EJONS
Uluslararası Matematik, Mühendislik ve Doğa Bilimleri Dergisi
International Journal on Mathematic, Engineering and Natural Sciences

Research Article e-ISSN: 2602 - 4136 https://doi.org/10.5281/zenodo.15768059

Effect of Ti/Cr Ratio on Wear Performance of (Ti,Cr)N Coatings

Elif BAŞER *[1] **Ege Anıl DİLER** [2]

[1] Ege University, Graduate School of Natural and Applied Sciences, Izmir, Turkey
[2] Ege University, Department of Mechanical Engineering, Izmir, Turkey
Corresponding Author Email: baserelif4@gmail.com

Article Info

Received: 04.05.2025
Accepted: 16.06.2025

Keywords
Coating,
CrN,
TiN,
(Ti,Cr)N,
Ti/Cr ratio,
Wear performance

Abstract: The wear performance of CrN, TiN, and (Ti,Cr)N coatings on Cr12MoV steel was thoroughly investigated. This research also delved into the impact of the Ti/Cr ratio within the (Ti,Cr)N coating, as well as the effects of the applied wear test load and sliding speed on the wear behaviour. The wear behaviours in CrN, TiN, and (Ti,Cr)N coatings was sought through the examination of their hardness, steady friction coefficient, and wear rate. TiN coating showed superior hardness compared to CrN. The CrN coating consistently demonstrated the lowest friction coefficient, whereas TiN coating showed the highest. Despite its high hardness, the TiN coating exhibited the highest wear rate due to its high friction. The CrN coating, with lower hardness, showed the highest wear resistance. The hardness of (Ti,Cr)N coatings was significantly influenced by the Ti/Cr ratio. (Ti,Cr)N coatings enabled friction control, and reducing the Ti/Cr ratio led to a decrease in friction coefficients. This, combined with their high hardness, resulted in a notably competitive wear performance.

1. Introduction

Tool steels fulfil a critical role across a diverse spectrum of processes, encompassing the cutting, drilling, and forming of metals. Their unique combination of high mechanical strength, exceptional wear resistance, and the ability to retain hardness even at elevated temperatures makes them indispensable engineering materials across a broad array of applications (Wang et al., 2025). Tool steels are exposed to abrasive and high-pressure applications such as cutting and stamping dies (Trzepieciński, 2023; Mei et al., 2024). To effectively perform their designated tasks in these challenging and varied operational conditions with prolonged lifespan, reliability, and efficiency, tool steels must possess a suite of critical and complementary mechanical and physical properties. Foremost among these is high hardness and strength, which directly dictate the resistance of the material to permanent deformation and mechanical failure under applied cutting and forming forces. Wear resistance, another vital attribute, minimizes material loss during the continuous and repetitive interaction of the tool with the workpiece.

To further enhance the critical properties of tool steels outlined above, optimize their operational performance, and significantly extend their service life, a combination of heat treatments and surface engineering techniques is widely employed (Machado et al., 2024). Surface engineering techniques offer effective and innovative solutions to address surface-related failure mechanisms in tool steels, such as wear and corrosion. Surface modification processes, such as nitriding, carburizing, and various surface coating processes, are increasingly utilized to significantly enhance surface hardness, reduce the coefficient of friction, improve chemical and thermal resistance, and consequently, substantially extend operational performance and service life (Borgioli et al., 2024; Kumar and Choubey, 2024; Kank et al., 2025). Among these surface engineering processes, one of the most significant and impactful is the precise application of coatings onto the critical working surfaces of tool steels. Executed through various sophisticated methods of physical vapour deposition (PVD) and chemical vapour deposition (CVD), this process imparts desirable properties such as high hardness, low coefficient of friction, superior wear resistance, and improved chemical stability to the tool surface, thereby significantly prolonging tool life and considerably enhancing machining performance (Bhise and Jogi, 2023; Jeje et al., 2025). Within the wide array of coating types employed in the industry, titanium nitride (TiN) and chromium nitride (CrN) coatings are widely preferred coatings due to their well-established performance, relatively reasonable costs, and broad applicability (Ghufran et al., 2020; Yin et al., 2022; Torsakul and Kuptasthien, 2024; Johny and Alphonse, 2024; Liu et al., 2024; Mandri et al., 2025). TiN coatings, owing to their high hardness and generally good wear resistance, provide effective and reliable protection, particularly in applications such as cutting, drilling, and forming operations (Nekouee and Elmkhah, 2018; Singhal et al., 2024). CrN coatings, in contrast to TiN coatings, stand out due to their superior corrosion resistance and generally lower coefficients of friction (Leonov et al., 2023; Narayana and Saleem, 2024). In applications where sliding wear and aggressive corrosive environments are significant factors, CrN coatings can exhibit longer service lives and more reliable operational performance compared to TiN, owing to their reduced friction and enhanced chemical stability (Vera et al., 2011).

Titanium chromium nitride (Ti,Cr)N coatings, which possess the potential to combine the high hardness and general wear resistance characteristics of TiN with the superior corrosion resistance and low coefficient of friction advantages of CrN, have garnered increasing interest through intensive research and development efforts (Uglov et al., 2011; Hangwei et al., 2014; Akbarzadeh et al., 2015; Poursaiedi et al., 2016). It is anticipated that (Ti,Cr)N coatings, through the synergistic interaction of titanium and chromium elements, can offer superior and more balanced property combinations compared to binary nitride coatings in specific application scenarios. Therefore, (Ti,Cr)N coatings are emerging as a promising and potentially alternative. In this context, it is understood that the titanium/chromium (Ti/Cr) ratio, which can be precisely controlled during the coating process, plays a critical and decisive role in determining the properties of (Ti,Cr)N coatings (Taweesup et al., 2019; Mohapatra and Oh, 2025). Variations in this ratio directly influence the microstructure of the coating, and consequently, its mechanical and tribological properties. Consequently, a systematic investigation into the effect of the Ti/Cr ratio on the coating properties is of critical importance for achieving the optimal (Ti,Cr)N coating design for a specific application.

