Effect of Carbon Target Current on Ultralow Frictional Behavior of CrCN Coatings under Glycerol Lubrication

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Abstract: The aim of this paper is to find an effective way to reduce the friction and wear of steel. CrCN coating was deposited on AISI 304 stainless steel by magnetron sputtering technology, and the friction and wear properties of the coating under glycerol lubrication were studied. The hardness of CrCN coatings on stainless steel surface can reach to 17.87 GPa when the carbon target deposition current is 2A. The CrCN coating presents low friction coefficient (COF) under the lubrication of glycerol, a highly efficient green lubricant. When the load is 0.5 N, the lowest friction coefficient is only 0.01. XPS analysis on the wear track suggested that glycerol decomposed during sliding and a fluid lubricating layer was formed, which provides ultralow friction. The paper shows that the glycerol could be used as an efficient lubricant for the CrCN coating.

Keywords: magnetron sputtering; CrCN coating; C target current; glycerol lubrication; ultralow friction

1. Introduction

In recent years, with the continuous advancement and development of PVD coating technology, binary metal hard nitride films have been widely used in the fields of cutting tools, automotive manufacturing, shipbuilding, and aerospace, and studied because of their excellent mechanical properties and wear resistance. CrN coating is the most prominent one [1–3]. However, the shortcomings of CrN coating also appear. Due to its large grain size [2], high friction coefficient (COF) [4], high wear rate [5], and low corrosion resistance [6], it is difficult to meet the needs of long-term application in some special environments [7,8]. Therefore, some studies were undertaken to improve the tribological properties of CrN coatings. Kabir et al. found that the incorporation of Ti can effectively block the growth of CrN columnar crystals and reduce the grain size, which led to the higher hardness of the CrN coating [9]. Shah et al. found that the addition of appropriate Si elements increased the hardness of the CrN coating by about 1 GPa while reducing its modulus [10]. Tan et al. reported that Si and Cu elements can inhibit the growth of columnar crystals in CrN coatings, refine crystal grains, and generate nanocrystalline structures [11]. Wang et al. successfully added Ti and Al elements to the CrN coating. The CrTiAlN coating has excellent radial crack resistance and improved the fracture toughness of CrN [12]. Zhou et al. tested the tribological properties of CrN-based coatings under water lubrication conditions and found that adding Ti to the CrN coating can effectively reduce the amount of coating wear. Among them, the quaternary hard coating CrTiBN has the lowest friction coefficient, about 0.2 [13]. It was also found that the doping of non-metallic carbon (C) element can effectively hinder the growth of large grains of CrN by changing the crystal structure of CrN coating, thus showing more outstanding mechanical and tribological
properties [14–16]. At present, most researchers only focus on the tribological properties of CrCN coating under unlubricated conditions [17]. Gilewicz et al. found that the wear resistance CrCN coating depends on the coating structure. The thicker the CrCN coating, the better the tribological performance [18]. Wang et al. studied the tribological properties of CrCN under water lubrication conditions and found that the friction coefficient can reach as low as 0.2 [19]. Guan et al. reported that, within a certain gas flow range, the smaller the coating grain size, the denser and smoother the coating. When the C$_2$H$_2$ gas flow rate is 30%, the tribological performance of the CrCN coating is the most excellent [20]. Hu et al. found that, as the C target current increases, the coating grains gradually become finer. When the current rises to 1.5A, the friction coefficient is the lowest, about 0.3, which is mainly due to the presence of the graphite phase and multilayer structure [21].

On the other hand, lubricating oils are used to reduce friction and wear of CrN-base coatings. Mandrino et al. used XPS to prove that the lubricant can form a friction film on the surface of the CrN coating [22]. Podgornik et al. found that, under boundary lubrication conditions, a layer of friction film can be effectively formed in the CrN/Steel friction pair, which has the effect of anti-wear and anti-friction [23]. However, lubricating oils are mostly mineral-based and entail pollution of the environment [24]. Thus, there is a need to use green lubricants which can be completely degraded and are pollution-free while ensuring the lubrication effect. Previous studies have shown that a variety of materials show a low friction and wear under glycerol lubrication [25–30]. It is, therefore, interesting to investigate the compatibility of glycerol with CrCN coating. Thus, in this paper, glycerol was used to improve the friction and wear properties of the CrCN coating, and its lubrication mechanism is analyzed.

