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Microstructure and mechanical properties of a CrCN/Cr multilayer film

Eryong Liu 1,2,*, Bo Yu 1, Yuan Xue 3, Jibin Pu 3,†, Shuangming Du 1 and Huiling Du 1

1 School of Materials Science and Engineering, Xi’an University of Science and Technology, Xi’an 710054, People’s Republic of China
2 Key Laboratory of Marine Materials and Related Technologies, Zhejiang Key Laboratory of Marine Materials and Protective Technologies, Ningbo Institute of Materials Technology and Engineering, Chinese Academy of Sciences, Ningbo 315201, Zhejiang, People’s Republic of China
3 Mechanical & Electronic Engineering College, Nanjing Forestry University, Nanjing 210037, Jiangsu, People’s Republic of China

* Authors to whom any correspondence should be addressed.
† E-mail: ley401@163.com and pujibin@nimte.ac.cn

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Abstract

CrCN/Cr multilayer films were synthesized by multi-arc ion plating deposition technique, and the microstructure, mechanical and tribological properties of films were systematically investigated. The results showed that the thickness of the CrCN and Cr layers in CrCN/Cr multilayer films was between 2.1 μm to 0.45 μm and 90 nm, respectively. X-Ray diffraction results indicated that the composite films were composed of CrN, Cr7C3 and metallic Cr phase, then the mechanical and tribological properties results confirmed that the multilayer structure not only increased the hardness and toughness of the CrCN multilayer film but also decreased the friction coefficient (16%) and wear rate (45%) when compared with a CrN film. This result was attributed to the presence of a complete and dense lubricating film on the worn surface. Therefore, the excellent performance of the CrCN/Cr multilayer films supports their potential application as a replacement for CrN films in industrial applications.

1. Introduction

To meet future energy conservation requirements and reduce the emissions of automobiles, manufacturers are trying to increase fuel efficiency and decrease emissions of suspended solid particles, carbon monoxide, and nitrogen oxide [1–3]. The energy balance of a passenger car indicates that the energy losses due to friction reach 33% in an engine, and the loss from piston rings reaches 45% of the overall friction loss [4, 5]. Thus, reducing the friction coefficient and wear rate between piston rings and cylinder liners plays a critical role in energy conservation and emission reduction [6]. Various surface modification techniques, such as electroplating, thermal spraying, chemical vapours deposition (CVD), and especially physical vapour deposition (PVD), have attracted the attention of engine manufacturers [7–10]. For example, hard electroplated chrome films and thermally sprayed molybdenum or cermet films are all commercial coatings for piston rings that improve their tribological properties and service life [11]. However, the drawbacks of these films, such as a low thermal stability, poor oil compatibility, and a high internal stress, limits the performance of the piston ring. Recently, hard ceramic films, such as TiN, CrN and DLC are considered as alternative films to electroplated chrome films or thermally sprayed molybdenum coating [12–14]. The nature of PVD ceramic films ensures that the engine components possess an increased load-bearing capacity, wear resistance, and corrosion resistance in addition to anti-adhesive properties and a low friction coefficient [15]. Among PVD films, CrN films are widely used in industrial applications due to their high hardness, high thermal stability, galling resistance and excellent anti-corrosion properties [16–18]. However, the COF of CrN films under dry sliding conditions is in the range of 0.4–0.7, which means that those films cannot effectively lubricate the rubbing pairs under dry sliding or oil-starvation conditions [19]. Thus, automobile manufacturers urgently need a new hard films that provides a combination of higher wear resistance and a lower friction coefficient.
The addition of carbon in CrN films not only reduces the internal stresses, wear rate and COF but also increases the hardness [20]. Our group Yuwei Ye previously studied the effect of carbon content on the microstructure and tribological properties of CrCN films, and the results show that the CrCN films have a lower COF and wear rate in seawater than CrN films, but the adhesion of CrCN films with a high carbon content is lower than that of CrN films [21–24]. It is well known that a perfect film in an engine should have good adhesion, a high wear resistance and a low friction coefficient. However, it is difficult to achieve these goals with a monolayer film; thus, multilayer films with different structures or chemical compositions reduce the wear rate and friction coefficient. Similar performance has been exhibited by CrCN/CrN or CrN/Cr multilayer films, which possess a higher hardness, wear resistance, corrosion resistance and a lower COF than CrN monolayer films [25–28]. In CrCN/CrN or CrN/Cr multilayer films, Cr layer rather than the CrN layer tends to deform plastically; thus, CrCN/Cr multilayer films may perform better than CrCN, CrN monolayer films or CrCN/CrN multilayer films. Therefore, CrCN/Cr multilayer films synthesized by multi-arc ion plating deposition technique are developed and characterized in this work.

