Effect of lubrication on the wear behaviour of CrN coating deposited by PVD process

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Abstract: This paper investigates the effect of SAE grade 20W50 engine oil as a lubricant on the wear behaviour of chromium nitride (CrN) coating deposited by PVD process at higher loads and speeds by pin on disc tribometer. The specific wear rate ranges from 9.82×10^{-5} to 2.87×10^{-5} mm^3/Nm in dry condition whereas in lubricated condition 0.97×10^{-5} to 0.19×10^{-5} mm^3/Nm. Successive increase of speed and load rises the temperature of wear track from 65°C to 178°C in dry condition while 34°C to 40°C in lubricated conditions results to decrease in friction coefficient, which has immense influence on the wear resistance of coating. The wear mechanism of the coatings was analysed by SEM and EDS and found deformation, cracks and, nitride particle pull-out, built up edge formation, erosion and adhesive wear coupled with oxidation wear. The highlights of the paper are: 1) tribology of CrN coating against cylinder liner material as counter face summarised; 2) research has practical applications for piston ring with the influence of engine oil; 3) temperature ranges from 65°C to 178°C in dry and 34°C to 39°C in lubrication during wear test; 4) the wear mechanism is combination of three body abrasion, metal transfer and oxidation.

Keywords: physical vapour deposition; PVD; CrN; wear; friction; lubrication; temperature.

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1 Introduction

Automotive industries are always in need of eco-friendly superior components to meet the ever increasing demand of high efficiency engines by taking consideration of available resources. These challenges can be overcome by utilising high strength and low weight materials as well as employing surfaces that generate low friction. Surface modification by means of different coatings has become an essential step to enrich the surface properties of the bulk materials like wear, corrosion, anti-adhesive nature, oxidation, etc. (Podgornik et al., 2016, 2015; Jha et al., 2013; Groche and Christiany, 2013; Eriksson and Olsson, 2011). To increase the efficiency of many engine components such as piston rings and liner combination, require surfaces that generate ultra-low wear and friction of mating surfaces. There are number of techniques that are available to deposit such coatings on bulk materials such as physical vapour deposition (PVD), plasma-assisted chemical vapour deposition (PACVD), thermal spray processes [X1], diffusion coating processes, etc. Out of above mentioned processes, PVD is widely used to deposit coatings on parts having in intrinsic geometry. PVD is an atomistic deposition technique that includes the vaporisation and subsequent deposition of target material in the form of coating. A wide range of materials such as metals, alloys and ceramics can be deposited in that way on most of the materials with wide range of shapes. Common examples of PVD deposited coatings are CrN, TiN, diamond-like carbon (DLC), etc. Though for cutting and forming applications, TiN coating on cutting/forming tools are commonly used due to their galling tendency; DLC coatings provide very low friction and superior running-in properties. CrN is another popular example of such PVD deposited coating that shows high hardness, low friction, excellent corrosion and high thermal stability properties. For lubricated condition applications, CrN is more foreseen in automotive industries, as large grain size and highly textured surface of CrN provide micro-reservoirs for lubricants and as a result reduces coefficient of friction (COF) (Lorenzo-Martin et al., 2013; Chen and Nie, 2011; Donnet and Erdemir, 2007; Petrogalli et al., 2014; Quinones-Salinas et al., 2015).

Some tribological components, like piston rings, forming tools and gears, bearings, etc. are generally lubricated. Sufficient lubrication is important for their best operation, due to severe contact conditions and to prevent failure, even when using thin film of hard coatings. Usually lubricants are prepared methodically for optimal performance with different additives and account for 4%–10% of fully formulated lubricants (Ortmann et al., 2003; Lubas, 2012). Additives interact with the mating parts of the material to form a tribo-chemical film as a protective layer. Haque et al. (2010) reported that, friction modifier (FM) additives mixed with engine oils in case of CrN/cast-iron systems, provide low friction as well as wear and attributed to tribo-chemical film formation. In that respect, little work has been reported to understand the performance for CrN coating on engine parts and effect of lubrication together with the effect of additive types and concentration. In contrast, it has been widely accepted in literature that CrN coating deposited by PVD can reduce friction and wear in substantial level. In most of such reposts, experiments have done on relatively low load (10–50 N) and speeds (0.3–1 m/s) (Singh et al., 2017). However in reality, during the component test of piston ring-cylinder liner applications where coatings are expected to withstand higher loads and speeds

(300–1,500 rpm) has been recommended (Söderfjäll et al., 2016). Capability of the coatings to withstand under higher load and speed reduces cost and increase equipment efficiency. So far there is no information available in open literature regarding tribological behaviour of PVD deposited CrN under high loads and speeds in lubricated conditions. The information on wear behaviour of this coating with cylinder lining material counter face is also unavailable. This information is imperatively needed for better understanding and wider application of such coatings. In view of that, aim of this research is to determine the influence of engine oil as a lubricant on tribological behaviour of PVD deposited CrN coating under high loads and speeds.

