High performance nanocomposites for tribological applications: Preparation and characterization

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Abstract

High performance nanocomposites were prepared by incorporating 0–12 vol.% nano-sized (39 nm) Al\textsubscript{2}O\textsubscript{3} particles into PEEK matrix using compression molding. The microhardness and dynamic mechanical properties of the nanocomposites increase with increasing Al\textsubscript{2}O\textsubscript{3} content. The wear resistance of the nanocomposites evaluated at a sliding speed of 1.0 m/s and nominal pressure from 0.5 MPa to 1.25 MPa under dry sliding conditions was improved more than threefold at 0.8 vol.% Al\textsubscript{2}O\textsubscript{3} content. However, the wear resistance of the nanocomposites containing above 1.67 vol.% Al\textsubscript{2}O\textsubscript{3} was deteriorated, despite their higher hardness and stiffness as compared to that of nanocomposites containing lower Al\textsubscript{2}O\textsubscript{3} content. The surface roughness of the wear track formed over the countersurface increases with increasing Al\textsubscript{2}O\textsubscript{3} content. The coefficient of friction of nanocomposites was higher than that of pure PEEK. SEM and optical microscopy have shown that wear of pure PEEK occurs by the mechanism of adhesion mainly, whereas of nanocomposites by microploughing and abrasion. Energy dispersive spectrometry (EDS) shows that Fe and alloying elements of countersurface transfer to the wear debris at higher Al\textsubscript{2}O\textsubscript{3} content.

Keywords: Nanocomposites; Microhardness; Stiffness; Wear; Friction; PEEK; Al\textsubscript{2}O\textsubscript{3}

1. Introduction

High performance semi-crystalline poly(ether–ether–ketone), hitherto referred to as PEEK, has been widely used in many applications due to its excellent thermal, mechanical, chemical and electrical properties. It is an attractive material for journal bearings and piston rings under various loading conditions as it is comparatively fatigue resistance and exhibits a low creep rate up to about 250°C [1–5]. Despite its low coefficient of friction, its wear rate often limits its utilization in tribological systems. The specific wear rate of PEEK was reported more than 10\textsuperscript{−6} mm\textsuperscript{3}/N m, which appear to be too large to be used as a rubbing surface material in machinery [6]. However, its wear resistance (inverse of wear rate) can be significantly improved by incorporating fibers such as carbon fiber [4], carbon nano-fibers [5], short carbon fibers [7] and particles such as CuS [8], Si\textsubscript{3}N\textsubscript{4} [9], SiO\textsubscript{2} [10], SiC [11], and ZrO\textsubscript{2} [12]. The improvement in wear resistance was attributed to the smoothing of the countersurface and the developing of a transfer film, which results in reduced ability for ploughing, tearing, and other non-adhesive components of wear.

Though, the incorporating of particles into polymers improved hardness and storage modulus (stiffness), which in turn result in improved wear resistance. However, the hardness and stiffness are not only the factors controlling the wear behavior, but also the nature and stability of the transfer film and its adhesion to the countersurface affects the wear properties [13,14]. The incorporating of Al\textsubscript{2}O\textsubscript{3} [15] and ZnO [16] nanoparticles into PTFE have improved wear resistance of PTFE by more than two orders of magnitude. However, addition of ZnO and SiC particles to polyphenylene sulphide deteriorated its wear resistance due to the poor adhesion of the transfer film with the countersurface [14]. This may be due to the fact that the wear resistance significantly depends on many factors such as dispersion state, size, volume fraction, and type of nano-sized...
particles, surface roughness of countersurface, and crystallinity of the polymers [13,17,18].

Recently, we have demonstrated the improvement in thermal, dynamic mechanical, and wear properties of PEEK by incorporating micron size Al$_2$O$_3$ particles [1,2,19]. The dynamic mechanical properties of PEEK composites have been found to increase with increasing Al$_2$O$_3$ [2] or AlN [20] particles both below and above the glass transition temperature of PEEK. Moreover, Al$_2$O$_3$ has been widely used to improve wear resistance of other polymers [13,15,18]. Qiao et al. [21] have studied the wear and friction behavior of 5 wt% nano- or submicron sized surface-treated Al$_2$O$_3$ particles filled PEEK by block-on-ring machine. Nevertheless, wear properties of nanocomposites depends upon particle’s shape, size, volume fraction and its adhesion with the matrix. In view of above, PEEK matrix nanocomposites was fabricated by incorporating nano-size (39 nm) Al$_2$O$_3$ particles ranging from 0 vol.% to 12 vol.% (30 wt%). The microhardness, dynamic mechanical (storage modulus), wear and friction properties were evaluated using Vickers microhardness, dynamic mechanical analyzer and pin-on-disk wear tester, respectively.