Based on previous work by our group [21, 22, 25, 29–31] involved CrN and CrCN monolayer films, CrCN/Cr multilayer films with different modulation ratios of the CrCN and Cr layers were designed, and the chemical composition, properties, hardness, friction coefficient, wear rate and scratch adhesion of the CrCN/Cr multilayer films were investigated systematically. Since the potential application of CrCN/Cr multilayer films is in engine piston ring, CrN films were chosen as contrast material in this study.

### 2. Experimental details

#### 2.1. Deposition

The CrCN/Cr multilayer films with different modulation ratios of the CrCN and Cr layers were deposited on both Si(100) and 316L stainless steel substrates (24 mm × 12 mm × 2 mm) using the multi-arc ion plating deposition technique (Hauzer Flexicoat 850). The modulation ratios of the CrCN/Cr multilayer films were as follows: CrCN:Cr=0, 16:1, 8:1, and 4:1 and which were denoted as CrCN, CrCN-16, CrCN-8, CrCN-4, respectively. Monolayer CrN films were also deposited as a contrast, as shown in table 1. Prior to deposition, all substrates were ultrasonically cleaned in acetone and ethanol. After cleaning, the substrates were fixed on a substrate holder, and the deposition chamber was pumped down to a background pressure of 4 × 10⁻⁶ Pa. Then, the substrates were cleaned by Ar⁺ bombardment with a negative bias of 900 V, 1100 V and 1200 V for 2 min at each bias, in order to remove the thin oxide layer and adherent impurities. An adhesive Cr layer was initially deposited before sputtering the CrCN film, and the deposition was conducted using the following parameters. The size of the three chromium targets (purity > 99.5 wt.%) was 63 × 32 mm, the bias voltage was −100 V, the target current was 60 A, the distance from the substrate to the target was 100 mm, the substrate temperature was 450 °C, and the chamber pressure was 0.4 Pa during deposition. The alternate times for the CrCN/Cr multilayer film and the N₂/C₂H₆ (purity 99.99%) flow rate during CrCN sputtering were 400 sccm and 80 sccm, the flow rate of N₂ (purity 99.95%) during CrN sputtering was 400 sccm, and the flow rate of Ar₂ (purity 99.95%) during Cr sputtering was 350 sccm. During sputtering, the rotation speed of the substrate was 3 rpm.

#### 2.2. Characterization

The phase composition of the films was investigated by x-ray diffraction (XRD, Bruker D-8 Advance) using Cu Kα radiation (λ = 0.154 nm). The current and voltage were 40 mA and 40 kV, respectively, the scanning angle range was 20 to 90°, the scanning speed was 4° min⁻¹ and the step size was 0.02°. The microstructure, chemical composition and wear tracks were studied by scanning electron microscopy (SEM, FEI Quanta FEG 250) equipped with EDS (OXFORD X-Max), high-resolution transmission electron microscopy (HRTEM), and glow discharge optical emission spectroscopy (GDOES). The hardness was measured by nanoindentation (MTS Nano Indenter G200 system) on an instrument equipped with a Berkovich indenter. During testing, the continuous stiffness measurement (CSM) mode was used, five measurements were completed and the average value was

