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EVALUATION OF PERFORMANCE CHARACTERISTICS OF THE ENVIRONMENTALLY FRIENDLY CUTTING FLUID WITH ZINC ASPARTATE

OCENA WŁAŚCIWOŚCI EKSPLOATACYJNYCH PROEKOLOGICZNEJ CIECZY CHŁODZĄCO-SMARUJĄCEJ ZAWIERAJĄCEJ ASPARAGINIAN CYNKU*

The effect of the cutting fluid with zinc aspartate on the quality of the workpiece surface layer is reported. Until now, zinc aspartate has been used primarily in medicine and pharmacology. This paper compares the ecological cutting fluid containing zinc aspartate with a classic mineral oil-based coolant. Toxicity tests and a controlled process of tool wear during face turning were performed. Test results indicate that the use of zinc aspartate-based cutting fluids contributes to the reduction of the material roughness parameter values up to 35%, benefitting the final quality of the workpiece.

***Keywords**: ecological cutting fluid, zinc aspartate, tool wear, surface topography, microbiological tests.*

W pracy przedstawiono wyniki badań wpływu cieczy chłodząco-smarującej z asparaginianem cynku na jakość technologiczną warstwy wierzchniej obrabianych elementów. Asparaginian cynku dotychczas nie był stosowany w takich rozwiązaniach, głównie wykorzystywany był w medycynie i farmakologii. W badaniach przeprowadzono analizę porównawczą proekologicznego chłodziwa zawierającego asparaginian cynku z klasycznym chłodziwem opartym na bazie oleju mineralnego. Ciecze chłodząco-smarujące poddano badaniom toksyczności oraz wykonano kontrolowany proces eksploatacji narzędzi w czasie toczenia poprzecznego. Wyniki badań wskazują, że zastosowanie chłodzenia cieczą na bazie asparaginianu cynku redukuje parametry chropowatości obrabianego materiału nawet o 35%, korzystnie wpływając na jakość finalną detalu.

***Słowa kluczowe**: proekologiczna ciecz chłodząco-smarująca, asparaginian cynku, zużycie narzędzia, topografia powierzchni, badania mikrobiologiczne.*

1. Introduction

Machining is the most commonly used method of manufacturing components and parts in virtually all production technologies [18, 20]. Machining operations use cutting fluids [2, 23] to cool, lubricate and improve the surface condition of the machined part [22], to transport chips from the machining zone [3] and temporarily protect the product against corrosion [6, 21]. In order to fulfil their tasks, cutting fluids must have a special chemical composition, which cannot adversely affect people or the environment [2, 6, 24]. The most widely used cutting fluids are based on water or oil. Despite the obvious advantages, including low cost, mineral oil-based fluids are toxic for the environment and their degradation processes are difficult to control [18, 20]. In addition, friction modifiers, extreme pressure (EP) and anti-wear (AW) additives, corrosion inhibitors, antioxidants, etc. [1, 3, 10, 16] used in the fluids may add to their harmful effects.

Yadav et al. [21] examined the impact of EP and AW additives in new and used engine oils class SAE 15W40 and SAE 20W50 on the wear of the test balls. The tests were carried out on a Ducom TR-30L four-ball tester at a temperature of 75ºC, under a load of 392 N and at a constant speed of 1250 rpm. The results indicated that the wear scare diameter after tests increased gradually with increasing oil use time. It was found that the effect of EP and AW additives was primarily determined by the engine oil operating conditions.

Maruda et al. [9] studied the impact of EP and AW additives on the topography of steel surfaces during MQCL turning with various coolants at varying flow rates. The results showed that the addition of phosphate ester-based additives to the active medium resulted in the formation of a tribofilm at the tool-chip interface, which reduced friction. The lubrication method using a minimum amount of coolant with EP/AW substances improved surface topography parameters.

In another article, Maruda et al. [10] compared dry machining and cooling with compressed air, emulsion mist, emulsion mist + Crodafos O4A-LQ-(MH) and emulsion mist + Crodafos EHA-LQ-(MH). They found that cooling with emulsion mist and modifiers can provide an 80% reduction of roughness parameters.

