Strojnícky časopis – *Journal of* MECHANICAL ENGINEERING,
VOL 73 (2023), NO 1, 67 - 85

MODEL OF INFLUENCE OF THE MACHINED MATERIAL PROPERTIES ON WEAR OF THE POLYMERIC-ABRASIVE TOOL FILAMENTS

HONCHAR Natalia, TRYSHYN Pavlo*, PAVLENKO Dmytro, STEPANOV Dmytro and KHAVKINA Olena

Machine Construction Department, National University "Zaporizhzhia Polytechnic", Zhukovskoho 64, Zaporizhzhia, 60063, Ukraine, e – mail: trishin87@gmail.com

Abstract: For polymer-abrasive brush tools (PABT) working on CNC machines it is necessary to correct their wear constantly, since it is much higher compared to the wear of metal tools. Based on the dependence of tool wear on machining parameters for various materials, it is necessary to study the influence of the physical and mechanical properties of the material machined. The purpose of the paper is to study the process of finishing the surfaces of parts made of materials of different types with PABT. The analysis of dimensional wear of disc PABTs during the polishing various materials with certain physical and mechanical properties is provided in the article. The polishing was carried out in rational modes that ensure high quality and productivity of surface treatment. The similarity theory and dimensional analysis were used to assess the influence of the properties of the material machined on the intensity of PABT filament wear. To calculate it, dimensionless complexes were established, which take into account the physical and mechanical properties of the machined materials and evaluate their resistance to the penetration of abrasive grains, the ability of the material to absorb mechanical energy in the process of deformation and destruction under the impact of PABT filaments. The developed model was created for the first time. It made it possible to solve the problem of predicting the degree of dimensional wear of the disc PABT when polishing various materials, including difficult-to-machine ones. Prediction of the intensity of PABT filaments wear allows timely correction of the tool position during machining on CNC machines to ensure a constant pressing of the PABT to the surface being machined. The obtained Kᴍ material coefficient takes into account the influence of the physical and mechanical properties of the machined material and then estimates the intensity of PABT filaments wear. The KM material coefficient can also be used to assess the PABT life and calculate the economic efficiency of the parts finishing treatment at the stage of technology development and the selection of polishing tools.

KEYWORDS: finishing, polymer-abrasive brush, similarity theory, wear, dimensional analysis, CNC machines.

1 Introduction

The formation of favorable surface quality parameters of the main parts of precision and power engineering products is the basis for ensuring their bearing capacity. To ensure these parameters, various finishing and hardening methods of machining the surfaces of parts are used [1]. However, given the complex configuration of most surfaces that determine the load-bearing capacity of power engineering parts, such as compressor blades for gas turbine engines, the use of most surface treatment methods for them leads to a distortion of their geometry. One of the promising methods for their machining is the use of polymer-abrasive tools.

Currently brush polymer-abrasive tools are widely used among the many methods of finishing and strengthening surface treatment. The wear of these tools during operation is inevitable; understanding the causes and essence of this process as well as the selection of the correct machining modes will help reduce its intensity [2].

DOI: 10.2478/scjme-2023-0006, Print ISSN 0039-2472, On-line ISSN 2450-5471

Rotary polymer-abrasive brush tools (PABT) are used for a wide range of finishing parts and constructions made of various materials, including difficult finishing methods: polishing surfaces, removing burrs and rounding sharp edges [3]. Increasingly, PABTs are used on CNC machines (with computer numerical control), replacing outdated, less productive, non-environmental methods [4].

Industrial application of disc PABTs in polishing surfaces [5, 6, 7] showed different intensity of filament wear depending on the material of the parts. Attempts to use these tools in automated installations of varying complexity raise the question of predicting the PABT dimensional wear. This is essential to ensure the accuracy of machining parts.

Modern scientific literature gives information about technologies of the manufacturing polymer-abrasive brush tools and their application. There are also studies in which the dependence of the surface quality on the processing modes, the force effect of the tool on the part and the temperature field in the tool-part zone were determined [8, 9, 10]. There are also publications that explore the possibilities of achieving high processing performance and their use for polishing certain materials or parts with special surface requirements [5]. The existing publications do not solve the issues regarding the influence of the machined material properties on the parameters under discussion in this research.

A large number of research studies devoted to PABTs are aimed at determining the mechanisms of tool-part interaction. In [11], the mechanism of the polishing process with elastic-abrasive tools on a curved surface is considered. It was established that the elastoplastic deformation of the abrasive surface and the constant wear of the contact surface lead to a decrease and fluctuation of the contact surface pressure. In [12] it was found that wear resistance is determined by thermal processes and depends largely on the material machined, tension, and processing speed. However, it should be noted that, while studying the interaction between the PABT and the part, most of existing studies focus on changing the quality of the machined surface of the part, not the tool.

In [13], the dependence of the wear intensity of BB-ZB abrasive brushes from Scotch-Brite on the machining modes when rounding the part edges was experimentally obtained. The tool used in these experiments is similar to PABT principle. In addition, it consisted of synthetic filaments with abrasive grains distributed evenly throughout their volume. In [14], the tribological interaction of polypropylene yarn, which is the basis of polymer-abrasive filaments, with the surface of metal equipment for its manufacture is considered. The factors influencing filament wear and measures to reduce this phenomenon are examined. These, and a number of other similar studies, consider the wear process from the point of view of tribology. Such a phenomenological approach allows the authors to explain the essence of the process and understand the influence of a particular factor. However, it does not allow interpolating the obtained patterns of wear beyond the studied ranges of factors.

One of the effective ways to control the accuracy and quality of machining parts using PABT is to build models that allow evaluating the influence of process parameters on the characteristics of accuracy and quality of surfaces machined. In [15], the effectiveness of elastic polymer-abrasive wheels when rounding edges has been proven. The research showed the influence of cutting speed, tool deformation and feed along the edge on the quality of the machined edge and the process productivity. Empirical equations are proposed for calculating the parameters of quality and productivity depending on the processing mode parameters. However, despite the regularities established by the authors, they do not allow solving the problem of maintaining a rational value of the PABT tension due to tool dimensional wear during processing. Also, the established regularities do not allow connecting the surface quality with the physical and mechanical characteristics of the machined materials. This makes it impossible to use them to predict the efficiency of machining a wide range of materials used in various high-tech engineering industries, for example, aircraft engine building [16].

The article [17] studies the wear intensity of elastic polymer-abrasive circles when processing the surfaces of parts made of high-strength aluminium alloys. Empirical dependencies of wear on cutting speed and tool deformation are obtained, on the basis of which a method of tool deformation correction with long-term, continuous surface treatment is proposed.

In [18], the wear and mechanical characteristics of LM26 were studied. It has been established that the wear rate of the studied materials progressively increases with increasing porosity. It is also shown that the wear rate decreases at the maximum reinforcement content. Increasing the contact area gradually reduces the wear rate as the sliding distance increases. It has also been observed that research samples obey the Archard theory, according to which the sliding distance is inversely proportional to the wear rate.

