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# Friction behaviour of diamond-like carbon films with varying mechanical properties

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**Abstract**

Diamond-like carbon (DLC) films deposited on silicon wafer with varying film thickness were investigated for their micro-scale friction behaviour. Films with three different thicknesses, namely 100 nm, 500 nm and 1000 nm, deposited by a radio frequency plasma-assisted chemical vapor deposition method on Si (100) wafer, were used as the test samples. The elastic modulus of the DLC samples increased with their film thickness. The micro-scale friction tests were conducted in a ball-on-flat type micro-tribotester, using soda lime glass balls with different radii (0.25 mm, 0.5 mm and 1 mm), and with varying applied normal load (load range: 1500 μN to 4800 μN). Results showed that the friction force increased with applied normal load, whereas with respect to the ball size, two different trends were observed. In the case of 100 nm thick sample, friction increased with the ball size at any given normal load, while for 500 nm and 1000 nm thick samples, friction had an inverse relation with the ball size at all applied normal loads. The friction behaviour in the case of the 100 nm thick film was adhesive in nature, whereas for the thicker films plowing was dominant. The friction behaviour of the test samples with the ball size, which was distinctly different, was discussed in terms of the contact area, influenced by their mechanical property, namely, the elastic modulus.


*Keywords:* Friction; Elastic properties; SEM; PACVD; Carbon

## 1. Introduction

Diamond-like carbon (DLC) films are promising candidates for a wide range of tribological applications [1]. These films are hard and hydrophobic, and exhibit relatively low surface energies [2,3]. Other interesting properties of DLC films include thermal stability, chemical inertness and the ability to be deposited at or near room temperature [2,3]. The properties of DLC films mainly depend upon their deposition processes [4–6]. The various deposition processes and the properties of DLC films were comprehensively overviewed [5,6]. In the last decade, DLC films have found their role as tribological coatings in several applications including magnetic media storage disks and microelectromechanical systems (MEMS) [2]. Most of the investigations found in literature that are related to the tribological behaviour of DLC films are at nano- and macro-scales [1,2]. Reports on micro-scale tribological behaviour of DLC films are meager. Investigation of tribological performance of DLC films at micro-scale is important especially for applications such as MEMS [7]. Liu et al. in their work [7] showed that the micro-friction of DLC films depend on the sliding speed, whereas its dependence on humidity was negligible. Further, they suggested that the contact area vs. load characteristics of DLC films at micro-scale could be approximated by the Hertz contact theory. Ahmed et al. [4] have reported on the micro-frictional properties of DLC films slid against different kinds of counterbodies such as silicon, sapphire and steel balls. They have also reported on the influence of parameters such as hydrogen content and roughness of the films on their micro-friction property. In our earlier work on the micro-scale friction behaviour of silicon wafer and 1 μm thick DLC film coated on silicon wafer [8], we have observed that the DLC film exhibited plowing under micro-scale loading owing to smaller area of contact.

In the present work, the micro-scale friction behaviour of DLC films with varying film thickness has been investigated experimentally. The friction behaviour of the films has been

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discussed in terms of the contact area, influenced by their mechanical property, namely, the elastic modulus.

## 2. Experimental details

DLC films with three different film thicknesses, namely 100 nm, 500 nm and 1000 nm were deposited on Si (100) by a radio frequency plasma-assisted chemical vapor deposition method (r.f.PACVD) using benzene ($C_6H_6$) as the reaction gas. The films were deposited at a negative bias voltage of 400 V and a deposition pressure of 1.33 Pa. The deposition time was adjusted to obtain the required thickness of the films. The elastic modulus of the 100 nm, 500 nm and 1000 nm thick films was 40 GPa, 85 GPa and 88 GPa respectively. The hardness of the 100 nm thick film was 6–8 GPa and that of the other two films was 11–12 GPa. The details of deposition parameters and coatings properties are given in Ref. [9].

Micro-scale friction tests were performed with a ball-on-flat type micro-tribotester [8] under reciprocating motion. Friction was measured at the applied normal loads of 1500 μN, 3000 μN and 4800 μN. The sliding speed and the scan length were kept constant at 1 mm/s and 3 mm respectively. Soda lime glass balls (Duke Scientific Corporation) with radii of 0.25 mm, 0.5 mm and 1 mm were used as counterface sliders. Each test was conducted for about 15 to 20 min. Tests were repeated more than three times and the average values were plotted. All experiments were conducted at ambient temperature (24±1 °C) and relative humidity (45±5%).

