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Influence of fibre orientation on three-body abrasive wear behaviour of unidirectional carbon fibre-reinforced polyetherimide composite

A. P. Harsha · Suresh Arjula

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Abstract Three-body abrasive wear behaviour of neat polyetherimide (PEI) and unidirectional carbon fibre-reinforced PEI (CF/PEI) has been studied using a rubber wheel abrasion test rig. The abrasive wear studies were carried out at different loads (5–20 N) at a constant sliding velocity ($v = 2.4$ m/s) of rubber wheel. The influence of fibre orientation, i.e. parallel (P-fibre orientation) and anti-parallel (AP-fibre orientation) on wear rate of CF/PEI composite has also been studied. The results showed that the fibre orientation has a significant influence on the three-body abrasive wear behaviour of CF/PEI. The abrasive wear rate was higher when fibres are oriented at anti-parallel than that of parallel orientation of fibres. The worn surfaces have been observed using scanning electron microscope to understand the possible wear mechanisms involved during material removal processes.

Introduction

The combinations of long and continuous fibres with amorphous thermoplastics as a matrix have several advantages over monolithic materials. These composites have high temperature stability, good mechanical properties and chemical stability. These advanced composite materials have been used in many tribological applications [1]. The unidirectional continuous fibre-reinforced composites have shown high degree of anisotropy with mechanical and tribological properties at different fibre orientations [2–4]. The wear rate of the composites materials are influenced by the orientation of the fibres relative to the sliding direction and also depend on the type of composite material under consideration as well as on the type of tribological system under which it operates [5]. It is also reported in the literature that tribological properties of unidirectional continuous fibre-reinforced composites strongly depends upon the type of matrix, fibre and volume fraction of the fibre and the interface bonding properties between the matrix and fibre [6–8].

In the past many investigators have reported about the influence of fibre orientation on the tribological behaviour of unidirectional fibre-reinforced composites under different wear situations viz., sliding wear [2–4, 9–15], abrasive wear [5, 10, 15–17] and fretting wear [18]. The results have shown that fibre orientation is one of the important material parameters affecting the wear behaviour of the composites. Because of the anisotropy exhibited by the composites, wear modelling of the composite is a difficult task [13]. Also the complex material removal processes are involved in the wear of composites. The wear mechanisms are dominated by fibre fracture, fibre pullout, matrix cracking and fibre and matrix thinning. Hence, there is no universal wear model available in the literature which can predict the wear rate of the composites. Also, the wear rate strongly depends upon the tribological system under which it operates, and hence the wear rates investigated are only valid for that tribological system.

The advanced fibre-reinforced composites are subjected to abrasive wear in various applications [1]. In practical applications, three-body abrasive wear is far more prevalent than two-body abrasive wear because most of the abrasive wear problems encountered in the industrial

A. P. Harsha (✉)
Department of Mechanical Engineering, Institute of Technology, Banaras Hindu University, Varanasi 221 005, India
e-mail: harshaap@gmail.com

S. Arjula
Department of Mechanical Engineering, S. R. Engineering College, Warangal 506 371, India

equipment components are three-body, whereas two-body abrasion is primarily involved in material removal process [19]. In the past, lot of efforts have been made to study the influence of fibre orientation of the fibre-reinforced composites in abrasive wear situations [5, 10, 15–17, 20–22]. Lhymn et al. [20] investigated the two-body abrasive wear of various short carbon and glass fibre-reinforced thermoplastic-based composites. Voss and Friedrich [21, 22] investigated the two-body abrasive wear of short glass, carbon fibre-reinforced polyetheretherketone (PEEK) and liquid crystal polymer. Cirino et al. [5, 15, 16] reported the influence of fibre orientation on two-body abrasive wear of continuous glass, carbon and aramid fibre-reinforced PEEK and epoxy. McGee et al. [17] reported the two-body abrasive wear of unidirectional graphite fibre-reinforced polyimide. Lhymn [10] also reported the two-body abrasive wear of unidirectional polyphenylene sulphide carbon fibre laminate composites. Recently Chin and Yousif [23] reported the high stress (three-body) abrasive wear behaviour of kenaf fibre (natural fibres) reinforced epoxy-based composite. They reported that fibre orientation has a great influence on the wear and frictional behaviour of the kenaf fibre-reinforced epoxy (KFRE) composite. It is clear from the literature survey that nothing has been reported on the influence of fibre orientation of unidirectional fibre-reinforced thermoplastic composites in three-body abrasive wear situation. In view of the above, this investigation was focused to study the effect fibre orientation of unidirectional carbon fibre-reinforced polyetherimide composites (CF/PEI) under three-body abrasive wear situations. Another aim was to study the wear mechanisms involved in the material removal processes.

Experimental details

Materials

The neat amorphous PEI (ULTEM 1000) was supplied by GE plastics, USA, in the form of injection-moulded plaques. The laminates were consolidated using 22 unidirectional prepreg tapes (size 305 mm × 305 mm, fibre areal weight 145 g/m^2); this led to the laminate thickness of 3 mm. Mechanical properties of CF/PEI were evaluated in the laboratory as per the ASTM standards. Table 1 provides the detail properties of neat PEI and CF/PEI composite. In this study, PEI has been chosen as a base matrix material because of its high strength, and rigidity at room and elevated temperatures, excellent chemical resistance and tribological properties. Therefore, it is widely used in mechanical applications such as thrust washers, sealing ring, unlubricated gears, bearings and agriculture devices. Therefore, a combination of PEI matrix with long and continuous carbon fibres is more suitable for structural applications.