2. Experimental

The substrate is made of 304 stainless steel with the size of 35 mm × 35 mm × 1.5 mm and the surface is polished to a roughness Ra = 0.04 µm. The 304 stainless steel sheet was successively cleaned by ultrasonic for 25 min under petroleum ether and alcohol, and then dried with nitrogen.

CrCN coating was deposited on 304 stainless steel surface by a home-made magnetron sputtering system. Carbon target (99.9%) and chromium target (99.9%) were selected as target materials. Firstly, the air compressor was turned on, the pressure in the deposition chamber was pumped to 5 × 10^{-3} Pa, and argon (80 sccm) was introduced to make the working pressure in the deposition chamber stable at 0.5 Pa. The bias was set at −800 V. Glow cleaning was carried out for 15 min, and the oxide layer and other impurities on the surface were removed to improve the adhesion of the coating. The pressure was maintained at 0.5 Pa, and temperature was 400 °C. Changing the flow rate of argon to 60 sccm and bias voltage to −50 V, the chromium coating was deposited for 10 min. After that, nitrogen gas (25 sccm) was passed, the argon flow rate (55 sccm) was changed (Table 1), and the chromium nitride coating was deposited for 10 min. Finally, the CrCN coating was deposited for 2 h with the different carbon target currents. For clarification, CrCN coating obtained at currents of 1A, 2A, and 3A are denoted as CrCN-1A, CrCN-2A, and CrCN-3A, respectively.

| Samples | N$_2$ Flow /sccm | Ar Flow /sccm | Working Pressure /Pa | Target Current /A | Bias Voltage /V | Deposition Temperature /°C | Deposition Time /min |
|---------|------------------|---------------|----------------------|-----------------|---------------|---------------------------|---------------------|
| CrCN-1A | 55               | 25            | 0.5                  | Cr:7, C:1       | −50           | 400                       | 120                 |
| CrCN-2A | 55               | 25            | 0.5                  | Cr:7, C:2       | −50           | 400                       | 120                 |
| CrCN-3A | 55               | 25            | 0.5                  | Cr:7, C:3       | −50           | 400                       | 120                 |

Table 1. Deposition parameters of coatings.
The surface, cross section and wear mark morphology of CrCN coating were characterized by SEM (MERLIN Compact, Carl Zeiss Microscopy GmbH, Jena, Germany), with a working voltage of 10 kV. The surface morphology and roughness of the coating were investigated by atomic force microscopy (AFM, Bruker Innova, MA, USA). The number of scanning lines and the number of scanning points on each line are both 512, and the scanning range is 5 µm × 5 µm. The phase structure of CrCN coating was analyzed by X-ray diffraction (XRD, D8-Discovery Brucker, Bruker, Innova, MA, USA) using Cu Kα radiation at 40 kV and 40 mA, and using small-angle grazing, the scanning angle is 10°–90°. After controlling the same pressing force (20 mN), the hardness of different coatings was measured using nano-indentation equipment (G200, MTS, Eden Prairie, MN, USA), with a Berkovich diamond indenter in continuous stiffness measurement (CSM) mode. In the case of not being affected by the matrix, about 1/10 of the thickness was selected as the hardness of the layer, and 3 indentation tests were performed to obtain the average value.

UMT-3 was used to test the COF of glycerol lubrication of CrCN coating under different loads. The tests were carried out in the ball-on-flat reciprocating mode using a GCr15 ball with diameter of 6 mm at room temperature of 20 ± 5 °C. In a tribological experiment, the stroke was 6 mm, the frequency was 2 Hz, the normal load is set at 0.5N and 2N, and the contact stress is about 500 and 810 MPa, respectively. XPS (AXIS-ULTRA, Kratos, Manchester, UK) was used to characterize the mechanism of glycerol lubrication. The XPS analysis was conducted using an Al Kα X-ray source which was operated at 12 kV and 6 mA and the C1s binding energy at 284.8 eV was used for peak calibration.