Maruda et al. [8] reported the results from introducing the additives in the emulsion mist first on the processed surface and then to the contact zone of the friction pair. The quality of the machined stainless steel surface improved as a result of reduced roughness, and phosphate ester-based additives used in the emulsion mist intensified this effect. The phosphate-based additives remained on the machined surface even after 30 minutes of machining under high loads, temporarily lowering the friction coefficient and temperature in the interfacial zone.

Lubricants based on vegetable oil are introduced to the market for their biodegradability and non-toxicity. They are a potential lubricant preparation alternative that does not use petroleum derivatives [15, 17]. Much work has been devoted to research on cutting fluids based on vegetable oils.

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl***

Ozcelik et al. [14] tested coolants based on sunflower and rapeseed oil with an EP additive at 8% and 12%. The metalworking fluid containing rapeseed oil provided a better surface quality of the workpiece than that based on sunflower oil by more than 11% and 4%, respectively. Kumar et al. [5] studied coconut oil coolant with EP additives. They showed that coconut oil reduced the feed force by 31%, the pressure force by 28%, the cutting force by 20%, the cutting tool temperature by 7% and the wear of the tool face by 34% compared to other machining fluids.

In turn, Zhang et al. [24, 25] tested soybean coolants, which were compared to petroleum-based machining fluids and dry machining. They showed that the soy-based coolant worked similarly to the petroleum-based fluid. At the same time, they obtained much better surface roughness and less tool wear, compared with coolant-free machining.

Trajano et al. [19] performed tribological tests of sunflower and soybean oils containing CuO additives and ZnO nanoparticles. In the case of soybean nanofluids with CuO and ZnO concentrations of 0.5 wt.%, the friction coefficient decreased by 11% and 18% respectively. However, for the sunflower oil with the same filler fraction, the coefficient of friction decreased for CuO and ZnO by 22% and 20%, respectively.

The literature review above shows that there are large gaps in coolant research. To date, no studies have been conducted to determine the effect of zinc aspartate as a biodegradable modifying additive for cutting fluids. Bibliometric analysis indicates the use of zinc aspartate only in medicine and pharmacology. The use of zinc aspartate as an additive to cutting fluids should improve the lubricating properties and maintain the machine and equipment in an appropriate operating condition. [4].

This paper presents the results obtained during the machining operation with the use of a non-toxic cutting fluid containing zinc aspartate. Its impact on selected factors and surface quality of the machined workpiece was also determined.

2. Materials

2.1. Metalworking fluids

The fluid used in the tests was an eco-friendly, demineralized water (DEMI) based cutting fluid with 5% zinc aspartate and, among others:

- alkanolamine borate;
- a biodegradable oligomer based on poly(aspartic acid) (PASA); and
- demineralized water.

Zinc polyaspartates ensure the fluid biostability. Physical and chemical properties of the cutting fluid used are summarized in Table 1.

A zinc aspartate-containing coolant was compared to a commercial cutting fluid based on mineral oil and containing ethoxylated aliphatic alcohols with chain lengths C16-18, boric acid, dicyclohexylamine, 3-iodo-2-propynyl butylcarbamate, and 1,2-benzisothiazol-3 (2H)-one. It is used for general to heavy machining of aluminium, steel, cast iron, non-ferrous metals, aluminium alloys, brass and copper. The fluid contributes to the good quality of machined surfaces. The basic parameters of the fluid are compiled in Table 2.

2.2. Machined materials and tools

A tool made of HS6-5-2C steel was used for turning the front faces on the workpiece. This steel is characterized by very good ductility, impact strength and abrasion resistance. It is designed for hot work and can be subjected to heat treatment at elevated temperatures: hardening - 1190 ÷ 1230 ° C and tempering - 550 ÷ 650 ° C. Its hardness after heat treatment at 500 ÷ 550 °C is 65 HRC. The chemical composition of HS6-5-2C steel is shown in Table 3.

The HS6-5-2C steel tools were chosen for their common use in machining (about 40% of all tools used in manufacturing) Despite the growing demand for cemented carbide tools that can be used at high speeds on CNC machines, high speed tool steel is still an economical alternative, given the price and easy sharpening. Steels obtained by sintering high-speed steel powders are increasingly used for tools, whose blades are coated with complex coatings dedicated to specific applications.