2 Experimental

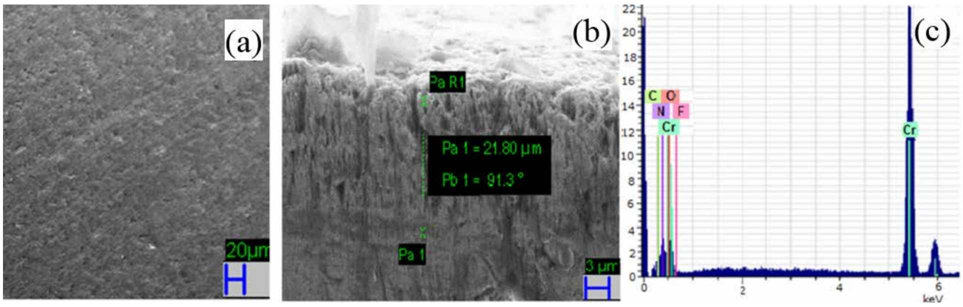
2.1 Coating characterisation

CrN coating was deposited on piston rings made of cast-iron whose elemental composition is given in Table 1. Prior to deposition of CrN, substrate material was well cleaned and roughened by a dry mechanical finishing process (micro-blasting) by using alumina particles of the particle size 15–45 µm to remove surface irregularities such as oxides, dirt, oils, etc. to ensure proper bonding of the coating with the substrate. In fact, hardness of deposited coating depends upon the state of the substrate surface. Substrate surface also needs to be in the state of fine ground finish, particularly for thin film coatings, to ensure coating thickness is higher than that of surface roughness for uniform and durable coverage. During the process, samples were heated up to 400°C for 80 minutes in vacuum chamber. The chamber was filled with carrier gas (nitrogen) and acetylene with argon as fuel under 550 MPa pressure. Cathode power was set at 2,500–2,700 W and pulse frequency was adjusted to form nitride phase of chromium. Detail x-ray diffractometry (XRD) analysis of the coatings were carried out as reported in our previous corresponds (Singh et al., 2017) and confirmed that the coatings structure is mainly face centred cubic (FCC) CrN with a trace of hexagonal CrN along (200) and (111) preferential orientation. Morphology of the coating as well as elemental analysis is shown in Figure 1. The coating consists of small grains and form dense structure [Figure 1(a)] throughout the film with short and disordered columnar texture [Figure 1(b)] and good adhesion with the substrate. Thickness of the coating is about 21.80 µm [Figure 1(b)] and composed of about 64% chromium and 22% nitrogen [Figure 1(c)]. Neither pinholes nor voids were seen throughout the structures. The mean surface roughness (Ra) was evaluated by a Taylor Hobson 3D surface profilometer and results of about 0.60 µm surface roughness.

Table 1 Composition of cast iron piston ring

Elemental content weight (%)	*Fe*	*C*	*Si*	*Mn*	*Cr*
	Balance	3.4–4	2.4–3.0	0.6–1	0.2–0.4
	W	*V*	*Ti*	*P*	*S*
	0.15–0.16	0.15–0.25	0.05	0.25–0.45	0.1

Figure 1 Morphology of as-deposited CrN coating, (a) top-view SEM micrograph, (b) cross-section view of coating with substrate and (c) EDS spectra of the coating (see online version for colours)



2.2 Lubricant

SAE grade 20W50 engine oil, characteristics details as given in Table 2, was used as a lubricant during pin-on-disk sliding test. During pin-on-disk tests, attention was given to mimic the exact contact configuration that took place in practical application between piston ring and cylinder liner configuration.

Table 2 Characteristics of engine oil used as lubricant

Engine oil	*SAE Grade (20W50)*	*Units*
Volumetric mass at 15°C	892	kg/m^3
Viscosity at 40°C	152	mm^2/s
Viscosity at 100°C	17	mm^2/s
Viscosity index	120	-
Flash point	> 200	°C
Pour point	–24	°C

Source: Söderfjäll et al. (2016)

2.3 Wear test

Sliding wear tests were performed on chromium nitride coated sample against uncoated cylinder liner material in both dry and lubricated conditions according to ASTM G99 Standard. The cylinder liners are made of uncoated grey cast iron to increase their tribological and mechanical properties, the addition of chromium, nickel, copper and molybdenum are required. Optical images of coated surface, coated pin and pin-on-disk configuration and wear test set-up is shown in Figure 2.

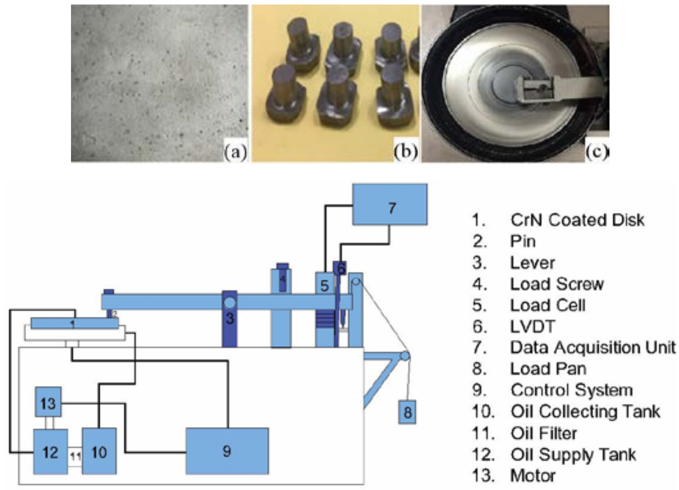
Wear volume was measured in three intervals: after 833 s, 1,250 s and 2,500 s. Total sliding distance of 2.5 km was constant in all cases and performed in ambient of 25°C and 50% relative humidity. Details of experimental parameters are given in Table 3. After wear tests, specimens were cleaned in ethanol to remove loosely adhering wear particles ultrasonically prior to weight loss measurement. Specific wear rate was calculated by a wear coefficient (K) which is often used to categories resistance to contact wear according to equation (1) (Ramalho and Celis, 2002; Steinschütz et al., 2010):

$$K = \frac{\text{Wear volume of pin}}{\text{Load} * \text{Sliding distance}} \tag{1}$$

$$\text{Wear volume} = \text{Wear volume} \times \text{Pin area} \tag{2}$$

Wear volume solved according to equation (2). The wear depth obtained by data acquisition system of the pin on disc tribometer and the area of the pin (counter-body) is 6 mm. The unit of wear volume is in mm^3, load is in Newton (N) and sliding distance is in metre. Wear track temperature during test was measured by a thermal imaging camera manufactured by Fluke thermography (model Ti400) with infrared sensor size of 320 × 240 and; emissivity and transmission of 0.95 and 1.0 has been used, respectively.