## 3. Results and discussion

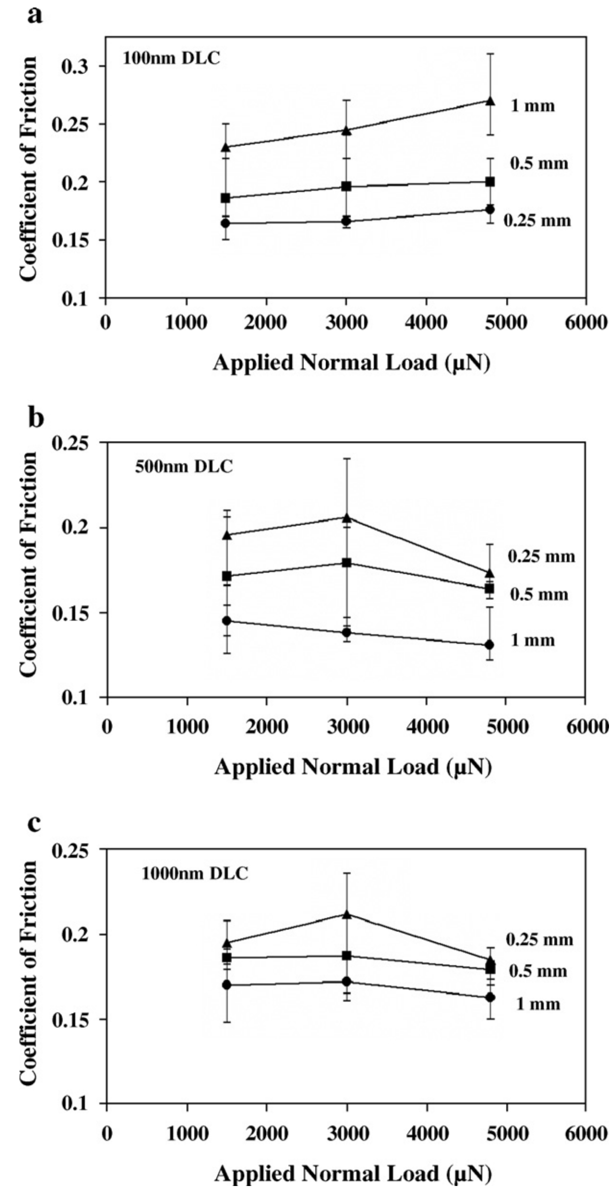


Fig. 1. a, b and c Coefficient of friction with applied normal load against glass balls of various sizes for 100 nm, 500 nm and 1000 nm thick DLC films respectively.

Fig. 1a, b and c show the variation of coefficient of friction with applied normal load against glass balls of various sizes for 100 nm, 500 nm and 1000 nm thick DLC films respectively. The coefficient of friction was estimated as the ratio of measured friction force to the applied normal load. From these figures it could be observed that the friction behaviour of the 500 nm and 1000 nm thick samples with respect to the ball size is distinctly different from that of the 100 nm thick sample.

In the case of 100 nm thick film, the coefficient of friction increases with the applied normal load and also with the ball size. These results could be understood by considering the fundamental law of adhesive friction given by Bowden and Tabor [10]. According to this law, the friction force is directly dependent on the real area of contact, for a single asperity contact. Eq. (1) gives the expression for the friction force.

$$F_f = \tau A_r \quad (1)$$

where, $\tau$ is the shear strength, an interfacial property and $A_r$ the real area of contact.

It has been earlier reported by Liu et al. [7] that at micro-scale, the contact area of DLC films could be estimated using the Hertzian theory. Eq. (2) gives the expression for the contact area according to the Hertzian model [11].

$$A_r = \pi[RF_n/K]^{2/3} \quad (2)$$

where, $R$ is the radius of the ball, $F_n$ is the applied normal load and $K$ the effective elastic modulus.

From Eq. (2) it could be seen that the real area of contact ($A_r$) directly depends on the applied normal load ($F_n$) and the ball size ($R$). Hence, any increase in the contact area either through the applied normal load or the ball size increases the friction force [8]. This explains for the increase in the coefficient of friction with the applied normal load and the ball size in the case of the 100 nm thick sample, which is due to the increase in the friction force with the contact area, and thus is very much consistent with the law of friction given by Bowden and Tabor (Eq. (1)).

