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The Impact of a Movement Type on Tribological Properties of AlTiN Coating Deposited on HS6-5-2C Steel

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ABSTRACT

This paper investigates the effect of the type of movement on the tribological properties of an AlTiN coating applied to a disc made of HS6-5-2C steel. Tribological tests were carried out with a tribometer operating on a ball-disc friction apparatus moving in to-and-from as well as in rotary motion. The tests were carried out under technically dry friction conditions, subject to the application of a cutting fluid used during machining in grinding, turning, milling, drilling and cutting processes. A scanning microscope was used to observe the morphology of the surface, the morphology of the AlTiN coating, and to determine its chemical composition and assess wear mechanisms. The topography of the surface was analysed before and after carrying out the friction and wear tests using a confocal microscope with interferometric mode. The results of the provided tests indicate that the cutting fluid used in the tests reduced the coefficient of friction in both rotary and the sliding – reciprocating motion about 75% and 65% respectively. It has also contributed to a reduction in linear wear in the sliding – reciprocating motion about 22%. In case of rotary motion, higher values of linear wear about 40% were recorded, due to wear of the counterspecimen.

Keywords: AlTiN coating, wear, friction, cutting fuild, sliding – reciprocating motion, rotational motion.

INTRODUCTION

The growth in the knowledge and technology give rise the need to produce new types of materials with improved performance properties. Considering the ever-increasing needs of industrial practice, classic materials are being replaced by newer ones. Technologies which increase the service life of products under various tribological, fatigue and corrosion stresses are commonly referred to as anti-wear technologies. They are used in every branch of modern industry. However, conventional technologies are insufficient to meet the requirements of such uses. Surface engineering techniques play a significant role in this process, aiming mainly to produce surface layers with the properties desired for a specific technical application. The currently used unconventional technologies include chemical and electrochemical deposition, [1] electro-discharge and laser machining [2, 3], increasingly widespread 3D printing [4, 5] and modern physical and chemical vapour deposition coating methods (PVD, CVD) [6]. The combination of the advanced surface coating techniques allows for a large range of modifications and customisations of the mechanical and chemical properties of the surface layer of materials, affecting tribological properties in a variety of industrial applications, including machining [7].

Increasing demands are now being placed on cutting tools to improve their performance properties, such as impact strength, hardness and wear resistance, as workpieces are made from increasingly hard materials [8, 9]. One solutions includes the application of thin, hard coatings onto cutting tools through PVD physical vapour deposition techniques [8]. Coating technologies not only improve the production efficiency and the service life of cutting tools, but also reduce the total cost of manufacturing the final product. Currently, among the coatings obtained by PVD processes, titanium-based coatings with carbides, nitrides and carbide-nitrides seem particularly interesting to researchers. Traditional TiN coatings do not perform well when cutting hard-to-machine materials due to their brittleness, poor adhesion and the lack of resistance to oxidation at high temperatures. The addition of Al atoms to the TiN coating produces an AlTiN coating with superior mechanical properties, greater chemical stability and oxidation resistance compared to TiC, TiN and TiCN coatings [11–13]. AlTiN coatings belong to the group of protective coatings used in difficult operating conditions due to their: high hardness, [13] low coefficient of friction and resistance to abrasion [11, 13, 14], corrosion resistance and chemical inertness [13]. When the friction pair acts together, both in model tests and during machining, they form a surface layer consisting of Alumina, Al_2O_3, which provides high oxidation resistance and thermal stability at temperatures even above 800 °C [11, 15].

Today, AlTiN is one of the most commonly used coating for cutting tools. The coating process parameters can significantly affect the properties of the tools. AlTiN coatings can be deposited using a variety of physical vapour phase PVD deposition techniques by: cathodic arc deposition [16] magnetron sputtering [16, 17] and hybrid vapour deposition/arc sputtering. The cathodic arc deposition method is characterised by high ionisation rates, deposition efficiency and can be used in the industrial production of coatings for cutting tools [9]. Coatings applied using this method are characterised by high density and good adhesion, but defects in the form of inclusions and voids reduce the corrosion resistance of these coatings [13].

In the friction node, which also includes the cutting tool – workpiece combination, in addition to the materials of which they are made, the coolant plays an equally important role. Various types of coolants are used to increase the service life of cutting tools and improve the quality of the workpiece during machining. Considering the environmental aspects and production costs, dry processing may, in some cases, be the optimal solution. The authors [18] investigated the cutting performance of AlTiN-coated end mill tools with two different application methods: conventional arc and splitting arc. They carried out the research during dry milling of hardened steel. The results of testing and analysis indicated that the coating applied by the splitting arc method had lower surface roughness and fewer structural defects. In addition, the coating had greater hardness, a lower coefficient of friction and better wear resistance compared to the coating produced by conventional arc. Tooptong et al. [19] conducted turning tests without using cooling agents. They used uncoated cemented carbide and film-coated cemented carbide for the study: Ti (C, N), Al_2O_3 (outer coating) with an additional, thin (1–2 μm) TiN coating on the application surface only. They observed significantly lower wear on the contact surface of the multi-coated carbide tool compared to the uncoated carbide tool. Siow et. al [20] investigated the effect of the carbon content and composition of coatings on their adhesion to tungsten carbide substrates. They then compared cutting tools for dry turning stainless steel. Of the coatings analysed, TiCN coating, TiC coating and TiN coating had the highest adhesion to the substrate, respectively. The adhesion of the TiCN coating was found to increase with carbon content. The C/N ratio or C-N bond had a decisive influence on the adhesion of the coating. Abrasive wear predominated during rolling. Not only did the coating delaminate, but it also caused accelerated tool wear. The improved adhesion of the coating promoted a longer operational life for the tool.

