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Surface Topography and Tribological Properties of Cutting Tool Coatings

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ABSTRACT

The surface topography formed during the technological process has an influence on the wear characteristics and modifies the surface topography of friction components during the operation process, including cutting tools. It is therefore important to carry out research to find the best material and construction solutions to increase their durability and reliability. The research and analysis covered selected coatings (TiN, TiCN, TiAlN) applied to cutting tools for their anti-wear properties. The coatings were obtained through physical vapour deposition PVD. For the purpose of evaluating the tribological properties of the coatings, friction-wear tests were carried out in rotary motion on a *ball-on-disc* device (ball made of 100 Cr6 steel, discs made of SW7M steel coated with selected coatings) at a constant load (10N), under coolant lubrication conditions. Investigations of the surface topography before and after tribological tests were carried out on a confocal microscope. The friction coefficient and the amount of wear (wear track) of the coatings were shown to vary under the same operating conditions. The highest friction coefficient was obtained for the TiCN coating (0.199), while the lowest for the TiN coating (0.144) – the surface topography of the balls deteriorated (parameters *Sq*, *Sz*, *Ssk*, *Sku* increased in value). The highest linear wear (281.1 μm) was obtained for the TiAlN coating (the coating was torn halfway through the test), where the ball surface topography has improved (lowered values of parameters *Sq*, Sz, *Ssk*, *Sku*, *Spd*, *Spc*).

Keywords: cutting tools, coatings, surface topography, tribology, friction coefficient, linear wear, wear track.

INTRODUCTION

The properties of the surface layer play a key role in the operating process, determining the durability of the cooperating components [1]. Examples include the cutting tool-to-workpiece system, where the component subject to wear is the tool, whereas the workpiece is shaped by the removal of material, with set machining parameters. The characteristics of surface topography of the cutting tool (in addition to the components of the tool design) and the conditions of the machining process (corresponding to the tool's operating process) influence the shaping of the machined component [2, 3] and the quality of the machined surface. It is therefore important to conduct research to find the best material and design solutions for cutting tools.

In the economy, friction and losses account for more than 30% of primary energy resources and exacerbate the energy crisis. For this reason, the development of new and the modification of existing anti-wear technologies is an important part of research and application work [4, 5]. Reducing friction and its associated processes has become an effective way to reduce energy losses and increase industrial productivity, including during machining [6]. One way to reduce the effects of friction and increase the service life of cutting tools is to apply hard but thin coatings to them obtained by physical and chemical vapour deposition (PVD, CVD) processes. The most commonly used materials include coatings based on titanium, carbon, nitrogen and alumina [6, 7]. One such example is titanium nitride (TiN), which has been around since the mid-1960s and is used solely to coat tool steels. They are characterised by low density, high melting point and chemical stability, as well as high hardness, good ductility, excellent lubrication qualities [7-9], as well as resistance to wear and corrosion [8, 9]. Thin TiN layers are obtained mainly by the physical vapour PVD deposition at temperatures in the order of 200–600 °C [5, 8]. Due to the high temperatures of the CVD chemical vapour deposition process (reaching up to 1,100 °C), this method is used less frequently to coat tool steels. The reason for this is the high temperatures, which cause a reduction in the adhesion of the coating and a dimensional change.

Titanium carbonitride (TiCN)-based coatings are attracting attention among numerous researchers. This is due to its high hardness at high temperatures, thermal conductivity, chemical, thermal and friction wear resistance and low friction coefficient when working with metals. With great success they are applied to cutting tools as they improve surface quality compared to WC-Co coatings, while ensuring the dimensional accuracy of the workpieces [10].

The aluminium content in titanium aluminium nitride (TiAlN)-based coatings intensifies the tribological wear resistance [11] at elevated operating temperatures and corrosion resistance better compared to TiN coatings. In addition, the TiAlN coating has greater hardness and thermal stability during the drying process at high temperatures and a lower thermal conductivity [8]. Aihuaet al. [12] indicated that the TiAlN coating had the best mechanical and tribological properties among the titanium, aluminium and chromium nitrogen coatings, displaying the best mechanical properties and the best wear resistance. The wear resistance tests carried out on tools with TiAlN, AlTiN and AlCrN coatings at elevated temperatures up to 500 °C indicated that the highest service life was obtained for the TiAlN coating. Levent et al. [13] showed that, among TiN, TiAlN, CrAlN, and TiAlN/TiSiN coatings, the chromium aluminium nitride (CrAlN) coating displayed the highest nano-hardness, wear resistance and scratch resistance. The TiAlN coating was the least wear-resistant coating, for which the abrasive wear mechanism predominated. Danisman et al. [14] compared the properties of TiN, TiAlN and TiCN coatings deposited on the surface of a titanium alloy to improve its tribological properties. Tribological tests were conducted at both different loads and sliding speeds under technically dry friction conditions. The results of the tests carried out showed that the smallest wear tracks were observed for the TiN coating, while at the same time higher friction coefficient values were obtained compared to the results for the TiCN coating.

