Influence of weave of glass fabric on the oscillating wear performance of polyetherimide (PEI) composites

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Received 12 October 2001; received in revised form 6 June 2002; accepted 6 June 2002

Abstract

Glass fabric of three weaves (plain, twill and woven) was selected as reinforcement for developing composites based on polyetherimide matrix. One more composite containing additional fillers (PTFE and Cu powder) was also formulated to investigate the influence of fillers on the wear performance. The composites were characterised for compositional, thermal and mechanical properties. Oscillating (small amplitude) wear studies were done on these composites on SRV Optimol Tester (ball on plate configuration) under different loads for all the composites and temperatures in the case of one. It was observed that plain weave proved to be the most effective in enhancing the wear behaviour of PEI by three times. Friction coefficient also was comparatively low in this case (=50% reduction at higher loads as compared to neat PEI and other composites). Inspection of worn surface revealed that very thin and uniformly spread layer of back-transferred polymeric material, adhering very strongly to the fabric was observed to be the reason behind this. Twill weave and fillers, however, performed poorly resulting significant deterioration in wear performance while woven fabric showed some improvement in wear performance at higher loads. Moreover, mechanical properties of the composites did not support the trends in the wear behaviour. Thus nature of weave proved to be the most prominent wear controlling factor. SEM studies were done on the worn surfaces to understand reasons for failure of some composites and influence of operating parameters.

Keywords: Fabric reinforced composites; Glass fabric; Polyetherimide composites; Weave effect; Low amplitude oscillating wear

1. Introduction

Polymers and 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 liners, palliatives, riveted, bolted and pinned joints, gripped components, seals, etc. undergo small oscillatory motions or vibrations. Such situations predominantly cause low amplitude oscillating wear of the components. Oscillating wear is further categorised in fretting, reciprocating, fretting fatigue, fretting corrosion, etc. depending on the operating parameters, environment and materials involved. Fretting and reciprocating wear of small amplitude differ by the magnitude of amplitude of oscillation. Generally, amplitude less than 0.3 mm lead to fretting wear in the case of metals [1]. In the case of polymers, however, amplitude as high as 2.5 mm [2] is reported to lead to fretting wear. There is no well-defined boundary of the amplitude for distinction of these two wear modes and hence these are also expressed by a broader term as oscillating wear of low amplitude rather than very specific nomenclature as fretting or reciprocating. Interestingly, not much is reported on the wear behaviour of polymers and composites in the fretting wear conditions [2-8] as compared to that in the adhesive and abrasive wear modes [9]. It is a well-accepted fact that the composite which performs well in one wear mode, does not necessarily perform equally well in other wear mode, since the requirement of material properties is different in different wear modes. At times, significant deterioration in performance is also observed.

A vast literature is available on the exploitation of short and long fibres and solid lubricants for improving the tribo-performance of engineering polymers in adhesive wear mode [9,10]. Surprisingly, very little is reported on the potential of fabric reinforcement in this aspect [11-16]. The available literature focus on the investigations on the
Table 1

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<tr>
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<tbody>
<tr>
<td>Density (g/cm³)</td>
<td>2.54</td>
<td>1.44</td>
<td>1.85</td>
</tr>
<tr>
<td>Tensile strength (MPa)</td>
<td>2200</td>
<td>3000</td>
<td>4100</td>
</tr>
<tr>
<td>Tensile modulus (GPa)</td>
<td>70-75</td>
<td>60-65</td>
<td>230</td>
</tr>
<tr>
<td>Failure strain (%)</td>
<td>18</td>
<td>2.4</td>
<td>10</td>
</tr>
<tr>
<td>Poisson's ratio</td>
<td>0.21</td>
<td>0.30</td>
<td>0.3</td>
</tr>
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Cost: = 10 times higher than the glass fabric.

