DEVELOPMENT OF MATHEMATICAL MODELS DESCRIBING THE PROCESS OF FRICTION AND WEAR OF META-ARAMID

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The study aims to describe the properties of heat-resistant coatings of tribological purpose based on meta-aramid and obtain mathematical models, that will provide simple usage of this data. These are results of experiments that show the dependencies of coefficient of friction and mass wear on two factors: load and filler content. All the experimental data is obtained for such filler materials: boron nitride, graphite, molybdenum disulfide. As a result, the number of mathematical equations that describe this experimental data is obtained. These equations allow to get interpolated value for any combination of arguments, present smooth 3D graphs, that show the form and character of all the dependencies.

KEYWORDS

Mathematical model, Coating, tribological, Meta-aramid, Approximation, Equation, Load, Filler, Coefficient of friction, Mass wear

1 INTRODUCTION

Modern machines and mechanisms have components that work under high loads. The most problematic issues here are the durability and reliability of friction pairs of heavily loaded machines. To solve the above-mentioned issues, new, modern materials of tribological purpose are used, polymer materials [Sezer Hicyilmaz 2021]. The issue of mathematical description of the properties of these materials for the purpose of their convenient analysis and usage is important nowadays.

One of the promising ways of usage the above-described materials is to apply them to the metal surfaces of parts, which allows, on the one hand, to use important characteristics of the main material of the part, such as strength, but to ensure excellent material properties in the friction zone, such as wear intensity, friction coefficient [Klymenko 2022, Klymenko 2014].

Aromatic polyamides [Buketov 2024, Sapronov 2017, Buketov 2016, Panda 2011], meta-aramid (Nomex), are a promising material for obtaining tribological coatings.

However, it should be noted that meta-aramid, like other aromatic polyamides, has low adhesion to metals, which makes it difficult to obtain high-quality coatings [Valicek 2016, Jurko 2011, Panda 2013a & 2021, Jurko 2012]. The influence of most solid layered fillers on the conditions of formation and performance of such coatings is also unknown.

Polyimide-based coatings have good adhesion to various materials such as metals, polymers, carbon, silicon-based materials (glass fiber, carbon fiber), etc. Aromatic polyamides are usually coated in a two-step process: in the first step, a polyamide acid solution is applied to the substrate, and in the second step, thermal or chemical imidization occurs [Panda 2011 & 2014, Jurko 2013, Dyadyura 2017a, Nahornyi 2022]. There are several coating methods such as solution deposition, immersion [Sukhodub 2018a, Zaloga 2019 & 2020], foaming [Acerbi 2020, Ren 2022, Ding 2022] or vapor deposition [Dyadyura 2017b, Kivimaa 2019, Sassanelli 2020, Panda 2020 & 2022], chemical deposition polymerization [Pandova 2018 & 2020], etc. New methods for applying polymer coatings have also been developed, such as liquid flame spraying, etc. [Harnicarova 2019, Sukhodub 2019].

There is a technique [Klymenko 2014] of obtaining antifriction coatings based on the aromatic polyamide Phenylon, which is a copolymer of meta-aramid. But it should be noted that this copolymer is not synthesized in Ukraine and European countries, and its production has never reached industrial scale.

The purpose of this work is to study and describe the properties of heat-resistant coatings of tribological purposes based on meta-aramid and obtain mathematical models. Since the dependencies between the composition of the material and its properties can be complex, the task is to propose and implement a method of mathematical description of the obtained experimental dependencies.

2 MATERIALS AND METHODS

Polymer coatings of thickness 80...100 µm were obtained by the method described in [Klymenko, 2022], namely by applying a solution of meta-aramid with a suitable filler to the surface of a metal substrate with subsequent evaporation of the solvent by drying. Fillers of these materials were layered solid lubricants: graphite, boron nitride, copper phthalocyanine and molybdenum disulfide. Selected antifriction fillers were used in finely dispersed form with a particle size of 1–2 µm. The filler content varied from 0 to 20 mas.%.

As a starting material for obtaining coatings, a finely dispersed powder with a bulk density of 0, 25 - 0,32 g/cm3 was used.

