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# THE IMPACT OF THE TYPE OF CUTTING FLUID ON THE TURNING PROCESS

## OCENA WPŁYWU RODZAJU CIECZY CHŁODZĄCO-SMARUJĄCEJ NA PROCES TOCZENIA

**Key words:** biodegradable cutting fluid, turning, friction, wear.

**Abstract** This article compares the test results concerning the wear of cutting tools after face turning under dry friction conditions and lubricated friction conditions with biodegradable cutting fluid or mineral-oil based emulsion. The turning was performed using a CTX 310 ECO machine tool. The wear of the cutting tools was measured by means of stereo zoom microscopy (SX80), while the elements were identified through scanning electron microscopy (JSM 7100F). The tribological tests were conducted for a ball-on-disc configuration in sliding contact using a T-01M tribometer. The surface textures of the face turned specimens were measured with a Talysurf CCI Lite optical profiler. The study also involved determining the foaming tendency and corrosive effects of both cutting fluids. The use of the biodegradable cutting fluid with low foaming tendency resulted in lower wear and higher corrosion resistance of the tool.

**Słowa kluczowe:** biodegradowalna ciecz obróbkowa, toczenie, tarcie, zużycie.

**Streszczenie** W artykule przedstawiono wyniki badań zużycia narzędzi skrawających po procesie toczenia czołowego w warunkach tarcia technicznie suchego, ze smarowaniem biodegradowalną cieczą obróbkową oraz emulsją opartą na oleju mineralnym. Badania wykonano na tokarce CTX 310 ECO. Po obróbce zmierzono zużycie narzędzi za pomocą stereoskopowego mikroskopu inspekcyjnego SX80, a identyfikację pierwiastków przeprowadzono z użyciem skaningowego mikroskopu elektronowego JSM 7100F. Testy tribologiczne wykonano na urządzeniu T-01M. Pomiary struktury geometrycznej powierzchni elementów toczonych czołowo wykonano profilometrem optycznym Talysurf CCI Lite. Dodatkowo przeprowadzono badania pienienia i korozji cieczy obróbkowych. Zastosowane w badaniach biodegradowalne chłodziwo wpłynęło na zmniejszenie wybranych wskaźników opisujących zużycie narzędzia, a także zapewniło lepsze właściwości przeciwkorozyjne oraz przeciwpienne.

## INTRODUCTION

Metalworking processes require the use of cutting fluids, which act both as coolants and lubricants. Their functions are numerous; they include cooling the cutting zone, lubricating the chip-tool-workpiece interface and removing chips from the cutting zone **[L. 1, 2]**.

Conventional cutting fuels are based on mineral oil, which is hardly biodegradable and as such contributes to environmental pollution. Globally, more than 2,000,000 m$^3$ of cutting fluids are used each year. Approximately 85% of them contain mineral oil. Improper disposal of spent cutting fluids leads to the pollution of surface water, groundwater, air, and soil, which, in consequence, affects food safety **[L. 3–5, 6]**. Metalworking fluids that are harmful to the environment and human health need to be replaced with ones that are safe and can be recycled or regenerated. The service properties of mineral oil-based cutting fluids are improved by introducing special-purpose additives, which generally are non-biodegradable and toxic to the ecosystem **[L. 7, 8]**. Cutting fluids also contain antiseptics to kill bacteria and fungi; prolonged or repeated exposure to these irritants may lead to occupational diseases such as skin inflammation, oil acne, respiratory tract infections, allergies, and even cancers **[L. 9]**.

Chemists and tribologists have created new blends to be used instead of mineral oil-based cutting

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fluids. Alternatives include vegetable oils, which are renewable, nontoxic, environmentally friendly, and easily biodegradable **[L. 10]**. They are also characterized by good lubrication, low volatility, low emission of hydrocarbons, and good thermal properties **[L. 11, 12]**. Currently, much research is devoted to cutting fluids based on vegetable oils, for example, soya bean oil, castor oil, palm oil, coconut oil, and rapeseed oil **[L. 13, 14]**.

The analysis presented in **[L. 15]** focuses on the effects of a cutting fluid based on neem oil. The results obtained for the alternative fluid were compared with those reported for a conventional cutting fluid and also those obtained under dry machining conditions. The turning process was performed using a TEX TRENCIN SN40B machine tool with tool bits made of HS6-5-2C high-speed steel (12x200 mm). The machining was carried out for three workpieces made of mild steel using different cutting depths and different spindle speeds. At the end of the process, the temperature was measured with a thermocouple. A PEL C960 digital camera was used to take photographs of the tools before and after turning in order to analyse their wear. The workpieces were cut into small pieces and then photographs were taken to examine their surfaces. The results show that the temperatures reported in machining with the neem oil-based cutting fluid were lower than those obtained during dry turning or turning with a conventional cutting fluid. From the analysis of the properties of the neem oil, it was evident that it is well-suited to be used as a metalworking fluid. The workpiece surface quality after turning with this alternative fluid was comparable with that obtained for a traditional cutting fluid.

