

Dry sliding and boundary lubrication performance of a UHMWPE/CNTs nanocomposite coating on steel substrates at elevated temperatures

M. Abdul Samad and Sujeet K. Sinha

Department of Mechanical Engineering, National University of Singapore, 9
Engineering Drive 1, Singapore 117576, Singapore
e-mail: mpesks@nus.edu.sg

Abstract

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Abstract

A nanocomposite polymer coating of ultrahigh molecular weight polyethylene (UHMWPE) reinforced with 0.1 wt% of singlewalled carbon nanotubes (SWCNTs) is developed and coated onto steel substrates for a possible application as a boundary lubricant in bearings and gears. Since temperature is one of the predominant factors in determining the tribological performance of polymer coatings, friction and wear experiments were carried out at elevated temperatures. Experiments are performed on a custom built tribometer simulating high contact pressures under dry and base oil lubricated conditions. Wear mechanisms of the nanocomposite coating and the counterface material are studied using optical profilometry. FESEM images are used to study the wear morphology of the coating. Possible changes in the crystallinity of the polymer due to temperature changes are studied by XRD. It is observed that the addition of SWCNTs to the polymer matrix not only helps in improving the mechanical properties such as hardness and the load bearing capacity of the coating but also enhances its frictional and wear properties at elevated temperatures.

Keywords Polymer coatings, UHMWPE, SWCNTs, boundary lubrication

1 Introduction

In the recent past, there has been a growing search for wear resistant, inert, environmentally sensitive and low friction polymeric tribological coatings because of their ability to be coated using simple techniques and their cost effectiveness [1]. Polymer coatings are one of the most promising materials to enhance the wear life of various substrates since some polymers have exceptionally high wear resistance coupled with low density, low cost and ease of fabrication into different shapes [2]. Research has shown that polymer coatings when deposited onto various metallic substrates such as steel and aluminium demonstrate excellent tribological properties [3–7].

Ultrahigh molecular weight polyethylene (UHMWPE) is one such unique polymer which has exceptional tribological properties such as high wear resistance and low coefficient of friction. It has the highest sliding abrasion resistance and highest notched impact strength of any commercial plastics. In its bulk form, UHMWPE is highly wear resistant compared to many other polymers such as polyetheretherketone (PEEK), polyethylene (PE), and polystyrene (PS) [8, 9]. The outstanding characteristics of UHMWPE can be maintained from $-269\text{ }^{\circ}\text{C}$ to $90\text{ }^{\circ}\text{C}$ and even higher for shorter periods of time. Since it does not melt flow or liquefy at its melting point of $138\text{--}142\text{ }^{\circ}\text{C}$, it retains excellent dimensional stability at temperatures up to $200\text{ }^{\circ}\text{C}$ [8].

Research on the tribological properties of UHMWPE films on a bare Si surface and suitably modified Si surface has shown that UHMWPE is an excellent candidate material as a thin film coating because of its very high wear resistance coupled with low coefficient of friction against metals and ceramic materials [10, 11]. UHMWPE was also coated successfully onto steel and Al substrates to improve the wear life of these metals [3, 7] by using the dip coating process. The coating demonstrated a very good wear life with a low value of coefficient of friction of ~ 0.02 to 0.2 . Due to its high resistance to corrosive chemicals it can be used in conjunction with various lubricants as well.

In spite of its excellent tribological properties, use of UHMWPE in demanding tribological applications has been limited due to various constraints such as its low load bearing capacity in the bulk form and thermal instability and thus is the subject of much tribological research in the areas of composites. Addition of reinforcements like carbon nanotubes is one approach to overcome these constraints. Carbon nanotubes (CNTs) due to their excellent mechanical (exceptionally high tensile strength and stiffness), electrical and thermal properties (thermal conductivity of 3000 W/mK) have caught the attention of researchers in recent years and are being considered as a potential filler material for many polymer matrices. Several studies have shown that the addition of CNTs resulted in significant improvements in the mechanical properties such as the elastic modulus and strength of the polymer matrices in bulk form [12–14]. An increase in the wear resistance of bulk UHMWPE with the CNTs addition has also been observed [15–18].

Recently, nanocomposite coatings of UHMWPE prepared by reinforcing the polymer with carbon nanotubes showed a significant improvement in its mechanical, thermal and tribological properties such as hardness, wear resistance and scratch resistance with a small increase in the coefficient of friction [19]. This nanocomposite coating when coated on Al substrates demonstrated excellent performance as a boundary lubricant under dry and base oil lubricated conditions at room temperature [20]. However, this increase in the wear life of the nanocomposite coating in the dry condition was associated with a slight increase in the coefficient of friction. Thus, in the present research we took up the approach of overcoating the

nanocomposite coating with a thin (few nanometer) layer of perfluoropolyether (PFPE) to reduce the coefficient of friction which would lead to a further improvement in the wear life of the nanocomposite coating. The lubricating property of PFPE is also very effective in eliminating any wear of the counterface. Perfluoropolyether is a unique lubricant which is safe, nontoxic, environmental friendly. Its chemical and thermal stability, low vapour pressure, low surface tension and good lubricity which are all essential for better tribological performances make it a potential candidate for tribological applications. PFPE has been used extensively as a top overcoat on hard coatings [22–24] and polymer coatings [3,10,11] alike to improve the tribological behaviour of these coatings.

Thus, due to its unique properties and the ability to protect surfaces from wear and tear, PFPE has been selected to overcoat the UHMWPE/CNT nanocomposite coating to further improve its tribological performance. In the present research, the performance of the nanocomposite coating with an overcoat of PFPE at elevated temperatures is evaluated under dry and base oil lubricated conditions.