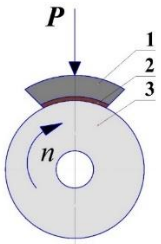

Figure 1. Scheme of the friction: P – load; n – frequency of rotation of the counter body; 1 – metal substrate; 2 – polymer coating; 3 – counter body

Dimethylacetamide (DMAA), which is widely used for dissolving aromatic polyamides, was used as a solvent. The samples were dried in a drying oven at a temperature of $150...165°C$ for 45...55 minutes. The study of the tribological properties of composite coatings based on meta-aramid was carried out in lubrication friction mode at a load of $P = 2{,}5 \ldots 10\ MPa$ and a sliding speed of $v = 1\ m/s$ on a friction machine SMT-1 according to the disc-pad scheme (Fig. 1), on a counterbody made of Steel 45 with a hardness of $45\text{–}50\ HRC$ and a diameter of 50 mm.

As a rule, a mathematical model is understood [Klymenko, 2022] as an approximate description of the basic patterns of a class of objects, systems, or processes using mathematical symbols in the form of equations, inequalities, etc. The development of mathematical models of technological processes is primarily aimed at conducting a computational experiment procedure.

A review [Sukhodub 2018b, Panda 2013b] of literary sources allows us to highlight the following main properties of mathematical models: completeness, accuracy, adequacy, economy, robustness, productivity, and visibility. Polynomial two-factor interpolation and approximation methods were used to solve the problem of describing experimental data. The generalized form of the approximating polynomial is presented in (1).

$$f(x,y) = \sum_{\substack{n=0..k \\ m=0..p \\ i=0..q}} a_i \cdot x^m y^n \qquad (1)$$

In the above expression, i is determined by the number of terms of the polynomial, m and n are determined by the degree of the polynomial. Under somewhat values of i, the polynomial can be complete, then the maximum values of m and n are the same.

Calculations were performed using Mathcad 14 software.

3 RESULTS

At the first stages of research, experimental data was obtained on the dependence of the coefficient of friction f and mass wear I on the load, filler content for different fillers cases. Dependencies for mass wear are presented in Figure 2.

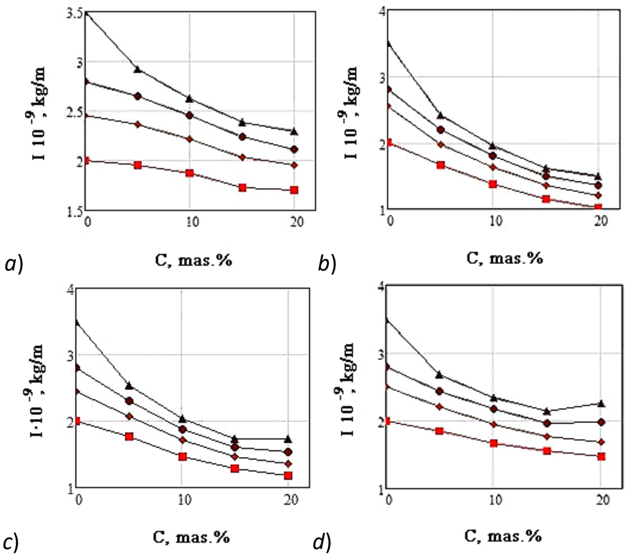

Figure 2. Experimental dependencies of mass wear on the concentration of the filler with different natures of the filler: a) boron nitride, b) copper phthalocyanine, c) graphite, d) molybdenum disulfide

Similar experimental dependences are obtained for the friction coefficient; they are presented in Figure 3.

The forms of above dependencies have simple general trends, but their exact behavior is complicated. The issue of a mathematical description of the experimental results obtained is important. We will describe the above data as the dependences $f(C,P)$ and $I(C,P)$, that is, the dependences of functions on two arguments. Compared to approximation by functions of one argument, this will significantly reduce the number of equations that describe the system, as well as allow finding the values of these functions at any intermediate points of the studied range, but it will also lead to an increase in the size of the interpolation function. Since the above experimental data is already the result of averaging raw experiment results, we will use interpolation to describe the data.