The workpiece was a 38 mm diameter roller made of C45 steel, which is a non-alloy, medium carbon steel for quenching and tempering, difficult to weld, easy to machine, with the chemical composition as in Table 4. Products made of C45 can be surface hardened to 50 ÷ 60 HRC.

3. Methods

A FTIR Spectrum Two infrared spectrometer with the Perkin Elmer ATR adapter was used to test the thermo-oxidative kinetics of operating fluids. Oligomer samples were measured as pure and after model tribological tests. The following analytical parameters were used during spectral tests:

Table 1. Properties of the zinc aspartate-based cutting fluid

Colour	Odour	*pH*, 3%	Density, g/cm^3	Water solubility
orange to red	specific	9.2 ÷ 9.7	1.20 ÷ 1.25	soluble

Table 2. Main parameters of the cutting fluid based on mineral oil

Colour	Odour	Mineral oil content	*pH*, 5%	Density, g/cm^3	Water solubility
yellow-brown	that of mineral oil	56%	9.1	0.92 ÷ 0.96	soluble

Table 3. Composition of HS6-5-2C steel

Chem. element	C	Mn	Si	P	S	Cr	Ni	Mo	W	V	Co	Cu
Content, %	0.82÷ 0.92	max 0.4	max 0.5	max 0.03	max 0.03	3.5÷ 4.5	max 0.4	4.5÷ 5.5	6 ÷ 7	1.7÷ 2.1	max 0.5	max 0.3

Table 4. Chemical composition of C45 steel

Chem. element	C	Mn	Si	P	S	Cu	Cr	Ni	Mo	Cu
Content, %	0.42÷ 0.5	0.5÷ 0.8	0.1÷ 0.4	max 0.04	max 0.04	max 0.3	max 0.3	max 0.3	max 0.1	max 0.3

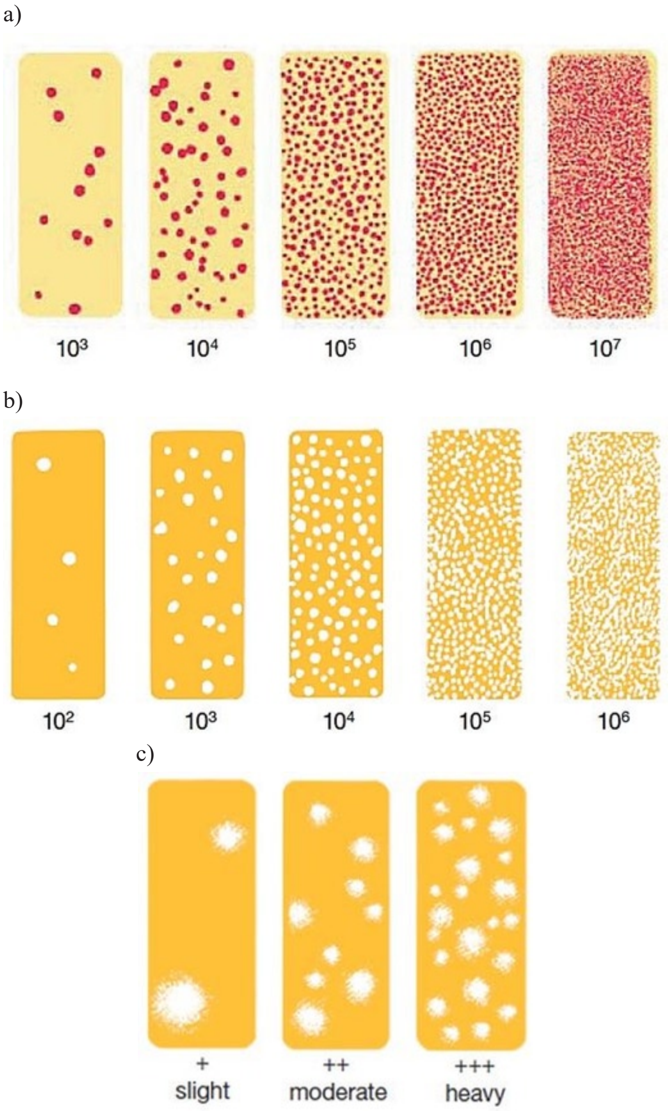


Fig. 1. Patterns of colonies of microorganisms: a) bacteria, b) yeast, c) mould [12]

- spectral range: 4000 ÷ 400 cm^{-1};
- number of background scans: air and samples – 4.