Table 1 Physical, thermal and mechanical properties of neat PEI and CF/PEI

Property	PEI[a]	CF/PEI[b]
Fibre volume fraction (%)	–	60
Density (g/cc)	1.27	1.59
Glass transition temperature, T_g (°C)	217	–
Tensile strength (MPa)	105	1650 (0°)
Tensile modulus (GPa)	3.45	110 (0°)
Tensile elongation at break (%)	60	–
Flexural strength (MPa)	152	1626 (0°)
Flexural modulus (GPa)	3.31	107 (0°)
Izod impact, notched (J/m)	53	1640
Fracture toughness[b], K_{IC} (MPa m$^{1/2}$)	3.8	–
Vickers hardness[b] (HV)	40	58

[a] Suppliers data

[b] Measured at laboratory

Methodology for evaluation of three-body abrasive wear studies

In this study three-body abrasive wear studies were carried out using dry sand/rubber wheel abrasion test rig (TR-50-M1, DUCOM, Bangalore, India). It was felt that this test produced the closest simulation of the real tribosystem (typical three-body abrasive wear situation). A schematic diagram of the test rig is shown in Fig. 1. The sample was placed in specimen holder and it was pressed against a rotating wheel at a specified force by means of lever arm. The abrasives are introduced between the test specimen and rotating wheel with chlorobutyl rubber tire. The abrasive feeding system consists of a hopper and it allows silica sand to fall under gravity through narrow throat onto a silica wheel. The silica wheel was rotated by motor through timer belt and motor speed determines discharge rate of silica sand. Initially silica sand was preheated to remove moisture before filling inside hopper. The rotation of the rubber wheel was such that its contact face moves in the direction of the sand flow. The pivot axis of the lever arm lies within a plane which was approximately tangent to the rubber wheel surface, and normal to the horizontal diameter along which load was applied. The experimental conditions are summarized in Table 2. The scanning electron micrograph (SEM) of the silica sand used is shown in Fig. 2. Three-body abrasive wear studies of CF/PEI composite were carried out at two different fibre orientations, i.e. parallel (P-fibre orientation) and anti-parallel (AP-fibre orientation) with reference to the flow of silica sand and rotating rubber wheel (Fig. 3).

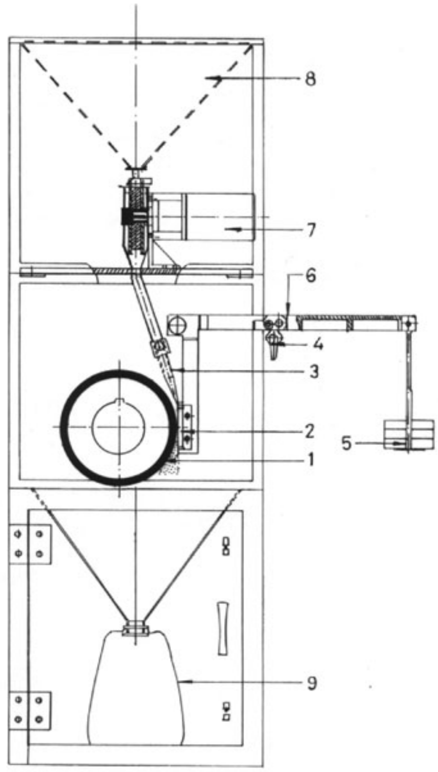

Fig. 1 Schematic diagram of dry sand/rubber wheel abrasive wear test rig. *1* Rubber wheel, *2* specimen and holder, *3* nozzle, *4* unloading bracket, *5* dead weight, *6* lever, *7* feeder-geared motor, *8* hopper, *9* dust collection bag

Table 2 Test conditions

Test parameters	Range
Load	5–20 N
Rotational speed of rubber wheel	200 ± 5 rpm ($v = 2.4$ m/s)
Diameter of rubber wheel	228.6 mm
Abrasive particles	Silica sand, angular, 150–250 μm
Sand flow rate	200 ± 3 g/min
Size of the specimen	76 mm × 25 mm × 3 mm
Total test duration	10 min
Fibre orientation	Parallel (P) and anti-parallel (AP)

Weight loss measurement was made at regular test intervals (200 cycles), using an electronic balance having sensitivity of 0.1 mg. This procedure was repeated till the abrasive wear rate attains a steady-state value. The specimen holder was designed to ensure that samples are removed and replaced during each test such that wear scar was always at the same location. Wear volume (ΔV), wear rate (w_r) and specific wear rate (K_o) were calculated from the following equations

