Friction and wear behavior of polyetherimide composites in various wear modes

Jayashree Bijwe*, J. Indumathi[1], J. John Rajesh, M. Fahim

Industrial Tribology, Machine Dynamics and Maintenance Engineering Center (ITMMEC), Indian Institute of Technology (Delhi), New Delhi 110 016, India

Received 21 August 2000; received in revised form 29 December 2000; accepted 21 May 2001

Abstract

A high performance engineering polymer, polyetherimide (PEI) and its two composites, one containing only short glass fibers (GF) 20% and the other, commercially established bearing material containing 25% GF and three solid lubricants were selected for studying the wear behavior in four types of wear modes. These included, adhesive (continuous sliding against metal); abrasive (abrading in single pass and multi pass against silicon carbide abrasive paper), and three-body abrasion (abrading against rubber wheel), fretting, and erosive wear modes. A bearing grade material proved to be extremely good in adhesive and fretting wear modes. The same composite, however, proved very poor in abrasive and erosive wear modes. Neat polymer performed best in these two modes. Thus, performance rankings of three materials in adhesive and fretting wear modes were identical while for abrasive and erosive wear modes, exactly the reverse trend was observed. SEM studies proved helpful in understanding the wear mechanism.

Keywords: Tribology of PEI composites; Three-body abrasion; Fretting wear mode; Erosive wear mode

---

1. Introduction

Fiber-reinforced and solid lubricated high performance engineering polymers are widely applied in various fields of engineering [1,2]. Polymers and composites especially fiber-reinforced composites (FRCs), form a very important class of tribo-materials and are used where components are supposed to run without any external lubricants. Performance of such components, however, is generally sensitive to application conditions. It is also a well-accepted fact that no material is universally resistant to all modes of wear. Hence, during material selection for typical tribo-applications it becomes imperative to know its complete spectrum of behavior in various possible wearing situations. Interestingly, less is reported on systematic studies on wear behavior of materials in diverse wearing situations and operating conditions. Anderson and Williamson [3] evaluated seven polymers in four wear modes viz. adhesive, abrasive, fretting and reciprocating and observed that the performance rankings of polymers varied significantly. No single polymer performed best or worst in all these wear situations. Interestingly, though the sliding motion in the reciprocating and fretting wear modes is same, performance rankings of polymers still differed. It is also accepted fact that though the fiber-reinforcement, solid lubrication or both, enhance performance of polymers very significantly, this is not necessarily true always. At times, it may worsen the performance of a neat polymer [4]. It is also a well-accepted fact that such fillers if successful in a typical wear mode may not be equally successful in other wear situations or they may not improve both the friction and wear of a neat polymer [5,6]. This clearly shows that tribo-properties of composites cannot be predicted apriori and have to be evaluated in the laboratory.

Polyetherimide (PEI) is known for its excellent mechanical, electrical (insulating) and thermal properties and resistance to most of the solvents, radiation, etc. [7,8]. PEI and its various composites and blends have been evaluated for their tribo-potential by various authors in various wear modes [9–18]. PEI and its four composites were studied in the authors' laboratory in adhesive and abrasive wear modes (single pass condition) [14]. Among these, a commercially available bearing grade containing short glass fibers (GF) along with three solid lubricants exhibited very good adhesive wear performance in severe operating conditions of load, speed and sliding duration [14–16]. On the other hand, it showed the poorest performance among the series of five composites in the abrasive wear mode both in single pass [17] and in multi pass conditions [18]. Hence, it was interesting to examine the wear behavior of such composites in the wear mode where both the wear mechanisms, i.e. adhesive and abrasive simultaneously play key roles to decide material performance. The fretting wear mode, hence, was selected for studying the wear behavior of three PEI composites. Moreover, it was also essential to know the trends in wear characteristics in the erosive wear mode also where wear controlling mechanisms are very different. Some results in the earlier work on the performance of these materials in adhesive and abrasive (single and multi pass conditions) wear modes are also incorporated in this paper to have a complete picture about the performance of these materials.