2 Experimental Procedures

2.1 Materials and Chemicals

AISI52100 bearing steel (Hardness = 60 HRC) cylindrical shaft of 40mm diameter and a flat AISI52100 bearing steel (Hardness = 60 HRC) plate of 20mm were used. In the context of a simple journal bearing application, the cylindrical shaft acts as a journal whereas the flat plate acts as the bearing housing to simulate a continuous line sliding contact. The cylindrical shaft was coated with the nanocomposite films and the bare flat steel plate was used as the counterface.

UHMWPE polymer powder (Grade: GUR X 143) used for coating the specimens was supplied by Ticona Engineering Polymers, Germany, and was procured from a local Singapore supplier (melt index MFR 190/15 = 1.8 ± 0.5 G/10 min; bulk density = 0.33 ± 0.03 g/cm³; average particle size = 20 ± 5 μm). Decahydronaphthalin (decalin) was used as the solvent to dissolve the polymer powder prior to dipcoating.

SWCNTs (diameter = 10 nm) were procured from Iljin Nanotech Co. Ltd., South Korea which were as processed grade and were produced using the arc discharge process. SN 150 Base oil (Grade I, kinematics viscosity@40 °C = 28–34 cSt, kinematics viscosity@100 °C = 5.2–5.4 cSt, viscosity index = 100, flash point = 200 °C, density = 868 kg/m³), which had no additives, was used as a liquid lubricant in the experiments. It was supplied by Premier Six Pte. Ltd. and Tecsia Lubricants Pte. Ltd., Singapore.

The PFPE used was Zdol 4000 (obtained from Solvay Solexis, Singapore) which was dissolved in HGalden ZV60 (obtained from Ausimont INC). Chemical formulae of Zdol and HGalden ZV60 are $\text{HOCH}_2\text{CF}_2\text{O}(\text{CF}_2\text{CF}_2\text{O})_p(\text{CF}_2\text{O})_q\text{CF}_2\text{CH}_2\text{OH}$ and $\text{HCF}_2\text{O}(\text{CF}_2\text{O})_p(\text{CF}_2\text{CF}_2\text{O})_q\text{CF}_2\text{H}$, respectively, where the ratio p/q is 2/3.

Table 1
Properties of the developed nanocomposite coating [19].

Property	Value
Hardness (Mpa)	97 ± 9
Elastic modulus (Gpa)	3.76 ± 0.55
Water contact angle (°)	139 ± 3
Thermal conductivity (W/mK)	0.64 ± 0.03

2.2. Deposition of the nanocomposite coating on steel substrates

Deposition of the nanocomposite coating on the steel substrates was carried out by using a dipcoating process. Prior to the actual dipcoating the nanocomposite solution of UHMWPE and CNTs was prepared. To take full advantage of the mechanical and thermal properties of the CNTs, it is essential that the CNTs are uniformly dispersed in the polymer matrix. Proper bonding between the CNTs and polymer matrix is important to assure the transfer of load onto the CNTs. Thus, the CNTs were air plasma treated and uniformly dispersed in the polymer matrix by using an ultrasonic homogenizer. The detailed procedure of the coating process can be found in our earlier publications [19,20]. The properties of the developed nanocomposite coating as measured are listed in Table 1 [19].

2.3. Deposition of DLC coatings on the steel samples

Tetrahedral amorphous carbon, taC (nonhydrogenated DLC) film was deposited onto steel substrates by Filtered Cathodic Vacuum Arc (FCVA) technology (Nanofilm Technologies International Pte. Ltd., Singapore) and the detailed deposition procedure can be found in Tay et al. [21]. The thickness of DLC film is in the range of 1–2 μm and hardness is 3000–5000 Vickers, as provided by the supplier.

2.4. Surface characterization and analysis

Surface roughness and the profile of the wear track of the pristine polymer and the nanocomposite coatings were measured using the Wyko NT1100 Optical profiler (Veeco, USA). The scan area used was 300 μm × 230 μm. The surface morphology of the coatings and the wear tracks were studied using Field Emission Scanning Electron Microscopy (FESEM). Prior to FESEM imaging, the samples were gold coated at 10 mA for 40 s using a JEOL, JFC1200 Fine Coater. X-ray diffraction of the film was conducted to determine the crystallinity and any possible degradation of the coating due to the addition of SWCNTs. XRD was carried out using Cu Kα ($\lambda = 1.542 \text{ \AA}$) radiation in a Shimadzu XRD 6000 X-ray diffractometer operating at 40 kV and 20 mA.

2.5. Tribological characterization

Friction and wear experiments were performed at elevated temperatures under dry and lubricated conditions. A custom built plate on cylinder tribometer simulating a line contact was used to conduct experiments at room temperature and elevated temperatures (up to 120 °C). Fig. 1(a) shows the experimental setup used to conduct the wear tests. The coated shaft is mounted onto an AC motor where a speed controller drives the cylindrical shaft at variable speeds. The loading weights are used to transmit a normal force onto the flat plate pivoted at one end of the cantilever arm. The strain gauges attached to the cantilever beam, measure the frictional force which is determined by the cantilever beam deflection during frictional loading. The output voltage is transmitted to a digital data logger. The transmitted data (frictional force) is displayed graphically as a function of frequency onto a computer with the aid of software (PCD Reader). The sliding conditions were maintained constant at a normal load of 60 N and a rotational speed of 54 rpm (linear speed = 0.11 ms^{-1}), as this set of conditions provided boundary lubrication

