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Microstructure and tribological study of TiAlCN and TiTaCN coatings

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ABSTRACT
The low coefficients of friction and wear rates of transition metal carbonitride make them excellent candidates for friction and wear applications. Coatings based on titanium carbonitride alloyed with Ta and Al were deposited using reactive magnetron sputtering on the surface of titanium VT1-0 and steel AISI 304. The effect of alloying titanium carbonitrides with Ta and Al and acetylene flow during deposition on the structure, composition, and tribological properties of the coating was studied. TiAlCN and TiTaCN coatings were deposited in various acetylene flows along with stable argon and nitrogen flows. Scanning electron microscopy, optical microscopy, X-ray phase analysis, and sliding wear test (ball-on-disk method) in two media were used to study the resulting coatings. The average coefficient of friction of the coating under friction without lubrication varied in the range of 0.13-0.85 and under friction with lubrication in the range of 0.0015-0.081. From the point of view of wear rate, it is shown that the most wear-resistant coating under friction conditions with and without lubrication is TiAlCN-2. The resulting coatings can be useful as protection for machine parts or tools that are subject to friction and wear.

Keywords: titanium carbonitride, magnetron sputtering, alloying, coefficient of friction, wear rate, wear resistance.

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Introduction

Hard protective coatings greatly contribute to increasing wear resistance and increasing the service life of components and machine structures that are constantly subjected to mechanical and chemical degradation due to wear processes [[1],[2], [3]]. The use of hard protective coatings such as TiC [4], TiN [5], TiCN [6], TiAlN [7], TiSiC [8], thin multi-layer coatings [9], diamond-like films [[10], [11]], and others are a suitable way to protect machine parts or tools from environmental hazards and wear. In these works, it is noted that coatings based on titanium carbides and nitrides provide good wear resistance due to a combination of ductility and hardness, and high adhesion to the substrate.

To date, various physical and chemical deposition technologies are used to obtain solid protective coatings. There are such methods as magnetron sputtering (MS) [12], cathode sputtering [13], plasma deposition [14], laser methods [15], CVD-based methods [16], and others. Among them, MS is very often used for applying various hard tribological coating based on titanium carbonitride (TiCN) with increased wear resistance. MS provides a low level of impurities and allows easy control of the deposition rate. Several studies of TiCN [[13], [17], [18], [19]] have been carried out to study the tribological properties coatings obtaining by magnetron sputtering. The advantages of these coatings over other coating materials are associated with their excellent friction characteristics in contact with steel, high hardness, and residual stress [[20], [21]].

To meet the increased requirements for wear-resistant coatings, it is necessary to complicate the composition of the coating more and more, using metal alloying additives. To improve the tribological properties of TiCN coatings, alloying with such metals as Al, Ag, O, Zr, Cr, etc. is carried out [[7], [22], [23]]. Srinath M.K. and colleagues [1] reported that TiCN-coated Al-7075 heat-treated at 500°C for 1 hour gives good results in terms of wear resistance and corrosion resistance. Recently, in [22], the authors reported that the addition of Ag to the TiCN coating can improve friction and wear resistance at room and elevated temperatures. In [20], the surface and tribological parameters of Ti(C,O,N) coatings were analyzed and discussed depending on the composition and structural features of the films, as well as their thickness. In our previous work [23], the tribological and corrosion properties of TiCN coatings doped with Cr and Zr were studied. The combined results of this work showed the most preferable composition, the $Ti_{21}Zr_{12}C_{35}N_{32}$ (TiZrCN-1) coating, which is resistant to wear and corrosion damage.

To date, a lot of data has been published on the efficient use of magnetron sputtering for the deposition of wear-resistant alloyed TiCN coatings. At the same time, information on the analysis of the wear characteristics of TiAlCN and TiTaCN coatings is very limited. Only a few works are devoted to the analysis of TiAlCN coatings, and there is even no work on the analysis of TiTaCN coatings. In this regard, it seems interesting to study the effect of doping with Al and Ta on the tribological characteristics of TiAlCN and TiTaCN coatings.

Materials and methods

Substrate preparation and coating process

The TiAlCN and TiTaCN coatings were deposited in a 100 kHz pulsed DC MS system. The distance between the target and the substrate holder was kept constant and equal to 30 cm. Composite targets were fabricated for the deposition of TiAlCN and TiTaCN coatings. To do this, an alloying element in the form of 3 disks of aluminum and tantalum was welded onto the sputtered surface of a VT1-0 titanium target. Three disks of aluminum and tantalum were welded onto the surface of the titanium target. Well-polished disks (Ø 58 mm) made of VT1-0 titanium and AISI 304 steel were used as substrates. When preparing the surface of the substrates for deposition, grinding with sandpaper, four-stage polishing with diamond paste and ion cleaning in a vacuum were used, which is described in detail. in [[19], [23]]. Before deposition, the chamber was evacuated to a base pressure below $3\cdot10^{-3}$ Pa. Scheme of the process of preparing the substrate and coating deposition shows in figure 1. The MS facility is equipped with an APEL-IS-21CELL ion source (Applied Electronics, Tomsk, Russia) and APELMRE100 magnetrons (Applied Electronics, Tomsk, Russia). The potential shift to the substrate was fixed at -70 V, which was supplied using an APEL-M-5PDC power supply (Applied Electronics, Tomsk, Russia). This potential value was chosen based on the results described in our earlier published work [19]. The flow rate of the inert and reactive gas was controlled using RRG-12 flowmeters (Eltochpribor, Moscow, Russia). Previously, composite targets were worked out to clean the surface from unwanted contaminants. The deposition parameters of all obtained coatings are presented in Table 1.