In [19], experimentally studied the effect of different tool rotation speeds on the abrasive-wear properties of AA6061-T6 inserts with/without nickel coating. Abrasion test results show that at 710 rpm, the nickel coating has a negative effect on wear resistance compared to uncoated inserts. However, at 1000 rpm, as well as at 1400 rpm, the wear rate of AA6061-T6 nickel-plated inserts is significantly reduced compared to uncoated inserts.

One of the common drawbacks of this and a number of other well-known studies related to modeling the processes of finishing and hardening treatment [20, 21] is the use of dimensional quantities in equations relating tool wear and the surface layer quality to the operating parameters of the process.

For example, [22] studies the influence of disc PABT parameters processing modes and the physical and mechanical properties of the material being processed on the dimensional wear during polishing difficult materials. The analytical dependence of the physical and mechanical properties of the material being processed and the wear of polymer-abrasive filaments was obtained as well as a model of the intensity of disc brushes wear. However, the main parameters of the model obtained by the authors were studied in a rather narrow range. At the same time, the authors propose to take into account the wear rate of PABT filaments depending on the part material, the processing speed and tension, the grain size and filament length in dimensional form. This approach limits significantly the practical application of mathematical models in the range of studied modes and processing conditions. This restriction also applies to the material and manufacturing technology of PABT and the material being machined.

To create models of dependences of tool wear on machining modes, a number of authors use different methods. An alternative approach widely used by researchers is based on statistical processing of research results [23]. Stochastic models do not reveal the essence of the wear process, however, they open up broad prospects in terms of predicting the influence of the factors studied on the response function [24]. Models based on the probabilistic approach [25] and artificial intelligence [26, 27] are also being actively developed. A common disadvantage of the latter is the need to process large samples in order to build adequate models of influence. Given the large number of influencing factors, in most cases, obtaining relevant samples is a difficult task.

To describe complex systems, such as machining, the use of the similarity theory and dimensional analysis is well suited [28, 29, 30]. These methods help identify and describe physically similar systems [31, 32]. In [33] on the basis of similarity theory and dimensional analysis, a method for material cutting analysis is proposed. The new method requires fewer tests and provides more reliable information regarding the cutting parameters.

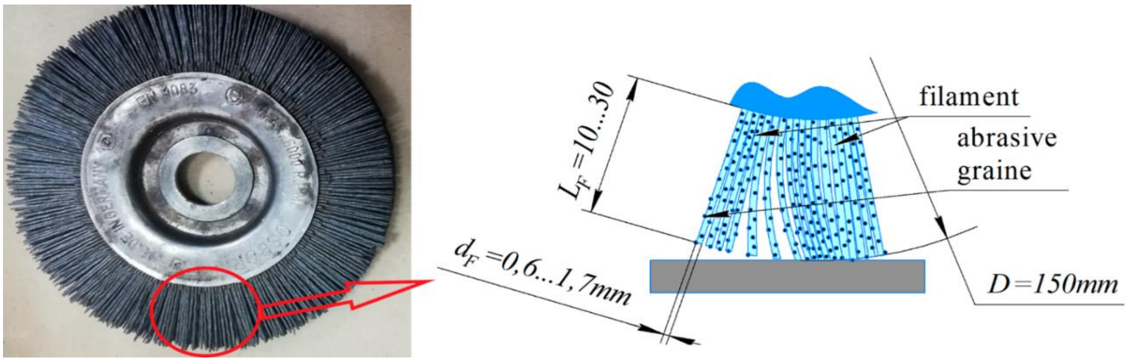
Based on the analysis of the literature, it can be stated that the study of wear of brush polymer-abrasive filaments has a number of difficulties and unsolved problems. This is related to the need to build improved phenological and stochastic models. Despite the existing research results and the given mathematical models, they are not sufficient to fully meet the needs of technologists during the design of technological operations for machining complex-profile parts with PABTs. First of all, this is due to the lack of information on the rate of PABT filaments wear depending on the processing modes and the properties of the machined materials. This makes it impossible to orient the tool in space relative to the surface being machined to maintain a rational level of tension during machining. Consequently, the study of the influence of the physical and mechanical properties of the machined material on the dimensional wear of PABT filaments is an urgent task.

The aim of the work is to study the dimensional wear of PABT filaments during machining various materials as well as the influence of physical and mechanical properties of the material machined. For the first time the authors of the article propose to develop a mathematical model using the similarity theory and dimensional analysis for a physical description of this process.

2 Materials and Methods

2.1 Materials

Samples were machined with disc PABT from "Osborn" and "LESSMANN" companies (Figure 1, a) with abrasive (silicon carbide) of size 80...100 μm, depending on the filament diameter (Figure 1, b). The filament diameter was d_F=0,6…1,7 mm (Table 1). The filament length was adjusted in the range of L_F=10...30 mm with two special side discs (Figure 2). The diameter of used brushes is D=150 mm; the width of the brush is 10 mm.



(a) (b)

Fig. 1 PABT – (a) general view; (b) filaments

Table 1. Filament characteristics

№ of the brush used	Filament diameter d_F, mm	Abrasive grit	Abrasive grain size, μm	Filament length L_F, mm
1	0,6	P180	63…80	10
2	1,2	P120	100…125	10
3	1,7	P80	200…250	10
4	0,6	P180	63…80	20
5	1,2	P120	100…125	20
6	1,7	P80	200…250	20
7	0,6	P180	63…80	30
8	1,2	P120	100…125	30
9	1,7	P80	200…250	30

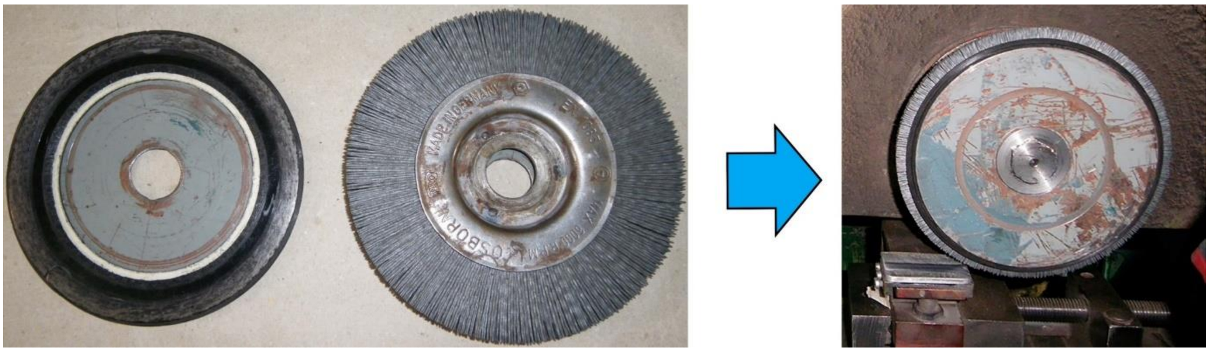


Fig. 2 Use of side discs for changing filament overhand

2.2 Laboratory samples

The surface roughness of laboratory samples (100×50×10 mm) made of Steel 20, aluminum AD0, brass L96, copper M2, titanium alloy VT8M-1, heat-resistant alloy HN45MVTUBR corresponded to the quality of milling Ra=3.2 μm. The values of the physical and mechanical properties of the sample materials were taken from reference literature, accompanying documentation or actually measured (Table 2).