A review of the literature indicates that there is a lack of resolution, as well as a clear statement as to which coating best meets its role as a protective and anti-wear material for cutting tools. The research presented in the publications is carried out under different conditions, using different substrates as base material. It is therefore crucial to conduct comprehensive tests, initially model-based, and at a later stage simulation and bench tests, to determine which material will perform best under the given conditions – minimising tool wear while ensuring the best possible quality of the machined surface.

The aim of the research carried out in this work is to show how TiN, TiCN and TiAlN protective coatings applied to cutting tools will behave under the same model friction-wear test conditions (first stage of the research) using the selected (previously unused) SwissCool 3000 coolant. Based on the results obtained, guidelines will be developed for further research.

METHODOLOGY AND OBJECT OF THE STUDY

The studied objects were selected TiN, TiCN and TiAlN protective coatings applied to cutting tools. The coatings were obtained by physical vapour deposition (PVD) on the surface of specimens made of SW7M steel. The thickness of each coating was, respectively, 3.0, 3.5 and 4.0 µm. The primary properties characterising the materials tested are summarised in Table 1.

The selection process of the coatings for testing was based on their unique anti-wear properties [15]. The most commonly used coating is the titanium nitride (TiN) coating. It is characterised by versatility of application and 3÷4 times greater durability compared to uncoated tools.The disadvantage isthe need for cooling during machining. The titanium carbonitride (TiCN) coating is characterised by high hardness and, at the same time, good ductility. Depending on the application, it

Table 1. Mechanical properties of the studied materials (coatings)

Properties	Material – coating		
	TiN	TiCN	TiAlN
Color	gold	blue-grey	purple-grey
Hardness [GPa]	30	37	33
Maximum operating temperature [°C]	600	400	900

displays 4–5 times the tool life, and cooling is required at higher cutting speeds. The titanium aluminium nitride (TiAlN) coating, on the other hand, is also a universal coating, increasing tool life by up to 10 times. It is characterised by high hardness at high temperatures and resistance to oxidation. When machining, high speeds can be used without cooling.

The tribological properties of the selected protective coatings were assessed by model friction-wear tests using an *Anton Paar*^{TRB3} tester, in accordance with ASTM G99. These friction-wear tests for each friction pair were repeated three times. A *ball-on-disc* friction node (ø6 mm ball made of 100 Cr6 steel, discs made of SW7M steel coated with TiN, TiCN, TiAlN) was subjected to a constant load (10N), under coolant lubrication – Figure 1.

Friction-wear test parameters during the rotational motion of a *ball-on-disc* friction pair:

- load P = 10 N,
- slip velocity v = 0.1 m/s,
- friction path s = 1000 m,
- ambient temperature T_o = 23±1 °C
- lubricant – SwissCool 3000 coolant (contains mineral oil, liquid for machining metals, steel and cast alloys, as well as common aluminium alloys).

Investigations of the surface topography of the manufactured and operated surface (including