This study investigated the wear behaviour of (Ti,Cr)N coatings with varying ratios of titanium and chromium deposited onto a commercially widely used tool steel substrate. The tribological performance of (Ti,Cr)N coatings with different Ti/Cr ratios will be compared with the wear performance of TiN and CrN coatings, aiming to elucidate the fundamental effects of the Ti/Cr ratio on the tribological properties and potential performance advantages of (Ti,Cr)N coatings. The findings of this research are expected to provide a significant body of knowledge for the potential applications of (Ti,Cr)N coatings and contribute to a deeper understanding of the role of this advanced coating type in enhancing the performance of tool steels. The results obtained are anticipated to provide guidance for the future design and development of higher-performance tool steel coatings tailored for specific applications.

2. Materials and Methods

Table 1 presents the elemental compositions of the CrN, TiN, and (Ti,Cr)N coatings with different Ti/Cr ratios, which were deposited onto the Cr12MoV steel substrate using physical vapour deposition.

Table 1. Chemical compositions (wt.%) of CrN, TiN, and (Ti,Cr)N coatings with different Ti/Cr ratios

Coating	Ti/Cr ratio	Chemical composition (wt.%)		
		Cr	Ti	N
CrN		49.35	–	50.65
TiN		–	50.61	49.32
(Ti,Cr)N	1.34	17.96	23.84	58.20
(Ti,Cr)N	1.07	20.10	21.49	58.41
(Ti,Cr)N	0.68	29.83	20.75	49.42

The hardness of the CrN, TiN, and (Ti,Cr)N coatings was evaluated using a Vickers microhardness tester. All tests were conducted at room temperature following the ASTM E384 standard. A diamond indenter with a square-based pyramidal shape and an angle of 136° was used to create indentations on the coated surfaces. For each coating type, a minimum of ten indentations were performed to ensure the reliability of the results. A test load of 50 gf was applied for a dwell time of 15 seconds. This specific load and dwell time were chosen to ensure sufficient indentation depth while minimizing the influence of the substrate material on the hardness measurements. Following the indentation, the lengths of the two diagonals of the resulting square-shaped indentation on the coating surface were measured using the integrated optical microscope of the Vickers hardness tester. The Vickers hardness number (HV) was calculated using the following formula (Eq. (1)):

$$\mathrm{HV} = \frac{2F\sin(\frac{136^\circ}{2})}{d^2} \tag{1}$$

where HV is the Vickers hardness number, *F* is the applied test load. The applied load was converted to kilograms-force for the calculation. *d* is the arithmetic mean of the lengths of the two diagonals of the indentation in millimetres.

To gauge the resistance to wear exhibited by CrN, TiN, and (Ti,Cr)N coatings applied to Cr12MoV steel substrates, a ball-on-disc tribometer was employed (Figure 1), adhering to the guidelines outlined in the ASTM G99 standard. Wear tests were carried out in a dry sliding regime at a load of 10 N, a speed of 0.3 m/s, and a sliding distance of 500 meters under the ambient atmospheric conditions. The opposing contact element consisted of a 6 mm diameter ball from tungsten carbide. Prior to the commencement of each wear test, both the coated specimen and the ball underwent a cleaning process to eliminate any potential surface contaminants that could influence the frictional and wear response. This cleaning procedure involved immersion in an ultrasonic bath containing analytical grade ethanol.

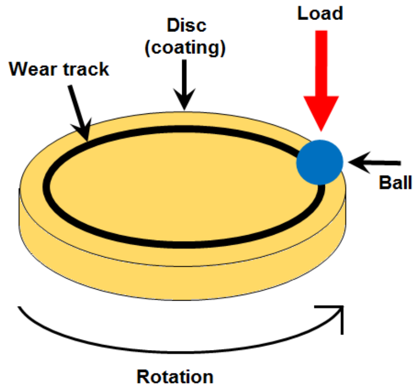

Figure 1. Schematic illustration of the ball-on-disc test

The steady-state friction coefficient was determined by averaging the instantaneous friction coefficient values recorded during the stable portion of the test. Typically, an initial run-in period is observed where the friction coefficient may fluctuate before stabilizing. Therefore, data from this initial run-in phase were excluded from the calculation. The average steady coefficient of friction was then calculated over the remaining steady-state region of the test. Each test was repeated a minimum of three times.

Following the evaluation of the wear test results, the wear behaviour of (Ti,Cr)N coatings with a Ti/Cr ratio of 0.68 was thoroughly investigated under varying loading and sliding speed conditions. An experimental design was strategically implemented to dissect the impact of two variables (factors): the applied normal load (5 N, 10 N, and 15 N), and the sliding speed (0.1 m/s, 0.3 m/s, and 0.5 m/s) with each test conducted at a sliding distance of 500 meters. To study the statistical significance of the parameters (factors) on wear behaviour of the (Ti,Cr)N coating with Ti/Cr ratio of 0.68, the statistical Design-Expert software was employed as the principal analytical platform for analysing of variance (ANOVA). This software not only facilitated the identification of statistically significant factors, but also enabled a granular investigation into the individual and interaction effects of the load and sliding speed on the wear characteristics of (Ti,Cr)N-coated Cr12MoV steel.