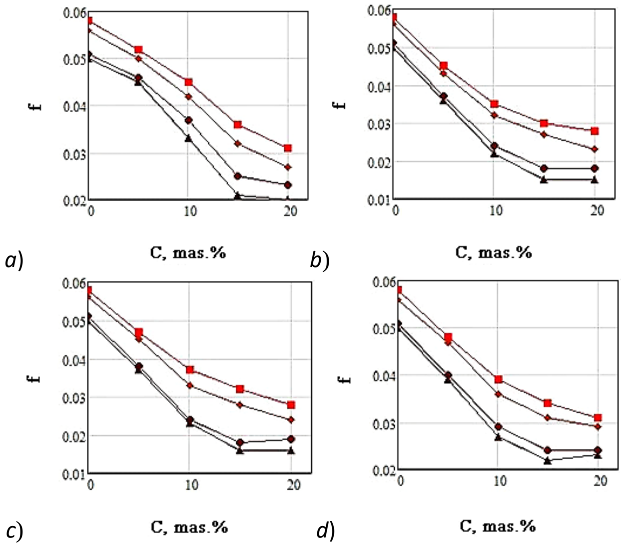

Figure 3. Experimental dependences of the coefficient of friction on the concentration of the filler with different natures of the filler: *a*) boron nitride, *b*) copper phthalocyanine, *c*) graphite, *d*) – molybdenum disulfide

Given the lack of data on the type of dependence that could describe the experimental data, we will use a polynomial for data interpolation, the number of members of it will be equal to the number of experimental points on one graph (20 members) (2). The application limits of this formula.

$$\begin{aligned} f(C,P) = {} & a_0+a_1P+a_2P^2+a_3P^3+a_4P^4+a_5C+a_6CP+ \\ & +a_7CP^2+a_8CP^3+a_9CP^4+a_{10}C^2+a_{11}C^2P+a_{12}C^2P^2+ \\ & +a_{13}C^2P^3+a_{14}C^2P^4+a_{15}C^3 \\ & +a_{16}C^3P+a_{17}C^3P^2+a_{18}C^3P^3+a_{19}C^3P^4 \end{aligned} \qquad (2)$$

$$C = 0 .. 20 \text{ mas. } \%$$

$$P = 2.5 .. 10 \text{ MPa}$$

where f is coefficient of friction, C is filler content, mas. %, P is load, MPa, $a_0 ... a_{19}$ are polynomial coefficients.

Table 1. Values of empirical coefficients for $f(C,P)$

Coefficient	The value of the coefficients of the polynomial			
	Boron nitride	Copper phthalocyanine	Graphite	Molybdenum disulfide
a_1	0.05	0.05	0.05	0.05
a_2	-0.0024667	-0.0043833	-0.0053667	-0.0081833
a_3	0.00067	0.00037167	0.0005866	0.001235
a_4	-0.0000693	-0.0000327	-0.0000453	-0.0000807
a_5	0.000002	0.00000113	0.0000013	0.0000018
a_6	0.0061333	0.0061333	0.0061333	0.0061333
a_7	0.0006477	0.0010978	0.0023089	0.0041378
a_8	-0.0003743	-0.000244	-0.0004673	-0.0008557
a_9	0.0000378	0.00002568	0.0000399	0.0000592
a_{10}	-0.0000010	-8.5333e-7	-0.0000011	-0.0000013
a_{11}	-0.00136	-0.00136	-0.00136	-0.00136
a_{12}	-0.0001293	-0.0001693	-0.0003706	-0.0006987
a_{13}	0.0000745	0.00003347	0.0000675	0.0001416
a_{14}	-0.0000076	-0.0000038	-0.000006	-0.0000098
a_{15}	2.1867e-7	1.3333e-7	1.8133e-7	2.24e-7
a_{16}	0.0000747	0.00007467	0.0000747	0.0000747
a_{17}	0.0000089	0.00000836	0.0000178	0.0000356
a_{18}	0	0	0	0
a_{19}	4.5511e-7	1.7778e-7	2.7022e-7	4.9778e-7
a_{20}	-1.28e-8	-6.4e-9	-8.5333e-9	-1.1378e-8

To describe the dependence for a specific material, it is necessary to substitute the values for the empirical coefficients $a_0 ... a_{19}$ in the polynomial, obtained by interpolation. The values of coefficients for coefficient of friction dependency are given in Table 1.

To visualize the obtained dependencies, we will construct spatial graphs combining the experimentally obtained points and the interpolation surface. Each graph represents a separate material with the $f(C,P)$ dependence for it (Figure 4).

