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# The study of the tribological properties under high contact pressure conditions of TiN, TiC and TiCN coatings deposited by the magnetron sputtering method on the AISI 304 stainless steel substrate

Mamaeva Axaule Alipovna[1], Kenzhegulov Aidar Karaulovich[1], Panichkin Aleksandr Vladimirovich[1], Alibekov Zhasulan Zhanuzakovich[1], Kshibekova Balzhan Bolatovna[1], Wojciech Wieleba[2], Tadeusz Leśniewski[2,*], Nauryzbek Bakhytuly[1]

[1]Institute of Metallurgy and Ore Beneficiation JSC at NJSC "Kazakh National Research Technical University named after K.I. Satbayev", Almaty, Kazakhstan

[2]Department of Fundamentals of Machine Design and Mechatronic Systems, Wrocław University of Science and Technology, Faculty of Mechanical Engineering, Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland

Titanium carbonitride coatings are widely used to improve the wear resistance of surfaces. The results of tribological investigations of TiC, TiN, and TiCN coatings deposited on an AISI 304 steel substrate by the magnetron sputtering method were presented. The research aimed to describe the wear processes of the coatings during friction in an emergency situation, i.e. with a lack of lubrication and concentration of pressure in a small contact area. Tribological tests were performed on a ball-on-disk tribotester in reciprocating motion under technically dry friction conditions. The Hertz pressure in the contact area was ph = 2500-2700 MPa. Additionally, scratch tests and microscopic observations of the surfaces of the samples were performed after tribological tests to describe the wear process of the coatings. The results showed cracking, and coatings detachment from the substrate occur during friction. Deformation wear was observed as bulges in the material at the edge of the friction path. The deformation occurred primarily in the substrate material despite friction occurring on the surface of the coating. The best coating in terms of tribological properties was the TiN coating, which showed the highest resistance to wear in an emergency situation and the friction coefficient in the final stage of the test (above 90 cycles of movement) was only slightly higher than the values recorded for the other coatings. The TiN coating had high hardness, showed good adhesion to the substrate, and was not cracked, protecting it from damage.

Keywords: *magnetron sputtering, titanium carbonitride, coefficient of friction, wear resistance, scratch test*

## 1. Introduction

The titanium carbonitride (TiCN) coating is widely used to improve the wear resistance of surfaces. Such coatings are widely used in industry for machine elements and aerospace components and in technological applications for cutting tools, moulds, etc. A great deal of information has been presented in the literature [1] on the physical and mechanical properties of coatings on various substrates, including the wear resistance of the coatings in the case of cutting tools [2] and moulds [3].

A significant increase in elastic modulus, nano- and microhardness [4], and consequently the wear resistance of these materials predetermine the main promising direction of their use, namely an increase in the durability of products and tools [2, 5]. Wear-resistant coatings are applied to various objects, particularly parts and assemblies in chemical engineering, gas turbine and rocket equipment components, and medical and biological objects exposed to simultaneous mechanical and corrosion-enabling chemical factors. Their effective use must be ensured by the coatings' high corrosion resistance and protective properties [6]. Machine parts wear out over time during prolonged

* E-mail: tadeusz.lesniewski@pwr.edu.pl

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machine operation. Replacement or restoration of these materials involves significant costs, often associated with a production shutdown. Therefore, different surface hardening and friction reduction methods are used to solve problems related to improving the performance and increasing the service life of machine parts, for example, in the textile industry [7].

There are various methods for producing coatings on working surfaces. One of these is the method of employing magnetron sputtering technology. The technological parameters at which the TiCN coating is deposited affect its microstructure and properties [8, 9]. The investigation results showed that the deposition rate of TiCN coatings decreases with increasing substrate voltage [10]. Furthermore, it was observed that the elemental composition of the resulting coatings could vary significantly depending on the voltage applied to the substrate. It was found that the substrate polarisation voltage during coating deposition leads to higher values of nanohardness and Young's modulus. Tribological tests showed that the substrate polarisation voltage reduces the wear rate of TiCN coatings by increasing the nanohardness. Zheng et al. [11] found that the structure and tribological properties of TiN/a-C coatings deposited onto the steel substrate by DC magnetron sputtering depend significantly on the ratios of graphite to Ti in the target. Chen et al. [12] presented a study of the effect of nitrogen flow rates on the structure and properties of TiCN nanocomposite films (coatings), finding that increasing nitrogen flow rates increased crystallinity, sp2 carbon content and the volume fraction ratio of TiN to Ti(C, N) nanocrystalline in the TiCN thin films.

The microstructure of a TiCN coating affects its mechanical and tribological properties. Studies addressing this topic are widely available in the literature. Research results confirming the relationship between the properties and structure of TiN/TiCN/TiC multi-layered coatings are presented, among others, in the study of Razmi and Yesildal [13]. The authors noted that such coatings could be deposited successfully using the CFUBMS technique on silicon and Cp–Ti substrates, and the coatings have very good mechanical properties. The TiCN coating has satisfactory thermal and wear resistance [14, 15], a higher oxidation temperature and relatively high thermal conductivity compared to coatings based on carbides and nitrides of other metals that are actively developed and used nowadays. Studies on the mechanical properties of TiC, TiN and TiCN thin films were prepared on silicon (1 0 0) substrates by plasma-enhanced chemical vapour deposition (PECVD) [16]. The authors observed that TiC coatings exhibited a lower surface roughness and a lower friction coefficient than TiN and TiCN coatings. The results also showed that Young's modulus and hardness decreased with increasing penetration depth for all samples. Another study, by Kenzhegulov et al. [6], presents the results of the tribological and corrosion properties of the TiCN, TiCrCN and TiZrCN coatings deposited by reactive magnetron sputtering. Tribological tests showed high wear resistance of TiCrCN and TiZrCN coatings. Nanohardness analysis showed that alloying TiCrCN coatings with zirconia significantly increases hardness compared to alloying with chromium. The tribological properties of TiCN coatings were also investigated in the presence of lubricants [17] and water [18]. The wear processes of the coatings in the presence of lubricating media are described. This type of coating is particularly suitable for deployment in industrial applications where lubricating machine components would be required.

Based on the literature review and preliminary experimental studies, it has been found that most of the studies of TiCN coatings obtained on various substrates concern the influence of manufacturing parameters on their properties. The results presented mainly concern mechanical properties and corrosion resistance. The results obtained are mostly explained by changes in the structure of the coatings. However, there is a lack of information on the wear resistance of such coatings under extreme conditions. This work aims to compare the tribological properties of TiC, TiN and TiCN coatings that were deposited by reactive magnetron sputtering on titanium substrates. The investigations were carried out under high contact pressure during reciprocating movement, which is the prevalent condition characterising machines and devices

in which sliding takes place over a short distance, and the contact pressure is high, for example gears, valves, cam mechanisms, etc.

