The effect of diamond like carbon coating on the wear resistance at dry sliding conditions

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Abstract

Wear due to sliding is an inevitable problem in many engineering applications. Protective surface coating is usually used to mitigate this problem. The development in this field is continuous and consistent. There are many types of coatings according to their compositions and the deposition methods. One of the coatings with the most promising properties, such as the hardness, is the Diamond-Like Carbon (DLC) coating. The tribological properties of this coating generated by Plasma-Assisted Chemical Vapor Deposition (PACVD) and applied on bearing steel 52100 ASTM are not available. In this study, the wear resistance of the DLC coating applied to bearing steel 52100 ASTM, was evaluated. The coating method employed was PACVD, which is regarded as one of the most distinctive coating techniques due to the unique tribological properties imparted to the coating. The pin-on-disc tribometer was used to examine the coefficient of friction and mass losses for samples of (steel disc against steel ball) and (DLC coated disc against DLC coated ball) under constant sliding velocity and constant sliding distance with four different loads (2, 5, 10 and 20 N) that results in maximum contact pressure below and higher than the maximum shear stress of the bearing steel. The wear coefficient was calculated using Archard’s equation based on the experimental results. It was found that the DLC coating may result in significant reduction, reaching 93.5%, in weight loss and 83% in COF at low contact pressure (less than the maximum shear stress). However, at high contact pressure (equals to or higher than the maximum shear stress) the weight loss and the COF for the DLC coating are higher than those of the bearing steel. This behavior indicates that the DLC coated pair may not be suitable at high loads. The wear coefficient is calculated for each testing condition and it is found to be affected by the applied load. The average wear coefficient for the DLC coating is provided which can be used with the Archared wear model to predict the wear rate within the range of the parameters used in this study.

1. Introduction

Diamond-Like Carbon (DLC) coatings have received a great deal of research interest in order to enhance the mechanical and tribological performance of engineering components such as bearings, gears, seals, metal cutting and forming tools, magnetic hard discs, etc. The DLC coating as well as other coatings have been utilized as a proposed solutions for persistent failure in some applications such as the White Etching Cracks (WECs) observed in wind turbine gearbox bearings [1–4]. Numerous research publications [5–10] explain their unusual mix of features, such as high hardness and elastic modulus, low friction coefficient, chemical inertness, and superior wear resistance. By providing superior frictional characteristics and significantly enhancing surface wear resistance coatings provide an excellent potential for additional performance and durability enhancements, as well as reductions in mechanical system frictional losses. DLC coatings provide good tribological characteristics for a variety of applications [11]. DLC may be divided into two types based on its
hydrogen content: hydrogenated and hydrogen-free. This parameter impact the tribological behavior of DLC films [10, 12]. Physical vapor deposition (PVD) and chemical vapor deposition (CVD) are among the technologies available for producing DLC coatings on diverse substrate materials [13]. It was discovered that the creation of a carbon-rich transfer layer on the counter face was responsible for the low friction coefficients of DLC coatings in the steady-state after a long-distance sliding. Despite the fact that DLC coatings exhibit minimal friction and wear under dry sliding conditions [14]. DLC enables the introduction of small quantities of other elements, such as Si, F, N, O, W, Nb, Cr, V, Co, Mo, and Ti, into the DLC coating while maintaining its amorphous phase. Si-DLC coatings exhibit outstanding tribological features, including extremely low friction, strong durability, good stability in humid situations, and enhanced performance at high temperatures. Metal doping or carbide doping has been created to enhance DLC coatings’ adhesion, thermal stability, and toughness. The Nb-DLC coatings give a low coefficient of friction and superior performance under circumstances of adhesive wear [15, 16].