Table 1 - Magnetron sputtering parameters for the obtained coatings

Coating	Coating deposition parameters				
	Chamber pressure, Pa	Plasma current, A	Flow of inert and reactive gas, sccm	Substrate bias, V	Deposition time, min
TiAlCN-1	0.45	2	Ar = 18; C_2H_2 = 3.4; N_2 = 3	-70 V	120
TiAlCN-2	0.45	2	Ar = 18; C_2H_2 = 4.6; N_2 = 3	-70 V	120
TiTaCN-1	0.45	2	Ar = 18; C_2H_2 = 3.4; N_2 = 3	-70 V	120
TiTaCN-2	0.45	2	Ar = 18; C_2H_2 = 4.6; N_2 = 3	-70 V	120

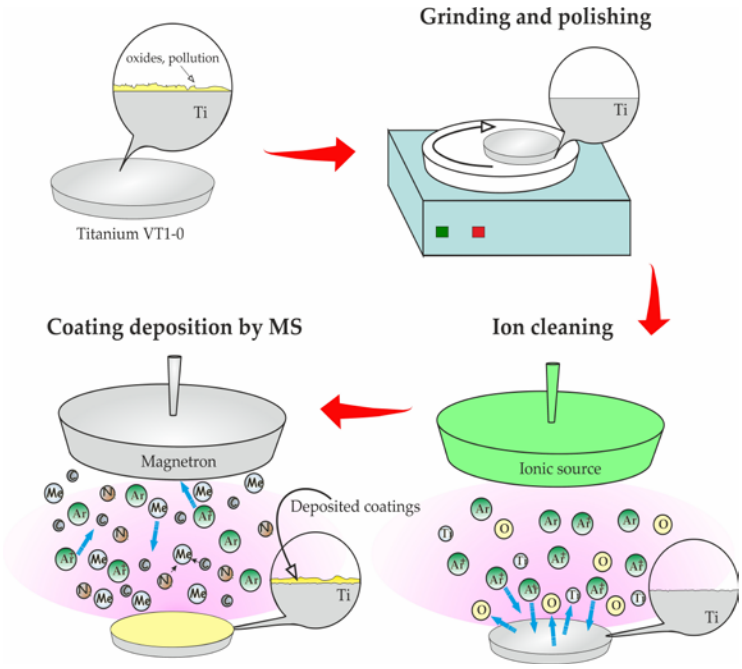


Figure 1 – Scheme of the process of preparing the substrate and coating deposition.

Morphology and composition of coatings

The surface morphology of the coating was studied by scanning electron microscopy (SEM). For these purposes, an electron microscope model JXA-8230 (JEOL, Tokyo, Japan) with an accelerating voltage of 25 kV and an electron beam current of up to 7 nA was used. All selected coatings were studied in the backscattered electron mode (COMPO). The elemental composition of the coating was analyzed by energy dispersive X-ray analysis (EDX) over the surface area of the coating 40 × 40 μm^2 at ×2000 magnification.

Optical microscopy was used to check the coating thickness. Micrographs were taken with a Leica DM IRM optical microscope (Leica, Wetzlar, Germany). The thickness of the coatings was measured in several areas at least 20 times. In the work, the average thickness of each coating was given.

The phase composition and crystal structure of the coating were determined on a D8 Advance diffractometer (BRUKER, Karlsruhe, Germany) with α-Cu radiation (λ ≈ 1.54 Å). Radiography was performed with focusing according to the Bragg–Brentano method. The diffraction patterns were recorded in the range of angles 2θ: 20–90° with a step of 0.05°, a shooting rate of 2 deg/min at a voltage of 35 kV and a current of 20 mA. The PDF 2 database was used for phase analysis.

Tribological tests

To measure the tribological characteristics of TiAlCN and TiTaCN, coatings were deposited on the surface of a substrate made of VT1-0 titanium and AISI 304 steel with a diameter of 58 mm. The tribological characteristics of the coatings were measured in the ball-on-disk sliding friction mode on a TRB^3 tribometer (CSM Instruments, Pese, Switzerland) at room temperature in friction conditions with and without lubrication. Test parameters in friction without lubrication: speed of movement of the sample surface relative to the counterbody – 1 cm/s, load – 2 N, the radius of the wear track – 4 mm, friction path – 300 m, data acquisition rate – 50 Hz, a ball of Si_3N_4 was used as a counterbody 6 mm in diameter.