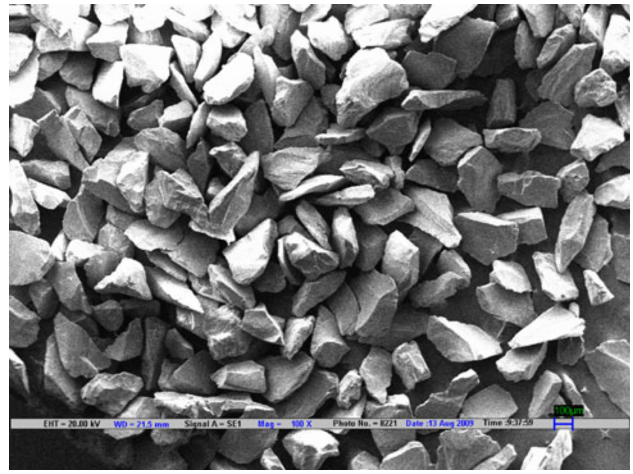

Fig. 2 SEM of silica sand

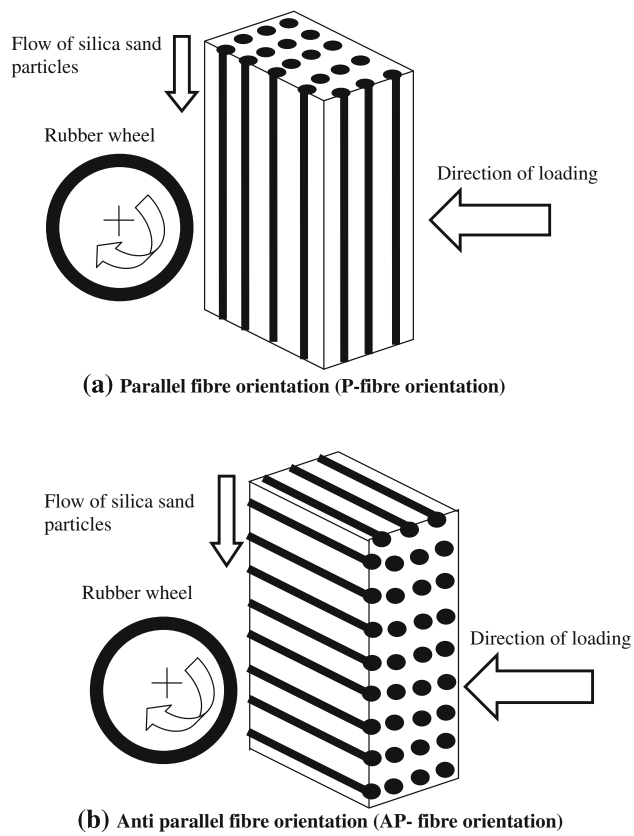

Fig. 3 Two basic fibre orientation tested for CF/PEI composites

$$\Delta V = \frac{\Delta m}{\rho}\left(\mathrm{mm}^3\right) \tag{1}$$

$$w_r = \frac{\Delta V}{M_a}\left(\frac{\mathrm{m}^3}{\mathrm{g}}\right) \tag{2}$$

$$K_0 = \frac{\Delta V}{Ld}\left(\frac{\mathrm{m}^3}{\mathrm{Nm}}\right) \tag{3}$$

where Δm is the mass loss (g), ρ the density of the test material (g/mm^3), M_a mass of abrasive (g), ΔV the volume loss (mm^3 or m^3), L the load (N) and d the sliding distance (m). Since the quantity of the abrasives interacting with the material surface is considered to be an important factor in determining the rate of material removal, the change in the wear volume was plotted as a function of abrasive mass rather than exposure time.

Results and discussion

Wear rate

Figure 4a, b shows wear volume as a function of the mass of abrasive for neat PEI and CF/PEI at different fibre orientations and loads. Wear volume of neat PEI with mass of abrasive did not showed linear relationship at higher loads (10–20 N), whereas for CF/PEI at different fibre orientations showed linear relationship at all loads. Wear volume strongly depends upon the applied load for neat PEI and composites. Also, fibre orientation has a grate influence on the wear volume. The variations in the wear rate (w_r) with mass of abrasive at different loads are shown in Fig. 5a, b. The wear rate (w_r) decreases with increasing mass of abrasives and it was in the range of 10^{-11} m^3/g at low load ($L = 5$ N) and at higher load (10–20 N) it was in the range of 10^{-10} m^3/g. The neat and CF/PEI showed relatively high initial wear rate (w_r) when the surfaces were new, which decreases systematically to an almost constant value (Fig. 5) with increasing mass of abrasive. During initial stage of abrasion, the hard abrasives will come in contact with soft matrix and results sever matrix damage and the rate of material removal is very high. Thus, wear rate (w_r) of all materials tends to become steady with increasing exposure time. Typical optical micrographs of CF/PEI samples before wear testing are shown in Fig. 6. It shows intact fibres with matrix and does not show any damage to the reinforcement.

Figure 7 shows average abrasive wear rate (steady state) as a function of applied load. The wear rate increases in a linear fashion with applied normal load. According to Archard's equation [24], the wear rate may be expressed in the following form

$$Q = K\frac{W}{H} \tag{4}$$

where Q is the wear rate, W the applied load, H the hardness of the wear specimen, K the dimensionless wear coefficient. From Eq. 4, the values of dimensionless wear coefficients (K) were calculated and summarized in Table 3. The values of K are consistent with those expected

