Tribological behaviour of TiBN and DLC top-layered coating systems

TiBN és különböző DLC fedőréteges bevonatrendszerek tribológiai teljesítőképessége

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Kulcsszavak
DLC bevonat,
tribológia,
karctérkép,
TiBN bevonat,
kopásvizsgálat

Absztrakt

A hidegalakító szerszámok élettartama jelentősen növelhető tribológiai bevonatok alkalmazásával. Szerkezetüket és anyagukat az alkalmazástól függően választjuk meg, emellett teljesítőképességüket nagymértékben befolyásolja a terhelés típusa. Cikkünkben egyrétegű TiBN és különböző alátétréteges DLC bevonatokat vizsgáltunk kopásos és karcolásos igénybevételek között. A legjobb karcállóságot a TiBN, míg a legkedvezőbb kopásállóságot a DLC fedőréteges bevonatrendszerek mutatták. A közölt eredmények, a vizsgált bevonatok átfogó karckárosodás-mechanizmus térképével együtt, hasznos információt nyújtanak a szerszámbevonatok célszerű megválasztásához, a tribológiai teljesítőképesség optimalizálásához.

Keywords
Diamond-like carbon,
tribology,
scratch map,
TiBN coating,
wear test

Abstract

The application of different tribological coatings increases the lifetime of cold-forming tools. The structure and material of coatings are selected according to application, but their performance depends on the loading type. This paper investigates monolayer TiBN and different multilayer diamond-like carbon coating systems under wear and scratch-type tribological loading conditions. The best scratch resistance was shown by the single-layer TiBN, while the multilayer DLC coating systems provided the most favorable wear performance. The published results, with the tested coatings' comprehensive scratch damage mechanism map, provide useful information for the appropriate coating selection.

1. Introduction

Nowadays, automotive producers have increased pressure to simultaneously reduce costs, increase tool life, and pay attention to environmental regulations. One of the most effective methods for this is the surface treatment of cold-forming tools, especially the application of coatings with unique and tailored properties [1-4]. There are numerous methods to produce coatings, of which the so-called Plasma-Assisted Chemical Vapor Deposition (PACVD) is increasingly applied due to its advantages [5-7].

In terms of the composition and structure of coatings, multilayer coatings conquer broader applications [8-12], through which the favourable properties of the individual coating layers can be efficiently combined, providing better resistance to various damages and increasing their performance in a particular application field.

Using TiBN ceramic monolayer on the surface of the tools can significantly increase the hardness up to 3500−5000 HV (where HV is the Vickers hardness number) [13] and improve the abrasive wear resistance, thus increasing the service life [14].

During industrial application, these tools can also be exposed to highly corrosive circumstances, which can be efficiently reduced by the TiBN coatings [15]. Another advanced solution for increasing the wear resistance of tools is the application of multilayered Diamond-Like Carbon (DLC) coating systems, which are receiving increasing attention from industry professionals due to their unusually low $\mu = 0.01 - 0.1$ friction coefficient achievable in different tribopairs [16].

These multilayer DLC coatings combine the benefits of the sp^2 and sp^3 bonds and depending on their ratio, the coatings' properties can be adjusted to a wide scale of requirements of different applications [17].

Diamond-like carbon coatings are widely used in electronics, tribology, and biomedical and optical applications. Friction between the contact surfaces exposed to mechanical stress consumes a lot of invested energy and destroys the surfaces, for which problem the application of DLC coatings can be a good solution. Their advantages make them suitable for application in the automotive industry, such as the coatings of tappets, camshafts, finger roller followers, camshaft sprockets, piston rings, and pistons [18, 19].

Choosing the most suitable coating for a given application is essential to increase the tools' performance. The current paper aims at comparing the tribological performance of different ceramic coating systems widely applied for tools in the industry. The tribological behaviour is characterized under scratch and wear type loadings representing the most critical causes of tool failures. The most important questions the authors seek answers are the following.

1. Which coating is the best choice under scratch-type loading conditions?
2. Which coating performs best in ball-on-disk wear-type loadings?
3. Which coating characteristics have the most decisive role in terms of increasing the scratch and wear resistance of the studied tool steel?