It is well known that friction force comprises of two components namely adhesive and plowing [10]. The expression for the adhesive friction has been mentioned earlier in Eq. (1). Eq. (3) gives the expression for the plowing friction [10]. From this equation it is seen that the plowing component of friction force ($F_p$) has a direct, but inverse relation with the size of the slider ($R$). In the present case, considering the effect of the ball size in 500 nm and 1000 nm thick DLC films, the coefficient of friction decreases with the ball size (Fig. 1b and c). This would be due to the larger contribution of the plowing component when compared to the adhesive component of friction.

$$F_p = d^3 P / 12R \quad (3)$$

where, $d$ is the track width, $P$ the mean pressure required to displace the material in the surface and $R$ the radius of curvature of the slider.

Fig. 2a and b show the representative surfaces of two DLC films taken after the tests using a scanning electron microscope (SEM). It is evident from these figures that the films have undergone wear. Fig. 2a shows the surface of a 100 nm thick sample tested against a glass ball of 1 mm radius at 4800 μN normal load. Fig. 2b is a high magnification micrograph of the

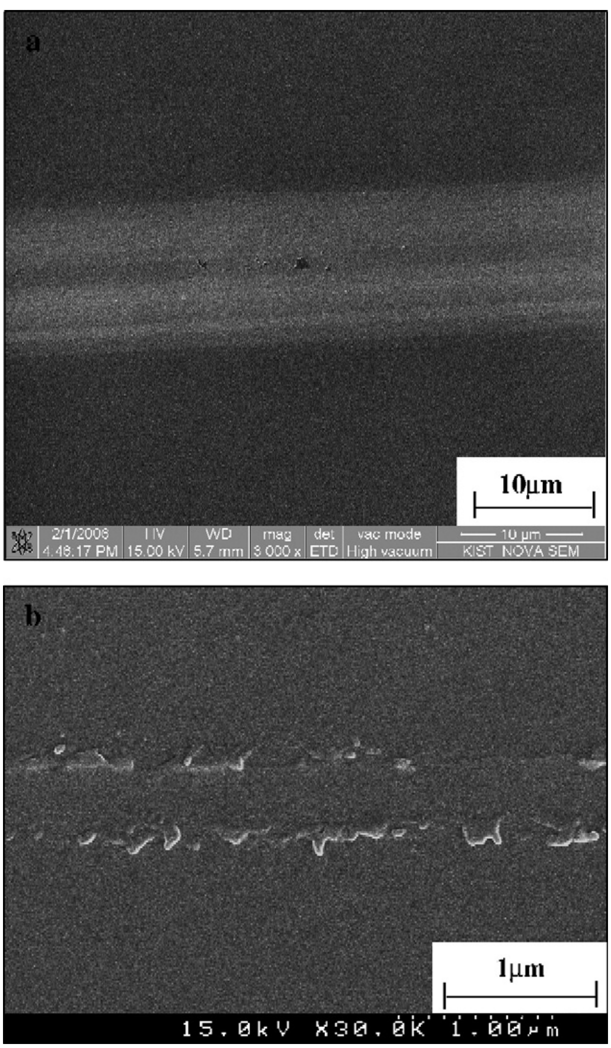


Fig. 2. a and b Representative surfaces of two DLC films taken after the tests using a scanning electron microscope (SEM). Fig. 2a shows the surface of a 100 nm thick sample (glass ball: 1 mm radius, load: 4800 μN). Fig. 2b shows the surface of a 1000 nm thick DLC film (glass ball: 0.25 mm radius, load: 3000 μN).

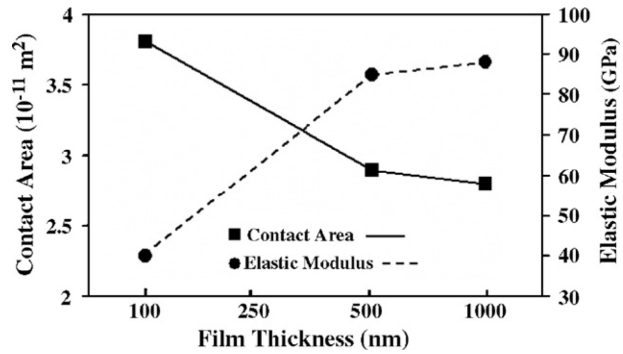


Fig. 3. Contact areas of the DLC films of three different thicknesses against a ball of radius 0.5 mm at the applied normal load of 3000 μN.