For the microbiological assessment of fluid toxicity, a special Microbiology Cult Dip Combi kit was used to determine the presence of microorganisms. It consisted of containers with attached test plates covered with appropriate media. One side of the test plates was lighter and was used to detect the presence of bacteria, and the other side was darker to detect the presence of yeast and fungi. All parts of the test kit were sterile. Toxicity tests according as per instructions [12] were applied to the zinc aspartate- containing fluid and the conventional mineral oil-based coolant. The samples were checked first after 48 hours, then after 96 hours and finally after 7 days. At 7 days the samples were subjected to organoleptic assessment and compared with microorganism colony standards (Fig. 1).

Table 5. Parameters of the cutting process

Cutting speed, v_c, m/min	Feed per revolution, f, mm/rev	Cutting depth, a_p, mm
47.5 ÷ 0	0.098	0.5

Facing was performed on a CTX 310 ECO numerically controlled lathe by DMG MORI using the Sinumerik 810 control system. By maintaining a constant rate of rotation at 400 m/min at each pass, the cutting speed v_c changed cyclically in the range 47.5 ÷ 0 m/min. In order to compare the properties of the fluid with zinc aspartate to those of the mineral oil-based coolant, face turning was performed using both fluids. After the operation, tool wear and built-up edge were measured. Turning parameters are shown in Table 5.

Replaceable cutting tools were used - insert tool bits with a square cross-section 10 mm x 10 mm, held in a bit socket. The inserts were made of high speed steel HS6-5-2C. The geometry parameters were as follows:

- major cutting edge angle K_r = 36.6° in the reference plane P_r,
- minor cutting edge angle K_r' = 53.4°,
- positive rake angle = 5.3°,
- tool included angle ε_r = 90°,
- cutting edge inclination angle λ_s = 7° in the cutting edge plane P_s,
- clearance angle α = 5.3°,
- rake angle γ = 7°,
- wedge angle β = 77.7°,
- nose radius r_s = 0.04 mm.

The workpiece material was a C45 steel roller with a diameter of 38 mm. During turning, conventional flood cooling was applied to the tool rake face. The view and diagram of the coolant supply and discharge system is shown in Figure 2.

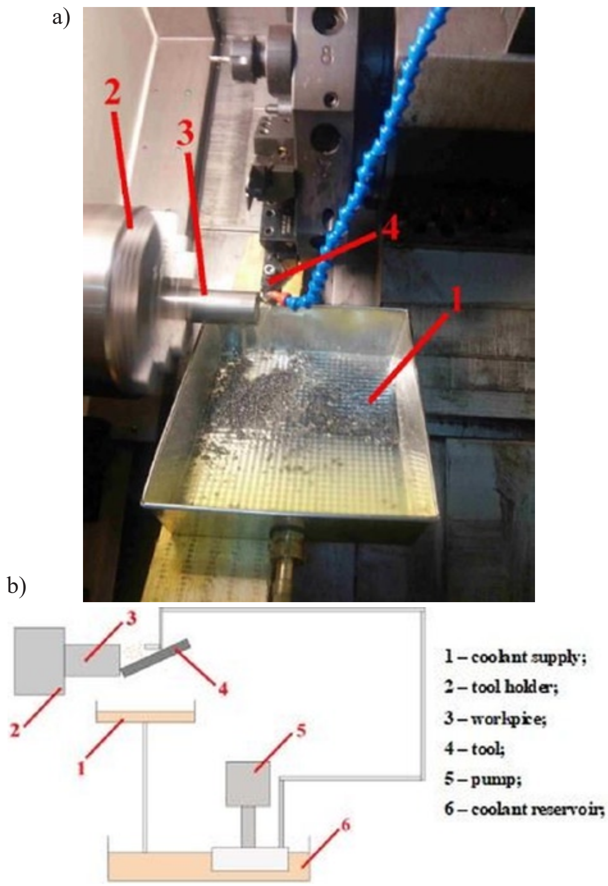


Fig. 2. External coolant circulation system during face turning on a CTX 310 ECO lathe: a) view, b) diagram

Ten stages of face turning were performed. The first stage consisted of 10 passes, and 10 more passes were added in each subsequent stage (Fig. 3). After each stage, a thin piece – a "slice" of the workpiece - was cut off and the cutting tool was replaced.