2. Experimental

2.1. Materials selected

PEI and its two composites as shown in Table 1 were selected for the studies.

2.2. Wear studies

2.2.1. Adhesive wear mode

Materials B and C were tested on the three pin-on-disc machine (schematic in Fig. 1a) in which three polymer pins of diameter 6.5 mm slid against a smooth mild steel disc under various operating conditions of load, speed, duration and counterface roughness. Since, the neat polymer showed excessive wear under severe loading conditions after a typical number of sliding cycles on the same machine, it was tested for its fatigue wear performance on a single pin-on-disc machine (Fig. 1b) where low loads were applied and initiation of wear track and appearance of powdery debris after particular sliding cycles could be noted [16]. Weight-loss in the pin was recorded after each experiment and the wear performance was expressed in terms of specific wear rate (K_0, $\mathrm{m^3/N\,m}$) as follows:

$$K_0 = \frac{\Delta W}{\rho L d} \qquad (1)$$

where ΔW is the weight-loss in kg; ρ the density of the material in $\mathrm{kg/m^3}$; d the sliding distance in meter and L is the load in Newton

2.3. Abrasive wear mode

2.3.1. Abrasion in single pass and multi pass conditions against SiC papers

Abrasive wear studies were done on a pin-on-disc machine (Fig. 1b) by sliding a polymer pin (6.5 mm diameter) against water proof silicon carbide (SiC) abrasive paper in single pass and multi pass conditions. Various loads, girt sizes and sliding distances were the different selected parameters [17,18]. K_0 was calculated as per Eq. (1).

2.3.2. Studies on rubber wheel abrasion tester (RWAT)

Schematic of RWAT is shown in Fig. 1c and consists of the gravity feeding of the abrasive particles (approximately 300 μm size) between the polymer sample and the rotating wheel of 20.3 cm diameter leading to three-body abrasion. The wheel is rimmed with chlorobutyl rubber lining of 1.27 cm thickness and is rotated with 100 rpm. A polymer pin of 75 mm × 25 mm × 6 mm was loaded against the rotating wheel with different loads in the range 4–18 N. K_0 was calculated as per Eq. (1).

2.4. Erosive wear studies

A sand blasting machine (Fig. 1d) was used to study erosive wear behavior of the materials. The sample (10 cm × 10 cm × 0.3 cm) was fixed in a plate holder which could be moved in two ways. By horizontal movement, distance between the blast gun and the sample could be adjusted while

Table 1
Details of the properties of PEI and its composites [7][a]

