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THE IMPACT OF BIODEGRADABLE CUTTING FLUID ON THE TRIBOLOGICAL PROPERTIES OF THE FRICTION PAIRS

WPŁYW BIODEGRADOWALNEJ CIECZY CHŁODZĄCO-SMARUJĄCEJ NA WŁAŚCIWOŚCI TRIBOLOGICZNE BADANYCH SKOJARZEŃ TRĄCYCH

Key words:

tribotechnology, biodegradable cutting fluids, TiAlN coating, friction, wear

Słowa kluczowe:

tribotechnologia, biodegradowalne ciecze obróbkowe, powłoka TiAlN, friction, zużycie

Abstract

This paper discusses the results of wear tests performed with a T-01 M tribometer for a ball-on-disc configuration in sliding contact. The tests were carried out for HS6-5-2C steel discs with and without a TiAlN coating deposited by physical vapour deposition (PVD), which were in contact with 100Cr6 steel balls. The tests were conducted under dry friction conditions and under lubricated friction conditions with a cutting fluid containing zinc aspartate. The coating structure was observed using a JSM - 7100F scanning electron microscope. The surface texture of the discs and the balls was analysed

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before and after the tribological tests with a Talysurf CCI Lite optical measurement system. The cutting fluid used in the tests contributed to a reduction in the friction resistance and offered anti-corrosion protection.

INTRODUCTION

Machining processes involve friction, which occurs between the cutting tool and the workpiece. This phenomenon is responsible for the generation of heat, which has a negative effect on the dimensional accuracy, surface quality and surface texture of the workpiece **[L. 1–3]** as well as the service life of the cutting tool **[L. 4]**. It is essential that machining processes be performed with the use of cutting fluids, because they reduce friction between the surfaces in contact, i.e. at the tool–workpiece interface and the tool–chip interface. Cutting fluids act as lubricants and coolants **[L. 1]**; as a result, they increase the tool service life and the process efficiency, they reduce the cutting forces **[L. 6]** and the workpiece deformation **[L. 5]** and, finally, they protect the machined material against corrosion **[L. 7–8]**.

More than 2 000 000 m^3 of cutting fluid is used all over the world every year; however, the volume of waste may be ten times higher because cutting fluid is generally diluted before use **[L. 8]**. Cutting fluids are formulated from mineral base oil, emulsifiers, surfactants, corrosion inhibitors, anti-friction, extreme-pressure (EP) and anti-wear (AW) additives, foam inhibitors, biocides, etc. **[L. 10]**. Because of this complex composition, cutting fluids are very toxic. If disposed incorrectly, they may contaminate air, soil, and water, causing serious damage to ecosystems around the world. Effluents containing cutting fluids can potentially contaminate surface water, groundwater, **[L. 7]**, air, soils, and, eventually, agricultural products **[L. 10]**. Cutting fluids may also be harmful to human health. Workers performing machining operations are exposed to cutting fluid vapour or mist (containing micro particles); they have an increased risk of developing eye irritation, skin irritation, allergies, respiratory diseases, cancer, or even genetic defects. For this reason, disposal and/or reuse of spent cutting fluids can be a serious challenge **[L. 7, 8, 11]**. Therefore, it is essential to use safe and biodegradable fluids and tools with new generation coatings, which enable minimum quantity lubrication (known as MQL).

The MQL technique involves spraying tiny droplets of lubricant in a stream of compressed air **[L. 12]**. Unlike in the conventional flood method, cutting fluid is not sprayed outside the cutting zone. As the air stream carries oil droplets directly into the cutting zone, it ensures effective lubrication of the moving components.

The MQL technique is suitable when cutting tools with thin, hard coatings are used, with the coatings being characterised by low-friction properties, anti-corrosive properties, thermal properties, high hardness, high resistance to wear, as well as good adhesion to the substrate. Coated tools can operate under dry and wet machining conditions, and they improve the operating parameters of the element. Such coatings can be produced by chemical vapour deposition (CVD), physical vapour deposition (PVD), or similar techniques **[L. 8, 4, 13]**.

MATERIALS

TiAlN coatings and cutting fluids

The tests were conducted for specimens coated with TiAlN. The coatings were produced by physical vapour deposition (PVD) on high-speed tool steel (HS6-5-2C) characterised by very good ductility, impact resistance, and abrasion resistance. HS6-5-2C steel is designed to operate at high temperatures, and it can be subjected to heat treatment: tempering at 1190–1230°C and quenching at 550–650°C. Its hardness after heat treatment at 500–550°C is 65 HRC.

