of the formed surface roughness of plates made of aluminum alloy of the AMts brand, the following conditions will be considered the most rational conditions for abrasive finishing in a magnetic field for their recommendation for production: B = 0,65 T, t = 4 min, n = 350 min^{-1}, S = 225 mm/min. These conditions of abrasive finishing in a magnetic field make it possible to ensure the surface roughness of plates made of aluminum alloy of the AMts brand equal to Ra = 0,23 µm.

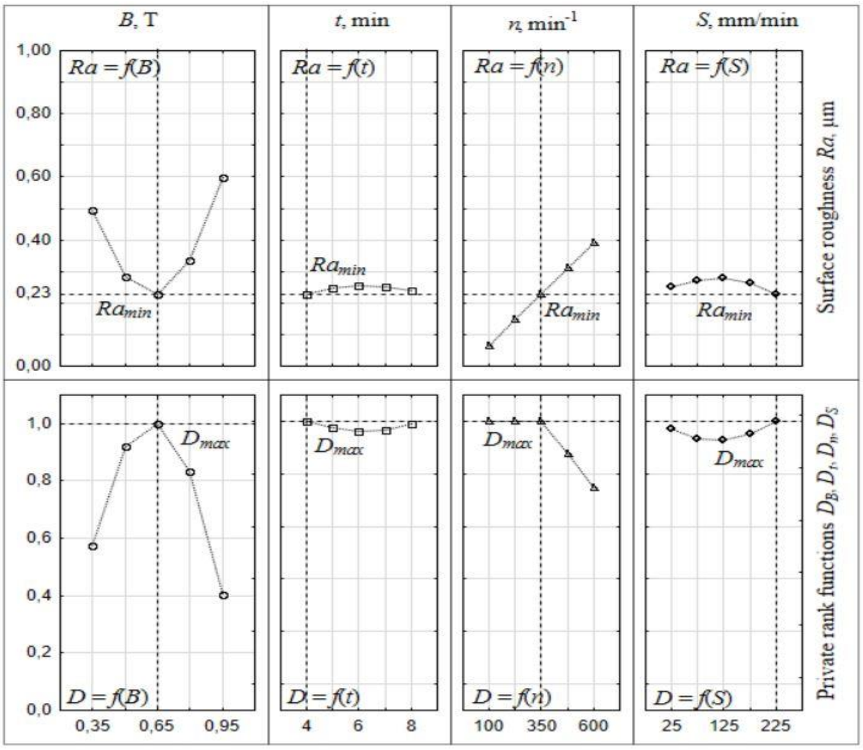

Figure 5. Determination of optimal conditions for abrasive finishing of the surfaces of plates made of aluminum alloy grade AMts in a magnetic field

4. CONCLUSION

Studying the peculiarities of abrasive finishing in the magnetic field of the surfaces of parts made of aluminium alloy grade AMz, the authors presented the following conclusions based on the results of the study:

- The finishing method of abrasive finishing in a magnetic field is an effective method for recommending it in practice for the purpose of final processing of the surfaces of parts made of aluminum alloy grade AMts. Since in a short time t = 4…12 min, it allows to reduce the roughness of the surfaces of parts from the original equal Ra = 1,3…1,9 µm to Ra = 0,23…0,85 µm (depending on processing conditions).
- Solving the optimization problem allows to determine the optimal conditions for abrasive finishing in a magnetic field of the surfaces of plates made of aluminum alloy of the AMts brand with achieving a minimum roughness value of Ra_{min} = 0,23 µm; the optimal conditions are: B = 0,65 T, t = 4 min, n = 350 min^{-1}, S = 225 mm/min.

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Persian Abstract

چکیده

این مقاله علمی نتایج تحقیقات را برای شناسایی نظم های ناشی از پرداخت ساینده سطوح قطعات ساخته شده از آلیاژ آلومینیوم (AMts) در میدان مغناطیسی ارائه می کند. در نتیجه آزمایش‌های انجام‌شده، روابط بین عوامل متغیر پرداخت ساینده در میدان مغناطیسی و شاخص‌های کیفی سطوح قطعات از آلیاژ آلومینیوم علامت AMts که با استفاده از مدل فیزیکی و آماری وابستگی‌های گرافیکی توابع تعریف شده به عنوان. Ra =f(t, n), بیان شده است ، Ra = f(B, S)، ثابت شده است که پرداخت ساینده در یک میدان مغناطیسی به مدت زمان ناچیزی اجازه می دهد تا زبری سطح را از ۱.۳...۱.۹ میکرومتر اولیه به Ra = 0.23 ... 0.85 میکرومتر کاهش دهد. بسته به شرایط پردازش). علاوه بر این، مشکل بهینه‌سازی تعیین شرایط بهینه پرداخت ساینده در میدان مغناطیسی، با ارائه حداقل مقدار زبری رامین = ۰.۲۳ میکرومتر از سطوح قطعات ساخته شده از آلیاژ آلومینیوم AMts حل شد.