regime for the liquid lubricated tests as revealed by plotting Stribeck curve [20]. To evaluate the nanocomposite coating at elevated temperatures, the counterface flat steel plate is heated using a cartridge heater as shown in Fig. 1(b). A feedback loop system is used to monitor the temperature at the point of contact by inserting a thermocouple in the flat plate as shown in Fig. 1(b). The variation in the temperature obtained at the contact surface was less than ± 5 °C. Care was taken to insulate the flat counterface plate properly to decrease the heat losses and also to prevent any damage to the strain gauges. For the tests under base oil lubrication, an oil reservoir as shown in Fig. 1(c) is used. A constant flow of oil is ensured in the contact region depending upon the rotational speed and the normal load. A thermocouple is also used to monitor the temperature of the oil bath during the experiment. The coefficients of friction and the wear lives of the nanocomposite UHMWPE coatings under dry and lubricated conditions at room and elevated temperatures were recorded.

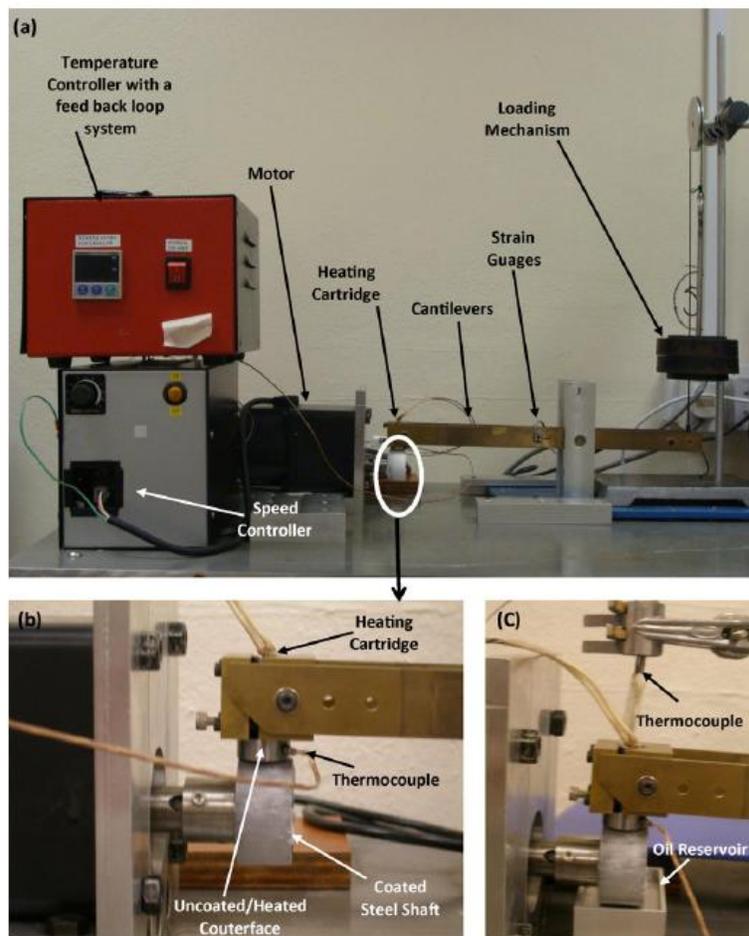


Fig. 1. (a) Different components of the experimental setup. (b) Setup for dry wear tests at room and elevated temperatures. (c) Setup for lubricated wear tests at room and elevated temperatures.

3. Results and discussions

3.1. Effect of PFPE overcoat on the tribological properties of the nanocomposite coating under dry conditions at room temperature

Wear tests were conducted at a normal load of 60N and a rotational speed of 54rpm (linear speed = 0.11ms^{-1}) under dry conditions to evaluate the tribological performance of the nanocomposite coating with and without an overcoat of PFPE. As mentioned earlier, PFPE is very thermally stable lubricant which is effective in reducing the coefficient of friction and increasing the wear life of components [3,10,11]. Fig. 2(a)–(c) shows the surface morphology of the wear track region and the nonworn region for the PFPE coated nanocomposite coating, as obtained from the optical profilometer after a test duration of 100 h. It can be clearly observed from the 2D profile [Fig. 2(a)] of the sample that the nanocomposite coating with the PFPE overcoat has just been smoothed out without any trace of wear. No trace of wear was observed on the counterface flat plate. Moreover, the overcoat of PFPE reduced the coefficient of friction of the nanocomposite coating from 0.14 to 0.09 as shown in Fig. 2(e). It was observed earlier that the addition of CNTs to the UHMWPE polymer film resulted in an improvement of its mechanical and thermal properties with a slight increase in the coefficient of friction [15,19]. However, adding an overcoat of PFPE on the nanocomposite coating resulted in a reduction in the coefficient of friction which in turn has increased the wear life and even the thermal stability of the nanocomposite coating.