3. Results and Discussion
3.1. Characterization of CrCN Coatings

Figure 1 shows the surface, cross section, and 3D surface topography of CrCN coatings obtained at various C target current. It can be seen that the surfaces of the three coatings are relatively smooth, without obvious defects. The thickness of the coating decreases first and then increases with the increasing C target current. The thickness of the CrCN-2A coating is the thinnest, which is only 212.1 nm (Figure 1e). From the 3D surface topography of the CrCN coating, it can be roughly observed that the surface particles of the CrCN-2A coating are finer and more uniform, while the surface of the CrCN-1A and CrCN-3A coatings have irregular, large particles.

Figure 2a shows the XRD patterns of CrCN films at different deposition currents. The diffraction peaks corresponding to CrN, Cr2N, CrCN, and Cr2O3 phases can be observed. However, the diffraction peak of CrN (111) increases and the diffraction peak of Cr2N (-1-11) decreases with increasing current. According to the XRD pattern, the grain size of each coating can be calculated by Scherrer’s formula. The average grain size of the CrCN-1A, CrCN-2A, and CrCN-3A coatings is calculated to be about 7.05, 6.12, and 9.25 nm, respectively. This is also supported by AFM analysis in that the grain size of CrCN-2A coating is the smallest and densest. At the same time, Tan et al. have proven that elemental doping can reduce the CrN grain size [11]. The parameter setting is also an important condition that affects its grain size. Appropriately increasing the C2H2 gas flow [20] or C target current [21] within a certain range will cause the grain refinement of the CrCN coating. However, an excessive increase may also increase the grain size, which may be due to the impact of too many high-energy particles on the surface, resulting in reverse sputtering.
The hardness comparison of different CrCN coatings can be clearly seen in Figure 2b. The hardness of CrCN-2A coating is the highest, which is 17.67 GPa. This may be because when the deposition current is 2A, the diffraction peak intensity of Cr2N phase in the coating is significantly higher than that of 3A, and the hardness of Cr2N is greater than that of CrN [31]. When the deposition current decreased to 1A, a strong diffraction peak of Cr2N phase could also be observed in the XRD pattern, but the hardness of the CrCN coating was lower, mainly because the diffraction peak intensity of the CrN (111) surface was significantly reduced, and the width of its associated peak was also larger, which indicated that the crystallinity of CrN (111) surface was lower. As is known to all, the crystal structure of CrN is similar to that of NaCl, and the slip system in which NaCl is most prone to slip is [110], <110>. When the loading force is applied on the (111) plane, the shear component force on the slip system is zero. Thus, the hardness of the CrCN films with the preferred orientation on the (111) plane is higher [32]. In addition, hardness and elastic modulus have always been the basic parameters to measure the properties of films,
but H/E and H$^3$/E$^2$ are the direct reflection of the wear resistance of materials. According to the figure, when the deposition current of C target is 2A, the H/E of CrCN film is 0.066, and the value of H$^3$/E$^2$ is 0.076. This indicates that the coating has better resistance to elastic strain failure and mechanical failure, and that the CrCN coating has better wear resistance at 2A.

3.2. Tribological Performance of CrCN Coating under Glycerol Lubrication

Tribotest is essential to investigate the wear resistance of coatings. By changing the load, the COF and wear track morphology of different CrCN coatings were obtained. As shown in Figure 3, it is evident that all CrCN coatings exhibit a lower COF than steel under glycerol lubrication. As shown in Figure 3a, the lowest COF of the CrCN-1A coating can reach around 0.01 under the load of 0.5N, but the COF cannot remain stable and go up progressively with sliding time, and finally reaches around 0.025. However, the COF of the CrCN-2A coating can be stabilized at about 0.02 in 1500 s. At the same time, with the increase of the load, the COF of CrCN-2A coating does not change too much. According to the observation of wear track morphology of different CrCN coatings, it is obvious that the wear trace width of the CrCN-2A coating is the narrowest. When the load is 0.5N, the wear mark width of CrCN-2A coating is only 92.3 µm, while the wear mark width of the other two coatings is about 140 µm. When the load is increased to 2N, the wear mark width of CrCN-2A coating is still the narrowest, which is 120.5 µm. Before discussing the lubrication mechanism of glycerol in the steel/CrCN friction pair, the lubrication state under experimental conditions is firstly determined by calculating the $\lambda$ value in Equation (1) [33].