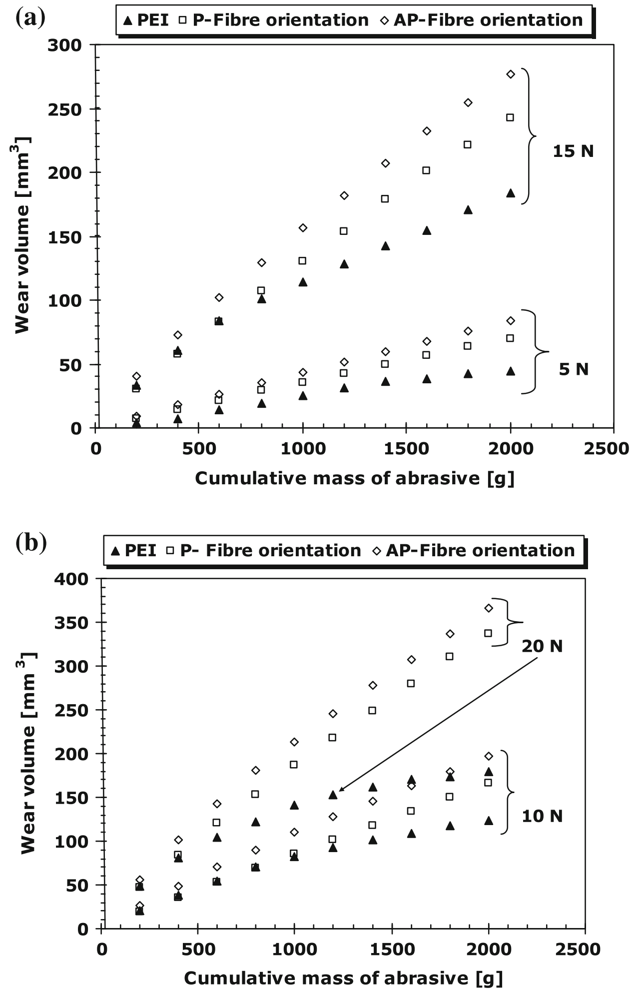

Fig. 4 Variations of wear volume with mass of abrasive for neat PEI and CF/PEI at different fibre orientations and loads

for three-body abrasive wear situations [7]. The dimensionless wear coefficient K depends upon the material properties as well as experimental parameters. Though Eq. 4 is only applicable to the isotropic materials, in this study the values of K are calculated to know roughly the quantitative values of K with the different loads. It is observed from the values of K that the severity of the wear processes is increased with increase in load.

Figure 8 shows specific wear rate (K_0) as a function of normal load. It is observed that the value of K_0 increases from lower to higher value with increasing load up to 10 N for neat PEI and CF/PEI. The neat PEI showed a sharp decrease in the value of K_0 as the load was further increased from 10 N, whereas CF/PEI exhibited an approximate a steady-state value. It is well known that the wear resistance of thermoplastic will not improve by adding the fibres, if the wear mechanism is highly abrasive in nature, and it is an agreement with results reported in the literature [21, 25, 26]. However, in general it is difficult to

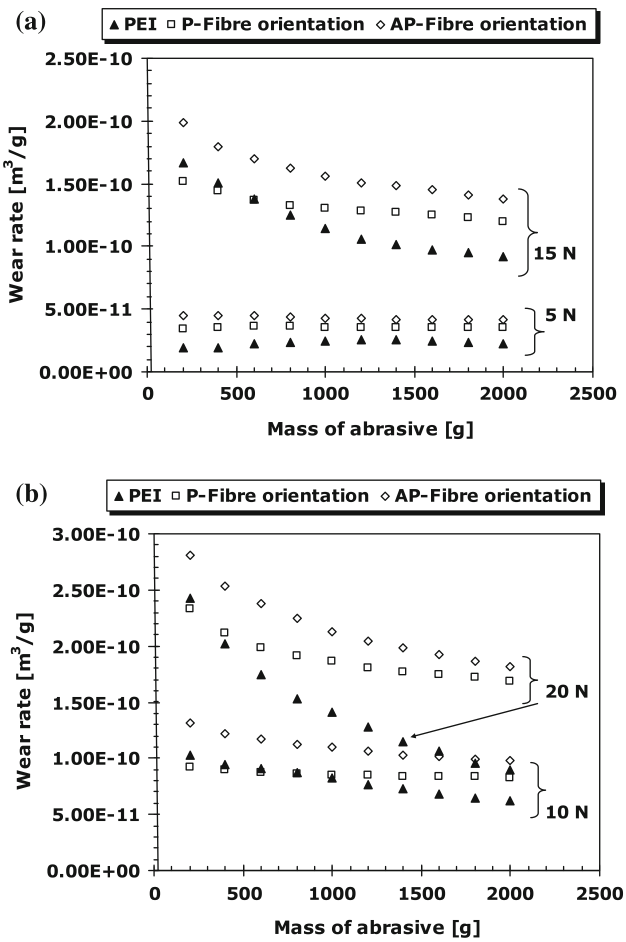

Fig. 5 Variations of wear rate (w_r) with mass of abrasive for neat PEI and CF/PEI at different fibre orientations and loads

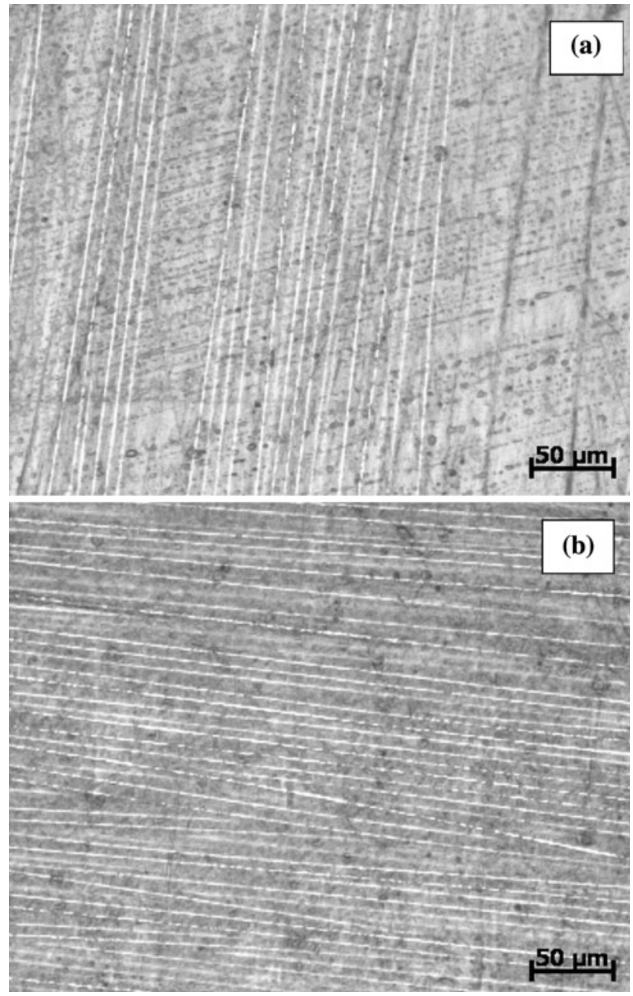

Fig. 6 Typical optical micrograph of CF/EPI samples before wear testing: **a** P-fibre orientation, **b** AP-fibre orientation