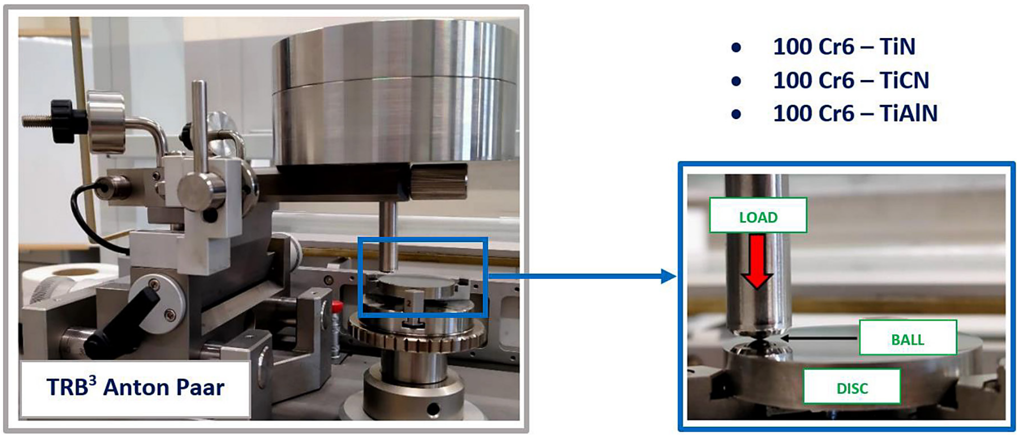


Fig. 1. Friction stand and friction pairs – tribological study type *ball-on-disc*

Fig. 2. Surface topography stand – Leica DCM8 (lens 20x)

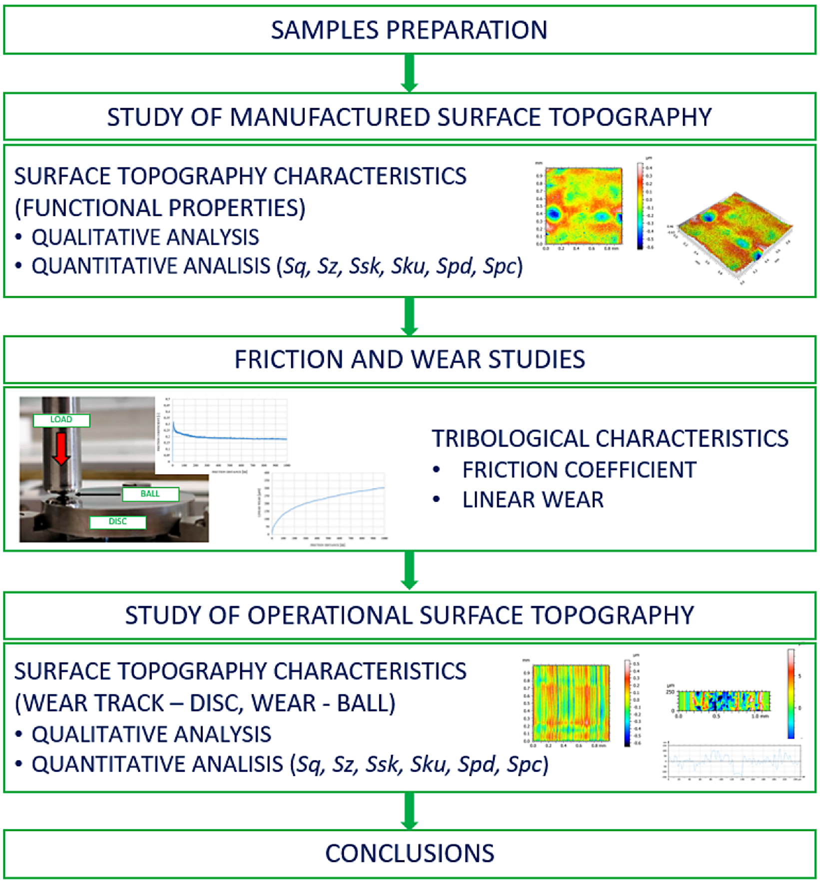


Fig. 3. Research programme

wear mechanism and wear tracks) were carried out using a DCM8 confocal microscope manufactured by Leica – Figure 2.

For the purpose of assessing the degree of wear of the investigated coatings, the surface topography formed during the technological process (samples made of SW7M steel coated with TiN, TiCN and TiAlN) was compared with the surface topography modified in the operation process of using these surfaces (after friction-wear tests were completed). The research programme is shown in Figure 3.

3D (surface topography – parameters *Sq*, *Sz*, *Ssk*, *Sku*, *Spd*, *Spc*) and 2D (surface profile – width and depth of the wear track) analysis was used to describe the surface shape. A similar type of analysis, albeit for a different research object, was used by Niesłony et al. [16], where the *Sq*, *Sz*, *Ssk*, *Sku* parameters were used to characterise tool surfaces and 3D surface morphology and 2D profile analysis was used to characterise machining marks on the workpiece surface. Whereas, on the other hand, Zagórski and Korpysa [17] used 2D and 3D parameter analysis in their study, which was the basis on which they characterised machined surfaces, assessing the quality of their manufacture resulting from the technological process and tool selection, and influencing the functional properties of the machined surfaces [1, 2, 15].