The aim of the study was to assess the basic operating characteristics of the new, zinc aspartate-based cutting fluid and the wear of the cutter during face turning.

A JEOL JSM-7100F scanning electron microscope was used to examine the surface topography of workpieces and cutting tools. The EDS microanalyzer enabled the identification of chemical elements on the surface of cutting tools at the built-up edge after the 10th turning cycle with coolants.

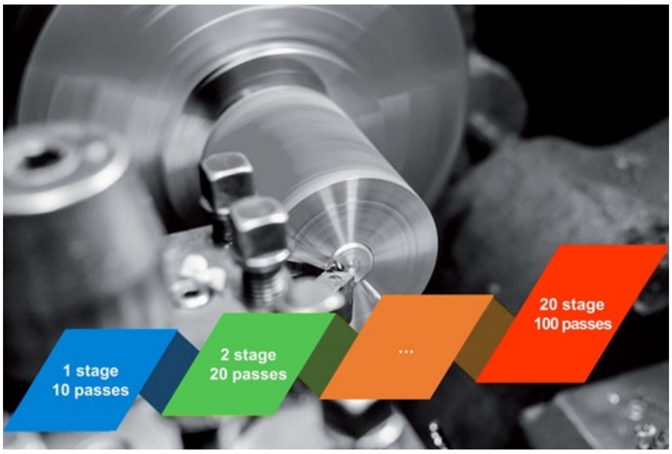


Fig. 3. Diagram of the face turning process for cutting tools

Geometry of the workpiece after turning was imaged using a DCM8 confocal microscope from Leica. In addition, the SX80 stereoscopic inspection microscope was used to observe the wear of the cutting tools after machining.

4. Results

Figure 4 compiles FTIR spectra which show a clear intensification of two bands with increasing load and friction path. The low intensity signals with a peak maximum at about 1394 and 1066 cm^{-1} correspond to C-O (COH) stretching vibrations and indicate the initiation of coolant degradation processes and the formation of a carboxyl group. Observations of the cutting fluid containing zinc aspartate after tribological tests reveal a change in its colour. With increasing load and friction path, the colour becomes darker, from light yellow to brown.

The cutting fluid can be regenerated by supplementing the basic component - zinc aspartate and controlling other operating parameters.

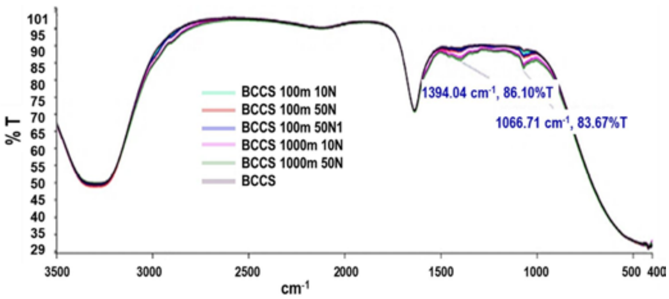


Fig. 4. FTIR spectra for the cutting fluid before and after tests

Toxicity of the zinc aspartate-based coolant and, for comparison, of the mineral oil-based fluid was evaluated using the Microbiology Cult Dip Combi kit. Two samples of each fluid were used in the tests. Observations began after 7 days (Figs. 5 and 6).

Fig. 5. View of test samples after 7 days – bacteria for the cutting fluid: a) containing zinc aspartate, b) containing mineral oil

Fig. 6. View of test samples after 7 days – yeast and molds for the cutting fluid: a) containing zinc aspartate, b) containing mineral oil

The cutting fluid containing zinc aspartate was found to be non-toxic. No colonies of bacteria (Fig. 5a), yeast or mould (Fig. 6a) were formed. However, on one of the slides earlier immersed in the mineral oil-based coolant several spots on the bacterial count side were observed (Fig. 5b). According to the guidelines [12], these spots indicate a minor infection. Considering the results obtained, the zinc aspartate coolant turned out to be better than the mineral oil-based coolant.

Using the inspection microscope software, wear measurements on the flank face were carried out in accordance with the standard [13], as shown in Fig. 7.