$$\lambda = \frac{h_{\text{min}}}{\sigma} = \frac{h_{\text{min}}}{\sqrt{\sigma_1^2 + \sigma_2^2}}$$

where $h_{\text{min}}$ is the minimum oil film thickness, which is calculated by the Hamrock-Dowson formula [34], $\sigma$ is the composite surface roughness of the friction pair, and $\sigma_1$ and $\sigma_2$ are the surface roughness of the ball and disk, respectively. According to formula (1), the value of $\lambda$ can be calculated to 1.427 and 1.302 for the steel/CrCN friction system with loads of 0.5N and 2N, indicating that the system is in a mixed lubrication state.

The results of tribological experiments show that glycerol exhibits excellent tribological properties on CrCN coatings. XPS was used to study the chemical composition of the lubricating film formed from a tribochemical reaction between the surface of the CrCN coating and glycerol during sliding. Figure 4 shows the XPS analysis results of CrCN coating inside and outside the wear mark. The most interesting is the O1s spectrum. In the O1s spectrum, the peak at 531.3 eV can be attributed to the carbonyl (O=C) bond [35]. It can be seen that the peak strength inside the wear track is significantly higher than that outside the wear track. The peak of C=O bond was also found at 287.4 eV in C1s spectra. The peak at 532.5 eV in the O1s spectrum corresponds to the (C–O–) bond. Another peak in the O1s spectrum at 534.3 eV is the adsorbed water molecules, which may be derived from degradation products of glycerol or from the moist air. While the (C–O–) functional group exists in glycerol, the carbonyl group, which is clearly observed in the C1s and O1s spectra, is the product of the degradation of glycerol during sliding.

XPS analysis of wear track in this study showed that the glycerol molecules were decomposed into water molecules and other fragments by tribochemical reaction with the coating. The tribofilm was composed of water molecules, degraded glycerol fragments and glycerol molecules. In the past, both experimental and MD simulations demonstrated that glycerol could undergo thermochemical dissociation at moderate pressures and relatively high temperatures [36,37]. The main products were water, ethanol, methanol, aldehyde, acrolein, CO$_2$, CO, H$_2$, etc., which were basically consistent with the results of XPS analysis.
Figure 3. The COF diagram of CrCN coatings with different deposition currents under (a) 0.5N load and (b) 2N load. Wear track morphology of (c,f) CrCN-3A coatings, (d,g) CrCN-2A and (e,h) CrCN-1A under load of 0.5N and 2N load, respectively.

Figure 4. The XPS spectra of (a) C1s and (b) O1s inside and outside the wear track of CrCN-2A coating at load of 2N.

Based on XPS analysis, the lower wear obtained in the steel/CrCN system under glycerol lubrication can be explained by Martin’s “H-bond network” model [26]. Due to the high viscosity of glycerol, a thin EHL film can be formed by hydrogen bonding. Under mixed lubrication, this film effectively reduces the contact area between the steel ball and the coating, resulting in a reduction of contact stress. At the same time, the glycerol mixes...
with its degradation products to form a fluid lubrication layer, which reduces the shear value of the glycerol, resulting in a lower coefficient of friction and a reduction in wear.

4. Conclusions
(1) By changing the deposition current of the C target, it can be found that the surface of CrCN-2A coating is the densest with highest hardness up to 17.87 GPa.
(2) CrCN-2A coating showed excellent lubrication performance, as indicated by a more stable low coefficient of friction and the lowest wear.
(3) It can be found that in the steel/steel friction pair, glycerol does not show excellent lubricating performance. Meanwhile, in the steel/CrCN system, the lowest friction coefficient under glycerol lubrication is only 0.01. This is mainly due to the fact that the degradation of glycerol generates the fluid lubricating layer during the friction process.

