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Predicting the coolant lubricating properties based on its density and wetting effect

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ABSTRACT

Introduction. The processes occurring in the cutting zone contribute to the rapid wear of the cutting tool and a decrease in the quality of the workpiece. It is possible to reduce the impact of negative factors during metal cutting through a rational choice of coolant. The **aim of the work** is to develop a methodology for the accelerated assessment of the coolant lubricating properties. **Methods.** This paper presents experimental studies of the lubricating effect of seven different grades of coolant, during friction of a *T15K6* (15 % *TiC*–79% *WC*–6 % *Co*) hard alloy pad and a rotating roller made of carbon structural *Steel 45* (0.45 % *C*) are presented. As a parameter of coolant efficiency in terms of lubricating effect, this paper proposes an efficiency coefficient K_c, which is equal to the ratio between the friction coefficient that occurs when using coolant and the friction coefficient during friction without coolant. The lower the coefficient K_c, the more effective this coolant is in terms of lubricating effect. **Results.** Empirical dependences of the coefficient K_c on the coolant density ρ and the limiting wetting angle Θ ($K_c = f(\rho; \Theta)$) are established. Since the low significance of the parameter ρ is established, the formula for the dependence of the K_c only on the limiting wetting angle Θ ($K_c = f(\Theta)$) is established in the work. It is established that the dependence formula ($K_c = f(\Theta)$ provides the highest accuracy of calculations. **Discussion.** After evaluating the research results presented in this paper, the following conclusions are made: 1) the paper establishes the influence of the coolant density and the limiting wetting angle on the coolant efficiency coefficient for the lubricating effect determined for the friction between a roller made of *Steel 45* and a pad made of *T15K6* alloy: $K_c = f(\rho; \Theta)$ and $K_c = f(\Theta)$; 2) the greatest accuracy of calculations from 2.75 to 15 % is provided by the formula for the dependence $K_c = f(\Theta)$; 3) the dependence $K_c = f(\Theta)$is proposed to be used for the method for the accelerated assessment of the coolant lubricating properties during friction of a pad made of *T15K6* alloy and a rotating roller made of *Steel 45*. The proposed method consists in measuring the limiting wetting angle of a coolant drop on the surface of the workpiece and calculating the derived empirical dependence of the coolant efficiency coefficient on the lubricating effect.

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Introduction

Metal cutting is accompanied by a variety of physical processes occurring in the cutting zone: high temperature, friction between the cutting tool, chips and workpiece, internal friction, high cutting force, vibrations of the cutting tool and the workpiece. These processes result in the rapid wear of the cutting tool and the workpiece quality reduction. Such processes include high temperature, friction between the chip and the cutting tool on the face, friction between the workpiece and the cutting tool on the flank, internal friction during plastic deformation of the workpiece material, high cutting force, and vibrations of the

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cutting tool and the workpiece. The ongoing processes lead to the cutting tool rapid wear and to a decrease in the quality of the workpiece being processed.

The elimination of negative factors in metal cutting is ensured by the rational choice of processing modes, cutting tools and the supply of coolant to the cutting zone. However, the rational choice of coolant at production site is not given due attention. At the same time, it is known that different coolants, due to different properties, have different effects on the cutting process. Machine tests are required for selecting a coolant that provides the required quality of the workpiece being processed, the longest period of durability of the cutting tool and high productivity of the processing [1–5]. However, such tests require a lot of time and expenditures for the most efficient cutting tools and coolant purchasing. In turn, laboratory tests are quite economical and require much less time than machine tests. Therefore, in order to develop a methodology for accelerated evaluation of the lubricating properties of a coolant, it was decided to carry out laboratory tests instead of machine ones.

Despite the advantages of laboratory tests, in the course thereof, it is not possible to reproduce all the conditions that arise during metal cutting. During such tests, not the entire process is simulated, but only some of its elements that have the greatest impact on the cutting process [5–16]. However, reducing the negative impact of even one factor can lead to a positive effect when cutting itself.

Based on the scientific literature about coolants, it can be concluded that the main functional actions of coolants are lubricating and cooling [17]. But modeling even one of the types of functional actions will allow choosing a coolant that will reduce the influence of negative factors occurring during the workpiece processing. What is important is only which of the functional actions is the most significant one under the given processing conditions.