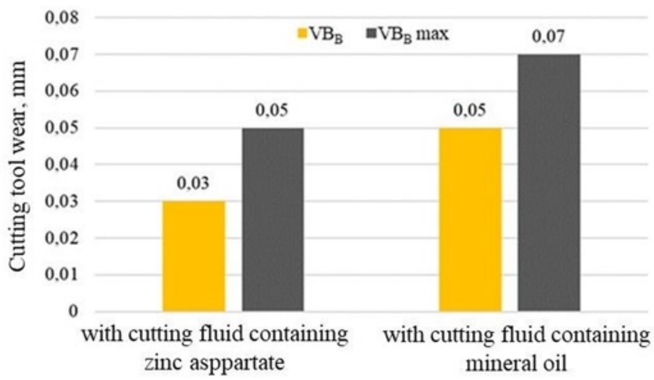


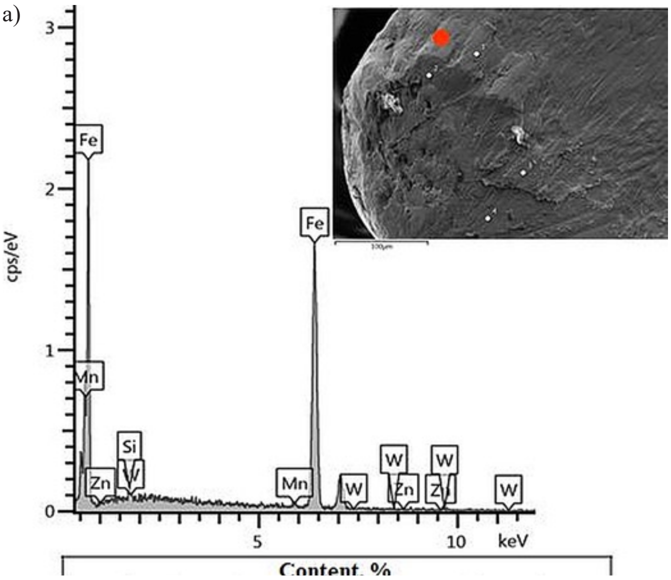
Fig. 7. Wear indices of cutting tools made of HS6-5-2C steel after turning with cutting fluids

The charts above show that the average VB_B and maximum VB_B-*max* values of the wear bandwidth were 0.03 mm and 0.05 mm respectively after the treatment with the coolant containing zinc aspartate. The tool wear parameters after turning with the coolant containing mineral oil were higher.

Figure 8 presents SEM images of cutting blades wear after dry machining and machining with the use of coolants, and the results of chemical composition analysed in micro-areas using the EDS method. After the final 10th turning test with coolants, built-ups formed in the place of wear on the cutting tools. Chemical composition of this excessive material was examined by scanning electron microscopy.

After turning with the zinc aspartate containing cutting fluid, a concentration of zinc atoms was recorded in addition to the elements included in the tool. This indicates that a thin surface layer of zinc compounds with anti-wear properties was formed as a result of tribochemical processes that occur mainly between improvers, contained mainly in lubricants, and friction surfaces. The speed and type of chemical reactions depend on the operating conditions of the friction node. The surface reaction layer produced in this way changes the working conditions of the friction pairs, which in turn leads to further tribochemical reactions. This surface layer reduces friction and extends the service life of friction pairs [16].

a)