Table 2. Physical and mechanical properties of the samples

Material / ASTM analogue	Thermal conductivity λ, Watt/m·K	Brinell hardness HB, MPa	Strength limit $\sigma_{в}$, MPa	Impact strength KCU, kJ/m^2	Young's modulus E, hPa	Elongation coefficient δ, %	Yield strength σ_T, MPa
VT8M-1 / Ti-5,5Al-4Mo-1Sn	20	298	1020	250	112	8	380
M2 / C12500	380	48	180	1400	110	32	90
Steel 20 / 1020	55	160	603	780	200	18	255
HN45MVTUBR / 10Cr15Ni45Mo5 Ti2W3NbMnAl	75	270	981	250	220	7	620
AD0 / A91060	226	65	80	1200	70	5	40
L96 / C21000	110	153	490	900	95	8	350

2.3 Methods of researching the wear and tear of PABT filaments

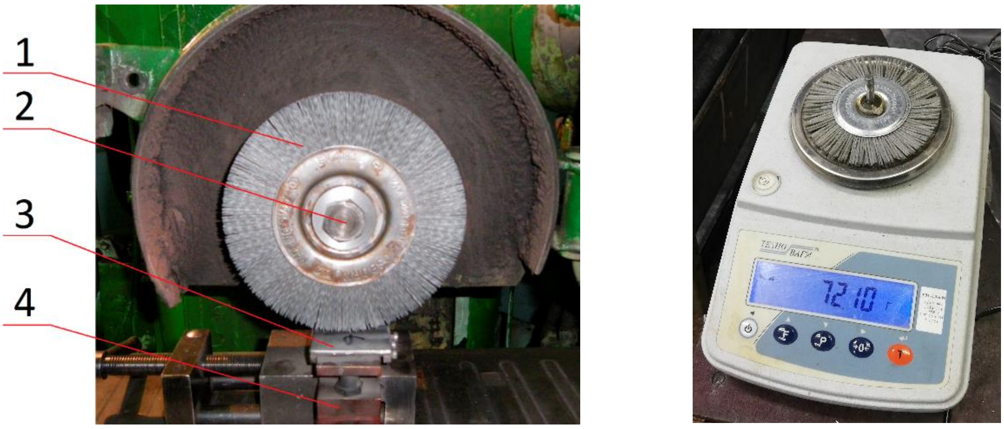
A workplace was designed to study the wear of disc brush filaments. Polishing of samples fixed on a special mandrel was performed on a surface-grinding machine 3G71 (Figure 3, a), for one hour. PABTs were weighed before and at the end of machining (Figure 3, b). To assess the maximum possible filament wear and the impact of parameters on it, the machining was carried out on rational modes without the use of coolant. The machining speed was changed due to the engine speed using a frequency converter in the range technologically recommended for PABT that is 6...21 m/s. The longitudinal feed was S=1 m/min, as a rational value for ensuring high quality polishing. The tension of the brush during machining was changed by moving the spindle vertically in the range of 0.5...2 mm. The tension change was controlled every 5 minutes.

Weighing of the brush was carried out on laboratory scales TVE-0.3-0.01. The maximum weighing limit of the scales was 2100 g, the discreteness of weighing was 0.01 g, the weighing accuracy was 0.02 g. A series of experiments for each brush was repeated three times to exclude observation errors; then the arithmetic mean of mass wear (ΔMF, g/h) was calculated.

Subsequently, the PABT mass wear was translated into the filament length wear (Δl, mm/h), that is, in the dimensional wear of the brush:

$$\Delta l = \frac{4\cdot\Delta M_F}{n\cdot\pi\cdot d_F^2\cdot\rho_F}, mm \qquad (1)$$

where ΔMF is the PABT mass wear, g/h; n is the number of filaments in the brush, pcs; dF is the filament diameter, mm; ρF is the density of the filament, g/mm.



(a) (b)

1 – disc PABT; 2 – spindle; 3 – sample; 4 – special vice

Fig. 3 General view of the device (a) and weighing brushes (b)

Simultaneously with the measurement of mass wear, the reduction in the filament length was monitored using a microscope. Due to the vibration during the operation filaments perform complex movements; they wear out at different angles, which constantly change during machining. As a result, the wear areas of the filament tops are not constant. Therefore, it is difficult to obtain consistent measurements of dimensional wear on a microscope.

Statistical processing of experimental results was performed using the STAISTICA software complex.

3 Results

3.1 Evaluation of the influence of processing parameters on the PABT filaments wear

The mechanism of filament wear during machining samples is complex and includes abrasive, adhesive, and diffuse components. The specific effect of each component depends on the material properties and processing conditions. Abrasion is the main cause of filament wear (Figure 4). Equally important is the adhesion of filament particles to the surface being machined with their subsequent tearing-off.

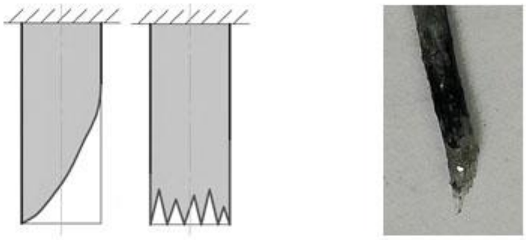


Fig. 4 The wear of PABT filaments

During the experiments, the dimensional wear of the PABT filament was obtained and the influence of processing modes and material properties of the samples on its intensity was explained. The results of measurements of filaments wear during machining of various materials show that when the tension changed from 0.5 to 2 mm (Figure 5), the wear increased by 2...3 times. Similarly, the wear increased with a decrease in the filament overhand from 30 to 10 mm (Figure 7). The intensity of wear significantly increased when the reduction in length was combined with an increase in filament diameter.