### Table 1. Alternate deposition times of CrCN/Cr multilayer film.

| Samples | CrCN Sputtering (Min) | Cr Sputtering (Min) | Alternate times | modulation ratio |
|---------|----------------------|--------------------|-----------------|-----------------|
| CrN     | 180                  | 0                  | 0               | 0               |
| CrN     | 180                  | 0                  | 0               | 0               |
| CrCN-16 | 32                   | 2                  | 5               | 16:1            |
| CrCN-8  | 16                   | 2                  | 10              | 8:1             |
| CrCN-4  | 8                    | 2                  | 18              | 4:1             |
calculated. After testing, the hardness and elastic modulus of the films were calculated using the Oliver–Pharr method. The adhesion of the films was assessed by a commercial scratch tester (CSM Instruments Revetest) with a Rockwell diamond stylus (the radius was 0.2 μm and taper angle was 120°). The adhesion testing parameters were as follows: the scratch length was 5 mm, speed was 5 mm min⁻¹, loading scale was 0–100 N and loading rate was 118 N min⁻¹. During the scratching event, force and acoustic emission (AE) were recorded when the films were broken, and the corresponding load was the adhesive critical load.

Tribological properties of CrCN/Cr multilayer films were tested on a UMT-3 tribometer (CETR, USA) in ambient air, and the relative humidity was 60 ± 5%. The counterparts comprised GCr15 balls (Chemical composition (wt.%) 1.40% ~ 1.65% Cr, 0.95% ~ 1.05% C, 0.25% ~ 0.45% Mn, 0.15% ~ 0.35% Si, 0.025% or less of P and S, Mo ≪ 0.10%, Ni ≪ 0.30%, Cu ≲ 0.25%, Ni + Cu ≤ 0.50%, and Fe balance) with a diameter of 6 mm (ASTM A 295: 1998) and a 25.8 HRC. The tests were conducted under dry sliding and oil-lubricated conditions (Mobil 1™ 5w-40 engine oil). To simulate the conditions of the piston ring system in the engine, the parameters of the wear test were determined according to the ASTM G181-11 standard as follows: the sliding distance was 2000 m and F was the normal applied load. The friction coefficient was continuously recorded. After testing, the volume loss of the wear track was detected by laser scanning confocal microscopy (LSCM, Keyence) according to ISO standard 4287-1997. Finally, the wear rates of films were calculated using the formula K = V/FS, where V was the wear loss of films, S was the sliding distance and F was the normal applied load.

3. Results and discussion

3.1. Microstructure of CrCN/Cr multilayer films

The phase and chemical composition of the CrCN/Cr multilayer films are analysed by XRD and micro-Raman spectroscopy, respectively, as shown in figure 1. The x-ray diffraction patterns of the CrCN films indicate that the (111), (200) and (220) diffraction peaks could be assigned to the CrN phase (ICDD: 76–2494). The (151) diffraction peaks are allocated to the Cr7C3 phase (ICDD: 36–1482), indicating that the CrN and Cr7C3 phase is coexisted in the CrCN films. For the CrN and Cr7C3 phases, the nitrogen atoms can be replaced by carbon atoms in chromium nitride to form chromium carbon; thus, the normal crystal arrangement of chromium nitride is disturbed by the addition of carbon, and the crystal structure of the CrCN films consists of a crystalline state and an amorphous state. In addition, with the addition of a Cr layer, the appearance of (310) Cr diffraction peaks (ICDD: 06–0694) means that a large amount of metallic Cr is doped into films, leading to a significant change in mechanical and tribological properties of CrCN/Cr multilayer films.