2. Materials and methods

2.1 Test samples and substrate material

The substrate material of the tested specimens is an X210Cr12 (1.2080) cold work tool steel with the following characteristic constituents: 2 wt% C, 0.25 wt% Si, 0.35 wt% Mn, 11.5 wt% Cr, and the rest is Fe.

The excellent wear resistance and edge durability of this steel is provided by the high Cr and C content and the tempered martensitic microstructure, produced by hardening at 980 °C for 30 min, cooling in nitrogen at p = 6 bar pressure, and tempering at 350 °C for 2 hours. The test specimens are ∅30×6 mm ground and polished discs.

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2.2 Investigated coatings

During this research work, single-layer TiBN and different multilayer DLC top-coated systems, namely TiBN+DLC, TiAlN+DLC, and CrN+DLC, were compared with the uncoated reference material.

TiBN monolayer coating is produced using Plasma Enhanced Magnetron Sputtering (PEMS), i.e., a Physical Vapor Deposition (PVD) process, which provides excellent mechanical and tribological properties to the coatings [20].

A pre-heating is applied at 260 °C for 2 h, followed by ion-etching at 280 °C for 30 min. The coating is produced by Ar+ ion bombarding a Ti+TiB target at T = 260 °C for 2 h in an active N atmosphere. The TiBN, TiAlN, and CrN sublayers for the investigated multilayer coatings were produced similarly.

The multilayer coatings have hydrogenated DLC top coatings produced by the PACVD process [21], having a cemented carbide (WC+Co) intermediate adhesion layer deposited by PVD, similar to the CrN sublayer. The layered architecture of the coating systems is seen in Figure 1.

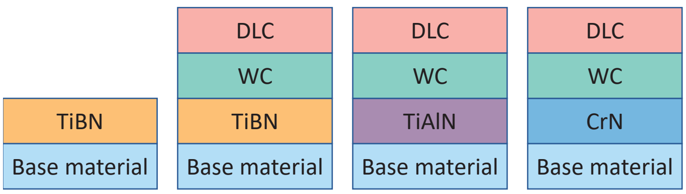

Figure 1. *The layer architecture of the investigated coatings*

2.3 Test procedures

The HV0.01 coatings' hardness and substrate hardness, i.e., the hardness of the uncoated samples, were measured by the microVickers test method (MITUTOYO MVK-H1), applying F = 0.1 N normal load. The thickness of coatings was determined by the ball cratering method (Calotest) [22] (instrument: Anton Paar-Calotest Compact CAT2c). The test was accomplished by applying a ∅30 mm quenched steel ball as a wearing counterpart, a rotational speed of n = 3000 1/min, and a wearing time of t = 3 min.

The tribological behaviour of the different coating systems was characterized by ball-on-disc type wear tests and instrumented scratch tests.

The ball-on-disc tests were accomplished on a UNMT-1 multifunctional surface tester (producer: CETR– Center for Tribology, Incorporation), applying three different normal loads of F = 5, 10, and 20 N, and sliding speed of 10 mm/s. The friction counterpart was a ∅6 mm SiC ball, and the wear track radius was R = 3 mm, and the total sliding distance was 288 m. Measurements were performed in dry sliding conditions at room temperature, at a relative humidity of 50 %. Friction coefficient diagrams vs sliding distance were recorded by the test machine.

The specific wear rate was calculated according to Eq. (1):

$$k = \frac{V}{F \cdot L}, \qquad (1)$$

where k is the specific wear rate [mm^3/Nm]; V is the worn volume [mm^3]; F is the loading force [N], and L is the total sliding distance [m]. The worn volume was approximated by Eq. (2):

$$V = 2R\pi \cdot A = 2R\pi \cdot \left[\frac{\arcsin\left(\frac{t}{D}\right)}{360} \cdot \frac{1}{2} D^2 \pi - \left(\frac{t \cdot \sqrt{D^2 - t^2}}{4} \right) \right], \qquad (2)$$

where V is the worn volume in mm^3; A is the worn cross-section approximated by a spherical cup; R is the wear track radius in mm; t is the width of the wear track in mm; measured by optical microscopy (OM); and D is the diameter of the friction counterpart ball in mm.