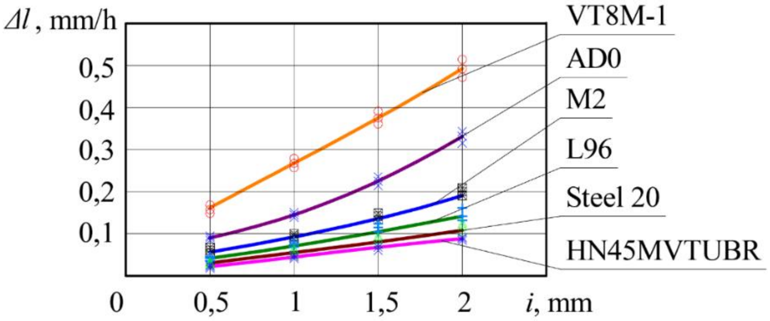


Fig. 5 Dependence of the PABT filaments wear (d_F =1.2 mm, L_F =30 mm, V=12 m/s) on tension i

Increasing the processing speed from 6 to 21 m/s (Figure 6) caused an increase in the brush filaments wear by 5…8 times. Several factors influenced the increase in wear rate in this case. Firstly, with the increase in the processing speed, the idle time (free rotation), during which the filaments self-cooled, decreased. As a result, the temperature in the contact zone increased depending on the thermophysical properties of the samples material. When the filaments reached the softening temperature in the contact zone, they lost abrasive grains more intensively. Secondly, the physical and mechanical properties of the samples material changed the intensity of filaments wear in different ways when the kinetic energy of the filaments impact increased.

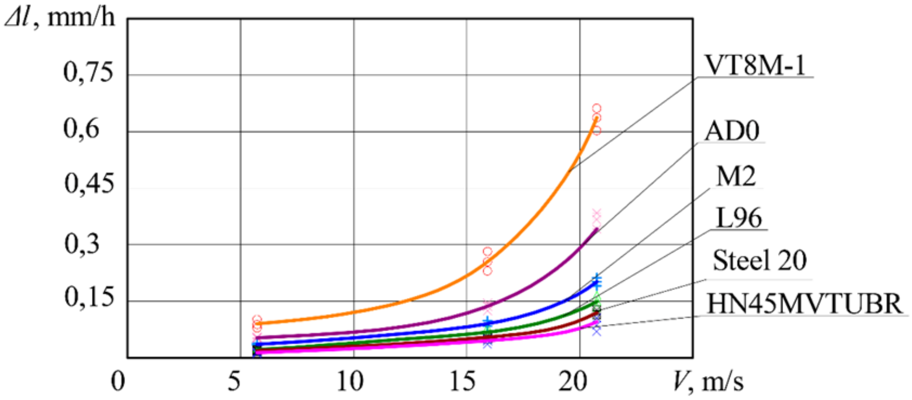


Fig. 6 The influence of processing speed on the PABT filaments wear (d_F =1.2 mm, L_F=30 mm, i=1 mm)

The established dependences of filament wear on cutting modes qualitatively coincide with the results of studies for similar tools considering the wear process from the point of view of tribology [13, 14, 15]. The results of the experiments confirm the studies [12, 17], in which it was substantiated that wear depends on thermal processes in the machining zone, the material being processed, interference and cutting speed. However, dependence of wear on the mechanical characteristics of the processed materials is not mentioned in these papers. In this regard, the next stage of the study was to establish the general pattern of wear for materials of various classes.

The experiment results showed that when polishing different materials, the filament wear differed significantly (Table 3). Consequently, among all the materials studied, the filament wear in the machining heat-resistant alloys was minimal, and for the titanium alloy it was maximum. The same dependence of filaments wear was obtained for different filament lengths (Table 4), (Figure 7) and for different filament diameters (Table 5), (Figure 8). We observe that the dependence of wear on the material of the machined sample is preserved in all experiments. The literature analysis showed that in most cases the coefficient KM of the machined material, and structural steel as a base material are used in order to take into account the properties of the machined material in determining the cutting modes and cutting tool durability. In this paper the wear Δl' (mm/h) during the machining Steel 20 was taken as the basic filament wear.

Table 3. Results of the experimental study of wear of the Δl filament (mm/h) of the disc PABT (d_F =1.2 mm, L_F =30 mm, P120)

Material / ASTM analogue	Cutting speed V, m/s	Tension i, mm			
		0,5	1	1,5	2
Steel 20 / 1020	6	0,011	0,020	0,030	0,041
	12	0,028	0,054	0,088	0,11
	21	0,072	0,126	0,189	0,246
HN45MVTUBR / 10Cr15Ni45Mo5Ti2W3NbMnAl	6	0,008	0,014	0,024	0,033
	12	0,025	0,044	0,072	0,080
	21	0,044	0,095	0,139	0,176
L96 / C21000	6	0,013	0,022	0,033	0,052
	12	0,038	0,066	0,107	0,135
	21	0,076	0,145	0,221	0,290
M2 / C12500	6	0,019	0,039	0,050	0,065
	12	0,054	0,091	0,129	0,192
	21	0,113	0,208	0,334	0,447
AD0 / A91060	6	0,033	0,055	0,080	0,107
	12	0,091	0,142	0,223	0,330
	21	0,195	0,334	0,542	0,706
VT8M-1 / Ti-5,5Al-4Mo-1Sn	6	0,052	0,093	0,129	0,170
	12	0,151	0,268	0,275	0,491
	21	0,328	0,617	0,914	1,147

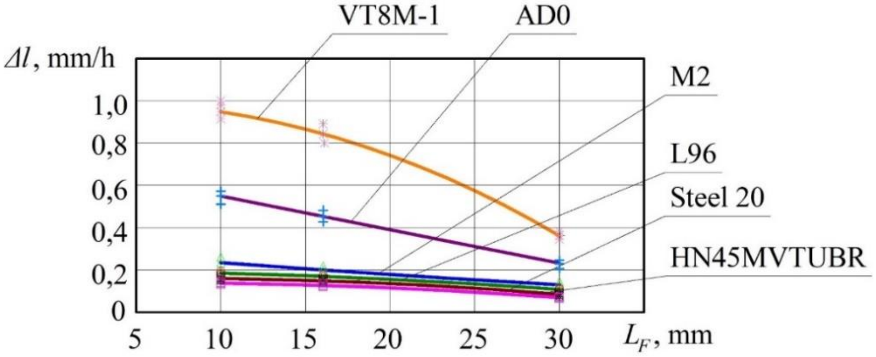


Fig. 7 Dependence of the PABT filaments wear (d_F =1.2 mm, i= 1.5 mm, V=12 m/s) on the filament length L_F

Table 4. Results of the experimental study of the wear of the Δl_F filament length (mm/h) of the disc PABT (d_F =1.2 mm, i=1.5 mm, P120)

Material / ASTM analogue	Cutting speed V, m/s	Filament length L_F, mm		
		10	20	30
Steel 20 / 1020	6	0,05	0,04	0,03
	12	0,16	0,15	0,09
	21	0,35	0,3	0,19
HN45MVTUBR / 10Cr15Ni45Mo5Ti2W3NbMnAl	6	0,04	0,03	0,02
	12	0,14	0,12	0,07
	21	0,29	0,25	0,14
L96 / C21000	6	0,06	0,05	0,35
	12	0,20	0,17	0,11
	21	0,42	0,35	0,22
M2 / C12500	6	0,09	0,07	0,05
	12	0,25	0,20	0,13
	21	0,62	0,50	0,33
AD0 / A91060	6	0,18	0,16	0,08
	12	0,52	0,45	0,22
	21	1,30	1,12	0,54
VT8M-1 / Ti-5,5Al-4Mo-1Sn	6	0,33	0,30	0,13
	12	0,95	0,88	0,37
	21	2,37	2,20	0,91