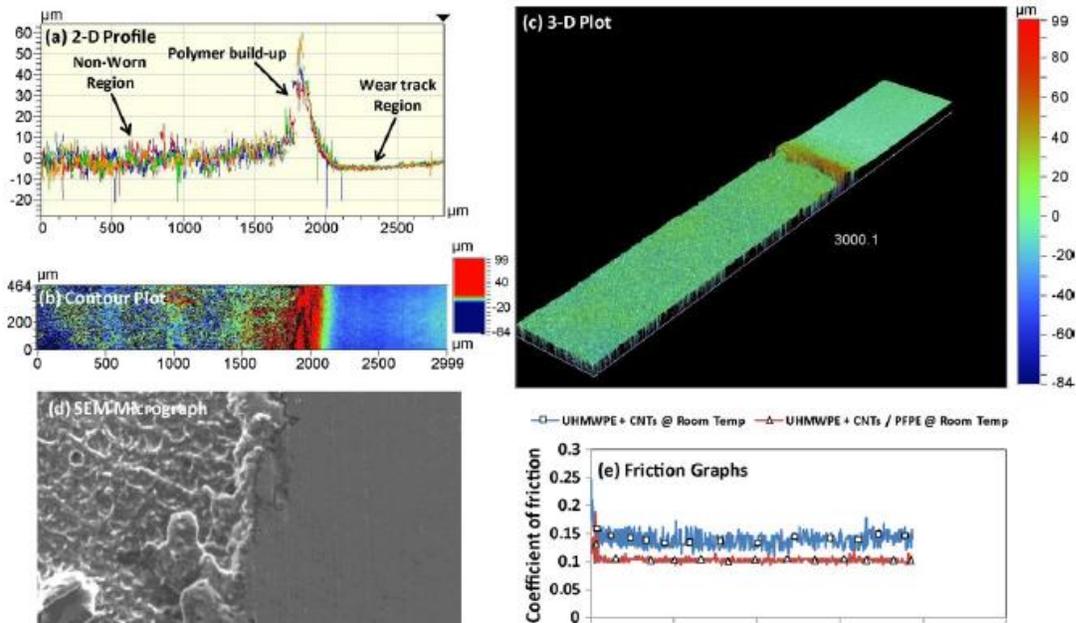


Fig. 2. (a)–(c) 2D profile, contour plot and the 3D profile of the coating across the wear track and the non-worn regions of the cylindrical shaft coated with the nanocomposite coating and an overcoat of PFPE. (d) SEM image of the surface morphology of the worn and the non-worn regions across the interface. (e) Typical frictional graphs for the nanocomposite coating with and without the PFPE overcoat at a normal load of 60N and a linear speed of 0.11 m s^{-1} under dry conditions.

3.2. Performance of the nanocomposite coating at elevated temperatures under dry conditions

Friction and wear experiments were carried out on the custombuilt tribometer at temperatures of 80 °C and 120 °C to evaluate the performance of the nanocomposite coating with and without the overcoat of PFPE at high temperatures. The experiments were conducted at a normal load of 60N and a rotational speed of 54rpm (linear speed = 0.11ms⁻¹). All the tests at elevated temperatures were run for a fixed duration of 50 h. Fig. 3 shows a comparison of typical frictional graphs of the nanocomposite coatings at different temperatures with the inset table showing the average coefficient of friction value for each case. It can be observed that for the nanocomposite coating without the PFPE overcoat, the coefficient of friction reduces significantly from 0.14 to 0.07 with an increase in temperature. This can be attributed to the softening of the polymer matrix due to the rise in temperature. However, in the case of the nanocomposite coating with an overcoat of PFPE, the reduction in the coefficient of friction is not very significant from a value of 0.09 to 0.08 when the temperature is raised from room temperature to 120 °C. This could be because of the thermal stability of the PFPE overcoat and the fact that the coefficient of friction was already low in the presence of PFPE.

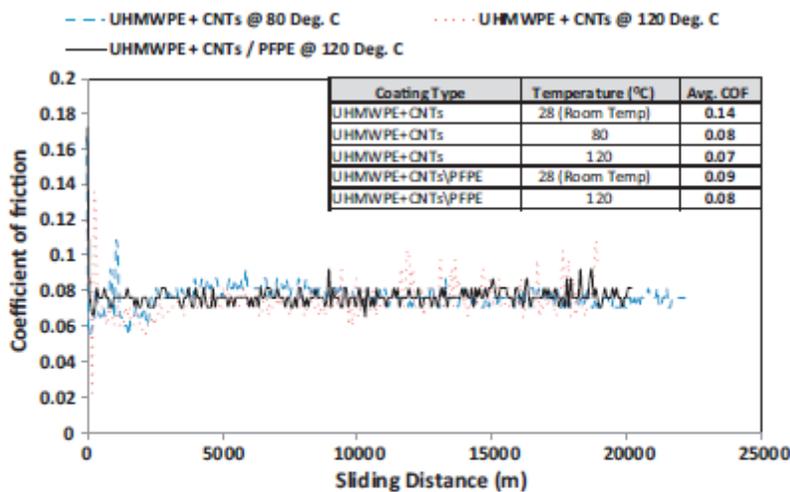


Fig. 3. A comparison of typical frictional graphs of the nanocomposite coatings with or without the PFPE overcoat at different temperatures with the inset table showing the average coefficient of friction values for each case for a normal load of 60 N and a linear speed of 0.11 m s⁻¹ under dry conditions.

Fig. 4(a) and (b) shows the FESEM micrographs for the nanocomposite coating without the PFPE overcoat for the experiment run at 80 °C and 120 °C, respectively. It can be observed that even though the nanocomposite film has not failed even after 50 h of test at 120 °C, as evident from the EDX spectrum, there is a change in the surface morphology of the wear track. We can observe that at 120 °C, the polymer has started to flow due to some plastic deformation resulting in an increase in the roughness of the wear track region. However, no significant change in the thickness of the film was observed even after running the test for 50 h at 120 °C. This improved performance of the nanocomposite coating at elevated temperatures can be attributed to the CNTs reinforcement to the polymer matrix which resulted in enhanced mechanical and thermal properties [19].