Similarly, the dependences of mass wear on the same parameters $I(C,P)$ can be obtained. The general form of the polynomial (2) remains unchanged, and only the function (and the value of the coefficients) changes.

$$I(C,P)=a_0+a_1P+\ldots+a_{19}C^3P^4 \qquad (5)$$

Coefficients $a_0...a_{19}$ remain unchanged by position but obtain new values.

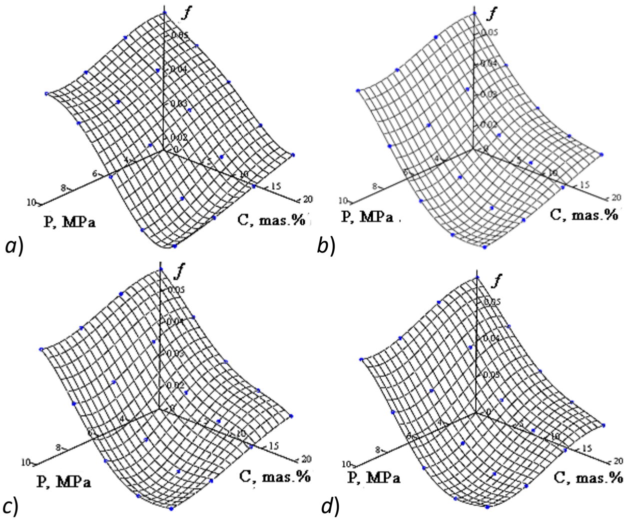

Figure 4. Graphs of dependencies f (C, P) for materials: a) boron nitride, b) copper phthalocyanine, c) graphite, d) molybdenum disulfide

This is due to the organization of experimental studies so that the conditions of their conduction are the same when measuring the coefficient of friction and mass wear. The values of coefficients $a_0...a_{19}$ for dependence (5) are given in Table 2.

Table 2. Values of empirical coefficients for $f(C,P)$

Coeffi-cient	The value of the coefficients of the polynomial			
	Boron nitride	Copper phthalocyanine	Graphite	Molybdenum disulfide
a_1	1.0	0.4	1.0	0.7
a_2	0.16367	0.4215	0.1485	0.217
a_3	-0.025333	-0.06945	-0.02865	-0.030167
a_4	0.001573	0.00418	0.00182	0.00188
a_5	-0.000035	-0.000086	-0.000038	-0.0000413
a_6	0.57	0.95	0.57	0.76
a_7	-0.12363	-0.31408	-0.1136	-0.15608
a_8	0.01951	0.045046	0.014409	0.017437
a_9	-0.00134	-0.0026742	-0.000832	-0.0009969
a_{10}	0.000032	0.00005524	0.0000167	0.0000209
a_{11}	-0.08	-0.144	-0.08	-0.112
a_{12}	0.025693	0.054893	0.021787	0.028893
a_{13}	-0.004078	-0.0079213	-0.0029413	-0.0032413
a_{14}	0.000275	0.00046667	0.0001685	0.0001755
a_{15}	-0.000006	-0.00000955	-0.0000033	-0.0000037
a_{16}	0.0048	0.008	0.0048	0.0064
a_{17}	-0.001675	-0.0031076	-0.001472	-0.0018062
a_{18}	0.000255	0.00044338	0.000204	0.0002059
a_{19}	-0.000016	-0.00002588	-0.000012	-0.0000109
a_{20}	3.84e-7	5.2622e-7	2.2756e-7	2.1333e-7

For this set of data, it is also possible to build graphic dependencies that highlight the features of the behavior of the function for different materials (Figure 5).