Szala et al. [21] examined AlTiN and TiAlN coatings for cavitation erosion and sliding wear. The results of their research indicated that AlTiN and TiAlN coatings were brittle and cracked and detached as a result of fatigue processes. In turn, from tribological tests at low loads of 0.8 N, they observed slight wear of the coating in the form of grooves, micro-scratches, micro-ploughing and rubbing of the tops of the columnar rings.

Walczak et al. [22] compared the Ti6Al4V alloy with nitrogen coatings deposited using the PVD method. They produced test samples from the Ti6Al4V alloy using two different techniques, conventional manufacturing from wrought material (in the annealed state) and direct metal laser sintering. PVD coatings: AlTiN and TiAlN were deposited by magnetron sputtering and then examined their mechanical and tribological properties. The test results showed that the coatings applied to the substrate for direct metal laser sintering were characterized by much higher adhesive properties, which was mainly due to a better adjustment of the Ecoating/Esubstrate ratio and higher compressive stresses. All coatings applied to the direct metal laser sintering substrate had almost 25% higher critical load (scratch test) than the same coatings applied to the conventionally manufactured substrate. This study investigates, AlTiN coatings applied by the arc method. The results of tribological tests carried out in back and forth, as well as rotary motions under technically dry friction conditions and with coolant used in machining were compared with one another. The new in this article is the performance of tribological tests for the AlTiN coating under lubrication conditions with Quakercool 3618 HBFF coolant, where the counter sample was 100Cr6 steel.

MATERIALS AND METHODS

Research materials

Discs made of HS6-5-2C with applied AlTiN coating were used for the tribological tests. HS6-5-2C steel is characterised by exceptional ductility, impact strength and abrasion resistance, and has a hardness of 65 HRC after quenching and tempering at 550 °C [23]. Table 1 presents the chemical composition of HS6-5-2C steel [24].

The 6 mm diameter balls used for tribological testing were manufactured from 100Cr6 steel; its chemical composition is summarised in Table 2 [25]. It is a high-carbon steel used for rolling components: balls, rollers, runners. It is characterised by very good resistance to wear and fatigue and stability at high temperatures [26, 27].

The selection of the AlTiN coating was based on their exceptionally good tribological properties (low coefficient of friction and wear), high hardness and resistance to oxidation. It was applied using a physical vapour deposition PVD processes (an arc-coating process) at a temperature below 500 °C. According to the manufacturer, it has a grey colour (*Oerlikon Balzers*), while the hardness of the AlTiN coating is 35 ± 3 GPa and the operating temperature is 1000 °C [28].

Wetting angle

The wetting angle was measured using tensiometer. Before test the disc was cleaned in ultrasound washer machine. The wetting angle was measured for the coolant which was used in tribological test and this wetting angle also was measured for the distilled water. Five repetitions were made and the given result is the average of these repetitions.

Tribological tests

Tribological tests were performed under technically dry friction TDF conditions and with an application of a lubricant in the form of Quakercool 3618 HBFF cooling agent. It is a cooling agent used for machining and grinding, turning, milling, drilling, indenting and thread cutting, as well as cutting. It is used for cast iron, steel, alloy steel, aluminium alloys and for titanium. It consists of a mixture of mineral oil, water, salt and functional additives [29, 30]. Table 3 shows selected physical and chemical properties of the cutting fluid used in the tests. The friction and tear tests were performed on a TRB^3 tribometer operating in a ball-disk system in a back and forth as well as frictional motion. The tests were performed in line with the parameters as summarised in Table 4. The tribological tests carried out made it possible to record changes in the coefficient of friction and linear wear as a function of the sliding distance. Tribological tests were performed based on the ASTM G99 standard.

Table 3. Physical and chemical properties of the cutting fluid [29, 30]

Properties	Value
Colour/appearance	Light amber/clear
Smell	Mild, characteristic
Corrosion threshold	4.5%, wg DIN 51360T2
pH	9,8
Boiling point	100˚C
Relative density, at 15˚C	1,001 g/cm^3
Solubility in water	Forms an emulsion
Viscosity, at 40˚C	Forms an emulsion

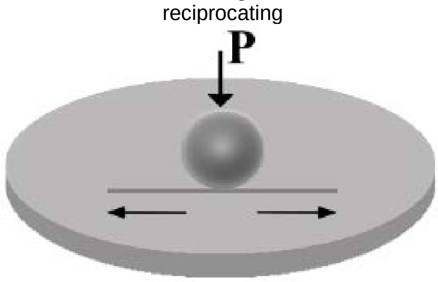
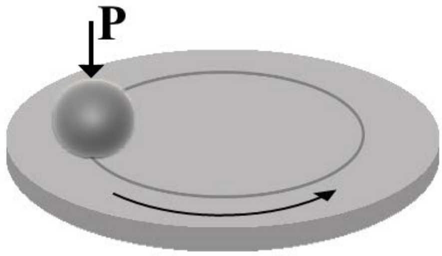
Table 1. Composition of HS6-5-2C steel [24]

Element	C	Mn	Si	P	S	Cr	Ni	Mo	W	V	Co	Cu
%	0.82÷0.92	≥ 0.4	≥ 0.5	≥ 0.03	≥ 0.03	3.50÷4.0	≥ 0.4	4.5÷5.5	6÷7	1.7÷2.1	≥ 0.5	≥ 0.3

Table 2. Composition of 100Cr6 steel [26, 27]