The composition of HS6-5-2C steel is shown in **Table 1**.

Table 1. Composition of HS6-5-2C steel
Tabela 1. Skład chemiczny stali HS6-5-2C

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

TiAlN coatings are characterised by the following:

- Very good tribological properties, i.e. low friction and high antiwear protection;
- Very good thermal and chemical resistance, which enables dry and wet machining;
- High hardness; and,
- Resistance to oxidation.

The tribological tests were performed using biodegradable cutting fluid, which can replace classical, usually toxic, cutting fluids. The biodegradable cutting fluid under analysis contains the following:

- Demineralised water (DEMI),
- Alkanolamine borane, and
- Biodegradable polymer – containing zinc aspartate – 5% vol.

The parameters of the demineralised water are shown in **Table 2**.

Table 2. Parameters of the demineralised water at 25°C
Tabela 2. Parametry wody demineralizowanej w temperaturze 25°C

pH	Conductivity [$mS \cdot cm^{-1}$]	Maximum resistivity [$M\Omega \cdot cm$]
5.0-7.2	$5.5^{-10} \cdot 10^{-5}$ (1.42 µS/cm)	18.2

METHODS

SEM/EDS analysis

A JSM 7100F scanning electron microscope was used to observe the metallographic sections of the disc surface before and after the tribological tests. The microscope was equipped with an EDS X-ray spectrometer, which enabled the identification of elements present at the disc surface.

Tribological tests

The tribological tests were performed using a T-01M ball-on-disc system according to the requirements of the ASTM G 99 standard.

The test parameters were as follows:

- Friction configuration:
  - 100Cr6 steel ball-on-HS6-5-2C steel disc
  - 100Cr6 steel ball-on-HS6-5-2C steel disc coated with TiAlN
- Load P = 50 N
- Sliding rate v = 0.1 m/s
- Sliding distance S = 1 000 m
- Relative moisture 50 ± 5 %
- Ambient temperature $T_0 = 23 \pm 1^{\circ}C$

The tests were carried out under dry friction conditions and under lubricated friction conditions with biodegradable cutting fluid CF at the interface.

The results obtained for dry friction conditions were used as the reference data for tests with cutting fluids.

Surface texture

A Talysurf CCI Lite was employed to measure the surface texture of the upper and lower specimens before and after the tribological tests. The tests were carried out at the Laboratory for Computer-Based Measurement of Geometrical Quantities of the Kielce University of Technology **[L. 14]**.

RESULTS AND DISCUSSION

SEM/EDS analysis of the TiAlN coating

Figure 1 shows SEM images of the TiAlN coating, which can be deposited on cutting tools. **Figure 1a** depicts a cross-section of the coating with a thickness of approximately 4.036 µm deposited on HS6-5-2C steel.

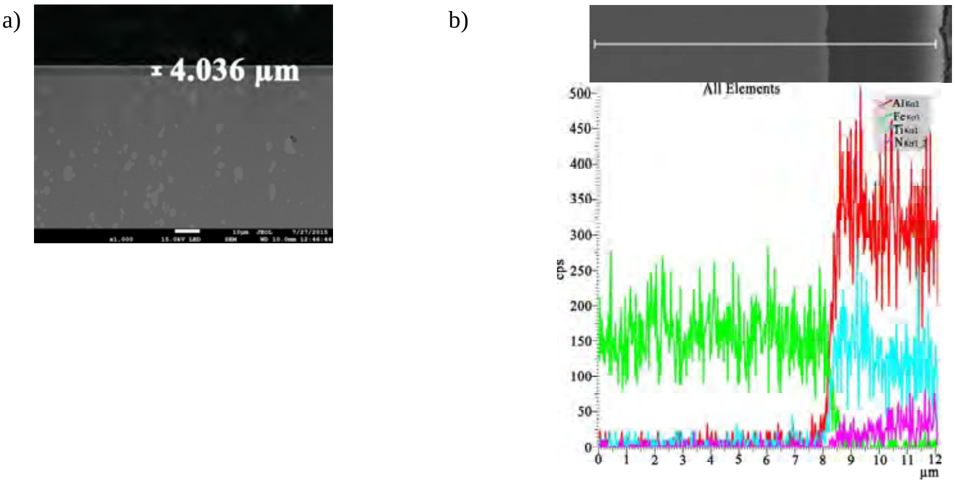


Fig. 1. SEM image: a) cross section of the TiAlN coating, b) EDS analysis

Rys. 1. Wyniki badań uzyskane za pomocą mikroskopii skaningowej SEM oraz mikroanalizy rentgenowskiej EDS: a) przekrój poprzeczny powłoki TiAlN, b) analiza EDS