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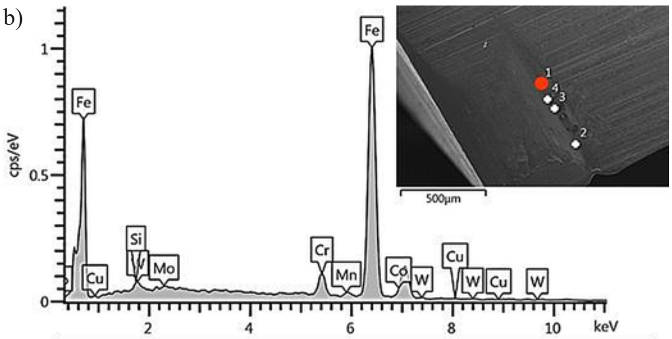
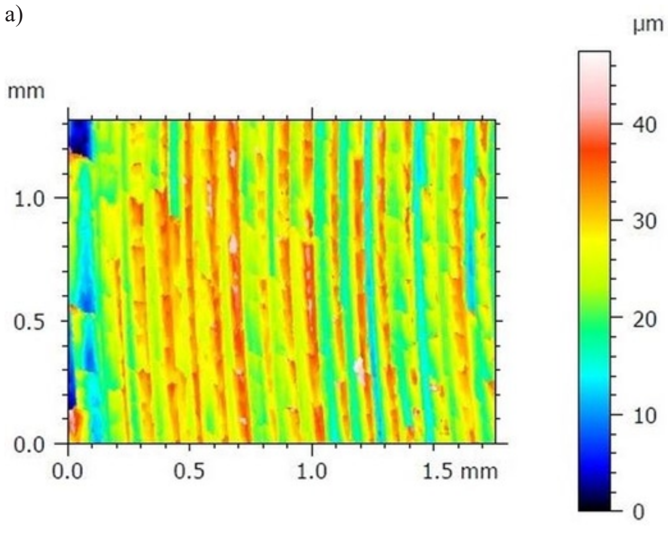


Content, %										
Si	V	Cr	Mn	Fe	Co	Ni	Cu	Mo	W	Total
0.76	-	4.34	0.82	89.12	0.83	-	0.80	0.49	0.65	97.37

Fig. 8. X-ray analysis of wear area of the cutting tool edge after turning with the cutting fluid containing: a) zinc aspartate, b) mineral oil

Figures 9 and 10 show the topography and surface roughness profiles of workpieces in selected areas, obtained after stage 10 of dry turning and that with the cutting fluids.

a)



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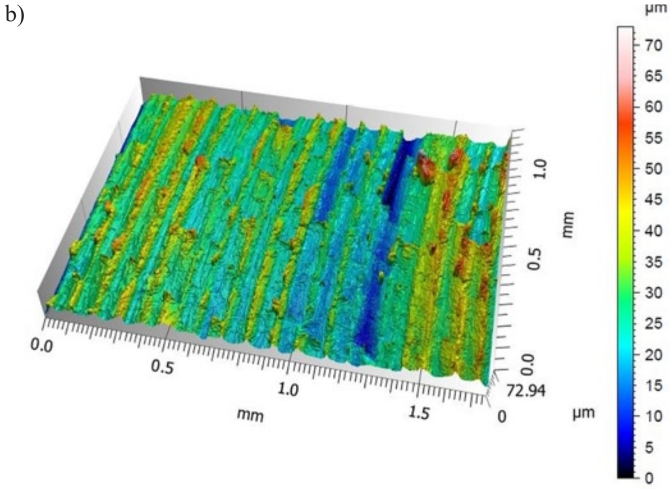


c)

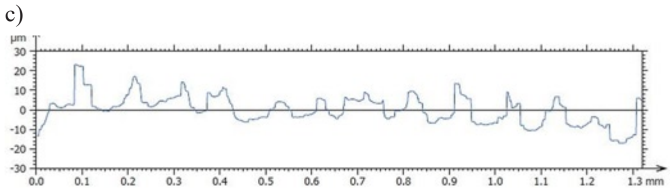


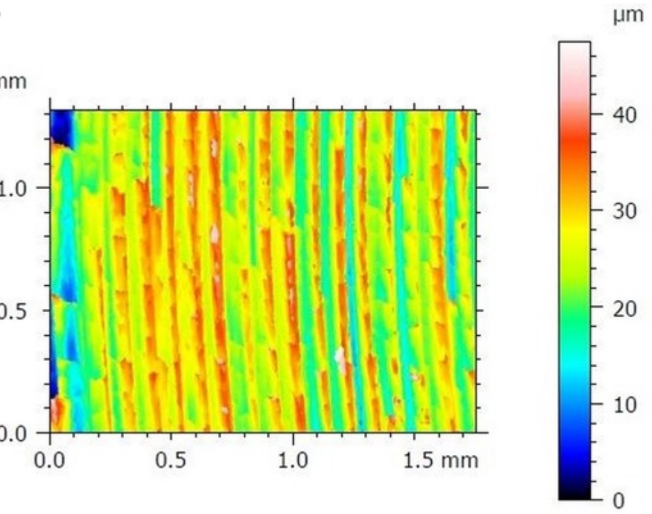
Fig. 9. Geometric structure of the workpiece edge after turning with the cutting fluid containing mineral oil: a) contour map, b) isometric image, c) primary profile

A comparison of the contour maps, isometric views and primary profiles reveals an even distribution of vertices [7] almost every 1 mm (feed: 0.098 mm) in both cases. The lowest elevations of approx. 16 µm and the shallow cavities of approx. 15 µm were formed on the workpiece after turning with the fluid containing zinc aspartate. In contrast, the highest elevations/peaks and depressions/valleys of about 20 µm were recorded after turning with the coolant containing mineral oil.

