On the abrasive wear behaviour of fabric-reinforced polyetherimide composites

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Abstract

The potential of fabric reinforcement in the thermoplastic polymers for enhancing the abrasive wear resistance has not been explored so far. Hence a series of seven composites of polyetherimide (PEI) reinforced with three types of fabrics viz. glass (with three different weaves), carbon and aramid (Kevlar 29) was fabricated and abrasive wear performance of these composites along with the neat polymer was evaluated. A polymer pin was abraded against silicon carbide (SiC) abrasive paper under various loads and two fabric orientations. It was observed that the aramid fabric (AF) revealed significant potential to improve abrasive the wear performance of PEI. When the fabric was perpendicular to the abrading surface, performance of the composites was substantially better than the case when it was in the parallel orientation. Carbon fabric (CF) and glass fabric also showed some potential for enhancing the wear resistance of PEI when the fabric was in the perpendicular orientation. The mechanical properties of the composites, however, could not be correlated with the wear performance. Worn surface analysis by SEM on the other hand, helped to correlate the performance of the composites with the surface topography, failure of fibres, resin and their interface. Difference in the failure mode of the fibres was thought to be mainly responsible for controlling the wear performance of the composites.

Keywords: Abrasive wear behaviour; Polyetherimide composites; Fabric reinforcement

1. Introduction

Among the various types of fibre reinforcements viz. short, long (unidirectionally reinforced, UD composites), fabric (bidirectionally reinforced, BD composites) and the combinations of fabrics or long fibres in various directions (multi-directionally reinforced), BD reinforcement offers a unique solution to the ever increasing demands on the advanced materials in terms of better performance and ease in processing. Their anisotropic properties, very good specific strength, possibility of tailoring the exact combination of desired properties without sacrificing the ease in processing, have made them as one of the most promising engineering composites. These advanced composites have been exploited almost to its full potential in various fields where excellent performance and reliability are important criterion for material selection. Interestingly, comparatively less has been reported on the exploration of tribo-potential of such composites [1-8], although numerous research publications

on the tribo-evaluation of fibre reinforced (short and long) and particulate filled polymer composites are mentioned [9].

The state of art of tribology of BD composites indicates that almost all the papers pertain to the investigations in the adhesive wear mode except a very few on fretting [10], fretting fatigue [2] and abrasive [8] wear modes. In the case of adhesive wear mode, Mody et al. [1] reported on the excellent tribo-potential of graphite fabric—PEEK composite, which was found to be higher than that of UD composite by an order of magnitude. Vishwanath et al. [3-5] studied the sliding wear behaviour of mainly glass woven roving composites using poly(vinyl)butyryl modified phenolic as a base matrix. Their efforts, however, were focussed on studying the effect of sliding speed and geometry of the fabric on the wear of composites rather than focussing on the contribution of the fabric on the extent of wear. In the subsequent work [6], based on evaluating tribo-potential of three types of BD reinforcements viz. E glass, high strength carbon and Kevlar 49, using the same matrix, it was reported that the glass fabric (GF) reinforced composite performed worst while Kevlar fabric composite exhibited the best performance. Interestingly, for this composite most of the mechanical properties such as tensile strength, flexural

modulus and impact strength, were not the best. Bahadur and Polineni [7] also studied the tribo-behaviour of GF reinforced polyamide (PA) composite filled with CuO and PTFE in various combinations. They reported almost two-times increase in the adhesive wear resistance of PA due GF reinforcement and this continued to improve with the increase in the concentration of selected fabric. The friction coefficient, however, could not be improved due to BD reinforcement. Friedrich [8] evaluated adhesive wear performance of epoxy composites reinforced with fabrics of glass, GF (50%v), carbon, (CF) (60%v) and aramid, (AF) (70%v). He reported the performance being in the order, CF > GF > AF for parallel orientation and AF >>> GF > CF for the normal orientation of the fabric with respect to the sliding plane.