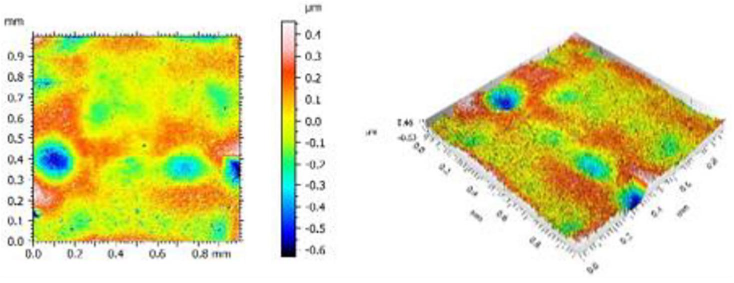
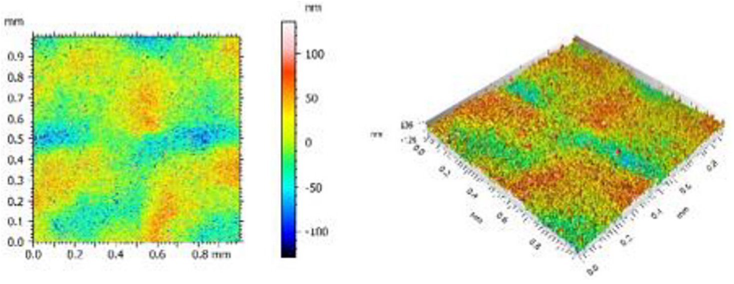
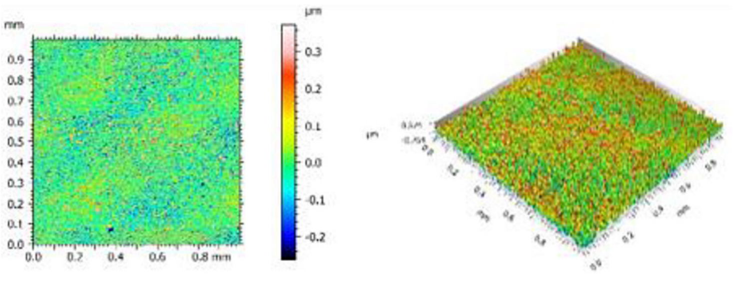
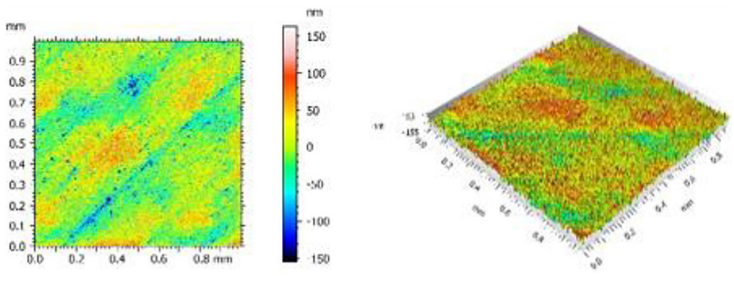
The current work uses fabricated surfaces subject to analysis for their potential functional properties, which were later verified by analysing the surfaces subject to wear and tear. The worn surfaces (discs and balls) all displayed a wear track, which was subject to analysis. Specialist metrology software Mountains Map v.9 was used to analyse the surface topography and wear tracks.

RESULTS AND DISCUSSION

The results of the surface topography of the manufactured and operated parts are presented in the form of tables – Tables 2 and 4. Considering the fact that the results are repeatable, representative results are presented in this work.

The surface finish of the balls was characterised by the roughness described by the parameters

Table 2. Characteristics of manufactured surface topography (ball and discs)

Material	Surface topography		
100 Cr6 (ball)		*Sq* [µm]	0.149
		Sz [µm]	1.09
		Ssk [µm]	-0.504
		Sku [µm]	4.26
		Spd [1/mm^2]	8065
		Spc [1/mm]	92.1
TiN (disc)		*Sq* [µm]	0.039
		Sz [µm]	0.265
		Ssk [µm]	0.104
		Sku [µm]	3.38
		Spd [1/mm^2]	14741
		Spc [1/mm]	42.3
TiCN (disc)		*Sq* [µm]	0.103
		Sz [µm]	0.638
		Ssk [µm]	0.795
		Sku [µm]	4.15
		Spd [1/mm^2]	12975
		Spc [1/mm]	102
TiAlN (disc)		*Sq* [µm]	0.044
		Sz [µm]	0.318
		Ssk [µm]	0.086
		Sku [µm]	3.90
		Spd [1/mm^2]	13840
		Spc [1/mm]	44.0

