Influence of fibers and solid lubricants on low amplitude oscillating wear of polyetherimide composites

J. Bijwe*, J. Indumathi

Industrial Tribology, Machine Dynamics and Maintenance Engineering Centre (ITMMEC), Indian Institute of Technology, Delhi, HauzKhas, New Delhi 110016, India

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Abstract

The influence of short fiber reinforcement and solid lubricants is widely studied in rotational sliding adhesive wear mode, but not much is reported in low amplitude oscillating wear situation. In this paper a series of polyetherimide (PEI) composites with increasing amount of short glass fibers (GF) in the step of 10%, was selected for investigating the influence of GF on friction and wear. A composite containing 25% GF and three solid lubricants was also selected to examine the influence of solid lubricants in the presence of GF. The studies were conducted under various loads and temperatures on a SRV Optimol tester. It was observed that the coefficient of friction was constant irrespective of the amount of GF in PEI, load, temperature and sliding duration. The inclusion of solid lubricants, however, reduced it significantly. Wear behavior, on the other hand, was benefited due to the presence of GF and lubricants as well. Among all GF reinforced composites 10% inclusion of GF showed highest wear resistance. Further inclusion of lubricants improved it significantly. With increase in load and temperature, the specific wear rate increased marginally for the composites and substantially for the PEI. SEM proved to be helpful in understanding the wear mechanisms.

1. Introduction

Polymeric composites form a very important class of tribo-engineering materials and are invariably used in bearings, bushes, bearing cages, gears, slides etc., where adhesive wear performance in non-lubricated condition is a key parameter for the material selection. However, most of the times, components such as bearings and liniers, flexible couplings, gears, pulliatives, riveted, bolted and pinned joints, gripped components, seals, multi-layer leaf springs etc. are operated in the conditions prone to vibrations or small oscillatory motion [1-3]. Such situations predominantly cause low amplitude oscillating wear of the components. Hence resistance to such type of wear also becomes an additional criterion for material selection. Interestingly, not much is reported on the influence of fibrous reinforcement and solid lubricants on wear behavior of polymers and composites in the fretting/reciprocating wear conditions [4-12] in contrast to the vast literature available in adhesive (rotational sliding) and abrasive wear modes [13-17]. Among the limited available research papers on the influence of solid lubricants, fibers/fabrics or their combinations in polymers on the fretting wear performance, no fixed trends appeared to emerge. Chivers and Gordelier [3] have reported the detrimental effect of MoS2 and graphite fluoride on the fretting wear of polyimide. Bill [9] also reported on the detrimental influence of graphite fluoride and MoS2 in fretting wear of PI. Rehbein and Wallaschek [5] reported four times reduction in wear of PTFE due to inclusion of CF without any adverse effect on Yu. PTFE in PI on the other hand, proved beneficial for both Yu and wear. Interestingly, CF in PI did not reduce wear but affected Yu adversely. However, combination of CF and PTFE in PI worked very well for reducing both friction and wear. Reinicke et al. [6] also confirmed the benefits endowed by the inclusion of 15% PTFE in four types of GF reinforced (30%) composites. Abuaru and Play’s [4] findings about fillers such as CF, PTFE, graphite and short GF in PI were also in the same tune. PTFE was used as a coating to raise the fretting fatigue strength of titanium and was also used as filler to reduce fretting wear of titanium. Thus it is confirmed that the influence of fillers on fretting/low amplitude oscillating wear of polymer composites is not predictable and the data on this have to be generated in the laboratory.
No efforts are reported in the literature on investigating the influence of increasing amount of fibres in a systematic series of composites, which is very important for the fundamental understanding in this area. Hence in this paper studies are focussed on the low amplitude oscillating wear of polyetherimide (PEI) composites containing 10-40% of GF. An additional composite containing combination of three solid lubricants and GF was also studied. PEI was selected as a base matrix because it is a high performance specialty-engineering polymer and its composites are reported to exhibit potential for tribo-applications [14].

2. Methodology

2.1. Details of materials selected

The PEI material and its glass fiber (short, E glass) reinforced composites as shown in Table 1 were supplied by GE Plastics, USA, in the form of tensile bars. The samples for tribo-testing were cut from these bars. The data on the properties are also included in Table 1.