Table 2

<table>
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<tr>
<th>Details of the properties of the selected reinforcements</th>
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<tr>
<td>Glass fabric: E-type</td>
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<tr>
<td>Thickness (mm) and breaking strength (N/10mm)</td>
</tr>
<tr>
<td>Weight (g/m²)</td>
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<tr>
<td>Plasm weave (G1)</td>
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<tr>
<td>Twill weave (G2) (2 x 2)</td>
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<tr>
<td>Woven (G3)</td>
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2. Experimental

The PEI material was supplied by GE plastics, USA, in granular and moulded (dumbbell shape) forms. The three types of glass fabrics (Table 2) designated as G1, G2 and G3 were selected as reinforcements. 12 plies (300 mm x 300 mm) were cut from the fabric to prepare each composite in which the plies were coated with viscous solution of PEI in dichloromethane and dried for 24 h in a stretched condition. The composites were prepared by hand lay up of the prepreg process. The stacks of dried prepregs were then compression moulded. Moulding temperature and pressure were 320 °C and 75 MPa, respectively. The composite CTRB was prepared specially to investigate the effect of PTFE, a solid lubricant and Cu metal powder (for enhancing thermal conductivity).

The powder of PTFE and Cu was dispersed uniformly on each prepreg of G3 fabric before compression moulding. The formulated composites were characterised for their compositional and mechanical properties. Table 3 highlights the composition and mechanical properties of the composites.
3. Oscillating (low amplitude) wear studies

In this work oscillating wear conditions were as per ASLE standards [18] prescribed for fretting. The oscillating wear studies were done on SRV Optimol Tester (Fig. 1), in which a chromium steel ball of diameter 10 mm was oscillated against a polymer plate (10 mm x 10 mm x 4 mm). The increase in temperature of the polymer sample due to frictional heating can be measured continuously with an in-built thermocouple (Ni/Cr/Ni) 4 mm away from the friction surface. A piezoelectric force transducer mounted at the base of the lower specimen block enables the measurement of friction force. Its output signal can be viewed on the oscilloscope and the rectified output is fed to the recorder for plotting friction coefficient as a function of time. With the help of electrical resistance heating sample can be heated to a desired temperature. The fabric was always in the direction parallel to that of the slip. The operating parameters were as follows.

Load: 50, 100, 150 and 200 N; stroke length (full oscillation width) 1 mm; oscillating duration 1 h; oscillating frequency 50 Hz (relative velocity 0.1 m/s); temperature is 25 °C except for C_TRB, where it was 25, 100, 150 and 200 °C in each experiment. The weight loss was calculated by weighing the specimen before and after wear experiment. The weight loss was converted in volume loss using density data and specific wear rate was calculated using the equation:

\[ K_0 = \frac{AV}{FNt} \]

where \( K_0 \) is the specific wear rate in \( \text{m}^3/\text{Nm} \), \( AF \) the wear volume (\( \text{m}^3 \)), \( FN \) the applied normal load (N) and \( d \) the total sliding distance (m). Distance slid was calculated from \( 2At \), where \( A \) was the full oscillation width (m), \( v \) the frequency (Hz) and \( t \) the experimental duration (s).

4. Results and discussion

The friction behaviour of four composites along with the neat polymer was almost identical. Friction coefficient did not vary with inclusion of fabric or with operating parameters most of the times. Since a constant friction coefficient (0.4) was recorded for most of the composites, the plots of \( f_i \) versus oscillating duration under different loads are not shown. In an exceptional case of CG1, it showed a little variation, as seen in Fig. 2. The specific wear rates \( (K_0) \) for selected materials as a function of load are shown in Fig. 3 a, while \( K_0 \) as a function of temperature for C_TRB...
Following salient points emerged from the studies:

- Friction behaviour of all the materials except CG1 was identical. Friction coefficient did not show any variation with fretting duration, load, fabric inclusion or its weave except in the case of CG1. CG1 showed quite low friction coefficient (=0.2) at higher loads.
- Specific wear rates of the composites were in the range $10^{-14}$-$10^{-15}$ m$^3$/Nm.
- Oscillating wear behaviour of composites, on the other hand, definitely depended on the weave and operating parameters as well. Among the three weaves, G1 weave (plain) showed very good wear performance especially at higher loads. In this case specific wear rate decreased by more than two times as compared to PEI. Moreover, the same composite showed lower friction coefficient =0.2 at higher loads leading to 50% reduction in the friction coefficient as compared to that of neat PEI. Other weaves, however, proved to be ineffective in reducing wear of PEI. As a matter of fact, significant deterioration in wear performance of PEI was observed because of inclusion of twill glass fabric G2. The woven fabric showed similar behaviour under low loads. At higher loads, it showed some improvement in wear performance though the extent was less. All the composites except CG2 and C0 showed increase in $K_0$ with increase in load.
- Incorporation of PTFE (a solid lubricant) and Cu powder (thermal conductivity booster) in a selected composite containing G3 weave did not help to reduce friction or wear in any operating conditions. On the contrary, this composite performed worst in all the selected operating conditions.