Fig. 5(a) shows the FESEM micrograph for the behaviour of the nanocomposite film with an overcoat of PFPE after a 50 h test run at 120 °C. Fig. 5(b) shows the 2D profile across the nonworn region and the wear track region. It can be seen that in this case the polymer buildup at the interface was very minimal and the surface morphology in the wear track region is not as rough as the one compared to that of the nanocomposite film without the PFPE overcoat. This can be attributed to the excellent thermal stability of the PFPE overcoat coupled with the enhanced thermal properties of the nanocomposite film due to the CNT reinforcements.

Fig. 6(a)–(c) shows the 2D profile of the counterface steel flat plate for the wear tests of the nanocomposite coating without the PFPE overcoat at 80 °C [Fig. 6(a)], at 120 °C [Fig. 6(b)] and that of the nanocomposite coating with an overcoat of PFPE at 120 °C [Fig. 6(c)]. As evident from the photographs of the flat plate (inset), no wear was observed on the counterface flat plate in all the three cases except that polymer transfer was seen in the case of wear tests that were conducted at 120 °C. Moreover the amount of polymer transfer in the case of the nanocomposite coating with an overcoat of PFPE was less when compared to that of without the PFPE overcoat. This suggests that the addition of a PFPE overcoat results in a better thermal stability of the nanocomposite coating.

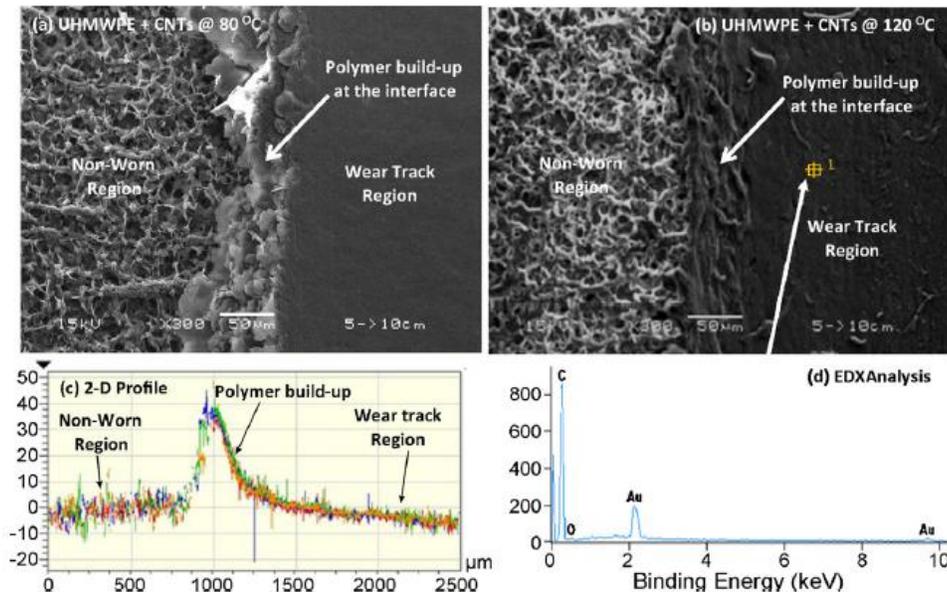


Fig. 4. (a) SEM micrograph after the test for the nanocomposite coating without the PFPE overcoat at 80 °C. (b) SEM micrograph after the test for the nanocomposite coating without the PFPE overcoat at 120 °C. (c) 2D profile of the worn and the non-worn regions across the interface for the nanocomposite coating without the PFPE overcoat at 80 °C. (d) EDX spectrum on the wear track for the nanocomposite coating without the PFPE overcoat at 120 °C. The experiments were conducted at a normal load of 60 N and a linear speed of 0.11 m s^{-1} under dry conditions for 50 h.

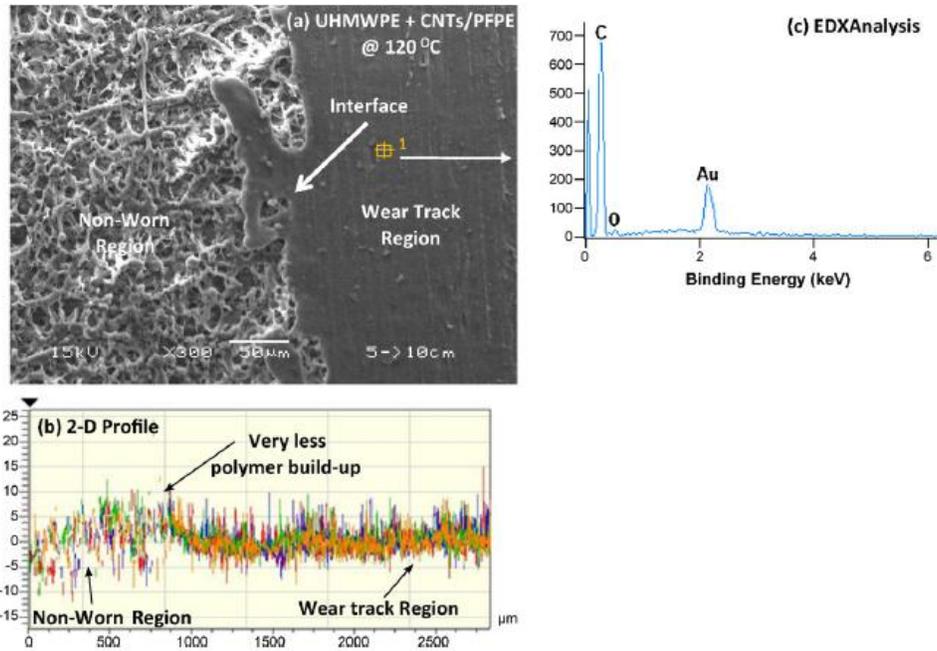


Fig. 5. (a) SEM micrograph after the test for the nanocomposite coating with an overcoat of PFPE at 120 °C. (b) 2D profile of the worn and the non-worn regions of the nanocomposite coating with an overcoat of PFPE after 50 h of test conducted at 120 °C. (c) EDX spectrum on the wear track region of the nanocomposite coating with an overcoat of PFPE. The experiments were conducted at a normal load of 60 N and a linear speed of 0.11 m s^{-1} under dry conditions for 50 h.