The scratch tests in a progressive loading mode were accomplished on an instrumented scratch tester, type SP15 (Producer: Sunplant, Hungary). The normal load increased from 2 to 150 N, and the loading force gradient was 10 N/mm. The velocity of the sample holder table was 5 mm/min, and the total scratch length was 15 mm. The diameter of the craters created during the ball cratering method and the morphology of the wear tracks obtained during ball-on-disc tests, and the scratch grooves were investigated by optical microscopy (Zeiss Axio Observer D1m).

During the hardness test 5-5, in the case of the other tests, 3-3 valid measurements by tested material/coating have been accomplished.

3. Results and discussion

3.1 Hardness test

HV0.01 microVickers hardness was measured on both uncoated and coated specimens. The results are shown in Figure 2.

Compared to the uncoated samples, the TiBN coating possessed a two times greater hardness, while the hardness of the DLC top-layer of the multilayer coatings was almost four times greater and was independent of the dominant sub-layer.

It should be mentioned that the coating hardness measured with the applied normal loads represents the so-called composite hardness of the coated system, i.e. not of the hard coating alone. Using such hardness characteristic is purposeful since, on the one hand, a substrate-free coating hardness is very difficult to define.

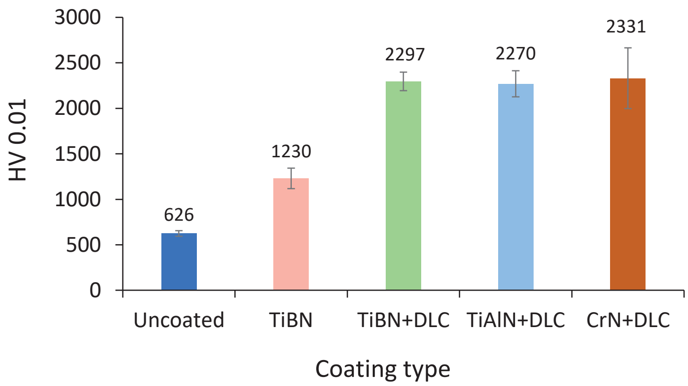

Figure 2. *Surface hardness of the investigated samples (HV0.01)*

On the other hand, the tribological behaviour of the coating systems depends on the composite hardness, which is defined by the substrate and coating system together [23, 24].

3.2 Layer thickness measurements by the ball cratering method

The layer thickness values for the monolayer TiBN and the multilayer coatings with DLC top layer are shown in Figure 3.

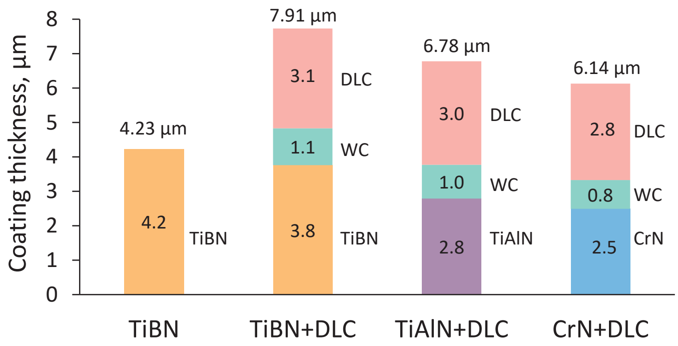

Figure 3. *The thickness of the different layers of the tested coatings*

The smallest (4.23 µm) layer thickness was observed for the single-layer TiBN coating, while the TiBN+DLC multilayer coating possessed the largest one (7.91 µm). The total thickness of the TiAlN+DLC and CrN+DLC multilayer coatings were similar, 6.78 µm and 6.14 µm, respectively. The thickness of the DLC top layers was closely identical (2.8÷3.1 µm) for the three multilayered coating systems.

3.3 Ball-on-disc wear tests

The wear tests were accomplished on the uncoated substrate, as a reference material, and on the TiBN, TiBN+DLC, TiAlN+DLC, and CrN+DLC coatings.

The characteristic friction coefficient curves obtained at $v = 10$ mm/s and $F = 20$ N loadings are illustrated in Figure 4. The curves provide information on the possible controlling wear mechanism, as follows. In the case of the uncoated substrate material, the friction coefficient stabilizes at the 120-200 m sliding distance. Then it shows a decreasing character, suggesting a tribofilm formation in the form of iron oxide compounds, characteristic for steels that provide lubrication during repeated sliding.