The most striking feature about the studies was the non-dependency of friction coefficient of PEI and composites (except CG1) on the operating parameters such as sliding duration and load. In the case of CTRB, it did not change with temperature also. Irrespective of inclusion of glass fabric, the friction coefficient was always 0.4, except in the case of CG1 at two loads. At 150 and 200 N, friction coefficient was around 0.2 (Fig. 2). While investigating the effect of other fabrics such as carbon [17], aramid or its combination with carbon [19] in identical testing conditions, the reduction in the friction coefficient has been reported in the authors’ laboratory. Carbon fabric reduced v from 0.4 to 0.2 while aramid fabric decreased it from 0.4 to 0.3. In the case of other neat polymers (not containing any solid lubricants) such as, PI and PEEK, however, same magnitude of friction coefficient (0.4) under identical oscillating conditions was recorded in the authors’ laboratory [20,21]. Inclusion of solid lubricants in PEEK and polyimide, however, decreased it significantly [20,21]. In the case of present work on CTRB, however, benefits endowed by solid lubricants did not surface out which could be because of either inadequate amount or improper dispersion of the lubricant. The wear behaviour of this composite was very poor as compared to neat PEI, CG1 and CG3. At 50 N, $K_0$ was higher than C0, CG1, CG2 and CG3 by 27, 10, 11 and 8 times, respectively. While at 200 N its wear performance was little better. It showed wear rates higher than C0, CG1, CG2 and CG3 by 4.5, 11, 2.5 and 5 times, respectively. Thus, very high specific wear rate ($a_0=10^{-13}$ m$^3$/Nm) was recorded indicating unsuitability of this material for tribo-applications. Moreover, mechanical properties of this composite (Table 3) were poor supporting the observed wear behaviour.

It was also observed that although composites CG1 was best in wear behaviour at higher loads, its mechanical properties were moderate (Table 3). This indicates that for fabric reinforced composites, fabric weave appears to be important parameter rather than the mechanical properties. Wear mechanisms in fretting/small amplitude oscillating conditions are different from that in adhesive wear mode. In the case of low amplitude oscillating wear situation, apart from adhesion, the major mechanism observed is the third body abrasion since wear debris is entrapped in between two surfaces and cannot escape from the wear-zone since slip

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1. This composite was investigated with SEM in-depth to identify reasons behind failure.
amplitude is very small. Powdery wear debris is produced from fibres, resin and metallic counterface and solid lubricant, if any. This debris forms a powdery bed called third body interphase, between moving surfaces and is under “shear flow” during movement. If the debris due to fibres is of lubricating nature, it will not further abrade metal counterface to that extent. On the other hand, the formation of lubricating film on the counterface is possible which can reduce abrasion of the metal due to abrasive fibres. Hence, in the case of oscillating wear of small amplitude, nature of
Fig. 5. Worn surfaces of CG2 under low load (50 N, RT): (a) general view of crater indicating less damage; (b) centre of the crater showing excessive fibre breakage; (c) edge of crater; fibres parallel to slip direction are less damaged (left portion) than in antiparallel direction (right portion).