Table 1 presents a fundamental description for some of the recent studies conducted to reveal the tribological properties of some types of the DLC coating. All the studies in this table used the pin-on-disc tribometer with the counter body as a ball of 6 mm diameter. It can be seen that various deposition techniques, substrates, counter bodies and experimental conditions result in different tribological properties such as CoF. This table also shows that the load in previous studies did not cover a high level where different tribological behavior may appear. For the PACVD deposition technique, which is considered in the current study, table 2 shows the testing conditions considered in some of the previous studies. Again, the load considered does not reach the load that causes shear stress exceeding the maximum shear stress of the substrate. Also, the bearing steel substrate was not considered and the DLC counter body was not considered as well. Accordingly, the current study aims to reveal the wear rate and the coefficient of friction for the DLC coating deposited on bearing steel under these conditions of high load and a counter body of DLC coated bearing steel ball. This study reveals the behavior of DLC on DLC pair under dry sliding and high load, and compares this behavior with that of bearing steel on bearing steel under same conditions. In addition, the wear coefficient of the DLC coating was not found in previous studies, and it is one of the most important constants in the Archard equation for estimating the wear rate. Accordingly, this constant was found in this study.

2. Experimental details

2.1. Substrate materials

The substrates used to prepare DLC coated specimens were ASTM 52100 bearing steel washers and for the counter body, balls of the same bearing steel were used. Steel 52100 is mostly used for small and medium sized bearing components. Additionally, it is often used for other machine components requiring high tensile strength and rigidity. Bearing steel 52100 ASTM is largely used in the manufacture of aircraft bearings and other high-fatigue components. Due to its high tensile strength and cleanliness, this steel has the qualities necessary to survive high cycle, high stress [26], where the mechanical properties and chemical composition are given in table 3.

2.2. Coating

The samples used in this study (bearing steel washers and steel balls) were coated with DLC coating using the PACVD process. The coating process was carried out according to the following steps:

**Step 1:** Using plasma etching to clean the substrate, specifically, in an inert atmosphere, arc discharge is performed with the magnetron target as the anode and the arc target as the cathode to generate plasma; the substrate is used as the cathode and the magnetron target as the anode to apply a bias voltage to the substrate; and the substrate is subjected to plasma etching and cleaning. The vacuum chamber is evacuated and heated until the air pressure is less than $5 \times 10^{-3}$ pa and the temperature approaches 100–300°C.

**Step 2:** Involves magnetron sputtering to deposit a metal transition layer on the substrate. Magnetron sputtering is performed in an inert atmosphere using the rotating magnetron target as the cathode and the rotating arc target as the anode; the rotating arc target as the anode and the workpiece as the cathode provide a bias voltage to deposit a metal transition layer on the substrate. In addition, the method for depositing a metal transition layer on the substrate includes supplying hydrocarbon raw gas and sequentially deposit metal carbide layer on the substrate.

**Step 3:** Using the PACVD method, place the DLC layer on the metal transition layer. Using the arc target as the anode and the workpiece as the cathode, a bias voltage is applied, and the DLC layer is deposited on the metal transition layer using the PACVD method. Table 4 lists the mechanical properties of the DLC coating.

| Substrate materials | Counter materials | Experimental conditions |
|---------------------|------------------|-------------------------|
| ASTM 52100 bearing steel washers | Steel balls | Pin-on-disc tribometer |
| Steel 52100          | Bear steel      | 6 mm diameter          |

Table 1: Fundamental description for some of the recent studies.
Table 1. Test DLC coatings deposited by various methods using a pin-on-disc device.