## MATERIALS

### Cutting fluids

The experiments were conducted to study the effects of a biodegradable cutting fluid containing alkanolamine borate, biodegradable oligomer (zinc aspartate), and demineralized water, which is designed specifically for metalworking processes. The fluid biostability is due to the presence of zinc polyaspartates, which also contribute to good lubrication of the moving parts of a machine tool, with this having a positive effect on the tool maintenance. Zinc ion added to the cutting fluid is not harmful to human health. The physical and chemical properties of the biodegradable cutting fluid are provided in **Table 1**.

**Table 1. Properties of the biodegradable cutting fluid**
Tabela 1. Właściwości biodegradowalnej cieczy chłodząco-smarującej

| | | |
|---|---|---|
| Colour | from orange to red | |
| Odour | mild, non-irritant | |
| pH value of a 3% solution | 9.2 – 9.7 | PN-89/C-04963 |
| Density at 20°C | 1.200 – 1.250 g/cm$^3$ | PN-92/C-04504 |
| Solubility in water | Soluble | |

**Table 2. Basic parameters of Bechem Avantim 361 cutting fluid**
Tabela 2. Podstawowe parametry cieczy chłodząco-smarującej Bechem Avantin 361

| Mineral oil content | pH value of a 5% solution | Corrosion protection in accordance with DIN 51360\2 | Refractometer factor |
|---|---|---|---|
| 56% | 9.1 | 5.00% | 1.0 |

The biodegradable cutting fluid was compared with Bechem Avantin 361 cutting fluid based on mineral oil. The coolant is used in metalworking operations to process steel, cast iron, non-ferrous metals, aluminium alloys, brass, and copper. Bechem Avantin 361 causes no irritation to the operator's skin. The basic parameters of the cutting fluid are shown in **Table 2**.

### Tool and the workpiece

The tool used for face turning comprised a holder and replaceable 10x10 mm tool bits made of HS6-5-2C high-speed steel. This material was selected because it is easy to coat, and further research will involve testing the tools when coated. HS6-5-2C steel is characterized by very good ductility, high impact strength, and high abrasive wear resistance. Its chemical composition is given in **Table 3**. The steel can be hot worked and heat treated at high temperatures. For instance, after thermal treatment at 500 – 550°C, its hardness reaches 65 HRC.

The workpiece was a C45 steel cylinder with a diameter of 38 mm. C45 steel is a non-alloy quality steel, which is difficult to weld, easy to process, and can be heat treated. Its composition is presented in **Table 4**. It is used for medium loaded machine parts. Products made of C45 steel can be case hardened to a hardness of 50–60 HRC.

**Table 3. Composition of HS6-5-2C steel**
Tabela 3. Skład chemiczny stali HS6-5-2C

| Element | C | Mn | Si | P | S | Cr | Ni | Mo | W | V | Co | Cu |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| % | 0.82–<br>–0.92 | ≥ 0.4 | ≥ 0.5 | ≥ 0.03 | ≥ 0.03 | 3.5–<br>–4.5 | ≥ 0.4 | 4.5–<br>–5.5 | 6–7 | 1.7–<br>–2.1 | ≥ 0.5 | ≥ 0.3 |

**Table 4. Composition of C45 steel**
Tabela 4. Skład chemiczny stali C45

| Element | C | Mn | Si | P | S | Cu | Cr | Ni | Mo | W | V | Cu |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| % | 0.42–<br>–0.5 | 0.5–<br>–0.8 | 0.1–<br>–0.4 | max 0.4 | max 0.4 | max 0.3 | max 0.3 | max 0.3 | max 0.1 | – | – | max<br>0.3 |

## METHODS

### Surface texture

A Talysurf CCI Lite optical profiler was employed to analyse the surface texture of the workpieces after dry and wet turning. The analysis was performed at the Laboratory for Computer-Based Measurement of Geometrical Quantities of the Kielce University of Technology **[L. 16]**. The surfaces of the tool bits and the machined workpieces were examined using a SX80 stereo zoom microscope.

### SEM/EDS

A JSM 7100F scanning electron microscope equipped with an EDS microanalysis system was employed to identify the elements on the surface of the tool bits in the built-up edge region after dry turning (reference system) and wet turning with the analysed cutting fluids.

### Turning process

The face turning tests were performed at the Conventional Machine Tools Laboratory of the Kielce University of Technology using a DMG Gildemeister CTX 310 ECO CNC compact machine tool controlled with Sinumerik 810.