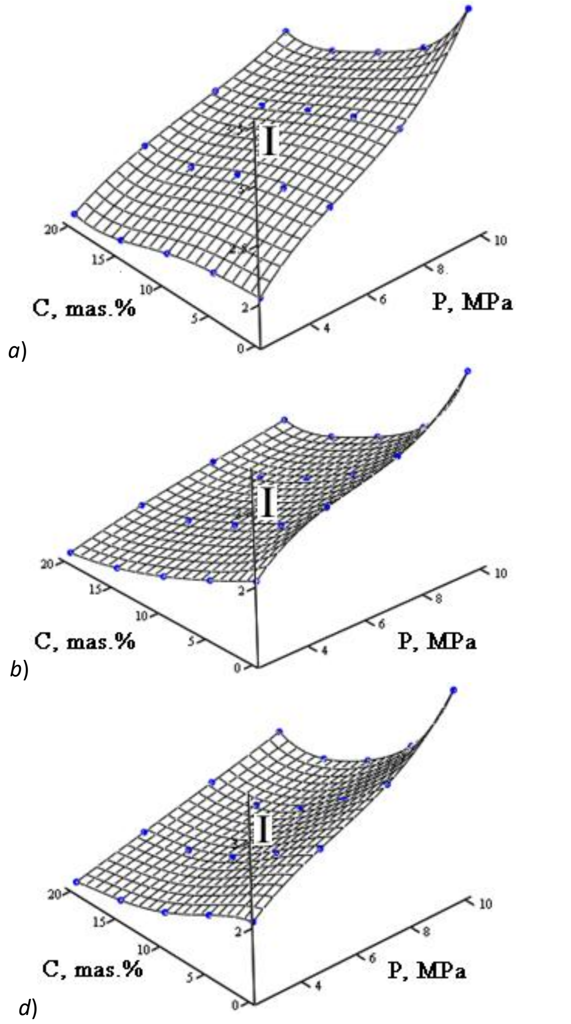

Figure 5. Graphs of dependencies $I(C,P)$ for materials: a) boron nitride, b) copper phthalocyanine, d) molybdenum disulfide

Figure 5 shows that the obtained dependences describe the experimental data well and provide important information about the behavior of the functions in the studied range of values.

4 CONCLUSIONS

The usage of materials with high tribological properties such as coatings for machines that work under heavy loads is the way to increase durability, reliability etc. And the best results may be obtained if we use the materials with the best set of properties for every case. The experimental dependencies between material (meta-aramid) composition and set of properties were already obtained.

As a result of the performed data approximation, the results of experiments became more systematic, a few empirical dependencies were obtained by interpolating the experimental data surfaces and now can be presented on 3D graphs for a more visual perception. Obtained models allow us to calculate the properties of given material from its composition, also we can get the needed materials compositions for given set of properties. All these results can help to find the proper material compositions and provide the best properties of high loaded machine parts.

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REFERENCES

[Acerbi 2020] Acerbi, F., Taisch, M. A literature review on circular economy adoption in the manufacturing sector. J. Clean. Prod., 2020, 123086.

[Balara 2018] Balara, M., Duplakova, D., Matiskova, D. Application of a signal averaging device in robotics. Measurement, 2018, Vol. 115, No. 2, pp. 125-132.

[Baron 2016] Baron, P., Dobransky, J., Kocisko, M., Pollak, M., Cmorej, T. The parameter correlation of acoustic emission and high-frequency vibrations in the assessment process of the operating state of the technical system. Acta Mechanica et Automatica, 2016, Vol. 10, No. 2, pp. 112-116.

[Buketov 2016] Buketov, A., Stukhlyak, P., Maruschak, P., Panin, S., Menou, A. Physical and chemical aspects of formation of epoxy composite material with microfilling agent. Key Engineering Materials, 2016, Vol. 712, pp. 143-148.

[Buketov 2024] Buketov, A.V., et al. Increasing the Lifetime of Water Transportation Vehicles by Using Multifunctional Composites with a Polymer Matrix, Ultradisperse Diamond, and Discrete Fibrous Filler. Journal of Superhard Materials, 2024, Vol. 46, No. 1, pp. 40-54.

[Chaus 2018] Chaus, A.S., Pokorny, P., Caplovic, E., Sitkevich, M.V., Peterka, J. Complex fine-scale diffusion coating formed at low temperature on high-speed steel substrate. Applied Surface Science, 2018, Vol. 437, pp. 257-270. ISSN 0169-4332.

[Ding 2022] Ding, T., Yan, G., Zhou, Z., et al. A novel manufacturing service model transformation method based on product lifecycle. Peer-to-Peer Netw. Appl., 2022, Vol. 15, pp. 1638-1652.

[Dyadyura 2017a] Dyadyura, K., Hovorun, T.P., Pylypenko, O.V., Hovorun, M.V., Pererva, V.I. Influence of roughness of the substrate on the structure and mechanical properties of TiAlN nanocoating condensed by DCMS. In: Proc. of 2017 IEEE 7th Int. Conf. on Nanomaterials: Applications and Properties (NAP), January 2017, 01FNC10.