Fig. 6. Worn surfaces of CG2 under high load (200 N, RT): (a) general view of crater indicating large size; (b) centre of the crater indicating extensive breakage, pulverisation of fibres and process of conversion in powdery wear debris to form third body interphase; (c) back transfer of molten PEI on the severely damaged glass fabric.

third body interphase is one of the most important decisive factors for governing the overall wear mechanism [11]. In the case of glass fibres, the debris is very abrasive and hence the friction coefficient was very high. PEI is also a very hard polymer and has been reported abrading the steel counterface significantly [19]. Hence the interphase containing hard particles was responsible for high friction coefficient. In the case of CG1 (plain weave), exact reason for lower friction coefficient at high loads could not be clear. The nature of cross-pockets in various weaves is responsible for holding the debris. Perhaps in this composite, hard fibre debris could not be trapped properly in the cross-pockets and hence the friction coefficient could be lower.

Papers on fretting/oscillating wear of fabric reinforced composites could not be available in the literature. Hence, the trends in the present work could not be compared with the literature. In the case of long carbon fibre reinforced epoxy composites, Ohmcoe et al. [22] reported on the anisotropy of long carbon fibre composites in fretting wear rather than comparing their performance with neat polymer. Schulte et al. [11] worked on unidirectional reinforcement (CF, AF and GF) in epoxy and reported that the fretting wear
performance of GF composite was worst. Performance of CF composite was better than GF composite by an order of 2. Comparison with neat matrix, however, was not reported. While reporting fretting wear behaviour of PEI reinforced with short glass fibres, Reinicke et al. [2] commented that though the fretting wear performance of short GF composite was poor, it improved after addition of 15% solid lubricant (PTFE). However, in this paper also, the performance of composite was not compared with the neat matrix (PEI) and the role of GF in this respect could not be highlighted.

The available literature thus does not clearly highlight the influence of glass fibre/fabric on fretting wear behaviour of polymers. In the work presented here, it was proved that nature of weave of glass fabric was important parameter and typical plain weave improved the wear behaviour of PEI significantly at higher loads.

5. SEM studies on the worn surfaces

Fig. 4 shows the worn surfaces of CG1, which has shown improvement in wear performance due to glass fabric of plain weave. Micrographs 4a-c and 4d and e are for worn surfaces at low (50 N) and at high load (200 N), respectively.
Crater view at low load (a) shows very smooth topography and fibre breakage only at the edges as compared to that at high load (d). Enlarged views bring out the influence of load on the worn surfaces very clearly. Micrographs 4b and e (same magnifications) show the topography similar to that in unidirectional sliding mode. Higher load has resulted in more fibre damage and extent of back transfer of molten PEI material from the ball surface to the pin surface. Micrograph 4e shows the thick patches (uppermost right corner) of molten PEI due to back transfer from the ball on the pin and then sheared during further oscillating. This can be more clearly seen in the micrographs 4c and f. Frictional heat generation is low at low load resulting in the lesser amount of melting of PEI and hence less extent of transfer and back transfer. At higher load larger frictional heat generation resulted in large extent of back-transferred patches, which were uniformly spread over the entire surface and protected the fabric from further damage. This was the rea-
son for improvement in wear behaviour at higher loads of this composite since such behaviour was not observed for other composites as discussed in the subsequent section.

Figs. 5 and 6 show micrographs of the surface of CG2 worn at low load (50 N) and high load (200 N), respectively. Composite CG2 showed poor wear performance. When micrographs 5a and 6a are compared, increase in the contact area of the crater due to higher load can be seen. Enlarged views of the craters (micrographs 5b and c; 6b and c) indicate that at lower load microcutting of fibres was the most dominating feature as evidenced from the large pieces of fibres on the surface. At higher load, however, further microcutting of these broken pieces of fibres takes place (micrograph 6b). The surface (Fig. 6b) was finely covered with rounded-shaped wear debris of GF which act as third body abrasives during oscillating. Another feature was the difference in the extent of back transfer of the molten material from the counterface. In the case of higher load, thicker and larger patches got transferred on the counterface. Due to a lot of frictional heating, PEI melts and in spite of the presence of third body interphase, it gets transferred on the counterface. During successive transfer it further gets back-transferred (Fig. 6c, middle portion) on the pin surface. At lower load, however, the matrix surface failed by brittle fracture since fractional heat was not adequate enough to melt the PEI.