3. Results and Discussion

The Vickers hardness of TiN, CrN, and (Ti,Cr)N coatings with different Ti/Cr ratios of 1.34, 1.07, and 0.68 was evaluated in this study. The measured hardness values provide crucial insights into the resistance to localized plastic deformation, a key indicator of wear performance for these coatings.

Figure 2 depicts the hardness variation of TiN, CrN, and (Ti,Cr)N coatings with different Ti/Cr ratios. TiN coating demonstrated a higher hardness compared to CrN coating. The difference in hardness between these two coatings can be attributed to variations in their bond strengths and crystal structures (Zhang et al., 2018; Leonov et al., 2023).

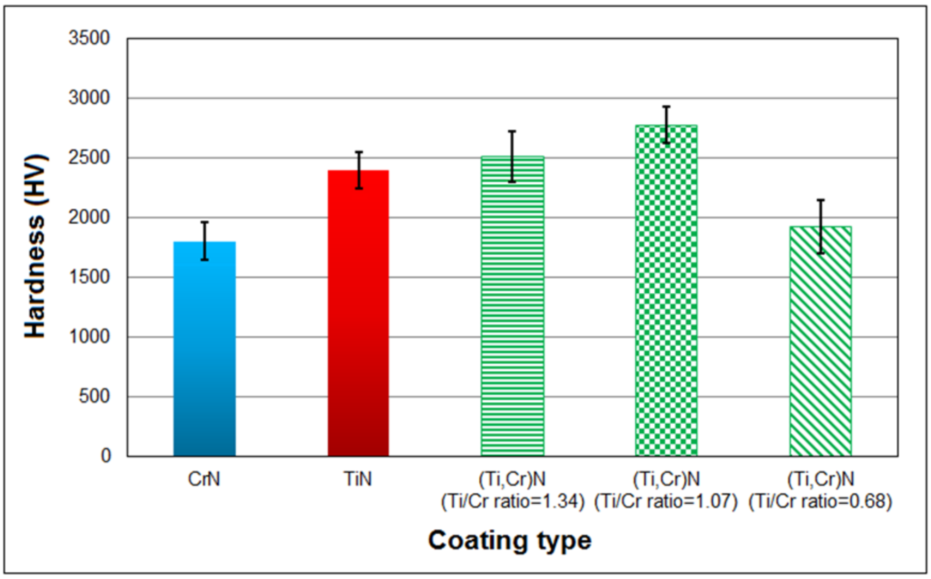

Figure 2. Vickers hardness values of TiN, CrN, and (Ti,Cr)N coatings with different Ti/Cr ratios (1.34, 1.07, and 0.68)

The (Ti,Cr)N coating with a Ti-rich composition (Ti/Cr = 1.34) exhibited a higher hardness than that of the TiN coating. The (Ti,Cr)N coating with a Ti/Cr ratio (1.07) displayed the highest hardness among the investigated compositions. Conversely, the (Ti,Cr)N coating with a Cr-rich composition (Ti/Cr = 0.68) exhibited the lowest hardness among (Ti,Cr)N coatings studied. While the addition of Ti into the CrN lattice still induces some solid solution strengthening, the overall hardness remains closer to that of CrN. This suggests that at this specific composition, the influence of the CrN matrix and the level of lattice distortion achieved by the relatively lower titanium content may have resulted in a hardness value that is improved compared to pure CrN but does not reach the levels observed at higher Ti/Cr ratios. These findings indicate the significant role of chemical composition in tailoring the mechanical properties of (Ti,Cr)N coating. The observed trend demonstrates the enhancing the hardness of TiN by the incorporation of chromium, with the most pronounced effect achieved at a Ti/Cr ratio of 1.07.

The dry sliding friction behaviour of coatings is a critical aspect for many industrial applications, and the selection of the coating material significantly influences the overall tribological performance. Figure 3 shows the average steady coefficient of friction of TiN, CrN, and (Ti,Cr)N coatings with different Ti/Cr ratios. As seen in Figure 3, the TiN coating exhibited the highest average steady coefficient of friction. In contrast, the CrN coating demonstrated a significantly lower friction coefficient. This performance can be attributed to the formation of chromium oxide at the sliding interface (Zhou et al., 2000). The (Ti,Cr)N coatings revealed a compelling trend where the friction coefficient systematically decreased as the Ti/Cr ratio decreased, as illustrated in Figure 3. Compared to the TiN coating, the lower friction coefficient observed for the (Ti,Cr)N with a Ti/Cr ratio of 1.34 can be attributed to the beneficial effect of chromium in forming lubricating oxides. However, this effect was likely somewhat diluted by the greater titanium content. A decrease in the Ti/Cr ratio to 1.07 resulted in a lower friction coefficient. This indicates a more balanced contribution from both titanium and chromium. The lowest friction among the (Ti,Cr)N coatings was observed with a Ti/Cr ratio of 0.68 (Cr-rich). This result is notably close to that of CrN coating. These findings demonstrate that while TiN had the highest average steady coefficient of friction, CrN, on the other hand, provided superior low-friction characteristics. (Ti,Cr)N coatings offered a remarkable ability to tailor tribological performance through precise control of the Ti/Cr ratio. Decreasing the Ti/Cr within the (Ti,Cr)N consistently led to a reduction in the average steady coefficient of friction for the (Ti,Cr)N coating.