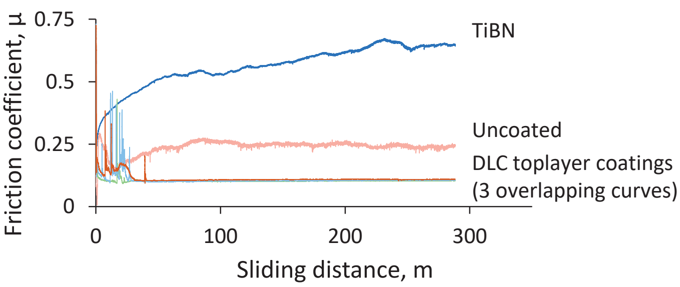

Figure 4. *The friction coefficient curves obtained during ball-on-disc wear tests for the uncoated and differently coated systems (v = 10 mm/s, F = 20 N)*

In the case of the TiBN coating, the stabilization of the friction coefficient occurs at much longer, i.e., at $s = 250$ m sliding distance, and the steady-state friction coefficient value ($\mu_{steady} = 0.6 \div 0.7$) is significantly higher compared to the uncoated reference samples. Due to the formation of hard debris particles originating from the coating, the dominant wear mechanism is three-body abrasive wear, due to which the coefficient of friction is high.

In contrast to the single TiBN monolayer, if using an additional DLC top-layer on it, i.e., in the case of the TiBN+DLC coating system, the stabilization occurs very early, at 30 m, and a much lower steady-state coefficient of friction, $\mu_{steady} = 0.1 \div 0.2$ is obtained that is common for DLC top-layers. This phenomenon is also observed for the curves of the other two DLC top-layered systems having different sub-layers. The curves for the three studied DLC multilayer systems appear as overlapping curves in the diagram. This very low coefficient of friction is about half and one-third of that of the uncoated state. Thus DLC top-coating may be advantageous to reduce the friction of the tool on this substrate material efficiently.

The steady-state friction coefficient values for the different loading conditions are presented in Table 1, reflecting that the monolayer TiBN coating showed less favourable friction behaviour than the uncoated reference material for all tested loading forces. The lowest µ value obtained in the case of the DLC top-layers and its loading force dependence is explained by the tribochemical wear, which happens for the hydrogenated DLC coatings in dry sliding friction at certain higher loading conditions, supposedly because the necessary activation energy of the tribochemical reactions is supplied by the increased loading force [25-28].

Table 1. *The steady-state friction coefficient derived from the ball-on-disc test*

Loading force, F [N]	Steady-state friction coefficient, μ_{steady},				
	Uncoated	TiBN	TiBN+DLC	TiAlN+DLC	CrN+DLC
5	0.29	0.6	0.2	0.2	0.2
10	0.05	0.7	0.1	0.1	0.1
20	0.26	0.6	0.1	0.1	0.1

For all multilayer DLC top-coating systems, the type of the supporting sub-layers did not significantly affect the friction behaviour of the coating system, being the DLC top-layer dominant in the friction behaviour under the given loadings. This fact is reflected by the integrity of the DLC coatings kept throughout the total sliding distance, as seen in Figure 5.

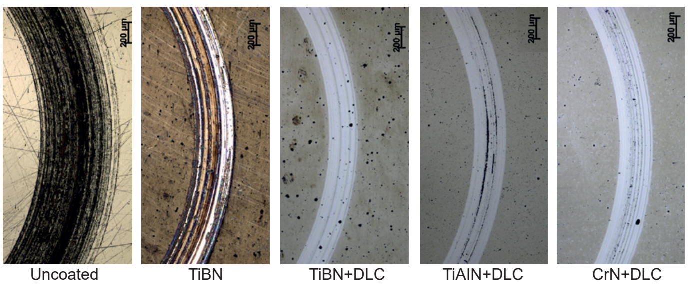

Figure 5. *OM photos of the worn tracks on uncoated and coated samples (v = 10 mm/s, F = 20 N)*

The width of the wear tracks, formed at identical loading conditions (at v = 10 mm/s, F = 20 N), were also measured in these optical microscopic images.