2. Experimental

2.1. Materials

A commercial PEEK (grade 5300PF) donated by Gharda Chemicals Ltd., Panoli, Gujarat, India under the trade name GATONETM PEEK was used as matrix in the present study. The nano-sized Al$_2$O$_3$ purchased from Aldrich Chemical Company was used as reinforcement without surface treatment. The reported average particle size and surface area of Al$_2$O$_3$ is 39 nm and 43 m$^2$/g, respectively. An ethanol from Merck was used for homogenizing the Al$_2$O$_3$ and PEEK mixture. The mean particle size of the PEEK powder is 25 $\mu$m. The scanning electron microscopy (SEM) micrographs of PEEK and Al$_2$O$_3$ powder are shown in Fig. 1. PEEK and Al$_2$O$_3$ powders have irregular rod-like and spherical-shaped particles, respectively.

2.2. Preparation

PEEK nanocomposites incorporating 0–12 vol.% Al$_2$O$_3$ were fabricated using the method, with slight change, described in our previous paper [1]. Dried powder of Al$_2$O$_3$ was suspended in an ethanol under ultrasonic bath for 60 min. The Al$_2$O$_3$/ethanol solution was mixed in PEEK/ethanol solution through magnetic stirring at 2000 rpm stirring rate in concurrence with heating. The resultant powder was dried in an oven at 120 $^\circ$C to remove the ethanol. The pure PEEK and its nanocomposites were prepared by using a laboratory compression molding (hot press) machine under a pressure of 15 MPa at 350 $^\circ$C. The nanocomposite samples were coded by AON–X, where AON and X are the nano-size Al$_2$O$_3$ and wt% of Al$_2$O$_3$ in PEEK matrix, respectively. Fig. 2 shows the SEM of 1.67 vol.% (5 wt%) Al$_2$O$_3$ particles filled PEEK. It can be seen that Al$_2$O$_3$ particles were not completely dispersed as isolated primary

\[ \text{Al}_2\text{O}_3 \] particles, and in some regions there were Al$_2$O$_3$ aggregates in the PEEK matrix. The nonuniform dispersion of Al$_2$O$_3$ in PEEK matrix might be attributed to the large specific area and high surface energy.

![Fig. 1. SEM of (a) PEEK powder (scale bar: 10 $\mu$m), (b) nano-Al$_2$O$_3$ powder (scale bar: 2 $\mu$m) with inset showing TEM image (scale bar: 200 nm).](image1)

![Fig. 2. SEM of AON-5 nanocomposite after 2 min etching (scale bar: 10 $\mu$m).](image2)
2.3 Characterization

Theoretical density of the nanocomposites was calculated by rule of mixture using the density of $\text{Al}_2\text{O}_3$ 4.00 g/cm$^3$ and of PEEK 1.29 g/cm$^3$ for 20\% crystalline powder. Experimental density of the nanocomposites was measured by Archimedes method. The relative density is the ratio of the experimental density to the theoretical density.

Microhardness test (Model: DVK-2S, Matsuzawa Seiki Co. Ltd., Tokyo) with a Vickers diamond pyramidal indenter was used to determine the microhardness of nanocomposites under a constant load of 100 g and a dwell time of 15 s. The average of the three hardness readings was reported as the microhardness of the samples.

The dynamic mechanical tests were carried out in the three-point bending mode using a Perkin-Elmer DMA 7e dynamic mechanical analyzer from 30°C to 250°C at a heating rate of 5°C/min and a frequency of 1 Hz. The specimen platform has a span length of 15 mm. The bending aspect ratio, i.e. ratio of span length to sample thickness, of samples was about 15. The test was carried out in argon atmosphere under static load of 110 mN and a dynamic load of 100 mN. Before starting the cycle, the samples were held for 5 min at 30°C to stabilize the position of the knife.