[Dyadyura 2017b] Dyadyura, K.O., Sukhodub, L.F. Magnesium-based matrix composites reinforced with nanoparticles for biomedical applications. In: Proc. of 2017 IEEE 7th Int. Conf. on Nanomaterials: Applications and Properties (NAP), January 2017, 04NB14, 2017.

[Flegner 2019] Flegner, P., Kacur, J., Durdan, M., Laciak, M. Processing a measured vibroacoustic signal for rock type recognition in rotary drilling technology. Measurement, 2019, Vol. 134, pp. 451-467.

[Flegner 2020] Flegner, P., Kacur, J., Durdan, M, Laciak, M. Statistical Process Control Charts Applied to Rock Disintegration Quality Improvement. Applied sciences, 2020, Vol. 10, No. 23, pp. 1-26.

[Harnicarova 2019] Harnicarova, M., et al. Study of the influence of the structural grain size on the mechanical properties of technical materials, Materialwissenschaft und Werkstofftechnik, 2019, Vol. 50, pp. 635-645.

[Jurko 2011] Jurko, J., Panda, A., Gajdos, M., Zaborowski, T. Verification of cutting zone machinability during the turning of a new austenitic stainless steel. In: Int. Conf. Advances in Computer Science and Education Applications (CSE 2011). Heidelberg: Springer, 2011, pp. 338-345.

[Jurko 2012] Jurko, J., Dzupon, M., Panda, A., Zajac, J. Study influence of plastic deformation a new extra low carbon stainless steels XCr17Ni7MoTiN under the surface finish when drilling. Advanced Materials Research, 2012, Vol. 538-541, pp. 1312-1315.

[Jurko 2013] Jurko, J., Panda, A., Behun, M. Prediction of a new form of the cutting tool according to achieve the desired surface quality. Applied Mechanics and Materials, 2013, Vol. 268, pp. 473-476.

[Kivimaa 2019] Kivimaa, P., Boon, W., Hyysalo, S., Klerkx, L. Towards a typology of intermediaries in sustainability transitions: A systematic review and a research agenda. Res. Policy, 2019, Vol. 48, pp. 1062-1075.

[Klymenko 2014] Klymenko, A., Sytar, V., Kolesnyk, I. Adhesion of poly (m-, p-phenylene isophtalamide) coatings to metal substrates. Progress in Organic Coatings, 2014, Vol. 77, pp. 1597-1602.

[Klymenko 2022] Klymenko, A.V., Sytar, V.I., Kolesnyk, I.V., Anisimov, V.V. Effect of filler particles on adhesive properties of poly (m-, p-phenylene isophtalamide) coatings. Voprosy khimii i khimicheskoi tekhnologii, 2022, Vol. 1, pp. 60-67.

[Krenicky 2020] Krenicky, T., Servatka, M., Gaspar, S., Mascenik, J. Abrasive Water Jet Cutting of Hardox Steels-Quality Investigation. Processes, 2020, Vol. 8, Issue 12, Art. No. 1652.

[Kurdel 2018] Labun, J., et al. Possibilities of Increasing the Low Altitude Measurement Precision of Airborne Radio Altimeters. Electronics, 2018, Vol. 7, No. 9., pp. 1-9.

[Kurdel 2022] Kurdel, P., Ceskovic, M., Gecejova, N., Labun, J., Gamec, J. The Method of Evaluation of Radio Altimeter Methodological Error in Laboratory Environment. Sensors, 2022, Vol. 22, No. 14, pp 1-21.

[Labun 2020] Labun, J., et al. A Simple High-Precision 2-Port Vector Analyzer. IEEE Access, 2020, Vol. 8, pp. 196609-196617. ISSN 2169-3536.

[Matiskova 2021] Matiskova, D., Cakurda, T., Marasova, D., Balara, A. Determination of the Function of the Course of the Static Property of PAMs as Actuators in Industrial Robotics. Applied sciences, 2021, Vol. 11, No. 16. https://doi.org/10.3390/app11167288.

[Michalik 2014] Michalik, P., Zajac, J., Hatala, M., Mital, D. and Fecova, V. Monitoring surface roughness of thin-walled components from steel C45 machining down and up milling. Measurement, 2014, Vol. 58, pp. 416-428, ISSN 0263-2241.