2.2. Methodology for wear studies

Low amplitude oscillating wear studies were conducted on SRV Optimol Tester as shown in Fig. 1. Pin on disc configuration as shown in Fig. 1 was selected for the studies. Polymer pin (11.5 mm x 6.5 mm x 3 mm) oscillated against the counterface of mild steel disc (diameter, 22.5 mm; thickness, 8.5 mm; \( R_a \), 0.1-0.15 (\( \mu \)m and hardness RB 75)). Fibres in the mould fill direction were parallel to the fretting plane. Following operating parameters were selected for the studies:

<table>
<thead>
<tr>
<th>Property</th>
<th>Load applied (N)</th>
<th>Temperature selected (°C)</th>
<th>Environment</th>
<th>Stroke length (mm)</th>
<th>Frequency (Hz)</th>
<th>Duration (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>70, 80, 90 and 100 N</td>
<td>Ambient, 100, 150 and 200 °C</td>
<td>Ambient</td>
<td>1 mm</td>
<td>50 Hz</td>
<td>1h</td>
</tr>
</tbody>
</table>

Coefficient of friction (\( \mu \)) was recorded on the chart paper as a function of time. Wear was calculated as a loss in weight of the polymeric pin. Specific wear rate was calculated using the equation:

\[
K_0 = \frac{\Delta m}{\rho L F N t}
\]

where \( K_0 \) is specific wear rate in \( \text{m}^3/\text{N m} \), \( \Delta m \) the weight loss in kg, \( \rho \) the density of the sample in kg/m\(^3\), \( FN \) the applied normal load in N and \( L \) the total sliding distance in m, which was calculated from \( 2A\nu t \), where \( A \) is the full oscillation width in m, \( \nu \) the frequency in Hz and \( t \) the experimental duration in s. Three tests were conducted for each sample and average value was reported. It was within the 95% of confidence level.

Since the tribo-composite GTRB, which contained three lubricants, exhibited best performance, an additional experiment was conducted to examine its utility in marine environment. The pin was dipped in the Analytical Grade Sodium Chloride (NaCl) (5 wt.%) solution while oscillating. The arrangement of the cup fabricated for this work to hold water is shown in Fig. 1.

Wear mechanisms were studied by examining worn surfaces using a Jeol, JSM 840 scanning electron microscope. EDAX studies on the selected samples were done using a Philips 515 scanning electron microscope.

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### Table 1: Details of the properties of PEI and its composites (Supplier's data)

<table>
<thead>
<tr>
<th>Property</th>
<th>Neat PEI</th>
<th>PEI + 10% GF</th>
<th>PEI + 20% GF</th>
<th>PEI + 30% GF</th>
<th>PEI + 40% GF</th>
<th>PEI + 25% GF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Designation</td>
<td>GB</td>
<td>G10</td>
<td>G20</td>
<td>G30</td>
<td>G40</td>
<td>G50</td>
</tr>
<tr>
<td>Trade-name (ULTEM)</td>
<td>1000</td>
<td>2100</td>
<td>2200</td>
<td>2300</td>
<td>2400</td>
<td>4000</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>1.27</td>
<td>1.34</td>
<td>1.42</td>
<td>1.51</td>
<td>1.61</td>
<td>1.7</td>
</tr>
<tr>
<td>Mechanical</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tensile strength at break (MPa) ASTM D638</td>
<td>96</td>
<td>115</td>
<td>140</td>
<td>160</td>
<td>186</td>
<td>195</td>
</tr>
<tr>
<td>Elongation to break (%)</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Flexural modulus (GPa)</td>
<td>3</td>
<td>4.5</td>
<td>6.9</td>
<td>9.0</td>
<td>11.7</td>
<td>9.0</td>
</tr>
<tr>
<td>Flexural strength at break (MPa) ASTM D790</td>
<td>145</td>
<td>150</td>
<td>200</td>
<td>230</td>
<td>250</td>
<td>115</td>
</tr>
<tr>
<td>Flexural modulus (GPa)</td>
<td>3.3</td>
<td>4.5</td>
<td>6.2</td>
<td>9.0</td>
<td>11.7</td>
<td>9.0</td>
</tr>
<tr>
<td>Impact, notched (J/m) ASTM D256</td>
<td>50</td>
<td>60</td>
<td>90</td>
<td>100</td>
<td>105</td>
<td>70</td>
</tr>
<tr>
<td>Thermal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vicat softening point, rate B (°C)</td>
<td>219</td>
<td>223</td>
<td>226</td>
<td>228</td>
<td>234</td>
<td>234</td>
</tr>
</tbody>
</table>