The aim of the tests was to check the basic functions of the new biodegradable cutting fluid. To assess the results, the tests were also conducted with a cutting fluid based on mineral oil (Bechem Avantin 361) and without any cutting fluid (dry turning).

**Table 5** shows the main parameters of the turning process.

The experiments involved performing ten face turning cycles. The first had ten passes. The number was increased by ten in each subsequent cycle.

**Table 5. Parameters of the turning process**
Tabela 5. Parametry toczenia

| Rotational speed n, rev/min | Turning diameter, d, mm | Cutting speed, $v_c$, m/min | Feed rate, f, mm/rev | Cutting depth, ap, mm |
|---|---|---|---|---|
| 400 | 38–0 | 47.5–0 | 0.098 | 0.5 |

### Tribological tests

The tribological tests were carried out with a T-01M ball-on-disc system in accordance with the ASTM G 99 standard. The turning was conducted at the following parameters:

- Friction configuration: 100Cr6 steel ball – HS6-5-2C steel disc;
- Load P = 50 N;
- Sliding rate v = 0.1 m/s;
- Sliding distance s = 1000 m;
- Relative moisture 40 ±5%;
- Ambient temperature $T_0 = 23 \pm 1°C$;
- Friction: dry friction conditions and lubricated friction conditions with the use of the biodegradable cutting fluid and Bechem Avantin 361 cutting fluid.

### Foam in the cutting fluids

The foaming tendency of the cutting fluids was determined using the Bottle Test recommended by the ASTM D3601-88 standard. The tests consisted in pouring 200 ml of a given cutting fluid into a 500 ml bottle and applying vigorous shakes to it (approximately 40 shakes in 10 seconds). Then, the initial height of the foam formed was marked and read. The bottle was allowed to stand undisturbed for 5 minutes and the height of the foam was read again **[L. 17]**.

### Corrosive effects of the cutting fluids on iron alloys

The corrosion properties of the cutting fluids were determined by performing the Ford-Test, as recommended in the PN-92-M-55798 standard. The tests involved spreading cast iron chips on filter paper and pipetting some of the cutting fluid on to the chips, which were then kept under specific conditions for 2 hours. After that time, the chips were removed and the filter paper was examined **[L. 18]**.

## RESULTS AND DISCUSSION

### Surface texture

The SX80 stereo zoom camera was used to take photographs of the wear of the tool bits. The surface was then observed with an inspection microscope. The results of the wear measurements are shown in **Figure 1.**

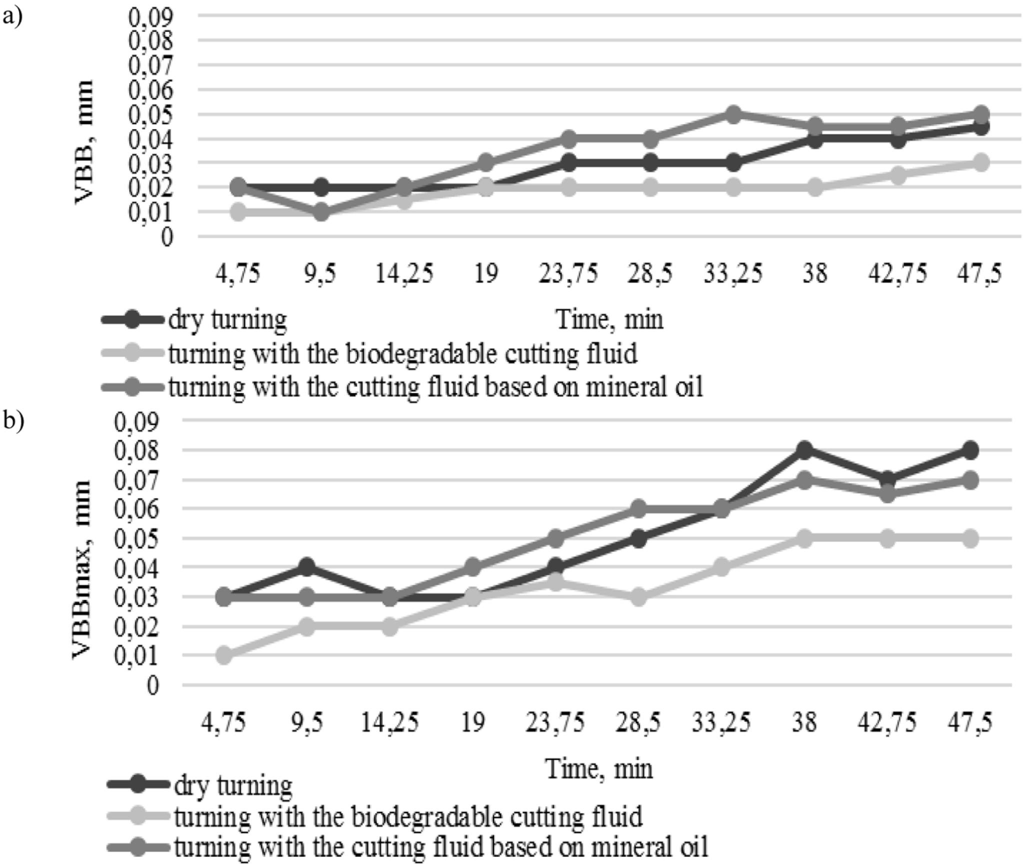


**Fig. 1. Wear of the cutting tools after: a) dry turning, b) turning with the biodegradable cutting fluid, c) turning with the cutting fluid based on mineral oil**