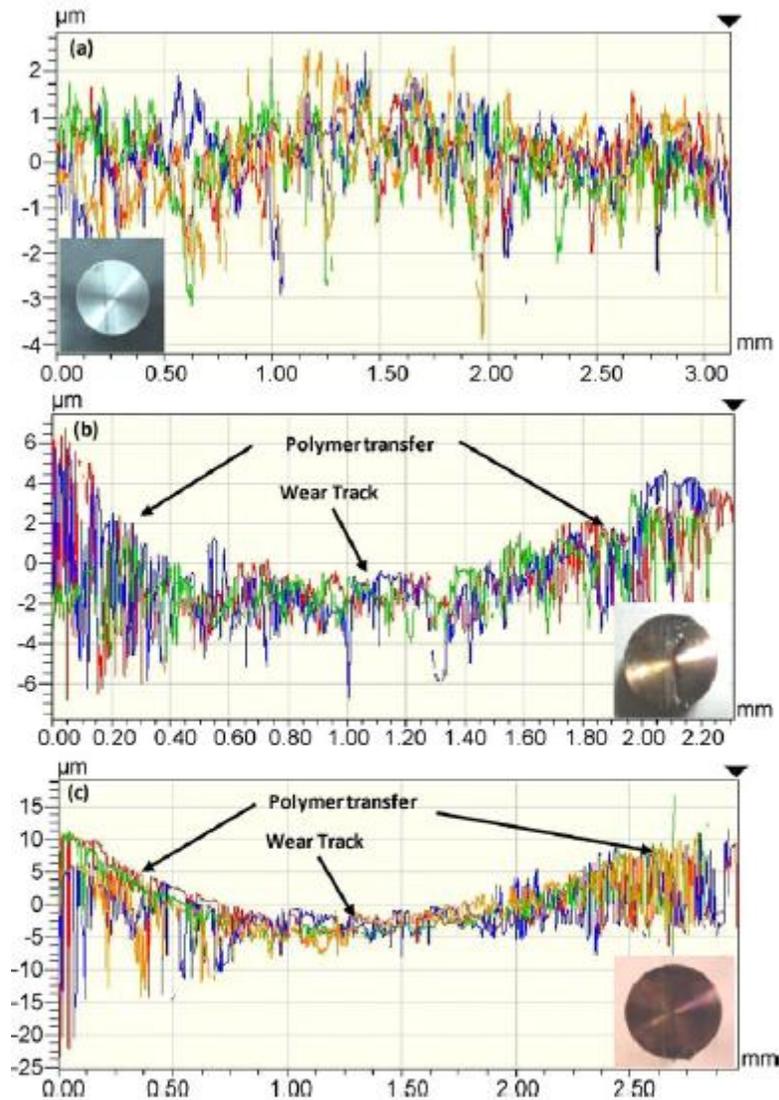


Fig. 6. 2D profile and inset – a photograph of the countersurface after the test for (a) nanocomposite coating without PFPE overcoat at 80°C. (b) nanocomposite coating without PFPE overcoat at 120°C. (c) nanocomposite coating with PFPE overcoat at 120°C. The experiments were conducted at a normal load of 60 N and a linear speed of 0.11 m s^{-1} under dry conditions for 50 h.

3.3. Effect of temperature on the crystallinity of the nanocomposite coating

To investigate the effect of temperature on the crystallinity of UHMWPE, X-ray diffraction test (XRD) was conducted on the nanocomposite coating without the overcoat of PFPE. XRD was conducted on the wear track after the test of 50 h duration at a load of 60 N and a rotational speed of 54 rpm to observe the effects of temperature on the crystallinity of the coating. Fig. 7 shows the XRD patterns obtained for the UHMWPE films at different temperatures. The diffraction peaks obtained at 21.6° , 24° and 44.01° of 2θ are assigned to the (1 1 0), (2 0 0) and (2 2 0) crystal planes of polyethylene [25]. The XRD patterns of the nanocomposite film have another diffraction peak at about 26.3° of 2θ , which is a signature of (0 0 2) crystal plane of carbon. The crystallinity of the films was computed by using XRD 600 computer software. It can be observed

from Fig. 7(inset) that the temperature did not affect the crystallinity of the film significantly. This is also evident from the fact that there was no obvious shift in the positions of the diffraction peaks at 2θ values of (1 1 0), (2 0 0) and (2 2 0) polyethylene crystal planes with the change in temperature.