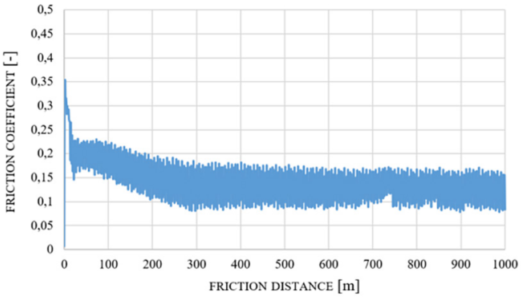
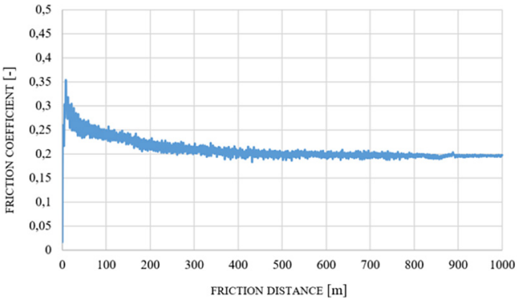
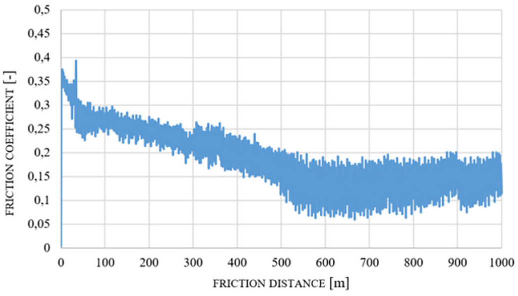
Sq and *Sz*, whose values were 0.15 µm and 1.1 µm, respectively. The surface of the balls in relation to the surface of the discs was characterised by a flat surface (negative value of *Ssk*) with unevenly distributed surface features – local depressions and hills (*Sku* > 3). The density of *Spd* elevation distribution was significantly lower for the ball surface, which was evidenced by a smaller bearing surface (fewer points of contact with another surface). The curvature of the hill tops denoted with the *Spc* parameter was comparable for TiCN-coated balls and discs, while the value of this parameter was more than twice as low for TiN- and TiAlN-coated discs, indicating a larger radius of roundness of the hill tops on these surfaces. In spite of using the same coating process, the SW7M steel discs coated with TiN, TiCN and TiAlN differed in the nature of the surface shape. In the case of TiCN discs, the surface roughness denoted by the *Sq* and *Sz* parameters was twice as high compared to TiN and TiAlN discs. The *Ssk* parameter was comparable for TiN and TiCN discs, while in the case of TiAlN, the value was ten times lower, pointing towards the flatter nature of this surface (greater susceptibility to wear, and less impact on the destruction of the co-operating surface). The parameter *Sku* denoting the nature of the distribution of features (local protrusions/depressions) on the surface showed a similarity for TiCN and TiAlN discs (*Sku* at approximately 4), which is also confirmed by surface maps and axonometric images. However, in the case of the TiN disc (*Sku* = 3.38), a more even distribution of features was observed. The density of distribution of *Spd* elevations on the disc surface was significantly elevated (above 12,000.00 1/mm^2), with the highest value recorded for the TiN disc (which may have been indicative of the greater bearing surface area of this coating). The highest value of the *Spc* parameter, showing the curvature of the hilltops, was recorded for the TiCN disc (value 2.5 times higher compared to TiN and TiAlN discs), which was indicative of the smaller radius of rounding of the elevations on the surface. This elevation characteristic may have the effect of intensifying the abrasive wear of the co-operating surface (in this case the ball), as the sharp tips of the elevations act as a cutting edge.

Once the testing and analysis of the surface shape of the fabricated components (balls and coated discs) had been completed, friction-wear tests were carried out. The results of these tests are presented in the form of a sample friction coefficient run and average values (based on a series of tests carried out) of friction coefficient and linear wear – see Table 3.