Rys. 1. Pomiary zużyć stalek po toczeniu: a) na sucho, b) z biodegradowalnym chłodziwem, c) z chłodziwem zawierającym olej mineralny

From the analysis of the tool wear data, it is evident that the highest point on the curve showing the average flank wear, $VB_B$, was reported for turning with the cutting fluid based on mineral oil, whereas the lowest was obtained for turning with the biodegradable cutting fluid. The highest point on the curve showing the maximum flank wear, $VB_B$max, was observed for dry turning, while the lowest for turning when the biodegradable cutting fluid was used.

**Figures 2** and **3** show the surface topographies and roughness profiles for the workpieces obtained after the 10th cycle of dry turning and wet turning with the cutting fluids. The comparative analysis of the surface profiles reveals that the lowest peak heights and the shallowest valley depths were reported after turning with the biodegradable cutting fluid. On the other hand, the highest peak heights and the deepest valley depths were observed after turning with the cutting fluid based on mineral oil.

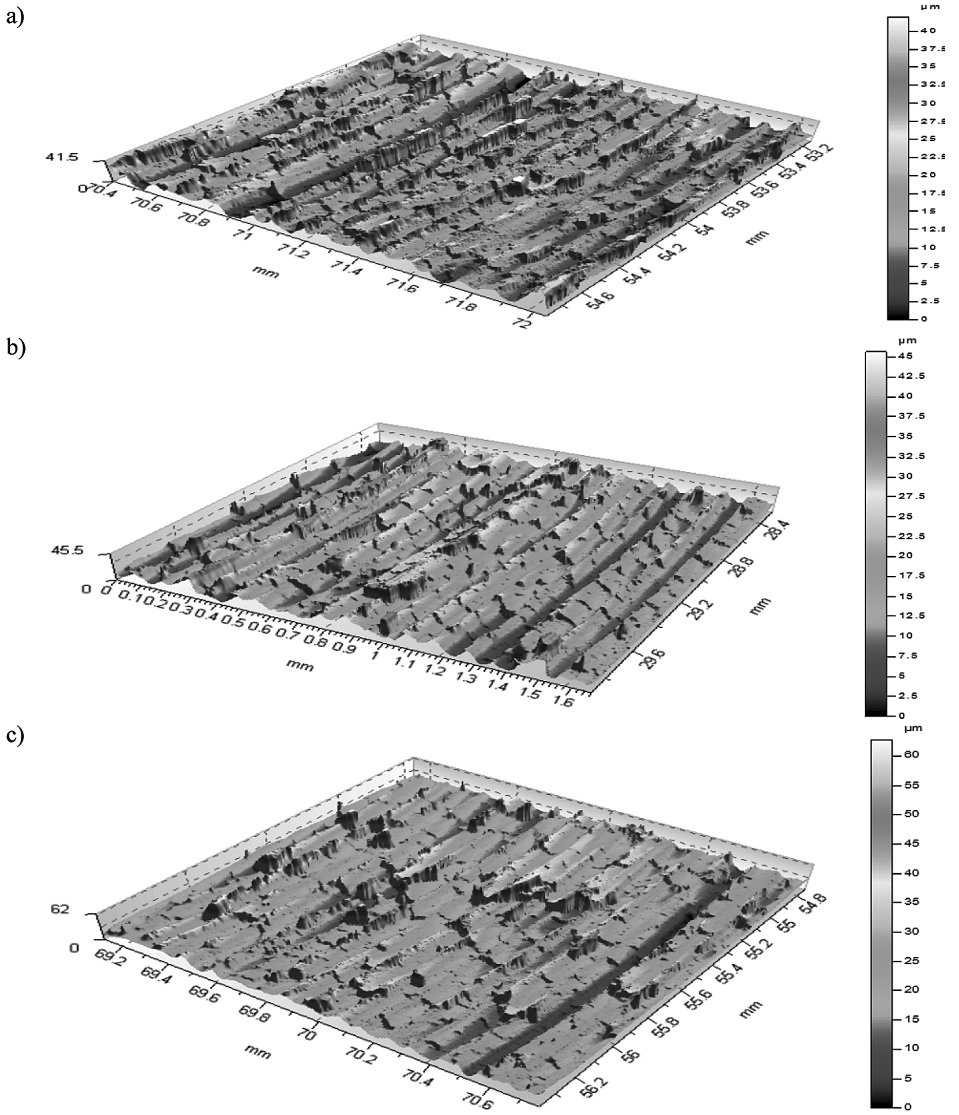


**Fig. 2. Surface topography after: a) dry turning, b) turning with the biodegradable cutting fluid, c) turning with the cutting fluid containing mineral oil**