Under lubricated friction conditions, TM-5-18 API GL-5 gear oil was used. Test parameters in friction with lubrication: speed of movement of the sample surface relative to the counterbody – 1 cm/s, load – 5 N, the radius of the wear track – 27 mm, friction path – 17500 m (200000 cycles), data acquisition rate – 50 Hz, as a counterbody a ball made of steel grade ShH15 (SUJ2) with a diameter of 3 mm was used. Test conditions are following international standards ASTM G99-959. The wear given in the work was calculated from the volumetric wear of the coatings during tribological tests. To do this, using a profilometer brand 130

(Proton, Zelenograd, Russia) measured the cross-sectional area of the wear track. Next, the wear rate was calculated according to formulas 1 and 2. Quantitatively, the loss of volume during wear is carried out according to the formula:

• sample volume loss, (mm^3)

$$\Delta V = S \cdot l \tag{1}$$

The wear I given in the work was calculated using the volume loss during the test ΔV for the values of the run N and the applied load P:

$$I = \Delta V / N \cdot P \tag{2}$$

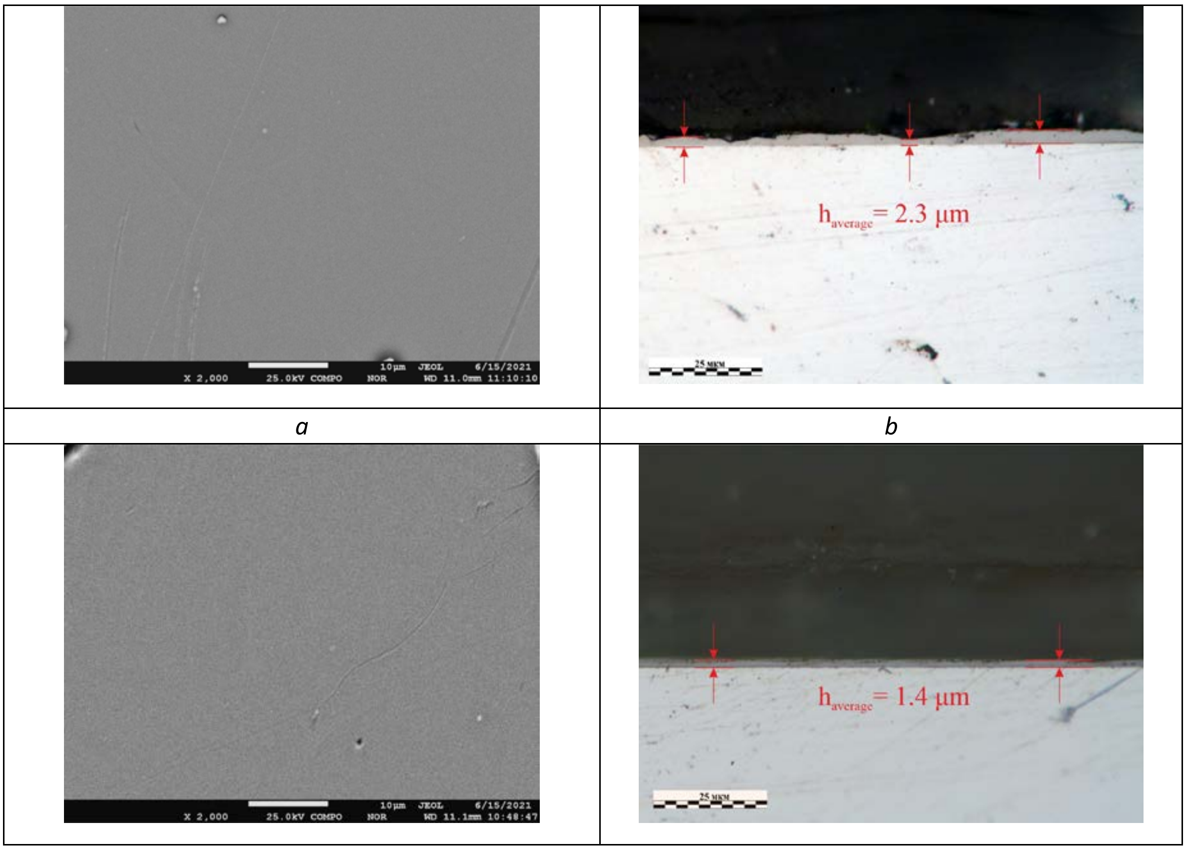
Optical microscopy was used to take pictures of the wear tracks after the tribological test.

Research results

Morphology and composition of coatings

The surface morphology of the coating and the thickness of the coatings was measured by SEM and optical microscopy, respectively. Figure 2 shows that the coating material was evenly distributed over the surface of the steel substrate. The morphology of the coatings has a smooth and dense structure without visible chips and cracks. It can be seen from the image that dome-shaped nuclei are locally located on the surface of the samples. All deposited MS coatings showed a similar surface structure, and no significant changes were observed after alloying with aluminum and tantalum. According to the results of optical microscopy, it was determined that the TiAlCN-1, TiAlCN-2, TiTaCN-1, TiTaCN-2 coatings have an average thickness of 2.30, 1.40, 2.56, and 2.23 µm, respectively. When coatings are deposited in an acetylene flow of 3.4 sccm, the thicknesses of the coatings are approximately similar in both cases (2.30 and 2.56 µm), while at a flow of 4.6 sccm, the difference is noticeably greater (1.40 and 2.23 µm). One of the reasons for these changes in thickness is the sputtering coefficients of aluminum and tantalum under the action of working gas ions.

