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Tribology of ultra high molecular weight polyethylene film on Si substrate with chromium nitride, titanium nitride and diamond like carbon as intermediate layers

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Abstract

This paper presents tribological studies on composite films consisting of different intermediate hard layers (chromium nitride (CrN), titanium nitride (TiN) and diamond like carbon (DLC)) on Si substrate followed by soft ultra high molecular weight polyethylene (4-5 µm thick) as the top layer. The tribological properties of the composite films were evaluated on a ball-on-disc tribometer (composite film sliding against a 4 mm diameter Si_3N_4 ball) at a normal load of 40 mN and a linear speed of 0.052 m/s. The wear durability of the composite films increases with increasing hardness of the intermediate layers. The composite film with harder intermediate layers (TiN with 24 GPa and DLC layers with 57 GPa and 70 GPa of hardness) provides the best tribological performance with more than 300,000 cycles of sliding when the experiments were stopped. The critical loads of scratching correlate with the wear performances of the composite films. Application of only a few nanometer overcoat of perfluoropolyether on the most wear resistant composite films can further increase the wear lives (more than one million cycles) even at a higher normal load of 70 mN.

1 Introduction

Polymers are extensively used as protective coatings in many engineering applications because of their superior corrosion resistance, low friction, cost effectiveness and ease of fabrication [1-5]. Due to their soft and self-lubricating nature, polymer coatings can reduce the shear stress at the contact points and decrease the friction to a great extent. On the other hand, these soft films have low load carrying capacity and they are easy to be penetrated that leads to larger contact area and lower wear life. One of the promising methods to enhance the load carrying capacity and wear life of the polymer film is to use a harder intermediate layer between the substrate and the polymer film. By adding a hard intermediate layer, the top polymer film reduces the friction while the underlying hard layer provides the load carrying capacity and thus, achieving both low friction and wear resistance for the composite film.

The tribological advantages of soft metallic films on hard substrates have been well investigated [6-10]. Recently, many researchers have studied the applications of polymeric soft coatings on hard substrates. Gadow and Scherer [11] have shown that using PTFE film on hard coatings such as Al_2O_3 or TiO_2 provides longer wear life coupled with low coefficient of friction. Jiang et al. [12] have demonstrated the advantage of soft MoS_2–polytetrafluoroethylene coated on hard cBN–TiN substrate in reducing the friction with a ball-on-disc method. Minn and Sinha [13] have also reported that ultra high molecular weight polyethylene (UHMWPE) as the top layer with the support of hard diamond like carbon (DLC) intermediate layer on Si substrate increases the wear durability to several orders in comparison with either soft UHMWPE or hard DLC film alone. Though superior tribological properties of composite hard and soft films have been well recognized, the relation between the wear life of the composite film and the hardness of the intermediate harder layer is not clear yet. An attempt is made in the present study to investigate such a relation.

In this study, polished silicon wafer was used as the substrate with its hardness value of 12.4 GPa and root-mean-square roughness value of 0.41 nm measured by the atomic force microscope in a scan area of 1 µm x 1 µm. Different hard intermediate layers such as CrN, TiN and tetrahedral amorphous carbon, (ta-C) known as DLC were deposited onto Si substrate followed by a soft UHMWPE film. UHMWPE was selected because of its better wear resistance compared with other polymers such as polyetheretherketone, polymethyl methacrylate, polystyrene and polytetrafluoroethylene in their bulk forms [14]. Firstly, the tribological properties of different composite films were compared under a fixed applied load of 40 mN. Secondly, scratch tests with different applied loads were conducted on the composite films in order to determine the critical loads for the delamination of the film. A correlation between the critical loads and the wear lives has been presented using scratch tests. Thirdly, perfluoropolyether (PFPE) was applied onto the UHMWPE film to further reduce the shear stress and enhance the wear life for the films.

2 Experiment procedures

2.1 *Materials*

Polished n-type Si (100) wafers (obtained from Engage Electronics (Singapore) Pte Ltd), of about 455-575 µm in thickness and with a hardness of 12.4 GPa, were used as the substrate. Chromium nitride, titanium nitride and tetrahedral amorphous carbon, ta-C (non-hydrogenated DLC) films with different hardness values were deposited onto Si substrate (Filtered Cathodic Vacuum Arc technique, Nanofilm Technologies International Pte Ltd, Singapore). The pressure was set to 1.5×10^{-3} Pa during deposition. The arc current was fixed at 60 A, and the duct electric bias at 15 V. The deposition rate was 0.5 nm/s. The detailed deposition procedure is available in ref [15]. The thicknesses of all hard coatings were in the range of 50 nm. UHMWPE powder (bulk density = 0.33 ± 0.03 g cm-3 and average particle size of 20 ± 5 µm) was supplied by Ticona Engineering Polymers, Germany, through a local Singapore supplier. Decahydronapthalin (decalin) was selected as the solvent to dissolve UHMWPE. With the purpose of extending the wear life of the film, a commercial perfluoropolyether (PFPE) Z-dol 4000 of 0.2 wt% (dissolved into H-Galden ZV60 purchased from Ausimont INC) was overcoated onto UHMWPE film. Chemical formulae of Z-dol and H-Galden ZV60 are $HOCH_2CF_2O\text{-}(CF_2CF_2O)_p\text{-}(CF_2O)_q\text{-}CF_2CH_2OH$ and $HCF_2O\text{-}(CF_2O)_p\text{-}(CF_2CF_2O)_q\text{-}CF_2H$, respectively, where the ratio p/q is 2/3.