Compared to the adhesive wear studies, less is reported on the potential of such composites in other wear modes. Schulte et al. [2] studied the fretting-fatigue studies on the CF reinforced epoxy composites Bijwe et al. [10] evaluated fretting wear performance of polyetherimide (PEI) composite and reported about the positive contribution of CF. In the case of abrasive wear, just a single paper was available in this context in which, Friedrich [8] reported on the various extents of positive contributions of AF, CF and GF in epoxy matrix.

Polymer composites are extensively used in the tribo situations where resistance to abrasive wear is an extremely important criterion. Typical examples are chute liners, conveyor aids, vanes, gears for pumps handling industrial fluids, sewage and abrasive contaminated water etc. It is also interesting to note that most of the time, composites (filled or reinforced) show inferior wear behaviour than that of the parent polymer and this is thought as a result of reduction in the Se factor (where S is the ultimate tensile strength and e is the elongation to break) [11]. Very few papers have reported on the beneficial effect (though not significant) of long fibre reinforcement on the abrasion wear resistance of a selected polymer [12]. In this background, it was thought worthwhile to examine the influence of BD reinforcement in PEI on the abrasive wear behaviour. PEI is a high performance thermoplastic engineering polymer with very good potential (in composite form) for sliding wear applications [9]. Hence it was selected as a base matrix and three types of fabrics (E glass with three weaves, carbon and aramid)

were selected to investigate the possible enhancement in the abrasive wear performance of PEI. The results are presented in the subsequent section.

2. Experimental

2.1. Materials selected

GE plastics USA supplied the PEI material in a granular form. Three types of weaves of glass viz. G1 (plain weave), G2 (twill weave) and G3 (woven GF) were selected to study the influence of weave on the wear behaviour. A hybrid composite, CHY containing both CF and AF, was also fabricated to observe the simultaneous influence of both fabrics on the wear behaviour. A special tribo-composite, CTRB containing solid lubricant and metallic filler along with GF reinforcement (G3) was also formulated to examine the influence of particulate fillers on the wear behaviour. Details of the conditions for developing the composites are given in Table 1. The plies (300 mm x 300 mm) cut from the fabric were coated with the viscous solution of PEI in dichloromethane and dried for 24 h in a stretched condition. The composites were prepared by hand lay up prepreg process. The dried stacks were then compression moulded to form sheets of 4 mm thickness. The formulated composites were characterized for their compositional and mechanical properties. Table 2 highlights the composition and mechanical properties of the developed composites.

2.2. Abrasive wear studies

The pin-on-disc machine discussed elsewhere [13] was selected for this work. The polymer pin in the form of block (10 mm x 10 mm x 3 mm) was abraded against a water proof silicon carbide (SiC) abrasive paper of 80 grade (grit size $\cong 176$ (xm) fixed on the disc rotating with constant speed (50 mm/s). The pin was loaded with various loads (6, 8, 10, 12 N). Since the composites did not show any measurable wear even after abrading for 3 m (after changing eight papers) in a single pass condition, the wear studies were done in a multi-pass condition. The pin was abraded against the same paper in the same track till the distance abraded

Table 1
Processing parameters and conditions used for fabricating composites

Composite (fabric)	No. of plies	Temperature (°C)	Pressure (MPa)	Breathing duration (s)	Number of breathings
CG1 (G1)	12	320	75	2-3	10
CG2 (G2)	12	320	75	2-3	10
CG3 (G3)	12	320	75	2-3	10
CTRB (G3 + fillers)	12	320	75	2-3	10
CAF (Kevlar-29, AF)	24	285 ^a	75	2-3	10
CCF (carbon)	24	320	75	2-3	10
CHY (carbon + Kevlar)	12 (AF) + 6 ^b (CF)	285 ^a	75	2-3	10

^a Since AF has lower melting point, processing of CAF composite was done at a lower temperature.

^b The sequencing of the layer was in 2:1 ratio.