One of the most important functional actions of the coolant is the lubricating action. This is justified by the fact that a decrease in the force and the coefficient of friction during cutting provides a decrease in the intensity of the cutting tool wear, an increase in the quality of the processed surface of the workpiece and a decrease in the temperature in the processing zone. Therefore, improving the lubricating effect of a coolant is an important task.

The analysis of the scientific literature published recently has shown that reducing the influence of friction on the cutting process is still an urgent task. Friction reduction is achieved in several ways:

– addition of particles of any substance that has an antifriction effect to the coolant composition [1, 3, 4, 6, 8, 9, 15–20];

– use of solid lubricants instead of liquid and anti-wear coatings on the cutting tool surfaces [7, 10–12, 21, 22];

– various physical phenomena effecting the coolant, such as ultrasound, electric current and others [11, 13, 14];

– using more effective oils as a coolant base [2, 20];

– increasing the service life of the coolant by its sterilization in various ways, which allows to maintain a low coefficient of friction for longer period [23];

– using ionic liquids as coolants [8, 14, 24].

Despite the large number of ways to reduce friction in the cutting zone, the problem of choosing the most effective coolant for cutting metal workpieces has not been completely solved at present. In addition, the choice of a coolant is also difficult because there is a fairly large constantly increasing range of coolants on sale.

This research work is aimed at developing a methodology for accelerated evaluation of the lubricating properties of a coolant. The results obtained will facilitate the selection of an effective brand of a coolant according to its lubricating action. Therefore, the presented results will be useful for those cutting conditions, under which large frictional forces arise, for example, during rough cutting. This is due to the fact that during roughing, a large cutting depth and feed rate are set.

Thus, **the purpose of this work is** to develop a methodology for an accelerated assessment of the lubricating properties of cutting fluids used in metal cutting. To achieve this purpose, it is necessary to solve the following tasks:

1) to evaluate experimentally the lubricating effect of the coolant on the friction machine;

2) to evaluate the density of the coolants used and its wetting effect in laboratory conditions;

3) to establish the dependence of the index of the lubricating action of coolants on its density and wetting action simultaneously and separately;

4) to establish the accuracy of calculations of the indicator of the lubricating action of the coolant according to the derived dependencies;

5) to develop a methodology for predicting the lubricating properties of coolant based on laboratory tests.

Research technique

Investigation of the lubricating properties of a coolant

In studies of the lubricating effect of a coolant, a friction machine of the model *II5018* was used. The parameter for evaluating the lubricating effect was the real coefficient of friction μ.

For the evaluation, water-based coolants were used, since this type is the most common in the production of metal parts. The applied coolants of various compositions were experimental developments of the company *NPO Promekologiya LLC* (Omsk). Therefore, all coolants were numbered and labelled as coolant 1, coolant 2, coolant 3, coolant 4, coolant 5, coolant 6, and coolant 7.

The studies were carried out according to the “pad – roller”. The pad was made of solid titanium-tungsten-cobalt alloy *15% TiC–79% WC–6% Co*, the roller was made of carbon structural *steel 45 (0.45% C)*.

The principle of operation of the machine presupposes the abrasion of a pair of samples pressed against each other with a force of R.

The “pad–roller” test scheme used allows simulating turning: the role of the workpiece is played by a rotating roller made of the material being processed, and the role of the tool — by a pad made of tool material pressed against the roller. The research was carried out with a pressure force on the pad P = 1,000 N and a roller rotation speed n = 250 rpm corresponding to low modes. This was done purposefully, since with increasing modes, the friction force and wear of the pads and roller increases, and the coefficient of friction changes slightly.

As a parameter of coolant efficiency by lubricating action, this paper proposes an efficiency coefficient K_c, which is equal to the ratio of the coefficient of friction arising from the use of coolant to the coefficient of friction while friction without coolant. The smaller the coefficient K_c, the more effective the coolant is in terms of lubricating action.

Since the purpose of the studies was to develop a methodology for accelerated evaluation of the lubricating properties of coolant, at the next stage it was decided to select coolant parameters that could potentially affect the lubricating effect of a coolant and would not require the use of complex equipment for its evaluation. One of these parameters is the density (ρ, kg/m^3), which is easy to estimate in the laboratory. Another property affecting the lubricating effect of a coolant is its wetting effect, which is estimated by the limiting wetting angle (Θ, degrees) [17].