[Monkova 2013] Monkova, K., Monka, P., Jakubeczyova, D. The research of the high speed steels produced by powder and casting metallurgy from the view of tool cutting life. Applied Mechanics and Materials, 2013, Vol. 302, pp. 269-274.

[Mrkvica 2012] Mrkvica, I., Janos, M., Sysel, P. Cutting efficiency by drilling with tools from different materials. Advanced Materials Research, 2012, Vols. 538-541, pp. 1327-1331. ISSN1022-6680.

[Murcinkova 2018] Murcinkova, Z., Baron, P., Pollak, M. Study of the press fit bearing-shaft joint dimensional parameters by analytical and numerical approach. Advances in Materials Sci. and Eng., 2018. DOI: https://doi.org/10.1155/2018/2916068.

[Nahornyi 2022] Nahornyi, V., et al. Method of Using the Correlation between the Surface Roughness of Metallic Materials and the Sound Generated during the Controlled Machining Process. Materials, 2022, Vol. 15, Article No. 823. https://doi.org/10.3390/ma15030823

[Nekrasov 2017] Nekrasov, A., et al. Sea Wind Measurement by Doppler Navigation System with X-Configured Beams in Rectilinear Flight. Remote Sensing, 2017, Vol. 9, No. 9., pp 1-17. ISSN 2072-4292.

[Nekrasov 2020] Nekrasov, A., Khachaturian, A., Labun, J., Kurdel, P., Bogachev, M. Towards the Sea Ice and Wind Measurement by a C-Band Scatterometer at Dual VV/HH Polarization: A Prospective Appraisal. Remote Sensing, 2020, Vol. 12, No. 20. ISSN 2072-4292

[Olejarova 2017] Olejarova, S., Dobransky, J., Svetlik, J., Pituk, M. Measurements and evaluation of measurements of vibrations in steel milling process. Measurement, 2017, Vol. 106, pp. 18-25.

[Panda 2011] Panda, A., Duplak, J., Jurko, J., Behun, M. Comprehensive Identification of Sintered Carbide Durability in Machining Process of Bearings Steel 100CrMn6. Advanced Materials Research, 2011, Vol. 340, pp. 30-33.

[Panda 2013a] Panda, A., Duplak, J., Jurko, J., Behun, M. New experimental expression of durability dependence for ceramic cutting tool. Applied Mechanics and Materials, 2013, Vol. 275-277, pp. 2230-2236.

[Panda 2013b] Panda, A., Duplak, J., Jurko, J., Pandova, I. Roller Bearings and Analytical Expression of Selected Cutting Tools Durability in Machining Process of Steel 80MoCrV4016. Applied Mechanics and Materials, 2013, Vol. 415, pp. 610-613.

[Panda 2014] Panda, A., Prislupcak, M., Pandova, I. Progressive Technology Diagnostics and Factors Affecting Machinability. Applied Mechanics and Materials, 2014, Vol. 616, pp. 183-190.

[Panda 2020] Panda, A., et al. A novel method for online monitoring of surface quality and predicting tool wear conditions in machining of materials. Int. J. of Advanced Manufacturing Technology, 2020, Vol. 123, No. 9-10, pp. 3599-3612.

[Panda 2021] Panda, A., et al. Increasing of wear resistance of linear block-polyurethanes by thermal processing methods. MM Science Journal, 2021, No. October, pp. 4731-4735.

[Panda 2022] Panda, A., et al. Ecotoxicity Study of New Composite Materials Based on Epoxy Matrix DER-331 Filled with Biocides Used for Industrial Applications. Polymers, 2022, Vol. 14, No. 16, Art. No. 3275.

[Pandova 2018] Pandova, I., et al. Use of sorption of copper cations by clinoptilolite for wastewater treatment. Int. J. of Environ. Research and Public Health, 2018, Vol. 15, No. 7, 1364.

[Pandova 2020] Pandova, I., et al. A study of using natural sorbent to reduce iron cations from aqueous solutions. Int. J. of Environmental Research and Public Health, 2020, Vol. 17, No. 10, Art. No. 3686.

[Pollak 2020] Pollak, M., Torokova, M., Kocisko, M. Utilization of generative design tools in designing components necessary for 3D printing done by a robot. TEM Journal, 2020, Vol. 9, No. 3, pp. 868-872.