The worn cross section and the worn volume were then calculated by Eqs (1) and (2) and are illustrated in Fig. 6.

Based on the results, the uncoated specimen had the largest worn volume (14.6 mm³), while the second largest one (5.6 mm³), being an order of magnitude lower, was obtained for the TiBN monolayer.

The most wear-resistant coatings were the TiBN+DLC system, followed by the CrN+DLC and the TiAlN+DLC systems in the ranking (3.9, 4.6 and 4.5 mm³, respectively).

When evaluating these results, it is essential to consider that the total layer thickness of the TiBN+DLC coating was the largest one of that of all tested coating systems, while the thickness of the TiBN under-layer was also the largest one of that of the applied sub-layers. This condition can play an important role in the better wear resistance of these coatings. The reason for the non-uniform layer thicknesses is the generally used internal standards of the industrial producer, developed for the particular type of these coatings. The specific wear rate (k) changed analogously with the worn volume (Figure 6) that follows from its interpretation, given by Eq. (1).

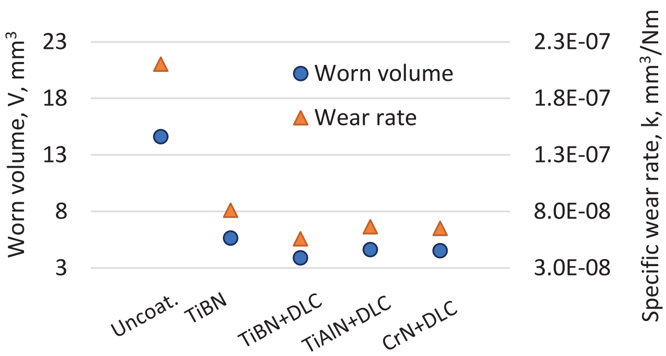

Figure 6. *The worn volume and specific wear rate (ball-on-disc test, v = 10 mm/s, F = 20 N)*

The calculated k values for the uncoated sample and the TiBN, TiBN+DLC, TiAlN+DLC and CrN+DLC systems were 21, 8.1, 5.6, 6.6 and 6.5 10^{-8} mm³/Nm.

3.4 Scratch test results

The most important findings were that the TiBN monolayer system and the DLC top-layered coating with TiBN under-layer operate with different scratch mechanisms. In the current study, completing the group of the DLC top-layered systems, the characteristic damage mechanisms for all of these multilayer coating systems were similar, as follows. Partial Tensile Cracking (PTC) and complete Tensile Cracking (CTC), Lateral Cracking (LC), Wedging Spallation (WS), and Total Delamination (TD), while in the case of the mono-layered TiBN coating Partial Recovery Spallation (PRS) and Complete Recovery Spallation (CRS) Buckling Spallation (BS), and Gross Spallation (GS) of the coating was found. These damage mechanisms and the associated critical and subcritical loads are summarized in the form of a scratch damage mechanism map (Figure 7). The damage mechanisms appearing at different subcritical and critical loads for the different coatings are represented by unified colours.

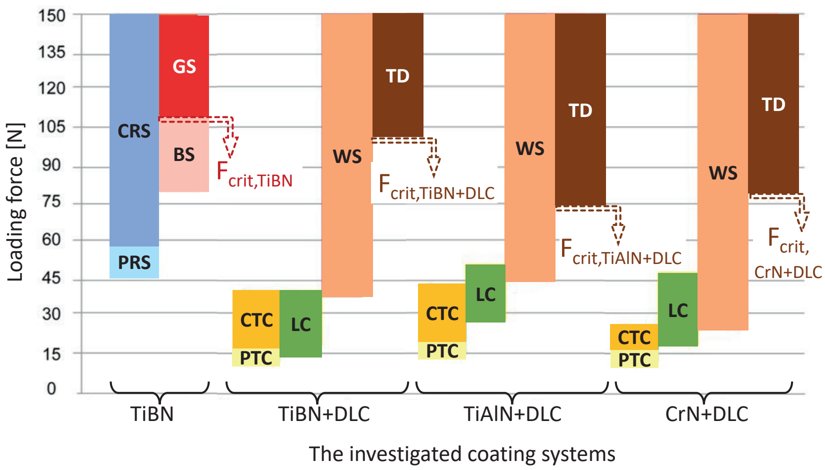

Figure 7. *The scratch damage mechanism map of the investigated coatings*

It is easily seen from the map that the monolayer TiBN and multilayer DLC top-coat systems represent two different groups of scratching behaviour characterized by different subcritical and critical damage mechanisms at different loadings. It is also clear that all tested DLC top-coat systems have identical failure mechanisms. The only difference for the DLC systems with different under-layers is the slight variation of the subcritical and critical loads.