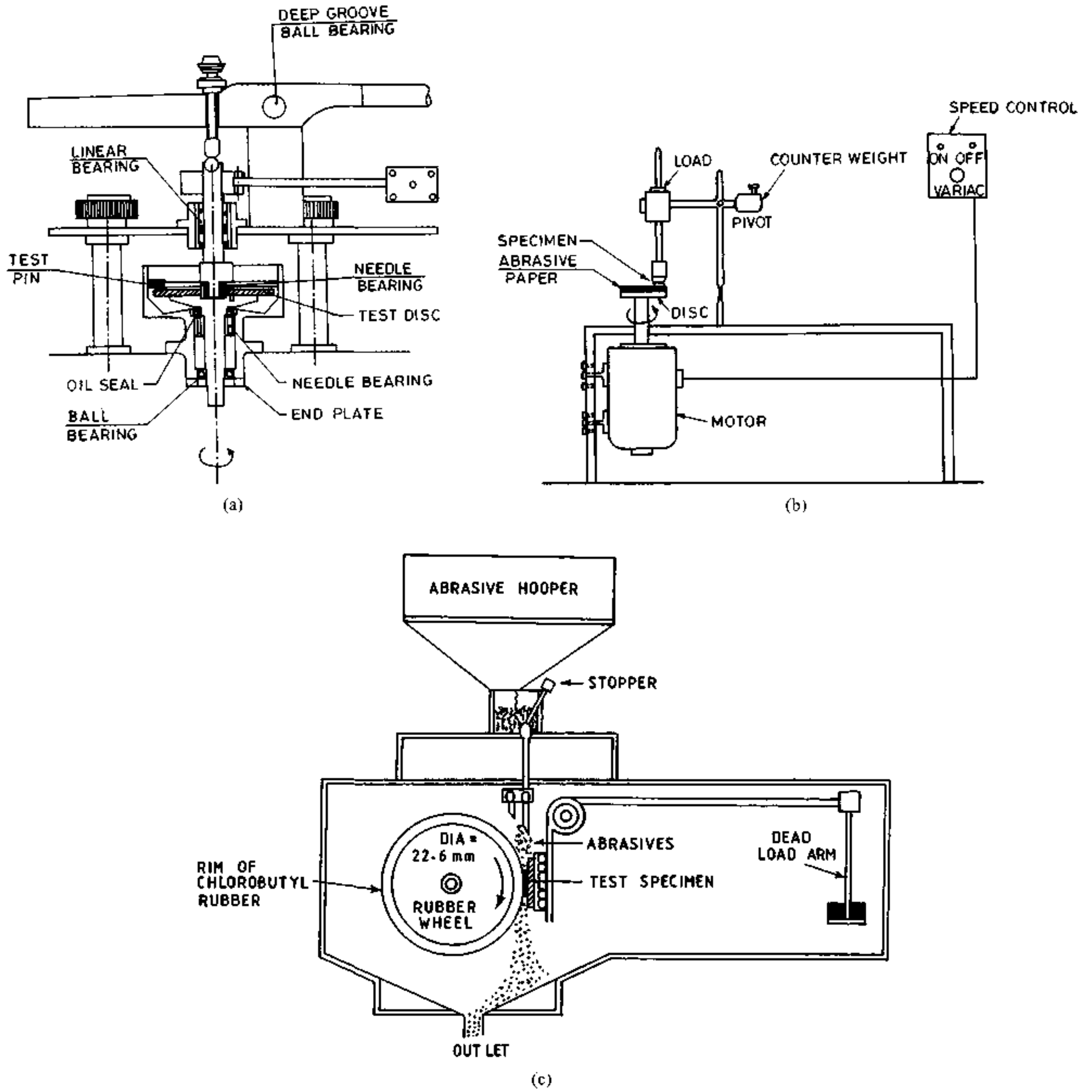
Property	Neat PEI	PEI + 20% GF	PEI + 25% GF + 15% PTFE + 15% ($\mathrm{MoS_2}$ + graphite)
Designation	A	B	C
Specific gravity	1.27	1.42	1.70
Mechanical			
Tensile strength at yield (MPa)	105	139	85
Elongation to break (%)	60	3.0	1.5
Tensile modulus (GPa)	3.0	6.9	7.1
Flexural strength (MPa)	150	200	115
Flexural modulus (GPa)	3.3	6.2	9.0
Izod impact, notched (J/m)	50	90	65
Izod impact, unnotched (J/m)	1300	480	150
Rockwell hardness	M 109	M 114	M 84
Compressive strength (MPa)	150	200	130
Shear strength, ultimate (MPa)	100	95	62

[a] Marketed as a bearing grade and composition was not revealed. Therefore, analyzed in the laboratory.

by rotation along the verticle axis, angle of impact could be changed. The erodent through hopper and blast gun was impinged on the sample with preset velocity and angle. The hopper was fitted with pneumatic vibrator to adjust the flow of the sand. Air pressure could be adjusted with a regulator so as to enable pressure of the erodent impinging on the sample. Following were the parameters selected for the studies: (i) erodent — silica sand of ≅80 μm size; (ii) rate of flow of sand — 1 kg/min; (iii) amount of erodent — 3, 6, 9, 12 and 15 kg; (iv) impact angle — 15, 30, 45, 60 and 75°; (v) air pressure — 45 psi; (vi) distance between the blast gun and the sample holder — 12 cm; (vii) nozzle diameter — 3 mm. Wear was measured by weight-loss method followed by the conversion into volume loss using density data.