## 2. Materials and methods

The TiC, TiN and TiCN coatings were deposed on steel substrates using a magnetron sputtering device using VT1-0 Ti targets, as described in the study of Mamaeva et al. [10]. The unit was equipped with an APEL-IS-21CELL (Applied Electronics, Tomsk, Russia) ion source and an APELMRE100 unbalanced magnetron (Applied Electronics, Tomsk, Russia). The sample chamber was evacuated to a base pressure $<5–10^{-5}$ torr before deposition. The substrates were then ionically purified with argon at an operating voltage of 2.5 kV, a current of 20–25 mA, a pressure of 1–$2.5 \times 10^{-3}$ torr and a duration of 20 min. The coatings were deposited on 60 mm thick polished substrate circles made of AISI 304 steel (equivalent to 1.4301 steel according to the EN 10088 standard) at bias voltages of 0 V. The substrates were cleaned with acetone and alcohol in an ultrasonic bath for 15 min and then placed on the turntable of the vacuum chamber. The flows of the inert and reaction gases were controlled using RRG12 flow metres (Eltochpribor, Moscow, Russia). The total gas flow rate $Ar/C_2H_2 + N_2$ was set at a level of up to 2 L/hr to maintain the chamber operating pressure at a level of up to 0.66 Pa. The flow of the working gases during TiCN coating deposition is presented in Table 1. Plasma was ignited after reaching the working pressure of $Ar/C_2H_2 + N_2$ gases. The plasma current was fixed in all experiments at 2 A. The voltage was automatically varied in the range of 500–800 V. The APEL-M-5PDC-1000A-1 power supply (Applied Electronics, Tomsk, Russia) was used for this purpose. The deposition time of the coatings was 2 hr.

Investigations into the structure and composition of coatings produced in this way have been presented in earlier studies in the literature, namely Kenzhegulov et al. [6] and Mamaeva et al. [10]. As determined by scanning electron microscopy (SEM), the TiC, TiN and TiCN films were about 1.5–2.0 μm thick [10].

Table 1. The flow rate of the working gases during the deposition of TiCN coatings on the steel substrate

| | Material | Flow rate ($\times 10^{-3}$ $m^3/h$) | | |
|---|---|---|---|---|
| | | Ar | $N_2$ | $C_2H_2$ |
| Coating | TiC | 1.1 | - | 0.47 |
| | TiN | 1.1 | 0.45 | - |
| | TiCN | 1.35 | 0.225 | 0.225 |

TiCN, titanium carbonitride

The geometric structure of the coating surface and the steel substrate was examined using the Leica 3D surface metrology microscope DCM8 (Wetzlar, Germany). The investigations were undertaken before and after the friction process. The average surface roughness (Ra) values for all samples tested before the friction process did not exceed 0.1 μm. The Ra parameter was chosen because of its popularity in engineering applications. More information on the geometric structure of the surface can be obtained from the parameters for 3D surface roughness. The average values of the selected parameters for the four measurement locations on the surface of the samples are shown in Table 2. Of interest are the parameters Ssk and Sku. The parameter Ssk provides information about the asymmetry of the surface. If the value of the parameter Ssk >0, then there is a predominance of peaks on the surface. The measurements showed that, for the TiCN coating before the friction process, the value of Ssk <0, which indicates a predominance of valleys. The value of this parameter for the substrate (AISI 304 steel) and for the other coatings was greater than 0. On the other hand, after the friction process, the average Ssk value was less than 0 for the TiN coating and the steel substrate, and for the other coatings took values above 0. In summary, it can be concluded that when the values of the Ssk parameter are negative, most of the material is located near the surface peaks.

The parameter Sku >3 indicates the presence of unexpectedly high peaks or deep valleys on the surface. Such values could be observed for the TiCN coating before the friction process (Sku = 6.745) and after the friction process for the steel substrate (Sku = 10.617) and the TiN coating (Sku = 3.828).

Table 2. Surface roughness parameters (ISO 25178) of TiCN coatings and the steel substrate before and after friction tests

| | Material | Average values of surface roughness parameters before friction tests | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | **Sa** | **Sq** | **Sz** | **Ssk** | **Sku** | **Sp** | **Sv** |
| Coating | TiC | 0.508 | 0.592 | 2.548 | 0.164 | 2.018 | 1.375 | 1.173 |
| | TiN | 0.278 | 0.327 | 1.946 | 0.027 | 2.151 | 0.763 | 1.183 |
| | TiCN | 0.251 | 0.309 | 2.317 | −0.797 | 6.745 | 0.666 | 1.651 |
| Substrate | AISI 304 steel | 0.567 | 0.680 | 3.585 | 0.129 | 2.261 | 1.917 | 1.667 |
| | | **Average values of surface roughness parameters after friction tests** | | | | | | |
| Coating | TiC | 0.613 | 0.731 | 4.172 | 0.012 | 2.503 | 1.941 | 2.2320 |
| | TiN | 0.597 | 0.744 | 5.788 | −0.709 | 3.828 | 2.013 | 3.775 |
| | TiCN | 0.275 | 0.336 | 1.866 | 0.212 | 2.532 | 1.017 | 0.849 |
| Substrate | AISI 304 steel | 0.909 | 1.196 | 11.867 | −0.986 | 10.617 | 4.065 | 7.803 |

TiCN, titanium carbonitride

Tribological tests were performed on a ball-on-plate test rig in a reciprocating motion. This stand was built at the Faculty of Mechanical Engineering of the Wrocław University of Science and Technology. It allows tribological tests to be carried out at maximum normal load $F_n$ = 100 N, maximum sliding speed $v$ = 0.05 m/s, maximum frequency of reciprocating movement 10 Hz and distance (amplitude) of movement 0.5–80 mm.

The test stand and the tested couple are shown in Figure 1. During the tests, the coated sample was moved in a reciprocating motion, and the friction force $F_t$, which was used to determine the friction coefficient, was recorded.

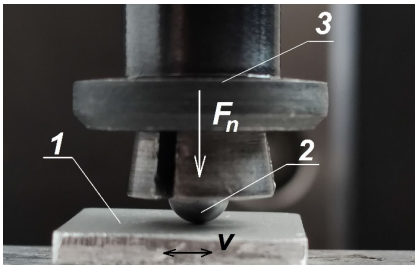



Fig. 1. Friction pair on tribotester ball-on-plate (1 – sample with tested coating, 2 – silicon carbide ball, 3 – ball holder, $F_n$ – normal load, $v$ – sliding speed in reciprocating motion)

In order to describe the wear process of coatings, microscopic examinations were carried out with the use of a Phenom ProX scanning electron microscope. After the friction process, the surface of the samples was also examined using the Leica 3D surface metrology microscope DCM8. Measurements were made by a confocal method using Leica Scan 6.5 software and a Leica EPI 20× lens. Post-processing of the results was performed using Leica Map 7.4 software. The obtained surface images facilitated determination of the depth of the friction marks on the surfaces of the samples, and comparison of the wear resistances of the tested coatings. Additionally, scratch tests were carried out for the investigated coatings using CSM MicroCombiTester (Peseux, Switzerland).