Investigation of a coolant density

Experimental estimation of the density of the coolant under investigation was carried out using analytical balance *AND DL-200* with a discreteness of 0.001 g. The analytical balance used is shown in figure 1.

Fig. 1. Analytical balance AND DL-200

During the tests, each coolant was poured into a measuring container. The volume of the studied coolant was 120 ml. The measuring container was put on the balance pan and held for

30 seconds to eliminate the influence of vibrations. After the mass value stopped fluctuating, its value was recorded in the table. Then the density values of each brand of a coolant were calculated according to the following formula:

$$\rho = \frac{m}{V}, \quad (1)$$

where m is the coolant mass, kg; V is the coolant volume, m^3 (which was equal to $120 \cdot 10^{-6}$ m^3).

Investigation of the wetting properties of a coolant

The wetting properties of the coolant are evaluated by the value of the wetting edge angle Θ. The values of the wetting edge angle were measured using an electronic digital microscope. For these studies, a workpiece made of the same alloy as the roller, used in the studies of the lubricating properties of a coolant, was used. During the tests, the axis of the electron microscope lens was installed in the same plane with the surface of the workpiece since in this position it is possible to set the true value of the wetting edge angle. The digital microscope is shown in figure 2.

Fig. 2. Digital microscope

During the tests, the investigated coolant was applied to the dry surface of the workpiece using a pipette. After the coolant drop assumed a static position, an image of this drop was recorded using a microscope. According to this technique, images of drops of all coolants were obtained. An example of such an image is shown in figure 3.

The assessment of the wetting edge angle of every coolant on the surface of the steel workpiece was carried out using a computer drawing software *COMPASS v18*. In this case, a straight line was drawn, which is a projection of the surface of the workpiece, as well as a line that is a projection of the interface between the coolant drop and the surrounding air. At the intersection point of the constructed lines, a tangent line was drawn to the surface line of the coolant drop. The wetting edge angle was the angle between the tangent

Fig. 3. A drop of a coolant on the surface of a steel workpiece:
1 – a coolant drop; 2 – a steel workpiece

line to the drop surface and the projection of the surface of the steel workpiece. One of the constructed edge angles of a coolant wetting is shown in figure 4.

According to the described method, the limiting wetting angle of every tested coolant brand was determined.

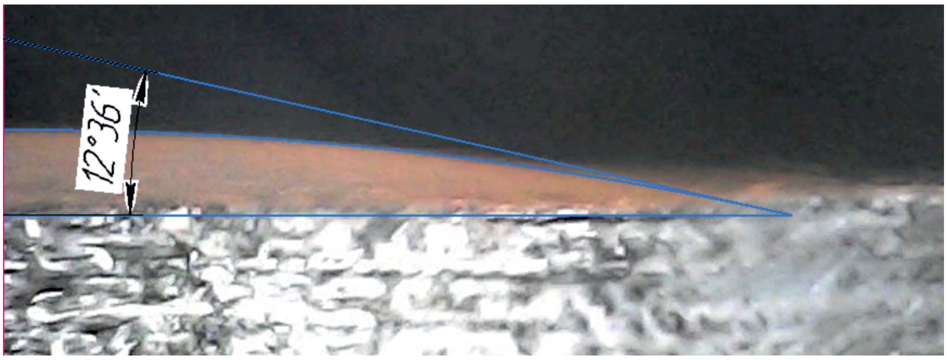


Fig. 4. Measured value of the coolant limiting wetting angle

Results and discussion

The obtained results of the evaluation of the lubricating effect of a coolant, its density and wetting action are presented in tables 1–3.

In the current study, it is assumed that the efficiency coefficient of coolant for lubricating action K_c depends on the coolant density ρ and the wetting contact angle Θ. In order to establish the empirical dependence of these parameters, the computer program *STATISTICA 12* was used. As a result, two graphical dependencies were built $K_c = f(\rho;\Theta)$: quadratic and linear (Fig. 5). The parameter *Var1* denotes the coefficient K_c, the parameter *Var2* is ρ, kg/m^3, and the parameter *Var3* is the wetting edge angle Θ, degrees. In addition,

Table 1

Indicators of the coolant lubricating effect

Coolants	μ	K_c
Without coolant	0.604	–
Coolant 1	0.148	0.25
Coolant 2	0.117	0.19
Coolant 3	0.130	0.22
Coolant 4	0.090	0.15
Coolant 5	0.082	0.14
Coolant 6	0.119	0.20
Coolant 7	0.119	0.20