Table 2
Details of the composition and properties of fabricated composites

Composites	C0 ^a	CG1	C _g 2	C _g 3	CTRB	CCF	CAF	CHY
Density (g/cm ³) ASTM D 792	1.27	2.65	1.97	2.47	1.76	1.58	1.33	1.24
Contents of fabric, vol.%, (wt.%)	-	75, (42)	60, (38)	75, (51)	G ₃ ^b -63, (44) ^c	75, (69)	75, (74)	AF 58, (55) CF 25, (23)
Hardness (shore D) ASTM D 2240	92	96	96	95	95	95	90	91
Tensile strength (MPa) ASTM D 638	105	280	285	300	250	540	318	196
Tensile modulus (GPa) ASTM D 638	3	22	25	24	19	62	19	40
Elongation at break (%) ASTM D 638	60	1.8	1.5	0.7	0.9	5.1	1.8	1.7
Flexural strength (MPa) ASTM D 790	150	170	260	350	90	620	98	83
Flexural modulus (GPa) ASTM D 790	3.3	14	22	20	8	24	11	6
Inter laminar shear strength (MPa), ASTM D 2344	-	23	20	33	16	46	13	20
Impact strength (kJ/m ²) Charpy impact	37	110	163	184	150	70	300	149/40 ^d
Toughness (J)	-	6.36	5.08	5.28	2.07	8.90	14.4	1.92

^a Properties of C0 as per data supplied by the supplier.
^b CTRB contains glass fabric of G3 weave (63 wt.%).
^c PTFE 5 wt.% and Cu powder 5 wt.%.
^d 149 when hammer strikes from AF side and 40 from CF side.

was 10 m. Before starting the experiment, pin was abraded against a fine abrasive paper of grade 1200 (grit size 5 (im) for uniform contact. Before and after the experiment, the pin was cleaned with a brush to remove particles/wear debris followed by weighing on Mettler balance with an accuracy of 0.0001 mg. The experiment was repeated for three times and the average value of wear was considered. The specific wear rate K_0 was calculated from the following equation:

$$K_0 = \frac{Am}{\rho Ld} \text{ (m}^3\text{/N m)}$$

(1)

where Am is the weight loss in kg, ρ the density in kg/m³, L the load in N and d the distance abraded in m.

The other parameter selected for the studies was the orientation of fabric with respect to the abrading surface. The two orientations, OI and OII as shown in Fig. 1 were selected. In the first (OI), the fabric was parallel to the abrading

surface and half of the fibres (F1) were parallel to the sliding direction while half were in the antiparallel direction. In OII orientation, the fabric was in the perpendicular direction to the abrading surface so that half of the fibres (F1) were perpendicular to the sliding direction while half (F2) were in the antiparallel direction. Since the sample thickness was 3 mm, the contact area and hence contact pressures on the pins were different in two orientations. In OI orientation the pin area was 100 mm² and in OII it was 30 mm². In the case of hybrid composite, the CF side was abraded in OI orientation. The surfaces of the composite worn under 12 N were studied with SEM after sputtering the samples with gold.

3. Results and discussion

The specific wear rate as a function of load in the two orientations for the selected materials is shown in Figs. 2

Fig. 1. Schematics of two orientations of fabrics in the composites selected for the studies.

Fig. 2. Specific wear rate as a function of load in the OI orientation.

and 3. Fig. 4 illustrates the possible wear mechanisms during abrasive wear. Fig. 5 shows the micrograph of the worn PEI, while the micrographs of AF composite and hybrid composite containing both AF and CF (abraded from CF side) in OI and OII orientations are shown in Figs. 6 and 7, respectively. Worn surfaces of CF composite in both the orientations are shown in Fig. 8.

The salient observations from the wear studies were as follows:

- Specific wear rates of all the materials were very low and in the range of $(0.2-10) \times 10^{-11} \text{ m}^3/\text{Nm}$.
- Load, fabric type and its orientation proved to have a significant influence on the abrasive wear performance.
- The extent of difference in the performance depended on the loading conditions and the fabric orientations. In the case of OI orientation, abrasive wear performance was observed to be in the following order:

$$\text{CAF} \gg \text{CO} \geq \text{CG3} = \text{CHY} \gg \text{CG1} \gg \text{CCF} \\ \geq \text{CG2} \gg \text{CTRB} \quad (\text{lowest load})$$

$$\text{CAF} \gg \text{CO} > \text{CG3} = \text{CG1} = \text{CHY} \gg \text{CCF} \\ \gg \text{CG2} > \text{CTRB} \quad (\text{highest load})$$

Fig. 3. Specific wear rate as a function of load in the OII orientation.