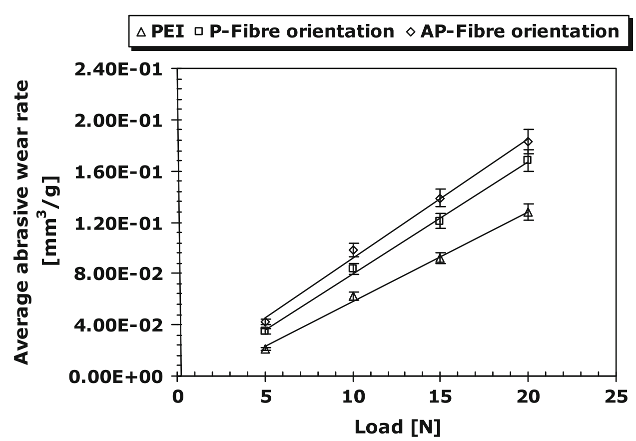

Fig. 7 Average abrasive wear rate (steady state) as a function of load

use neat polymers in many tribological situations where combinations of good mechanical and tribological properties are required [26, 27], hence it is more imperative to use polymer composites in such applications.

Wear mechanisms and influence of fibre orientation

Typical wear scars of the abraded specimens are shown in Fig. 9. According Zum Gahr [7], the rate of material removal in three-body abrasion can be one order of magnitude lower than that of two-body abrasion, because the lose abrasive particles abrade the solid surfaces between which they are situated for only about 10% of the time while they spend about 90% of the time in rolling. Figure 10 shows schematic representation of different zones on the wear scar under three-body abrasive wear test condition. The wear scar has three different zones: an entrance zone where abrasive first come into contact with specimen, central zone in which particle may roll as well as slide and an exit zone where abrasive particles leave the specimen. The entrance and exit zones subjected to multiple indentations by angular abrasive particles, whereas in central zone the angular particles have a rolling component to their motion across the specimen surface,

Table 3 Wear rates and dimensionless wear coefficients

Material	Load (N)	Wear rate ($mm^3/g \times 10^{-2}$)	Dimensionless wear coefficient K ($\times 10^{-3}$)
PEI	5	2.11	2.41
	10	6.21	3.55
	15	9.20	3.51
	20	12.8	2.57
CF/PEI—P-fibre orientation	5	3.48	5.61
	10	8.31	6.69
	15	12.1	6.50
	20	16.8	6.79
CF/PEI—AP-fibre orientation	5	4.18	6.73
	10	9.84	7.92
	15	13.9	7.44
	20	18.3	7.37