Table 2 shows the composition of the TiAlCN and TiTaCN coatings deposited at different flows of the reaction gases of acetylene and nitrogen. The concentration of Al and Ta in the deposited coatings undergoes insignificant changes in the range from ~ 4.8 to 6.7 at. %. Also, titanium in all coatings



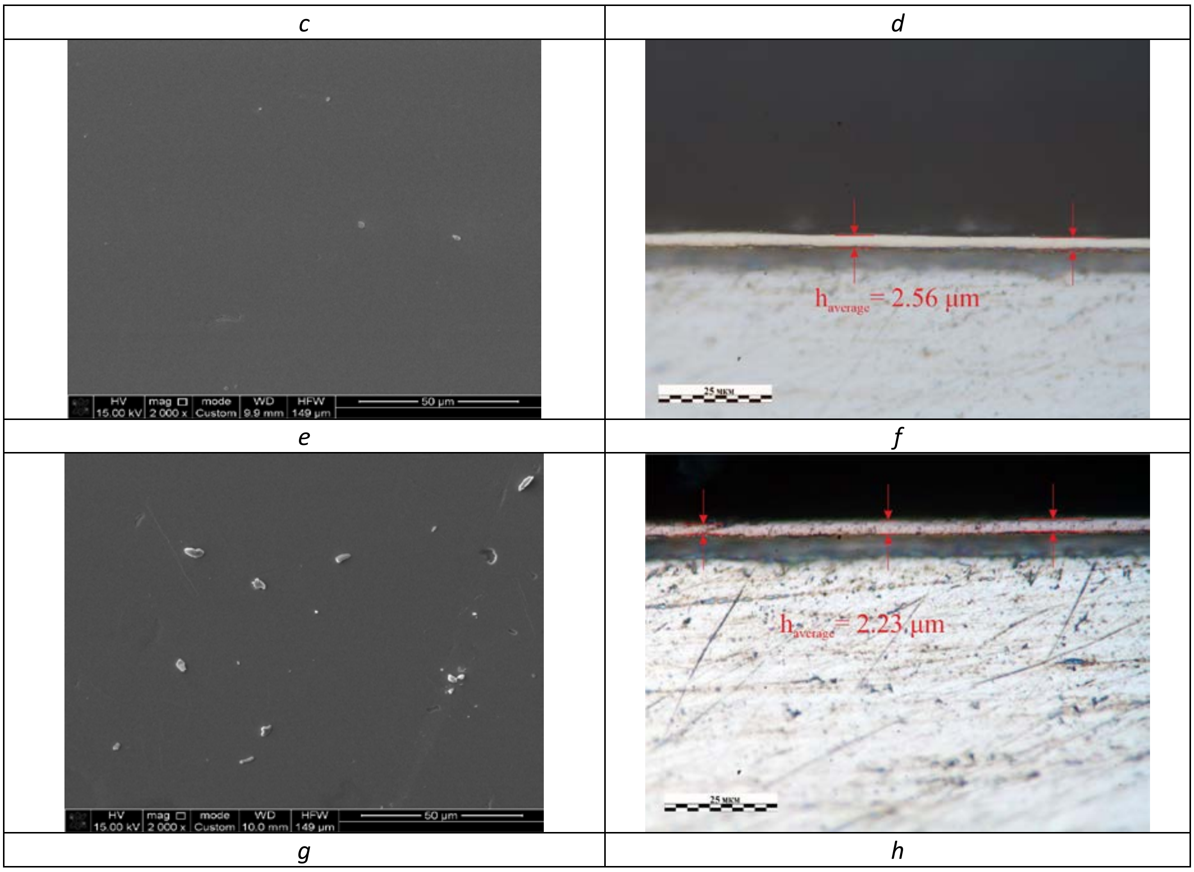


Figure 2 – SEM images of the morphology and optical images of the thickness of the cross sections of samples: (a) TiAlCN-1 surface, (b) TiAlCN-1 thickness, (c) TiAlCN-2 surface, (d) TiAlCN-2 thickness, (e) surface TiTaCN-1, (f) TiTaCN-1 thickness, (g) TiTaCN-2 surface, (h) TiTaCN-2 thickness

Table 2 - Elemental composition and (C+N)/(sum of metals) of deposited coatings

Coating	Elemental composition of deposited coatings, at.%					(C+N)/(sum of metals)
	Ti	Al	Ta	C	N	
TiAlCN-1	31.6	4.8	–	21.1	42.5	1.75
TiAlCN-2	36.7	5.5	–	29.9	27.9	1.37
TiTaCN-1	32.9		6.7	19.5	40.9	1.84
TiTaCN-2	31.5		6.4	24.5	37.6	1.97

showed only small changes in the region of 31-37 at. %. It is interesting to note that carbon content only in the TiAlCN-2 coating is closer to 30 at. %, in other coatings it is stable within 19-24 at. %, this in turn has the opposite effect on nitrogen. The ratio (C+N)/(sum of metals) for TiAlCN coatings decreases from 1.75 to 1.37 with increasing acetylene flow, and in the case of TiTaCN coating, it increases from 1.84 to 1.97.

The phase composition of the deposited coatings was analyzed using X-ray phase analysis. Figure 3 shows the results of the analysis of all obtained coatings. As shown in the X-ray diffraction patterns, the TiAlCN coatings consist of several phases with preferred orientations in the [100] and [200] directions, and in the case of TiTaCN coatings, in the direction [111] and [200]. In TiAlCN coatings, X-ray diffraction patterns show peaks of carbonitride and nitride phases, such as Ti_2CN, $TiC_{0.5}N_{0.12}$, $(TiN)_{0.96}$, $Ti_2Al(N_{0.5}C_{0.5})$ and $Ti(C_{0.25}N_{0.75})$. In the TiTaCN coatings, phases consisting of $Ta_{0.47}Ti_{0.53}N_{0.47}C_{0.53}$, $TiC_{0.496}N_{0.502}$, $TaTiN_2$, $(TaTi)C_2$ and $TaC_{0.7}N_{0.3}$were identified in the X-ray diffraction patterns. As the rate of C_2H_2 flow into the TiTaCN-2 coating increases, an additional peak appears, indicating the presence of the $(TaTi)C_2$ phase.