The tribological characteristics presented herein show that after the co-operating components had reached the *ball-on-disc* friction node stage (approximately 100 m), the most stable friction coefficient was recorded for the TiCN-coated disc. A similar result, albeit less stable, was recorded for the TiN-coated discs. In the case of the TiAlN-coated disc, the first phase of stabilisation of the friction coefficient course (after 100 m) was followed by a sharp drop in the friction coefficient and stabilisation again (after 500 m). This can probably be explained by the breakage of the coating layer and the ball working with the surface of the uncoated disc.

Comparison of the friction coefficients obtained for the tested coatings with the results obtained by other research teams (conducted under

Table 3. Tribological characteristics for studies friction pairs

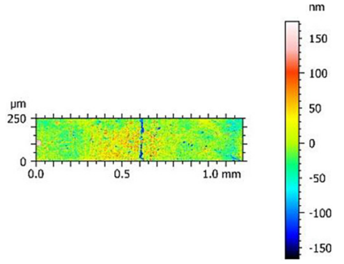
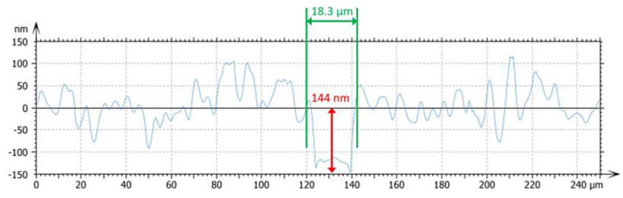
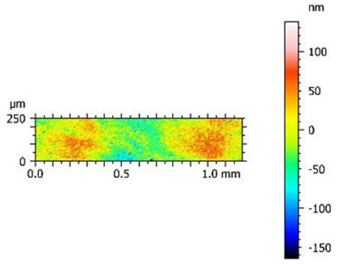
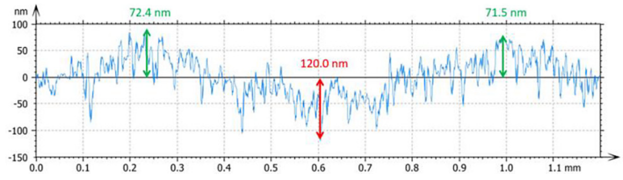
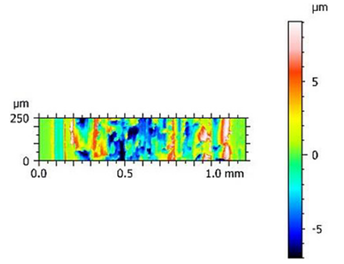
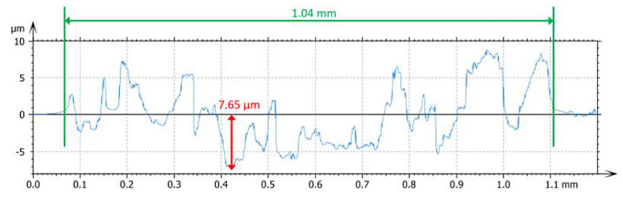
Friction pair	Friction coefficient and linear wear		
100 Cr6-TiN		*μ* [-]	0.144 ± 0.0028
		L_w [μm]	175.32 ± 4.945
100 Cr6-TiCN		*μ* [-]	0.199 ± 0.0081
		L_w [μm]	251.50 ± 18.838
100 Cr6-TiAlN		*μ* [-]	0.183 ± 0.0060
		L_w [μm]	281.10 ± 26.935

similar conditions) indicates some differences. For the TiN coating tested in polyalphaolefin (PAO8) synthetic oil with added MoS_2 nanotubes [18], the friction coefficient is comparable and amounts to 0.08–0.12, while tests using water as a medium [19] showed a much higher result, amounting to 0.6–1.3. This means that in the case of a TiN coating, the type of medium used is important; in the presented research it allowed the friction coefficient to be reduced to an average of 0.144 (Table 3). For the TiCN coating tested in mineral oil cutting fluid as well as non-toxic cutting fluid (alkanolamine borate with a zinc aspartate and demineralised water) [20], in both cases the friction coefficient was at the level of 0.11, while the tests conducted using water [19] showed a friction coefficient in the range of 0.3–1.4. That results, as in the case of the TiN coating, confirm the need to use a medium (as cutting fluid, lubricant) other than water. In the presented research, the friction coefficient was on average 0.199 (Table 3), so the medium used reduced its value, although it was twice as high as in the case of the use of non-toxic cutting fluid. For the TiAlN coating tested using polyalphaolefin (PAO8) synthetic oil with added MoS_2 nanotubes [18], the friction coefficient was 0.13–0.14, and for tests conducted in biodegradable cutting fluid containing an alkanolamine borate with a zinc aspartate and demineralised water [21] – the average value of 0.46 was obtained. The almost three times higher value of the friction coefficient compared to the presented results for TiAlN may result not only from the use of a different medium, but also from the five times higher load. Moreover, in the works [20, 21], the tests were carried out using a steel ball with a radius of 10 mm, and not 6 mm as in this work. Therefore, the unit pressure in the friction contact for the friction node using a ball with a diameter of 6 mm was definitely higher than for a ball with a diameter of 10 mm and amounted to 1,011 MPa and 1,421 MPa, respectively (almost 30% difference).