| Coating | Substrate | Deposition Technique | Experimental condition | Coefficients of friction (CoF) / counter body | References |
|---------|-----------|----------------------|------------------------|---------------------------------------------|------------|
| DLC     | Glass slide | Pulse Laser Deposition (PLD) | Load (N) 3, Speed (m s\(^{-1}\)) 0.16, Distance (m) 4, Temp (°C) 100–500 | 0.191–0.398/steel | [17] |
| H-DLC   | Ti6Al4V    | unbalanced magnetron sputtering | 5, 0.12, —, 25–500 | 0.11–0.57/WC | [18] |
| W-DLC   | high speed steel | High-power impulse magnetron sputtering (HIPIMS) | 1, 2, 0.1, 1000, Room temp. | 0.2–0.16/Al2O3 | [19] |
| T3-DLC  | Ti6Al4V    | Physical Vapor Deposition | 5, 0.063, —, Room temp. | 0.22–0.25/steel | [20] |
| DLC     | Stainless steel/CoCrMo Ti6Al4V | Filtered cathode vacuum arc (FCVA) | 2, 0.021, 5, — | 0.2/Al2O3 | [21] |
| DLC     | Hydrogenated nitrile butadiene rubber (HNBR) | unbalanced magnetron sputtering | 1, 3, 0.1, —, 20–22 | 0.167–0.194/steel | [22] |
After determining the coating thickness using Scanning Electron Microscopy (SEM) as shown in figure 1, DLC coating density was determined by dividing coating masses (calculated by subtracting the mass of stainless steel from the total mass) by coating volume.

2.3. Wear testers
Wear due to sliding between contacted parts in dry condition is one of the most common surface damage mechanisms. In the current study, this condition is simulated using the pin-on-disc tribometer. Both the coefficient of friction and the mass loss were measured in this study.

The coefficient of friction is tested by applying load to the ball and rotating the sample to create movement across the surface. The mass of the sample and the ball is measured before and after the test, which allows to calculate the mass removed.

As shown in figure 2(A), a pin on disc device, model MT/60/NI/HT/L, was used in this study. The required test parameters are rotational speed, weight, ball diameter, and distance. The coefficient of friction is then shown in a curved form during the duration of the test, and the amount of mass change for the sample and the ball is determined prior to and after the test utilizing a high-precision balance as illustrated in figure 2(B).

2.4. Test procedure
In this test, sixteen samples of ASTM 5210 bearing steel washers with an outside diameter of 28 mm, an inner diameter of 15 mm, and a thickness of 2.8 mm were used. Additionally, sixteen steel balls with a diameter...
of 6 mm were employed. Eight samples of washers and eight samples of balls were kept uncoated as shown in figure 3. Eight samples of washers and eight samples of balls were coated with DLC coating as shown in figure 4.

This study used four different loads (2, 5, 10, and 20 N) to investigate the effect of changing the load on the wear rate. The distance traveled by the ball on the disc is 200 m in 15 min at a speed of 200 rpm, and the radius of the wear track is 10.75 mm. These conditions result in sliding velocity of 0.225 m s$^{-1}$. All samples were weighed (washer and ball) before and after each test using a high precision balance to figure out the weight difference. The surface of the samples was examined after conducting the test using a digital microscope to see the effect of the parameters on the surface.

All tests were conducted twice under identical experimental conditions, in order to check the repeatability of the results. In all total, sixteen tests were conducted.
3. Theoretical and experimental analysis

In this section, the values of the wear coefficient will be determined using the Archard equation and the maximum contact pressure is calculated using Hertz equation. There have been some proposed equations for adhesive wear, but none of them apply universally. Archard’s equation is the one most commonly referenced by researchers and used by designers. Using this formula, we can calculate the wear per unit of sliding distance after the value of the wear coefficient is calculated. The following is the Archard’s equation used in this study:

\[
\frac{V}{L} = K \frac{S}{H}
\]

where \(V\) is volume loss of the specimen or the ball (m³), \(S\) is the sliding distance (m), \(L\) is the normal load (N), \(H\) is hardness of the specimen. \(K\) is a dimensionless factor added to match the calculated wear values with the experimental values for a specific material combination. \(K\) is known as the wear coefficient.

3.1. Wear coefficient

Samples (disc and ball) are weighed before and after the test to determine mass losses. The volume removed is calculated by dividing the mass removed \((M)\) by the density of the samples, as given in equation (2).

\[
V = \frac{M}{\rho} \times 10^{-6}
\]

\(\rho\) is the density of the disc or ball (g cm⁻³). Where the density of steel is used in the case of steel disc against steel ball, and the density of coating is used in the case of DLC coated disc against DLC coated ball.