## 3. Experimental results and discussion

The experiment aimed to compare the tribological properties of the coatings on the steel substrate and to describe their wear during dry friction at high contact pressure.

### 3.1. Tribological research

Tribological tests were carried out on a ball-on-plate tester in a reciprocating motion. The test conditions were adopted based on preliminary pilot tests, so that the friction process under these conditions would not lead to the complete removal of the coatings from the substrate. The amplitude of the displacement was 3 mm. The tests were carried out over 50 cycles of back-and-forth movement with an average speed of 6 mm/s. The mating element was a silicon carbide ball with a diameter of 4 mm. The

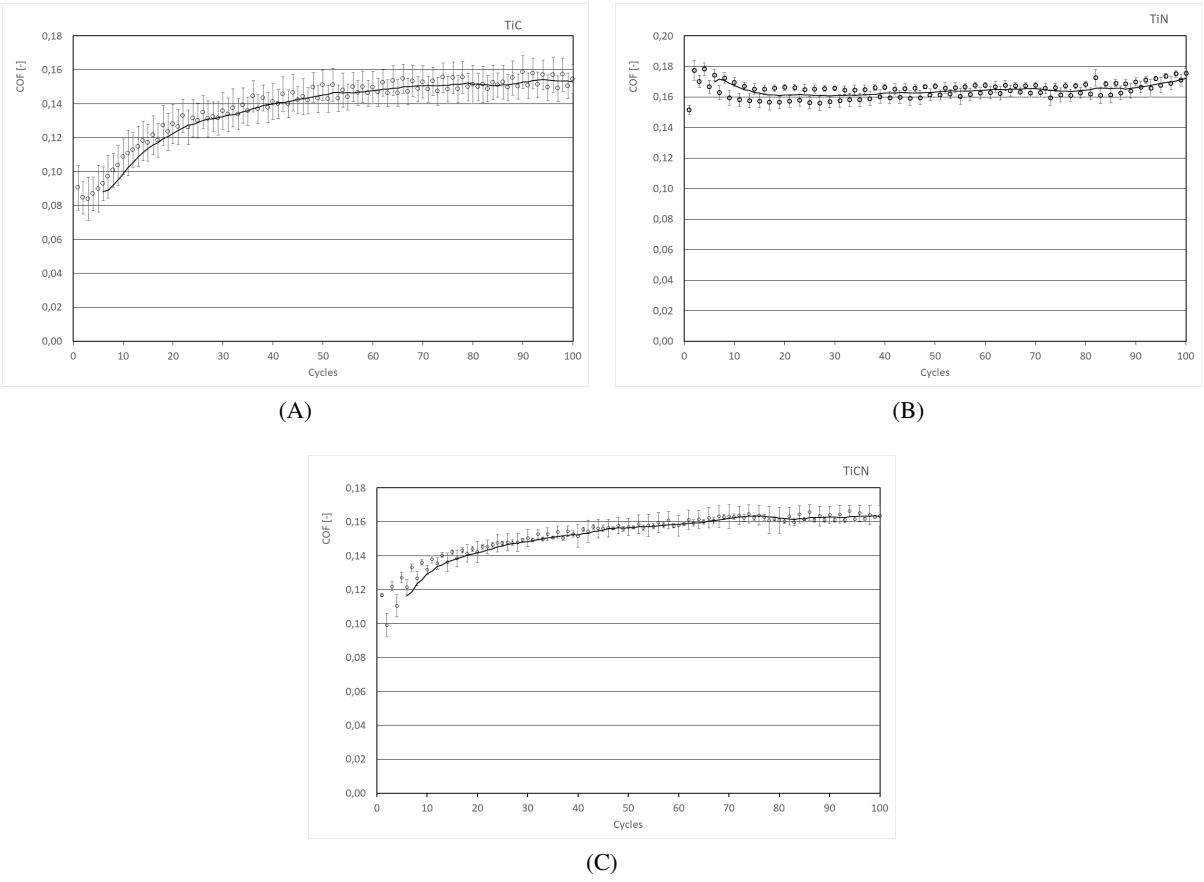



Fig. 2. Examples of changes in the friction coefficient as a function of successive movements (cycles) for the tested coatings: **(A)** TiC, **(B)** TiN, **(C)** TiCN. TiCN, titanium carbonitride

Table 3. The average coefficient of friction for the tested coatings and the confidence intervals for the initial (Cycle 1–20) and final friction period (Cycle 90–100)

| | **Material** | **Coefficient of friction** | **Confidence interval** | **Coefficient of friction** | **Confidence interval** |
|---|---|---|---|---|---|
| | | **Cycle: 1–20** | | **Cycle: 90–100** | |
| Coatings | TiC | 0.122 | ±0.003 | 0.143 | ±0.002 |
| | TiN | 0.165 | ±0.001 | 0.168 | ±0.001 |
| | TiCN | 0.145 | ±0.002 | 0.166 | ±0.002 |
| Substrate | AISI 304 steel | 0.139 | ±0.002 | 0.152 | ±0.002 |

TiCN, titanium carbonitride

ball material was chosen because its high hardness meant that wear on the ball during testing would be negligible. The normal force that pressed the ball against the sample surface was $F_n$ = 20 N. The Hertzian pressure was determined, taking into account the mechanical properties of the ball and sample materials (substrate and coating). This contact pressure was $p_h$ = 2,500–2,700 MPa at the beginning of the experiment. The tests were carried out at an ambient temperature of $T_0$ = 24°C under technically dry friction conditions. During the tests, the friction force was recorded to determine changes in the coefficient of friction during successive displacements and its average value. The tests

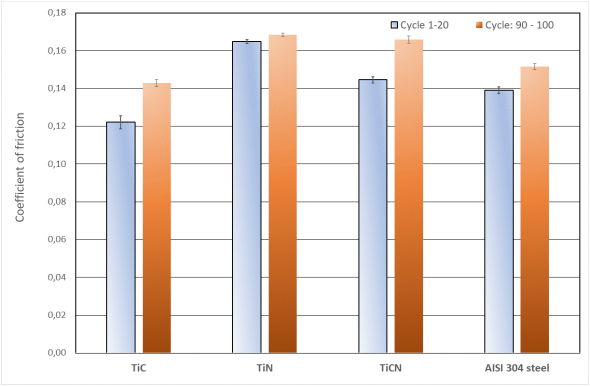



Fig. 3. Average coefficient of friction for TiCN coatings and steel substrate for the initial (Cycle 1–20) and final friction period (Cycle 90–100) (error bars correspond to confidence intervals of the confidence level $\alpha = 0.05$). TiCN, titanium carbonitride

were repeated at least thrice for each of the coatings tested. Figure 2 shows examples of changes in the coefficient of friction for different coatings during tribological investigations. The error bars indicate the confidence intervals for the normal distribution at a confidence level of $\alpha = 0.05$. The test results are presented in Table 3 and Figure 3.