Fig. 4. Possible wear mechanisms in the selected fabric orientations. (a) OI orientation: (1) microcrack originating in the fibre (antiparallel to sliding direction) leading to the microcutting and micropulverization of the fibre; (2) deterioration in the fibre (parallel)-matrix adhesion/bonding, responsible for easy peeling off of the cracked fibres in further sliding; (3) entrapped wear debris (fine powder or very small pieces) of glass fibres in the resin pockets resulting in harder (more abrasion resistant) material at higher load (responsible for increase in K_0 with increase in load). (b) OII orientation: (1) microcracks in the fibres antiparallel to the sliding; (2) microcracks in the fibres perpendicular to the sliding; (3) gradient in fibre-matrix debonding along the length resulting in the reduction in load carrying capacity and easy breakage of fibres followed by pulling out of the fibre pieces (responsible for disproportionately high K_0 at higher loads).

For OII Orientation, it was as follows:

$$\text{CAF} > \text{CHY} > \text{CCF} > \text{CG3} > \text{CG1} \gg \text{CO} \\ > \text{CG2} > \text{CTRB} \quad (\text{lowest load})$$

$$\text{CAF} > \text{CHY} \wedge \text{CCF} > \text{CG3} > \text{CO} > \text{CG1} \gg \text{CG2} \\ \gg \text{CTRB} \quad (\text{highest load})$$

Fig. 5. SEM micrographs of the worn surface of PEI.

Fig. 6. SEM micrographs of the worn surfaces of CAF: (a-c) OI orientation, (d and e) OII orientation.

- The AF reinforcement was found to be the most effective in reducing the wear rate of PEI in both the orientations and under all the loads. In the case of OI orientation, 1.5 times improvement was shown. In the case of On orientation, the extent of improvement was very high and very much depended on the load. At lowest load, it was almost 16 times, while at highest load it was about 6-7 times. Tribo-composite (CTRB) and CG2 performed worst in both the orientations and under all the loads.
- In the case of OI orientation, only AF proved to be beneficial in reducing wear of neat PEI. Other composites CG3 and CHY exhibited almost comparable wear behaviour with the PEI while rest of the composites showed deterioration in the performance.
- In the case of OII orientation, except two composites (CTRB and CG2) all other five composites viz. CAF, CCF, CHY, CG3 and CG1 proved having potential for enhancing the wear behaviour of PEI. This indicated that long

Fig. 7. SEM micrographs of the worn surfaces of CHY: (a and b) OI orientation, (c-e) OII orientation.

- fibres perpendicular to the sliding surface are beneficial for improving the abrasive wear resistance.
- CF reinforcement proved beneficial in the OII orientation only while in OI orientation, it proved substantially detrimental ($\approx 50\%$ inferior at high load).
- Combination of AF and CF reinforcement resulted in the enhancement in the abrasive wear performance in OII orientation only. Thus, both the fabrics were beneficial individually and their combination worked almost as a rule of mixture (CAF > CHY > CCF).

Fig. 8. SEM micrographs of the worn surfaces of CCF: (a) OI orientation, (b-d) OII orientation.

- With the increase in load, wear rates decreased in OI orientation while in OII orientation, those increased very slowly.

The results confirmed the significant potential of the AF in improving abrasive wear behaviour of PEI. The literature on the correlation studies on the short fibre reinforced composites indicates that generally, the abrasive wear performance is directly related to Se factor where S is the ultimate tensile strength and e is the elongation to break [11]. Various other factors such as S , e , H (hardness), HSe , S^2e are also reported to be responsible for controlling the wear performance [13]. In the fabric-reinforced composites selected in this work, however, these properties could play hardly any role in controlling the wear. The Se factor or HSe factor is the highest for CCF (Table 2), while its performance was not the best. The CAF, on the other hand, showed moderate Se and HSe factors but its performance was the best. Interestingly it exhibited best impact behaviour. This property; however, plays important role in controlling erosive wear behaviour of the material and not the abrasive wear.