Regarding all the tested tribosystems, the F_{crit} load – causing the total delamination or gross spallation of the coating – was the highest (F_{crit} = 109 N) for the monolayer TiBN coating, while among the DLC top-coat systems, the most favourable case (F_{crit} = 101 N) was realized by the one having the TiBN underlayer.

The weakest scratch resistance of all the tested coating systems was observed in the case of the DLC coating with CrN under-layer.

4. Discussion

For a comprehensive evaluation of these findings, test results are summarized in Figure 8, comparing the percentage change in hardness, coefficient of friction, and wear rate concerning that of the reference material while displaying the scratch test results numerically since these latter characteristics cannot be interpreted on the uncoated raw material.

Based on this overview chart, the following conclusions can be established:

The wear rate was lowered for each tested coating systems compared to the uncoated material. The decrease was 62% ÷ 73%. The wear rate was closely related to the surface hardness of the coatings. i.e., with increasing the hardness, the wear resistance was significantly improved.

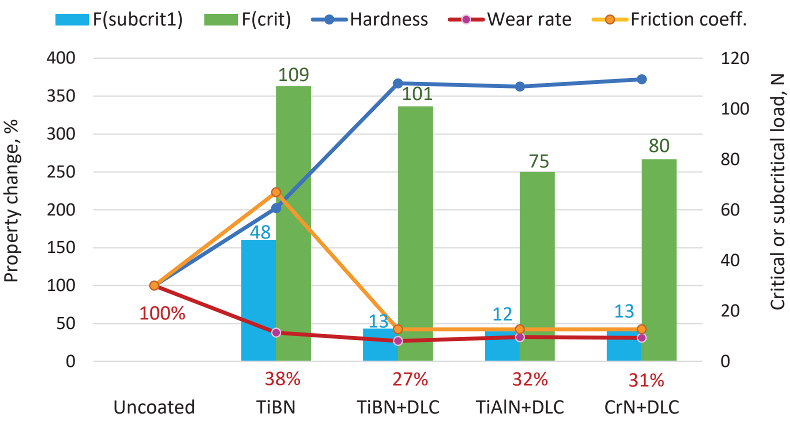

Figure 8. *Results of tribological investigation of the different coated samples*

The friction coefficient did not change analogously with the wear rate. For the monolayer TiBN, besides an improvement of the wear resistance (decreasing wear rate), a significant increase in the coefficient of friction was observed.

The lowest (0.1-0.2) steady-state friction coefficient was measured for the DLC top-coat systems, which are about one-third of that of the reference material (0.04-0.3) due to their tendency to a tribofilm formation, while for the TiBN monolayer coating, prone to abrasive wear, this value fell between 0.6-0.7, which was two times greater compared to the uncoated reference sample. This behaviour can be explained by the different controlling wear mechanisms of the TiBN monolayer coating, compared to that of the reference material and DLC top-coat systems, as mentioned above.

The wear resistance of the tested coatings didn't correlate with the scratch resistance. The monolayer TiBN had the best scratch resistance regarding the Fcrit and Fsubcrit forces but showed the lowest wear resistance among the tested coatings. In terms of the measured Fcrit and Fsubcrit values, this coating surpassed the multilayer DLC systems by 8-45 % and 270-300 %, respectively.

In contrast, the scratch resistance of DLC top-coated multilayer systems lagged far behind that of the monolayer TiBN while showing excellent wear resistance with a 16-29 % lower wear rate than that of the TiBN monolayer system.

During scratching of the multilayer DLC top-coat systems having different sub-layer architecture, the subcritical events related to the initial failure of the DLC top-layer occurred at closely identical subcritical forces (12-13 N), while a more expressed difference was found in terms of the critical loading force (75-101 N), related to the final failure of the coating influenced by the characteristics of the under-layers.