Figure 2 (a) Coated sample (disc), (b) Counter body (pin), (c) Pin on disc during wear test, (d) Pin on disc wear test set-up (see online version for colours)



(d)

Table 3 Experiment details of process parameters

Expt.	*Samples*	*Load (N)*	*Slide speed (m/s)*
1	Coated sample in dry condition	50	1
2	Coated sample in dry condition	80	1
3	Coated sample in lubricated condition	50	1
4	Coated sample in lubricated condition	80	1
5	Coated sample in dry condition	60	2
6	Coated sample in dry condition	90	2
7	Coated sample in lubricated condition	60	2
8	Coated sample in lubricated condition	90	2
9	Coated sample in dry condition	70	3
10	Coated sample in dry condition	100	3
11	Coated sample in lubricated condition	70	3
12	Coated sample in lubricated condition	100	3

3 Results and discussion

Friction and wear are most important factors in tribological study of piston rings and liner combination. Characterisation of chromium nitride coatings by tribometer (pin-on-disc) tests in terms of specific wear rate, COF, temperature rise in wear track during the process and overall wear has been analysed in dry and lubricated conditions as reported in subsequent sections.

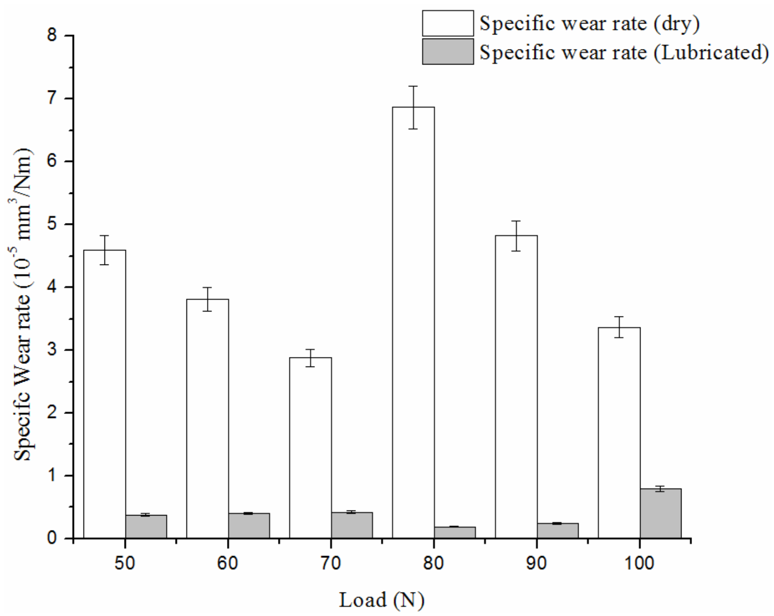
3.1 Specific wear rate

Figure 3 shows a comparison of specific wear rate of current investigated materials under different experimental conditions. Increase of normal loads causes an increase in wear rate as a result of standard weighted increase of frictional heat produces at the interface and hence, decrease of materials' strength. Combined effect of loads and sliding speeds affect the amount of friction force. Wear rate was found to decrease with increase in hardness (de Wit et al., 1998; Holmberg and Mathews, 1994; Al-Samarai et al., 2012; Paul and Sellamuthu, 2016). The effect of engine oil as a lubricant on the wear coefficient has been reported in this section. Wear factor in dry conditions is much higher than lubricated conditions. It is seen in the experiment that the wear coefficient is 4.59×10^{-5} mm^3/Nm in dry and 0.38×10^{-5} mm^3/Nm in lubricated conditions at 50 N load and speed 1 m/s. At the same sliding speed when the amount of load is increasing from 50 to 80 N the wear rate is 6.86×10^{-5} mm^3/Nm in dry and 0.19×10^{-5} mm^3/Nm in lubricated conditions. It can be observed from above results that specific wear rate is increased when the load is increasing at a constant velocity in dry conditions and decreasing in lubricated conditions at the same operating parameters. A similar pattern is observed at different test conditions; wear rate is 3.81×10^{-5} mm^3/Nm and 0.40×10^{-5} mm^3/Nm in dry and lubricated conditions at 60 N load and 2 m/s sliding speed. While the load is increasing from 60 to 90 N at the same speed (2 m/s), the wear coefficients are 4.82×10^{-5} mm^3/Nm in dry and 0.24×10^{-5} mm^3/Nm in lubricated conditions. At the load of 70 N and sliding velocity, 3 m/s the wear coefficient is 2.87×10^{-5} mm^3/Nm of coating in dry conditions and 0.42×10^{-5} mm^3/Nm in lubricated conditions. With the increase of load from 70 to 100 N the wear rate is 3.36×10^{-5} mm^3/Nm in dry and 0.97×10^{-5} mm^3/Nm in lubricated conditions.

The wear coefficient is a function of sliding velocity and time of contact, wear rate magnitude and the mechanism at the wear track and counter body both are dependent upon the sliding speed. The dependence of specific wear rate on velocity can be clarified in the following way. Momentum transfer in the normal direction increases when the speed increases, which yields an upward force on the top layer of the coating. This results to increase the gap between the mating parts which will results to decrease in the real contact area. Contributing to the fact of increased the separation at higher sliding velocity, the time in which opposing asperities wrapped each other is reduced and increasing the level on which the upper surfaces move.

The specific wear (wear coefficient) rate is also higher in dry conditions as compare to lubricated conditions, due to the fact, formation of a lubricious transfer layer on the counter face (pin). The chemical reaction of engine oil and coating can lower the frictional properties, to match the different counter faces and minimise a progressive loss of disc and pin both. While pin on disc tribometer is a unidirectional wear test, the applied normal load causes to increase the re-orientation of the top layers (even those are re-crystallised) of the coating such that base planes and sample surface are parallel. Increase in applied loads causes more re-orientation and cause to increase in wear coefficient at a constant speed and lower friction coefficients.