The results of the friction coefficient test showed that it was the highest for the TiN coating ($\mu = 0.165$–$0.168$) and the lowest for TiC ($\mu = 0.122$–$0.143$). However, for the TiN coating, changes in the value of the friction coefficient during the test were negligible, while for the other coatings, the friction coefficient at the beginning of the test was significantly lower than that at the end.

The wear of the samples was determined by the depth of the friction tracks on their surface. These were examined using the Leica 3D surface metrology microscope DCM8. The occurrence of a material pile-up effect made it difficult to precisely determine the width of the friction track, and this parameter was therefore abandoned as a measurement result. The depth of the wear track, which should be considered qualitatively rather than quantitatively, was adopted as the wear-defining parameter.

Example results of wear are shown in Figures 4–6. In the cross-sectional profiles of the groove (friction path), uplifts of the substrate material and coating can be observed at the edges of the groove. This indicates the occurrence of deformation wear in addition to other types of wear such as abrasive wear, fatigue (fracture) or adhesive wear.

The average value of the maximum groove depth measured from the flat surface of the sample was used as a parameter describing the wear of the test samples (material pile-up was ignored). The wear results of the tested coatings are shown in Table 4 and Figure 7. The TiN coating showed the highest wear resistance (average groove depth 3.05 μm) and the TiCN coating the lowest resistance (average groove depth 5.65 μm).

Table 4. Wear of TiCN coatings as an average of the maximum friction track depth after 100 cycles of movement

| Material | Wear (μm) | Confidence interval |
|---|---|---|
| TiC | 4.64 | ±0.58 |
| TiN | 3.05 | ±0.17 |
| TiCN | 5.65 | ±0.38 |

TiCN, titanium carbonitride

It should be noted that the maximum depth of the groove exceeded the thickness of the coating, but as the microscopic examination showed, the interiors of the friction grooves were still covered by the coating material.

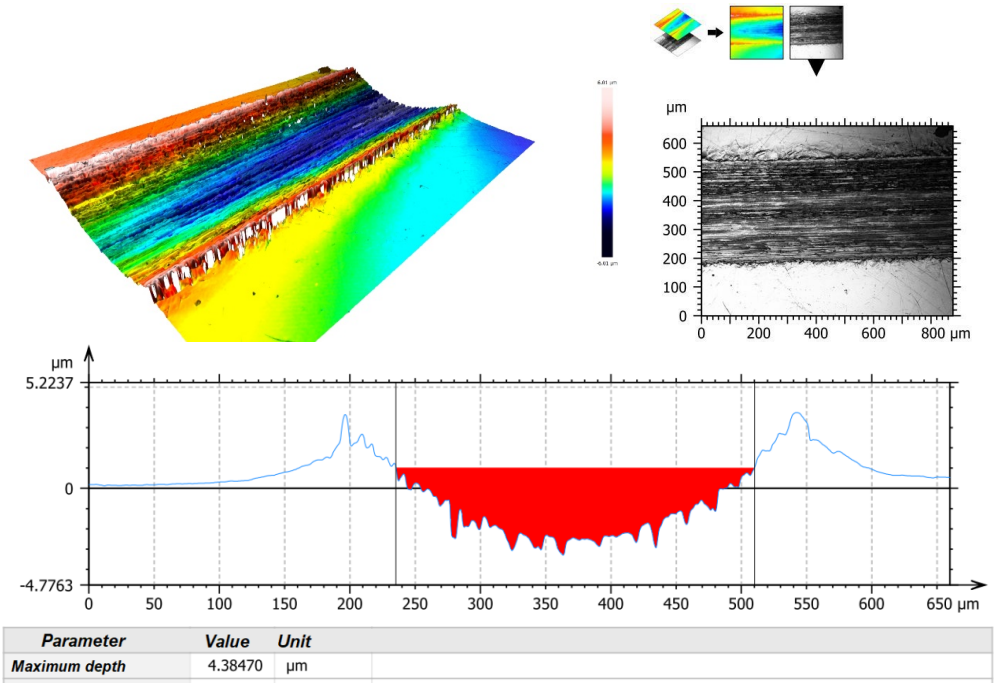
## 3.2. Microscopic studies

Microscopic studies of the surfaces of the samples after the friction process allowed the description of the processes occurring during friction in the region of the surface layer of the coating.

Figure 8 shows surface micrographs using a Phenom ProX SEM.

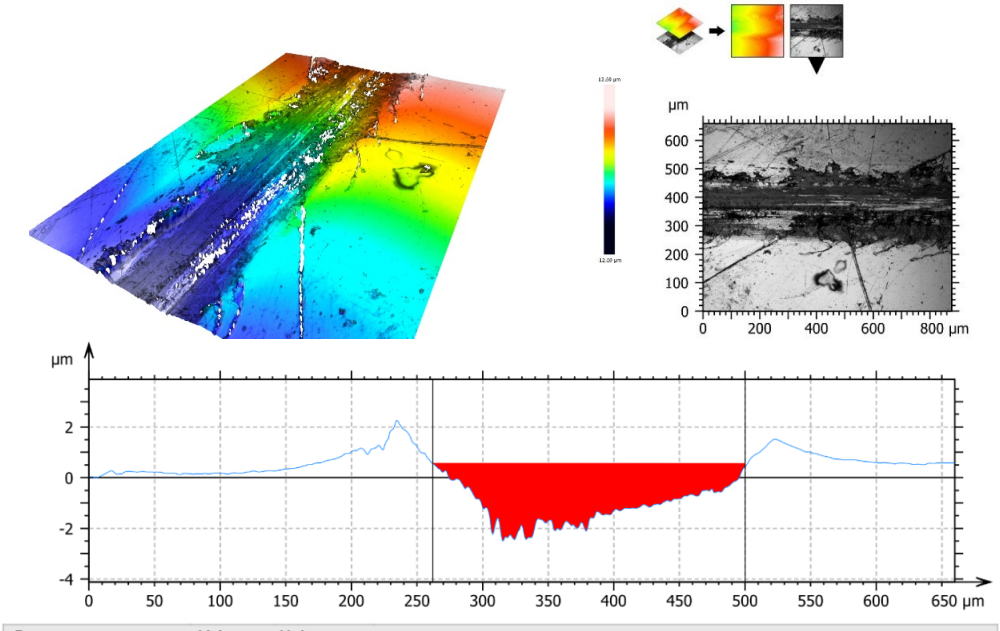
From the microscopic observations, it can be seen that the tested coatings have not been removed from the wear track and remain inside the groove after tribological tests. The following observations can be made:

- The TiN coating is hard and brittle, which is evident in the way it wears. During friction, the process of its cracking (crushing) and detachment from the steel substrate dominated (Figure 8B). However, its fragments




| Parameter | Value | Unit |
|---|---|---|
| Maximum depth | 4.38470 | µm |

Fig. 4. Example of wear (groove) test results on a TiC coating surface using a 3D surface metrology microscope: **(A, B)** wear track, **(C)** cross-section of wear track




| Parameter | Value | Unit |
|---|---|---|
| Maximum depth | 3.14390 | µm |

Fig. 5. Example of wear (groove) test results on a TiN coating surface using a 3D surface metrology microscope: **(A**, **B)** wear track, **(C)** cross-section of wear track

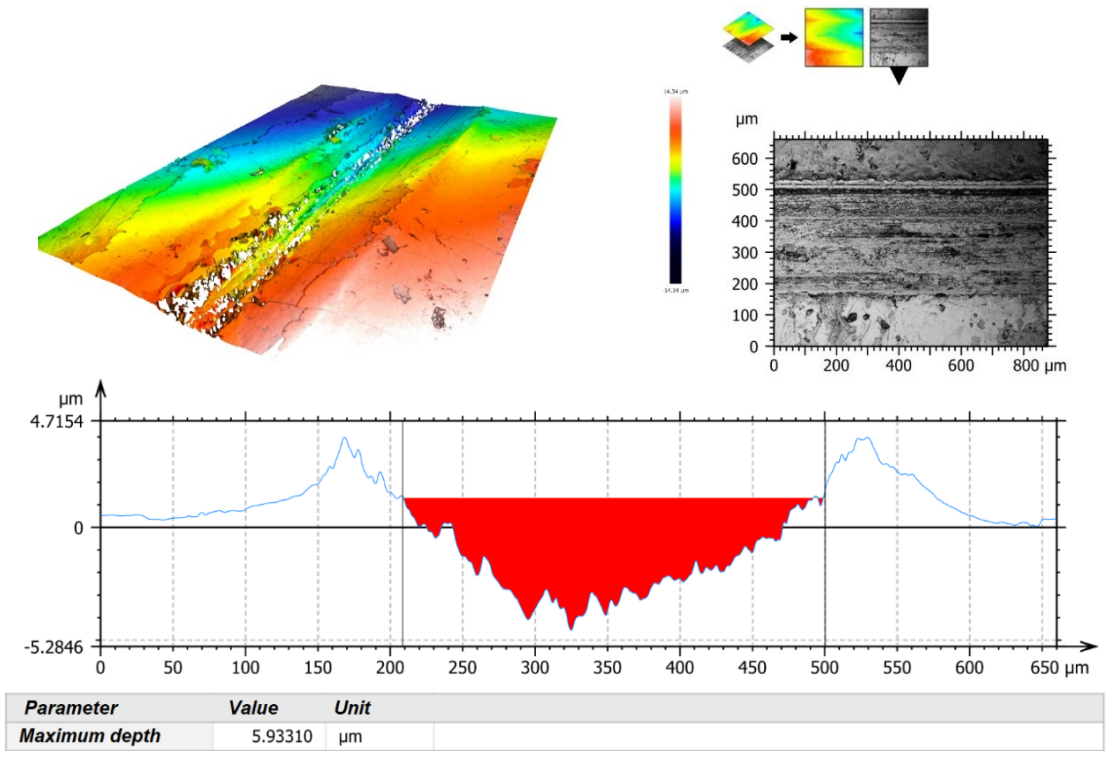



Fig. 6. Example of wear (groove) test results on a TiCN coating surface using a 3D surface metrology microscope: **(A**, **B)** wear track, **(C)** cross-section of wear track. TiCN, titanium carbonitride

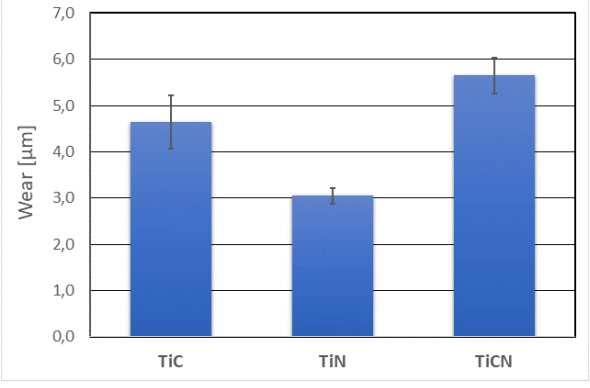



Fig. 7. Wear of TiCN coatings as an average of the maximum friction track depth after 100 cycles of movement during tribological tests (error bars correspond to confidence intervals of the confidence level $\alpha = 0.05$). TiCN, titanium carbonitride

remained in the wear track, covering the surface of the groove and participating in the friction process.

- The TiCN coating also cracked during friction, but the cracks are much less visible than in the TiN coating. The bright areas near the edges of the groove (friction path) visible on the microphotograph (Figure 8C) indicate that the TiCN coating peels off during the friction process. This can probably be attributed to insufficient adhesion to the substrate surface.
- In the case of the TiC coating, no cracks can be seen in the microphotographs (Figure 8A), nor its detachment from the steel substrate. This demonstrates its flexibility and good adhesion to the substrate, as no removal from the surface of the grooves (wear track) occurred due to the friction process.

### 3.3. Scratch test

The scratch test was carried out in addition to tribological tests. Its purpose was to determine the load at which there occurs cracking of the coating and its detachment from the substrate. The scratch