2.2 *Preparation of different layers on Si substrate*

The detailed procedures of cleaning substrates and preparing UHMWPE solution have been described in references [13, 16]. Cleaned samples were dipped in UHMWPE solution for 30 seconds with a fixed dipping and withdrawal speeds of 2.4 mm/s. The thickness of the UHMWPE film was 4-5 µm and its roughness (Ra) was approximately 0.56 µm. For some samples, PFPE (0.2 wt.% in H-Galden ZV60) was dip-coated onto UHMWPE film at dipping and withdrawal speeds of 2.4 mm/s with a fixed dipping duration of 30 s. The thickness of PFPE is expected to be a few (3-4) nanometers as measured in an earlier study. After coating, the samples were kept in a clean room for 24 hours before any test was carried out. A schematic diagram and a field emission scanning electron microscopy (FESEM) image of the coated layers on the Si substrate are provided in Fig. 1. The image shows cross-section of the sample. The polymer coating is clearly visible whereas the hard intermediate coating is not very precisely identifiable due to very low thickness (~ 50 nm).

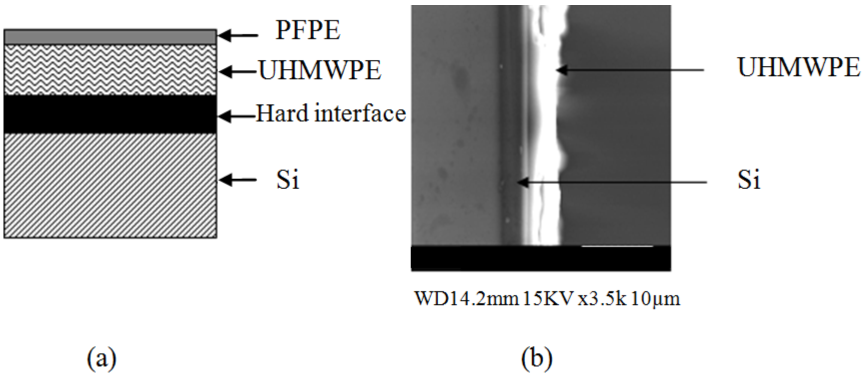


Fig. 1 *(a) Schematic (not to scale) diagram of different layers coated onto Si substrate and (b) FESEM image of the cross-sectional image of UHMWPE (white region) coated on Si substrate. The thickness of the polymer film is in the range of 4-5 µm.*

2.3 *Surface characterizations*

The surface wettabilities of different hard interfaces on Si substrate were determined by measuring the water contact angles with a VCA Optima Contact Angle System (AST product, Inc., USA). Distilled water droplets of 0.5 µl were used for the measurements. The contact angles were reported as an average of five independent measurements on the samples. The measurement error was within ± 3°.

In order to verify the hardness of different interfaces provided by the supplier, nanoindentation tests were also carried out on samples using a constant load 300 µN with a 100 nm radius of diamond tip. The nanoindentation system consists of the Nanoscope IIIa controller (Digital Instruments, Santa Barbara, CA, USA) with a triboscope indenter system (Hysitron Inc., MN, USA). The time taken during loading on the sample was 5 seconds with a constant holding time of 10 seconds before unloading. The penetration depth of indentations was less than 5 nm.

In order to understand the load bearing capacity of the composite films, Microhardness tests were conducted on the Si/UHMWPE films with different hard intermediated layers using Shimadzu-HMV automatic digital microhardness tester. The microhardness test was performed using a Vickers indenter under a test load of 10 gf and a dwell time of 15 s.

2.4 *Friction and wear tests*

Friction and wear tests were carried out on a custom-built ball-on-disc tribometer. A 4-mm diameter silicon nitride (Si_3N_4) ball (Vickers hardness = 1500 HV, from supplier's data) was used as a stationary counterface whereas the coated Si substrate acted as the disc. The test radius was 1 mm with a fixed disc rotational speed of 500 rpm (linear relative speed at the sliding contact = 0.052 m/s). During the sliding tests, the vertical and lateral displacements of the cantilever holding the ball were carefully measured using laser instruments (MTI Instruments Inc., New York, USA). These displacement values were then converted to forces using a calibration chart. The sensitivity of the laser instrument is 0.5 μm which is equivalent to a force of 0.125 mN according to the calibration chart of the present cantilever. In this study, the wear life of each sample is defined as the number of cycles when the coefficient of friction exceeds 0.3 or large fluctuations of the coefficient of friction occur continuously, whichever happens earlier. Energy dispersive spectroscopy (EDS) (Hitachi S4300 FESEM/EDS system) tests were conducted on the wear tracks in order to confirm the failure of the sample by checking for the presence of Si peak. The FESEM operating voltage was 15 kV. EDS tests were performed with an accelerating voltage of 15 kV and a beam current of 10 μA at a constant detecting time of 30 seconds. The signals were detected by a silicon detector at a take-off angle of 30 degrees. The friction and wear tests were conducted in a class-100 clean booth environment at a temperature of 25 ± 2˚C and a relative humidity of 55 ±5 %. The reported friction and wear data are averages of at least three repeated tests.