Figure 3 Specific wear rate of coating under dry and flooded condition



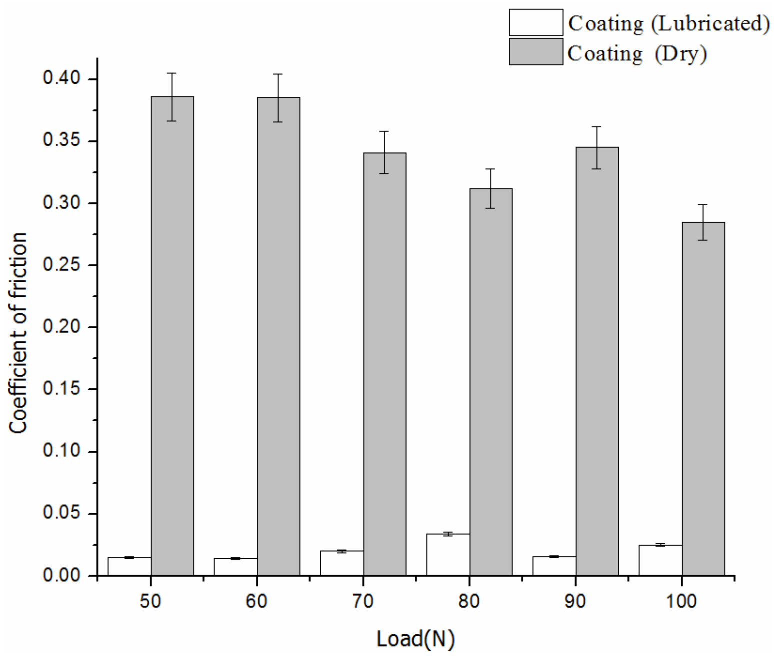
3.2 Coefficient of friction

Steady-state friction coefficient was decreasing from 0.07 to 0.05 due to increase in load from 50 to 80 N. This is due to the amount of debris accumulated and formation of transfer layer on the mating parts that increases with time and found to be constant while the friction coefficient reaches a steady-state value.

To study and simulate the behaviour of engine cold-starting on tribological properties, the CrN-coating with the ethanol-oil blend was studied in running. It was reported that the engine oil results the lowest friction of the coated sample (Pramanik, 2016; Basak et al., 2014; Stallard and Teer, 2004). It is also reported that uncoated Ti-6Al-4V titanium alloys, which exhibited a lower COF due to the change of wear mechanism to slight abrasion wear from severe delamination. The friction coefficient of the plasma nitrided samples fall in order of 0.47–0.53 due to the presence of a compound layer with very good frictional characteristics caused even lower values of the COF. As the loads increase, the friction coefficients of the laser surface cladding Ni-base alloy coatings change among 0.29–0.39, and the average value is 21.2% less than that in dry friction (Gangatharan et al., 2016; Taktak et al., 2014; Tan et al., 2016).

Figure 4 illustrates about the COF in dry and lubricated conditions. Initial stage of the wear test, COF of coating is 0.38 in dry condition at 50 N load and 1 m/s sliding speed and decreases up to 0.015 in lubricated condition at the same load and speed. While load increases from 50 N to 80 N at the same speed of 1 m/s, the COF is 0.33 in dry condition and 0.034 in lubricated condition. It can be clearly seen in lubricated conditions, the engine oil as a lubricant showing large reduction in COF. While considering separately in the dry and lubricated condition at 1 m/s sliding speed, when load is increasing friction coefficient is decreasing. The higher applied load reduces the friction coefficient. The reduction in COF due to localised surface melting result to decrease in shear strength and COF drops to a low value determined by the viscous force in liquid layer.

Figure 4 Combined effect of load and sliding velocity at COF in dry and wet conditions



Friction coefficient of the coating is 0.38 in dry condition at 60 N load and speed 2 m/s while at the same load and sliding speed it is 0.014 in lubricated conditions. At the load of 90 N and 2 m/s sliding speed, the COF is 0.34 in dry condition and 0.016 in lubricated conditions. It can be clearly stated that at a constant velocity, when load is increasing COF is decreasing in both the condition of dry and wet. At a fix load and velocity, friction coefficient of coating in dry condition is significantly higher than that of lubricated condition. A quite similar result also can be seen in Figure 4 at the variable load of 70 to 100 N and speed 3 m/s, under dry and lubricated conditions. COF at 70 N load and speed 3 m/s is 0.34 of CrN coating in dry condition while in lubricated condition; it is 0.020 at the same operating condition of tribometer. At the 100 N load the COF is 0.28 of coating in dry condition while 0.025 in lubricated conditions.

From all the above discussion, it can be clearly seen that COF reached a nearly constant value due to the transfer layer and debris collected on the mating parts increases with the running in period. COF during the wear test is an intricate phenomenon, as it typically involves a third body presence between the CrN coating and the counter-body. The applied normal load during the wear test creates a lubricious film of graphite between the mating parts (coating and the counter-body) at the surface due to structure transformations. As the normal load increases during wear test it results in larger level of re-crystallisation at the top layer of the CrN coating and lower the steady-state value of COF.

3.3 Wear track temperature generation

Influence of generated temperature at the wear track in relation to friction, wear and failure of coating has been reported by authors due to change in mechanical properties. It is also reported that flexible material becomes brittle under some operated conditions if the operating temperature is reduced, while some brittle materials showed ductile fracture at higher temperatures and brittle fracture at low temperature. Study also reports about the decrease in friction from0.64 to 0.41 while operating temperature is increasing from 200°C to 500°C (Field et al., 2004; Bandeira et al., 2013; Arun and Venkatesha, 2008).