In the case of epoxy matrix composites reinforced with fabrics of carbon, aramid and glass, Friedrich [8] reported about the improvement in the abrasive wear performance to various extents due to inclusion of fabrics. The performance was in the order, $AF > GF > CF$. Almost 2.5 times improvement in the abrasive wear of epoxy matrix against alumina coated paper counterface was recorded due to AF. Normal orientation of fabric proved to be more beneficial than the parallel one. The long fibres in equal amount proved to be almost ten times inferior to the fabric reinforcement in this context. In the present work also, AF in the perpendicular orientation performed the best. The extent of improvement in this thermoplastic polymer was significantly large than in the thermoset polymer studied by Friedrich [8].

The available literature deals with the data on the abrasive wear of UD composites of other matrices such as epoxy, PEEK, PI, etc. Lhymn [14] reported on the abrasive wear performance of the carbon fibre reinforced poly-phenylenesulphide composites in the three orientations, and observed the performance in the order, normal $>$ antiparallel $>$ parallel irrespective of the load and speed.

Mc Gee et al. [15] studied the orientation effect of UD composites of Bismaleimide (BM) and reported that the normal orientation was more wear resistant than the other two. Most of the available papers on the abrasive wear of UD composites have been reported by Friedrich and coworkers. In the case of glass fibre mat (randomly oriented bundles of long fibres) reinforced polyester composite [16], Friedrich reported an increase in the abrasive wear resistance and hardness. The short CF and GF, on the other hand, were reported to deteriorate the abrasive wear performance of PEEK [17], while in the case of UD composites of AF, CF and GF, it was reported that the aramid fibres oriented in the normal direction and carbon fibres in parallel direction could improve the performance of PEEK. In fact, it was predicted that the composite containing aramid fibres oriented in the normal direction to the abrading surface and carbon fibre in the parallel direction would be an ideal material for high wear resistance. As per hypothetical model in the literature [12,18] for best wear behaviour, the carbon fibres should be in the parallel direction and aramid fibres should be in the normal direction. However, from the present studies, it appears that instead of such hybrid composite containing two types of fibres in two directions, the BD composite with aramid fibres in both the directions will be more resistant to abrasive wear, less expensive and lighter in weight.

The KO VS load behaviour of the composites showed typical trends. In the OI orientation, it showed a slow decrease with increase in load while in the OII orientation, reverse trend was seen. When the fabric is parallel to the abrasive surface, it contains fibres in the directions both parallel and antiparallel to the abrading direction. During abrasion even at low loads, the dominant wear mechanisms are microcracking and microcutting of the fibres. The long fibres in antiparallel direction get microcracked and microcut very easily as compared to the parallel fibres. The stresses during shearing of the fibre bundles against abrasive grains deteriorate the fibre-matrix bonding very effectively and hence pulverized fibre debris is released from the composite surface very easily. When the load is increased, the microcutting and microcracking processes also increase proportionally, but the increase in the number of released wear debris from the fibres on the surface get interlocked into the cross pockets of the fabric which hinders further abrasion to some extent by forming an interphase of hard fibrous debris. Hence in a multi-pass condition, the normalized wear rate (wear per unit load per unit sliding distance) decrease to some extent with the increase in the load.

For the OII orientation, the wear mechanisms are different. Since the fibres in the normal direction are responsible for load carrying and wear controlling, the microcutting mechanism is minimal. For other fibres F2, which are in antiparallel direction, the microcracking and microcutting is very high as in the earlier case. With the increase in load, fibres in the normal orientation are exposed to more shearing and hence fibre-matrix adhesion along the depth of the fibre gets deteriorated with further sliding under high load. This

results in reduction in load carrying capacity of fibres due to debonding and easy pullout of fibres. This contributes more than the proportionate breakage of perpendicular fibres at higher contact pressures. The possible wear mechanisms are shown in Fig. 4.