2.4.1. *Fretting wear studies*

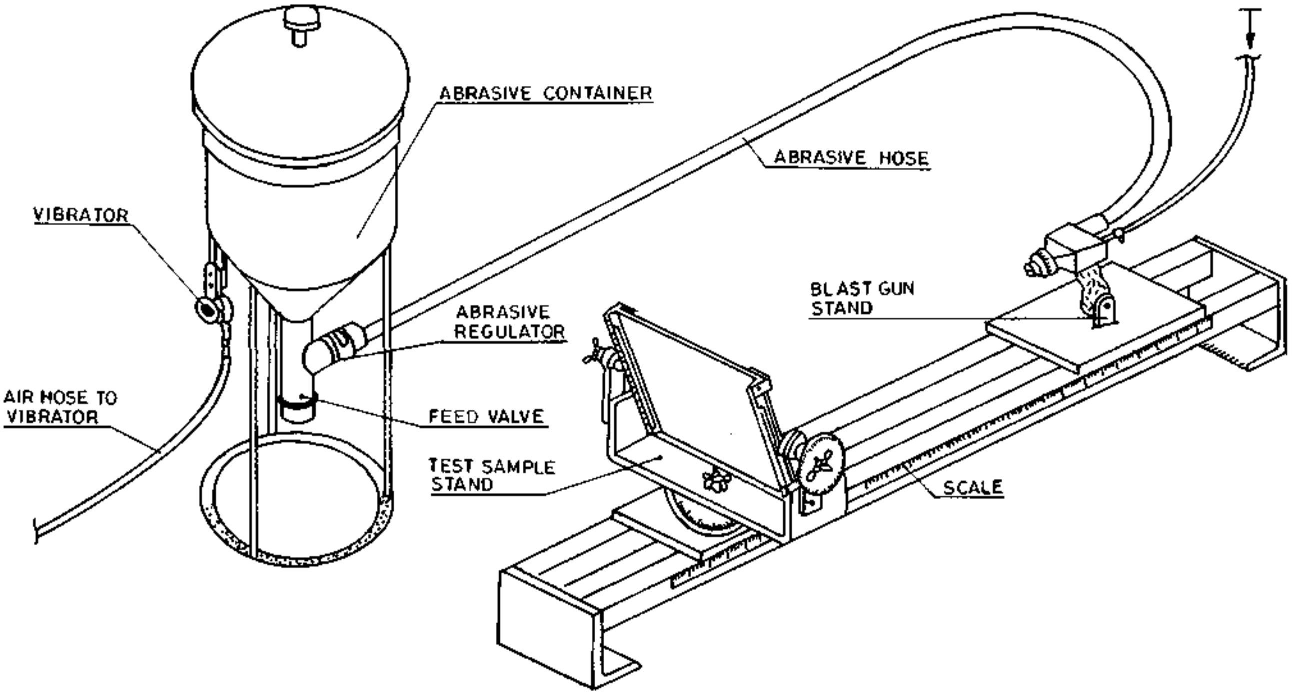
Fretting wear studies were done on SRV optimol tester whose configuration is shown in Fig. 1e. Polymer pin (11.5 mm × 6.5 mm × 3 mm) fretted against stationary mild steel disc (diameter of 22.5 mm, thickness 8.5 mm and R_a 0.1–0.15 μm). The selected operating parameters



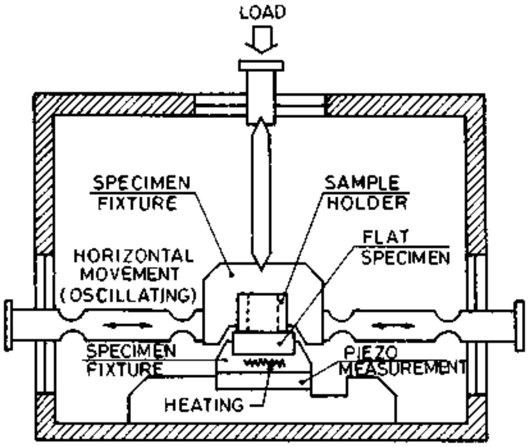
(a) (b)

(c)

Fig. 1. (a) Schematic of three pin-on-disc machine (adhesive wear studies); (b) schematic of a single pin-on-disc machine (abrasive wear studies); (c) schematic of rubber wheel abrasion tester (RWAT); (d) schematic of erosive wear test rig; (e) schematic of SRV optimol tester (fretting wear studies).