\(^a\) The supplier did not reveal composition. Hence was analyzed in the lab.
3. Results and discussion

\( \mu \) as a function of time, load and temperature for all the composites except GTRB was constant (0.4). \( \mu \) as a function of oscillation duration under various loads and temperatures for GTRB is shown in Fig. 2. Fig. 3 shows the stabilized \( \mu \) of the composites as a function of load (broken line for GTRB in salt water) and temperature. Fig. 4 is for specific wear rate \( (K_0) \) of the composites as a function of fiber concentration while Figs. 5 and 6 are for \( K_0 \) as a function of temperature. 

![Fig. 1. Sketch of SRV Optimol tester.](image)

![Fig. 2. Coefficient of friction (\( \mu \)) for GTRB as a function of time (frequency of oscillation 50 Hz, amplitude 1 mm): (a) at various loads (a1: 70 N, a2: 80 N, a3: 90 N and a4: 100 N) under room temperature, (b) at various temperatures (b1: 25°C/RT, b2: 100°C, b3: 150°C and b4: 200°C) under constant load (100 N).](image)
load and temperature. Figs. 7-11 show SEM micrographs of worn surfaces of composites and discs.

Following were the salient observations from these studies:

- $\mu$ of all the materials except GTRB was unaffected by variation in fretting time, load, temperature and inclusion of GF at various concentrations. It showed an almost constant value of 0.4.
- Inclusion of PTFE, graphite and MoS$_2$ in a 25% GF reinforced composite (GTRB), however, affected $\mu$ in a beneficial way. All the parameters viz. fretting time, load and temperature affected the $\mu$ of GTRB to different extents. The $\mu$ as low as 0.25 was recorded for this composite when fretted at high load and temperature. It was observed that with the increase in sliding time, load and temperature, $\mu$ changed very slowly ($0.2-0.3$, $0.32-0.28$) and ($0.32-0.28$), respectively.

- The salt water environment reduced the $\mu$ of GTRB further to 0.1.
- All the composites except GTRB exhibited wear rates in the order of $10^{-14}$ m$^3$/N m while GTRB composite showed in the range of $10^{-15}$ m$^3$/N m.
- Unlike friction coefficient, specific wear rates of all the composites certainly depended on load, temperature and concentration of fibres as well.

Fig. 3. Stabilized $\mu$ of the composites as a function of: (a) load (broken line for $\mu$ of GTRB in salt water) and (b) temperature.

Fig. 4. Specific wear rate ($K_0$) for the composites as a function of fiber concentration (frequency of oscillation 50 Hz, amplitude 1 mm, duration of fretting 1 h and temperature ambient).

Fig. 5. Specific wear rate ($K_0$) as a function of load for (a) PEI-GF composites and (b) GTRB (broken line for salt water dipped condition) (frequency of oscillation 50 Hz, amplitude 1 mm, duration of fretting 1 h and temperature ambient).

Fig. 6. Specific wear rate ($K_0$) as a function of temperature for (a) PEI-GF composites and (b) GTRB (frequency of oscillation 50 Hz, amplitude 1 mm, load 100 N).
In the case of GF composites, amount of GF influenced the wear behavior to the higher extent than the operating parameters. GF inclusion certainly and significantly reduced the wear rate of neat PEI almost by 5-6 times. Optimum percentage of fibres in the selected range for maximum wear resistance was 10% under all operating parameters. With further increase in GF, K₀ slowly increased. Following performance ranking was observed in the case of GF reinforced composites under all the loads and temperatures: do > G20 > G30 > G40 > G0.

- GTRB showed highest wear resistance among all the composites. GF of 25% along with three lubricants viz. PTFE, MoS₂ and graphite in GTRB improved the friction and wear performance of PEI further (10-17 times depending on operating parameters). GTRB performed best in both the aspects of friction and wear.

- With increase in load and temperature wear performance of all the materials deteriorated. Wear performance of fiber-reinforced composites was less sensitive to a change in operating parameters. In the case of neat PEI, however, it decreased significantly at higher temperatures and loads.