The analysis of the wear level allows to reach a conclusion that the nature of the friction coefficient run influenced the value of the average linear wear, which was highest for the TiAlN-coated disc (281.1 µm) compared to the other tested coatings. The lowest average linear wear, as well as the lowest friction coefficient, was recorded for the TiN-coated disc.

After the tribological tests had concluded, surface topography measurements were carried

Table 4. Characteristics of operated (worn) surface topography (discs) with wear tracks

Disc	Worn surface topography	
TiN		
TiCN		
TiAlN		

out in order to assess the nature and degree of wear of the coatings on the surfaces of the discs and balls: for the discs – surface map and scuff mark profile (evaluation of the depth and width of the wear track); for the balls – surface shape within the scuff mark (evaluation of the quality of the worn surface in relation to the manufactured surface).

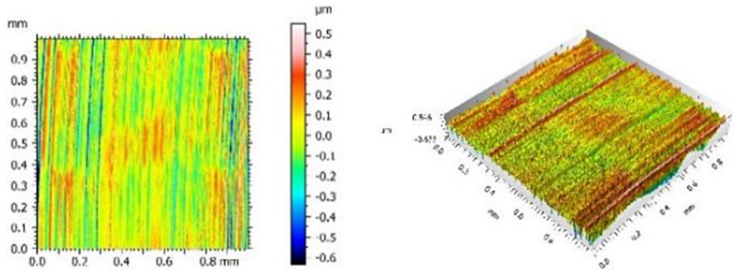
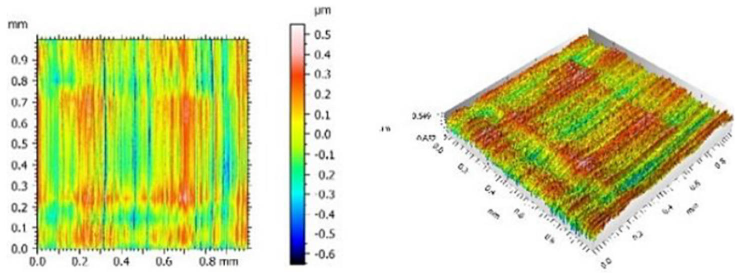
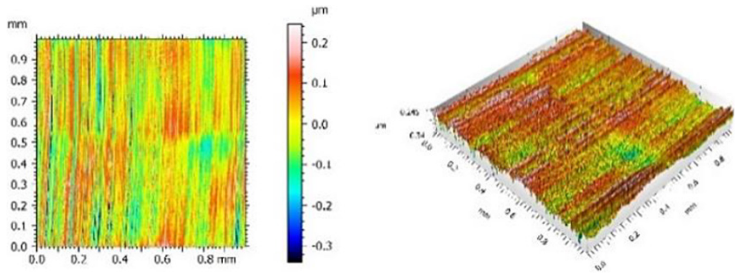
The surface characteristics of the co-operating elements in the friction nodes studied are summarised in the Tables 4 (discs) and 5 (balls).