Volume losses are used in the Archard’s equation and as stated in equation (1) to get the values of the wear factor at each of the loads employed, and then the average of the values of the wear factor is determined, which can be used to determine the values of the wear rate at any load as shown in equation (3).

\[
K = \frac{VH}{LS}
\]

3.2. Pressure contact

As shown in figure 5, when a sphere is pressed against disc under a normal load \(L\), contact will occur between the two over a circular area of radius \(a\), given by:

\[
a = \left(\frac{3L R}{4E'}\right)^{1/3}
\]

Such a contact is generally referred to as a point contact. \(R'\), the equivalent radius of curvature of the contacting bodies, is defined in terms of the radii of the two bodies \(R_1\) and \(R_2\) as follows:
Since the radius of the disc’s surface is finite, the equivalent radius is equal to the sphere’s radius. The equivalent young’s modulus \(E'\) which depends on the young’s modulus of the two bodies, \(E_1\) and \(E_2\), and on their respective Poisson’s ratios, \(\nu_1\) and \(\nu_2\), is defined as shown in equation (6).

\[
\frac{1}{E'} = \frac{1 - \nu_1^2}{E_1} + \frac{1 - \nu_2^2}{E_2}
\]  

(6)

Since the ball and disc are of the same material, the equivalent modulus is:

\[
\frac{1}{E'} = \frac{2(1 - \nu^2)}{E}
\]  

(7)

The pressure \(P(r)\) in the contact varies with distance \(r\) from the center of the contact as:

\[
P(r) = P_m \sqrt{1 - \frac{r^2}{a^2}}
\]  

(8)

where \(P_m\) is the maximum pressure that occurs at the center of the contact \((r = 0)\). The load supported by the contact is simply the integral of the pressure over its area:

\[
L = \int_0^a 2\pi r P(r) \, dr = \frac{2}{3} \pi a^3 P_m
\]  

(9)

and therefore

\[
P_m = \left(\frac{6LE'}{\pi^2 R^2}\right)^{1/3}
\]  

(10)

4. Results and discussion

4.1. Weight loss and wear coefficient

Based on the experimental findings the total mass removed (the mass removed from the ball and disc) rises as the load increases in both cases (steel disc against steel ball and DLC coated disc against DLC coated ball), as shown in figure 6. There is a difference in the wear process between the two cases. In the first case (steel disc against steel ball), the most of mass loss occurs from the disc, while in the second case (DLC coated disc against DLC coated ball), the most of mass loss originates from the ball. The most plausible explanation for the wear that happens in the first case is a plastic deformation caused by frictional heat, followed by the production of welding joints between the ball and the disc, and as a result of the continuous movement, the joints separate from the disc to the forward and sides as shown in figure 7(A), causing the disc’s mass to decrease. In the latter case, the coating’s hardness prevents the plowing on the disc side as shown in the figure 7(B), while the accumulated stress on the ball may resulted in surface fatigue and mass loss. At a load of 20 N, the DLC-coated disc loses a significant amount of mass. This is caused by the hard coating debris. Owing to the lack of lubrication that removes these
particles, they remain trapped between the ball and the disc, causing wear to accelerate due to the particle’s hardness and shape [27–29].

To calculate the coefficient of wear, the volume removed is first calculated using equation (2) then using equation (3) the value of the wear coefficient can be found as shown in table 5.

If the average values for the wear coefficients of the bearing steel and DLC coating are considered with neglecting the value at 20 N due to the excessive failure on the disc surface, the values will be $K_{\text{ave, Steel}} = 1.737 \pm 0.118 \times 10^{-3}$ and $K_{\text{ave, DLC}} = 1.998 \pm 0.54 \times 10^{-3}$.