Table 6 shows the parameters of the geometric structure of machined surfaces formed after turning with the use of zinc aspartate and mineral oil cutting fluids.

The values of surface roughness parameters of machined elements after the turning process with zinc aspartate containing coolant are lower than those for the mineral oil coolant. This indicates that the cutting fluid improves the surface quality of the workpiece.

a)



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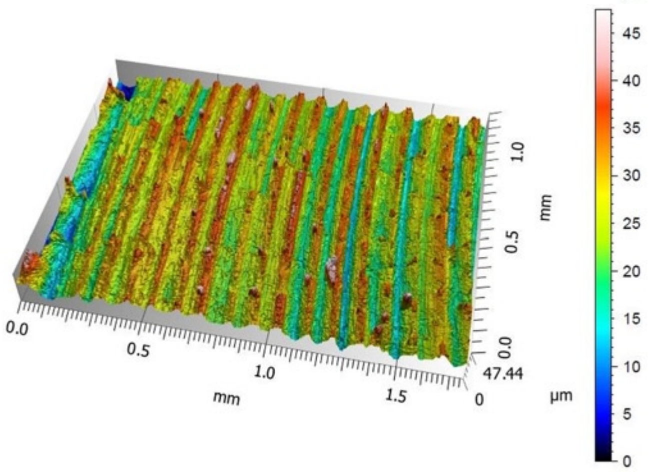

4. Conclusion

The conclusions based on the test results are the following:

1. The cutting fluid with zinc aspartate used in the turning process reduced the wear of elements of the tribological system by forming layers containing zinc compounds with good anti-wear properties.
2. The workpiece subjected to turning with the zinc aspartate containing fluid had the lowest elevations and shallowest recesses after the process.
3. Surface morphology in the turning process depends on the direction of movement and size of the feed.
4. The non-toxic coolant with zinc aspartate was undergoing transformation as a result of the reactions dependent on the operating conditions.
5. The cutting fluid containing zinc aspartate does not show any toxic properties and can be subjected to simple regeneration.
6. Due to its good ecological properties, the tested cutting fluid with zinc aspartate can be used during operation on conventional lathes, where the operator's direct contact with the coolant is greater than on numerically controlled lathes.
7. The cutting fluid with zinc aspartate provided better technological quality of the surface layer of machined elements and extended the life of high speed steel tools compared to classic coolants. The surface roughness values after the use of zinc asparatate cutting fluid were lower (by 22% for Sa, by 25% for Sq, by half for Sp, by 11% for Sv, by 35% for Sz, more than 2 times for Ssk, and by 17% for Sku).

c)

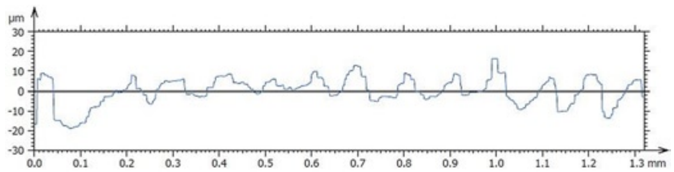

Fig. 10. Geometric structure of the workpiece edge after turning with a cutting fluid containing zinc aspartate: a) contour map, b) isometric image, c) primary profile

Table 6. Surface texture parameters obtained for the discs after turning

Turning conditions	Surface texture parameters						
	Sa	Sq	Sp	Sv	Sz	Ssk	Sku
	µm	µm	µm	µm	µm	-	-
with the mineral oil-based coolant	6.41	8.44	44.32	28.62	72.94	0.26	4.06
with the zinc aspartate-based coolant	5.00	6.31	22.12	25.32	47.44	-0.22	3.34

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