The EDS analysis of the coating (**Figure 1b**) confirms the presence of the main elements: aluminium – Al, titanium – Ti and nitrogen – N.

Surface texture before the tribological tests

Figures 2 and 3 show the surface topographies of the uncoated disc and the disc coated with TiAlN, respectively, before the tribological tests.

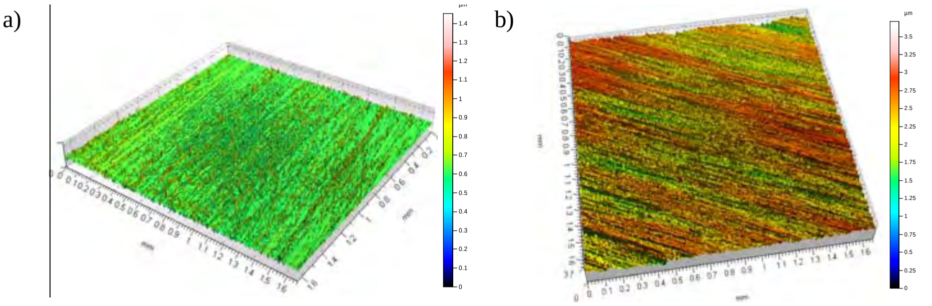


Fig. 2. Surface topographies of: a) the uncoated HS6-5-2C steel disc, b) the HS6-5-2C steel disc coated with TiAlN

Rys. 2. Topografia powierzchni tarczy ze stali HS6-5-2C: a) bez powłoki, b) z powłoką TiAlN

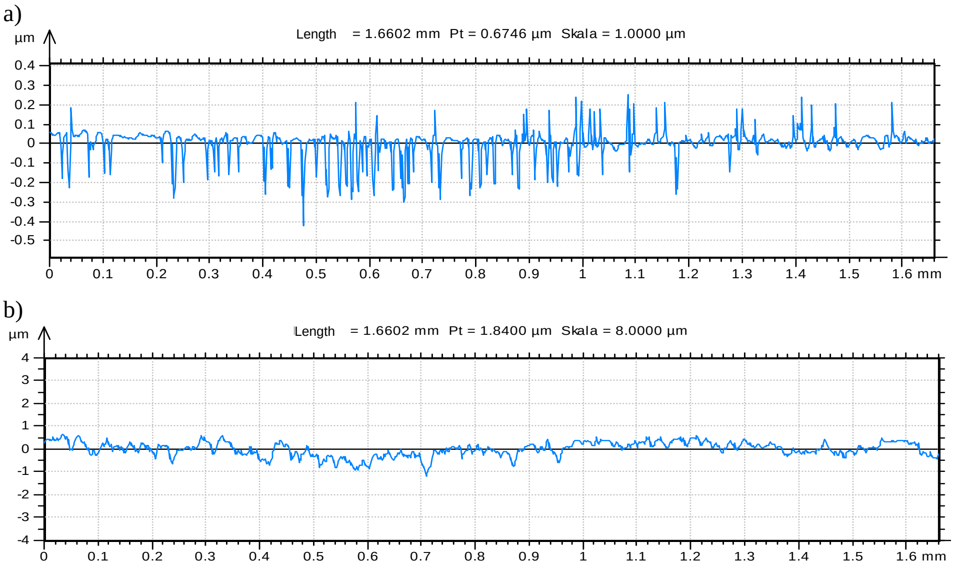


Fig. 3. Surface profile of a) the uncoated HS6-5-2C disc, b) the HS6-5-2C disc coated with TiAlN

Rys. 3. Profil powierzchni tarczy ze stali HS6-5-2C: a) bez powłoki, b) z powłoką TiAlN

There was a clear difference in the surface texture profiles between the uncoated HS6-5-2C steel discs and the HS6-5-2C steel discs coated with TiAlN (**Figure 3**); however, the irregularities were smaller for the TiAlN coated specimens.