Figure 8 shows the percentage of improvement, as there is a clear improvement for the samples that have been DLC-coated at the load of (2, 5, 10) N. It can be seen that the improvement reaches more than 68% at a load of 10 N due to the high COF as it is discussed in the next section. The resulted high surface traction results higher maximum shear stress for the DLC-on-DLC pair despite that the Hertzian contact pressure for this pair is less than that for the steel-on-steel pair as shown in table 6. Accordingly, the limit for the preferable DLC performance is that the maximum contact pressure does not exceed the maximum allowable shear stress for the substrate. The maximum shear stress estimated based on the calculated maximum contact pressure gives an indication for the limit of the preferable tribological performance of the DLC coating. However, for more accurate calculation for the maximum shear stress the surface traction should be considered [30].

4.2. Coefficient of friction (CoF)

All the curves in figure 9 show a starting up (or initial running in) part where the CoF highly increases in a short time and it can be seen that the time of this region is different from one curve to another. Identifying the end of this region may not be easy; however, the overshoot can be used as an indicator for an intermediate point in this region which is followed by a less step increase in the CoF until a relative stability is reached which can be
considered as the end of the starting up. In general, the starting up takes more time in the DLC versus DLC curves than in the steel versus steel curves. This behavior may be caused by the higher roughness and hardness of the DLC coating, as can be seen in tables 3 and 4, and thus the asperities smoothing spans longer. It can be noticed that at low load, the CoF curves keep showing a slight increase if they are compared to the curves at high load, specifically at 20 N. This may be explained by the observed plowing occurs in the DLC versus DLC and the steel versus steel tests at this load where at this load the wear mechanism evolves faster reaching the state of continuous penetration of the ball and removal of the disc’s material. In general, for all loads, the DLC versus DLC curves show smoother curves with less waviness which may reveal a less stick and slip in these tests than that occurs in the steel versus steel tests.

The steady-state coefficients of friction for the uncoated ball and disc calculated from the curves shown in figure 9 were 0.71 ± 0.03, 0.83 ± 0.04, 0.57 ± 0.02 and 0.47 ± 0.03 for the loads of 2, 5, 10 and 20 N respectively. At loads of 2, 5, 10, and 20 N, the steady-state coefficients of friction between the DLC-coated disc and the DLC-coated ball were 0.34 ± 0.02, 0.14 ± 0.01, 0.58 ± 0.01, and 0.51 ± 0.03 respectively. Figure 10 shows the microscopic examination for the wear traces on the testing specimen of balls and the washers. In this figure the difference between the effect of load 10 N and 20 N can be seen. Figure 10(A) shows the removal of DLC coating from the ball only when the load is 10 N; while figure 10(B) shows the removal of DLC coating from the ball and the washer when the load is 20 N. On the other hand, the microscopic examination for the wear traces at the load of 2 and 5 N shows no removal for the DLC coating from the balls or the washers. According to the microscopic examination and the steady-state coefficients of friction values, it can be concluded that when the DLC coating is not removed as in the load of 2 and 5 N, higher load reduces the CoF. At the load of 10 N that causes coating removal from the ball only, which forms steel on DLC sliding, the highest CoF occurs. Further increase of the load to 20 N causes DLC coating removal from the ball and the washer, which forms steel on steel sliding and results slightly lower CoF than that at a load of 10 N where steel on DLC sliding occurs.