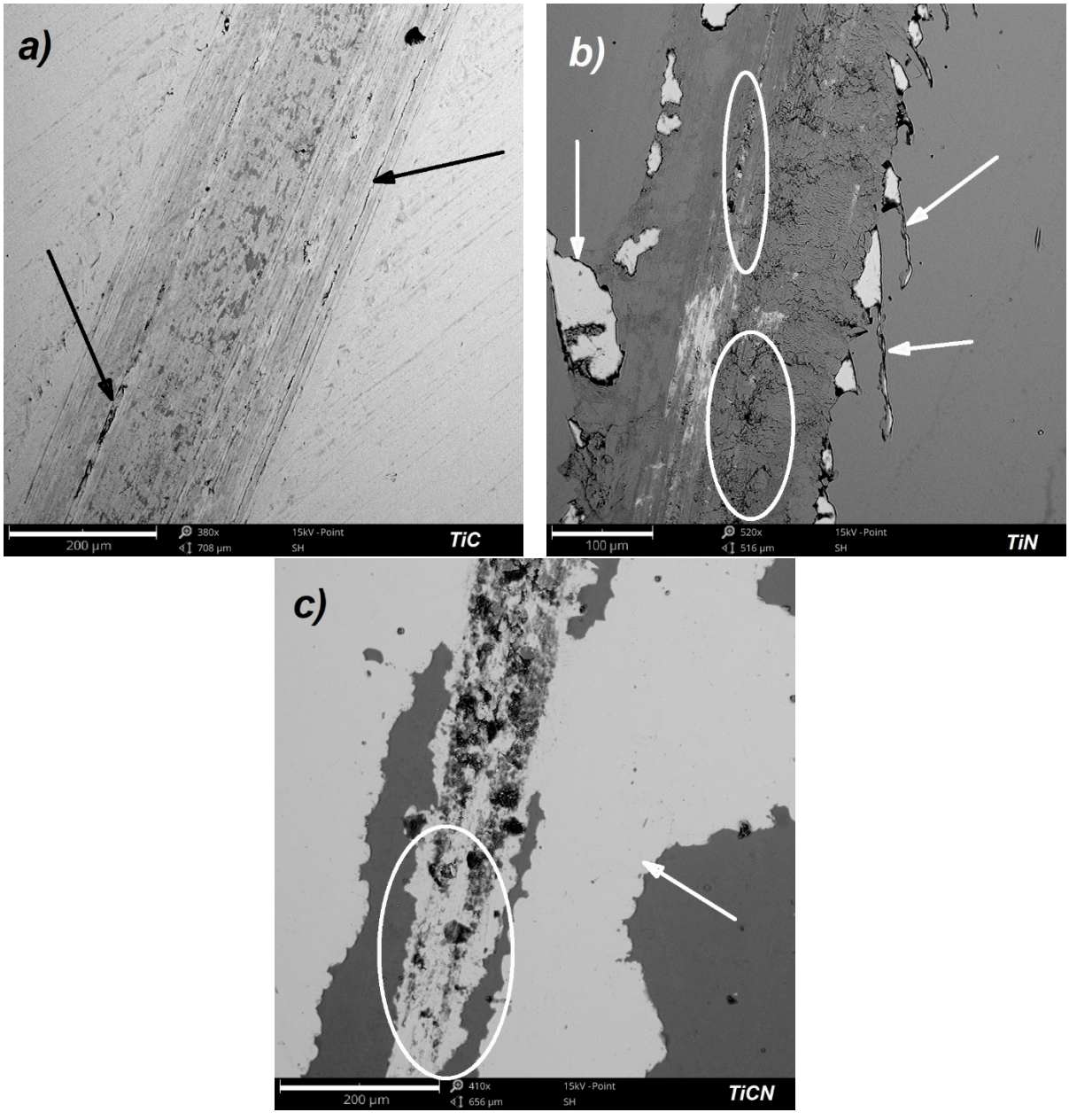



Fig. 8. SEM microphotographs of friction tracks for coatings: **(A)** TiC, **(B)**TiN, **(C)** TiCN. The arrows indicate the area of cracking and the detachment of the coating from the substrate. SEM, scanning electron microscope; TiCN, titanium carbonitride

test with the following parameters was used for investigations of all coating samples:

- indenter type: Rockwell, r = 100 µm;
- scratch distance: L = 2 mm;
- initial normal force: $F_n$ = 10 mN;
- final normal force: $F_n$ = 2,500 mN; and
- loading rate: 622.5 mN/min.

The results of the scratch test of the investigated coatings are presented in Figures 9–12.

The graphs in Figure 9 show the variation of normal force and friction force as a function of displacement. Figure 9 presents the value of normal force when significant oscillations of the friction

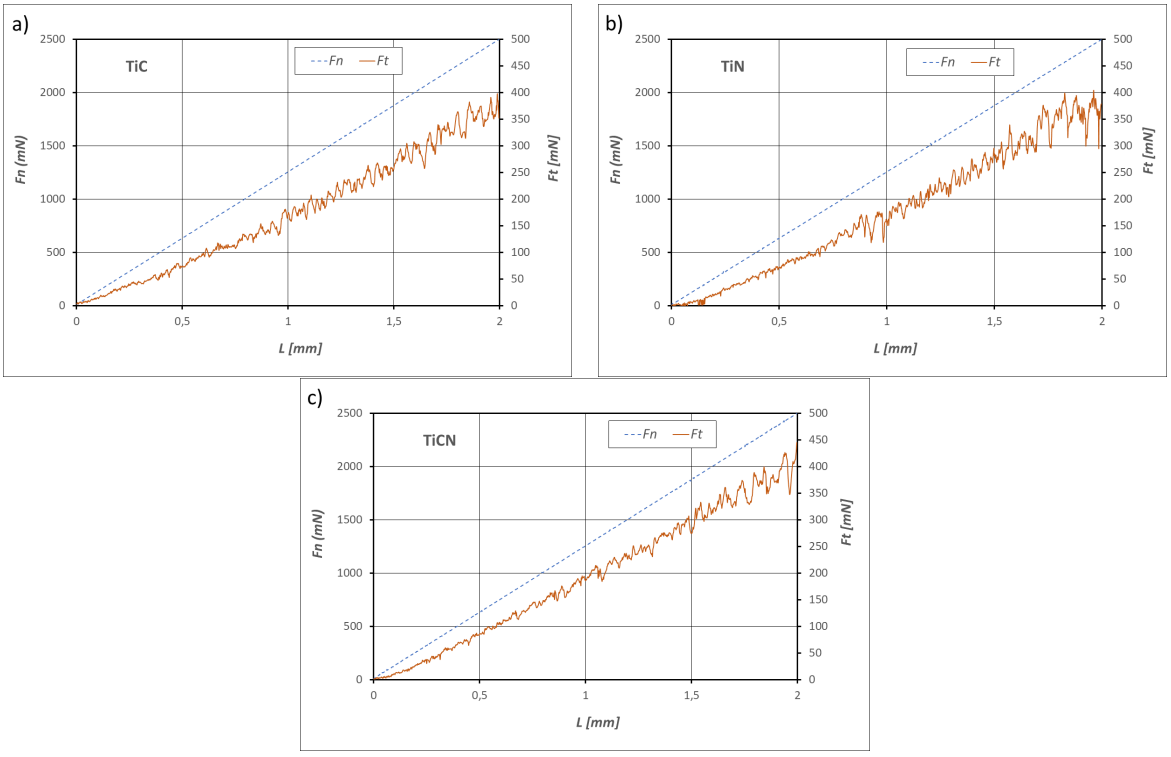



Fig. 9. Normal force $F_n$ and frictional force $F_t$ versus distance L in the scratch test for coatings: **(A)** TiC, **(B)** TiN, **(C)** TiCN. TiCN, titanium carbonitride