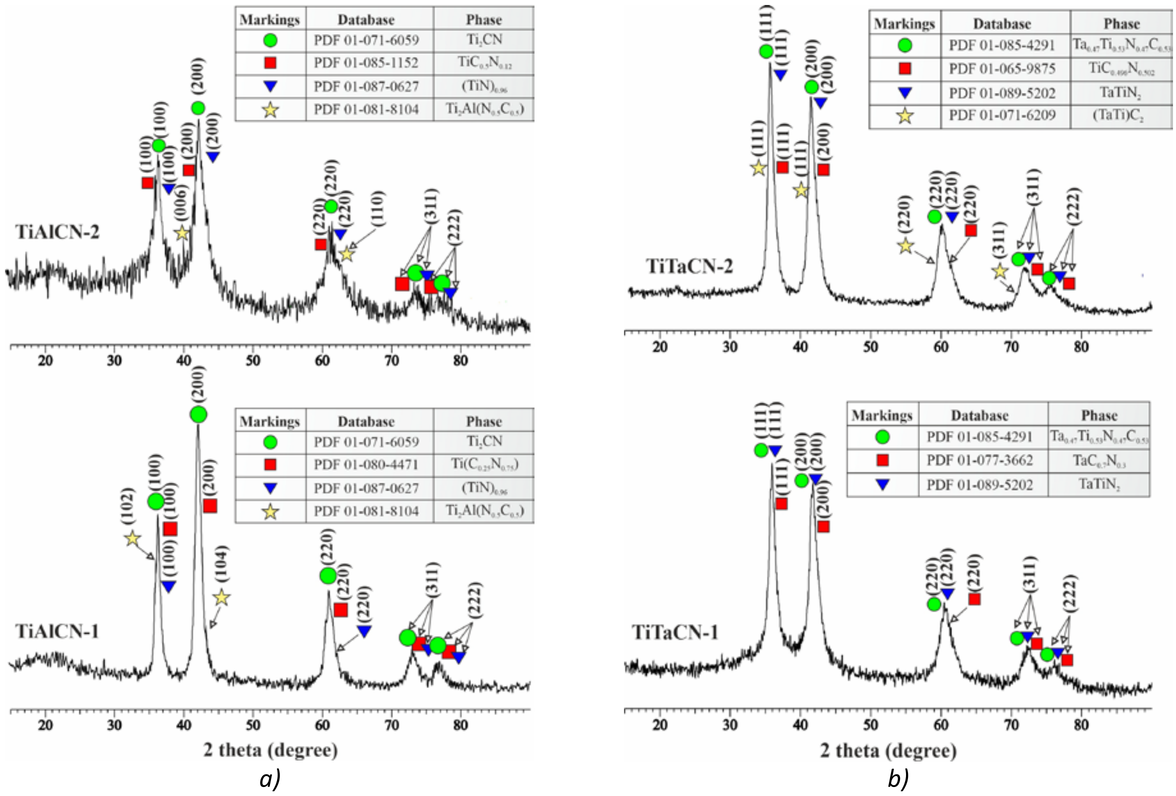


Figure 3 - Results of phase analysis of coatings: (*a*) TiAlCN, (*b*) TiTaCN

Tribological testing of coatings

The friction wear test was performed under friction conditions with and without lubrication. According to friction conditions without lubrication, where the coatings were tested on the surface of a titanium substrate with a diameter of 58 mm. Figure 4 shows the coefficient of friction (CoF) plots with the averaged value of all deposited TiAlCN and TiTaCN coatings obtained at different flows of carbon-containing gas. The TiAlCN-2 coating shows the lowest and most stable CoF compared to other coatings. TiAlCN-1 and TiTaCN-2 coatings in the friction area from 0 to 150 m are characterized by an increase in CoF and then CoF becomes stable.

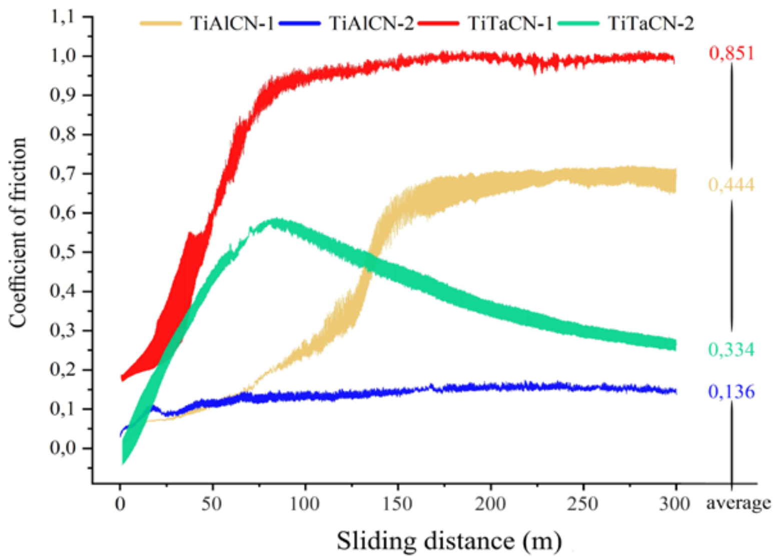


Figure 4 - CoF coatings with an average value obtained under friction conditions without lubrication