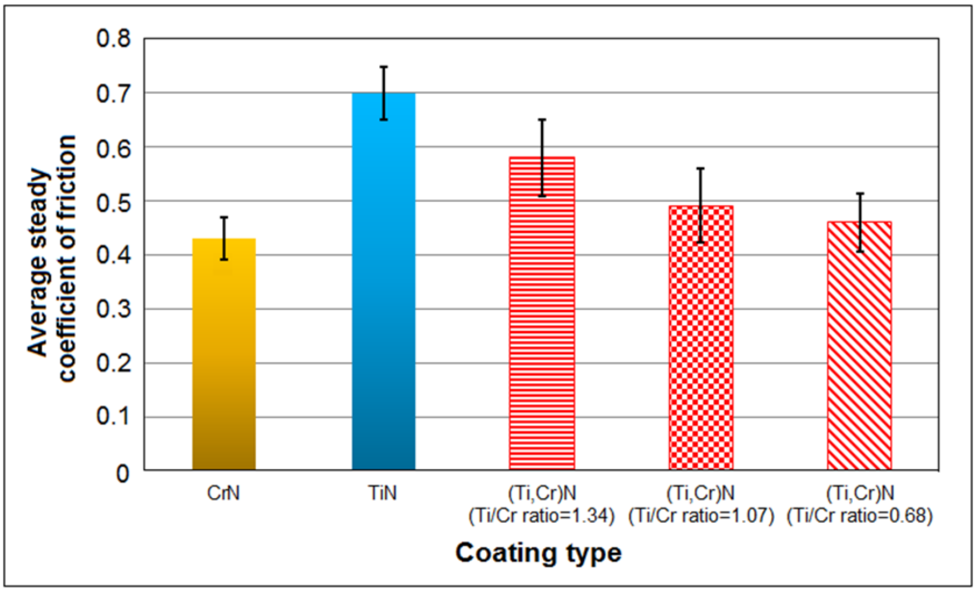

Figure 3. Average steady coefficient of friction of TiN, CrN, and (Ti,Cr)N coatings with different Ti/Cr ratios (1.34, 1.07, and 0.68)

Figure 4 illustrates the wear rate of TiN, CrN, and (Ti,Cr)N coatings with different Ti/Cr ratios. The observed trends in wear rates (Figure 4) directly correlated with the friction coefficient (Figure 3), providing a unified perspective on the tribological performance of the coatings. Generally, lower friction indicates reduced energy dissipation as heat and less material removal, thus leading to a lower wear rate (Bhushan, 2013).

Although it possessed the highest hardness (Figure 2), the TiN coating also exhibited the highest coefficient of friction (Figure 3), and consequently, the highest wear rate (Figure 4). The CrN coating, which exhibited a low friction coefficient, demonstrated a lower wear rate than the TiN coating (Figure 4), despite having a lower hardness. It can be due to the fact that the Cr_2O_3 film formed during sliding provides the effective protective barrier (Li et al., 2025), profoundly minimizing material loss and surpassing the performance of TiN.

The wear rates of (Ti,Cr)N coatings with Ti/Cr ratios of 1.34 and 1.07 were higher than that of the CrN coating but lower than the TiN coating, even though they possessed higher hardness than the CrN coating. This result indicates that there is no direct correlation between the hardness and the wear resistance of these coatings. On the other hand, the wear resistance of the (Ti,Cr)N coating with a Ti/Cr ratio of 0.68 was very close to that of the CrN coating. While titanium generally has a less effective influence on wear resistance compared to chromium, which could lead to lower wear resistance in (Ti,Cr)N coatings than in CrN, the slightly higher hardness of the (Ti,Cr)N coating with a Ti/Cr ratio of 0.68 compared to CrN may have compensated for this disadvantage. These results indicate that there is no direct relationship between the hardness and the wear resistance of the coatings studied. However, optimizing the Cr content within (Ti,Cr)N coatings, even at the expense of peak hardness, proves to be an effective strategy for achieving superior tribological performance.

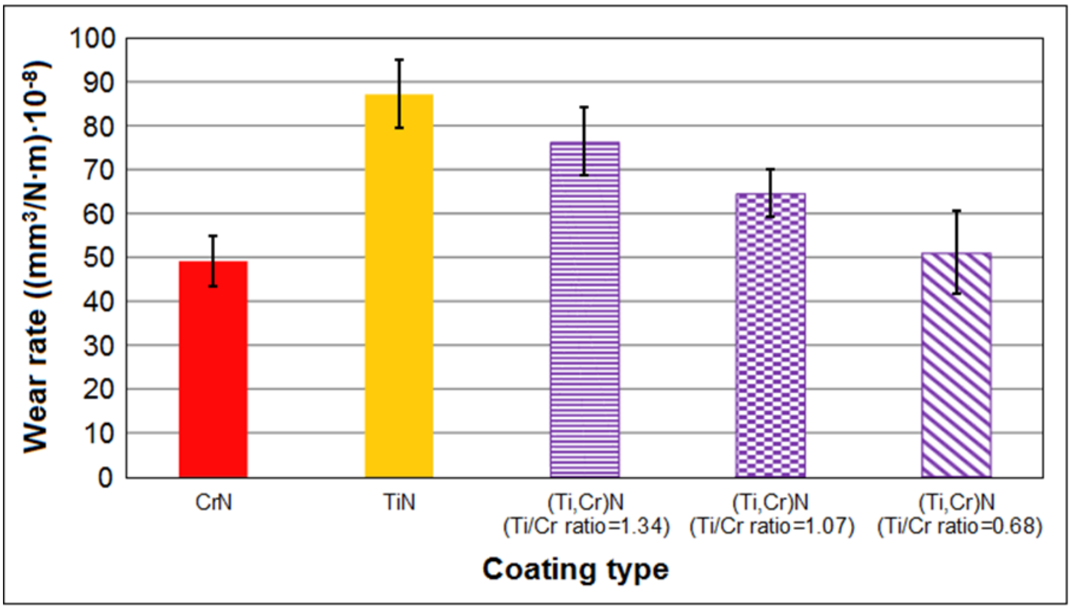

Figure 4. Wear rate of CrN, TiN, and (Ti,Cr)N coatings with Ti/Cr ratios of 1.34, 1.07, and 0.68