Thermal stability of the film is a most important factor at a higher temperature. Figure 5 shows the temperature generation of coated sample in dry and lubricated conditions with increasing load and sliding speed. It is clear that the recorded test temperature of the coating in dry condition is higher than the coated sample in lubricated conditions under the same test conditions.

a In the first set at load 50 N and sliding speed 1 m/s the recorded temperature was 65°C and 34°C of dry and lubricated condition respectively. When load increases from 50 N to 80 N at the same sliding speed 1 m/s, recorded temperatures are 96°C and 36°C respectively of coating in dry and lubricated condition. This increased temperature of coating in dry condition from 65°C to 96°C causes to decrease in friction coefficient from 0.38 to 0.31.

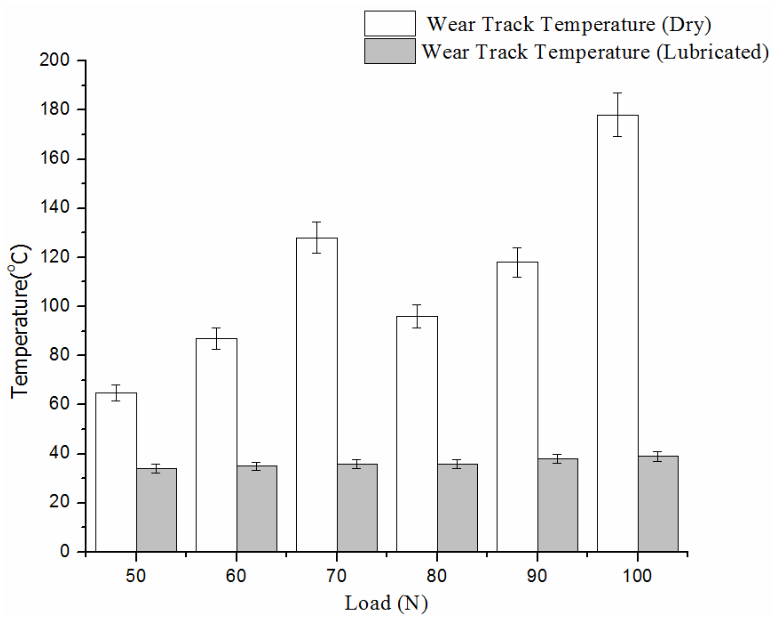
b When the load is 60 N and speed 2 m/s in the second case the recorded temperatures are 87°C and 37°C for coated samples in dry and lubricated conditions respectively. At the same velocity 2 m/s when the load is increasing from 60 N to 90 N temperatures are118°C and 380°C respectively for coated samples in dry and lubricated conditions. The friction coefficient of the coating in dry condition is also decreasing from 0.38 to 0.34 by growth in temperature from 87°C to 118°C of the coating.

c In the third set with load 70 N and sliding speed 3 m/s generated temperatures are 128°C and 36°C for coating in dry and lubricated conditions respectively. When the load is increasing from 70 N to 100 N at the same velocity the temperatures of coating in both dry and lubricated conditions are 178°C and 39°C.

The temperature rises from 65°C to 178°C of coating in dry condition in all the operating conditions the maximum and minimum friction coefficients are 0.47 and 0.28. While the maximum and minimum recorded temperature in lubricated conditions are 34°C to 40 °C. This is because the temperature of wear track significantly influences the sliding wear behaviour of CrN coating after the long-term run (large sliding distance) at this temperature. Oxidation at the mating parts and formation oxide layers which can avoid the adhesion between the CrN coating and the counter body (pin) possesses self-lubricating properties.

COF is a significant factor to estimate the adhesive wear resistance. 'In general, a lower friction coefficient means a higher wear resistance'. Above decrease of COF and increase of wear could be clarified that the increase in temperature causes to the formation of oxides layer on the coated sample and inter splats, which will result to decrease in hardness, affect the propagation and formation of parallel micro-cracks followed by coating delamination.

Figure 5 Wear track temperature generation during wear test



3.4 Wear mechanism

The progressive loss of materials from the mating parts during the relative motion in known as wear. The loss of material from the contacting surface affects the dimensions of the component of IC engines like piston and rings arrangement. That leads to high noise, high vibrations and system malfunctions. To control such type of failure we prefer to use engine oil as a lubricant. Wear volume measurement of CrN coating against the pin of cylinder liner material was calculated by Holmberg and Matthews equation as described above. Figure 9 and Figure 11 show the SEM micrograph of wear track in dry and wet conditions.

3.4.1 Surface conditions of counter face

The pictures of counter face before and after wear test in dry and wet conditions are given in Figure 6. The figure does not show a major difference in micrographs before and after wear test in dry conditions. While the wear face of counter body in lubricated condition shows less metal transfer due to shear but more plastic deformation of the lobes at surface. Both of the surfaces before wear test and after wear test in dry condition contain wave like lobes due to plastic deformation and ductile shearing at moderate temperature. However, the compositions of these surfaces are not similar as shown in Figure 7. It is found that only the proportion of the carbon decreased after the test in dry condition while increasing in wet conditions. On the other hand, the proportion of Fe increased significantly and remains nearly constant in wet conditions, also in addition to the minor increase of oxygen (O_2), chromium (Cr) and silicon (Si). This indicates that carbon was diffused to the coating from the counter-body material and the counter-body experienced oxidation in addition to the diffusion of Cr from the coating. The rest of the elements are then balanced out.