Rys. 2. Topografia powierzchni obrobionego przedmiotu po toczeniu: a) na sucho, b) z biodegradowalnym chłodziwem, c) z chłodziwem zawierającym olej mineralny

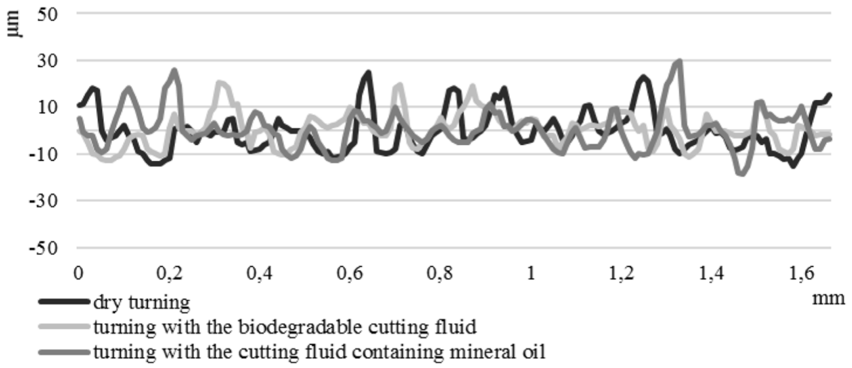


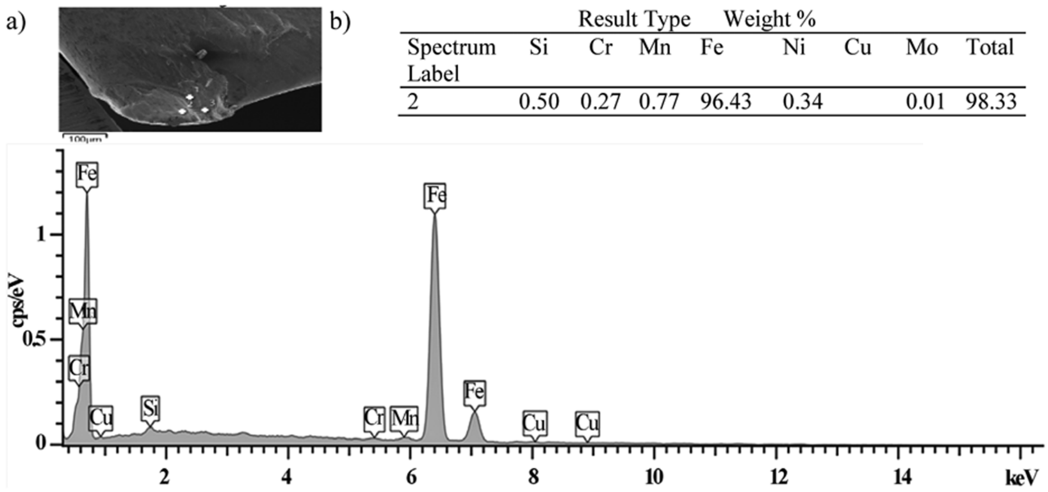
**Fig. 3. Roughness profiles after: a) dry turning, b) turning with the biodegradable cutting fluid, c) turning with the cutting fluid containing mineral oil**

Rys. 3. Profil powierzchni obrobionego przedmiotu po toczeniu: a) na sucho, b) z biodegradowalnym chłodziwem, c) z chłodziwem zawierającym olej mineralny

## SEM/EDS

**Figures 4–6** show SEM images of the wear tracks on the tool bits and X-ray energy spectra after dry turning and wet turning with the cutting fluids.

After the last 10th cycle of turning performed both under dry and wet conditions, a built-up edge was observed on the tool bit. Its chemical composition was examined using a scanning electron microscope. After wet turning, the constituent elements of the tool material, including tungsten and vanadium, were observed locally on the built-up edge. After dry turning, no such elements were reported, which suggests that the material found at the build-up edge was transported through adhesion from the workpiece material. After turning with the biodegradable cutting fluid containing zinc aspartate, zinc atoms were also present at the selected point. This indicates that a thin layer of zinc compounds formed; as a result, the coefficient of friction and the tool wear were lower. The layer formation was also reported during model tests with the T-01M system.