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References
1. Ruden, A.; Restrepo-Parra, E.; Paladines, A.U.; Sequeda, F. Corrosion resistance of CrN thin films produced by DC magnetron sputtering. *Appl. Surf. Sci.* 2013, 270, 150–156. [CrossRef]
2. Shan, L.; Wang, Y.; Li, J.; Jiang, X.; Chen, J. Improving tribological performance of CrN coatings in seawater by structure design. *Tribol. Int.* 2015, 82, 78–88. [CrossRef]
3. Chang, Z.; Wan, X.; Pei, Z.; Gong, J.; Sun, C. Microstructure and mechanical properties of CrN coating deposited by arc ion plating on Ti6Al7V substrate. *Surf. Coat. Technol.* 2011, 205, 4690–4696. [CrossRef]
4. Warcholinski, B.; Gilewicz, A.; Kuklinski, Z.; Myslinski, P. Hard CrCN/CrN multilayer coatings for tribological applications. *Surf. Coat. Technol.* 2010, 204, 2289–2293. [CrossRef]
5. Mo, J.L.; Zhu, M.H.; Leyland, A.; Matthews, A. Impact wear and abrasion resistance of CrN, AlCrN and Al2TiN PVD coatings. *Surf. Coat. Technol.* 2013, 215, 170–177. [CrossRef]
6. Shan, L.; Zhang, Y.; Wang, Y.; Li, J.; Jiang, X.; Chen, J. Corrosion and wear behaviors of PVD CrN and CrSiN coatings in seawater. *Trans. Nonferrous Met. Soc. China* 2016, 26, 175–184. [CrossRef]
7. Nordin, M.; Larsson, M.; Hogmark, S. Mechanical and tribological properties of multilayered PVD TiN/CrN. *Wear* 1999, 232, 221–225. [CrossRef]
8. Mendibide, C.; Steyer, P.; Fontaine, J.; Goudeau, P. Improvement of the tribological behaviour of PVD nanostratified TiN/CrN coatings—An explanation. *Surf. Coat. Technol.* 2006, 201, 4119–4124. [CrossRef]
9. Kabir, M.S.; Munroe, P.; Zhou, Z.; Xie, Z. Structure and mechanical properties of graded CrN/CrTiN coatings synthesized by close field unbalanced magnetron sputtering. *Surf. Coat. Technol.* 2017, 309, 779–789. [CrossRef]
10. Shah, H.N.; Jayaganthan, R.; Pandey, A.C. Nanoindentation study of magnetron-sputtered CrN and CrSiN coatings. *Mater. Des.* 2011, 32, 2628–2634. [CrossRef]
11. Tan, S.; Zhang, X.; Wu, X.; Fang, F.; Jiang, J. Comparison study on structure of Si and Cu doping CrN films by reactive sputtering. *Appl. Surf. Sci.* 2011, 257, 5595–5600. [CrossRef]
12. Wang, Q.; Zhou, F.; Yan, J. Evaluating mechanical properties and crack resistance of CrN, CrTiN, CrAlN and CrTiAlN coatings by nanoindentation and scratch tests. *Surf. Coat. Technol.* 2016, 285, 203–213. [CrossRef]
13. Zhou, F.; Ma, Q.; Zhang, M. Comparison of tribological properties of CrN, CrTiN and CrTiBN coatings sliding against SiC and SUS440C balls in water. *Appl. Phys. A* 2020, 126, 796. [CrossRef]
14. Wang, Y.; Zhang, J.; Zhou, S.; Wang, Y.; Wang, C.; Wang, Y.; Sui, Y.; Lan, J.; Xue, Q. Improvement in the tribocorrosion performance of CrCN coating by multilayered design for marine protective application. *Appl. Surf. Sci.* 2020, 528, 147061. [CrossRef]
15. Tong, C.; Lee, J.; Kuo, C.; Huang, S.; Chan, Y.; Chen, H.; Duh, J. Effects of carbon content on the microstructure and mechanical properties of cathodic arc evaporation deposited CrN thin films. Surf. Coat. Technol. 2013, 231, 482–486. [CrossRef]
16. Huang, S.; Tong, C.; Hsieh, T.; Lee, J. Microstructure and mechanical properties evaluation of cathodic arc deposited CrCN/ZrCN multilayer coatings. J. Alloys Comp. 2019, 803, 1005–1015. [CrossRef]