When analysing the surface maps of the discs subject to wear, significant differences were noted due to the surface shape of the process, the characteristics of which are stated above. The largest wear track was recorded for the TiAlN-coated disc, which was more than 1 mm wide and more than 7 µm deep which, considering the coating thickness (4.0 µm), indicates abrasion of this coating (this is also confirmed by the tribological characteristics – see Table 3). The smallest wear track was obtained for the TiN-coated disc of the following widths and depths: 18.3 µm and 144 nm, and therefore cause the tearing off (the coating thickness was the smallest at 3 µm). In the case of the TiCN-coated disc, in spite of having the highest friction coefficient, there were no clean wear track. It should be noted that the TiCN-coated disc was characterised by the highest surface roughness and the lowest curvature of the tops of the protrusions, and thus it is likely that it had a positive effect on no wear of this coating, as well as the shape of the surface of the ball cooperating with the TiCN disc. In spite of the finding, an accumulation of material was noted on the surface in the form of localised hills around 72 nm high and slightly larger depressions – approximately 120 nm, each with a width of approximately 0.3 mm.

As a result of tribological testing, the surfaces topography of the balls were modified. Since the study focused on the disc as a tool and the balls were treated as a workpiece, the analysis was carried out inside the wear track on the surface of the balls, which would reflect the quality of the machined surface.

Considering the characteristics of the ball surface topography (Table 2), the best quality of the surface used was obtained for the ball cooperating with the TiAlN disc – roughness parameters

Table 5. Characteristics of operated (worn) surface topography (balls)

Ball	Worn surface topography		
100 Cr6 (TiN)		*Sq* [µm]	0.153
		Sz [µm]	1.18
		Ssk [µm]	-0.466
		Sku [µm]	4.11
		Spd [1/mm^2]	4578
		Spc [1/mm]	77.5
100 Cr6 (TiCN)		*Sq* [µm]	0.170
		Sz [µm]	1.20
		Ssk [µm]	-0.307
		Sku [µm]	3.18
		Spd [1/mm^2]	4686
		Spc [1/mm]	103.0
100 Cr6 (TiAlN)		*Sq* [µm]	0.088
		Sz [µm]	0.585
		Ssk [µm]	-0.337
		Sku [µm]	3.39
		Spd [1/mm^2]	6827
		Spc [1/mm]	57.4

such as *Sq*, *Sz* reduced their value twofold. In the case of the remaining TiN-coated and TiCN-coated discs, the values of these parameters increased, indicating a deterioration in surface quality. The visual comparison of the surface maps displayed a significant ordering of features on the surface of the bead co-operating with the TiAlN disc, as well as a uniform distribution of scratch marks (parallel vertical lines). In the case of the other balls (working with TiN and TiCN discs), the distribution of features was uneven. The density of the distribution of *Spd* elevations on the surface of the ball decreased, being highest for the balls in the friction nodes tested (for the balls cooperating with TiN and TiCN disks, the *Spd* value increased nearly twofold). The curvature of the *Spc* protrusions decreased significantly, indicating an increase in the roundness of the highest points of the protrusions on the surface of the ball co-operating with the TiAlN disc. In the case of other friction nodes, the *Spc* value for the ball co-operating with the TiN disc decreased, while it increased for the ball co-operating with the TiCN disc.

CONCLUSIONS

An analysis of the results of surface topography and model tribological studies did not conclusively show which of the anti-wear coatings applied to cutting tools performs its role best – counteracting and/or minimising the wear of the tool (the disc) and ensuring the quality of the machined surface (the ball).

In spite of that, the following sub-conclusions are hereby laid down to guide future research and analysis:

1. The shape of the surfaces produced, in spite of using the same coating technology (PVD), displayed differences in surface roughness. During the qualitative analysis (surface map and an axonometric image), the greatest variation in surface shape was obtained for the TiAlN-coated disc, while in the quantitative analysis (roughness parameters), the greatest roughness was obtained for the TiCN-coated disc.
2. Tribological tests showed that the most stable friction coefficient behaviour was found for the 100 Cr6-TiCN friction pair, i.e. for the TiCN-coated disc. In contrast, the most scattered tracing was displayed by the 100 Cr6-TiAlN friction pair; in this case, the coating was abraded after 500 m of friction distance.
3. As a result of the tribological tests, shaping of the operating surface with a wear track. The largest wear track was observed on the surface of the TiAlN-coated disc, both in terms of size (width and depth) and surface shape within the wear track.
4. The observation of the balls that cooperated with the selected coatings showed that the best quality was obtained for the ball cooperating with the TiAlN-coated disc (as shown under qualitative and quantitative analysis alike).

The research carried out indicates the need to continue this, with modifications to the friction conditions, with a particular focus on increasing the friction path as well as the load on the friction junction. During the next step, simulation studies should also be carried out for the purpose of verifying results obtained in the model studies.

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