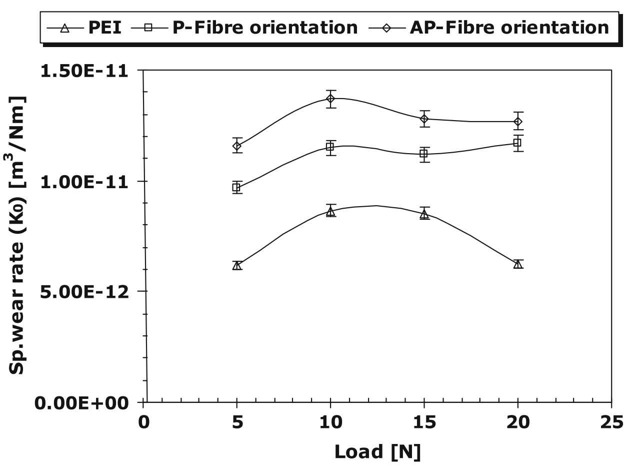

Fig. 8 Specific wear rate (K_0) as a function of load

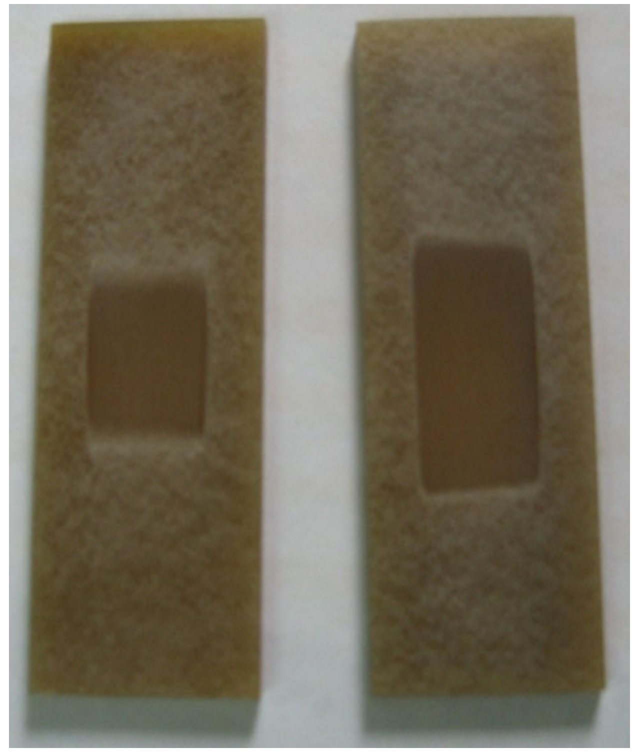

Fig. 9 Typical appearance of wear scar of the specimens at different loads

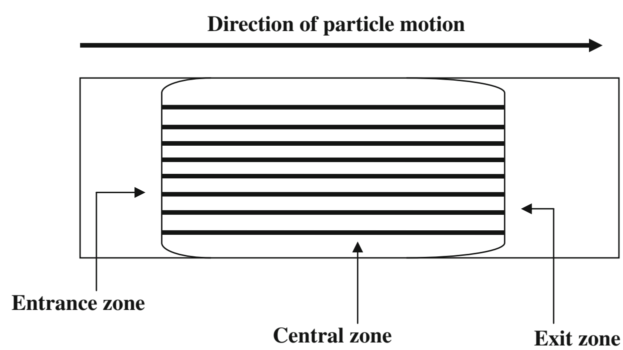

Fig. 10 Schematic representation of different zone on the wear scar

and it creates repeated contact on the loading surface. These may lead to localized fatigue damage and removal of material surface. Figure 11 shows SEM micrograph of worn surface of neat PEI abraded under a load of 10 N. The worn surface (central zone) indicates brittle failure mechanism though PEI is a ductile polymer and having elongation at break is 60%. The wear debris appears as fine fibrils removed from the surface, and also there, is evidence of particle rolling. The wear pattern reveals that there is more rolling of angular particles than sliding. Overall, dominant wear mechanism appears to be surface fatigue (cyclic loading) damage, leading to removal of material.

In this study, the fibre volume fraction in the matrix it was about 60% was used in the composite. Therefore, wear behaviour was strongly dominated by the fibre than the matrix. It is well known that fibre reinforcement to the polymer matrix will modify the wear rate of the composite. Also, fibre failures during tribological situations will accelerate the increase in the wear rate of the composite [28, 29]. It is observed from Figs. 7 and 8 that the fibre orientation has a great influence on three-body abrasive wear of composite. Similar to the present results, in the past also many researchers have reported that tribological behaviour of the composites was strongly influenced by the fibre orientations under different wear situations [2–5, 9–18]. Under all loads, the composite exhibited a better wear resistance when the fibres oriented at P-fibre orientation than at AP-fibre orientation. It was suggested by Chin and Yousif [23], while studying the high stress three-body

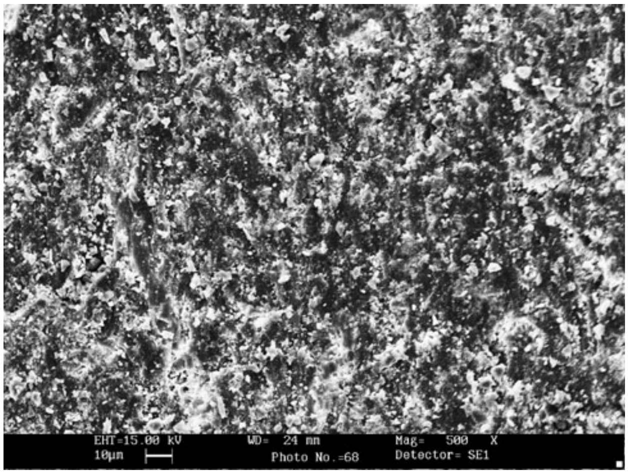

Fig. 11 SEM of abraded surface of neat PEI at load of 10 N

abrasive wear of KFRE composite, that the movement of the particles at the interface is controlled by the orientation of the fibres in the composite surface, which in turn influences the wear performance of the composites. They have reported that at low load (5 N), the KFRE composite showed a higher abrasive wear rate in AP-fibre orientation than P-fibre orientation, whereas at higher loads this trends were reversed. It is very difficult to compare the present results with Chin and Yousif [23] because they have conducted their experiments under high stress abrasive wear situations as per ASTM B 611 standards and using a stainless steel wheel as counterface. The other reason is that they studied three-body abrasive wear behaviour of polymeric composite based on kenaf natural fibre. Unfortunately no results are available on three-body abrasive wear of synthetic fibre-based composites. The literature reports that the influence of fibre orientation of unidirectional fibre-reinforced composite during abrasive wear situations is limited [5, 10, 15–17] to two-body abrasive wear conditions. Cirino et al. [5, 15, 16] investigated the influence of fibre orientation on two-body abrasive wear behaviour of unidirectional continuous carbon fibre-reinforced PEEK. The composite exhibited the highest wear rate when fibres are oriented in AP-fibre orientation to the sliding direction. A similar observation was also reported by McGee et al. [17], while studying the influence of fibre orientation on two-body abrasive wear of unidirectional graphite fibre-reinforced polyimide. However, Lhymn [10] reported that P-fibre orientation showed the highest wear rate in case of carbon fibre-reinforced unidirectional polyphenylenesulphide composite under two-body abrasive wear situation. Thus the present results are in agreement with Cirino et al. [5, 15, 16] and McGee et al. [17]; however, in contrast with Lhymn [10]. It has been reported in the literature [7, 8] that abrasive wear behaviour of composites depends upon the microstructural parameters such as the volume fraction and mechanical properties of the reinforcing fibres and matrix and nature of the interface between matrix and reinforcement.