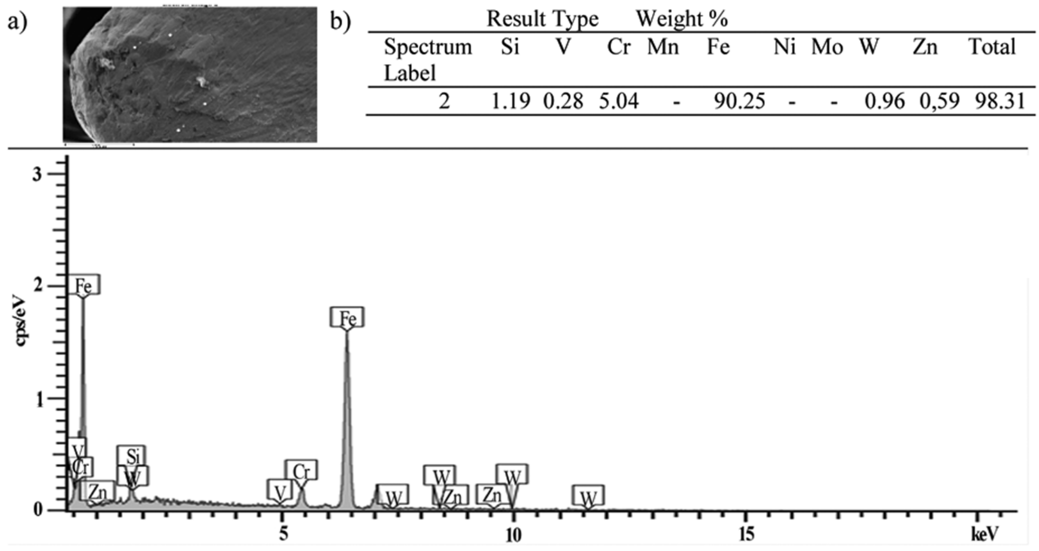


Result Type Weight %

| Spectrum Label | Si | Cr | Mn | Fe | Ni | Cu | Mo | Total |
|---|---|---|---|---|---|---|---|---|
| 2 | 0.50 | 0.27 | 0.77 | 96.43 | 0.34 |  | 0.01 | 98.33 |

**Fig. 4. SEM analysis of the tool wear after dry turning: a) image of the wear track and b) X-ray energy spectrum**

Rys. 4. SEM: a) widok obszaru śladu zużycia stalki po toczeniu na sucho, b) analiza punktowa pierwiastków

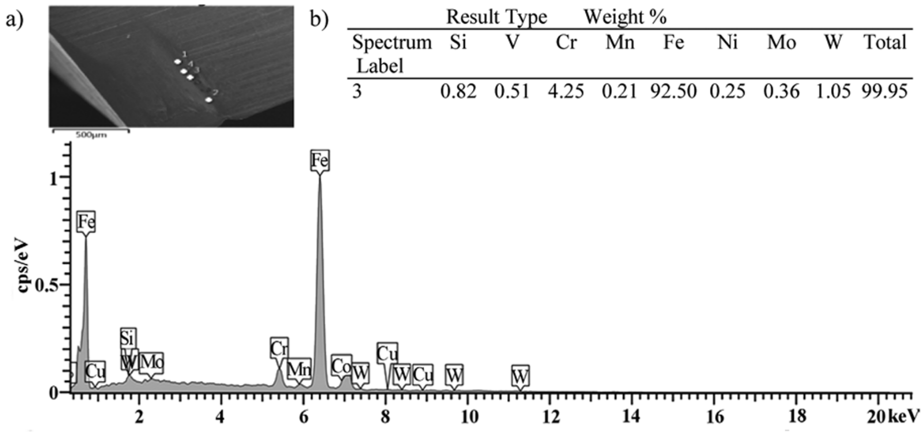


Result Type Weight %

| Spectrum Label | Si | V | Cr | Mn | Fe | Ni | Mo | W | Zn | Total |
|---|---|---|---|---|---|---|---|---|---|---|
| 2 | 1.19 | 0.28 | 5.04 | - | 90.25 | - | - | 0.96 | 0,59 | 98.31 |

**Fig. 5. SEM analysis of the tool wear after turning with the use of the biodegradable cutting fluid: a) image of the wear track and b) X-ray energy spectrum**

Rys. 5. SEM: a) widok obszaru śladu zużycia stalki po toczeniu z biodegradowalnym chłodziwem, b) analiza punktowa pierwiastków



| Result Type | Weight % | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Spectrum Label | Si | V | Cr | Mn | Fe | Ni | Mo | W | Total |
| 3 | 0.82 | 0.51 | 4.25 | 0.21 | 92.50 | 0.25 | 0.36 | 1.05 | 99.95 |

**Fig. 6. SEM analysis of the tool wear after turning with the use of the cutting fluid containing mineral oil: a) image of the wear track and b) X-ray energy spectrum**

Rys. 6. SEM: a) widok obszaru śladu zużycia stalki po toczeniu z chłodziwem z olejem mineralnym, b) analiza punktowa pierwiastków

## Tribological tests

The tribological tests performed with the T-01M tester involved registering the values of the coefficient of friction and linear wear after dry friction conditions and under lubricated friction conditions with two types of cutting fluid for the HS6-5-2C steel–100Cr6 steel system. The reference values were those obtained under predefined dry friction conditions with predetermined tribological test parameters.