3.1. Worn surface studies with SEM

Micrograph in Fig. 5 shows the worn surface of PEI. Deep furrows due to microploughing by the abrasive grits are evident. Though the PEI is hard, amorphous yet ductile polymer, the micrograph shows brittle fracture as a main failure mode. Fig. 6a-c is for OI orientation, while micrographs Fig. 6d and e are for OII orientation of worn CAF composite. In both the orientations, this composite has shown best wear behaviour among all the formulated composites. The most interesting feature of the worn surfaces containing AF was the extensive fibrillation of aramid fibres, which is a characteristic property of this fibre and was invariably observed on all the worn surfaces of the composites. Another striking feature of the worn surfaces of AF composite and even hybrid composite containing AF and CF (as discussed in the subsequent section) was a smooth topography along with the indication of extensive melt flow of aramid material, in general. The melting point of aramid fibre (320°C) is lower than that of PEI (380°C), CF and GF. When the topography of the surface in the OI orientation was compared with that in the OII orientation, it was observed that the extent of molten flow was maximum when aramid fibres were in the normal direction (OII orientation) (Fig. 6d and e) indicating that the increase in contact pressure resulted in excessive melting or softening of the fibre tips. Fibrillation from the tips and uniform spreading of the material on the pin surface in the form of thin layer took place in successive sliding. Another prominent feature of the worn surfaces of AF composites was the appearance of shallow furrows due to microploughing by the abrading grit. However, the material removed by the plastic deformation or other processes appeared to be almost negligible. This appeared to be the main reason for excellent wear performance of the composites especially in OII orientation. As discussed in the case of other composites in the later part, microploughing in the resin and microcutting of the fibres was several times severe than that in the CAF. Fig. 6a shows general topography of the abraded surface and extensive fibrillation from few points. Fig. 6b shows an enlarged view in general, showing the array of cross fibres of the fabric. The fibre damage is almost negligible. Fig. 6c shows the enlarged view of the fibre elongation followed by fibrillation due to shearing by the grit on the softened aramid fibres. Fibres are not easily removed from the surface. Moreover, they hinder the removal of matrix during abrasion. Fig. 6c shows this fibrillation and ductility of softened AF more clearly in the enlarged view (zoom x 2). Because of the repetitive tensile stresses along the length of the fibre during abrasion, fibres not only get elongated, but also fibrillated extensively. The distinct feature of the

surface topography is the minimal extent of fibre (aramid) breakage or pulverization and debonding in the fibre-matrix adhesion. Moreover, the extent of pulling out or peeling off of such fibres from the matrix is also negligible. In fact, the lowest wear of this composite was due to this typical feature of AF. The surface topography of the composite in On orientation (Fig. 6d and e) is significantly different. Fig. 6d shows very smooth topography as if the molten aramid material has spread over the surface after melting. Fibre tips protruding from very shallow furrows drawn across the surface as a result of microploughing during abrasion can also be seen. An enlarged view (zoom x 8) shows extensive fibrillation of the fibre tips when stressed by SiC grit. Fig. 6e shows this phenomenon more clearly. Since fibres were in the perpendicular direction to the abrading surface, protruding fibre tip got extensively elongated in the form of thin sheet. An enlarged view (zoom x 5) of such tip indicates the diameter approximately to be 10 μm . Another feature is the uniform spreading of the aramid material in the form of thin patches on the verge of detachment from the surface. Such features are indeed, characteristic of adhesive wear where molten polymer material gets back transferred and then detached in the form of thick patches. This indicates that in the case of abrasive wear of AF composite when fibres are normal to the sliding direction, delamination of molten material plays important role in dominating the wear mechanisms.