[Ren 2022] Ren, S., Zhang, Y., Sakao, T., et al. An Advanced Operation Mode with Product-Service System Using Lifecycle Big Data and Deep Learning. Int. J. of Precis. Eng. and Manuf.-Green Tech., 2022, Vol. 9, pp. 287-303.

[Rimar 2016] Rimar, M., Smeringai, P., Fedak M., Kuna S. Technical and software equipment for the real time positioning control system in mechatronic systems with pneumatic artificial muscles. Key Engineering Materials, 2016, Vol. 669, pp. 361-369.

[Sapronov 2017] Sapronov, O.O., Buketov, A.V., Zinchenko, D.O., Yatsyuk, V.M. Features of structural processes in epoxy composites filled with silver carbonate on increase in temperature. Composites: Mechanics, Computations, Applications, 2017, Vol. 8, No. 1, pp. 47-65.

[Sassanelli 2020] Sassanelli, C., Urbinati, A., Rosa, P., Chiaroni, D., Terzi, S. Addressing Circular Economy through Design for X approaches: A Systematic Literature Review. Comput. Ind., 2020, Vol. 120, pp. 1-23.

[Sezer Hicyilmaz 2021] Sezer Hicyilmaz, A., Celik Bedeloglu, A. Applications of polyimide coatings: a review. SN Appl. Sci., 2021, Vol. 3, 363. https://doi.org/10.1007/s42452-021-04362-5.

[Straka 2018a] Straka, L., Hasova, S. Optimization of material removal rate and tool wear rate of Cu electrode in die-sinking EDM of tool steel. Int. J. of Adv. Manuf. Technol., 2018, Vol. 97, No. 5-8 , pp. 2647-2654.

[Straka 2018b] Straka, L., Hasova, S. Prediction of the heat-affected zone of tool steel EN X37CrMoV5-1 after die-sinking electrical discharge machining. J. of Engineering Manufacture, 2018, Vol. 232, No. 8, pp. 1395-1406.

[Sukhodub 2018] Sukhodub, L., Dyadyura, K. Design and fabrication of polymer-ceramic nanocomposites materials for bone tissue engineering. Journal of Nano- and Electronic Physics, 2018, Vol. 10, No. 6, 06003.

[Sukhodub 2018] Sukhodub, L., Panda, A., Dyadyura, K., Pandova, I., Krenicky, T. The design criteria for biodegradable magnesium alloy implants. MM Science J., 2018, No. December, pp. 2673-2679.

[Sukhodub 2019] Sukhodub, L., Panda, A., Sukhodub, L., Kumeda, M., Baron, P. Hydroxyapatite and zinc oxide based two-layer coating, deposited on Ti6Al4V substrate. MM Science Journal, 2019, No. December, pp. 3494-3499.

[Vagaska 2017] Vagaska, A., Gombar, M. Comparison of usage of different neural structures to predict AAO layer thickness. Technicki Vjesnik-Technical Gazette, 2017, Vol. 24, Issue 2, pp. 333-339.

[Vagaska 2021] Vagaska, A., Gombar, M. Mathematical Optimization and Application of Nonlinear Programming. Studies in Fuzziness and Soft Computing, 2021, Vol. 404, Iss. 2021, pp. 461-486.

[Valicek 2016] Valicek, J., Harnicarova, M., Panda, A., et al. Mechanism of Creating the Topography of an Abrasive Water Jet Cut Surface. Advanced Structured Materials, 2016, Vol. 61, pp. 111-120.

[Zaborowski 2007] Zaborowski, T. Ekowytwarzanie. Gorzow, 2007, 100 p.

[Zaloga 2019] Zaloga, V., Dyadyura, K., Rybalka, I., Pandova, I. Implementation of Integrated Management System in Order to Enhance Equipment Efficiency.

Management Systems in Production Engineering, 2019, Vol. 4, pp. 221-226.
[Zaloga 2020] Zaloga, V., Dyadyura, K., Rybalka, I., Pandova, I., Zaborowski, T. Enhancing efficiency by implementation of integrated management system in order to align organizational culture and daily practice. Management Systems in Production Engineering, 2020, Vol. 28, No. 4, pp. 304-311.

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