In order to understand the details of wear mechanisms at different fibre orientations, SEM micrographs of worn surfaces at different loads are used for discussion (Figs. 12 and 13). Figure 12 shows SEM micrograph of CF/PEI

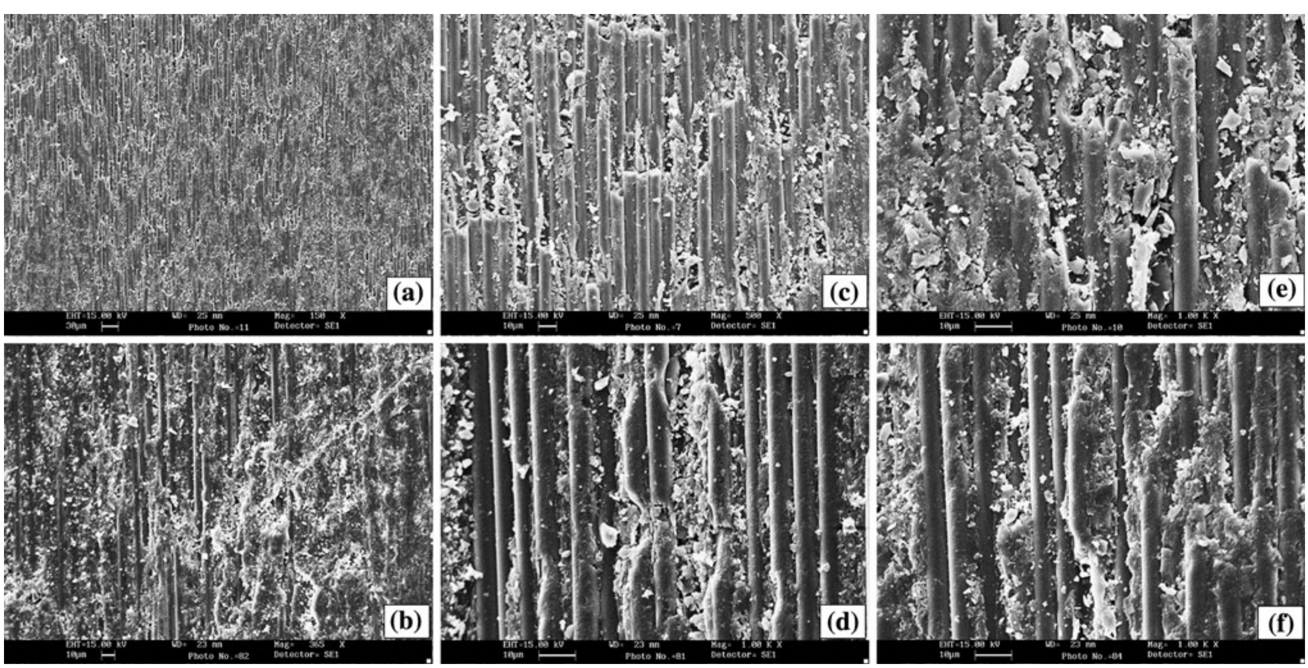

Fig. 12 SEMs of CF/PEI abraded at P-fibre orientation at different loads. **a**, **c** and **e** $L = 10$ N and **b**, **d** and **f** $L = 20$ N

abraded under different loads at P-fibre orientation. During initial stage of abrasion, the hard angular silica sand particles come in contact with softer matrix and results in severe matrix damage. With continuing abrasive wear, the fibres are gradually exposed to abrasive environment. Figure 12a, b shows worn surfaces of micrographs under low magnification; in general, damage surface shows protruding of half broken carbon fibres and the broken fibres are still adhered to the matrix. In principle, worn surfaces of CF/PEI in P-fibre orientation at different loads look similar except the variations in severity of damage. The continuous movement of abrasive particles along parallel direction can results in fibre fracture, fibre pull-out, fibre cracking and deterioration of fibre and matrix interface. This can be seen clearly in the higher-magnification micrographs in Figs. 12c–f. Fine wear particles are also present on the worn surfaces and consistent with direction of flow of the abrasive particles indicating rolling as well as sliding of abrasive particles throughout the worn surface. Lamy and Burtin [6] conducted scratching tests to analyse surface damage of the composite materials subjected to abrasive wear. According to them, the amount of energy loss during scratching, perpendicular to the fibres, is greater than the energy dissipated during grooving, parallel to the fibres. They reported that a complex fibre fracture and fibre pullout mechanism depends upon the contact geometry. They have also reported that the rate of material removal and the morphology of surface damage are directly depends upon pulling off process. However, the present results are in contrast with Lamy and Burtin [6], because three-body abrasive wear of UD composites strongly depends on the type of fibre and the interface property of the fibre and matrix. Also the interaction of abrasive particles with composite surface is more complex during three-body wear situations. Lamy and Burtin [6] used a pendulum scratching apparatus to perform single tip abrasion under controlled condition. Whereas in this study, more number of abrasive particles was in contact with composite surface during wear testing. Therefore, the present experimental method is different from Lamy and Burtin [6] and obviously results are in contrast with them.

Micrographs of worn surfaces of CF/PEI abraded under AP-fibre orientation at different loads are shown in Fig. 13. The wear scar in AP-fibre orientation is distinctly different from P-fibre orientation. Under low-magnification worn surfaces (Fig. 13a, b) evident with multiple particle indentations. This multiple indentations on the worn surfaces indicate typical abrasive particle rolling. In this study AP-fibre orientation showed higher wear rate; this may be due to higher frequency of fracture of the fibres at the interaction on the worn surface. This is evident from micrographs at higher magnification (Fig. 13c–f). According to McGee [17] higher wear rate exhibits in the AP-fibre orientation possibly because fibres are subjected to torsional loading in addition to shear by abrasive particles. The abrasive particles, abraded the fibres in the transverse direction, are subjected to transverse bending and torsional loads are induced to the abrasive particle due to the rotation of rubber wheel, resulting in fragments of fibres removed from the matrix. Cirino et al. [15, 16] reported that in the