2.5 Scratch tests

In order to compare the adhesion strength and the load carrying capacity of the samples, a 2 μm radius diamond tip was used to conduct scratch test on every sample. The scratching of the UHMWPE film was carried out under an increasing applied normal load from 10 mN to 100 mN with an increment of 10 mN. The scratching velocity and the linear scratch distance were fixed at 0.1 mm/s and 5 mm, respectively. After the scratch test, the surface topographies of the scratches were studied under an FESEM in order to observe debris particles or delamination of the film. EDS tests were also conducted on the scratches to record carbon and silicon peaks for additional confirmation of film failure, if any.

3 Results and discussion

3.1 Surface analysis

The surface wettability of a liquid is the balance between adhesive and cohesive forces. If the adhesive force between the molecules of the substrate and the liquid is stronger than the cohesive force between the liquid molecules, the degree of surface wettability becomes high. Therefore, the surface wettability is a good parameter to predict the adhesion between the substrate and the polymer film. It is easy to determine the surface wettability from the water contact angle measurement. A low water contact angle gives hydrophilic surface which can generally provide better adhesion. However, at the same time, this hydrophilic surface tends to attract more water molecules from atmosphere if the humidity is high. The presence of water molecules on a solid substrate prior to film deposition will reduce the adhesion strength between the film and the substrate [17]. The relationship between surface wettability and wear durability has been reported in ref [16]. In addition to surface wettability, the hardness of the substrate is also an important factor in determining the tribological properties of composite films as it can provide better load carrying capacity.

The contact angle and hardness values of different hard intermediate layers are provided in Table 1. The water contact angle of bare Si shows 21˚ that indicates very hydrophilic nature. The contact angles of all the rest coatings are in the range of 68˚ -81˚. Within this range, the effect of contact angle (surface wettability) on the adhesion strength between UHMWPE film and the substrate is assumed to be comparable. In the presence of UHMWPE as top layer, all composite films show a contact angle of 91˚. The water contact angle for the Si_3N_4 ball surface was measured as 70˚.

Bare Si and Si/CrN have the lowest hardness values measuring 12.4 GPa and 13.5 GPa respectively. Higher hardness values were observed for DLC15, TiN, DLC57 and DLC70 as 15 GPa, 24 GPa, 57 GPa and 70 GPa respectively. The numerals in the nomenclatures of DLC films represent the hardness of the respective DLC film in GPa. The measured nanoindentation hardness of the UHMWPE film was 35 MPa for all samples regardless of the interface and the variation was within the measurement errors where the indentation depth was approximately 400 nm. This shows that in nanoindentation test there is a negligible substrate effect on several micron thick polymer films.

Table 1. *Water contact angles and nanohardness for different intermediate hard layers.*

Interface	Bare Si	Si/CrN	Si/DLC15	Si/TiN	Si/DLC57	Si/DLC70
Contact angle (°)	21	80	79	68	81	80
Nanohardness (GPa)	12.4	13.5	15	24	57	70

3.2 *Friction and wear results of composite films*

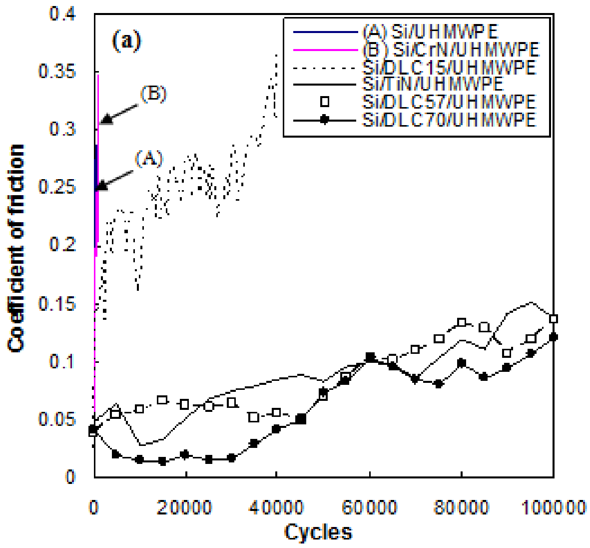
Tribological tests were conducted on all hard layers used, before depositing UHMWPE film onto them, to understand their individual performances. Sliding test results against Si3N4 ball (normal load of 40 mN and a linear speed of 0.052 m/s) are summarized in Table 2. Data show that except for DLC70, all other hard films gave lower friction initially (in the first 4 seconds of sliding), however, the value increased above 0.3 within 50-400 number of sliding cycles which was considered as film failure. CrN has the shortest wear life. In all cases, we observed wear of the silicon nitride ball and a clear wear track was seen on the film indicating wear of the film as well. DLC70 film gave very low coefficient of friction and also the wear life was much longer than for other hard films. However, even for this film, the maximum life was only ~11,000 after which there were large fluctuations in the coefficient of friction reaching as high as 0.25. Both the silicon nitride ball and the film showed wear even in this case.