To further analyse the bonding structure of the films, micro-Raman spectroscopy results indicate that the intense peaks at 780, 1000, and 1300 cm⁻¹ could be assigned to the CrN phase in the CrCN/Cr film, and the Cr7C3 phase presents an intense peak at 700 to 900 cm⁻¹. Furthermore, the D band (1340 cm⁻¹) and G band (1580 cm⁻¹) of carbon indicate a typical undisrupted flat region, disruptive flakes and growth defects on the CrCN/Cr coating. The D band is due to the vibration modes of the rings, and the G band is due to bond stretching of sp² atoms in rings and chains, which also confirms that the as-deposited films contain amorphous carbon. These hard particles provide a dispersion-strengthening function in the CrCN film; thus, the hardness of the CrCN film is higher than the film compounds of the CrN phase. Therefore, a CrCN film consisting of chromium nitride, chromium carbide and amorphous carbon may possess a higher hardness and lower friction coefficient than a CrN film.

**Figure 1.** Phase composition of CrCN/Cr multilayer film (a) XRD results (b) Raman results.
Figure 2 shows the cross-sectional morphologies of the CrCN/Cr multilayer films with different modulation ratios. It can be seen that a compact and dense structure is observed for all the CrCN/Cr multilayer films. First, the total thickness of the monolayer CrCN film is approximately 12 μm with a CrCN layer thickness of approximately 10.8 μm and a Cr adhesive layer thickness of 1.2 μm. Furthermore, CrCN/Cr films generally present multilayer structures in a terrace-like fracture surface, and the thickness values of the Cr layer and CrCN layer are shown in the SEM images. The bilayer thicknesses of the different films are between approximately 2.1 μm and 0.54 μm, which was calculated from the ratio of total thickness versus the deposited layer numbers. Thus, the corresponding individual layer thickness ratios of CrCN/Cr in the bilayer thickness were estimated from the deposition rate and approximately equal to CrCN:Cr ~ 23:1 for CrCN-16, CrCN:Cr ~ 12:1 for CrCN-8, and CrCN:Cr ~ 5:1 for CrCN-4. In addition, high-magnification SEM indicates that the thickness of the Cr layer is approximately 90 nm; thus, the actual deposition rates of the Cr layer and CrCN layer are 45 nm min⁻¹ and 65 nm min⁻¹, respectively.

The chemical composition of the CrCN-16 film can be further analysed by GDOES, as shown in figure 3. From the spectra, the alternative individual Cr and CrCN layers can be observed by the modulation of the Cr and N signals at increasing depths. In addition, it can be seen that the Cr layer in the CrCN film not only consisted of metallic Cr but also comprised N and C, which can be attributed to the fact that N₂ and C₂H₂ gas is also present during the Cr layer deposition. Although the Cr layer is not a pure metallic Cr layer, it also plays an important role in the improvement of the mechanical and tribological performance of the CrCN film.

The cross-sectional high-resolution electron microscopy images and SAED patterns were used to analyse the microstructure of the metallic Cr and CrCN layers of the CrCN-16 film, which had the largest modulation ratio (CrCN/Cr) of 16:1, as shown in figure 4. The alternating light grey and dark grey colour regions indicate the layered structure of the CrCN and Cr film, where the CrCN grains are disrupted by the CrCN-Cr layer. The grains have a ‘V’ shape and are small near the interface and large at the surface. In addition, the typical stress evolution in multilayer films is a gradient from the large grains (high stress) to the small grains (low stress). The corresponding phases for the Cr and CrCN layers are shown in figures 4(c) and (d), respectively. It can be seen that the CrCN layer is composed of CrN crystallites surrounded by Cr₇C₃ and a-C phases, acting as barriers to restrict the movement or sliding of dislocations. In the Cr layer, the dark grey area consists of CrN crystallites and metallic Cr, and the light grey area is mainly composed of metallic Cr. In addition, the CrCN deformed lattice is
due to N being substituted by C in the CrN or C being substituted by N in the Cr7C3 because of the high-energy ion bombardment during deposition. The reason is that the residual N2 and C2H2 gas used during the alternating deposition process is difficult to remove rapidly. Thus, it can be further proven that the phases of Cr and CrCN is coexisted in the multilayer films. The twin crystal structure in the CrN crystallites plays an
important role in improving the toughness and hardness of CrCN films, and a decrease in the hardness of the CrCN/Cr multilayer films can be attributed to an increase of Cr layer.