- Friction coefficient of GTRB decreased marginally with increase in load and temperature. In salt water also, GTRB showed very good friction and wear performance. In saline water, the K₀ further reduced by 50% of the value exhibited in dry condition (K₀ dry = 0.32, K₀ water = 0.2 (low load); K₀ dry = 0.2, K₀ water = 0.1 (high load)). K₀, however, increased almost by two times under low loading condition. With increase in load, the difference in wear performance reduced to the extent that at highest load, K₀ in dry condition was little higher than that in water lubricated condition.

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The most striking feature in these studies was that the K₀ of all composites except GTRB was almost constant (0.4) irrespective of inclusion of fibres in PEI, its concentration, load, temperature and sliding duration. As per Schulte et al. [7] in the case of fretting wear, in fact, as soon as sliding commences, wear debris is generated from both the mating surfaces. This debris gets entrapped in the contact region. This accumulated debris separates the two original rubbing surfaces and the "third body" in the interfacial region cause a transition from solid body friction to a kind of either third body abrasion or dry lubricated friction depending upon the nature of debris entrapped. Thus, the fretting friction differs significantly from the unidirectional sliding friction [7]. Different types of fillers and fibres produce different types of interphase leading to different interphase dynamics.

In the present case the wear debris produced during the initial fretting could be mainly of powders of glass, resin and metal due to abrasion by fibres to the counterfaces and consequently to the pin surface also. In the case of solid lubricated composites in addition to this, loose dry lubricant particles accumulate in the third body interphase (TBI). This TBI in all the cases consisted of similar wear debris, though the particulate amount of each constituent could be different depending on the amount of fiber reinforcement. Neat PEI is a hard and amorphous polymer and its friction coefficient in unidirectional sliding mode against mild steel is quite high [18]. A neat polymer, when fretted under moderate load, abraded the disc surface significantly and the disc showed measurable weight loss. Hence fretting became a third body abrasion phenomenon in which the TBI comprised of wear debris of PEI and metallic debris from the mild steel counterface. SEM studies as discussed in the later part supported this. At higher temperature two body adhesion could be
a dominating wear mechanism because of molten viscous layer on PEI on the pin surface and transferred layer on the counterface. This could be responsible for high $\nabla$. (This was supported by SEM and is discussed in the subsequent section.) Thus, in all the cases, $\mu$ remained high (0.4).

In literature, just one paper [6] is reported on the fretting wear of two composites of PEI (PEI + 30% GF, PEI + 30%GF + 15%PTFE). The operating conditions, however, were different from the present studies (Table 2). In this work, Reinicke et al. [6] reported the benefits of PTFE in the composite, which already contained 30% short GF. Since neat polymer was not studied, the influence of GF, however, was not commented. In true sense, the data should not be compared quantitatively because of some differences in the testing conditions. However, the trends and the influence of the testing parameters can certainly be compared.

It can be clearly seen from Table 2 that in both studies PTFE proved beneficial in reducing $\mu$ under all testing conditions of load and temperature. However, Reinicke et al. [6] reported quite a less amount of improvement in friction and wear due to PTFE as compared to the improvement due to three lubricants in the present work. In both cases, $\nabla$ decreased with increase in load and temperature. A striking difference between the two studies, however, was reflected in the wear behavior at high temperature. A PTFE inclusion deteriorated the performance of the GF composite at 150 °C almost by two times [6]. This indicated that PTFE was not a proper choice for high temperature lubrication. In the present work, however, a combination of two more lubricants viz. graphite and MoS2 along with PTFE worked very well even at high temperatures.

The effect of saline water on friction and wear behavior of GTRB is shown in Figs. 3 and 5. Water lubrication has brought down $\mu$ to very low values. With increase in load, it has further reduced to 0.1. Thus, the beneficial effect of water lubrication on wear and friction could be due to washing away of abrasive wear debris generated during fretting; due to the reduction in temperature rise in the disc and reduction of shearing stresses on the pin surface due to boundary lubrication by water.

With increase in load and temperature, specific wear of selected composites increased. In case of fiber-reinforced
polymers, $K_0$ increases with increase in load and temperature because of the following mechanisms. As the contact pressure increases, the probability of fiber cracking, fiber breaking and fiber-matrix debonding increases leading to excessive wear of the composite. When temperature is high, $K_0$ increases because an increase in temperature deteriorates the fiber-matrix adhesion and enhances the pulling out tendency of fibres from the matrix leading to excessive wear and hence increase in specific wear rate.