Table 2. *The initial coefficient of friction and wear durability of the different intermediate hard layers used. The ball and the film are worn at failure in all cases.*

Sliding pair	Initial coefficient of friction	Wear durability (Cycles)	Remark at failure
CrN film – Si_3N_4 ball	0.25 ± 0.15	50	CoF is above 0.3
DLC15 film – Si_3N_4 ball	0.14 ± 0.11	200	CoF is above 0.3
TiN film – Si_3N_4 ball	0.13 ± 0.05	400	CoF is above 0.3
DLC57 film – Si_3N_4 ball	0.18 ± 0.05	400	CoF is above 0.3
DLC70 film – Si_3N_4 ball	0.05 ± 0.018	11,000	Occurrence of large fluctuations between 0.03 and 0.25

The tribological properties of the UHMWPE film coated onto different hard layers are shown in Fig. 2. At the start of the test, the initial coefficient of friction is related to the shear strength of the UHMWPE film and is in the range of 0.08~0.13 for all composite films. During the test, the coefficients of friction of Si/UHMWPE and Si/CrN/UHMWPE are above 0.3 when the sliding cycles reach 1,000 and 2,000, respectively. This early failure relates to the hardness of the intermediate layer. Though UHMWPE has self-lubricating property and it can reduce the coefficient of friction, it is easy to be penetrated in its coated form owing to its softness. The easy penetration of the counterface ball increases the real area of contact and the amount of polymer peeled from the film increases as well. The results suggest that the substrates with lower hardness limit the wear life of the composite film. When UHMWPE is coated onto a harder layer (Si/DLC15/UHMWPE), the wear life extends to 50,000 cycles. With further increase in the hardness of the intermediate layer as in Si/TiN/UHMWPE, Si/DLC57/UHMWPE and Si/DLC70/UHMWPE, the composite films do not show any sign of failure till

300,000 cycles of sliding when the experiments were stopped. The results indicate that higher hardness of the intermediate layers provides better penetration resistance to soft UHMWPE film and reduce the contact area of the ball and promote wear durability [13]. The microhardness data in Table 3 also confirms that the film with harder intermediate layer provides higher overall hardness and hence better load carrying capacity. Consistent with the nanoindentation hardness of the intermediate layers, there is phenomenal increase in the microhardness of the composite films with the DLC57 and DLC70 intermediate layers.



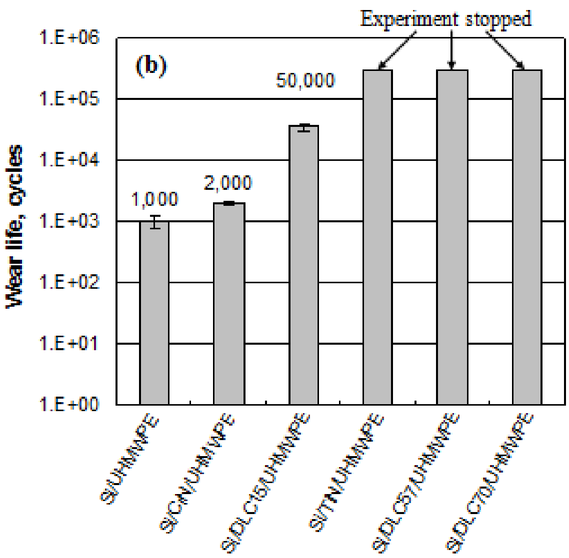


Fig. 2 *(a) Coefficient of friction and (b) wear life of Si coated with different composite films. The applied load was 40 mN and the rotational speed was 500 rpm (linear speed = 0.052 m/s).*

3.3 Polymer transfer mechanism

The polymer transfer mechanism during sliding between the ball and the polymer film is an important phenomenon as the transfer film influences the friction and wear characteristics. When a hard ball is slid against soft UHMWPE film, the transfer film will eventually be formed on the ball and the sliding will become between the polymer film and the transfer film deposited on the counterface. At this stage, because of the self-lubricating property of UHMWPE, the shear stress will reduce further and so will the coefficient of friction [18-22]. As the sliding continues, the polymer will deform plastically and more polymer debris will accumulate on the ball (counterface) which in turn widens the wear track and increases the friction gradually.

Table 3. *The microhardness, critical loads in scratching and wear lives of UHMWPE films with different intermediate hard layers. The applied load used for wear life determination was 40 mN.*

Interface	Bare Si/UHMWPE	Si/CrN/UHMWPE	Si/DLC15/UHMWPE	Si/TiN/UHMWPE	Si/DLC57/UHMWPE	Si/DLC70/UHMWPE
Microhardness (HV)	11.2 ± 1	11.4 ± 1	12 .5 ± 0.8	15.4 ± 1.7	23 ± 1.7	30.7 ± 1.9
Critical load (mN)	20	20	30	60	60	80
Wear life (cycles)	1,000	2,000	35,000	>300,000	>300,000	>300,000

The transfer process is studied under an optical microscope. The optical images of the balls and the wear tracks for Si/TiN/UHMWPE, Si/DLC57/UHMWPE and Si/DLC70/UHMWPE films are shown in Fig 3. The sliding test conditions were fixed as 40 mN applied load, 500 rpm rotational speed and 300,000 sliding cycles. The transferred polymer consists of lumps that seem to be from the asperities of the film which were sheared by the ball. The lumps from Si/TiN/UHMWPE (which has lower hardness than the other two) are larger and thicker. The transfer amount of polymer is directly related to the track width as the polymer has been pulled out from the track. It is obvious that, because of its lower hardness, TiN layer provides lower penetration resistance to UHMWPE film in comparison with DLC57 and DLC70 layers. As a consequence, the contact area or track width on Si/TiN/UHMWPE film becomes larger with greater polymer transfer. There are also many scratches in the track region of Si/TiN/UHMWPE due to large amount of back transfer of the polymer between the ball and the polymer film in continuous sliding. Lower hardness and poor load carrying capacity of Si/TiN/UHMWPE film is largely responsible for the increase in the area of contact and polymer transfer (Fig. 3a).