**Figure 7** shows the coefficients of friction for the analysed friction configurations. The lowest value was reported after wet turning with the cutting fluid based on mineral oil, whereas the highest value was observed after dry turning.

**Figure 8** illustrates the intensity of linear wear under dry and wet turning conditions.

The lowest intensity of linear wear was observed after turning with the cutting fluid based on mineral oil, while the highest was reported after dry turning.

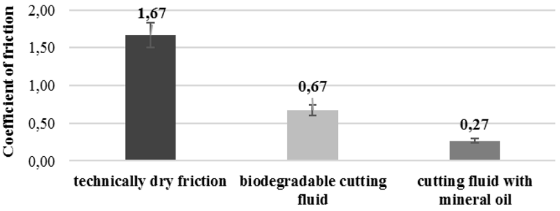


**Fig. 7. Coefficient of friction after dry and wet turning**

Rys. 7. Współczynnik tarcia w zależności od substancji smarowej

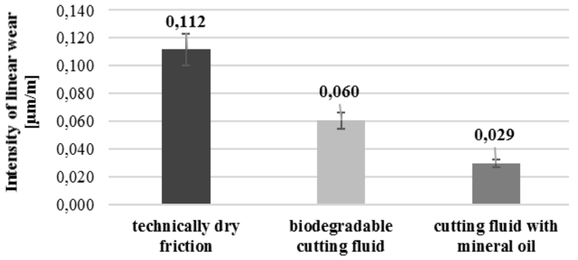


**Fig. 8. Intensity of linear wear after dry and wet turning**

Rys. 8. Intensywności zużywania liniowego w zależności od substancji smarowej

## Foam in the cutting fluids

The foaming tendency of the cutting fluids was determined according to the ASTM D3601-88 standard **[L. 17]**. Forty shakes were applied and, after 5 minutes, the foam height was measured for both fluids. As can be seen from the photograph in **Figure 9**, the foam in the biodegradable cutting fluid (1) subsided faster than that in the cutting fluid containing mineral oil (2), where the whole surface was covered with foam.

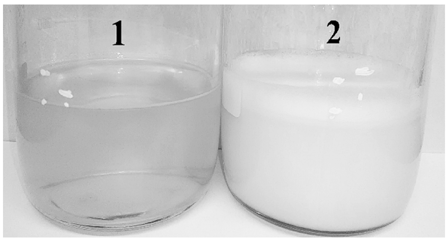


**Fig. 9. View of the bottles after 5 minutes: 1 – biodegradable cutting fluid, 2 – cutting fluid containing mineral oil**

Rys. 9. Widoki butelek po upływie 5 minut: 1 – biodegradable ciecz chłodząco-smarująca, 2 – chłodziwo zawierające olej mineralny

## Corrosive effects of the cutting fluids on iron alloys

The comparative analysis of the corrosive effects of the cutting fluids showed that the filter paper used for testing the biodegradable cutting fluid had a single rust spot, while the filter paper used for testing the mineral oil-based cutting fluid had several spots of rust, with the largest being 2 mm in diameter.

According to the PN-92-M-55798 standard specifying the degrees of rusting **[L. 18]**, the biodegradable cutting fluid was classified as 1 (the filter paper showed only traces of rust), while the cutting fluid containing mineral oil was classified as 2 (light corrosion with rust not exceeding 1% of the surface area of the filter paper and rust spots being more than 1 mm in diameter).

## CONCLUSIONS

The experiments discussed in this article coincide with the latest studies on allergy-free lubricants. The reason for intensive research in this area is the need to ensure health and safety in the workplace.

From the values of the maximum flank wear $VB_B$max and the average flank wear $VB_B$, it is evident that the abrasive wear of the tool at the flank face was the lowest when the biodegradable cutting fluid was used, and it was lower than during dry turning or wet turning with the mineral oil-based cutting fluid.

The built-up edge observed on the tool after turning was examined by scanning electron microscopy. The analysis showed that dry turning caused local transfer of the workpiece material. After wet turning, on the other hand, the elements present in the built-up edge were the same as those found in the tool material. Additionally, zinc layers were reported at the selected points along the cutting edge after wet turning with the biodegradable cutting fluid containing zinc aspartate.