Wear rate and coefficient of friction were conducted on a pin-on-disk wear tester at a sliding speed of 1.0 m/s and nominal pressure of 0.5–1.25 MPa. The tests were conducted for a total sliding distance of 9 km, which were divided into three stages with 3 km each cycle. The EN-24 steel (C 0.4\%, Si 0.2\%, Mn 0.6\%, Ni 1.5\%, Cr 1.2\%, Mo 0.3\% and Fe bal.) disk of diameter 76.48 mm and 5 mm thick was used as a countersurface. It was heat treated to harden to $R_c$: 50–52. The disk surface was abraded with waterproof SiC paper to a surface roughness of $R=0.06$ μm. The surface of the countersurface and pin was cleaned thoroughly with cotton dipped in acetone. The test was performed under a 48±2 relative humidity and 30°C condition. The dimensionless wear rate of the samples can be given by the following equation:

$$\bar{h} = \bar{W}k = f \left( \frac{\rho}{H} \right)$$

where $h$ is the height of the sample removed, $s$ the sliding distance, $H$ the hardness of the softer material, and $p$ is the nominal pressure. The $f$ is called the coefficient of wear or wear factor, and it expresses the probability of forming wear particles. The $f$ value can only be determined by experimentally. It can be seen from Eq. (1) that the relationship between the height loss per unit sliding distance and nominal pressure is linear. Therefore, specific wear rate ($W_s$) can be determined by the slope of the line between the $h/s$ and $p$. The composite pin height losses were measured by measuring height to an accuracy of 1 μm. The height loss versus nominal pressure was plotted for each composite. Thus, the specific wear rate was obtained from the slope of the graph between the wear rate (μm/km) and nominal pressure. In order to investigate the role of transfer film on wear rate, the specific wear rate of mild steel was also determined under the similar test conditions.

Scanning electron microscopy (SEM) (Philips XL-30) was used to examine the worn surface of the composite pins and wear debris. SEM was also used to examine the morphology of PEEK powder, $\text{Al}_2\text{O}_3$ powder, and AON-5 nanocomposite samples. For examining the $\text{Al}_2\text{O}_3$ particles distribution in AON-5, sample was etched for 2 min in a 2\% (w/v) solution of potassium permanganate in a mixture of four volumes of orthophosphoric acid and one volume of water. All samples were coated with a thin layer of gold to make them electrically conductive prior to examining on SEM. Energy dispersive spectrometry (EDS) was used to test the elemental composition of the wear debris of the nanocomposites. The transfer films formed between the pin and countersurface were examined by optical microscopy (Nikon).

3. Results and discussions

3.1 Density

Table 1 shows theoretical and experimental density of the PEEK/$\text{Al}_2\text{O}_3$ nanocomposites. The experimental density of the nanocomposites is slightly higher than that of theoretical density below 12 vol.% $\text{Al}_2\text{O}_3$ reinforced PEEK, which may be attributed to porosity-free samples and slightly increased crystallinity of PEEK as a result of nucleating effect of $\text{Al}_2\text{O}_3$ [22]. However, the experimental density of the PEEK containing 12 vol.% $\text{Al}_2\text{O}_3$ is slightly lower than theoretical density. This may be due to the presence of porosity in the sample. As more and more $\text{Al}_2\text{O}_3$ is added into PEEK, inter-particle–particle distance is decreased, which results in aggregation of particles.

<table>
<thead>
<tr>
<th>Sample code</th>
<th>$\text{Al}_2\text{O}_3$ in PEEK by</th>
<th>Theoretical density (g/cm$^3$)</th>
<th>Experimental density (g/cm$^3$)</th>
<th>Relative density (%)</th>
</tr>
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<tr>
<td></td>
<td>Weight (%)</td>
<td>Volume (%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AON-0</td>
<td>0</td>
<td>0</td>
<td>1.290</td>
<td>1.304</td>
</tr>
<tr>
<td>AON-1</td>
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<td>0.41</td>
<td>1.301</td>
<td>1.320</td>
</tr>
<tr>
<td>AON-2</td>
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<td>0.82</td>
<td>1.312</td>
<td>1.329</td>
</tr>
<tr>
<td>AON-5</td>
<td>5.0</td>
<td>1.67</td>
<td>1.335</td>
<td>1.355</td>
</tr>
<tr>
<td>AON-10</td>
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<td>3.46</td>
<td>1.384</td>
<td>1.409</td>
</tr>
<tr>
<td>AON-20</td>
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<td>7.46</td>
<td>1.492</td>
<td>1.504</td>
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<tr>
<td>AON-30</td>
<td>30</td>
<td>12.14</td>
<td>1.619</td>
<td>1.607</td>
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</table>
These aggregates hinder the infiltration of molten PEEK due to its high melt viscosity, hence results in porosity in the PEEK composites containing higher Al₂O₃ particles.