No direct comparison can be made between the CoF results in this study and those from previous studies presented in table 1 and 2 due to the different operation conditions such as speed, load and counter body as well as different coating properties such as substrate, deposition method, interlayer and coating thickness. However, it can be seen from table 1 and 2 that the CoF for DLC coating against counter body of different material is less than that of DLC coating against counter body of DLC. Despite the different testing conditions and coating properties, the CoF value found in the current study is comparable for a certain extend to the value of 0.4 reported by S. Akaike et al [25] since the same testing configuration of DLC against DLC was used in this

| Table 6. Maximum contact pressure at each loading condition. |
|---|---|---|---|---|
| Ball | Disc | Load (N) | E’ (GPa) | $P_m$ (MPa) |
| Steel | Steel | 2 | 115.4 | 830.42 |
| Steel | Steel | 5 | 1127.05 |
| Steel | Steel | 10 | 1420.01 |
| Steel | Steel | 20 | 1789.09 |
| DLC | DLC | 2 | 114.6 | 826.58 |
| DLC | DLC | 5 | 1121.84 |
| DLC | DLC | 10 | 1413.43 |
| DLC | DLC | 20 | 1780.81 |

Figure 8. The improvement percentage of mass losses.
Although an increase in the CoF with increasing the load is reported in previous study where a steel counter body was used [24], this was not exactly the case in the current study of DLC against DLC which is again may be caused by the various operation conditions and coating properties. The current study reflects that at a wide range of loading the DLC coating may show different wear mechanisms such as adhesion, three-body abrasion and plowing. Accordingly, the behavior of the CoF and wear rate may not be stable with increasing the load. At load of 10 N, the coating is removed from the ball only and the weight loss occurs mainly in the ball not the disc. This may indicate an adhesion between the disc and the ball. This adhesion due to the accumulation of strain and temperature on the ball is followed by coating separation from the ball surface as a result of constant motion. Accordingly, weight loss and coating peeling off the ball occur, as shown in figure 10(A). After a distance of sliding, debris accumulation in front of the ball indicates the occurrence of three body abrasive wear. At the highest load of 20 N, the plowing wear is clearly visible where grooves of different heights can be observed on the wear trace as shown in figure 10(B).

It is observed that the CoF for the DLC coated pairs at the load of 2 and 5 N is lower than that when the DLC coating is removed at the load of 10 and 20 N. Figure 11 shows the percentage of reducing or increasing in the
CoF when the CoF for the coated pairs is compared to that of the uncoated pairs at the same load. It can be seen from this figure that the rate of improvement for the CoF varies with the load where this rate increases at low loads and reaches 83% at 5 N; while at high load (10 and 20 N) there is no improvement in the CoF. The significant improvement in the CoF at the moderate load, where the maximum contact pressure does not exceed the maximum shear stress of the bearing steel, indicates the desirable tribological properties of the DLC coating. However, the DLC coating does not improve the CoF when higher load that normally causes stress exceeding the elastic limit of the substrate results in removal of the DLC coating.

5. Conclusions

In this study, the tribological properties (wear rate and coefficient of friction) for bearing steel coated with PACVD-DLC were investigated and compared with that of uncoated bearing steel. The tests were conducted using nonconforming contact of pin-on-disc with constant velocity and sliding distance. The effect of different normal loads was investigated by applying four different values. Through this study, the following conclusions can be drawn.
1- Compared to the bearing steel ball on disc, the DLC coated ball on disc showed higher wear resistance represented by less weight loss of 93.5% at 2 N and 68% at 5 and 10 N. However, at high load of 20 N the behavior of the DLC samples was changed to severe damage causing higher weight loss of 75%.

2- Similar to the weight loss, at low load (2 and 5 N) the COF for the DLC coated samples was less than that for the uncoated bearing steel samples with percentage of improvement reaches 83%. However, at higher load of 10 N, the uncoated samples showed slightly less COF by 1.7% and at 20 N this percentage increases to 8.7%.

3- The weight loss and the COF results revealed that the DLC coated pair may not be preferable at high load due to the failure of the coating by peeling, patches detaching from the substrate, plowing and adhesion wear.

4- This study provides an average wear coefficient for the PACVD-DLC coating which can be used in the Archard wear model to predict the wear rate at different conditions within the range of variables used in this study.

5- It was found that at high maximum contact pressure that exceeds the maximum shear stress the wear rate and the COF for the DLC coated specimens exceeds that for the steel specimens.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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