Harder intermediate layers (such as Si/DLC57/UHMWPE and Si/DLC70/UHMWPE) can provide better penetration resistance to UHMWPE film and reduce the contact area. Hence, the amount of polymer transfer becomes less with reduced contact area. It can be seen that the lumps become less and thin (Figs. 3b and 3c).

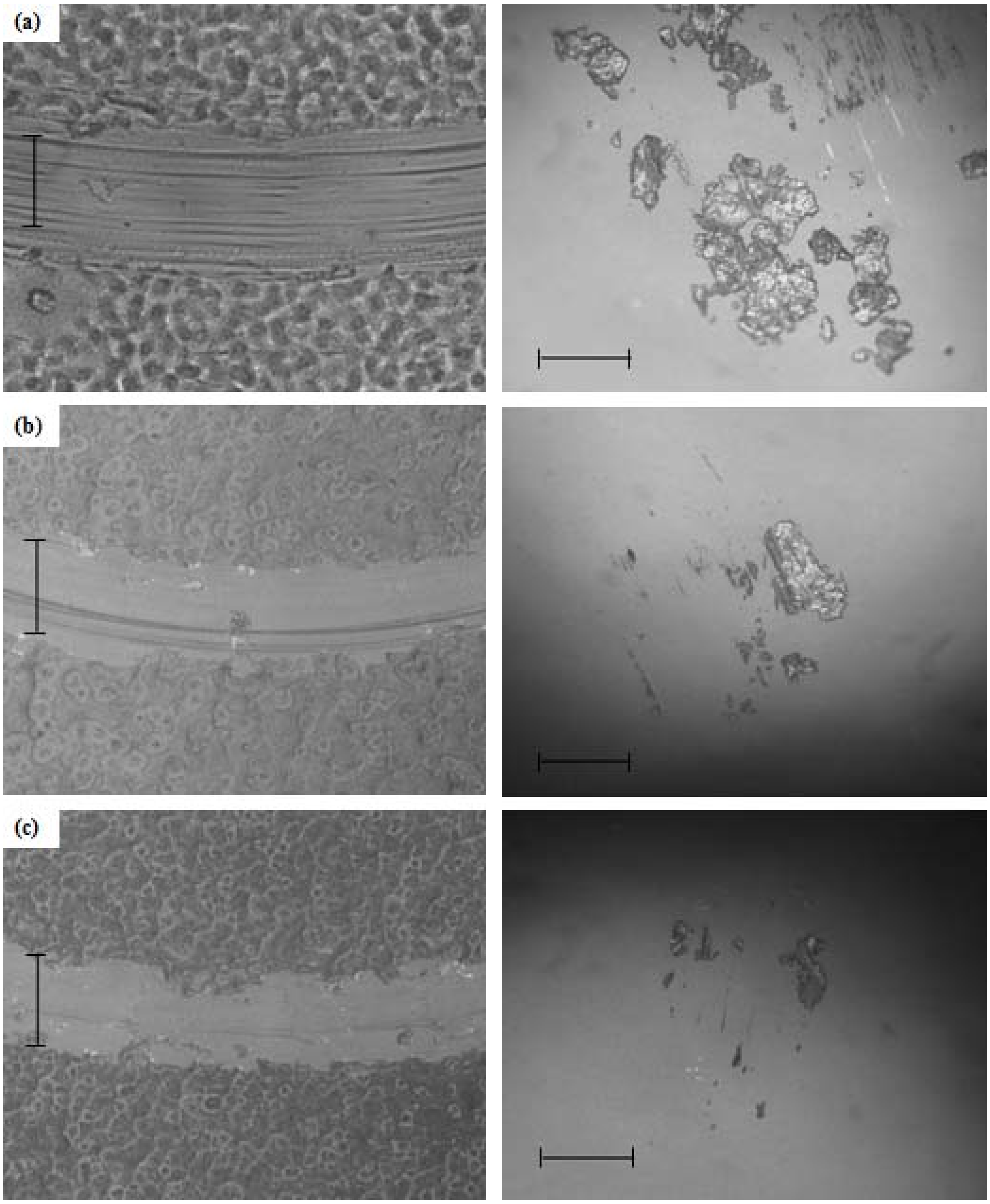


Fig. 3 *Optical microscopy images of (a) Si/TiN/UHMWPE, (b) Si/DLC57/UHMWPE and (c) Si/DLC70/UHMWPE films (first column) after sliding against respective Si_3N_4 balls (second column) for 300,000 cycles where the normal load is 40 mN and the linear sliding speed is 0.052 m/s. The vertical and horizontal scales correspond to 100 μm.*