3.2. Microhardness

The microhardness of PEEK/Al₂O₃ nanocomposites as a function of Al₂O₃ content is shown in Fig. 3. The hardness of nanocomposites increases from 24 kg/mm² for the pure PEEK to 33 kg/mm² for AON-30 nanocomposite. This indicates that load carrying capacity of the nanocomposites is improved with increasing Al₂O₃ content. The uniform distribution of Al₂O₃ particles in PEEK matrix, as discussed in SEM section, may result in increase of resistance to indentation of PEEK matrix. Nevertheless, the inter-particle—particle distance decreases with increasing Al₂O₃ content which can resist well the local plastic deformation of the PEEK matrix. Moreover, increase in PEEK crystallinity [1] and higher microhardness of Al₂O₃ (2000 kg/mm²) as compared to pure PEEK might increase the microhardness of the nanocomposites.

3.3. Dynamic mechanical properties

Dynamic mechanical properties are highly sensitive to the structure of materials. Therefore, they were studied from 30 °C to 250 °C at a heating rate of 5 °C/min under argon temperature. Fig. 4 shows the storage modulus as a function of temperature for the PEEK/Al₂O₃ nanocomposites. As expected, the storage modulus increases with increasing Al₂O₃ content in PEEK matrix. The modulus increases due to the high modulus of Al₂O₃ (345 GPa) and from the interface formed between the Al₂O₃ and the matrix. Fig. 5 shows tangent delta as a function of temperature. The glass transition temperature ($T_g$) of PEEK was characterized by the temperature at the peak of tan δ. The $T_g$ decreases by 2–5 °C with increasing Al₂O₃ content. The broadening in tan δ curves of nanocomposites was found. This might be the resultant of two glass transitions, which occurs due to the bulk PEEK matrix and tightly bounded PEEK [23].

3.4. Wear and friction properties

Fig. 6 shows the variation of wear rate of PEEK/Al₂O₃ nanocomposites as a function of nominal pressure. It can be seen that wear rate increases with increasing nominal pressure at con-
stant sliding speed. This may be due to the fact that the increasing load results in plastic deformation of the specimen surface, which makes the transfer film unstable and specimen wears away easily. Hence wear rate increases with increasing nominal pressure. To determine the specific wear rate a linear regression line is fitted to data as shown in Fig. 6. A good fit is achieved between the experimental values with a correlation factor $r = 92–99\%$. The specific wear rates for the mild steel, PEEK and PEEK/Al$_2$O$_3$ nanocomposites are shown in Fig. 7. The specific wear rate of PEEK and mild steel is $9.7 \times 10^{-6} \text{mm}^3/\text{N m}$ and $95 \times 10^{-6} \text{mm}^3/\text{N m}$, respectively under the similar test condition. In other words, the specific wear rate of mild steel is approximately one order of magnitude higher than that of pure PEEK. This is despite much higher Vickers microhardness of mild steel (125 kg/mm$^2$) as compared to that of pure PEEK (24 kg/mm$^2$). It may be due to the poor transfer film of mild steel on the countersurface. This indicates that the transfer film developed during sliding wear has major role compared to sample hardness. Fig. 7 shows that the specific wear rate of nanocomposites reaches to minimum level, i.e., $2.8 \times 10^{-6} \text{mm}^3/\text{N m}$ at 0.82 vol.% Al$_2$O$_3$ (AON-2) content. In other words, the wear rate of AON-2 nanocomposite decreases more than 3-fold and 30-fold as compared to pure PEEK and mild steel, respectively. When the Al$_2$O$_3$ content is 1.67 vol.% or higher, the wear rate increases despite their higher hardness and stiffness than that of nanocomposites containing lower Al$_2$O$_3$ content. But in all cases of nanocomposites, the wear rate remains less than 50% of mild steel. Similar type of trends were investigated for nano-sized ZrO$_2$ filled PEEK [12] and Al$_2$O$_3$ filled poly(phenylene sulphide) (PPS) [13] composites. They investigated that wear rate decreases to a minimum level at an optimum loading, i.e., 2 vol.% Al$_2$O$_3$ or 7.5 wt% ZrO$_2$, while increases on further adding the particles. To understand the wear mechanisms of present system, SEM of the nanocomposites samples is discussed in the next section.