Table 2

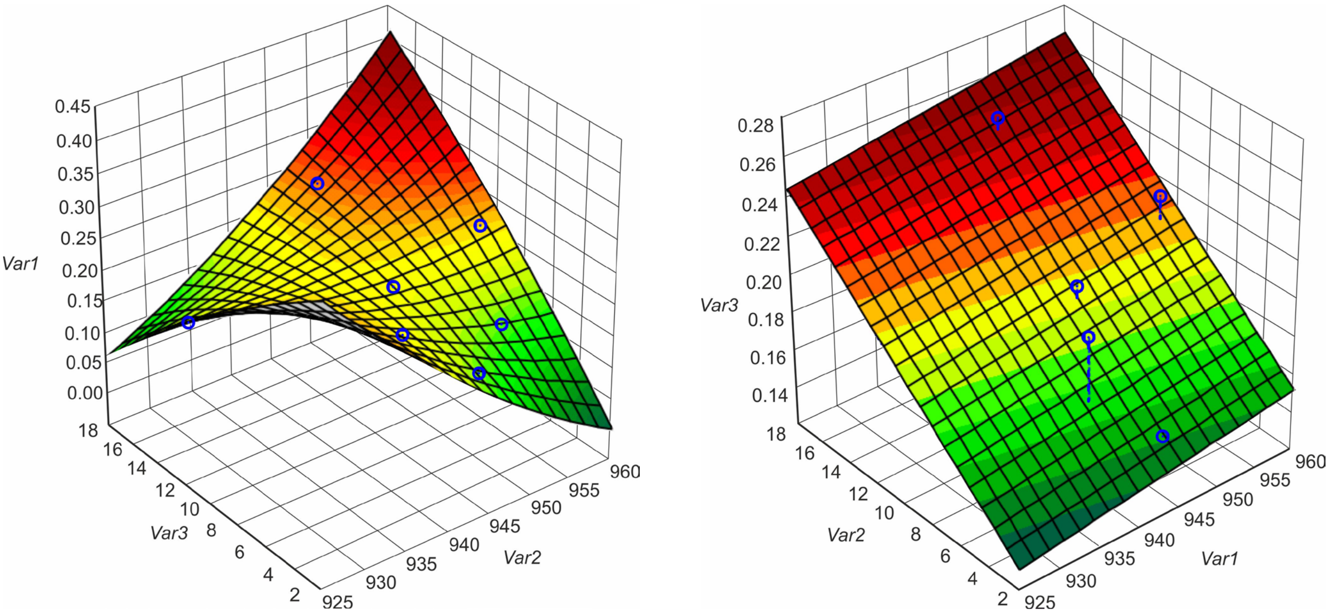
Coolant densities

Coolants	ρ, kg/m^3
Coolant 1	947.76
Coolant 2	926.56
Coolant 3	957.60
Coolant 4	945.29
Coolant 5	953.43
Coolant 6	940.36
Coolant 7	945.14

Table 3

Coolant limiting wetting angles

Brand of coolant	Θ, °
Coolant 1	16.13
Coolant 2	12.6
Coolant 3	10.02
Coolant 4	3.38
Coolant 5	6.2
Coolant 6	5.72
Coolant 7	9.1



a *b*

Fig. 5. Characteristic curves $K_c = f(\rho;\Theta)$:
a – quadratic; *b* – linear

with the help of the specified program, mathematical formulas describing the presented dependencies were established.

In addition, using the *STATISTICA 12* software, mathematical formulas describing the presented dependencies were established:

$$K_c = 100.9073 - 0.2001\rho - 1.225\Theta + 9.8915 \cdot 10^5\rho^2 + 0.0013\rho\Theta - 0.0003\Theta^2; \quad (2)$$

$$K_c = -0.4622 + 0.0006\rho + 0.0071\Theta \quad (3)$$

At the next stage of research, in order to determine the most accurate of the obtained dependencies, calculations were performed using formulas (2) and (3). The obtained values were compared with experimental values of K_c and the values of relative calculation errors were found. As a result, it was found that the error of calculations according to formula (2) modulo was from 1.49 to 41.16 %. The error of calculations according to the formula (3) modulo ranged from 3.58 to 28.68 %. Thus, the accuracy of calculations according to formula (3) is 1.44 times higher than according to formula (2).