It is important to mention that the accuracy of the reported material testing data is influenced by several external and internal factors characteristic of each type of measurement.

The detailed discussion of the type and effect of these factors exceeds the framework of the current paper. However, the statistical features defined for the different test results summarized in Table 2. can help evaluate the reliability of the executed test procedures.

The repeatability of the different measurements can be characterized by the variation coefficient of the test data, which varied from 4.4 to 6.3 % for the microVickers tests, and from 6.4 to 13.1 % for the coating thickness values. Regarding the wear test characteristics, the range of the variation coefficient was 1.1… 5.6 % for wear track width data, 0…10.8 % for the friction coefficient values and 3.9… 21.8 % for the wear rates obtained during the ball-on-disc wear testing. During progressive loading scratch testing, the variation coefficient of the critical force values changed between 6.0 and 20.1 %

These values were characteristically the highest in the case of the CrN+DLC coating system, indicating a considerably higher inhomogeneity of the coating, especially in terms of the coating hardness, which directly affects the wear rate and scratch resistance. To increase the reliability of these tribological results, the influencing factors should be thoroughly analyzed and kept constant as much as possible.

5. Summary

Considering the objective of the publication, the literature data and the results of the performed tests, the following conclusions can be drawn.

1. The investigated PACVD DLC top-coated systems are the most favourable in terms of wear resistance

Table 2. *Overview of the statistical features obtained for the different test data*

Coating type	Hardness, HV0.01			Coating thickness, (Calotest) s, µm			Ball-on-disc wear test: Width of the wear track, t, µm			Ball-on-disc wear test: Friction coefficient, (v=10 mm/s, F=20 N), µ, –			Ball-on-disc wear test: Wear rate, kx10^{-9}, mm^3/Nm			Progr. loading scratch test: Critical load, F_{crit}, N		
	Average	St. Dev.	Var. coeff., %	Average	St. Dev.	Var. coeff., %	Average	St. Dev.	Var. coeff., %	Average	St. Dev.	Var. coeff., %	Average	St. Dev.	Var. coeff., %	Average	St. Dev.	Var. coeff., %
Uncoated	626	30.7	**4.9**	–	–	–	788.0	39.0	**5.0**	0.26	0.01	**3.70**	21.0	3.1	**14.7**	–	–	–
TiBN	1230	50.5	**5.0**	4.2	0.4	**8.9**	378.0	7.0	**1.9**	0.58	0.07	**10.77**	8.1	0.3	**3.9**	109	6.5	**6.0**
TiBN+DLC	2297	101.2	**4.4**	7.9	0.5	**6.4**	267.0	15.0	**5.6**	0.11	0.01	**5.25**	5.6	0.7	**11.7**	101	13.1	**12.9**
TiAlN+DLC	2270	143.2	**6.3**	6.8	0.9	**13.1**	315.0	5.0	**1.6**	0.11	0.00	**0.00**	6.6	0.3	**5.0**	75	6.8	**9.1**
CrN+DLC	2331	334.1	**14.3**	6.1	0.5	**7.4**	308.0	3.0	**1.1**	0.11	0.00	**0.00**	6.5	1.4	**21.8**	80	16.1	**20.1**

characterized by the wear rate.

2. The best scratch resistance – represented by the highest critical force causing the coating delamination – was observed for the PEMS PVD monolayer TiBN coating.
3. Regarding the factors having the most decisive role in the wear and scratch resistance of the tested coatings, the following conclusions can be made.
   3.1. In terms of wear resistance, coating hardness, and dominant wear mechanism, the beneficial effect of tribochemical wear, characteristic of the DLC coatings, should be emphasized. The latter one, parallel with the friction coefficient, is controlled by the type of the top layer.
   3.2. The type of the applied sublayer slightly modified the wear resistance of the multilayer coatings having the same DLC top coating. The performance was the best applying a TiBN under-layer, while it was the weakest using the TiAlN sub-layer.
   3.3. Regarding scratch resistance, layer adhesion is the dominant factor, which was the most favourable for the monolayer TiBN coating.