### 3.2. Mechanical properties

Currently, thick CrN films (e.g., 30 μm) are commercially used for piston ring films and provide excellent wear resistance. Thus, a CrN film was selected as the contrast for the CrCN and CrCN/Cr multilayer films in this study. First, the hardness and Young’s modulus of the as-deposited CrCN multilayer films are tabulated in figure 5. It can be seen that the CrCN and CrCN/Cr multilayer films display higher hardness values than monolayer CrN films. Furthermore, the hardness decreases with decreasing modulation ratio of CrCN:Cr, and the maximum hardness for CrCN-16 is 29.6 GPa. Thus, the interfaces between the films produce barriers to inhibit grain growth and dislocation glide, acting as the key factor in improving the hardness. However, as for the different individual hardness values of the Cr and CrCN layers, the increased thickness of the high hardness CrCN layer strengthens the CrCN/Cr multilayer films. Thus, the hardness enhancement effect decreases when the number of metallic Cr layers increases. Therefore, the increased hardness CrCN films can be correlated with the optimized modulation ratio of CrCN/Cr in CrCN multilayer films.

The durability and plastic deformation resistance of the CrCN/Cr multilayer films are related to the H/E and H²/E² ratios, which are closely related to the wear resistance. Thus, increased values of the H/E and H²/E² ratios indicate an increased film resistance to plastic deformation and a rapid decrease in the stress. The calculated H/E and H²/E² ratios of the as-deposited films are shown in figure 5(b), which play an obvious role in measuring the strength of the films when exposed to local dynamic loads, such as wear process. The H/E and H²/E² ratio decreases with increasing modulation ratio of CrCN:Cr. Meanwhile, the H/E and H²/E² ratios of the CrCN-16 film are 0.0757 and 0.162, respectively, which are higher than those of the CrN film. This is due to the high content of Cr–C, and solid solution hardening from the carbon atoms in the CrCN films compared to the CrN films. Thus, CrCN/Cr multilayer films with modulation ratios of 16:1 (CrCN-16) are selected as the films for further study of the effect of the Cr layer on the mechanical and tribological properties of the CrCN film.

Furthermore, Vickers indentation testing is conducted to evaluate the toughness of the CrN, CrCN and CrCN-16 coatings, as shown in figure 6. The Vickers indentation results show that a large number of radial cracks are present in the CrCN film, and radial cracks obviously decrease in the CrCN/Cr multilayer films. This
is because the elastic recovery of the Cr-rich interlayer is higher than that of the CrCN layer; thus, the toughness of the CrCN film is significantly improved by embedding of a Cr layer. Furthermore, comparing the plastic strain with the total strain from nano-indentation testing of different films directly gives a simple, rough but quick indication of the toughness [32]. Figure 6(d) indicates that the plasticity of the CrN, CrCN and CrCN-16 films is 70%, 56% and 62%, respectively. In contrast, CrN film possesses the best plasticity, and the toughness of CrN is also higher than that of CrCN/Cr films. Therefore, the toughness of the CrCN/Cr multilayer films is higher than that of the CrCN monolayer films, indicating that the stress in the multilayer films is more easily relaxed by the addition of the metallic Cr layer.

The adhesion of the CrN, CrCN and CrCN-16 films are shown in figure 7. The results show that the Lc1 value of the CrN film is 64 N, which is higher than that of monolayer CrCN films and lower than that of the CrCN-16 film. This means that addition of carbon decreases the adhesion of the Cr-N system coating, and the adhesion is significantly improved by the multilayer structure. Thus, CrCN/Cr multilayer films meet the requirements for the application of industrial piston ring, such as the comprehensive performance of increased hardness and adhesion than CrN films.