Tribological tests

The aim of the wear tests was to study the effects of biodegradable cutting fluid on the tribological performance of the analysed friction configurations.

Figure 4 shows the values of the friction coefficient for the uncoated HS6-5-2C steel disc–100Cr6 steel ball system and the TiAlN-coated HS6-5-2C steel disc–the 100Cr6 steel ball operating under dry friction conditions and under lubricated friction conditions with cutting fluid CF.

The lowest value of the friction coefficient was reported when one of the surfaces in contact was coated with TiAlN and cutting fluid CF was present at the interface. At the beginning of the test, the coefficient of friction μ increased to $\mu \cong 1.15$. Then, it decreased reaching $\mu \cong 0.4$ at the sliding distance S = 60 m. It continued to increase until $\mu \cong 0.75$ at the sliding distance S = 190 m. Before the end of the test, the coefficient of friction decreased reaching $\mu \cong 0.45$.

The highest value of the friction coefficient was observed for the uncoated disc under dry friction conditions. It was $\mu \cong 1.7$.

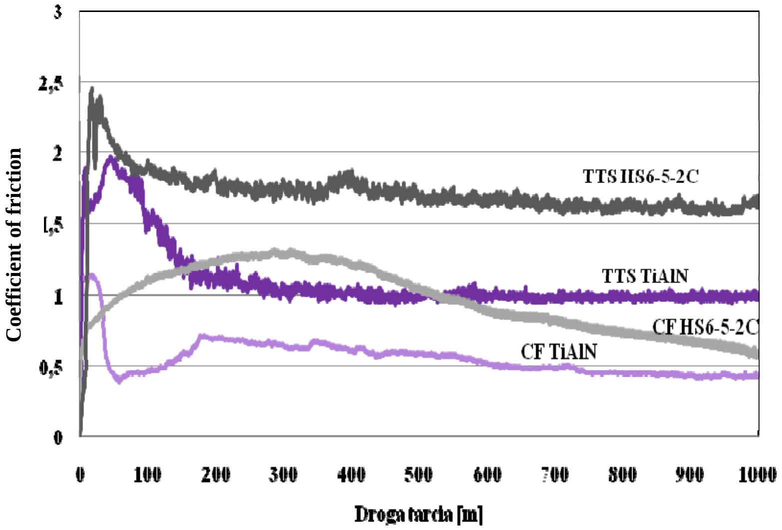


Fig. 4. Coefficients of friction plotted for all the friction configurations
Rys. 4. Przebiegi współczynników tarcia badanych skojarzeń trących

When one of the surfaces in contact was coated with TiAlN, the values of the coefficient of friction were more stable. They were also much lower than for the uncoated disc whether under dry friction conditions or lubricated friction conditions with a cutting fluid.

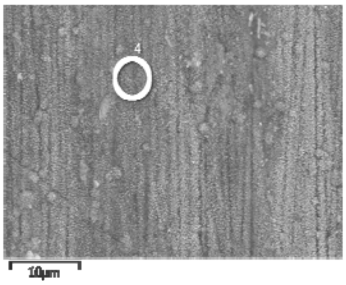
SEM/EDS analysis after the tribological tests

Figure 5 shows a SEM view of the surface of the TiAlN-coated HS6-5-2C steel disc after wear tests with the use of biodegradable cutting fluid containing zinc aspartate. **Figure 5** also presents an EDS X-ray spectrum obtained for the characteristic points along the sliding distance of 1 000 m at a load of 50 N.

The atomic concentrations of aluminium, titanium, and nitrogen at the surface of the disc were higher; the concentrations of zinc and iron, on the other hand, were lower.