Element	C	Mn	Si	P	S	Cr	Cu
%	0.93÷1.05	0.25÷0.45	0.15 ÷ 0.35	< 0.025	< 0.03	1.35÷1.60	< 0.30

Table 4. The parameters of tribological tests

Parameters of the tribological tests	Type of movement	
	Sliding - reciprocating 	Rotational 
Load	10 N	
Linear speed	v = 0.1 m/s	
Frequency	2.65 Hz	1 Hz
Sliding distance	s = 1000 m	
Amplitude/radius	6 mm	16 mm
Friction pair	Ball made of 100Cr6 steel – disc made of HS6-5-2C steel with AlTiN coating	
Friction conditions	• technically dry friction • friction with lubrication Quakercool cutting fluid	

Surface characteristics

Prior to tribological testing, the surface topography of the samples and counterspecimens was observed through a confocal microscope with Leica DCM8 interferometric mode. On the other hand, wear marks were observed on discs and balls after the friction-wear tests were carried out. In addition, ball wear after tribological tests was calculated using the following formulae (1 and 2):

$$V_{ball} = \frac{1}{3}\pi h^2(3R - h) \tag{1}$$

$$h = R - \sqrt{R^2 - r^2} \tag{2}$$

where: r – radius of the wear mark, h – height of area used, R – radius of the ball.

The surface morphology of the AlTiN coating was examined and the chemical composition analysed with a Phenom XL scanning electron microscope equipped with an EDS microanalyzer.

RESEARCH RESULTS AND DISCUSSION

Surface characteristics before tribological testing

Figure 1 shows an image of the morphology and chemical composition of the AlTiN coating at two selected points. Droplet-shaped particles were observed in the coating during the application process. The presence of titanium, nitrogen, carbon, aluminium, iron and silicon was identified at point 1. On the other hand, nitrogen, titanium, aluminium, as well as elements from the substrate: carbon, iron and silicon, were determined at point 2. Wetting angle tests were later carried out on the AlTiN-coated surface. Distilled water and the coolant used in the tribological tests were used. Figure 2 shows exemplary views of droplets deposited on the surface of the AlTiN coating and the average values of the wetting angle. In the case of the liquids tested, the wetting angle values with distilled water and the cutting fluid tested were lower than 90°. A lower wetting angle value of about 25% was recorded for the coolant as compared to distilled water. This indicates that the application of a cooling agent provides better surface wetting. This should translate into a reduction in friction coefficient values during tribological testing.

Tribological tests

Tribological tests were performed in the subsequent stage. During their implementation, the waveforms of friction coefficients and linear wear as a function of sliding distance were recorded. The tribological test were repeated and the exemplary graphs are summarised in Figure 3 and Figure 4. The tribological test results show that the lowest friction coefficient value (Fig. 3) was achieved under coolant lubrication in both reciprocating and rotary motion. The highest value was recorded under conditions of technically dry