The findings show that the wear resistance of (Ti,Cr)N coating with a Ti/Cr ratio of 0.68 is competitive with CrN coating; therefore, the wear behaviour of (Ti,Cr)N coatings with a Ti/Cr ratio of 0.68 under varying loading and sliding speed conditions was investigated. An experimental design was implemented to dissect the influence of load and sliding speed (Table 1). A 2-factor, 3-level full factorial experimental design with five replicates was used. Following the experimental studies conducted according to the design, a statistical investigation utilized regression analysis and ANOVA to evaluate the significance of load, sliding speed, and their interaction effect on the wear rate.

Table 1. Experimental design and the wear rate results of (Ti,Cr)N coating with a Ti/Cr ratio of 0.68 as a function of load and sliding speed

Number of experiment	Coded value		Actual value		Wear rate $((mm^3/N \cdot m) \cdot 10^{-8})$
	Load	Sliding speed	Load (N)	Sliding speed (m/s)	
1	−1	−1	5	0.1	29.19
2	−1	0	5	0.3	33.81
3	−1	1	5	0.5	40.77
4	0	−1	10	0.1	42.22
5	0	0	10	0.3	51.13
6	0	0	10	0.3	52.05
7	0	0	10	0.3	51.87
8	0	0	10	0.3	50.90
9	0	0	10	0.3	51.94
10	0	1	10	0.5	63.66
11	1	−1	15	0.1	48.43
12	1	0	15	0.3	75.08
13	1	1	15	0.5	98.24

To estimate pure error, experiments numbered from 5 to 9 were replicated at the central levels of load and sliding speed. The regression model performed well, as evidenced by its high coefficients of determination. For the (Ti,Cr)N coating with a Ti/Cr ratio of 0.68, the R^2 value was a remarkable 0.9911. This means that 99.11% of the variations in wear rate can be statistically explained by the factors (load, sliding speed) and their interaction for the (Ti,Cr)N coating (Ti/Cr ratio 0.68). The ability of a model to predict improves significantly as its R^2 value gets closer to 1 (Chicco et al., 2021). Delving deeper into its fit, the adjusted R^2 for this coating was 0.9848. This value provides a more realistic view of the explanatory power of the model by accounting for the number of predictors. Moreover, the predicted R^2, which estimates how well the model will predict new data, stood at 0.9140 for the (Ti,Cr)N coating (Ti/Cr ratio 0.68).

The statistical significance of the developed regression model was thoroughly evaluated using Analysis of Variance (ANOVA), with the results summarized in Table 2. The model proved to be highly significant ($p < 0.0001$, F=156.73), indicating its strong ability to explain the observed variation in the response variable. A detailed examination of the individual factors revealed that both load (F=472.62, $p < 0.0001$) and sliding speed (F=232.95, $p < 0.0001$) had a highly significant impact on the response. Furthermore, the interaction effect (Load×Sliding speed) between load and sliding speed also demonstrated significant influence (F=74.44, $p < 0.0001$). This suggests that the effect of one factor on the response is dependent on the level of the other. Conversely, the quadratic terms, Load×Load ($p=0.1643 > 0.05$) and Sliding speed×Sliding speed ($p=0.6841 > 0.05$), were not statistically significant. This indicates that a linear relationship with respect to these individual factors adequately captures their contribution to the model within the experimental range, without requiring higher-order polynomial terms for their individual effects.

The Lack of Fit test was also found to be significant ($p=0.0019$, F=40.33), implying that the current model may not perfectly describe the experimental data and some unknown variability might still exist, or that a more complex model might provide a better fit. However, given the overall high significance of the model and the strong individual factor effects, the model remains a robust descriptor of the main relationships.

Table 2. Analysis of variance (ANOVA) for wear rate depending on the factors of load and sliding speed for (Ti,Cr)N coating with a Ti/Cr ratio of 0.68

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	3846.50	5	769.30	156.73	< 0.0001	significant
Load	2319.88	1	2319.88	472.62	< 0.0001	
Sliding speed	1143.47	1	1143.47	232.95	< 0.0001	
Load×Sliding speed	365.38	1	365.38	74.44	< 0.0001	
Load×Load	11.84	1	11.84	2.41	0.1643	
Sliding speed× Sliding speed	0.8838	1	0.8838	0.1801	0.6841	
Residual	34.36	7	4.91			
Lack of Fit	33.26	3	11.09	40.33	0.0019	significant
Pure Error	1.10	4	0.2749			
Cor Total	3880.86	12				

The developed regression model, presented in coded factors (Table 1), quantifies the relationship between the independent variables and the wear rate. The model equation (Eq.(2)) to predict the wear rate of (Ti,Cr)N coating (Ti/Cr ratio 0.68) depending on load and sliding speed is given below:

$$\text{Wear rate} = 51.81 + 19.66 \cdot A + 13.80 \cdot B + 9.56 \cdot A \cdot B + 2.07 \cdot A^2 + 0.5657 \cdot B^2 \qquad \text{Eq.(2)}$$

Where A represents the coded value of load and B represents the coded value of sliding speed (Table 1). The equation reveals the distinct contributions of individual factors and their combined interactions. The positive coefficients for A (+19.66) and B (+13.80) indicate that both load and sliding speed increase the wear rate; an increase in either factor leads to a higher wear rate. The significant positive coefficient for the interaction term A·B (+9.56) suggests that the combined effect of load and sliding speed is more than just additive, meaning the influence of one factor is amplified by the presence of the other. The quadratic terms, A^2 (+2.07) and B^2 (+0.5657), while having smaller coefficients, indicate a slight curvature in the response surface.