force begin. This oscillation is caused, among other reasons, by the formation of cracks in the coating and its detachment from the substrate. The detailed mechanism of coating failure during the scratch test can be observed in the microphotographs shown in Figures 10–12. For the TiC coating, no visible cracks were observed along the entire scratch length during the scratch test. This shows that the coating deforms with the substrate without crack propagation (Figures 10D and 10E). In contrast, the TiN and TiCN coatings show a tendency to crack. In the case of the TiN coating, a clear increase in the oscillation of the friction force was observed with a normal force load of $F_n$ = 1,200 mN. At the same time, the first cracks are visible in the crack images (Figure 11B). Nevertheless, even with increasing normal force loading $F_n$, no peeling of the coating from the substrate was observed. For TiCN, however, the first cracks were observed with a normal force load of $F_n$ = 850 mN. Still, in this load, there is no clear change in the oscillation of the friction force. Therefore, the coating is not broken and remains still inside the scratch. However, the microphotographs of the scratch (Figures 12C and 12D) for this coating show that the coating is detaching from the substrate near the scratch.

The tests showed a difference in the scratching behaviour of the coatings. The TiC coating proved to be the best in terms of resistance to detachment during scratching, as it did not crack but only deformed during the test. The TiN coating cracked significantly due to its considerable hardness in relation to the steel substrate. The TiCN coating, on the other hand, is additionally detached from the substrate in the area around the scratch (Figures 12C and 12D). This may indicate insufficient adhesion to the substrate. A similar situation occurred during tribological tests carried out on a ball-on-plate tribotester. SEM microscopic examination of the surface after the friction process (Figure 8C) also showed detachment of this coating from the steel substrate during tribological tests.

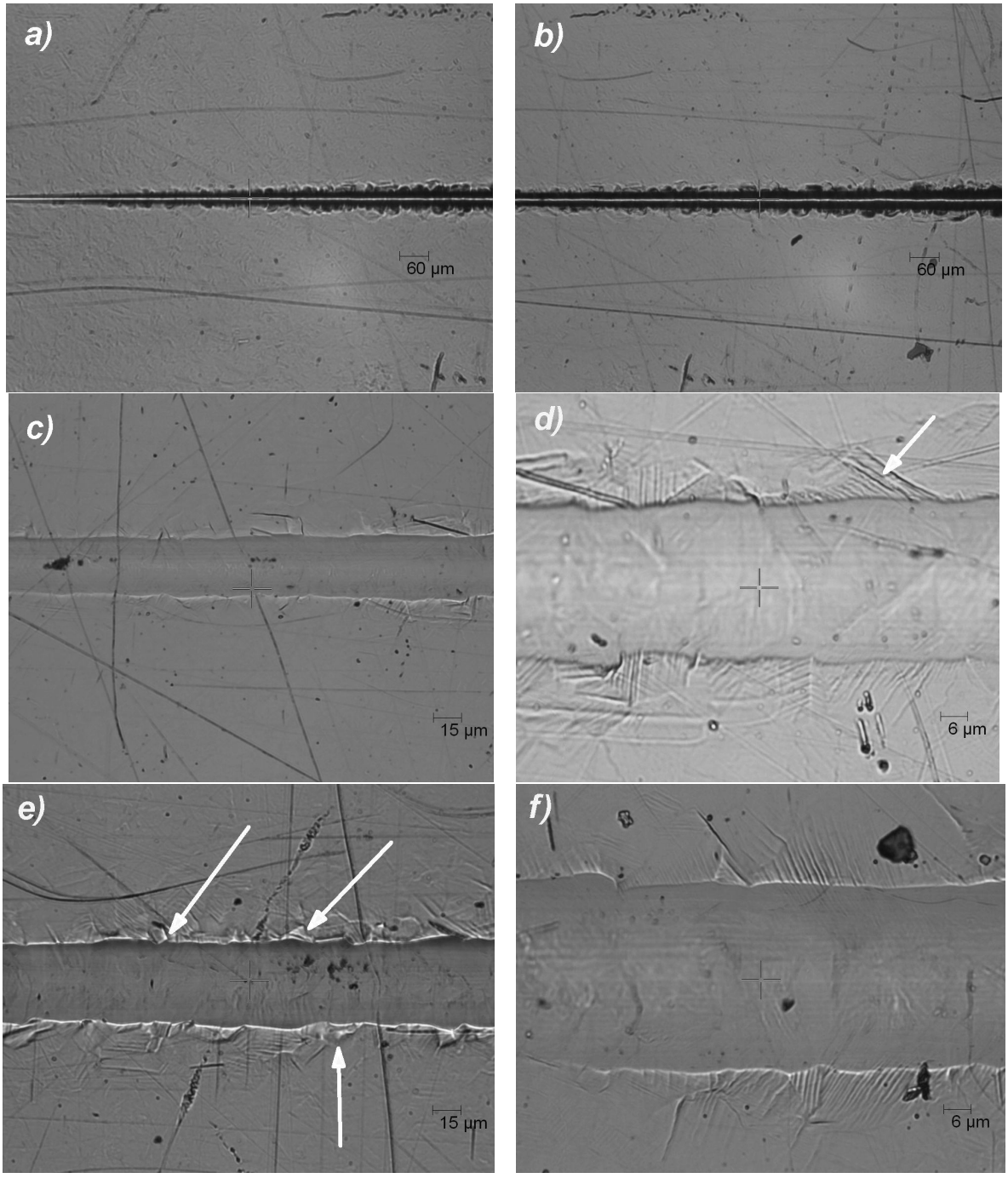



Fig. 10. Scratch microphotographs for TiC; **(A)** normal force in the range $F_n$ = 10–1,400 mN , **(B)** normal force in the range $F_n$ = 1,450–2,400 mN, **(C)** normal force in the range $F_n$ = 1,250–1,500 mN, **(D)** normal force in the range $F_n$ = 1,250–1,500 mN, **(E)** normal force in the range $F_n$ = 2,000–2,400 mN, **(F)** normal force $F_n$ = 2,000–2,400 mN. The arrows indicate the area of the detachment of the coating from the substrate