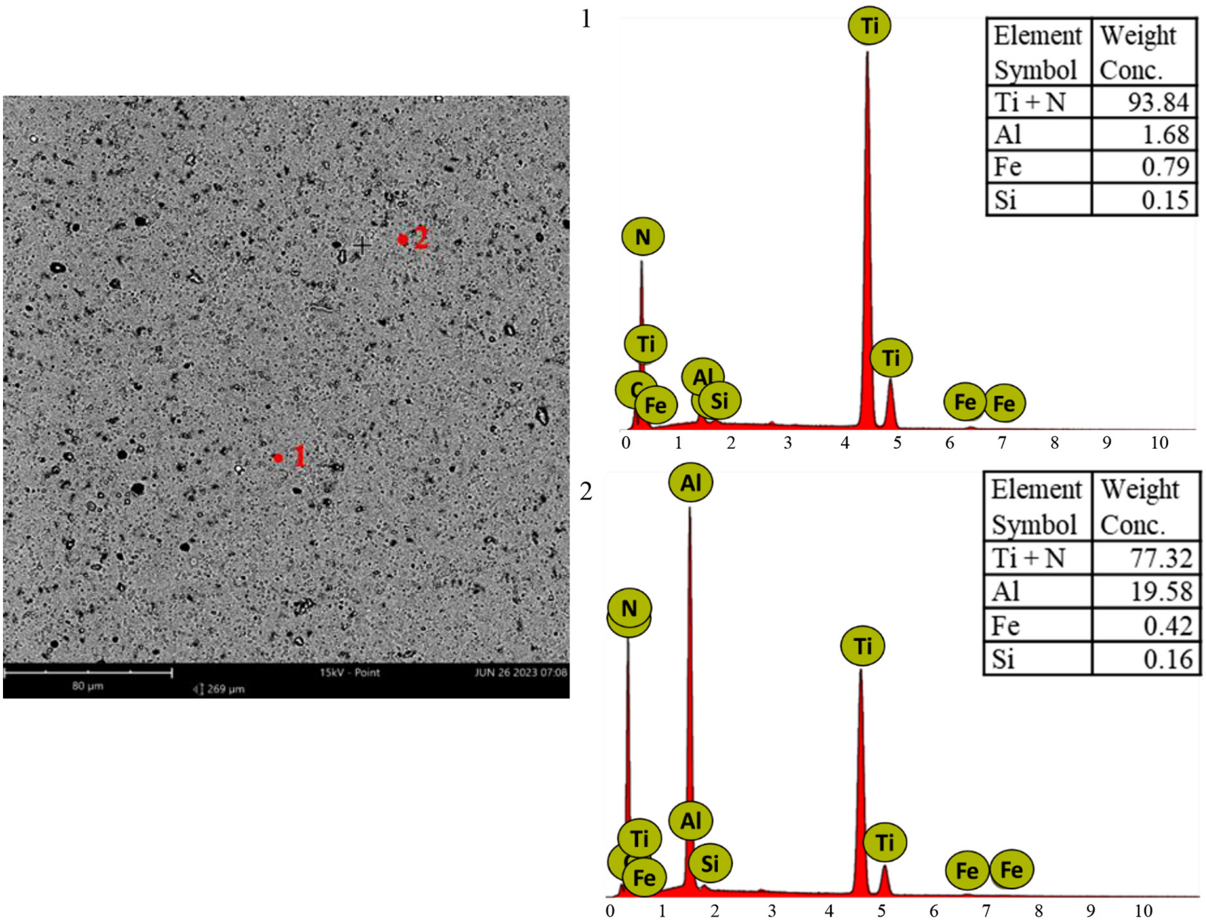


Figure 1. X-ray spectrum of the AlTiN coating

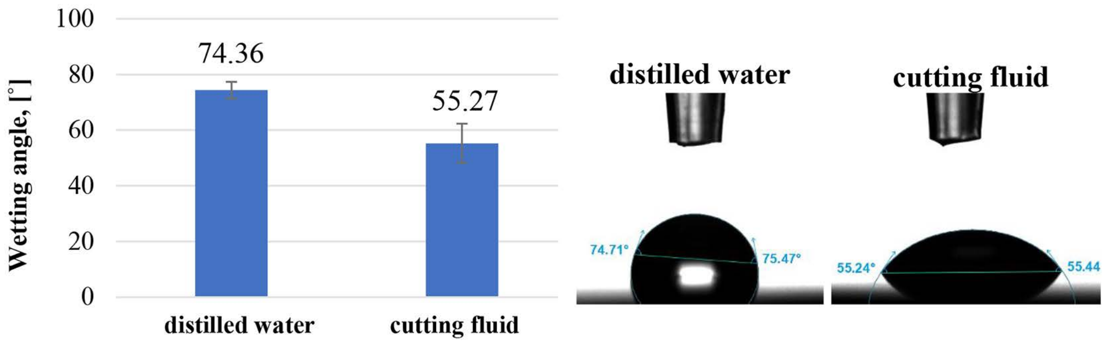


Figure 2. Wetting angles of surfaces with AlTiN coating for distilled water and the cutting fluid

friction in sliding – reciprocating motion. The coolant used in the tests reduced the coefficient of friction by approximately 76% for reciprocating motion and approximately 63% for rotary motion.

The smallest value of linear wear was obtained under frictional conditions with lubrication by the coolant under test in reciprocating motion, and the largest in rotary motion. The recorded linear wear is the total wear of the sample and the counter specimen. In order to determine the amount of wear on the balls and discs, they were subjected to microscopic observations.

Surface characteristics after tribological testing

Using a confocal microscope with interferometric mode, the surfaces of the discs and balls before (Fig. 5) and after tribological testing (Fig. 6 and Fig. 7).