Figure 5 presents a scatter plot where the predicted wear rate values demonstrate strong agreement with their experimental results. The close alignment of the actual data points with the regression line confirms the excellent fit of the model.

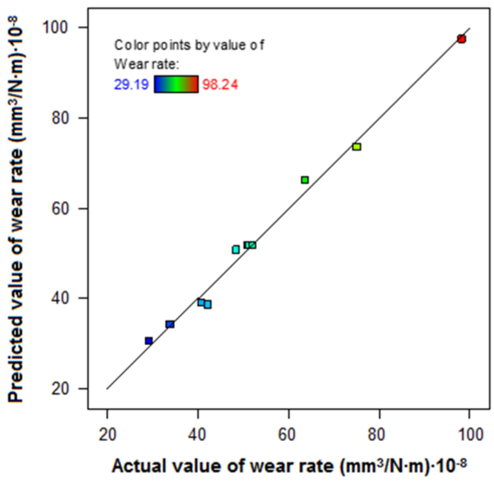

Figure 5. Correlation graph between the predicted and actual (experimental) values of wear rate of the (Ti,Cr)N with a Ti/Cr ratio of 0.68

Figure 6 illustrates the main impact of both load and sliding speed on the wear rate of (Ti,Cr)N with a Ti/Cr ratio of 0.68. The wear rate increased with both load and sliding speed, with a more pronounced effect observed at higher values of each. Notably, load exerted a more substantial influence on the wear rate than sliding speed. This trend is much more clearly observed in the three-dimensional response surface curve and two-dimensional contour plot presented in Figure 7(a) and (b), respectively.

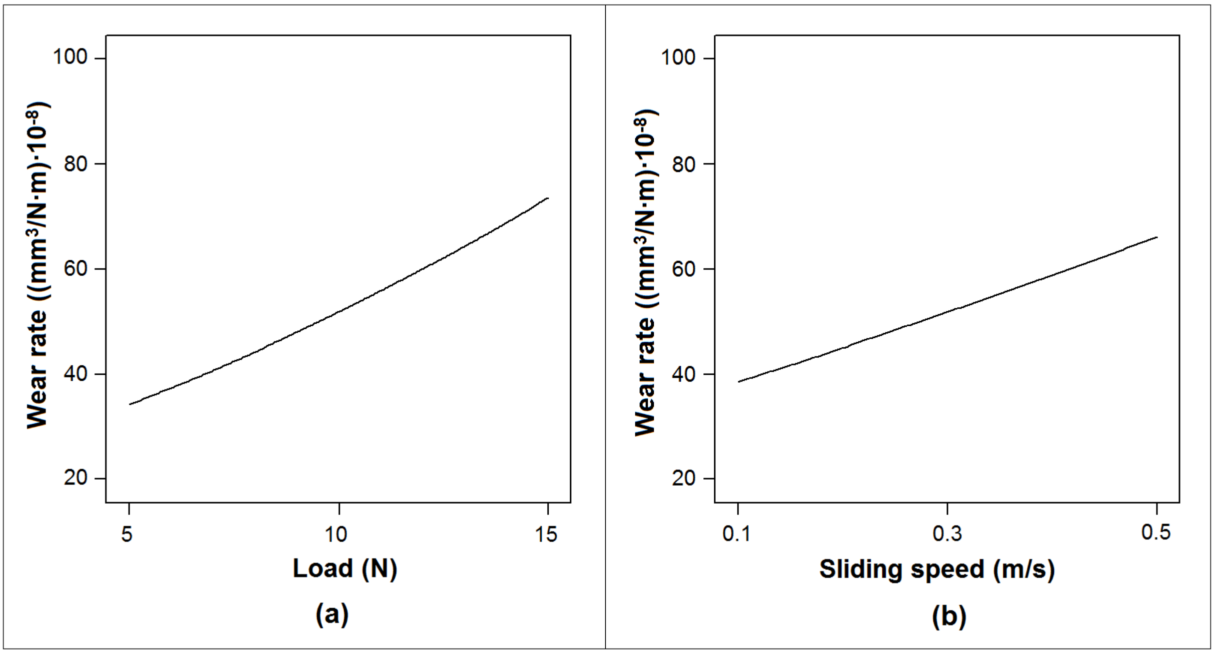

Figure 6. Main effect of **(a)** load and **(b)** sliding speed on the wear rate of the (Ti,Cr)N with a Ti/Cr ratio of 0.68