The darker areas at the friction interface (**Figure 5a**) were identified as thin layers of zinc characterised by very good anti-wear properties, which resulted from the electrochemical affinity of zinc to the disc material. As the tests showed, the thin layers of zinc were rebuilt during friction.

a)



b)

Element	Mass %	Mass % Sigma
N	23.85	1.10
Al	35.73	0.67
Ti	36.40	0.73
Fe	2.99	0.41
Zn	1.02	0.28
Total:	100.00	

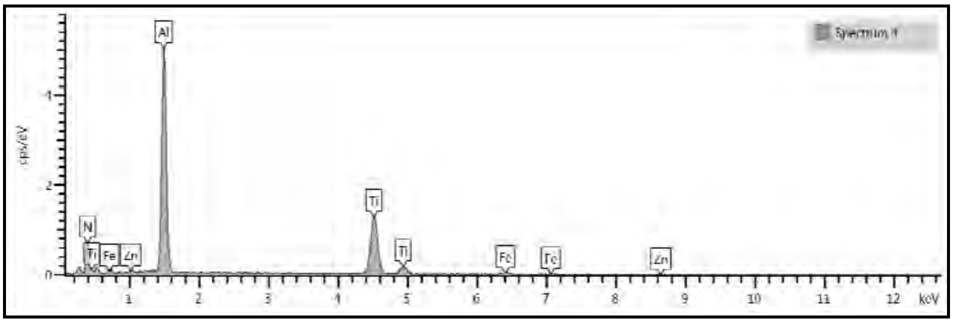


Fig. 5. SEM images of: a) wear tracks on the HS6-5-2C steel disc coated with TiAlN after the wear tests with CF for a sliding distance of 1000 m at a load of 50 N, b) EDS X-ray spectrum

Rys. 5. SEM: a) widok obszaru śladu zużycia tarczy ze stali stal HS6-5-2C z powłoką TiAlN po współpracy tarciowej z CF na drodze tarcia 1000 m przy obciążeniu 50 N, b) analiza punktowa pierwiastków

Surface texture after the tribological tests

Figures 6–9 show the surface texture of the discs and balls in the analysed configurations after the wear tests using biodegradable cutting fluid.

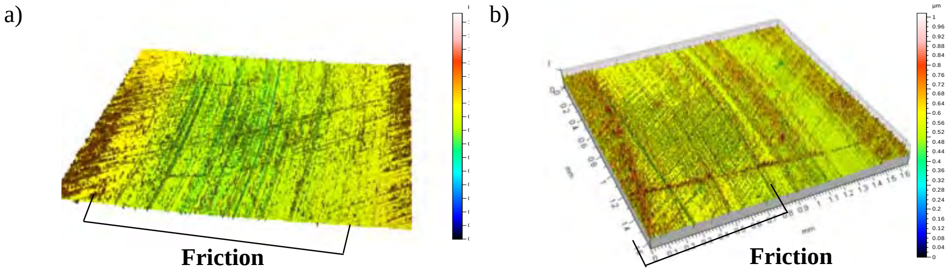


Fig. 6. Surface topographies of a) the uncoated HS6-5-2C steel disc, b) the TiAlN-coated HS6-5-2C steel disc, in contact with the 100Cr6 steel ball

Rys. 6. Topografia powierzchni tarczy ze stali HS6-5-2C: a) bez powłoki, b) z powłoką TiAlN współpracującą z kulą ze stali 100Cr6

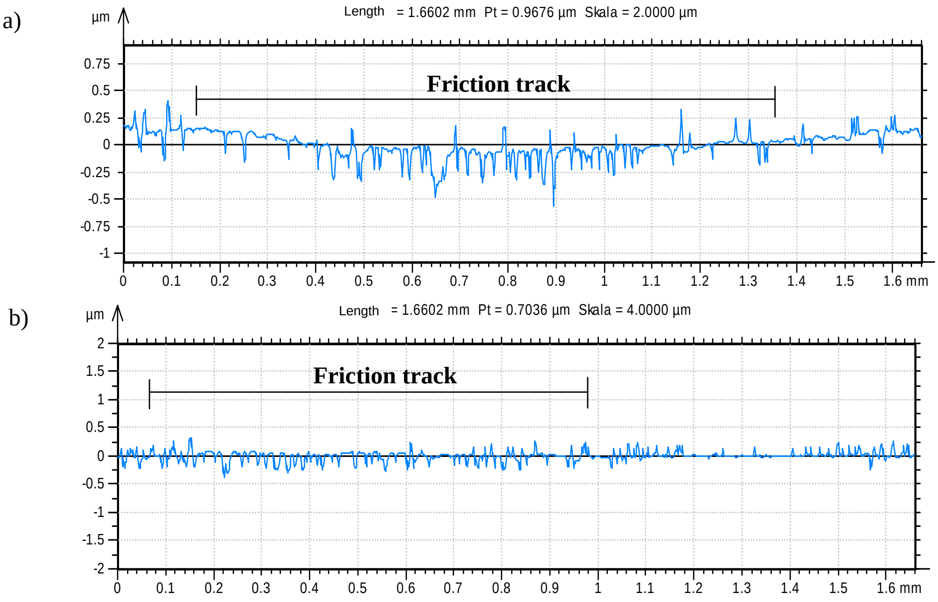


Fig. 7. Surface profiles of a) the uncoated HS6-5-2C steel disc, b) the TiAlN-coated HS6-5-2C steel disc, in contact with the 100Cr6 steel ball