Figure 6 Surface of counter face, (a) before wear test and (b) after wear test at load 80 N and speed 1 m/sec on coated samples in dry condition (c) after wear test at load 80 N and speed 1 m/sec on coated samples in lubricated condition

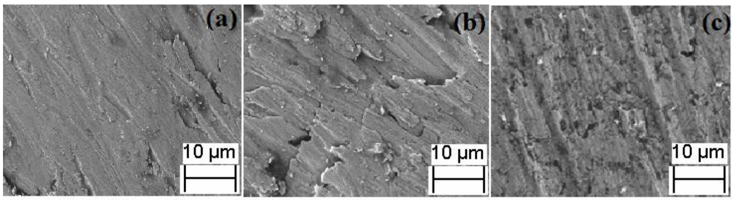
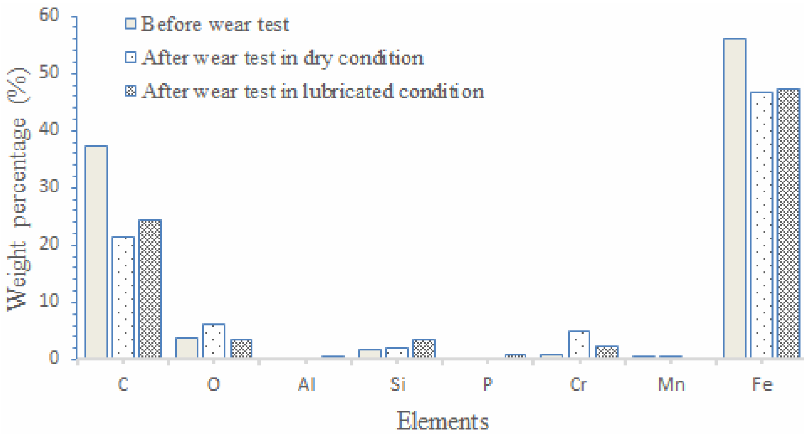


Figure 7 EDS analysis of counter body before and after wear test at load 80 N and speed 1 m/s (see online version for colours)



3.4.2 Wear mechanism in dry conditions

To provide a clear understanding of wear mechanism of CrN coating in dry condition for a run of 2,500 m at higher load and sliding velocity. Wear track of the coated sample has been shown in Figure 8. The worn surface has been analysed by the SEM that is not confirming the dominant nature of abrasion and erosion but the combined effect of these

a delamination

b sliding marks

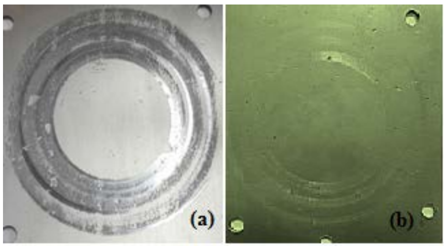
c plastic deformation

d abrasion and material pull out

e cracks

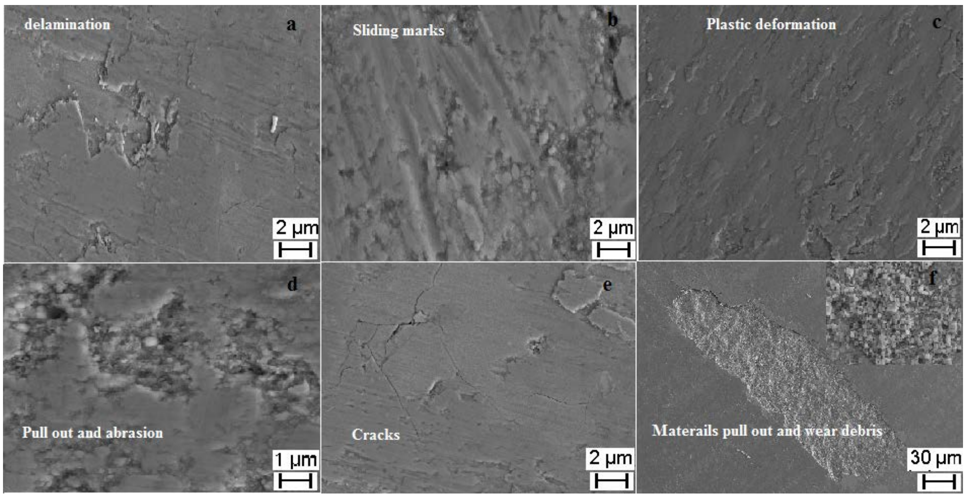
f materials pull out and accumulation of wear debris.

Figure 8 Wear tracks after test (a) dry condition (b) lubricated condition (see online version for colours)



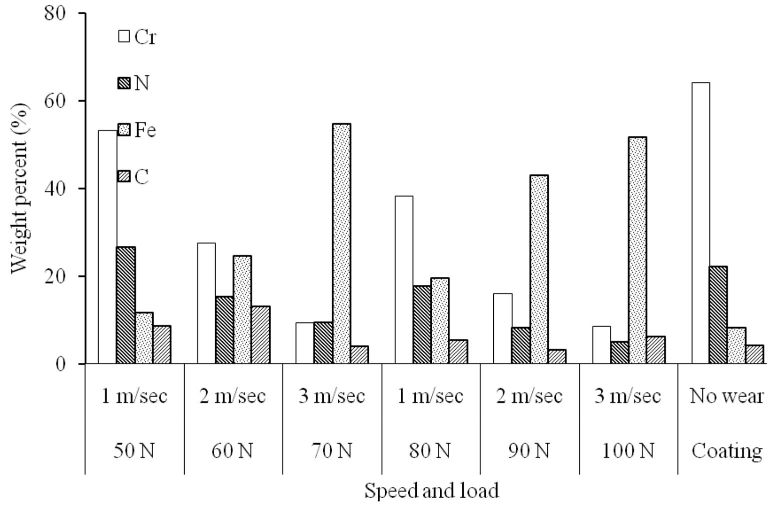
For the duration of wear test, when the dispersed hardened phases and inserted strengthened layer are totally worn away, the progressive loss of material, i.e., wear behaviour proceeds to a next stage, that is affected by the tribology of the CrN thin film coating until ultimate failure due to some voids and cracks remarked in the deposited coating. The primary fragment points that cause the coating to be poorly wear-resistant (Hong et al., 2017). SEM micrographs of CrN film deposited by PVD on cast iron cylinder surfaces by normal operation condition were observed almost no wear, while deep wear grooves, surface cracks and severe deformation on the uncoated cast iron cylinder tubes (Wesmann and Espallargas, 2016). The wear track is covered with a lot of nano-scale needle-like rolls and some accumulation of wear debris around the worn surface is visible even under optical microscopy (Weng et al., 2008).