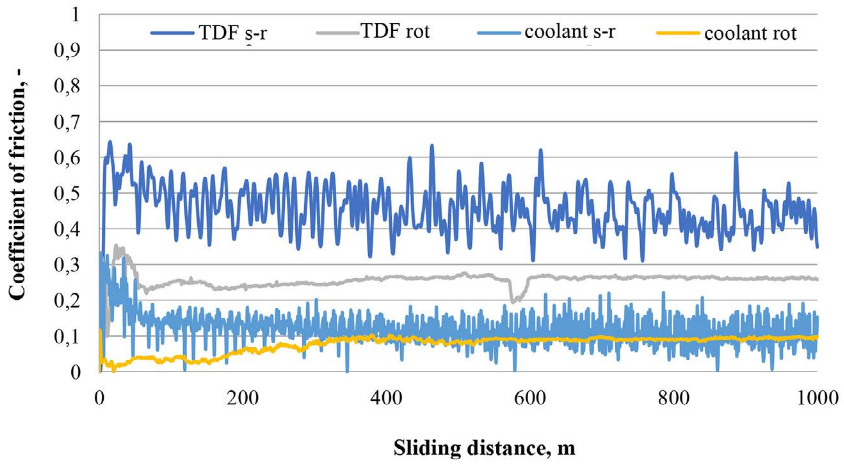


Figure 3. The results of the tribological tests – coefficient of friction

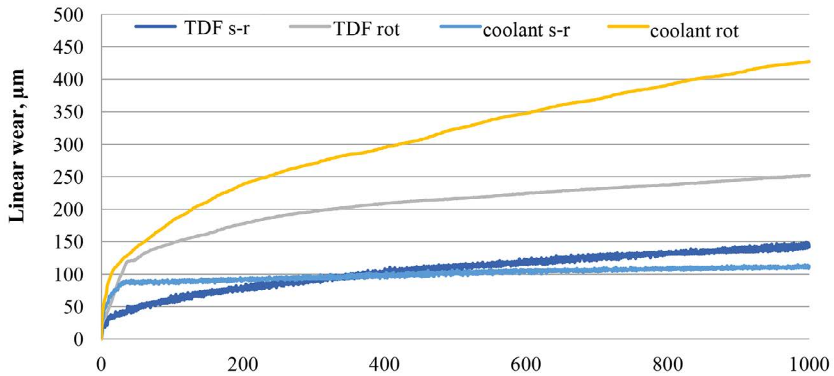


Figure 4. The results of the tribological tests – linear wear

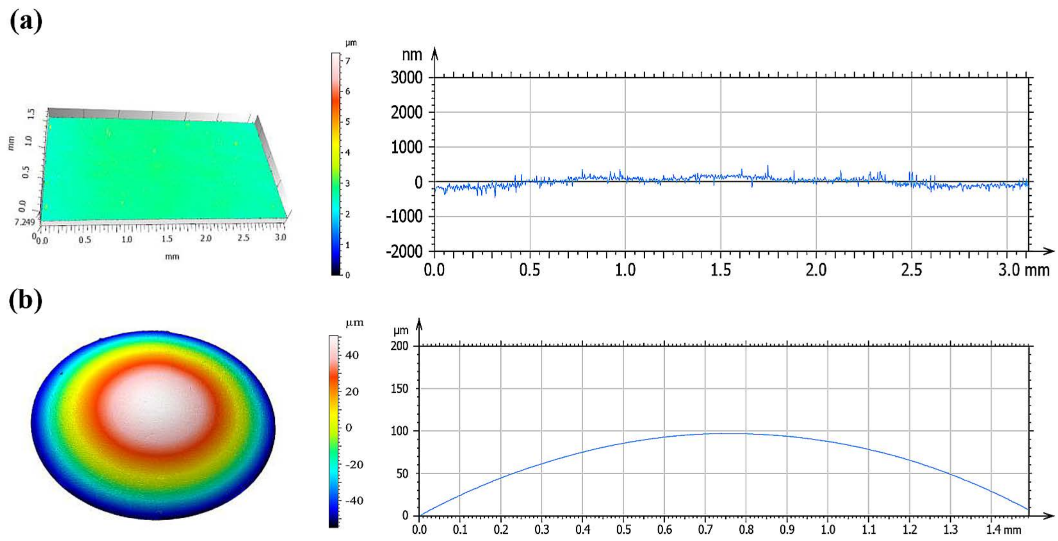


Figure 5. Isometric views and primary profiles before the tribological tests of: (a) the steel disc with AlTiN coating, (b) the steel ball

Comparing the wear of the discs after friction-wear tests under lubrication conditions displayed a lower wear on the disc in rotational motion (rot) compared to sliding – reciprocating motion (s-r). After technically dry friction, the formation of growths on the surface of the discs was noted at the friction trace, which resulted from the transfer of the material of the ball – 100Cr6 steel – to the

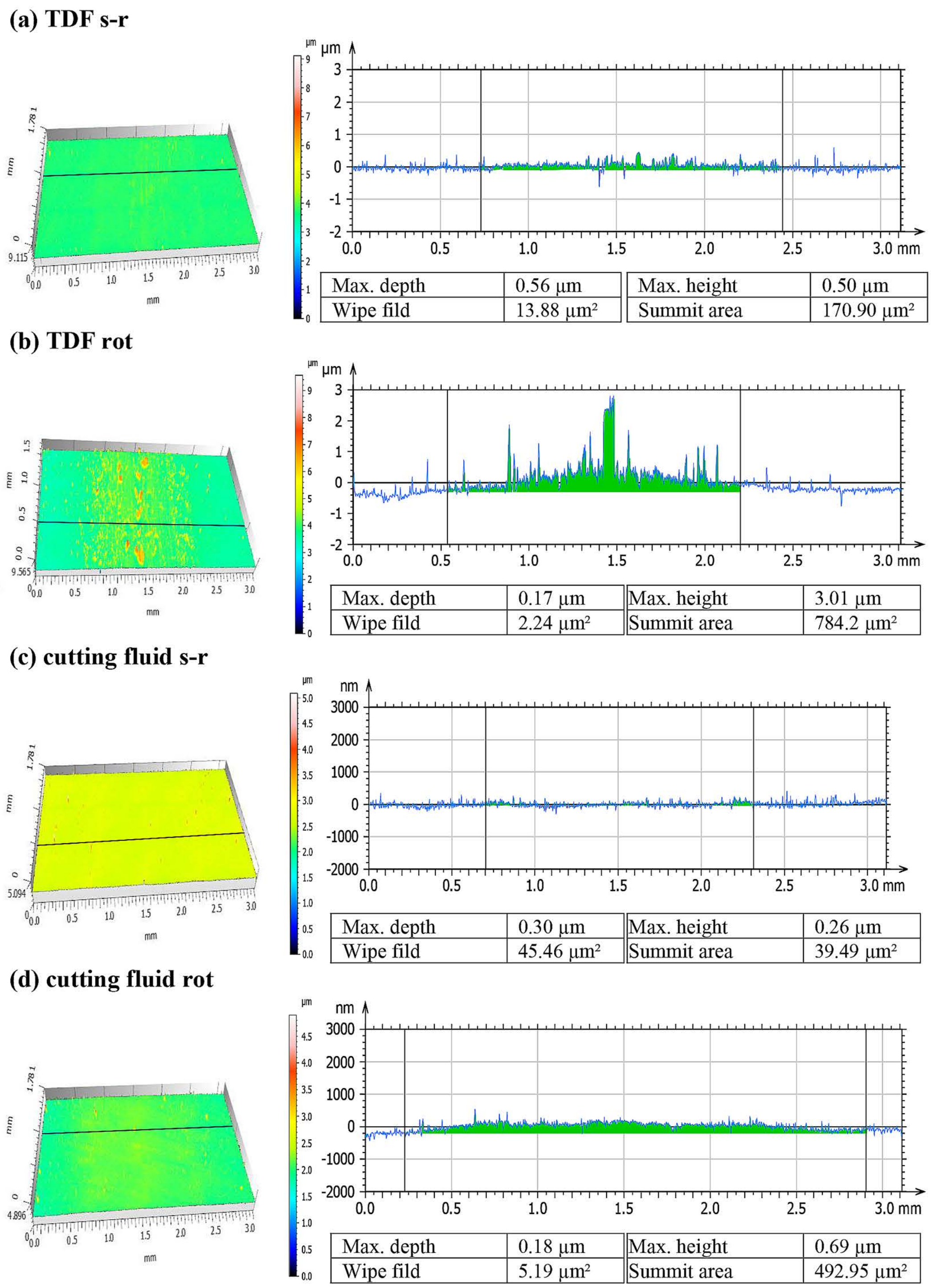


Figure 6. Isometric views and primary profiles of the discs after the tribological tests after lubrication

disc. In order to clarify the wear mechanism, a scanning microscope study was carried out in the next stage of the study. Table 5 shows the counted values of ball wear after tribological tests.