Fig. 7 is for the micrographs of worn CHY composite containing AF and CF. This has shown the second best performance (especially in the OII orientation) in the series. Fig. 7a and b shows the worn surfaces in the OI orientation, whereas, Fig. 7c-e is for the OII orientation. When the pin was abraded in the OI orientation, leading surface was of CF. Fig. 7a indicates the array of carbon fibres in both the directions. The extensive breakage of the CF, which are more brittle than the AF has led to the high wear. This can be more clearly seen in Fig. 7b. When the grit abrades the fibre in the antiparallel direction, maximum damage to the fibre is expected. The fibres are subjected to bending, torsion and loading by the grits leading to excessive damage which indeed is seen in Fig. 7b. A typical fibre (extreme left bottom portion) indicates the severity of such pulverization. Clearly carbon fibres when embedded in PEI, did not support the wear inhibition of PEI. On the contrary, they accelerated the wear.

Fig. 7c-e shows the worn surface of the composite in the OII orientation, which has shown very good wear performance. Overall surface topography is very smooth because of melting and spreading of thin molten layer of AF (Fig. 7c). Microploughing by the grit in the direction of abrasion can also be seen in the form of shallow furrows. Third body abrasion because of trapped grit rolling across these furrows (middle portion) is also evident. An enlarged view (x8) in Fig. 7d again indicates extensive fibrillation of the AF due to tensile stresses during abrasion. Surface topography supported the very low wear of the composite. Damage to the fibres is also minimal. This typical surface was charac-

terized by alternate bands/strips as shown in the left side of the micrograph. The appearance of these strips, however, could not be explained. Fig. 7e shows the presence of both the types of fibres on the surface. In the enlarged view, the CF can be identified from the nature (brittle) of fracture (small broken pieces in the lower middle portion of surface) while AF shows the ductile behaviour and elongation.

Worn surfaces of CF composite (CCF) in both the orientations are shown in Fig. 8a-d. Fig. 8a is for OI orientation, whereas Fig. 8b-d is for OII orientation. In the OI orientation, this composite has shown excessive wear while in the OII orientation, it has shown better behaviour than the neat PEI. Reinforcement by CF in the direction normal to the sliding surface has improved the wear behaviour of PEI substantially. As seen from Fig. 8a, the direction of sliding can be confirmed from the linear marks of cutting the fibres across the length (middle portion). Brittle fracture of the longitudinal and cross fibres of CF has led to the extensive breakage leading to very high wear of this composite. Because of the tensile stresses imposed by the grits on the surface of fibres (across the length), they get easily cracked and broken. Microcracked and microcut cross fibres on the verge of detachment from the pin surface resulting in high amount of wear debris can be seen on the surface (extreme left, bottom portion). Various stages of fibre removal after microcracking and microcutting, which are the main factors for excessive wear of this composite, can be seen in the micrograph. Fig. 8b-d shows the worn surface in On orientation in which wear resistance of CCF had increased significantly. Fig. 8b shows the abrading direction and furrows due to abrasion and confirming the less damage to the surface. An enlarged view (x 8) of the micrograph shows the microcracked fibre when abraded across the length. Fig. 8c shows the general topography and abrading direction and few carbon fibres which were in the normal direction (an enlarged view of the fibre tip). Compared to the OI orientation, damage to the surface and fibres is significantly less, supporting the less wear of the composite in the OII orientation. Fig. 8d at higher magnification shows many fibre tips in the direction normal to the abrading plane. Few cavities left after consumption of broken fibres can also be seen.

4. Conclusions

The abrasive wear performance of the neat PEI and its seven composites reinforced with three types of fabrics was evaluated and it was concluded that the AF has significant potential for improving the abrasive wear resistance of PEI under selected operating conditions. It was also concluded that the extent of improvement depended on the operating parameters. If the fabric is in the direction perpendicular to the sliding surface, wear behaviour is improved very significantly. Almost 16 times improvement was recorded for AF composite in this orientation. CF and GF with two types of weaves also showed an improvement in the abrasive

wear behaviour of PEI in a perpendicular orientation only. Among the three weaves of GF, woven fabric showed the best wear performance followed by the plain weave. Twill weave performed poorly. The inclusion of the solid lubricant and metallic filler in the woven GF composite proved to be excessively detrimental. This composite showed poor mechanical and wear properties. Mechanical properties of other composites did not support the observed wear behaviour of the composites. The worn surface studies, however, proved very much helpful for correlating wear behaviour of the composites with the surface topography and fibre failure.

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