When micrographs 4e and f are compared with 6b and c, difference in wear behaviour of CG1 and CG2 can be correlated. The surface of CG1 has shown very less damage to the fabric. Fibre damage and pulverisation was minimal because of uniformly distributed thin patches of back-transferred PEI material acting as protective layer. Adhesion of such protective back-transferred material to the fabric on the surface is possibly weave-dependent. This was not seen in the case of CG2.

In-depth studies on the worn surface of tribo-composite were done because of two reasons. The first, to investigate wear mechanisms to analyse its poorest wear performance and second, to examine whether the added fillers viz. PTFE and Cu powder appeared on the wearing surface or not. Micrographs of the worn surfaces at high load (200 N, room temperature, RT) and high temperature (200 °C, 100 N) are shown in Figs. 7a-c and 8a-c. When the crater sizes (micrographs 7a and 8a) were compared, the appreciable difference in the size could not be observed. When these were compared with the earlier one for CG2, both the size and depth of the craters of CTRB were found to be significantly large thus supporting the higher damage and poor wear behaviour of CTRB. It was observed that high load had resulted in more damage to the fibres (Fig. 7b and c) while high temperature had led to more damage to the matrix in terms of melting (Fig. 8b and c). The surfaces appear to be covered with fine debris of GF. The molten PEI (back transferred) is spread almost over the entire surface (micrograph 8c). Interestingly, on this surface (edge of the crater) few intact fibres were also seen because load was not as severe as in the previous case (200 N).

Possibility of back transfer of PTFE from the third body interphase on the pin surface could not be ruled out. Hence, energy dispersive X-ray analysis (EDAX) studies were done on the worn surface of CTRB (200 N, RT) and micrographs are shown in Fig. 9a-f. A typical location showing a layer of material in between two fabric layers (Fig. 9a) was thought of consisting of filler material. Hence, Cu and F (Fluorine) element mapping of this location (Fig. 9b) indicated PTFE debris on the right side of the surface. It was also of interest to locate glass fabric on this surface. Si dot mapping indicated poor dot density suggesting thereby that the GF probably were fully covered with polymeric materials especially in the central portions. In the left portion, fine powdery debris is apparent and this was confirmed by Si dot mapping (extreme left side). It was also of interest to examine back transfer of Fe from the counterface. Since this composite showed poorest performance, possibility of heavy back transfer of Fe was not ruled out. However, EDAX studies did not show appropriate amount of Fe on the surface, especially in the central portion (Fig. 9f). This reconfirmed the proposed mechanism that the wear debris certainly consisted of PTFE and hindered the abrasion of ball by the sharp glass fibre debris. This indicated that excessive wear of this composite was not because of (i) excessive pulverisation of fibres or (ii) excess melting/softening of PEI or PTFE or (iii) excessive scratching of the counterface by GF and hence, inclusion of Fe debris in the third body abrasive interphase. It failed because of its own poor mechanical properties and low ILSS (Table 3). Since the adhesion between plies was poor and the compatibility of fillers with the matrix was inadequate, it was easy to remove the fibres from the matrix leading to high wear.

6. Conclusions

It was concluded from the fretting wear studies on composites of glass fabric with three weaves that the friction coefficient did not depend on the type of weave (except in few situations), load and fretting duration. Specific wear rate on the other hand, very much depended on the weave of fabric and operating parameters such as load and temperature. Among the three weaves, plain weave proved most effective for increasing oscillating wear resistance of PEI. Moreover, this composite showed low friction coefficient in the typical loading conditions indicating its good potential in oscillating wear mode. In-depth studies of plain weave PEI composites containing varying amount of fabric, however, are required for investigating optimum percentage for best possible performance. Studies on SEM for failure
analysis proved to be very much helpful in understanding wear mechanisms and reasons for differences in wear behaviour of the selected composites. In the case of CG1, back-transferred thin molten layer of PEI spread uniformly over entire surface and protected the fabric from further damage. Adhesion of this layer to the plain weave fabric was the best and was the main reason for superior performance of this composite. Microcutting and micropulverisation of fibres and back transfer of PEI were observed to be the prominent features of wear mechanism.

Acknowledgements

Authors gratefully acknowledge the financial aid by Council of Scientific and Industrial Research (CSIR), New Delhi, India.

References