Analysing the radii and heights of the worn balls after the friction tests, it has been discovered that the least worn ball was the one subject to friction with an applied coolant lubrication, moving in sliding - reciprocatingmotion. In contrast, the highest wear was also obtained after friction with coolant lubrication in rotary motion. The surface roughness parameters of the discs and ball before and after the friction tests are summarised in Table 6.

Comparing the roughness parameters of the discs before and after tribological tests subject to lubrication with a coolant in reciprocating and rotary motion, the following reduction in the values

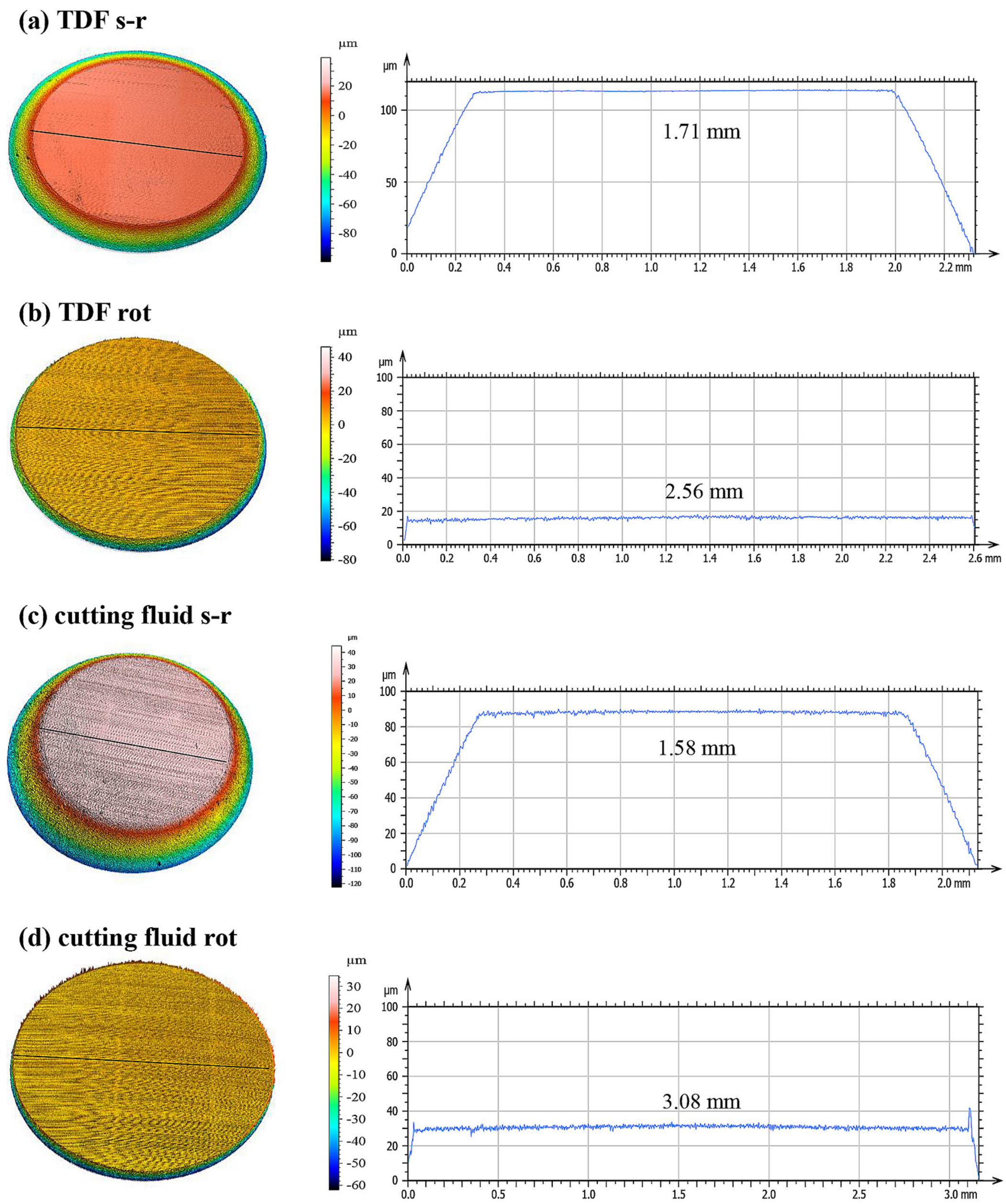


Figure 7. Isometric views and primary profiles of the balls after the tribological tests after lubrication

of the height parameters was observed: Sa – arithmetic mean deviations of surface roughness Sq – mean squared deviation of surface roughness and Sz – maximum surface height exceeding 40%, 28% and 15% respectively. This shows that the surface has been smoothed, i.e., the cooling agent used in the tests has fulfilled its function by producing a machined surface of good quality.