Rys. 7. Profil powierzchni tarczy ze stali HS6-5-2C: a) bez powłoki, b) z powłoką TiAlN współpracującą z kulą ze stali 100Cr6

From the comparative analysis of the texture profiles obtained for the discs subjected to the wear tests (**Fig. 7**), it is clear that smaller irregularities of about 0.2 µm were reported for the disc coated with TiAlN. The friction tracks in the uncoated discs were deeper. This suggests that the coating used in the study was more resistant to wear than HS6-5-2C steel.

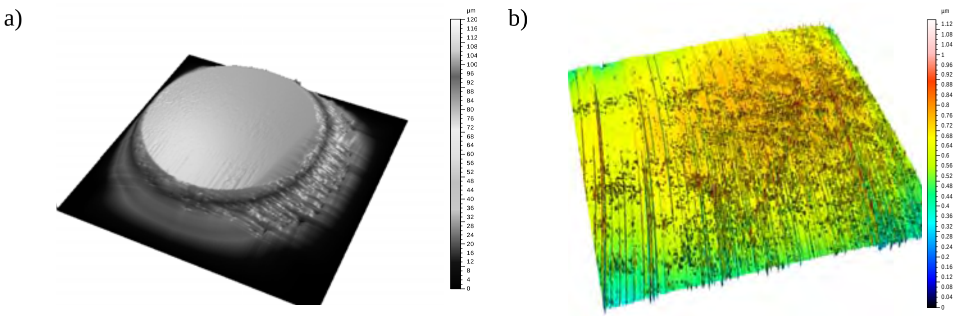


Fig. 8. Surface topographies of the 100Cr6 steel ball in contact with a) the uncoated HS6-5-2C steel disc, b) the TiAlN-coated HS6-5-2C steel disc

Rys. 8. Topografia powierzchni kuli ze stali 100Cr6 współpracującej z tarczą ze stali HS6-5-2C: a) bez powłoki, b) z powłoką TiAlN

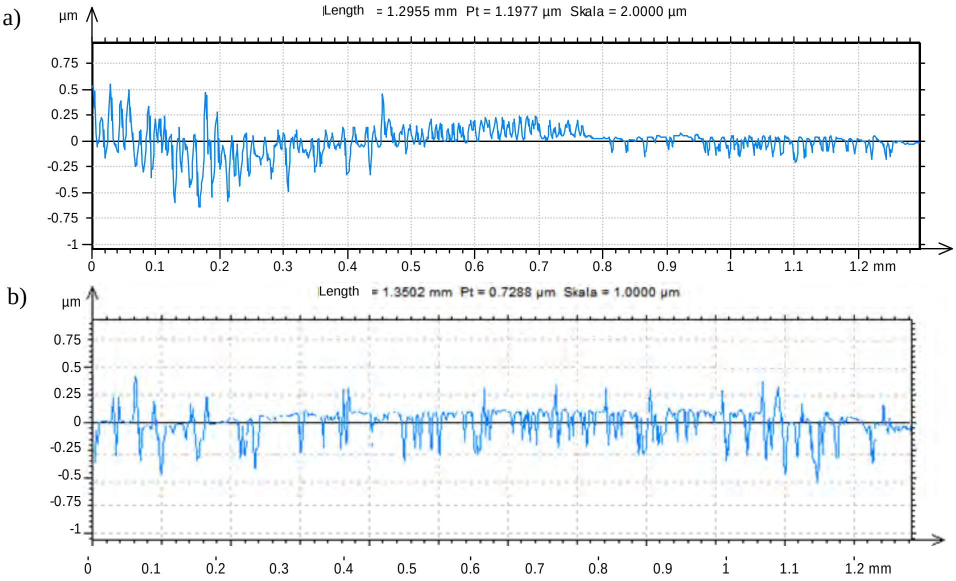


Fig. 9. Surface profiles of the 100Cr6 steel ball in contact with a) the uncoated HS6-5-2C steel disc, b) the TiAlN-coated HS6-5-2C steel disc

Rys. 9. Profil powierzchni kuli ze stali 100Cr6 współpracującą z tarczą ze stali HS6-5-2C: a) bez powłoki, b) z powłoką TiAlN

The topographies and surface texture profiles obtained for the ball (**Figs. 8** and **9**, respectively) indicate that the friction tracks were smaller and the surfaces were smoother when the disc in the friction configuration was coated with TiAlN.