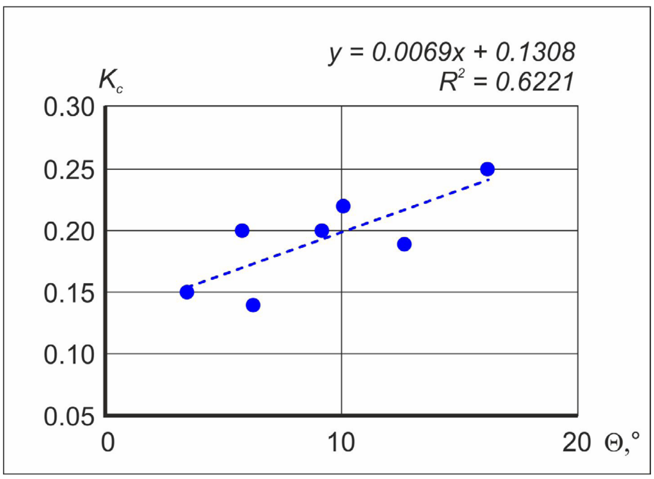


Fig. 6. Characteristic curve $K_c = f(\Theta)$

The evaluation of formula (3) shows that the constant coefficient for the variable ρ is significantly less than the coefficient for the variable *Θ*: by 11.83 times. This indicates the higher importance of the wetting edge angle when calculating the coefficient K_c Therefore, finding out the dependence $K_c = f(\rho)$ is impractical, and the previous purpose of the research was to find out the dependence $K_c = f(\Theta)$. The constructed graph is shown in figure 6.

The dependence shown in figure 6 is approximated by a straight line. The formula describing the constructed line is also shown in figure 6. By comparing the calculated values of C_{lub} with the experimental values of K_c, the relative error of calculations was established: from 2.75 to 23.99 %. It should be noted that the calculation error of 23.99 % was obtained only at one point. The error in determining K_c at other points did not exceed 15 %. Thus, a point with an error of 23.99 % can be neglected.

Since it was found that the calculation error according to the formula of the dependence $K_c = f(\Theta)$ is the smallest, the following dependence can be used to predict the effectiveness of the coolant by the lubricating action during friction of the *15% TiC–79% WC–6% Co* alloy pad and the rotating roller made of *steel 45 (0.45% C):*

$$K_c = 0.0069 \cdot \Theta + 0.1308. \quad (4)$$

Thus, the method of accelerated evaluation of the lubricating properties of coolant used in metal cutting presumes the following algorithm:

1) apply a drop of the test coolant to the workpiece made of the required material using a pipette;

2) after the coolant drop has assumed a static position, fix its image using an electron microscope;

3) using a *CAD* software (*COMPASS v18* or another similar one), draw a straight line on the resulting image, which is a projection of the surface of the workpiece, as well as a line that is a projection of the interface between the coolant drop and the surrounding air;

4) at the intersection point of the constructed lines, draw a tangent to the surface of the coolant drop;

5) measure the angle between the tangent line to the drop surface and the projection of the workpiece surface (wetting edge angle);

6) calculate the efficiency coefficient of coolant by lubricating action according to the formula (4) (for steel workpiece);

7) by the value of K_c, evaluate the efficiency of coolant. At the same time, the efficiency of coolant can be discussed if the value of $K_c < 0$. The smaller the K_c, the more effective the coolant is in terms of lubricating action.

Conclusion

After evaluating the results of the studies presented in this paper, the following conclusions were made.

1. In the work, the dependences of the coolant efficiency coefficient on the lubricating action determined for the friction between the roller made of *steel 45 (0.45% C)* and the pad made of *15% TiC–79% WC–6% Co* alloy on the coolant density and the coolant limiting wetting angle are established: $K_c = f(\rho;\ \Theta)$, $K_c = f(\rho\ )$ and $K_c = f(\Theta)$.

2. The greatest accuracy of calculations from 2.75 to 15% is provided by the formula of dependence $K_c = f(\Theta)$:

$$K_c = 0.0069 \cdot \Theta + 0.1308.$$

3. The dependence $K_c = f(\Theta)$ is proposed to be used for the methodology of accelerated evaluation of the lubricating properties of coolant during friction of the *15% TiC–79% WC–6% Co* alloy pad and the rotating roller made of *steel 45 (0.45% C)*.