Table 5. Results of the experimental study of wear of the Δl filament length (mm/h) of the disk PABT (i=1.5 mm, L_F =10 mm)

Material / ASTM analogue	Cutting speed V, m/s	Abrasive grain size	
		P180	P80
		Filament diameter d_F, mm	
		0,6	1,7
Steel 20 / 1020	6	0,16	0,035
	12	0,25	0,16
	21	0,45	0,34
ХН45МВТЮБР / 10Cr15Ni45Mo5Ti2W3NbMnAl	6	0,12	0,025
	12	0,2	0,11
	21	0,36	0,26
Л96 / C21000	6	0,19	0,04
	12	0,28	0,17
	21	0,51	0,36
М2 / C12500	6	0,25	0,06
	12	0,38	0,26
	21	0,68	0,57
АД0 / A91060	6	0,42	0,09
	12	0,7	0,4
	21	1,28	0,9
ВТ8М-1 / Ti-5,5Al-4Mo-1Sn	6	0,72	0,16
	12	1,08	0,7
	21	1,97	1,5

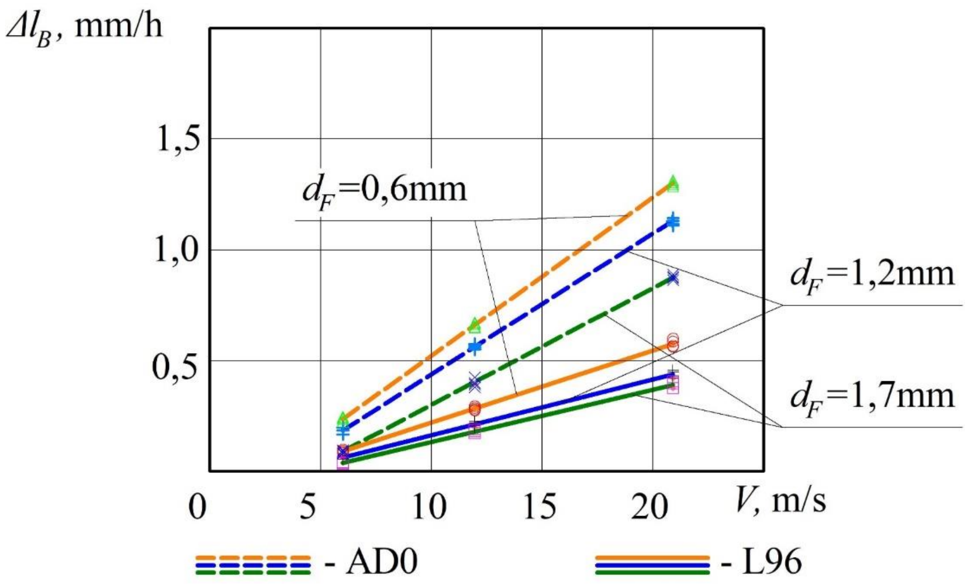


Fig. 8 Dependence of the PABT filaments wear (L_F=10 mm, i=1,5 mm)

By comparing the obtained values of wear when machining different materials under the same conditions, with the values for the base material (steel 20), a conditional degree of filament wear was obtained. Then this indicator was averaged for further analysis (Table 6).

Table 6. Comparative table of the conditional degree of filaments wear when machining different sample materials (d_F =1.2 mm, L_F =30 mm, P120, i=1.5 mm)

Tension *i*, мм	Cutting speed *V*, m/s	Steel 20	HN45MVTUBR	L96	M2	AD0	VT8M-1
0,5	6	1	0,73	1,18	1,73	3,0	4,73
	12	1	0,89	1,36	1,93	3,25	5,39
	21	1	0,61	1,06	1,57	2,71	4,56
1	6	1	0,7	1,1	1,95	2,75	4,65
	12	1	0,81	1,22	1,69	2,63	4,96
	21	1	0,75	1,15	1,65	2,65	4,9
1,5	6	1	0,8	1,1	1,67	2,67	4,3
	12	1	0,82	1,22	1,47	2,53	3,13
	21	1	0,74	1,17	1,77	2,87	4,84
2	6	1	0,8	1,27	1,59	2,61	4,15
	12	1	0,73	1,23	1,75	3,0	4,46
	21	1	0,72	1,18	1,82	2,87	4,66
Average degree of filament wear (*Y*)		1	0,76	1,19	1,72	2,8	4,56

3.2 Determination of the sample material parameters affecting the filament wear the most

To study the degree of influence of each parameter determining the physical and mechanical properties of the machined material (Table 2) on the intensity of PABT wear, the correlation analysis was performed. Samples of the studied factors were tested for normality according to the Kolmogorov-Smirnov and Shapiro-Wilk criteria. These samples did not have a normal distribution, that is why Spearman's rank criterion was chosen as a criterion for assessing the relationship between the samples.

Table 7. The examined physical and mechanical properties of the machined material

№	Symbols	Factor	Dimension
1	λ	thermal conductivity	Watt/m·K
2	HB	Brinell hardness	MPa
3	σ_B	strength limit	MPa
4	KCU	impact strength	kJ/m^2
5	E	Young’s modulus	hPa
6	δ	elongation coefficient	%
7	C_p	specific heat	J/kg·K
8	ρ	density	kg/m^3
9	α	temperature conductivity	m^2/s
10	G	shear modulus	MPa
11	σ_T	yield strength	MPa
12	μ	Poisson's ratio	-

The factors "temperature conductivity" had correlation values less than 0.3, but were left because they characterize the temperature in the contact zone, and temperature is one of the main factors influencing the PABT filament wear [12]. From the very beginning, rational machining modes were assigned in the studies, in which no filament overheating was observed, so the wear was stable (there was no catastrophic effect of filament softening and melting), due to which the factors "temperature conductivity" had a low impact on the correlation.

Factors of thermal conductivity, specific heat and density were not included, due to their direct interaction with temperature conductivity, which is calculated from the equation:

$$\alpha = \frac{\lambda}{\rho \cdot C_p} \tag{2}$$

Such factors as the shear modulus and the Poisson's ratio were not included due to their direct dependence on the Young's modulus, which can be calculated from the equation:

$$E = 2G \cdot (1 + \mu) \tag{3}$$

The strength limit factor was not included, as it has a direct dependence on hardness and can be determined for each material from empirical dependence:

$$HB = k \cdot {\sigma_B}^n + A \tag{4}$$

where *k, n, A* are coefficients characterizing the material and its heat treatment.