The values of the Ssk parameters – the coefficient of asymmetry (skewness) of the surfaces in the case of the discs after tribological testing – have negative values in almost all cases; this is indicative of the flatness of their surfaces. While the Sku parameter – the clustering coefficient (kurtosis) of the surface for a normal distribution of ordinates Sku = 3. The kurtosis values obtained show that the ordinate distributions for the targets are not close to a normal distribution [31, 32].

Wear marks were also subjected to observations on a scanning microscope along with

Table 5. Wear balls after the tribological tests

Friction conditions	r [mm]	h [mm]	V [mm^3]
TDF s-r	0.86	0.12	0.14
TDF rot	1.28	0.29	0.75
Cutting fluid s-r	0.79	0.11	0.10
Cutting fluid rot	1.54	0.43	1.62

Table 6. Surface texture parameters for the discs and balls before and after the tribological tests

Surface texture parameters	Before test		Past test							
			TDF s-r		TDF rot		Cutting fluid s-r		Cutting fluid rot	
	Disc	Ball	Disc	Ball	Disc	Ball	Disc	Ball	Disc	Ball
Sq [μm]	0.12	0.29	0.10	7.15	0.63	0.69	0.07	12.43	0.07	0.67
Ssk [-]	2.71	0.45	-0.64	0.29	2.61	-0.22	-3.53	0.32	-4.10	-0.29
Sku [-]	122.22	4.47	41.82	2.17	9.50	3.25	117.10	2.17	151.40	3.77
Sp [μm]	2.88	3.03	1.51	18.04	4.41	8.42	1.53	30.32	1.96	3.46
Sv [μm]	2.08	2.16	2.90	12.34	1.51	7.21	2.65	20.72	2.14	3.93
Sz [μm]	4.95	5.19	4.41	30.38	5.92	15.64	4.18	51.04	4.10	7.39
Sa [μm]	0.07	0.22	0.07	6.034	0.38	0.55	0.05	10.45	0.05	0.53

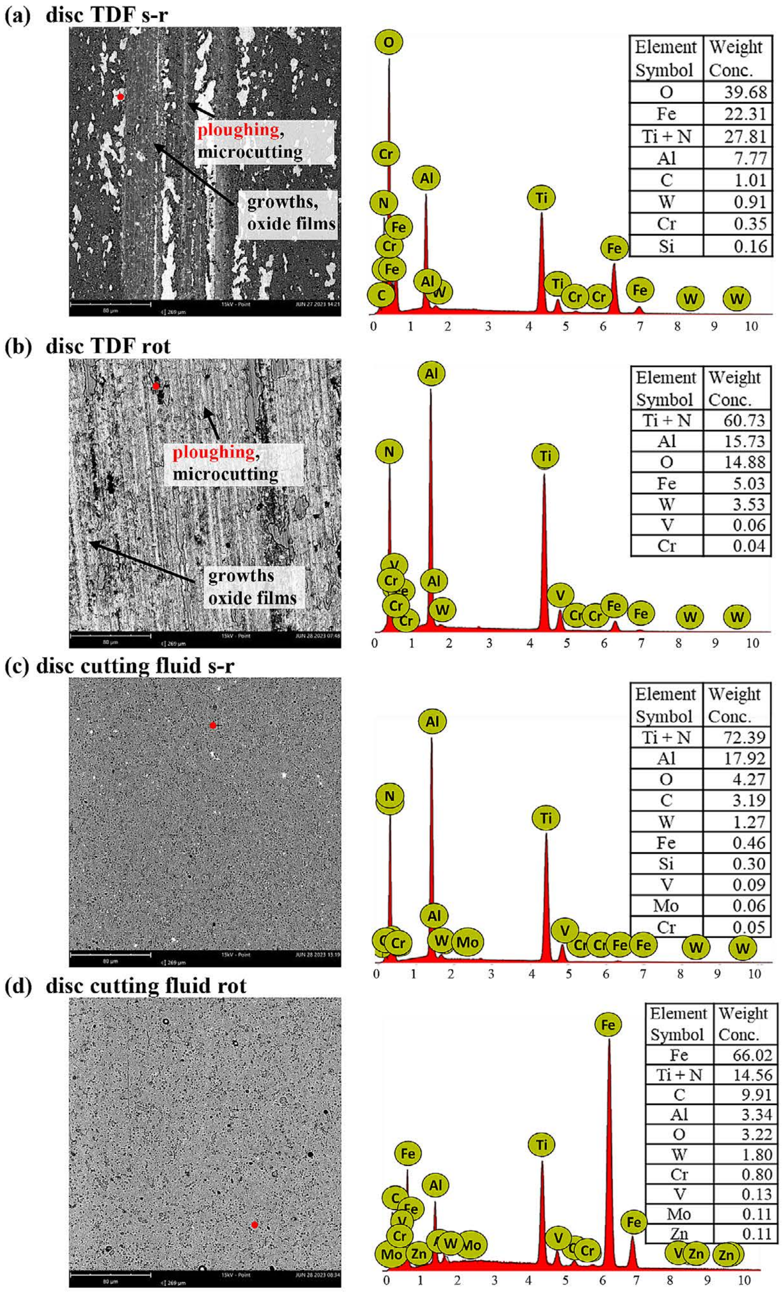


Figure 8. SEM: view of the wear track and characteristic X-ray spectrum of discs with AlTiN coating after tribological tests