It was interesting to note that studies on the two body abrasive wear of this series of composites against SiC paper in a single-pass condition reported in our earlier work [17]

Fig. 9. SEM micrographs of pin surfaces for G40 (a and b) worn at RT, (c-f) worn at 200 °C, (d) Fe dot mapping in the EDAX studies confirming the back transfer of metallic wear debris on the pin surface of G40 and (c and f) for central zone. [Micrograph (a) generation stage of wear debris, (c) back transferred thick patches of molten PEI, (2) fine powdery debris of GF]
revealed that the performance ranking was G30 > G40 > G0 > G20 > G10. Thus though both the wear modes, two body abrasion and fretting involved abrasion as a dominant wear mechanism, ranking order of the composites was not the same. G10 was best in fretting wear mode and poorest in the two body abrasive wear mode. This was because of the significant influence of associated additional wear mechanisms.

4. SEM studies of worn surfaces

SEM studies on the worn surface of various composites and discs are collected in the form of micrographs in Figs. 7-11. Arrows are marked to show the direction of fretting. PEI pins worn under room temperature (RT) and 200 °C are shown in the micrographs 7a and b, respectively, while micrograph 7c shows the Fe dot mapping data obtained during energy dispersive X-ray analysis (EDAX) studies for PEI worn at 200 °C. Both surfaces (micrographs 7a and b) clearly show the embedded debris of steel, which was confirmed in EDAX studies during Fe dot mapping as shown in micrograph 7c. High temperature led to the melting of PEI. When molten material solidified after completion of the experiment, boundaries between two overlapped layers can be observed in the micrograph (shown by the window and enlarged portion in micrographs 7b).

Micrographs in Fig. 8 are for the worn surfaces of G10. Micrographs 8a and b are for ambient temperature studies, while 8c and d are for 200 °C studies. These surfaces distinctly differ from the earlier ones in Fig. 7 in terms of presence of GF wear debris, which is almost uniformly spread over the entire surface. This was again confirmed with silicon (Si) dot mapping (micrograph 8b) during EDAX studies on the pin surface but at different location. Embedded in the surfaces are the powdery debris of GF and Fe. A broken fiber (marked in the middle portion of 8a) and cavities left after complete removal of the adjacent fibers (marked) can be seen in the micrograph. High temperature (200 °C) during fretting of G10 made the surface more soft and smoother (micrographs 8c and d). Wear-thinned longitudinal surface of a broken fiber (intermediate stage of fiber pulverization)
with the tips lying nearby can also be seen. In the next fretting cycles such small pieces are crushed, pulverized and transferred to the TBI. Back transferred molten patches of PEI (marked) and a large-scale transfer of debris from TBI are the characteristic features of micrograph 8d.

Micrographs of a worn surface of G40 at RT and 200 °C temperature are shown in Fig. 9a-f. This composite showed the highest wear among all the GF reinforced composites. Micrographs 9a and b are for RT fretting while micrographs 9c-f are 200 °C fretting. Extensive breakage and wear thinning of fibres along the axis, enhanced fiber-matrix debonding and the transfer of wear debris from TBI are the prominent features of the micrographs in Fig. 9. In micrograph 9a, a long fiber just broken (shown in the window) was enlarged in the right portion (Zoom X8). This is a stage of generation of powdery wear debris of glass. The size and
shape of GF debris lying in between two broken pieces can also be seen. This debris then forms the interphase and is responsible for the third body abrasion. The micrograph 9b shows the wear-thinned pieces of GF. The major difference in fretting of this composite at two temperatures is in terms of back transferred patches of molten PEI (9f) and the number of worn GF appearing on the surface (micrographs 9b from the TBI. Such composite transfers a film of lubricant MoS2. The surface topography was distinctly different from polymer can be seen along with powdery bed of GF debris. Micrographs 9e and f show the exact central region of the pin where the temperature was highest and maximum amount of debris was trapped. Thick patches of molten PEI were present. Micrographs 9d and f show the exact central region of the pin where the temperature was highest and maximum amount of debris was trapped. Thick patches of molten PEI were transferred as evident from the thick and b. Fibres micro-cut at various places can also be seen in micrographs 10a and c. Moreover, fibres in the micrograph 9c appear to be covered with a thin film of back transferred molten material. Micrograph 9d is for Fe dot mapping during ED AX studies of back transferred patches of molten PEI (9f) and the number of worn GF appearing on the surface (micrographs 9b and c). Moreover, fibres in the micrograph 9c appear to be covered with a thin film of back transferred molten material. Micrograph 9d is for Fe dot mapping during ED AX studies almost on the same location. This is an evidence of third body abrasion due to TBI. Moreover, Fe debris was transferred on the PEI surface and not on the locations where GF were present. Micrographs 9b and f show the exact central region of the pin where the temperature was highest and maximum amount of debris was trapped. Thick patches of molten polymer can be seen along with powdery bed of GF debris.