Summarizing these results with attention to the appropriate coating selection, the most important findings of the research are as follows:

All tested ceramic coating systems improved the tribological performance compared to the uncoated state. In terms of wear resistance, the TiBN+DLC multilayered system, while regarding scratch resistance, the TiBN monolayer provides the best performance on the given quenched and tempered X210Cr12 steel substrate.

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Előadások - Betekintő

Trampus Péter	Paradigmaváltás a roncsolásmentes vizsgálatban - úton az NDE 4.0 felé
Szávai Szabolcs, Dudra Judit, Erdei Réka	NDE 4.0 szerepe és lehetőségei
Tóth László, Trampus Péter, Mankovits Tamás	Szerkezetintegritási és roncsolásmentes vizsgáló szakmérnöki képzés
Török Béla, Rácz Árpád	Röntgensugaras roncsolásmentes módszerek alkalmazása régészeti leletek vizsgálatánál
Koroknai László, Dr. Pór Gábor, Szabados Ottó, Agócs Mihály, Molnár János, Kocsó Endre, Gárdonyi Gábor, Morvai Tibor, Csincsi Zsuzsanna	3D akusztikus mikroszkóp gépészeti és vezérlő szoftverének fejlesztése
Aleksandar Hiršl	APR vizsgálatok hőcserélő berendezéseken
Takács Csaba, Rózsahegyi Péter	Gőzfejlesztő csövek vizsgálata APR eljárással
Geréb János	Az AE műszerezés evolúciója Magyarországon
Joó Gyula	Petrolkémiában alkalmazott tömörségvizsgálatok
Méhész István	Műszaki folyamatok tervezése a Petrolszolg Kft-nél
Mirjana Opačić, Aleksandar Sedmak, Gordana Bakić, Nenad Milošević, Nikola Milovanovic	Application of advanced NDT methods to assess structural integrity of pressure vessel welded joints (Fejlett NDT módszerek alkalmazása nyomástartó edények hegesztett kötésein, szerkezeti integritásának felmérésében)
Samu Tamás, Bulla Péter Ágoston, Szabó Richárd	Vegyipari termelés támogatása NDT eszközökkel
Horváth Márk	Ipar 4.0 karbantartás roncsolásmentes eszközökkel (drónok, robotok, PTZ kamerák)
Homoki Ádám	Vasúti kerekek futófelületének ultrahangos vizsgálata
Magyar Katalin	Állapotalapú karbantartás és online gépdiagnosztika jelentősége a fenntartható fejlődés tükrében (SDG irányelveknek való megfelelés
Maloveczky Anna, Takács Sándor	Sprinkler rendszerben végbemenő biológiai korrózió sebességének becslése ultrahangos falvastagságmérés alapján
Mészáros István Attila, Berecz Tibor, Kemény Dávid	Korrózióálló acélban lezajló spinodális bomlási folyamat NDT vizsgálata
Windisch Márk, Maloveczky Anna, Rigó István, Veres Miklós, Dankházi Zoltán, Vida Ádám	Felületerősített Raman-spektroszkópiában alkalmazott, lézerrel létrehozott SERS-hordozó vizsgálata
Szabó József	Roncsolásmentes szabványosítás hírei
Tallósy Judit	Laboratóriumok akkreditálása a gyakorlatban
Szabó Tamás	Comet Mesofocus – A röntgen technológia új generációja
Pál Csaba	Nyomástartó berendezések időszakos szerkezeti vizsgálata komplex akusztikus emissziós mérésekkel
Dénesné Wiegand Krisztina	Brexit és az UKCA jel
Szűcs Pál	MSZ EN ISO 9712:2022, ami az anyagvizsgálókra vonatkozik
Ralph Giese	Digitális radiográfia az új 9712 tükrében
Fücsök Ferenc	A MAROVISZ jártassági vizsgálatok tapasztalatai és jövője
Ralf Zeiberts	Repedések előjelzése riluminàti alkalmazásával
Benedek Béla	Röntgencsövek fókuszfolt mérése digitális technikával
Horváth Márk	Roncsolásmentes minőség ellenőrző eszközök a gyártási folyamatokban (Ultrahang, videó endoszkóp és érintés alapú ellenőrzések és mérések)