3.3. Tribological properties

To evaluate the feasibility of CrCN/Cr multilayer films for the application of piston ring, the tribological properties of CrN, CrCN and CrCN-16 films against GCr15 balls were tested, as shown in figure 8. According to the ASTM G181-11 standard, dry sliding and oil-lubricated conditions were selected to simulate the working conditions of the piston ring. Under dry sliding conditions, the results show that the COF of the CrN film is 0.40, approximately 25% lower than that of the CrCN film. Furthermore, the results indicate that the COF of the CrN film is also higher than that of CrCN-16 in oil-lubricated environment, such as the COF of CrCN-16 is approximately 16% lower than that of the CrN film. In addition, the real-time friction in figures 8(c) and (d) show that the breaking-in time of the CrCN film is significantly shorter than that of the CrN film, confirmed that the carbon and multilayer structure improve the tribological properties of the CrN film. Therefore, the use of CrCN/Cr films meets the future requirements of energy conservation and emission reduction of piston rings in engine.

Under dry sliding and oil-lubricated conditions, wear rate of CrCN-16 film is approximately 37% and 45% lower than that of CrN and CrCN film. The results show that the addition of carbon and multilayer structure all...
Figure 7. Adhesion strength of CrN, CrCN and CrCN-16 film.

Figure 8. Tribological properties of CrN, CrCN and CrCN-16 film (a) Friction coefficient (b) Wear rate (c) Real-time friction coefficient under oil lubricating (d) Real-time friction coefficient under dry sliding condition.
decrease the wear rate, confirming that the CrCN/Cr multilayer film is suitable for the piston ring application of under harsh working conditions.

To determine the wear mechanism of the CrN, CrCN and CrCN-16 films in dry sliding conditions, SEM and EDS analyses of the wear tracks are done and the results of are shown in figure 9 and table 2. Under dry sliding conditions, worn surface of the CrN film is covered by a discontinuous film and large fragments, indicating that the wear mechanism is dominated by delamination and microfracture. Furthermore, an increased number of fragments appears on the worn surface of the CrCN film, and the lubricating film obviously decreases, suggesting that the wear mechanism is also dominated by delamination and microfracture. With the addition of the Cr layer, the worn surface of CrCN-16 film presents a whole-scale film accompanied by a small number of spalling pits, demonstrating that the wear mechanism is dominated by delamination. In addition, EDS results in table 2 show that the worn surface of the CrN film is composed of 4.27 Cr, 69.55 Fe, 1.23 C, and 24.94 O (wt.%), indicating that the film is mainly formed by the transferred elements of coupled parts. Therefore, if a CrN film is added to the surface of engine components, it causes severe wear of coupled parts. In addition, the chemical

| Samples (wt.%) | Cr  | Fe  | C   | O   | N   |
|----------------|-----|-----|-----|-----|-----|
| CrN            | 90.27 | —   | 0.54 | —   | 9.19 |
| CrCN           | 86.73 | —   | 4.32 | —   | 8.95 |
| CrCN-16        | 87.16 | —   | 4.13 | —   | 8.71 |
| Point 1        | 4.27 | 69.55 | 1.23 | 24.94 | —   |
| Point 2        | 41.26 | 38.56 | 3.04 | 12.63 | —   |
| Point 3        | 4.35 | 70.78 | 1.03 | 23.84 | —   |
| Point 4        | 7.58 | 73.57 | 0.98 | 17.87 | —   |
| Point 5        | 14.25 | 62.12 | 0.90 | 20.92 | 1.80 |
| Point 6        | 5.69 | 69.42 | 1.52 | 23.34 | —   |

Figure 9. The morphologies of the wear tracks on CrN, CrCN and CrCN-16 film under dry sliding conditions (a) CrN (b) CrCN (c) CrCN-16.

Table 2. EDS results of worn surfaces tested under dry sliding conditions.
composition of the worn surface on the CrCN/Cr film is significantly changed by carbon elements and multilayer structure, leading to the formation of a C-rich layer on rubbing surfaces, and the formation of a C-rich film is beneficial for the improvement of tribological performance.