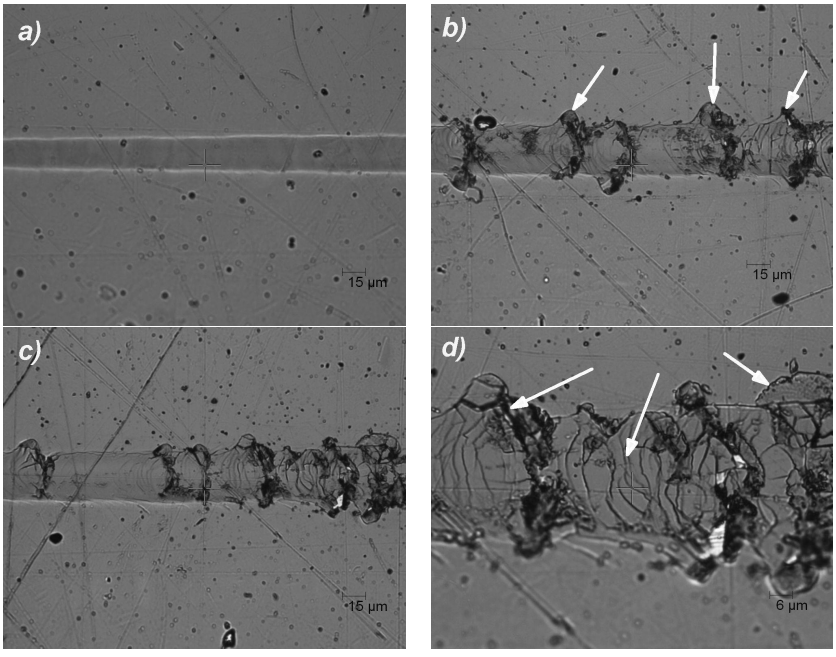



Fig. 11. Scratch microphotographs for TiN; **(A)** normal force in the $F_n$ range = 10–1,200 mN , **(B)** normal force in the $F_n$ range $F_n$ = 1,250–1,500 mN, **(C)** normal force in the $F_n$ range $F_n$ = 1,550–1,850 mN, **(D)** normal force $F_n$ = 1,800 mN. The arrows indicate the area of cracking and the detachment of the coating from the substrate

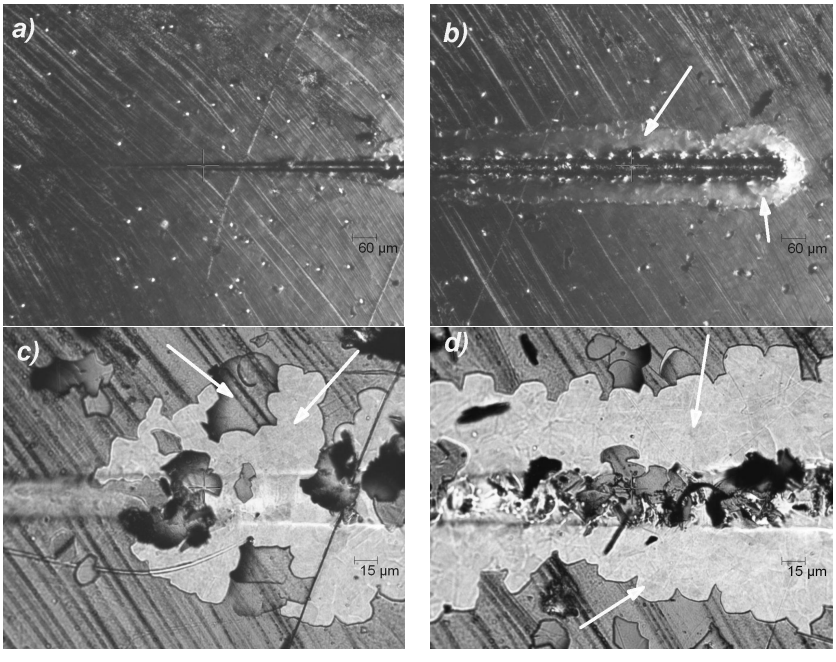



Fig. 12. Scratch microphotographs for TiCN; **(A)** normal force in the $F_n$ range $F_n$ = 10–860 mN , **(B)** normal force in the $F_n$ range $F_n$ = 1,050–2,500 mN, **(C)** normal force in the $F_n$ range $F_n$ = 800–1,200 mN, **(D)** normal force $F_n$ = 1,350–2,400 mN. The arrows indicate the area of the detachment of the coating from the substrate. TiCN, titanium carbonitride

## 4. Conclusions

The analysis of the results of the tribological test and the scratch tests makes it possible to describe and explain the differences in wear of TiC, TiN and TiCN coatings deposited using the magnetron sputtering method on the AISI 304 in emergency conditions, that is to say, with concentrated contact, high contact pressure and lack of lubrication (technically dry friction).

- Investigations of the friction tracks on the surface of the samples using an optical profilometer showed the occurrence of a material pile-up effect at the edges of the friction tracks. It indicates deformation wear resulting primarily from plastic deformation of the substrate and material displacement at the edge of the friction marks. A similar effect can be seen in the scratch microphotographs (e.g. Figure 10E).
- The TiC coating did not show cracks or detachment from the substrate due to friction. However, its low hardness did not protect the substrate from deformation wear. A similar behaviour of the TiC coating was observed in the microphotographs of the scratch test (Figure 10).
- The TiN coating was subject to cracking, but its fragments were slightly detached and removed from the friction surface. The coating protected the substrate well against wear. Microphotographs of scratches on the TiN coating (Figure 11) confirm this behaviour of the coating.
- The TiCN coating cracked as a result of friction, and in addition, significant areas of detachment from the substrate were visible not only in the friction path area but also around it. This type of damage to the TiCN coating was also observed during the scratch test (Figure 12).

Comparing the tested coatings leads to the conclusion that the TiN coating has the highest wear resistance during emergency conditions. Although fractured, it has high microhardness, with the result that significant parts forming part of the substrate remained unscathed; it can additionally be inferred that this is the property playing a significant role in protecting the coating from excessive wear.

The results of the friction coefficient tests showed that the value of all tested coatings ranged from 0.122 (TiC) to 0.168 (TiN). This does not represent a significant difference when the testing is performed under dry friction conditions. In the case of the TiN coating, despite the highest friction coefficient value, its changes during the test were negligible. On the other hand, for the other coatings (TiC and TiCN), the friction coefficient at the beginning of the test was significantly lower than that at the end. This can be explained by the different hardness characteristics of the tested coatings and the way they wear.

In summary, the best coating in terms of tribological properties turned out to be the TiN coating, which showed the greatest wear resistance in emergency conditions, and the value of the coefficient of friction at the final stage of testing (above 90 cycles of movement) was only slightly higher than the values recorded for the other coatings. The friction coefficient for TiN was $\mu = 0.168$, while for TiN it was $\mu = 0.143$ and for TiCN it was $\mu = 0.166$.

A more detailed explanation of the observed differences in the wear modes of the tested coatings during the friction process under emergency conditions requires more detailed analyses of the composition and structure of the tested coatings and their adhesion to the substrate. Such studies are planned for the near future.

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