When investigating the physical and mechanical properties of the machined materials, it was established that each property separately did not allow characterizing the PABT wear fully, and this effect was complex. It was found that the influence of hardness, impact strength, Young's modulus, and thermal conductivity coefficient of the material were the strongest. Therefore, in order to simplify further calculations of the dependence of the PABT wear rate on the specified physical and mechanical properties of the machined materials, it was proposed to calculate the material coefficient ($K_{м}$), which characterizes the abrasion of the PABT filaments.

4 Discussion

The concept of practical similarity can be used to analyze the influence of physical and mechanical properties on the PABT filament wear [28, 29]. From the point of view of the adequacy of the physical nature of such phenomena occurring during the polishing real details and samples, there is a basic type of similarity - physical similarity [33]. Physical similarity implies compliance with the conditions of the high-speed friction process, physical and mechanical characteristics of materials, forces in the contact zone, temperatures and heat flows [30, 31]. It can be assumed with a certain approximation that the physical nature of PABT filament wear in the machining various metals does not change. In the general case, using the similarity theory in the form of functional dependencies, it is possible to describe the relationship between the model and the original, i.e. to predict the intensity of PABT filament wear by reducing the number of tests significantly.

To validate and use the factors that determine the degree of PABT filament wear in the finishing different materials, the similarity theory and dimensional analysis are used. The factors influencing the degree of PABT filament wear are grouped in the form of dimensionless criteria, the structure of which reflects their physical interaction. According to the literature analysis, based on a priori information, according to the method of determining similarity criteria [28, 32], independent factors were identified that characterize the influence of physical and mechanical properties of the machined material on the intensity of PABT filament wear.

It should be noted that the factors characterizing the tool parameters (brush diameter DF, brush width B, filament length LF, filament density ρF, abrasive grain size P, abrasive grain concentration C, abrasive grain material) and machining modes (tension i, speed n, feed S, lubricating and cooling technological medium) were not included in the model of the influence of physical and mechanical properties on the PABT filaments wear. All these factors form a separate complex - "machining parameters", which independently affects the PABT filament wear. The factor "PABT filaments wear Δl" was used to build the model as an indicative factor. The factor "filament diameter dF" was used in the model because it is a characteristic parameter that can estimate the unit area of interaction with the machined surface and friction in the filament-detail area and, consequently, the filament wear itself. The machining speed factor «cutting speed V» was also used in the model, as it affects the energy components of the filament impact in the process of deformation and destruction of material particles. It also affects the conditions of high-speed friction, characterized by Peclet criterion [34]:

$$P_e = \frac{V \cdot \delta}{\alpha} \tag{5}$$

where δ is the characteristic linear size of the heat transfer surface, m. The diameter d_F was taken as such a size when the PABT filament wear was studied; V is the flow rate of the medium relative to the heat transfer surface, m/s. In the study of PABT filament wear, the maximum speed V_{max} was selected as such speed, which is technologically recommended for this tool.

The general ratio, which includes the most significant factors affecting the PABT filament wear and reflects the significant links between them, can be represented as a functional dependence:

$$f(\Delta l, E, KCU, HB, \alpha, V, d_F)=0 \tag{6}$$

To compile a complete matrix of dimensions $|A|$, the dimensions of all factors were presented in the system of basic units $[L, M, T]$: the number of rows of the complete matrix of dimensions corresponded to the total number of factors (m=7), and the number of columns corresponded to the number of basic units of measurement (q=3) (see Table 8).

The number of independent factors k is equal to the rank of the complete matrix of dimensions $|A|$, and the number of similarity criteria K_π=4 is the difference between the total number of factors m=7 and the number of independent factors: k=3.

Table 8. Complete matrix of dimension |A| for selected factors

№	L	M	T	Factor
1	1	0	-1	V
2	2	0	-1	α
3	-1	1	-2	HB
4	0	1	-2	KCU
5	-1	1	-2	E
6	1	0	0	Δl
7	1	0	0	d_F

The studied process can be represented as a functional dependence between the found similarity criteria:

$$\psi(\pi_1, \pi_2, \ldots, \pi_8) = 0 \qquad (7)$$

The total number of all groups of independent parameters (all combinations of m factors using K_π) is determined by the formula:

$$C_m^k = \frac{m!}{k!(m-k)!} \qquad (8)$$

In this case, there are 35 possible combinations of independent factors and, therefore, for 4 similarity criteria (K_π=4), 35 forms of F_π records are possible. Taking into account the physical sense, the following similarity criteria were recommended for testing:

$$\pi_1 = \frac{\Delta l}{\Delta l'}; \pi_2 = \frac{E}{HB}; \pi_3 = \frac{KCU}{HB \cdot d_B}; \pi_4 = \frac{V \cdot d_B}{\alpha} \qquad (9)$$

Due to the fact that one of the similarity criteria (the determinative one) is necessarily a function of other (independent) similarity criteria, the final criterion equation can be written as follows:

$$\pi_1 = \Phi(\pi_2 \ldots \pi_4) \qquad (10)$$

The total number of values determining the nature of the studied process decreases to m-k-1=3. The determining criterion of similarity is $K_M = \Delta l / \Delta l'$. It is a material coefficient, which characterizes the difference in of PABT filament wear depending on the physical and mechanical properties of the machined material in relation to the basic wear.

Analyzing the identified similarity criteria, the following conclusions can be made:

(1) Criterion π_1 is the determining parameter; it is the material coefficient.
(2) Criterion π_2 characterizes the resistance of the machined material to the penetration of abrasive grains during machining.
(3) Criterion π_3 characterizes the ability of the machined material to absorb the mechanical energy in the deformation and destruction processes under the PABT filament impact during machining.
(4) Criterion π_4 in its physical essence coincides with the Peclet criterion, which is a criterion of similarity for the processes of convective heat transfer.
(5) Analysis of the physical essence of the similarity criteria π_3, π_4 shows that they are close in content, and it is advisable to turn them into one criterion $\pi_3 \cdot \pi_4 = \frac{KCU \cdot V}{HB \cdot \alpha}$.

Taking into account all the transformations made, the criterion equation takes the following final form:

$$K_M = \frac{\Delta l}{\Delta l'} = \Phi\left(\frac{E}{HB}; \frac{KCU \cdot V}{HB \cdot \alpha}\right) \qquad (11)$$

To determine the dependence of K_M, the results of the study on the effect of properties of six machined materials on the PABT filament wear were statistically processed. After statistical processing of the experiment results, the regression equation of the material coefficient was obtained:

$$K_{\text{M}} = 9{,}1 - 1{,}8 \cdot \frac{E}{HB} + 2{,}48 \cdot \frac{KCU \cdot V}{HB \cdot \alpha} + 0{,}24 \cdot \left(\frac{E}{HB}\right)^2 + 0{,}39 \cdot \frac{E}{HB} \cdot \frac{KCU \cdot V}{HB \cdot \alpha} - 0{,}17 \cdot \left(\frac{KCU \cdot V}{HB \cdot \alpha}\right)^2 \qquad (12)$$

The correlation coefficient of the equation was $R > 0.8$, which indicates a high approximation of factors. The calculated Fisher's criterion was less than 0.05, which confirms the adequacy of the model obtained.