The proposed method presupposes measuring the limiting wetting edge angle of a drop of coolant on the surface of the workpiece and calculating the derived empirical dependence of the coolant efficiency coefficient on the lubricating action.

The lubricating action is one of the main, but not the only functional action of the coolant. Therefore, with different processing modes, the degree of influence of this action on the cutting process will be different. The use of coolant chosen according to the proposed method will have a positive effect, but the greatest effect will be under conditions when the lubricating action is dominant. For example, at low cutting speeds, when high temperatures do not occur in the processing zone and the lubricating effect overlays.

References

1. Li G., Yi S., Li N., Pan W., Wen C., Ding S. Quantitative analysis of cooling and lubricating effects of graphene oxide nanofluids in machining titanium alloy Ti6Al4V. *Journal of Materials Processing Technology*, 2019, vol. 271, pp. 584–598. DOI: 10.1016/j.jmatprotec.2019.04.035.

2. Joseph Babu K., Prabhakaran Nair K., Joy M.L. Development of cutting fluid from transesterified coconut oil and evaluation of its tribological properties. *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology*, 2019, vol. 233 (3), pp. 369–379. DOI: 10.1177/1350650118785467.

3. Anand R., Raina A., Irfan Ul Haq M., Mir M.J., Gulzar O., Wani M.F. Synergism of TiO_2 and graphene as nano-additives in bio-based cutting fluid – An experimental investigation. *Tribology Transactions*, 2021, vol. 64 (2), pp. 350–366. DOI: 10.1080/10402004.2020.1842953.

4. Öndin O., Kıvak T., Sarıkaya M., Yıldırım Ç.V. Investigation of the influence of MWCNTs mixed nanofluid on the machinability characteristics of PH 13-8 Mo stainless steel. *Tribology International*, 2020, vol. 148, p. 106323. DOI: 10.1016/j.triboint.2020.106323.

5. Bhowmick S., Eskandari B., Khan M.Z.U., Alpas A.T. Investigation of the role of tribolayer formation in improving drilling performance of Ti-6Al-4V using minimum quantity of lubrication. *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology*, 2021, vol. 235 (2), pp. 396–409. DOI: 10.1177/1350650120933420.

6. Rajmohan T., Hemanth Kumar D., Nivithetha R., Elamburthi, Kalyan Chakravarthy V.V. Synthesis and tribological characteristics of a nano CuO particle-filled water-based lubricants. *IOP Conference Series: Materials Science and Engineering*, 2020, vol. 954, p. 012045. DOI: 10.1088/1757-899X/954/1/012045.

7. Kumar Rakesh G., Suresh Kumar Reddy N. Tribological studies of EN31 steel and Ti-6Al-4V alloy materials using pin-on-disc tribometer. *Materials Today: Proceedings*, 2019, vol. 28 (2), pp. 1216–1220. DOI: 10.1016/j.matpr.2020.01.509.

8. Ferri C., Troise M., Lizarazo S., Iglesias P. Ionic liquids as additives to cutting fluids to reduce machine tool friction and wear. *ASME International Mechanical Engineering Congress and Exposition: Proceedings (IMECE)*, 2018, vol. 12, p. V012T11A046. DOI: 10.1115/IMECE2018-86810.

9. Ajay Vardhaman B.S., Amarnath M., Ramkumar J., Rai P.K. Experimental investigations to enhance the tribological performance of engine oil by using nano-boric acid and functionalized multiwalled carbon nanotubes: A comparative study to assess wear in bronze alloy. *Journal of Materials Engineering and Performance*, 2018, vol. 27 (6), pp. 2782–2795. DOI: 10.1007/s11665-018-3384-9.

10. Madej M., Kowalczyk J., Ozimina D., Milewski K. The tribological properties of titanium carbonitride TiCN coating lubricated with non-toxic cutting fluid. *Materials Research Proceedings*, vol. 5, pp. 47–53. DOI: 10.21741/9781945291814-9.

11. Wu Z., Li S., Zhou F. Electrochemical and tribological properties of TiSiCN coatings in coolant. *Materials Science-Medziagotyra*, 2019, vol. 25 (2), pp. 159–165. DOI: 10.5755/j01.ms.25.2.19252.