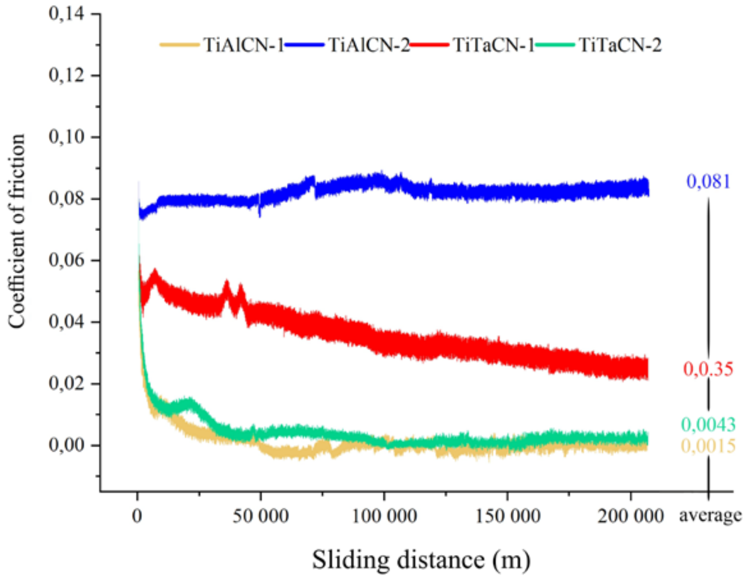


Figure 5 - CoF coatings with an average value obtained under friction conditions with lubrication

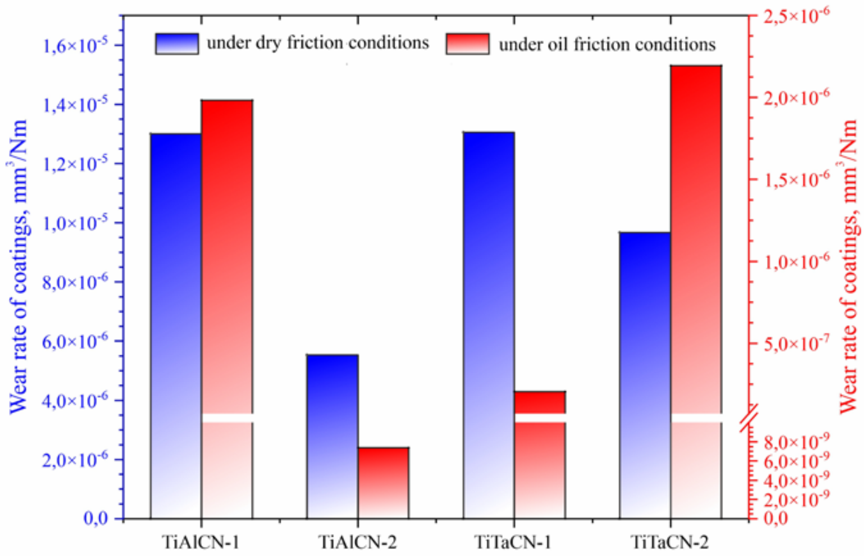


Figure 6 - Wear rates of the studied coatings in two friction conditions

In the case of testing under lubricated friction conditions, very low CoFs were recorded. The results of these tests are presented in Figure 5, where the coatings were tested on the surface of a steel substrate with a diameter of 58 mm. TiAlCN-1 and TiTaCN-2, which had CoF of 0.0015 and 0.0043, had the smallest CoF among the studied coatings. After them, there is a coating of TiTaCN-1. The TiAlCN-2 coating had the highest CoF value of 0.081, although this coating under friction condition without lubrication showed the best result with a low CoF. In general, when the friction test enters a relatively stable stage, all coatings show a stable CoF value with rare small fluctuations.

Figure 6 shows the wear rates of all coatings under frictional wear conditions with and without lubrication. To compare the results, the wear test of the coatings in each medium was carried out under the same conditions in the ball-on-disk system. The results under friction conditions without lubrication show a spread in wear rate (WR) from 5.5×10^{-6} to 1.3×10^{-5} mm^3/Nm. When tested under friction conditions with lubrication, the coatings wore out much lower due to the lubricating medium with WR from 7.4×10^{-9} to 2.2×10^{-6} mm^3/Nm. In the case of the TiAlCN coating, WR decreases with an increase in the carbon content in the TiAlCN coatings due to an increase in the C_2H_2 flux during the deposition process and reaches the lowest value among the studied coatings (7.4×10^{-9} mm^3/Nm). With respect to TiTaCN coatings, WR increases with an increase in the carbon content in the composition. This was probably caused by the low hardness of the TiTaCN-2 coating.

Research discussions

An increase in the acetylene flow from 3.4 to 4.6 sccm leads to an increase in the carbon concentration and a change in nitrogen composition in the deposited coatings. The interaction between C and N atoms can also contribute to a nonlinear change in the C content, as described in [[24], [25]]. It is known that the ratio (C + N)/(sum of metals) should tend to 1, however, there are works where the ratio is higher than unity. In particular, in our previous work [23], a TiZrCN coating with a (C+N)/(Ti+Zr) ratio of 2.04 characterized by the highest wear resistance among the studied coatings. Also, other works show high abrasion resistance of coatings with a ratio greater than one: (C+N)/(Ti+Al) up to 1.75 [26], (C+N)/(Zr+Hf) [27] up to 3.1.