The stereo zoom images of the machined surfaces, the surface topographies, and roughness profiles obtained with an optical profiler suggest that, after dry turning and wet turning with the mineral oil-based cutting fluid, there are visible grooves after each tool pass. The surface was smoother and had higher peak heights and shallower valley depths after turning with the biodegradable cutting fluid.

The foaming tendency of the biodegradable cutting fluid was compared with that of the mineral oil-based cutting fluid (Bottle test). Their corrosive effects were also analysed (Ford tests). The biodegradable cutting fluid provided better protection against rust. The foaming tendency of the biodegradable cutting fluid turned out to be better; the foam height was smaller, and the foam subsided sooner.

The results of the tribological tests indicate that, after turning with the mineral oil-based cutting fluid, the coefficient of friction was lower, the linear wear was lower, and the wear tracks on the disc and the ball were smaller and shallower than after turning with the biodegradable cutting fluid.

However, after turning with the biodegradable cutting fluid, a smaller wear of the tools and smoother surface of the workpiece were observed.

The findings reveal that the biodegradable cutting fluid analysed here can be used in turning. Further tests will focus on the properties of the cutting fluid in other machining operations.

## REFERENCES

1. Siniawski M., Bowman C., Metal working fluids: Winding green in the manufacturing process, Industrial Lubrication and Tribology, 61, 2, 2009, pp. 60–66.
2. Doll K., Sharma B., Emulsification of chemically modified vegetable oils for lubricant use, Journal of Surfactants and Detergents, 14, 2011, pp. 131–138.
3. Adhvaryu A., Liu Z, Erhan S.Z., Synthesis of novel alkoxylated triacylglycerols and their lubricant base oil properties, Industrial Crops and Products, 21, 2005, pp. 113–119.
4. Kajdas C., Karpińska A., Kulczycki A., Industrial Lubricants. Chapter 8: Chemistry and Technology of Lubricants, Third Edition, Springer Dordrecht Heidelberg, London, New York 2010.
5. Soković M., Mijanović K., Ecological aspects of the cutting fluids and its the cutting processes, Journal of Materials Processing Technology, 109, 2001, pp. 181–189.
6. Wilson B., Lubricants and functional fluids from renewable sources, Industrial Lubrication and Tribology, 50, 1, 1998, pp. 6–15.
7. Ozimina D., Kowalczyk J., Madej M., Nowakowski Ł., Wpływ biodegradowalnej cieczy chłodząco-smarującej na zużycie narzędzia i strukturę geometryczną powierzchni po obróbce skrawaniem, Mechanik, 8–9, 2016, pp. 1094–1095.
8. De Chiffre L., Belluco W., Investigations of cutting fluid performance using different machining operations, Lubrication Engineering, 58, 200, pp. 22–29.
9. Rebeccal G., Rogere M., Peter A., Biodegradable lubricant, Lubrication Engineering, 7, 1998, pp. 10–16.
10. Petterson A., High-performance base fluid for environmentally adapter lubricants, Tribology International, 40, 2007, pp. 638–645.
11. Asdauskas S., Perez J.M., Duda J.L., Lubrication properties of castrol oil–potential basestock for biodegradable lubricants, Lubrication Engineering, 53, 1997, pp. 35–41.
12. Manekotte J.K., Kailas S.V., Experimental investigation of coconut and palm oils as lubricants in four-strokeengine, Tribology Online, 6, 1, 2011, pp. 76–82.
13. Somashekaraiah R., Suvin P.S., Gnanadhas D.P., Kailas S.V., Chakravortt D., Eco-Friendly, Non-Toxic Cutting Fluid for Sustainable Manufacturing and Machining Processes, Tribology Online, 11, 5, 2016, pp. 556–567.
14. Zhang J.Z., Rao P.N., Eckman M., Experimental evaluation of a bio-based cutting fluid using multiple machining characteristics, International of Journal of Modern Engineering, 12, 2, 2012, pp. 35–44.
15. Ademoh N.A., Didam J.H., Garba D.K., Investigation of Neem Seed Oil as an Alternative Metal Cutting Fluid, American Journal of Mechanical Engineering, 4, 5, 2016, pp. 191–199.
16. Adamczak S., Świderski J., Wieczorowski M., Majchrowski R., Miller T., Łętocha A., Założenia do oceny wiarygodności pomiarów topografii powierzchni w różnych skalach, Mechanik, 3, 2015, pp. 81–87.
17. ASTM D3601-88 Standard Test Method for Foam In Aqueous Media (Bottle Test), 2002.
18. PN-92-M-55798 Badanie działania korodującego cieczy technologicznych na stopy żelaza.