When estimating the cost of the finishing process with PABT, the main factor is the cost of the worn tool, which depends on the properties of the machined material and cutting modes. The use of the dimensionless coefficient of materials K_M allows predicting the intensity of PABT filament wear on materials that have not been studied (see Table 9), and solving the problem of manufacturing optimization. The analysis of the calculated value of the material coefficient K_M (see Figure 9) for materials of different classes used in mechanical engineering, shows the effectiveness of the PABTs use for finishing these materials and allows assessing the tool durability.

Table 9. Physical and mechanical properties of the materials machined

Material class	№ material	Material / ASTM analogue	Physical and mechanical properties				K_M
			HB, MPa	*KCU*, kJ/m^2	*α*, 10^{-6}m^2/s	*E*, hPa	
Structural steels	1	Steel 20 / 1020	160	780	14	210	1,0
	2	Steel 45 / 1045	180	550	14	210	1,0
	3	Steel 30ХГСА / 30CrMnSiA	220	490	9,6	210	0,9
Heat-resistant steel	4	HN45MVTUBR/ 10Cr15Ni45Mo5Ti2W3NbMnAl	270	410	4,3	220	0,8
	5	HN51KVMTUB / 5Cr10Ni52Mo4Ti2W6Nb3Al5Co15Hf	350	400	4,3	220	0,7
	6	Inconel 718 / B637	330	380	3,2	205	0,7
Copper and copper alloys	7	L96 / C21000	130	1400	28	118	1,2
	8	LZhMts59-1-1 / CuZn40Fe1Mn1	88	500	30	118	1,2
	9	M2 / C12500	95	1800	112	110	1,6
Aluminium and aluminium alloys	10	AD0 / A91060	79	900	90	70	2,8
	11	D16 / 2024	45	350	90	70	2,9
	12	AMг2 / A95052	78	950	90	70	2,6
Titanium alloys	13	VT8M-1 / Ti-5,5Al-4Mo-1Sn	298	250	10,4	112	4,9
	14	VT9 / Ti-6Al-3Mo	350	310	10,4	112	4,8
	15	VT6 / Ti-6Al-4V	335	360	10,4	112	4,2

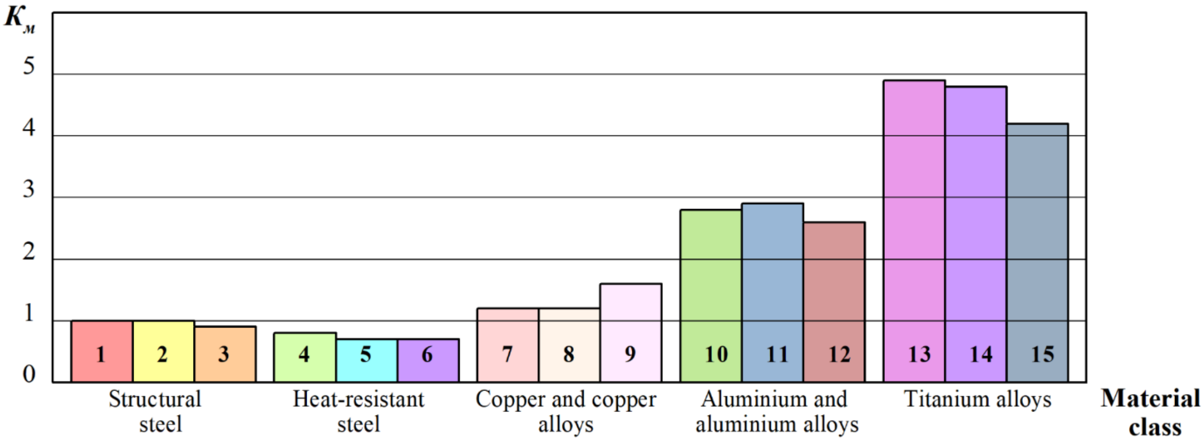


Fig. 8 Evaluation of the influence of the 1…15 (see Table 9) machined material properties on the intensity of PABT filament wear

CONCLUSION

The following conclusions can be made from this study:

(1)The determined dependance for Kм material coefficient takes into account the influence of the physical and mechanical properties of the machined material and then estimates the intensity of PABT filaments wear. For example, for aluminum alloy D16, the calculated coefficient is equal to 2.9. This means that during machining this material the brush filaments wear by 2.9 times quicker than when machining Steel 20.

(2)Prediction of the intensity of PABT filaments wear allows timely correction of the tool position during machining on CNC machines to ensure a constant pressing of the PABT to the surface being machined. Providing stable pressing increases the quality of surface machining and the accuracy of the obtained dimensions.

(3)The use of the Kм material coefficient makes it possible to evaluate the tool life and the cost of manufacturing a part. For example, for a brush with LF =30 mm and a minimum permissible filament overhand of 10 mm, the brush life when machining parts from Steel 20 is 200 hours, and from VT8M-1 is 40 hours.

REFERENCES

[1] Pavlenko, D., Kondratiuk, E., Torba, Y., Vyshnepolskyi, Y., Stepanov, D. “Improving the efficiency of finishing-hardening treatment of gas turbine engine blades”. Eastern-European Journal of Enterprise Technologie 1 (12-115), pp. 31 – 37, **2022**. DOI: 10.15587/1729-4061.2022.252292

[2] Davim, J. P. (ed.) “Tribology for engineers: A practical guide”, Elsevier, **2011**.

[3] Kannan, S., Kui, L. “Experimental investigation of surface integrity during abrasive edge profiling of nickel-based alloy”, Journal of manufacturing processes 39, pp. 40 – 51, **2019**. DOI: 10.1016/j.jmapro.2019.01.052

[4] Stary, M., Novotny, F., Horak, M., et. al., “Summary of the properties and benefits of glass mechanically frosted with an abrasive brush”, Construction and Building Materials 206, pp. 364 – 374, **2019**. DOI: 10.1016/ j.conbuildmat.2019.02.062

[5] Raymond, N., Soshi, M. “A study on the effect of abrasive filament tool on performance of sliding guideways for machine tools”, Procedia CIRP 45, pp. 223 – 226, **2016**. DOI: 10.1016/j.procir.2016.02.169

[6] Bergs, T., Schneider, S. A. M., Amara, M., et. al. “Preparation of symmetrical and asymmetrical cutting edges on solid cutting tools using brushing tools with filament-integrated diamond grits”, Procedia CIRP 93, pp. 873 – 878, **2020**. DOI: 10.1016/j.procir.2020.04.028