The phase composition of the TiAlCN-1 and TiAlCN-2 coatings differs in that $Ti(C_{0.25}N_{0.75})$ transforms into $TiC_{0.5}N_{0.12}$ as the C_2H_2 flow rate increases due to the difference in the elemental composition. In addition, the half-width of the peaks shows that with an increase in the carbon content, the probability of the formation of an amorphous phase increases, which contributes to a decrease in crystallinity. If the concentration of C exceeds its solid state solubility in the crystalline phase, excess C will begin to form a carbon-rich amorphous phase [28]. In the case of TiTaCN, no broadening of the half-width of the peaks is observed, i.e., there is no decrease in the crystallinity of the coating, as in TiAlCN-2. Apparently, the carbon content was not excessive (24.5 at %) for the formation of a carbon-rich amorphous phase.

As can be seen from the friction results without lubrication, the TiAlCN-2 coating has the lowest and most stable CoF compared to the other coatings, indicating that this coating has low friction resistance [[29-32]]. In addition, low CoF can be associated with the formation of debris in the wear track, which leads to the subsequent formation of a lubricating transition layer, mainly due to an increase in carbon sp^2 [33]. Moreover, the elemental and phase composition of this coating has the highest carbon content. With the TiTaCN-2 coating, one can observe a significant increase at the beginning of the test and a subsequent gradual drop in CoF, which is related to the run-in period. The running-in period can be characterized by grinding of the roughness peaks on the coating surfaces [[34], [35]]. A possible reason for the sharp increase in CoF for TiAlCN-1 and TiTaCN-2 coatings may be related to the onset of the degradation process, although no serious damage to the coating was observed after testing. Summarizing the results of CoF, we can say that an increase in the acetylene flow during the deposition of carbonitride films leads at least to a decrease in CoF in friction without lubrication. The presence of amorphous carbon in composite films can significantly reduce the friction coefficient [36].

In the case of testing under friction conditions with lubrication, CoF has significantly lower values compared to the results of CoF in conditions without lubrication. Such a difference in the results depends on many factors: tribochemical processes during abrasion, counterbody material, lubricating medium, load, etc. As a rule, the friction parameters on the contact surface is largely determined by the physical state of the contact surface and the chemical interactions between the sliding surfaces and the environment. medium [37]. As can be seen in Figures 4 and 5, the frictional behavior of the deposited coatings under friction conditions without lubrication was more unstable with sharp jumps or a decrease in CoF after running in, and under friction conditions with lubrication, CoF of tribo-pairs showed the most stable performance with small jumps.

It has been determined that an increase in the C_2H_2 flow during MS deposition leads to a decrease in the WR of the coating. Since, according to the graph in Figure 6, it can be seen that the TiAlCN-2 and TiTaCN-2 coatings have low WR in friction without lubrication compared to the results of the TiAlCN-1 and TiTaCN-1 coatings. One of the reasons for the decrease in WR with an increase in the carbon content in the coatings can be associated with formation of a thin lubricating tribolayer formed upon contact of friction bodies. This is

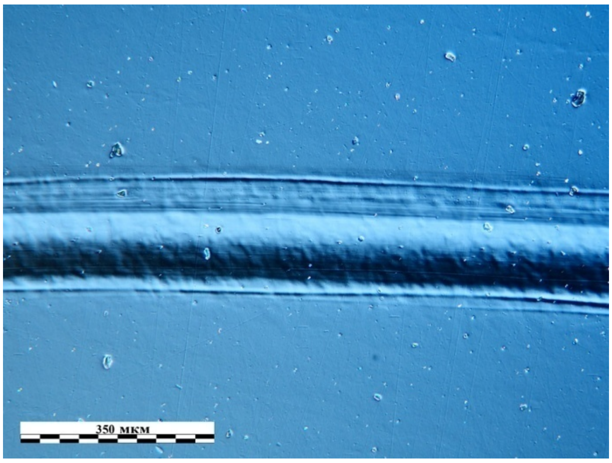


Figure 7 - Deformation of the surface of the substrate coated with TiAlCN-2 after a friction test with lubrication

mainly due to the increase in carbon sp^2 [33]. In a tribological test with respect to steel ShKh15 (SUJ2) under lubricated friction conditions, the deposited coatings showed completely different WR results compared to the test without lubrication. When sliding along a steel ball-coating scheme, the change in the tribological characteristics of the coatings was strongly influenced by the difference in hardness between the ball and the coating. In most cases, in the wear track, the coating was "punched" along with the surface of the substrate material. Figure 7 shows the local deformation caused by the action of the counterbody on the surface of the substrate through the coating, which occurred when testing the TiAlCN-2 coating with lubrication.