3.4 Critical load in scratch tests and film adhesion

In order to obtain better understanding of the supportive role of different hard intermediate layers on the tribological properties of top UHMWPE film, scratch tests were conducted using a 2 μm diamond tip with a fixed scratching velocity of 0.1 mm/s and scratching distance of 5 mm. As the critical loads required to peel the top film can vary with different hard intermediate layers, the applied load was varied from 10 mN to 100 mN with an increment of 10 mN. In this study, the critical load is defined as the respective applied load when the film fails during scratching exposing the intermediate layer and the substrate. The failure of the film is confirmed by observing the debris shape coming from the film and by measuring the Si peak inside the scratches using EDS. Because of the 50 nm thickness of the intermediate layers used in this study, it is difficult to measure the peaks of the elements such as Cr, N and Ti when the film fails. And hence, Si peak is used as the reference peak to indentify polymer film failure from the substrate.

The summary of the critical loads of UHMWPE films with different hard intermediate layers is provided in Table 3. It is seen that the critical loads of Si/UHMWPE and Si/CrN/UHMWPE are the lowest at 20 mN. The critical load of Si/DLC15/UHMWPE increased to 30 mN. Further increase in critical load was found for Si/TiN/UHMWPE and Si/DLC57/UHMWPE as 50 mN and 60 mN respectively. For Si/DLC70/UHMWPE film, the high intensity of Si peak was observed when the applied load was 80 mN; a four times increase over bare Si as the substrate. Fig. 4 shows an FESEM image of Si/DLC70/UHMWPE film where the applied load was 80 mN. Clear signs of severe plastic deformation with brittle debris were produced at both edges of the scratch and the debris at the centre of the scratch was Si fragments, as confirmed by EDS (see Fig. 4 inset). This debris behavior was observed for all samples when the films failed by scratching.

The critical loads of the films are consistent with their respective wear lives as presented in Table 3. The critical loads in scratching are directly related to the wear lives of the composite films. The critical loads of Si/UHMWPE and Si/CrN/UHMWPE are the lowest and their wear lives are 1,000 cycles and 2,000 cycles respectively. The critical load of Si/DLC15/UHMWPE is 30 mN and its wear life extends to 35,000 cycles. The critical loads of the rest three films are 60 mN (for Si/TiN/UHMWPE and Si/DLC57/UHMWPE) and 80 mN (for Si/DLC70/UHMWPE) and they did not fail till 300,000 cycles when the experiments were stopped. Higher critical load means great load bearing capacity of the film and hence higher wear life.

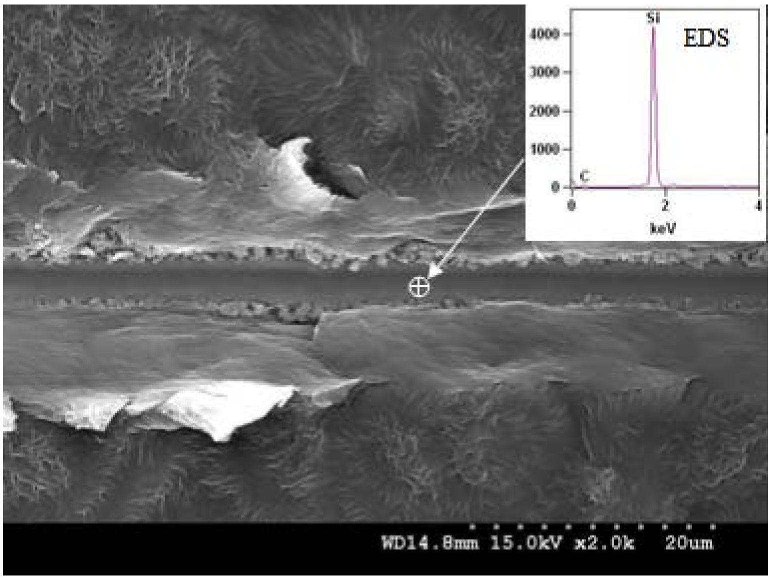
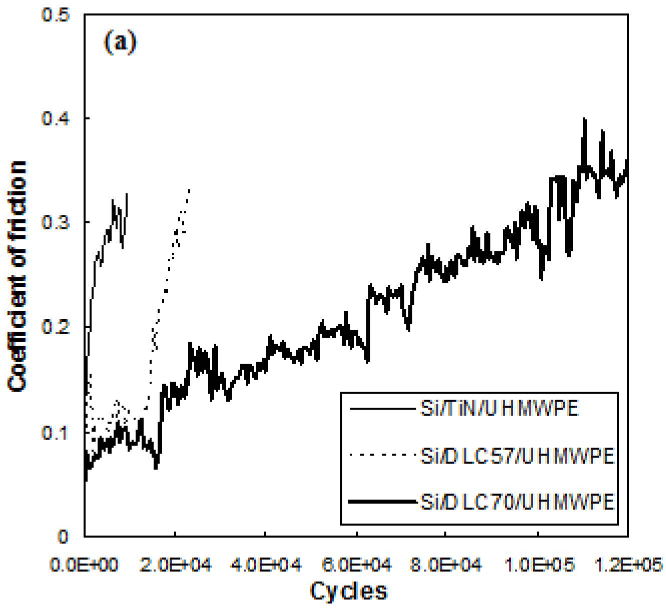