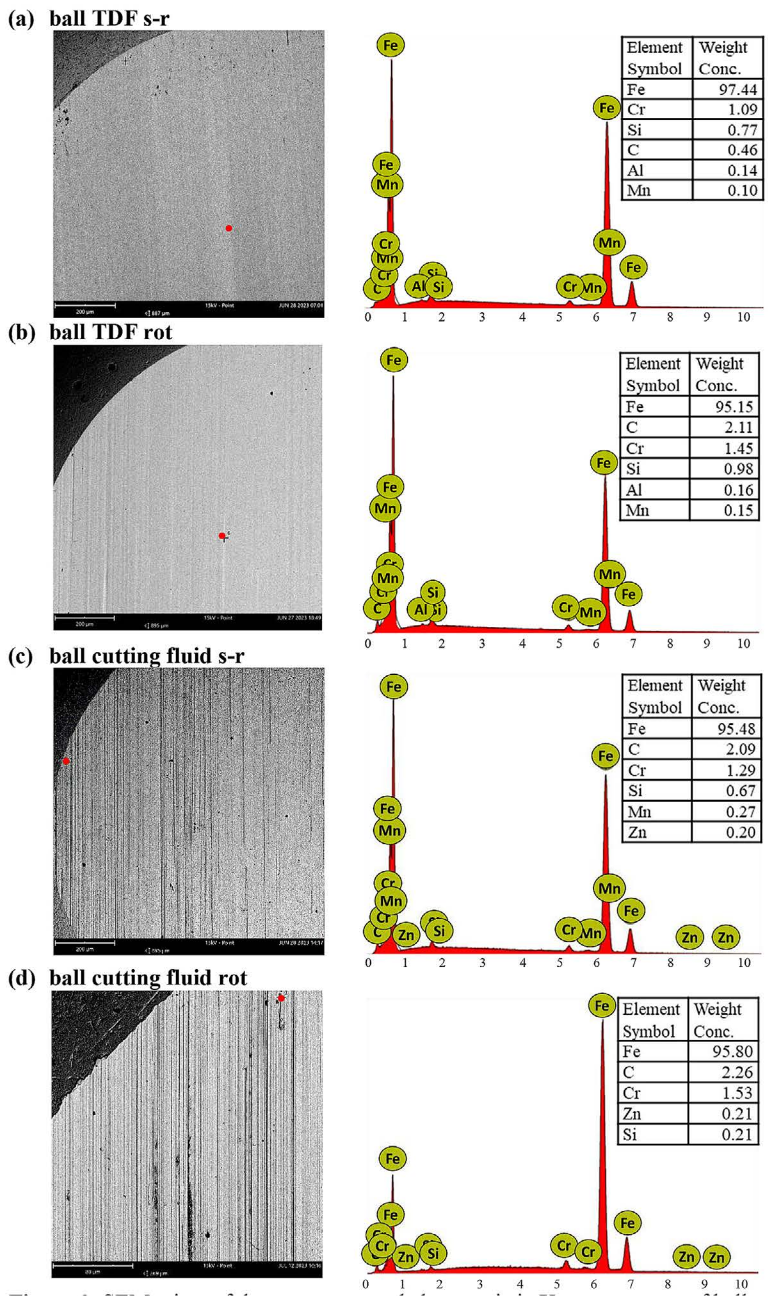


Figure 9. SEM: view of the wear trace and characteristic X-ray spectrum of balls with AlTiN coating after tribological tests

chemical composition analysis. Figure 8 and Figure 9 show images and chemical composition analysis from the wear marks for the discs and bullets respectively. EDS analysis of the wear marks of the discs indicated that a high oxygen content was recorded on the samples after technically dry friction, which may indicate oxidation of the surface layer of the coating consisting of aluminium. The predominant wear mechanism included abrasive wear with ploughing and micro-cutting, while adhesive wear was also observed, as evidenced by the formation of growths and oxide films [33]. Lubrication with the coolant resulted in a reduction in oxidation of the surface layer of the coating by more than 80%. The coolant used in the tests protected the active surfaces from direct contact with air and protected the discs from wear. The presence of coating elements (Ti, Al and N) and from the substrate (Fe, C, Cr, Si) was identified in the areas of abrasion on the discs.

The presence of zinc was designated on the surface of the balls following the friction with lubrication (Figs. 9c and 9d). Zinc come from the coolant and indicate the formation of an anti-wear boundary layer on the surface of the 100Cr6 steel [23]. The zinc only deposited on the steel balls with a more active surface. The elements derived from the coolant have not deposited in the AlTiN-coated wipe marks, indicating its passive nature.

CONCLUSIONS

The following conclusions have been drawn from the research carried out. The smallest value of linear wear was recorded during reciprocating lubrication with coolant. In this case, both the ball and the disc wore out the least, and the wear mark of the smallest diameter was recorded. The highest value of linear wear was observed after friction with coolant lubrication in rotary motion. That was primarily due to the greater wear of the counter sample, as evidenced by both the analysis of the wear marks and the volumetric wear values of the balls. In such case, no wear was observed on the AlTiN-coated sample.

The lubricant used in the study interacted synergistically with the counterspecimens – steel balls. A concentration of zinc atoms was observed on the balls, after friction tests under coolant lubrication, thus indicating the formation of an anti-wear surface layer formed by tribo-chemical reactions on their surface. The coolant used in tribological tests wetted the surfaces better than distilled water, as evidenced by the wetting angle results. During machining operations where rotary motion is used, i.e., machining operations such as: grinding, turning AlTiN coatings can be used on cutting tools to increase their efficiency and service life. The application of the cooling agent contributed to increased wear on the ball, which is desirable when machining, as a steel workpiece should wear faster than an AlTiN-coated cutting tool. After technically dry friction, the disc wore out more in rotation than in reciprocating motion. In addition to plowing, microcutting and growths oxide films, coating peeling was also observed.

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