Summarizing the results of tribological testing in the two studied mediums, we can say that after the completion of the tests, no obvious destruction of the deposited coatings was observed. The clear favorite among all obtained coatings is the TiAlCN-2 coating with WR 7.4×10^{-9} mm^3/Nm under friction conditions with lubrication and 5.5×10^{-6} mm^3/Nm under friction conditions without lubrication. The difference and scatter of all wear rate results can also be related to the thickness of the coating. As is known that with an increase in the thickness of the coating of the resulting MS, the adhesion strength to the substrate decreases, which negatively affects the tribological characteristics. But the residual stress of the resulting coatings can also be of great importance, even if they cannot be quantified for the studies given. Thus, Al alloying of titanium carbonitride coatings can increase the service life of machine parts and mechanisms operating under friction and wear conditions than Ta alloying. Although it should be noted that the TiTaCN-1 coating also had good wear resistance.

Conclusions

In this work, TiAlCN and TiTaCN coatings were deposited by reactive magnetron sputtering in an argon-acetylene-nitrogen atmosphere. The carbon content of the coatings varied with the acetylene flow, which in turn affected the nitrogen content. The resulting coatings had a dense structure with thicknesses from 1.4 to 2.5 μm with a stoichiometric ratio (C+N)/(sum of metals) from 1.37 to 1.97. It has been determined that carbonitride phases are formed in TiAlCN coatings with preferential orientation in the [100] and [200] directions and the case of TiTaCN coatings [111] and [200] directions. The average coefficient of friction of the coating under friction without lubrication varied in the range of 0.13-0.85 and under friction with lubrication in the range of 0.0015-0.081. It has been established that an increase in the flow of acetylene during the deposition of TiAlCN and TiTaCN coatings leads at least to a decrease in CoF and WR during friction without lubrication. In the case of tribological testing under lubricated friction conditions, it was found that an increase in the carbon content in the TiAlCN coatings due to an increase in the C_2H_2 flux during the deposition process contributes to a decrease in WR. In relation to TiTaCN coatings, WR increases, probably due to the low hardness of the coating and insufficient content of carbon amorphous phases.

Thus, alloying titanium carbonitride (TiAlCN-2) coatings with aluminum can increase the service life of parts of machines and mechanisms operating under friction conditions, since such coatings showed the least result in terms of wear rate (7.4 × 10^{-9} mm^3/Nm under lubricated friction conditions and 5.5 × 10^{-6} mm^3/Nm under friction conditions without lubrication) and low coefficients of friction.

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TiAlCN және TiTaCN жабындарының микроқұрылымы мен трибологиялық зерттеуі

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ТҮЙІНДЕМЕ
Өтпелі металл карбонитридтерінің үйкеліс пен тозу жылдамдығы коэффициенттерінің төмен болуы, оларды механикалық үйкеліс пен тозу саласында қолдануда таптырмас материал етеді. Та және Al легірленген титан карбонитридіне негізделген жабындар титан VT1-0 және AISI 304 бетінде реактивті магнетронды шашырату арқылы тозаңдатылды. Жабындының құрылымына және құрамына, трибологиялық қасиеттеріне титан карбонитридін Та және Al қоспаларымен легірлеу және тозаңдату кезінде ацетилен ағынының әсерлері зерттелді. TiAlCN және TiTaCN жабындары тұрақты аргон және азот ағындарымен бірге әртүрлі ацетилен ағындарында тозаңдатылды. Алынған жабындарды зерттеу үшін сканерлеуші электронды микроскопия, оптикалық микроскопия, рентгендік фазалық талдау және екі ортадағы сырғымалы тозу сынағы (дисктегі шар әдісі) қолданылды. Құрғақ үйкеліс жағдайында жабынның орташа үйкеліс коэффициенті 0,13-0,85 және майлы үйкеліс жағдайында 0,0015-0,081 аралығында өзгерді. Тозу жылдамдығы тұрғысынан TiAlCN-2 ауада және майлы ортада тозуға ең төзімді жабын екені анықталды. Алынған жабындар үйкеліс пен тозуға ұшырайтын машина бөлшектерінің немесе құралдардың қорғанышы ретінде пайдалы болуы мүмкін.
Түйін сөздер: титан карбонитриді, магнетронды шашырату, легірлеу, үйкеліс коэффициенті, тозу жылдамдығы, тозуға төзімділік.

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Микроструктура и трибологическое исследование покрытий TiAlCN и TiTaCN

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АННОТАЦИЯ

Низкие коэффициенты трения и скорости износа карбонитридов переходных металлов делают их отличными кандидатами для применения в областях трения и износа. Покрытия на основе карбонитрида титана легированные Ta и Al были нанесены с использованием метода реактивного магнетронного распыления на поверхность титана ВТ1-0 и AISI 304. Исследовано влияние легирования карбонитрида титана Ta и Al и потока ацетилена в процессе осаждения на структуру, состав и трибологические свойства покрытия. Осаждались TiAlCN и TiTaCN покрытия в разных потоках ацетилена наряду со стабильными потоками аргона и азота. Для исследования полученных покрытий использовались сканирующая электронная микроскопия, оптическая микроскопия, рентгенофазовый анализ и испытание на износ при скольжении (метод шар на диске) в двух средах. Средний коэффициент трения покрытия в условиях сухого трения варьировалась в диапазоне 0.13-0.85 и в условиях маслянного трения в диапазоне 0.0015-0.081. С точки зрения скорости износа показано, что наиболее износостойким покрытием на воздухе и в масленной среде является TiAlCN-2. Полученные покрытия могут быть полезны в качестве защиты для деталей машин или инструментов, которые подвергаются к трению и износу.

Ключевые слова: карбонитрид титана, магнетронное распыление, легирование, коэффициент трения, скорость износа, износостойкость.

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