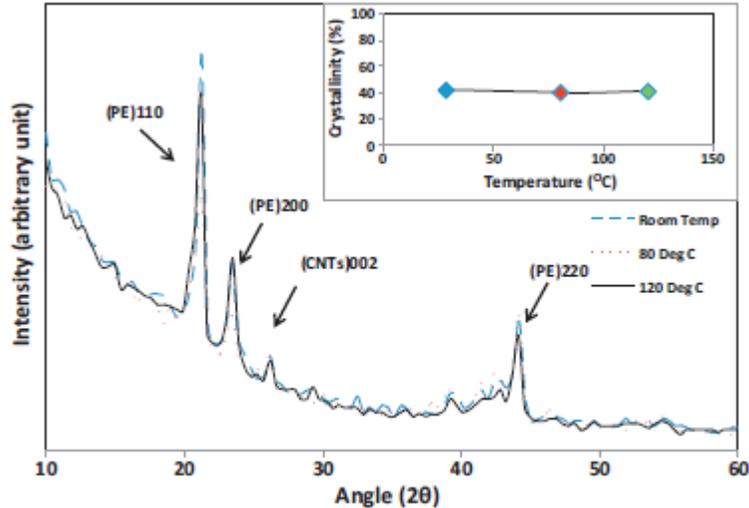


Fig. 7. XRD spectrums obtained for the nanocomposite coatings after the test at various elevated temperatures for 50 h.

3.4. Performance of the nanocomposite coating at elevated temperatures under base oil lubricated conditions

Fig. 8 shows typical frictional graphs for the nanocomposite coating with an overcoat of PFPE under base oil lubricated conditions. It is observed that the nanocomposite coating performed well under a temperature of 80 °C. The quality of the oil was unchanged without any debris particles as shown in Fig. 8(c) for both the cases, i.e. at room temperature and at 80 °C. No polymer transfer and wear was observed on the counterface after the test. Fig. 8(d) shows the counterface surface after the test conducted at room temperature. However, with a rise in temperature to approximately 105 °C a considerable softening of the nanocomposite coating is observed in the beginning. It may be due to the rise in temperature coupled with the diffusion of the base oil into the top rough part of the coating resulting in a significant drop in the coefficient of friction as can be seen from Fig. 8. However, the test was continued for another 50 h after removing this mobile top layer of the nanocomposite coating and changing the base oil. It was observed that the nanocomposite coating performed well without failing until 50 h as can be seen from the frictional graph of Fig. 8. Thus, a possible reason for this phenomenon would be that at elevated temperatures due to the diffusion of the base oil into the coating the top layer of the polymer gets softened considerably resulting in its peeling off of the top mobile layer. However, when this top layer is physically removed and the experiment is again restarted with a fresh supply of base oil, the film lasted for another 50 h without any failure. This initial softening of the top layer does not harm the coating wear performance in any way and may be considered as the running in event for this case.

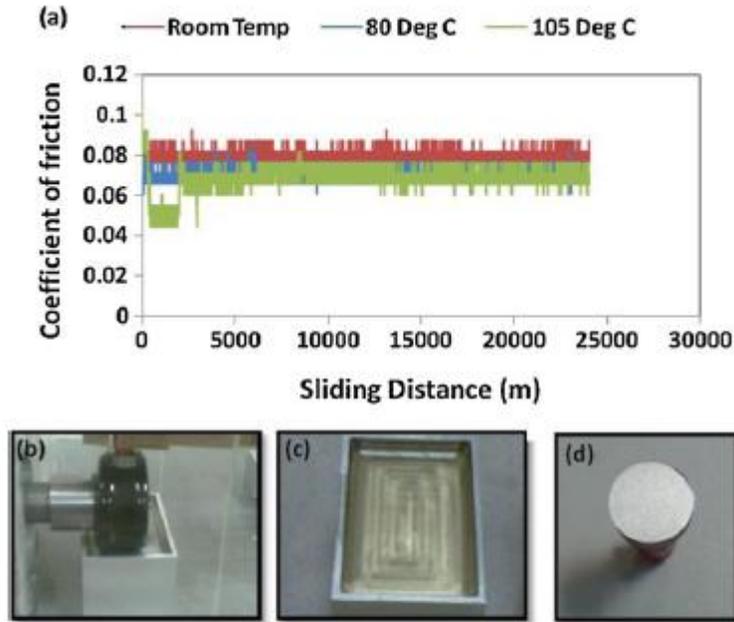


Fig. 8. (a) Comparison of typical frictional graphs for the nanocoatings with PFPE overcoat at room temperature, 80 °C and 105 °C, respectively under base oil lubricated conditions at a normal load of 60 N and a linear speed of 0.11 m s^{-1} after 50 h. (b) A photograph of the lubricated test at room temperature. (c) Quality of the oil after the test at room temperature. (d) The counterface surface after the lubricated test conducted at room temperature.

3.5. Comparison of the nanocomposite coating with the DLC coatings in dry and lubricated conditions

Friction and wear experiments were conducted with the cylindrical shafts coated with DLC coatings. Tests were carried out under dry and base oil lubricated conditions. The counterface used is the bare AISI52100 bearing steel flat plate. Fig. 9(a) shows the comparison of the typical frictional graphs for the DLC coating and the nanocomposite coating with an overcoat of PFPE at room temperature in dry conditions, under a normal load of 60N and a linear speed of 0.11 ms^{-1} . The nanocomposite coating with the PFPE overcoat showed lower coefficient of friction of 0.09 when compared to that of 0.15 for the DLC coating. This can be attributed to the lubricious nature of the UHMWPE and PFPE combine. No significant wear was observed on both the nanocomposite films and the DLC films. However, a considerable amount of wear was observed on the counterface flat plate when it is slid against the DLC coating when compared to that when slid against the nanocomposite coating. Fig. 9(b) and (c) represents the 3D plots of the wear groove formed on the flat steel plate when slid against the DLC and the nanocomposite coatings, respectively. This again can be attributed to the excellent tribological properties of the nanocomposite coating and the PFPE overcoat. UHMWPE based coating is relatively softer than the counterface and hence is able to protect both the substrate and the counterface.