Figure 9 Wear tracks on the coated samples in dry conditions at different loads and speeds respectively (a) 50 N and 1 m/s (b) 60 N and 2 m/s (c) 70 N and 3 m/s (d) 80 N and 1 m/s (e) 90 N and 2 m/s (f) 100 N and 3 m/s



It can be clearly seen some micro-cracks and the delamination of coating at a particular area in Figure 9(a). There is also a type of material damage consisting of small cracks lead to failure. It may occur on coating during the load strain of coating. Some micro-pullout and sliding marks can also be seen in Figure 9(b) in the direction of sliding. Material layer is also being transferred in the in the direction of sliding and some plastic deformation can be observed in Figure 9(c). Figure 9(d) shows the built-up edge formation and accumulation of wear debris on the wear track due to involves of some hard and foreign particles, either confined between two mating surfaces and abrading to one or both surfaces, or fixed in a softer surface and abrading the opposing one. At the onset of abrasive wear in Figure 9(d) and Figure 9(f), the particles strike and penetrate into the softer surface under the pressure of mating parts. The tangential force forced during the wear test, the metal removal mechanism in the softer surface showed the combined effects of 'micro-ploughing', 'micro-cutting' and 'micro-cracking'. Accordingly, the worn surface is characterised by scratches and grooves. The wear debris shown in the form of small or micro-cutting chips which are shown in Figure 9(f). Whereas some cracks can be seen in the coating in Figure 9(e) at 90 N load and speed 2 m/s.

Figure 10 Weight percentage of Cr, N and Fe of coating after test



The compositions of the coating, substrate and counter face before wear test were presented in Figure 12 where highest percent of material was Fe in substrate (piston ring) and counter face (cylinder liner) in weight% of 91–90 and 56.02, respectively. On the other hand, the coating contained 64.15% Cr and 22.19% N_2 by weight. However, after the sliding in the tribometer at different loads and speeds the materials compositions of the coating surface in dry conditions changes significantly as shown in Figure 10. The figure shows Fe has been migrated to coating and the coating content has been reduced significantly in all the cases. The migration of the Fe might be due to adhesion, attrition and diffusion. The N_2 content of the coating does not change significantly with the variation of load and speed but the proportion and content of Fe and Cr changed significantly. At less sever conditions, such as at speed 1 m/sec with loads 50 and 80 N and speed 2 m/sec with load 60 N the coating surface contained higher amount of Fe compare to that of Cr. In the other conditions which can be considered as very sever conditions; the content of Cr was higher than that of Fe. It seems that at less sever conditions; the migration of Fe to the coating takes place due to adhesion and attrition which occur by Fe build-up from the counter face material. But with the increase of load and speed the Fe build-ups are removed and tribo-chemical reaction starts. This diffuses Fe to the coating tracks.

3.4.3 Wear mechanism in lubricated conditions

Figure 11 depicts the SEM Micrograph of wear track in with a constant flow rate of SAE grade 20W50 for a run of 2,500 m at different load and sliding velocity are:

a erosion and accumulation of wear debris

b sliding marks and micro-pullout

c tribo-chemical action and metal transfer

d deep grooves and sliding marks

e abrasion

f material transfer.

Severe wear of the piston ring (disc) against the cylinder liner material (pin)mostly take place in the running condition of the engine, so the surface is worn off by the counter-body, and the mating surfaces finally get the improved conformity. Under lubrication conditions, damaged surface studied by Lorenzo-Martin et al. with the help of SEM micrograph, the wear was mostly abrasive, against coating, which produced partial formation of tribo-film. Abrasive wear followed by two and three-body abrasion and the overall effect of wear rate can be tribo-chemically progressed by lubricant that have been trapped in the ring zone. The wear of the piston rings decreases when surface irregularities of the liner reduced, consequently the progressive loss of material, i.e., counter-body decreases when the rings become smoother after some running period (Öner et al., 2009; Ouyang and Sasaki, 2004; Priest et al., 2000; Lorenzo-Martin et al., 2013).

It can be clearly seen the combination of wear at the surface under lubrication, plastic deformation due to strong adhesion force between the CrN coating (disc) and the cylinder liner (pin) leads to scuffing that involves higher frictional force and the formation of wear scars on the mating parts. Some micro-pullout and sliding marks can also be observed in Figure 11(b) in the direction of sliding. Metal transfer and some tribo-chemical reaction can be seen in Figure 11(c). The wear mechanism is followed by abrasive on the coating surface, when wear debris progressed to the mating interface. Erosion on the top layers can be on the top layer of coating, whereas the accumulation of wear debris can also be seen in top corner of Figure 11(a). These wear debris are not similar as the wear debris in dry conditions. Some metal transfer can also be seen in Figure 11(c) due to adhesion in the wet conditions. On the coating and counter-body surfaces as evidence of scuffing some wear scars are present those are indicating, e.g., abrasive ploughing, adhesive transfer and the plastic deformation of work hardened cast iron to a CrN coated piston ring, and a ‘white layer’. Figure 11(d) and Figure 11(f) shows the micro-chipping and small erosion and deep groves at the coating surface, temperature, running speed and surface roughness, are the most important parameters that affect the wear at the lubrication regime most.