surface of a 1000 nm thick DLC film, which was tested against the glass ball of 0.25 mm radius at 3000 μN normal load. The morphology of the wear track shows some evidences of plowing and deformation. Ridges (material flow) formed on both the sides of the wear track can also be seen, which are due to the plowing effect. There is no wear debris at the wear track. Thus, in this case it is evident that the real pressures at the contact have indeed been high enough to cause plowing and deformation. The mechanism of transfer film formation followed by interfilm sliding has been frequently observed earlier in DLC coatings [1,11–13]. Under such circumstances, the material removal occurs at the third body layer (tribochemically mixed and compacted transfer layer) in the form of rolled debris. This rolled debris is usually seen at the wear track along its length [11–13]. In the present case, the absence of such rolled debris at the wear tracks (Fig. 2) indicates that there is no formation of tribolayer. Moreover, the formation of transfer film usually occurs at applied normal loads that are significantly higher than those used in the present investigation [11–13].

The different trends seen in the behaviour of the coefficient of friction of the test samples with the ball size (Fig. 1a, b and c) could be understood in terms of the contact area, influenced by their mechanical property, namely, the elastic modulus. Though the hardness of the films also varies with the film thickness [9], it should be noted that the hardness and the elastic modulus are inter-related [6,14]. In the present case, the mechanical property of the DLC films, namely the elastic modulus is considered in the discussion as with its value the contact area can be readily estimated using the Hertzian theory (Eq. (2)). Fig. 3 shows contact area of the DLC films of three different thickness estimated using the Hertzian theory (Eq. (2)), considering their Poisson's ratio to be 0.3 [9]. For the counterface slider, the elastic modulus was taken as 68 GPa and the Poisson's ratio 0.16 [8,15]. The contact area shown in the figure is estimated for all the three test samples for the contact against a ball of radius 0.5 mm at the applied normal load of 3000 μN. It is worthwhile to note that for any chosen values of applied normal load and ball size (externally applied parameters) the trend of the contact area with film thickness (elastic modulus, mechanical property) remains the same. From Fig. 3 it could be seen that the contact area in the 100 nm thick film is comparatively larger than the other two films. Further, the contact area in the 100 nm thick film would remain larger at any given ball size and applied normal load when compared to the other two films (due to its lower elastic modulus, Eq. (2)). As the contact area increases the adhesive friction force also increases (Eq. (1)) [10]. Thus, it seems that in the present case, the friction behaviour of the 100 nm thick sample is greatly influenced by the adhesive component of friction. This further explains the relationship between the values of the coefficient of friction of this sample with respect to the applied normal load and the ball size, which is mainly due to the adhesive component of friction.

On the contrary, the contact areas of the 500 nm and 1000 nm thick samples are comparatively smaller than that of the 100 nm thick film (Fig. 3). The smaller contact areas in these two films generate higher real contact pressures, which assist the plowing mechanism. Furthermore, for surfaces making contact at a number of asperities (multiple asperity) the plowing term decreases with the increase in the number of points of contact, for the same load [8,10]. In the present work, at the micro-scale, the contact is not exactly a single asperity contact but a multiple asperity contact. This also explains for the decrease in the coefficient of friction in the case of the two DLC films (500 nm and 1000 nm) with the ball size, and also for its reduction at higher normal loads (Fig. 1b and c).

As mentioned earlier, friction force in a sliding contact is said to be an additive of adhesive and plowing forces [10,11]. However, there could be a continuous interplay between these two components [11]. Further, the frictional behaviour of a material not only depends on the properties of the material but also on the contact conditions [11,16]. Depending upon the nature of the tribological contact, one of the friction components may dominate. This is seen from the present investigation where the plowing component played a major role in the friction performance when the contact areas were relatively smaller (films with higher elastic modulus (500 nm and 1000 nm thick films)), and the adhesion component prevailed over the plowing component when the contact area was larger (film with lower elastic modulus (100 nm thick film)).

## 4. Conclusion

The micro-scale friction behaviour of DLC films with varying film thickness was investigated experimentally. In these films the elastic modulus increased with their film thickness. The results of the present investigation can be summarized as follows: Two different trends were observed in these films with respect to their relationship of friction property with ball size. The friction behaviour in the case of the 100 nm thick film was adhesive in nature, whereas for the much thicker films plowing was dominant. The friction behaviour of the films was discussed in terms of the contact area, influenced by their mechanical property, namely, the elastic modulus. In the present case, the plowing component played a major role when the contact areas were relatively smaller, and the adhesion component prevailed over the plowing component when the contact area was larger. It could be concluded that in DLC films with varying elastic modulus (dependent on the film thickness) one of the friction components out of the two (adhesive and plowing) dominates their friction behaviour at the micro-scale depending upon the nature of the tribological contact.

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