Fig. 4 *The FESEM image of a scratch on Si/DLC70/UHMWPE. The normal load during scratching was 80 mN and the scratching velocity was 0.1 mm/s.*

3.5 Friction and wear results of Si/TiN/UHMWPE, Si/DLC57/UHMWPE and Si/DLC70/UHMWPE films at higher normal load

To facilitate a better understanding of the tribological performances of the best three films, the applied load was increased to 70 mN. The friction and wear data of these three films are shown in Fig. 5. A sharp increase in the coefficient of friction for Si/TiN/UHMWPE and Si/DLC57/UHMWPE films is observed in early cycles and their wear lives are 8,000 cycles and 22,000 cycles respectively. Large amount of lumpy polymers pulled-out from the film is found around the contact point of the ball in both cases. For Si/DLC70/UHMWPE film, its coefficient of friction gradually increases with the number of sliding cycles and reaches above 0.3 after 120,000 cycles. The hardest intermediate layer (DLC70) still provides maximum wear life. When the applied load is increased to 70 mN, the contact radius is larger and the shear stress force is largely determined by the shear property of the composite film [23]. As a result, the coefficient of friction increases and the wear lives of the composite films are shortened.



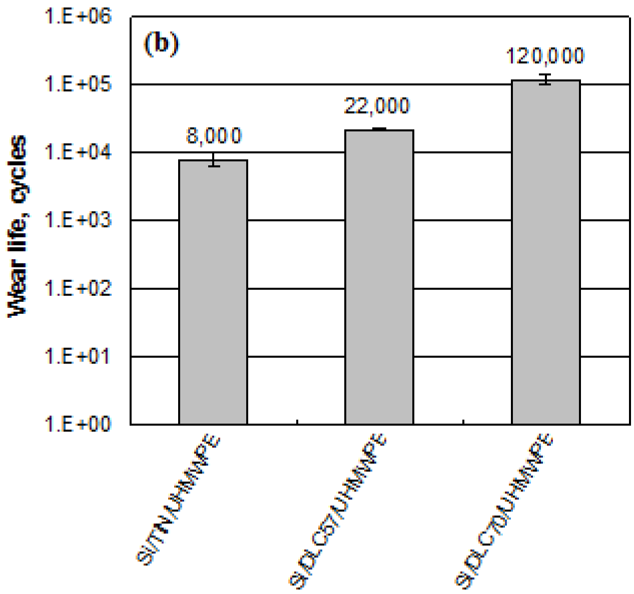


Fig. 5 *(a) Coefficient of friction and (b) wear life of Si substrate coated with different composite layers (as mentioned in the figures). The applied load was 70 mN at a rotational speed of 500 rpm (linear speed = 0.052 m/s).*

3.6 Effects of PFPE overcoat on composite films

In order to increase the wear lives of the composite films by further reducing the shear stress, PFPE was used as a nano-lubricant and over-coated onto UHMWPE. Friction tests were conducted on Si/Ti/UHMWPE/PFPE, Si/DLC57/UHMWPE/PFPE and Si/DLC70/UHMWPE/PFPE with an applied normal load of 70 mN and at a rotational speed of 500 rpm. With PFPE overcoat, none of the three films failed till one million cycles when the experiments were stopped. UHMWPE film used in this study has no reactive chemical group and it is not expected to form chemical bonding between UHMWPE and PFPE. It is assumed that PFPE molecules are trapped in the valleys of the UHMWPE film [24]. PFPE over-coated layer provides more hydrophobic property with a water contact angle of 102°. High contact angle means lower surface energy which in turn reduces the adhesion between the ball (counterface) and the film (thus, nearly eliminating polymer transfer).

The optical images of the balls and the films after friction tests are shown in Fig. 6. The track widths with PFPE overcoat (at 70 mN) are narrower than those without PFPE (at 40 mN; see Fig (3)). The optical images of the ball surfaces do not show any significant amount of polymer transfer. Another advantage of PFPE is its thermal stability which can withstand high frictional heat generated at the interface without degrading the property of the polymer film. Furthermore, some PFPE molecules can transfer to the ball and provide lubrication. The low friction and wear resistance characteristics of PFPE coated films are seen even after one million sliding cycles at the highest applied normal load used.