Table 3 shows the 3D surface texture parameters obtained for the discs and the balls before and after the wear tests when cutting fluid was used.

Table 3. 3D surface texture parameters of the discs and balls before and after the tribological tests

Tabela 3. Parametry chropowatości powierzchni tarcz i kul przed i po testach tribologicznych

Surf. text. param. Material			Sa	Sq	Sp	Sv	Sz	Ssk	Sku
			µm	µm	µm	µm	µm	-	-
Before	HS6-5-2C	Disc	0.04	0.07	0.84	0.62	1.45	-1.03	8.94
	100Cr6	Ball	0.10	0.13	0.32	1.41	1.74	-1.11	4.75
	TiAlN	Disc	0.25	0.32	1.41	2.30	3.71	-0.61	3.66
After	HS6-5-2C	Disc	0.07	0.10	0.78	0.88	1.66	-0.24	4.83
	100Cr6	Ball	0.09	0.14	1.62	0.77	2.40	0.93	11.06
	TiAlN	Disc	0.05	0.08	0.81	2.30	3.11	-0.73	19.78
	100Cr6	Ball	0.09	0.12	0.52	0.61	1.14	-1.02	5.25

The analysis of the 3D surface texture parameters obtained for the HS-6-5-2C steel discs before and after the tribological tests indicates that the values of

- Sa, Sq, Sv, Sz – increased, and
- Sp, Ssk, Sku – decreased.

In the case of the HS-6-5-2C discs coated with TiAlN, however, the values of the surface texture parameters before and after the tribological tests changed as follows:

- Ssk, Sku – increased,
- Sa, Sq, Sp, Sz – decreased, and
- Sv – remained unchanged.

From the surface texture analysis, it is evident that, when the wear tests involved applying biodegradable cutting fluid, the surface of the TiAlN-coated disc was smoother than that of the uncoated disc.

CONCLUSION

The tests described in this paper have contributed to the development of more environmentally friendly lubrication technologies and safer cutting fluids. Today, machining operations require the use of biodegradable cutting fluids and cutting tools with new generation coatings.

The friction configuration with one of the contact surfaces coated with TiAlN deposited by PVD exhibited lower values of the coefficient of friction.

The results of the wear tests confirm that the use of new generation biodegradable cutting fluid and TiAlN coated tools can improve the efficiency of machining processes and reduce their negative impact on the environment.

It was found that the specimens made of HS6-5-2C steel coated with TiAlN were more resistant to wear than were the uncoated specimens.

The cutting fluid used in the tests performs all the necessary functions:

- It reduces the resistance resulting from friction.
- It transfers internally generated heat.
- It removes impurities (debris or externally introduced contaminants) and has a less negative influence on the environment and human health.

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Streszczenie

W artykule przedstawiono wyniki badań tribologicznych na testerze T-01 M pracującym w skojarzeniu trącym kula-tarcza w ruchu ślizgowym. Testy zrealizowano dla tarcz ze stali HS6-5-2C bez powłoki i z powłoką TiAlN naniesioną techniką fizycznego osadzania z fazy gazowej PVD oraz kul ze stali 100Cr6. Badania wykonano w warunkach tarcia technicznie suchego i ze smarowaniem cieczą chłodząco-smarującą zawierającą dodatek uszlachetniający – asparginian cynku. Obserwacje struktury powłoki zrealizowano przy użyciu mikroskopu skaningowego SEM JSM - 7100F. Analizę struktury geometrycznej powierzchni tarcz oraz kul przed i po testach tribologicznych wykonano profilometrem optycznym Talysurf CCI Lite. Użyta do badań ciecz obróbkowa wpłynęła na zmniejszenie oporów ruchu oraz dodatkowo zapewniła ochronę antykorozyjną w czasie prowadzenia testów.