Fig. 8 shows the variation of coefficient of friction of the PEEK/Al$_2$O$_3$ nanocomposites as a function of load. The coefficient of friction for pure PEEK and its nanocomposites decreases with increasing load up to 35 N. Thereafter, no significant change in coefficient of friction was observed with increasing load. The coefficient of friction of all nanocomposites is almost higher than that of pure PEEK. This is similar to the results of PEEK/CuO [8], PPS/Al$_2$O$_3$ [13], PEEK/Al$_2$O$_3$ [21], PEEK/Cu [24], PTFE/Ni [25], and poly(phthalazine ether sulphone ketone)/Al$_2$O$_3$ [26] composites. The higher coefficient of friction of nanocomposites may be attributed to the increased contribution to the deformation component of friction by the hard Al$_2$O$_3$ particles during sliding against the nanocomposites, i.e., microploughing due to the third body abrasion [8,24]. This is verified by the measurement of the surface roughness of the wear track over the countersurface, which increases as the Al$_2$O$_3$ content increases as shown in Table 2. The increase in surface roughness with increasing Al$_2$O$_3$ content indicates that wear mechanism is changed from adhesion wear to abrasion wear [27]. However, the coefficient of friction of nanocomposite containing 12 vol.% Al$_2$O$_3$ (AON-30) is very close to that of pure PEEK at load below 35 N. Moreover, for nanocomposites containing more than 1.67 vol.% Al$_2$O$_3$, the coefficient of friction is lower than that of pure PEEK above 35 N. This may be attributed to the smoothening of the countersurface from abrasion [13]. The smoothening action might decrease bond strength of transfer film with countersurface and thus, the wear debris or film can be easily peeled off during successive sliding [13]. Therefore, wear rate of AON-30 increases to a value higher than that of pure PEEK.

3.5. Optical microscopy study on transfer films

Fig. 9 shows the nature of transfer film formed on the EN-24 steel countersurface due to sliding wear of nanocomposites. Fig. 9(a) shows the as-polished initial surface of

<table>
<thead>
<tr>
<th>Description</th>
<th>Surface roughness</th>
<th>As-polished countersurface</th>
</tr>
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<tbody>
<tr>
<td>Wear track of</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AON-2</td>
<td>0.16</td>
<td></td>
</tr>
<tr>
<td>AON-20</td>
<td>0.26</td>
<td></td>
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</table>
Fig. 9. Optical micrographs of transfer films developed on steel countersurface during sliding wear for (a) as-polished countersurface, (b) AON-0 (PEEK), (c) AON-2, and (d) AON-20. Arrow shows sliding direction. (sliding speed: 1 m/s, sliding distance: 3 km; load: 25 N).

Fig. 10. SEM of worn surfaces of (a) AON-0, (b) AON-2 with inset showing SEM image near to worn sample edge, (c) AON-30, and (d) AON-30 at higher magnification [scale bar: 300 μm (a–c) and 50 μm (d)] (sliding speed: 1 m/s; sliding distance: 3 km; load: 25 N).
the countersurface. Fig. 9(b)–(d) shows the transfer films developed after 3 km sliding by AON-0 (PEEK), AON-2, and AON-20 nanocomposites, respectively. Fig. 9(b) shows that pure PEEK forms a continuous transfer film, which covers trough and asperities of the countersurface effectively. In the case of AON-2 nanocomposite, formation of a thin, tenacious and uniform transfer film occurs as shown in Fig. 9(c). This contributes to a significant decrease in specific wear rate of PEEK. However, in case of AON-20 nanocomposite, there was hardly any development of transfer film on the countersurface as shown in Fig. 9(d). In addition, some grooves could be observed on the countersurface. This might be due to the poor bond strength of transfer film with countersurface [13]. Moreover, much higher hardness of Al₂O₃ than countersurface results in abrasive action or uncovered asperities on the countersurface. It is well known that at higher ceramic particle loading particle–particle interaction occurs, which results in aggregation of particles. The resultant ceramic aggregates hinder the formation of a continuous transfer film and results in dramatic increase in wear rate of corresponding composites.