Micrographs in Fig. 10 are for GTRB surface fretted at RT (a and b) and 200 °C (c and d). This composite contained 25% GF and three solid lubricants viz. PTFE, graphite and MoS2. The surface topography was distinctly different from others because of the back transfer of the solid lubricants from the TBI. Such composite transfers a film of lubricant on the disc during the first stroke forward. During the back-stroke, the pin tries to take it off. If it adheres very well, complete removal is difficult. Thus part of the film left on the disc is responsible for low friction and wear of the composite. Part of this film enters the TBI, reducing the severity of third body abrasion. The flakes of graphite and thin film of PTFE are clearly seen as marked in the micrographs 10a and b. Fibres micro-cut at various places can also be seen in 10b. High temperature fretting is more dominated by melting of PEI. Flow of PEI after melting and elongated sheets of PTFE particle can be clearly seen in the micrograph 10a. Thick compressed back transferred flakes of graphite overlapping on each other (marked in the micrograph), cavities left after fiber consumption can be seen in micrographs 10c.

A disc surfaces worn under high temperatures against G0 (micrographs 11a, b, c and d) G0 and c. Moreover, fibres in the micrograph 9c appear to be covered with a thin film of back transferred molten material. Micrograph 9d is for Fe dot mapping during ED AX studies almost on the same location. This is an evidence of third body abrasion due to TBI. Moreover, Fe debris was transferred on the PEI surface and not on the locations where GF were present. Micrographs 9b and f show the exact central region of the pin where the temperature was highest and maximum amount of debris was trapped. Thick patches of molten polymer can be seen along with powdery bed of GF debris.

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better (coherent and uniform) in the case of do (micrograph 11c) when compared to that of G0. This is in tune to the observation of lower wear of this composite. In the case of G40, the disc (1 ld) is fully covered with PEI film, though the film is not as thin as in case of G10. (Wear of G40 was little higher than that of G10). The best film transfer (in terms of thin and coherent film) on the disc was observed for GTRB (11e). Three lubricants in this composite transferred the film very efficiently on the disc thereby reducing the abrasion and hence friction and wear. This composite could transfer a good quality film on the disc even in the presence of salt water (11f), though it was not as good as observed in 11e.

5. Conclusions

It was concluded that polyetherimide exhibits a high coefficient of friction (0.4) and moderate wear rate (in the range of 10^{-9} -10^{-10} Nm) when evaluated under low amplitude oscillating wear mode under various operating conditions. Incursion of short GF (10, 20, 30 and 40%) in PEI improved the wear performance significantly (5-6 times) without affecting the coefficient of friction. Though the wear rates of the composites did not differ much, the following performance ranking order was observed: G30 > G20 > G10 > G0. Thus 10% inclusion of GF was found to be the best for highest wear resistance. Further inclusion of three solid lubricants viz. PTFE, MoS2 and graphite in 25% GF reinforced PEI proved to be very much beneficial from both friction and wear point of view. This composite showed a /x as low as 0.28 and a 10-17 times improvement in wear rate was observed. The same composite when tested in water-lubricated condition, exhibited very good friction and wear performance. The formation of a third body interface due to the generation of wear debris of GF, metal and polymer separating the two contacting surfaces increased the /x by increasing the abrasive component. In the presence of solid lubricants, a thin coherent and uniform film was transferred on the disc and the interphase also contained lubricant particles thereby reducing the severity of the third body abrasion. This led to a drastic reduction in wear and friction.

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