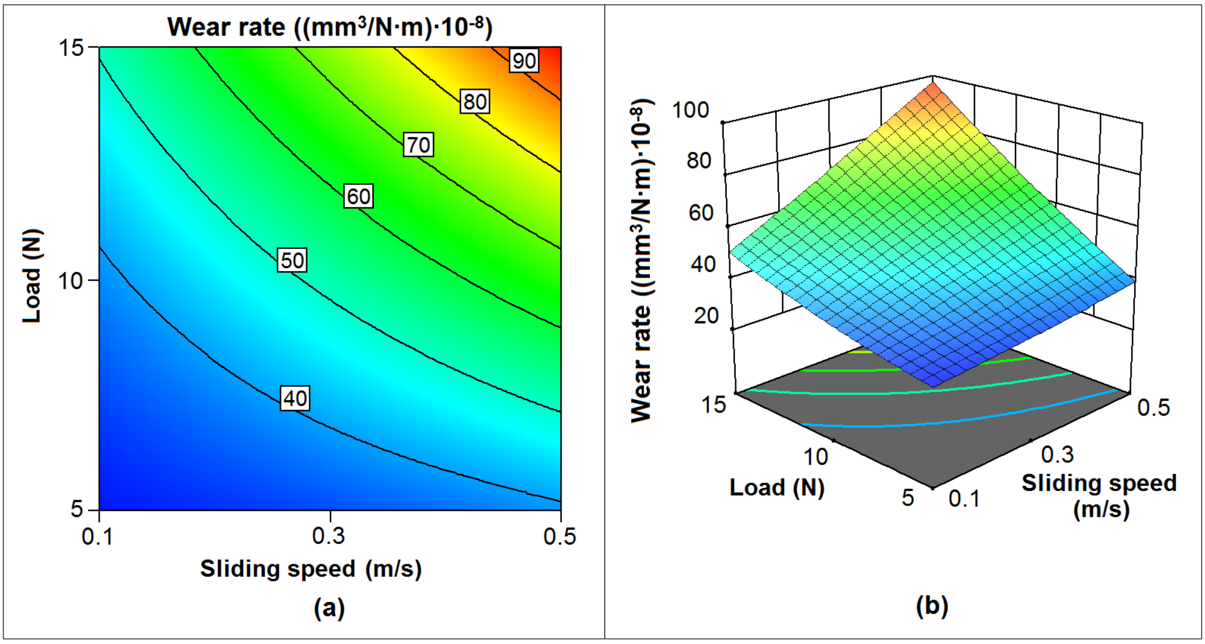

Figure 7. (a) Two-dimensional contour plot and **(b)** Three-dimensional response surface plot showing the interaction effect between load and sliding speed on the wear rate of (Ti,Cr)N with a Ti/Cr ratio of 0.68

4. Conclusions

The wear properties of CrN, TiN, and (Ti,Cr)N coatings with a different Ti/Cr ratios was investigated in this study. The results are presented below:

(1) TiN coating demonstrated higher hardness than CrN coating. For (Ti,Cr)N coatings, the hardness was highly dependent on the Ti/Cr ratio. This suggests a synergistic effect of combining titanium and chromium.

(2) CrN coating exhibited the lowest friction coefficient. Conversely, TiN coating showed the highest friction. (Ti,Cr)N coatings allowed for precise control over friction, with coefficients systematically decreasing as the Ti/Cr ratio was reduced. The Cr-rich (Ti,Cr)N coating (Ti/Cr = 0.68) achieved a friction coefficient remarkably close to that of CrN coating.

(3) The findings indicate no direct relationship between the hardness and wear rate of the coatings studied; however, observed wear rates correlated with the average steady coefficient of friction. Despite its high hardness, TiN coating exhibited the highest wear rate due to its high friction. While CrN coating, with its lower hardness, showed superior wear performance. For (Ti,Cr)N coatings, wear resistance improved with increasing Cr content.

(4) Furthermore, a detailed statistical analysis of the (Ti,Cr)N coating with a Ti/Cr ratio of 0.68 confirmed its promising wear behaviour. A robust regression model, validated by high R^2 values and significant ANOVA results, demonstrated that both load and sliding speed, as well as their interaction, significantly influence the wear rate. Higher values of load and sliding speed led to more pronounced increases in wear.

The results highlight the significant potential for tuning the Ti/Cr ratio in (Ti,Cr)N coatings, which directly impacts their tribological behaviour and offers a means to achieve specific wear characteristics for various applications.

References

Akbarzadeh, M., Shafyei, A., Salimijaz, H.R., 2015. Comparison of the CrN, TiN and (Ti, Cr)N PVD coatings deposited by cathodic arc evaporation. *Iranian Journal of Materials Science and Engineering*, 12(1): 43–51.

Bhise, V.Y., Jogi, B.F., 2023. Some studies on cutting tools and coatings for machining of superalloys under dry and sustainable lubrication environment. *Advances in Materials and Processing Technologies*, 10(4): 3662–3679.

Borgioli, F., Adachi, S., Lindner, T., 2024. Advances in low-temperature nitriding and carburizing of stainless steels and metallic materials: formation and properties. *Metals*, 14: 1179.

Bhushan, B., 2013. Principles and Applications of Tribology, Wiley.

Chicco, D., Warrens, M.J., Jurman, G., 2021. The coefficient of determination R-squared is more informative than SMAPE, MAE, MAPE, MSE and RMSE in regression analysis evaluation. *PeerJ Computer Science*, 7: e623.

Ghufran, M., Uddin, G.M., Arafat, S.M., Jawad, M., Rehman, A., 2020. Development and tribo-mechanical properties of functional ternary nitride coatings: Applications-based comprehensive review. *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology*, 235(1): 196–232.

Hangwei, C., Yuan, G., Lin, Y., Zhikang, M., Chenglei, W., 2014. High-temperature oxidation behavior of (Ti,Cr)N boating deposited on 4Cr13 stainless steel by multi-arc ion plating. *Rare Metal Materials and Engineering*, 43(5): 1084-1087.

Jeje, S.O., Mpofu, P., Malatji, N., Kanyane, L.R., Shongwe, M.B., 2025. Multi-principal element alloy coatings: A review of deposition techniques, applications, and future prospects. *Metals and Materials International*.

Johny, B.S., Alphonse, M., 2024. Friction and wear behaviour of AlCrN and TiN coated H13 tool steel. *Tribology and Materials*, 3(3): 131–140.