[7] Tryshyn, P., Honchar, N., Kondratiuk, E., Stepanov, D. “Development of technological restrictions when operating disc polymer-abrasive brushes”, Eastern-European Journal of Enterprise Technologies 6, no 1(108), pp. 27 – 33, **2020**. DOI: https: 10.15587/1729-4061.2020.212820

[8] Gonchar, N., Kachan, O., Stepanov, D., et. al., “Measurement of non-rigid tools action force during finishing”, DSMIE-2018. Springer, pp. 23 – 32, **2018**. DOI: 10.1007/978-3-319-93587-4_3

[9] Wang, C., Guo, H., Zhao, Y., et al. “Statistical analysis of industrial grinding brush force characteristics based on finite element approach”, Mathematical Problems in Engineering, **2018**. DOI: 10.1155/2018/7362705

[10] Podashev, D. “Theory of formation of edge surface roughness finished by radial polymer-abrasive brushes”, Materials Science Forum 1037, pp. 571 – 580, **2021**. https://doi.org/10.4028/ www.scientific.net/MSF.1037.571.

[11] Wu, X., Tong, X., Sun, H., et al. “Parameter optimization of polishing M300 mold steel with an elastic abrasive”, Mathematical Problems in Engineering, **2018**. DOI: 10.1155/2018/3965405.

[12] Abrashkevych, Y., Machyshyn, G. “Vpliv teplovih protsesiv na pratsezdatnist polimerno-abrazivnoyi schitky”, Promislove budivnitstvo ta Inzhenerni sporudi 1, pp. 44 – 47, **2012**.

[13] Dimov, Yu. V., Podashev, D. B. “Efficient machining by elastic abrasive wheels”, Russian Engineering Research 37 (7), pp. 655 – 659, **2017**. DOI: 10.3103/S1068798X17070097

[14] Aldousiri, B., Shalwan, A., Chin, C. W. “A review on tribological behaviour of polymeric composites and future reinforcements”, Advances in Materials Science and Engineering, **2013**. DOI: 10.1155/2013/645923

[15] Dimov, Y., Podashev, D. “Rounding sharp edges of machine parts with elastic polymer abrasive wheels”, IOP Conference Series: Materials Science and Engineering 709 (2), p. 022056, **2020**. DOI: 10.1088/1757-899X/709/2/022056

[16] Pavlenko, D., Dvirnyk, Y., Przysowa, R. “Advanced materials and technologies for compressor blades of small turbofan engines”, Aerospace 8 (1), pp. 1 – 16, **2021**. DOI: 10.3390/aerospace8010001

[17] Podashev, D. “Control of deformation of elastic polymer-abrasive circles at their wear”, Modern Trends in Manufacturing Technologies and Equipment: ICMTMTE 21, pp. 329, **2021**. DOI: 10.21741/9781644901755-58.

[18] Konda, L.C., Srinivas, K. “Evaluation of Wear Behaviour Based on Mechanical Properties and Particle Size in LM26 MMC”, Strojnícky časopis – Journal of Mechanical Engineering 72 (2), pp. 93 – 102, **2022**. DOI: 10.2478/scjme-2022-0019

[19] Bahuguna, S., Arya, P. K., Patel, V. K. “Mechanical and abrasive wear properties of

friction stir welded joints of aluminum alloy AA6061-T6 with/without nickel coating," Strojnícky časopis – Journal of Mechanical Engineering 70 (2), pp. 21 – 36, **2020**. DOI: 10.2478/scjme-2020-0017

[20] Dimov, Y., Podashev, D. "The wheels for final processing of parts", IOP Conference Series: Materials Science and Engineering 971 (2), p. 022029, **2020**. DOI: 10.1088/1757-899X/971/2/022029

[21] Halila, F., Czamota, C., Nouari, M. "Modeling of abrasive tool wear in machining using statistical and tribological approaches", 5th World Tribology Congress (WTC 2013) 3, pp. 1917 – 1920, **2014**.

[22] Gonchar, N., Tryshyn, P. "Kompleksnaya otsenka faktorov. vliyayushchikh na razmernyy iznos diskovykh shchetochnykh polimerno-abrazivnykh instrumentov," Vestnik dvigatelestroeniya 1, pp. 89 – 95, **2019**.

[23] Halila, F., Czarnota, C., Nouari, M. "New stochastic wear law for predicting the abrasive flank wear and tool life in machining process", Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology 228, p. 1243, **2014**. DOI: 10.1177/1350650114521405

[24] Kunitsyn, M., Usov, A. "Improvement of a stochastic dynamic model for grinding of cylindrical surfaces with wear-resistant coatings", Grabchenko's International Conference on Advanced Manufacturing Processes, pp. 534 – 544, **2021**. DOI: 10.1007/978-3-030-68014-5_52.

[25] Niaki, F. A. "A probabilistic-based approach to monitoring tool wear state and assessing its effect on workpiece quality in nickel-based alloys", PhD Thesis, Clemson University, **2016**.

[26] Baig, R. U., Javed, S., Khaisar, M., Shakoor, M., Raja, P. "Development of an ANN model for prediction of tool wear in turning EN9 and EN24 steel alloy", Advances in Mechanical Engineering 13 (6), p. 16878140211026720, **2021**. DOI: 10.1177/16878140211026720

[27] Tabaszewski, M., Twardowski, P., Wiciak-Pikuła, M., Znojkiewicz, N., Felusiak-Czyryca, A., Czyżycki, J. "Machine learning approaches for monitoring of tool wear during grey cast-iron turning", Materials 15 (12), p. 4359, **2022**. DOI: 10.3390/ma15124359. PMID: 35744419; PMCID: PMC9230642

[28] Rzasinski, R. "Technological similarity theory model for series of types of constructions", International Journal of Materials and Product Technology 50 (3-4), pp. 289 – 304, **2015**.

[29] Sterrett, S. G. "Similarity and dimensional analysis", Philosophy of technology and engineering sciences, pp. 799 – 823, **2009**.

[30] Simon, V., Weigand, B., Gomaa, H. "Dimensional analysis for engineers", Springer, **2017**.

[31] Bowers, B., Schatzman, L. "Dimensional analysis", Developing grounded theory, pp. 86 – 126, **2016**.

[32] Gibbings, J. C. "Dimensional analysis", Springer Science & Business Media, **2011**.

[33] Serdobintsev, Y. P., Krylov, E. G., Makarov, A. M., Barabanov, V. G., Kozlovtseva, N. V. "More efficient analysis of the machining of new structural materials", Russian Engineering Research 35(11), pp. 864 – 867, **2015**.

[34] Syzyi, Yu., Ushakov, O., Slipchenko S., et al. “Simulation of the contact temperature in the cylindrical plunge grinding process”, Diagnostyka 21 (2), pp. 77 – 86 , **2020**. DOI: 10.29354/diag/122532