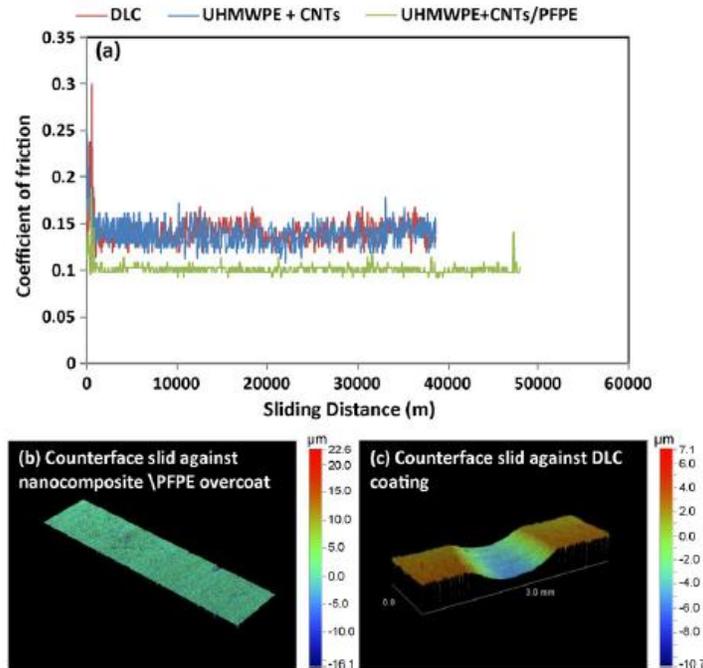


Fig. 9. (a) Comparison of typical frictional graphs for the nanocoatings with and without the PFPE overcoat and DLC coatings under dry conditions at room temperature. (b) 3D plot of the counterface surface when slid against the nanocomposite coating with PFPE overcoat. (c) 3D plot of the counterface surface when slid against the DLC coating.

Under the base oil lubricated conditions also, the same phenomenon is observed. Fig. 10(a) shows the comparison of typical frictional graphs obtained for the nanocomposite coating with an overcoat of PFPE and the DLC coatings under the base oil lubricated conditions. The DLC coating showed a higher coefficient of friction value of 0.09 when compared to that of the nanocomposite coating with the PFPE overcoat which showed a coefficient of friction value of 0.07. Fig. 10(b) and (c) shows the photographs of the flat plate counterface after a test of 100 h under the base oil lubricated conditions at a load of 60N and a speed of 0.11 m/s when slid against the DLC and the nanocomposite coating, respectively. The wear scar is very clearly seen on the counterface plate when slid against the DLC coating, whereas no wear was observed for the plate slid against the nanocomposite coating. This can be attributed to the excellent lubricious nature of the UHMWPE coating.

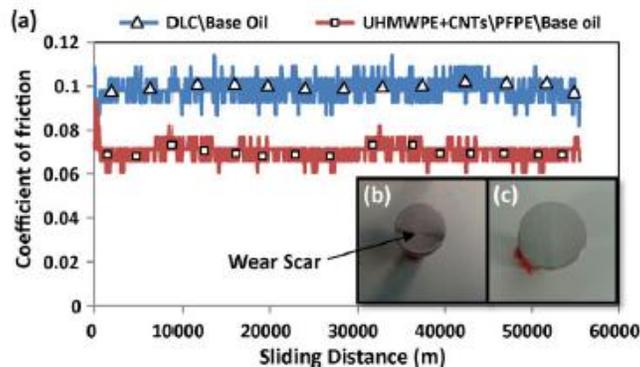


Fig. 10. (a) Comparison of typical frictional graphs for the nanocomposite coating with the PFPE overcoat and DLC coatings under base oil lubricated conditions at room temperature. (b) Photograph of the counterface flat plate after sliding against the DLC coating for 100 h under base oil lubricated conditions. (c) Photograph of the counterface flat plate after sliding against the nanocomposite coating for 100 h under base oil lubricated conditions.

4. Conclusions

The following conclusions can be drawn from this study:

- The PFPE overcoat on the UHMWPECNT nanocomposite coating is very effective in reducing the coefficient of friction from 0.14 to 0.09 under dry conditions.
- The nanocomposite coating with or without the PFPE overcoat performed extremely well at elevated temperatures of 80 °C and 120 °C, respectively at a load of 60N and a linear speed of 0.11ms^{-1} , under dry conditions for 50 h without failure (number of cycles of rotation = 150,000).
- Under the base oil lubricated conditions the nanocomposite coating with the overcoat of PFPE performed well at 80 °C for 50 h. However, at 105 °C considerable softening of the top layer of the coating is observed during the running in. The coating performed well up to 50 h after the initial softened layer was physically removed and the oil was changed.
- The nanocomposite coating can be effectively used as a boundary lubricant at elevated temperatures up to 105 °C in tribological applications such as bearings and gears where base oil is used as the lubricant.
- The nanocomposite coating showed excellent performance when compared to that of the DLC coatings, especially in terms of low coefficient of friction and nearly no wear of the coating, substrate or the counterface materials.

Acknowledgements

This study was funded by a research grant from the Faculty of Engineering, NUS (Grant#R265000248112). We also wish to thank Mr. K.C. Chung, Ticona Representative Office, Singapore, for donating UHMWPE powder for this study. One of the authors (M. Abdul Samad) would like to acknowledge the Graduate School of Engineering, NUS for the scholarship awarded to support his studies at NUS.

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