Figure 11 Wear tracks on the coated samples in lubricated conditions at different loads and speeds respectively (a) 50 N and 1 m/s (b) 60 N and 2 m/s (c) 70 N and 3 m/s (d) 80 N and 1 m/s (e) 90 N and 2 m/s (f) 100 N and 3 m/s

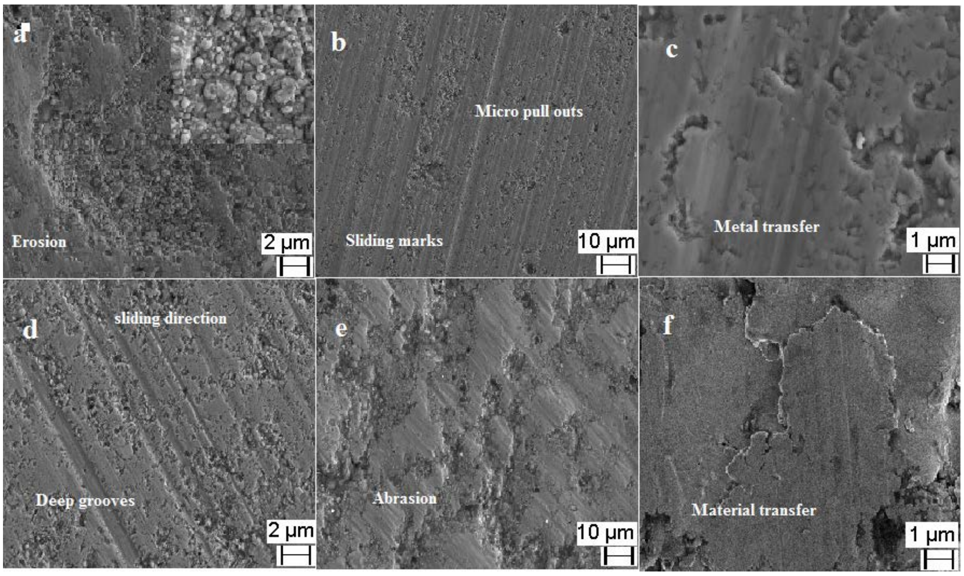
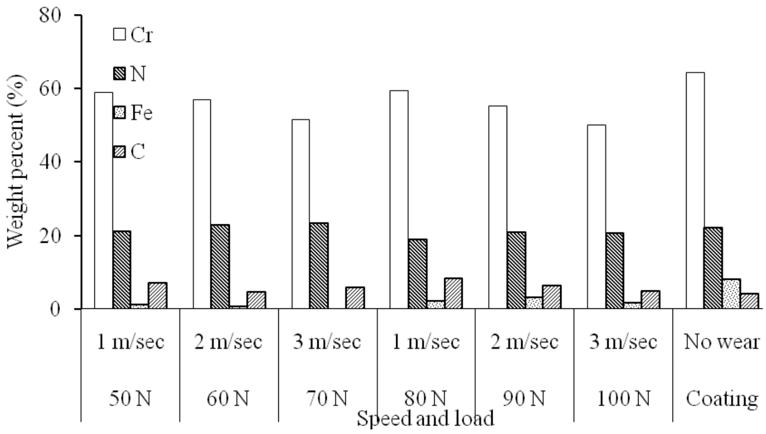


Figure 12 Weight percentage of Cr, N and Fe of coating after test



Wear track materials composition in lubricated conditions has been reported after the test at diverse loads and speeds of the coating surface changes significantly as shown in Figure 12. The figure shows that the Cr content in not showing a major difference in all the wear track while in the dry conditions Cr is changing significantly. Fe has been migrated to coating and the coating content has been reduced significantly in all the cases. The migration of the Fe might be due to adhesion, attrition and diffusion. The N_2 content of the coating does not change significantly with the variation of load and speed, but at a speed 1 m/s when load is increasing from 50 N to 80 N the N_2 content is decreasing slightly. Similar trend can also be observed at a speed when load is decreasing the N_2 content showing slight decrease. Whereas at all the load and speed conditions, such as at speed 1 m/sec with loads 50 and 80 N, and speed 2 m/sec with load 60 N the coating surface contained less amount of Fe compare to that of N_2 and Cr. Whereas the compositions of the coating, substrate and counter face before wear test were presented in Figure 12 where highest percent of material was Fe in substrate (piston ring) and counter face (cylinder liner) in weight% of 91–90 and 56.02, respectively. On the other hand, the coating contained 64.15% Cr and 22.19% N_2 by weight.

4 Conclusions

A practical comparison has been presented in this paper between dry and lubricated condition of CrN coating during pin on disc wear test. The following conclusions derived from the above results and discussions:

1. Flatness of the sample is crucial while establish the contact during the wear test along with the alignment (perpendicularity) between pin holder and disc axis to ensure the cross-section contacts the disc properly.
2. The coating consists of small grains and form dense structure throughout the film with short and disordered columnar texture and good adhesion with the substrate. Coating thickness is about 21.80 µm composed of about 64% chromium and 22% nitrogen and surface roughness about 0.60 µm.
3. Specific wear rate is increasing with the load at constant velocity in dry conditions and decreasing in lubricated conditions at the same operating parameters. This is due to the chemical reaction of engine oil and coating, causes to its low friction characteristics, to suit different counter faces and minimise wear of disc and pin both.
4. COF during the wear test is an intricate phenomenon, as it typically involves a third body presence between the CrN coating and the counter-body. As the normal load increases during wear test it results in larger level of re-crystallisation and the partial melting wear debris at the top layer of the CrN coating and lower the steady-state value of COF. Above statement is also supported by the temperature at point of contact ranges from 65°C to 178°C in dry conditions while 34°C to 39°C in wet conditions.
5. The wear mechanism of the coatings was found deformation, cracks, fracture or pullout, built up edge formation nitride particle pull-out, erosion of top layers and adhesive wear dominated by metal transfer, and a combination of oxidation wear.

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