In oil-lubricated conditions, the worn surface and wear mechanism of the hard film is shown in figure 10 and table 3. First, the worn surface of the CrN film is relatively smooth, only some shallow groove and spalling pits appear on the worn surface, which can be attributed to the mild polishing effect. With the addition of carbon, the worn surface of the CrCN film improves, and the groove depth also decreases, indicating that the main wear mechanism is plastic deformation. Furthermore, the lubricating film formed by plastic deformation of the CrCN-16 film is complete and more compact; thus, the CrCN/Cr film is more suitable in oil-lubricated conditions. Furthermore, EDS results indicate that the worn surface of the CrN film consists of

**Figure 10.** The morphologies of wear tracks on CrN, CrCN and CrCN-16 film under oil-lubricated conditions (a) CrN (b) CrCN (c) CrCN-16.

**Table 3.** EDS results of worn surfaces tested under oil-lubricated conditions.

| Samples (wt.%) | Cr  | Fe  | C   | O  | N  |
|---------------|-----|-----|-----|----|----|
| Point 1       | 90.28 | —  | 1.18 | 0.52 | 8.02 |
| Point 2       | 85.51 | 1.27 | 9.43 | 1.52 | 2.27 |
| Point 3       | 86.10 | —  | 4.46 | 2.54 | 6.89 |
| Point 4       | 55.60 | 1.69 | 37.20 | 5.52 | —  |
| Point 5       | 87.02 | —  | 4.17 | 0.30 | 8.52 |
| Point 6       | 59.14 | 1.03 | 34.86 | 4.97 | —  |
90.28Cr, 1.18 C, 0.52 O, 8.02 N (wt. %), which confirms that the lubricating films are mainly formed by the polishing effect. Subsequently, the carbon and oxygen contents of the worn surface on CrCN-16 films increases, suggesting that the lubricating films are very effective in reducing COF. In addition, the spall pits on the CrCN-16 film are mainly composed of carbon and chromium, indicating that the lubricating film on the worn surface is easily destroyed under the alternating pressures of wear testing. Therefore, the composition and microstructure are concluded to be the main reason for an improvement in the tribological properties of a CrCN/Cr multilayer films.

In summary, CrCN/Cr multilayer films not only possessed high hardness/toughness, but also had better tribological properties than monolayer CrN film and CrCN film. The carbon in the CrN-based film reacted with chromium to form Cr7C3, acted as a strengthening second phase in the CrN film. In addition, the embedded metallic Cr layer played a role in the stress relaxation and crack deflection. Thus, the synergistic effect of the carbon and multilayer structure was the main reason for the improvement in the mechanical properties of the CrN-based films. Therefore, CrCN/Cr films can play a critical role in the energy conservation and emission reduction of engines, especially when used in piston rings compared to CrN films.

4. Conclusions

This work studied the microstructure, adhesion and tribological properties of CrCN/Cr multilayer films. The films were fabricated by the multi-arc ion plating technique. The results showed that the Cr layer improved both the toughness and adhesion of the CrCN film, and the toughness was obviously reduced. Compared to the monolayer CrN film and CrCN film, not only the hardness of the CrCN/Cr multilayer films increased but also the friction coefficient and wear rate markedly decreased, especially under oil-lubricated conditions. During wear testing, a dense lubricating film was the main factors in reducing the friction coefficient and wear rate. Therefore, the synergistic effect of the carbon addition and multilayer structure played a major role in the improvement of tribological properties. Thus, the excellent performance demonstrated supports the potential application of a CrCN/Cr multilayer as a protective film for piston rings under harsh conditions.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

ORCID iDs

Eryong Liu ORCID iD https://orcid.org/0000-0002-5279-2121
Jibin Pu ORCID iD https://orcid.org/0000-0002-6513-6617

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