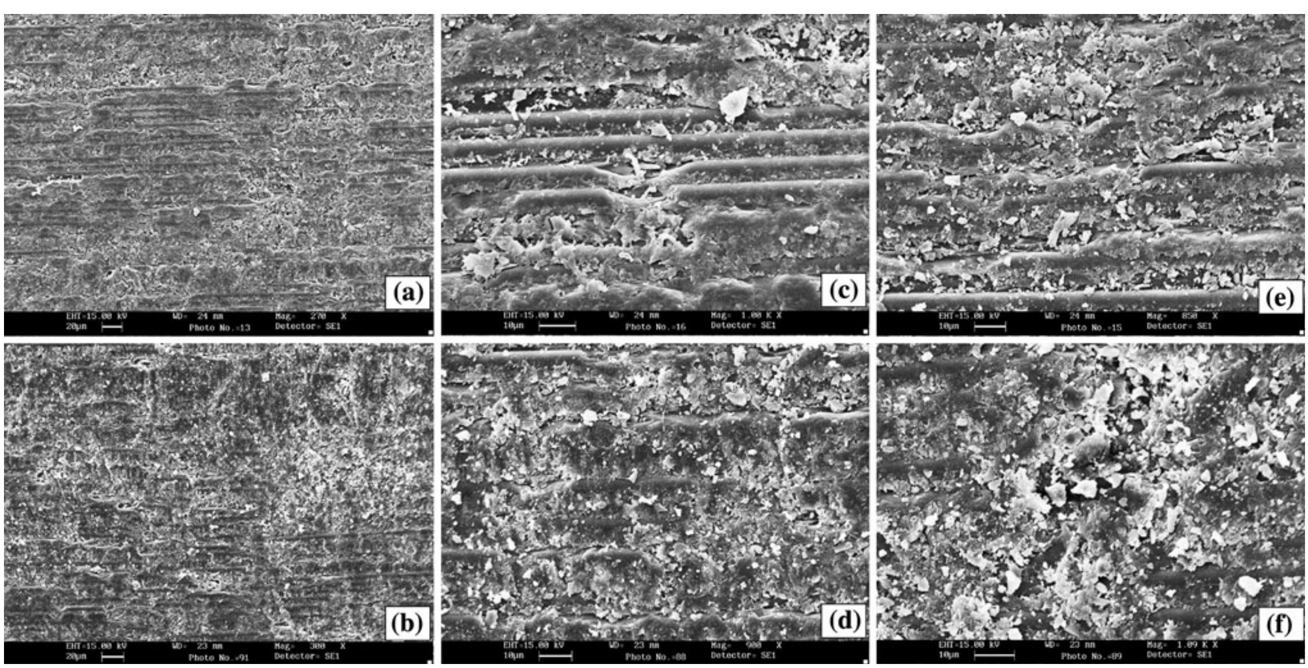

Fig. 13 SEMs of CF/PEI abraded at AP-fibre orientation at different loads. **a**, **c** and **e** $L = 10$ N and **b**, **d** and **f** $L = 20$ N

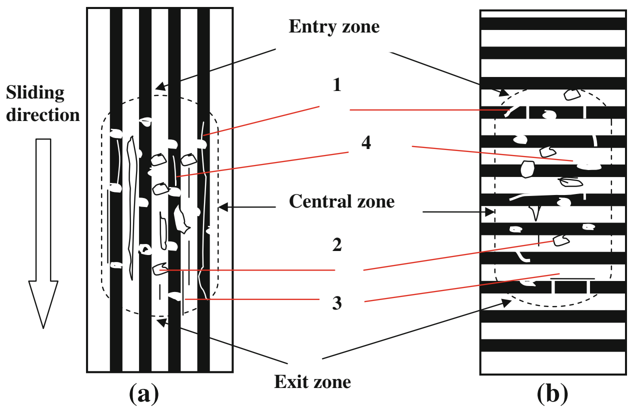

Fig. 14 Schematic representations of the basic failure wear mechanisms observed in the (**a**) P-fibre orientation, (**b**) AP-fibre orientation. *1* Fibre cracking, *2* wear debris, *3* fibre matrix debonding, *4* fibre fracture

AP-fibre orientation fibre bundles were broken from the surface due to bending action imposed by passing abrasive particles. The fibres were then subsequently removed separately or as bundles after fibre/matrix separation and hence AP-fibre orientation showed higher wear rate. It is also evident from one of the micrographs that pulverized matrix and debris in large scale adhered to the worn surface. This may be due to the hard abrasive particles can easily dig out small portions of fibres and cut the fibres (Fig. 13f). Because of the excessive wear three to four layers of fibres were removed from the surface. Also fibre/matrix interface is significantly deteriorated (Fig. 13c–e). The dominant wear mechanisms operating during three-body abrasion of CF/PEI are schematically shown in Fig. 14.

Conclusions

The following conclusions can be drawn from the present results obtained in this study.

1. The neat PEI showed better abrasive wear resistance than CF/PEI composite.
2. Wear rates of the CF/PEI composite are strongly influenced by the fibre orientation relative to the sliding surface.
3. The abrasive wear rate of the composite was higher at AP-fibre orientation than P-fibre orientation at different loads.
4. The worn surface of neat PEI reflected brittle failure features in the micrograph even though neat PEI is ductile polymer.
5. The wear mechanism of CF/EPI at P-fibre orientation dominated by fibre fracture, fibre pull-out, fibre cracking and deterioration of the fibre–matrix interface. Whereas at AP-fibre orientation fibre fractures were dominated by multiple particle indentation (typical rolling) and slicing of fibres into small pieces. Because of the different wear mechanism involved in the material removal process this could produce different wear rates at two fibre orientations.

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