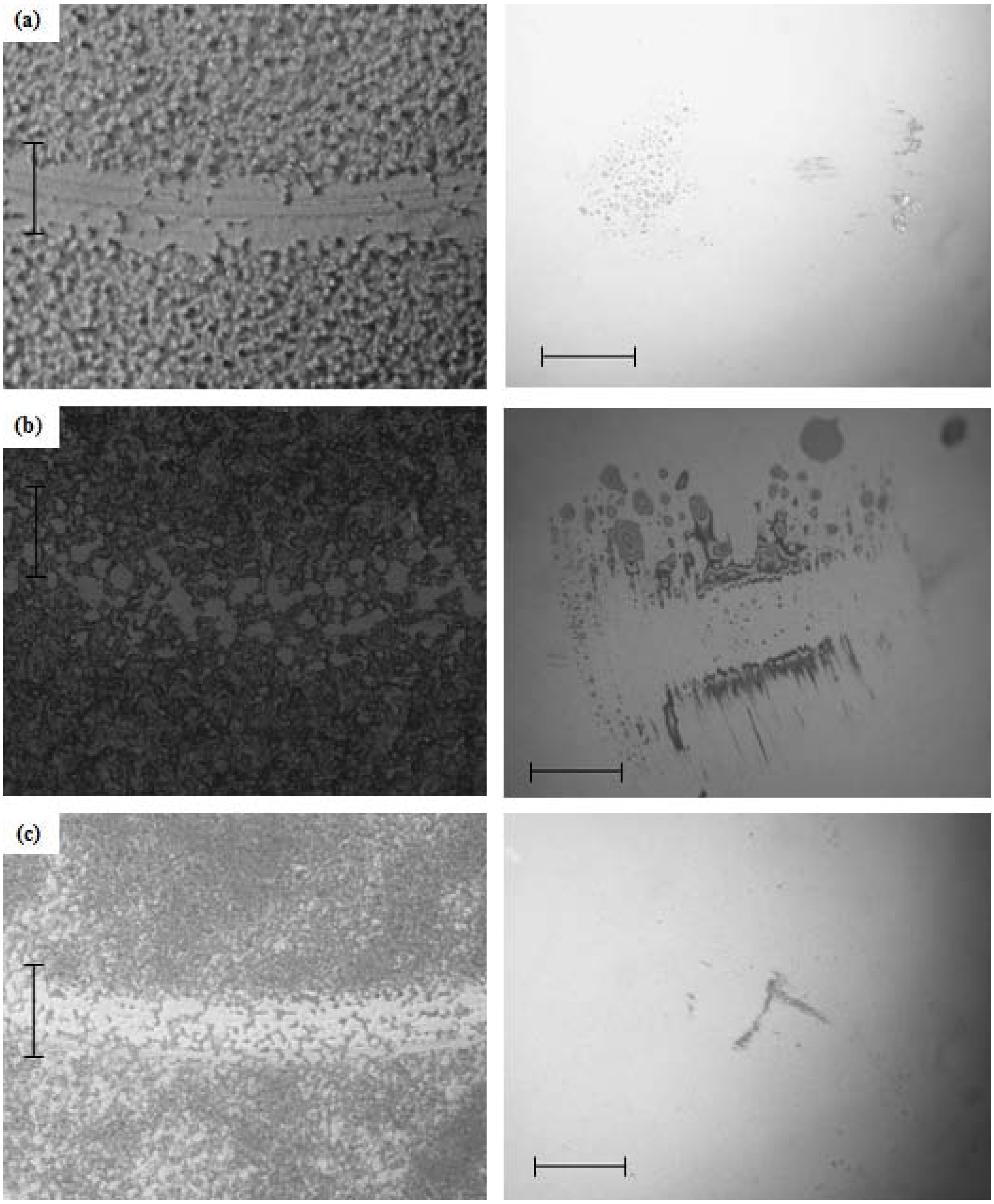


Fig. 6 *Optical microscopy images of (a) Si/TiN/UHMWPE/PFPE, (b) Si/DLC57/UHMWPE/PFPE and (c) Si/DLC70/UHMWPE/PFPE films (first column) after sliding against respective Si_3N_4 balls (second column) for one million sliding cycles. The applied load was 70 mN and the linear sliding speed was 0.052 m/s. The vertical and horizontal scales correspond to 100 μm.*

4 Conclusions

The tribological properties of UHMWPE film (thickness of 4~5 μm) coated onto different hard intermediate layers (CrN, DLC15, TiN, DLC57 and DLC70) are studied using a ball-on-disc method. The top UHMWPE film reduces the shear stress and the coefficient of friction because of its self-lubricating property while the hard intermediate layers provide higher load carrying capacity that can increase the wear durability. The wear life of UHMWPE composite film is also directly related to the hardness of the intermediate layer as higher hardness provides longer wear life. The lowest hardness layer, i.e. bare Si/UHMWPE, has a wear life of 1,000 cycles whereas the higher hardness layers, Si/TiN/UHMWPE, Si/DLC57/UHMWPE and Si/DLC70/UHMWPE have shown the wear lives of more than 300,000 cycles at an applied normal load of 40 mN and a sliding speed of 0.052 m/s. The critical loads from scratch tests are also consistent with the tribological test results, as Si/UHMWPE failed at 20 mN whereas Si/DLC70/UHMWPE with the hardest intermediate layer at 80 mN. Based on the critical load data, the friction and wear tests are conducted on the best three composite films at a higher applied load of 70 mN. The influence of hard intermediate layer on the wear life is still observed as the wear lives of Si/TiN/UHMWPE, Si/DLC57/UHMWPE and Si/DLC70/UHMWPE are 8,000 cycles, 22,000 cycles and 120,000 cycles respectively. Over-coating with few nanometers thickness of PFPE as top layer on these three films further reduces the friction and extends the wear lives to more than one million cycles under an applied normal load of 70 mN and a sliding speed of 0.052 m/s.

The present composite films will find applications in many tribological components such as bearing and gears where extremely high wear life is desirable with low and stable coefficient of friction.

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Note: Names of the suppliers and manufacturers have been mentioned for the purpose of the completeness of the facts. By any means, this does not indicate our endorsement of their products and services.

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