Kang, K., Su, S., Yu, B., Sun, Z., Hu, S., Wang, Z., Zhao, C., Wu, L., Luo, G., Wei, R., 2025. The review and prospect of tool coating technology. *The International Journal of Advanced Manufacturing Technology*, 137: 3107–3139.

Kumar, N., Choubey, V.K., 2024. Recent trends in coating processes on various AISI steel substrates: A review. *Journal of Materials Science*, 59: 395–422.

Leonov, A.A., Denisova, Y.A., Denisov, V.V., Syrtanov, M.S., Shmakov, A.N., Savostikov, V.M., Teresov, A.D., 2023. Structure and properties of CrN/TiN multi-layer coatings obtained by vacuum-arc plasma-assisted deposition method. *Coatings*, 13: 351.

Li, H., Chen, X., Shen, M., Guo, C., 2025. Effect of oxygen flow rate on structure and properties of Cr-based coatings deposited by arc ion plating. *Journal of Physics: Conference Series*, 3009: 012011.

Liu, Y., Yang, Y., Liu, X., Zheng, J., Zhang, S., 2024. Tribocorrosion of CrN coatings on different steel substrates. *Surface and Coatings Technology*, 484: 130829.

Machado, A.R., Da Silva, L.R R., Pimenov, D.Y., De Souza, F.C.R., Kuntoğlu, M., De Paiva, R.L., 2024. Comprehensive review of advanced methods for improving the parameters of machining steels, *Journal of Manufacturing Processes*, 125: 111–142.

Mandri, A.D., Colombo, D.A., Sanchez, N.V., Brühl, S.P., Dommarco, R.C., 2025. Rolling contact fatigue of ion nitrided and TiN coated AISI 4140 steel under pure rolling condition. *Engineering Failure Analysis*, 170: 109311.

Mei, T., Zhang, Q., Liu, X., Bin, H., 2024. Research on tribological behavior and mechanism of laser surface texturing on tool surface in hot stamping of Al-Si-coated high-strength steel. *The International Journal of Advanced Manufacturing Technology*, 133: 4347–4364.

Mohapatra, S., Oh, M.S., 2025. Evaluating the tribological properties and residual stress of TiCrN thin films deposited by cathodic-arc physical vapor deposition technique. *Applied Sciences*, 15: 2466.

Narayana, T., Saleem, S.S., 2024. Comparative investigation and characterization of the nano-mechanical and tribological behavior of RF magnetron sputtered TiN, CrN, and TiB_2 coating on Ti6Al4V alloy. *Tribology International*, 193: 109348.

Nekouee, K.A., Elmkhah, H., 2018. Characterization of TiN coatings deposited on H11 tool steel by PECVD method. *Protection of Metals and Physical Chemistry of Surfaces*, 54: 662–667.

Poursaiedi, E., Salarvand, A., 2016. Effect of coating surface finishing on fatigue behavior of C450 steel CAPVD coated with (Ti,Cr)N. *Journal of Materials Engineering and Performance*, 25: 3448–3455.

Singhal, M., Kumar, R., Walia, R.S., Pandey, S.K., 2024. Evaluation of tribological and cooling performance of TiN and DLC-coated pistons for miniature stirling cryocooler. *MAPAN* 39: 851–862.

Taweesup, K., Visuttipitukul, P., Yongvanich, N., Lothongkum, G., 2019. Corrosion behavior of Ti-Cr-N coatings on tool steel substrates prepared using DC magnetron sputtering at low growth temperatures. *Surface and Coatings Technology,* 358: 732–740.

Torsakul, S., Kuptasthien, N., 2024. Tool life improvement for stamping dies in the coining process. *Advances in Materials and Processing Technologies*, In press.

Trzepieciński, T., 2023. Approaches for preventing tool wear in sheet metal forming processes. *Machines*, 11: 616.

Uglov, V.V., Remnev, G.E., Kuleshov, A.K., Saltymakov, M.S., 2011. Modification of (Ti,Cr)N coatings on a hard alloy under the action of high-power pulsed ion beams. *Inorganic Materials: Applied Research,* 2: 242–246.

Vera, E.E., Vite, M., Lewis, R., Gallardo, E.A., Laguna-Camacho, J.R., 2011. A study of the wear performance of TiN, CrN and WC/C coatings on different steel substrates. *Wear,* 271(9–10): 2116–2124.

Wang, X.X., Wang, Y.H., Ling, Z.C., Yuan, Z.P., Shi, J.J., Qin, J., Sun, H.W., Pan, K.M., Geng, Z.M., Ma H.L., Yang, Z.J., Liu, S., Wu, Y.M., Peng, Y., 2025. Strategies for superhard tool coating materials: focus on preparation methods and properties. *Journal of Iron and Steel Research International*, In press.

Yin, Q., Zhang, K., Fu, X.Z., Wang, X.Z., Luo, J.L., 2022. Rapid coating preparation strategy for chromium nitride coated titanium bipolar plates of proton exchange membrane fuel cells. *International Journal of Hydrogen Energy,* 47(73): 31435–31445.

Zhang, S., Jin, W., Yang, H., Gao, K., Pang, X., Yan, L., Volinsky, A.A., 2018. Comparative study of Ti and Cr adhesion to the AlN ceramic: Experiments and calculations. *Applied Surface Science*, 457: 856-862.

Zhou, Y.M., Asaki, R., Higashi, K., Soe, W.H., Yamamoto, R., 2000. Sliding wear behavior of polycrystalline TiN/CrN multilayers against an alumina ball. *Surface and Coatings Technology*, 130(1): 9-14.