17. Fuentes, G.; Díaz de Cerio, M.; García, J.; Martínez, R.; Bueno, R.; Rodriguez, R.; Rico, M.; Montalá, F.; Qin, Y. Gradient CrCN cathodic arc PVD coatings. Thin Solid Films. 2009, 517, 5894–5899. [CrossRef]
18. Gilewicz, A.; Warcholinski, B. Tribological properties of CrCN/CrN multilayer coatings. Tribol. Int. 2014, 80, 34–40. [CrossRef]
19. Wang, Q.; Zhou, F.; Ding, X.; Zhou, Z.; Wang, C.; Zhang, W.; Li, L.; Lee, S. Microstructure and water-lubricated friction and wear properties of CrN (C) coatings with different carbon contents. Appl. Surf. Sci. 2013, 268, 579–587. [CrossRef]
20. Guan, J.J.; Wang, H.Q.; Qin, L.Z.; Liao, B.; Liang, H.; Li, B. Phase transitions of doped carbon in CrCN coatings with modified mechanical and tribological properties via filtered cathodic vacuum arc deposition. Nucl. Instrum. Methods Phys. Res. Sect. B Beam Interact. Mater. At. 2017, 397, 86–91. [CrossRef]
21. Hu, P.; Jiang, B. Study on tribological property of CrCN coating based on magnetron sputtering plating technique. Vacuum 2011, 85, 994–998.
22. Mandrino, D.; Podgornik, B. XPS investigations of tribofilms formed on CrN coatings. Appl. Surf. Sci. 2017, 396, 554–559. [CrossRef]
23. Podgornik, B.; Sedaček, M.; Mandrino, D. Performance of CrN coatings under boundary lubrication. Tribol. Int. 2016, 96, 247–257. [CrossRef]
24. Wu, X.; Yue, B.; Su, Y.; Wang, Q.; Huang, Q.; Wang, Q.; Cai, H. Pollution characteristics of polycyclic aromatic hydrocarbons in common used mineral oils and their transformation during oil regeneration. J. Environ. Sci. 2017, 56, 247–253. [CrossRef] [PubMed]
25. Hábchi, W.; Matta, C.; Joly-Pottuz, L.; De Barros, M.; Martin, J.; Vergne, P. Full film, boundary lubrication and tribochemistry in steel circular contacts lubricated with glycerol. Tribol. Lett. 2011, 42, 351. [CrossRef]
26. Joly-Pottuz, L.; Martin, J.; Bouchet, M.; Belin, M. Anomalous low friction under boundary lubrication of steel surfaces by polyols. Tribol. Lett. 2009, 34, 21–29. [CrossRef]
27. Shi, Y.; Minami, L.; Grahn, M.; Björling, M.; Larsson, R. Boundary and elastohydrodynamic lubrication studies of glycerol aqueous solutions as green lubricants. Tribol. Int. 2014, 69, 39–45. [CrossRef]
28. Kuzharov, A.A.; Luk’Yanov, B.S.; Kuzharov, A.S. Tribochemical transformations of glycerol. J. Fric. Wear 2016, 37, 337–345. [CrossRef]
29. Fu, X.; Cao, L.; Qi, C.; Wan, Y.; Xu, H. Ultralow friction of PVD TiN coating in the presence of glycerol as a green lubricant. Ceram. Int. 2020, 46, 24302–24311. [CrossRef]
30. Ma, Q.; He, T.; Khan, A.M.; Wang, Q.; Chung, Y. Achieving macroscale liquid superlubricity using glycerol aqueous solutions. Tribol. Int. 2021, 160, 107006. [CrossRef]
31. Pakala, M.; Lin, R.Y. Reactive sputter deposition of chromium nitride coatings. Surf. Coat. Technol. 1996, 81, 233–239. [CrossRef]
32. Raza, H.A.; Shafiq, M.; Naeeem, M.; Naz, M.Y.; Díaz-Guillén, J.C.; Lopez-Badillo, C.M. Cathodic cage plasma pre-treatment of TiN-coated AISI-304 stainless steel for enhancement of mechanical strength and wear resistance. J. Mater. Eng. Perform. 2019, 28, 20–32. [CrossRef]
33. Martin, J.M.; Bouchet, M.I.D.B.; Matta, C.; Zhang, Q.; Goddard, W.A.; Okuda, S.; Takumaru, S. Gas-phase lubrication of ta-C by glycerol and hydrogen peroxide. Experimental and computer modeling. J. Phys. Chem. C 2010, 114, 5003–5011. [CrossRef]