12. Wu Z., Cheng Z., Zhang H., Xu Z., Wang Y., Zhou F. Electrochemical and tribological properties of CrAlN, TiAlN, and CrTiN coatings in water-based cutting fluid. *Journal of Materials Engineering and Performance*, 2020, vol. 29 (4), pp. 2153–2163. DOI: 10.1007/s11665-020-04772-3.

13. Chhattal M., Tonggang L., Kun Y., Xin L.Ü., Guangsheng L. Development of a tribotester for investigation of ferrofluids lubrication performance on the thrust pad bearing. *Tribology Transactions*, 2020, vol. 63 (6), pp. 1095–1102. DOI: 10.1080/10402004.2020.1794092.

14. Michalec M., Svoboda P., Krupka I., Hartl M., Vencl A. Investigation of the tribological performance of ionic liquids in non-conformal EHL contacts under electric field activation. *Friction*, 2020, vol. 8 (5), pp. 982–994. DOI: 10.1007/s40544-019-0342-y.

15. He J., Sun J., Meng Y., Yan X. Preliminary investigations on the tribological performance of hexagonal boron nitride nanofluids as lubricant for steel/steel friction pairs. *Surface Topography: Metrology and Properties*, 2019, vol. 7 (1), p. 015022. DOI: 10.1088/2051-672X/ab0afb.

16. Zhao C., Chen Y.K., Ren G. A study of tribological properties of water-based ceria nanofluids. *Tribology and Lubrication Technology*, 2017, vol. 73 (3), pp. 56–66.

17. Said Z., Gupta M., Hegab H., Arora N., Khan A.M., Jamil M., Bellos E. A comprehensive review on minimum quantity lubrication (MQL) in machining processes using nano-cutting fluids. *International Journal of Advanced Manufacturing Technology*, 2019, vol. 105 (5–6), pp. 2057–2086. DOI: 10.1007/s00170-019-04382-x.

18. Madanchi N., Zellmer S., Winter M., Flach F., Garnweitner G., Herrmann C. Investigation on the effects of nanoparticles on cutting fluid properties and tribological characteristics. *International Journal of Precision Engineering and Manufacturing – Green Technology*, 2019, vol. 6 (3), pp. 433–447. DOI: 10.1007/s40684-019-00053-0.

19. Cetin M.H., Korkmaz S. Investigation of the concentration rate and aggregation behaviour of nano-silver added colloidal suspensions on wear behaviour of metallic materials by using ANOVA method. *Tribology International*, 2020, vol. 147, p. 106273. DOI: 10.1016/j.triboint.2020.106273.

20. Bhaumik S., Paleu V., Pathak R., Maggirwar R., Katiyar J.K., Sharma A.K. Tribological investigation of r-GO additived biodegradable cashew nut shells liquid as an alternative industry lubricant. *Tribology International*, 2019, vol. 135, pp. 500–509. DOI: 10.1016/j.triboint.2019.03.007.

21. Zhang M., Zhou F., Fang H., Wu Z. Influence of C content on the structure, mechanical and tribological properties of CrAlCN films in air and water-based cutting fluid. *Applied Physics A: Materials Science and Processing*, 2020, vol. 126 (8). DOI: 10.1007/s00339-020-03782-1.

22. Ozimina D., Madej M., Kowalczyk J. Determining the tribological properties of diamond-like carbon coatings lubricated with biodegradable cutting fluids. *Archives of Metallurgy and Materials*, 2017, vol. 62 (4), pp. 2065–2072. DOI: 10.1515/amm-2017-0306.

23. Miyamoto J., Kodama M., Kawada S., Tsuboi R. Tribological properties of cutting fluid sterilized by atmospheric-pressure plasma treatment. *Tribology Online*, 2018, vol. 13 (5), pp. 248–253. DOI: 10.2474/trol.13.248.

24. Panneer R., Panneerselvam T. Experimental investigation on the effect of ionic liquids ($C_{16}H_{36}BrP$ and $C_{16}H_{36}BrN$) on the tribological performance of neem oil. *International Journal of Surface Science and Engineering*, 2020, vol. 14 (1), pp. 16–33. DOI: 10.1504/ijsurfse.2020.105877.

Conflicts of Interest

The authors declare no conflict of interest.