3.6. SEM study on worn surfaces and wear debris

The SEM micrographs of the worn surfaces of the pure PEEK and its nanocomposites are shown in Fig. 10. The pure PEEK shows sign of adhesive wear as shown in Fig. 10(a), which may be due to the removal of flaky or lamellae like debris. This shows that adhesion is the dominant wear mechanism for pure PEEK. In contrast, Fig. 10(b) shows that adhesive wear is almost abated. This is verified by a uniform and tenacious transfer film formed on the countersurface as shown in Fig. 9(c). The inset of Fig. 10(b) shows the SEM image taken near to the edge of wear scar. It shows fine wear debris on the worn surface of AON-2 nanocomposite. In contrast, Fig. 10(c) and (d) shows the worn surface of AON-30 indicates minor adhesive wear with sign of microploughing. The microploughing might be due to the presence of wear debris in between nanocomposite pin and countersurface as shown in Fig. 10(d). It can be seen from Fig. 10(d) that wear debris of AON-30 consists of sharp-edged particles, which causes microploughing. Hence, the wear rate of nanocomposites was increased at higher Al₂O₃ content.

Fig. 11. SEM of wear debris of (a) mild steel, (b) AON-0, (c) AON-2, (d) AON-10 and (e) AON-30 [scale bar: 100 μm (a–e) and 50 μm (f)] (sliding speed: 1 m/s; sliding distance: 3 km; load: 25 N).
Fig. 11 shows the SEM micrographs of the wear debris of the mild steel, AON-0, AON-2, AON-10, and AON-30 nanocomposite samples. It can be seen from Fig. 11(a) that the size of wear debris generated by mild steel is from few microns to more than 50 μm. Its wear debris has sharp edges, which results in much higher wear rate as compared to pure PEEK and its nanocomposites. The pure PEEK transfers lumpy and flaky or lamellae-like debris of more than 100 μm sized as shown in Fig. 11(b), which may be contributed to the relatively higher wear rate than that of AON-2 nanocomposite. Fig. 11(c)–(e) shows that the size of AON-2, AON-10 and AON-30 wear debris, respectively, decreases (less than 100 μm) with increasing Al2O3 content. Despite lowest debris size among PEEK nanocomposites, AON-30 has shown wear rate even higher than that of pure PEEK. It indicates that wear debris size cannot be correlated with the wear rate of nanocomposites. It is interesting to see from Fig. 11(c) that wear debris of AON-2 are relatively packed in a preferable plane than that of pure PEEK and other nanocomposites. The preferable packing of wear debris might also be the reason of lowest wear rate for AON-2.

3.7. Energy dispersive spectrometry (EDS)

Fig. 12 shows the EDS spectrum on wear debris of AON-30 sample. The EDS spectrum shows presence of Al, Fe, Mo, Si, Mn, and Cr elements. This reveals that Al and rest elements were transferred from the composite pin and countersurface, respectively to the wear debris of composite pin. It supports that Al2O3 particles cause microploughing in AON-30 nanocomposite as verified from optical microscopy. It is obvious that in this case the adhesive and tenacious film is quite discontinuous. Thus, higher wear rate is observed in nanocomposites containing higher Al2O3 content.

4. Conclusions

Based on the above investigations, the following conclusions can be drawn:

1. The experimental density of the nanocomposites is slightly higher than that of theoretical density below 12 vol.% Al2O3 content whereas, it is slightly lower for nanocomposite containing 12 vol.% Al2O3.

2. The microhardness and stiffness of the nanocomposites increases with increasing Al2O3 content. There is no direct correlation between hardness and wear rate.

3. Wear resistance of PEEK is 10-fold better than that of mild steel. It increases more than 3-fold and 30-fold as compared to pure PEEK and mild steel, respectively at 0.82 vol.% Al2O3 content. The improvement in wear resistance is attributed to the increased stiffness of composites and formation of a thin and coherent transfer film.

4. Wear resistant of nanocomposites containing 1.67 vol.% or more Al2O3 decreases. The SEM and EDS examination of worn nanocomposites indicates that adhesive film becomes discontinuous and microploughing mechanism becomes operative due to third body abrasion resulting from hard particles (Al2O3 and steel) in the debris, and even hard countersurface also gets damaged generating metallic particles. The wear and coefficient of friction cannot be correlated. The coefficient of friction of nanocomposites is higher than that of pure PEEK.

Acknowledgements

We thank Dr. P.D. Trivedi, Polymer Division, Gharda Chemicals, India for providing PEEK powder for this research work. We are grateful to Dr. T.L. Prakash, Executive Director of C-MET for his interest in this work. We also thank Mrs. V. Girmarkar/Dr. T. Seth for performing SEM analysis.

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