(d)



(e)

Fig. 1 (*Continued*).

were: loads applied — 70, 80, 90 and 100 N; temperature selected — ambient; environment — ambient; frequency — 50 Hz and stroke length [2] — 1 mm. Friction coefficient was recorded continuously as a function of time on the chart paper. Increase in temperature due to frictional heating (when the experiment was conducted on ambient temperature) was also recorded. Specific wear rate was calculated from the weight-loss method using following equation:

$$K_0 = \frac{\Delta W}{\rho L 2 A \nu t} \tag{2}$$

where ΔW is weight-loss in kg; ρ the density of the material in kg/m^3; L the load in Newton; A the amplitude in meter; ν the frequency of oscillation in Hz and t is the sliding time in second.

---

[2] Though the reciprocating and fretting wear modes differed by the amplitude of oscillation, there is no thin line of demarcation. Generally, fretting wear is evaluated in the amplitude range of 10–300 μm. However, this is not strictly true. ASLE standards [19] for example, have prescribed amplitude of the stroke as 1.2 mm while Reinicke et al. [13] have used 2.5 mm as stroke length for fretting wear studies on SRV optimol tester. Hence, in this work, 1 mm amplitude was selected for the fretting wear studies.

3. Results and discussion

3.1. Adhesive wear studies

Wear behavior of PEI was characterized by a typical feature. Initial period was characterized by non-generation of wear debris for typical number of cycles which was then followed by catastrophic wear. Number of cycles to initiate wear depended on various parameters such as load, speed, history of pin surface preparation, etc. [16]. The dominant wear mode was fatigue. Suh [20] has classified polymers into four types according to the nature of wear mechanisms. PEI is a hard, amorphous and yet ductile polymer [7]. It wears by fatigue phenomenon rather than a film transfer on the counterface. Under very high load, a molten layer was transferred on the surface. Specific wear rate of the polymer was in the range of 10^{-13} m^3/N m after the incubation cycles of approximately 12 000 in a typical experiment. The friction coefficient was $\cong$0.3 [16].

Composite B exhibited very good wear performance. K_0 (Eq. (1)) being in the range of 10^{-15} m^3/N m. The friction coefficient, however, was very high and unsteady indicating its unsuitability as a tribo-material [16]. GF inclusion, thus, improved the wear performance, but deteriorated the friction behavior of neat PEI. It also transferred a molten layer of polymer under severe operating conditions.

Composite C which contained short GF (25%) along with the solid lubricants exhibited excellent friction and wear properties. K_0 was in the range of 10^{-16} m^3/N m and the friction coefficient as low as 0.1 was recorded. Fig. 2 shows a gist of friction and wear behavior of PEI and composites. Worn surfaces of composite C and discs slid against materials A, B and C are shown in the micrographs in Fig. 3. Thus, among three PEI materials, friction performance was in the following order C$\gg$A>B and the wear performance was in the following order C$\gg$B$\ggg$A.

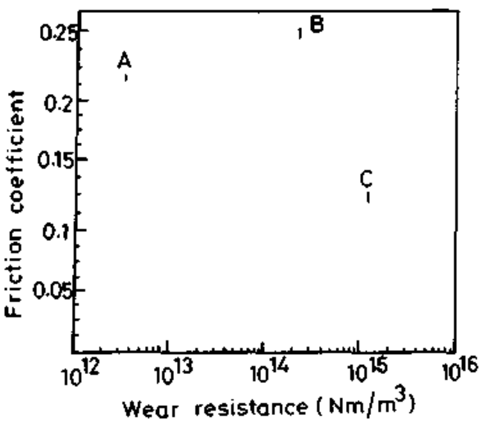


Fig. 2. Tribo-potential (friction coefficient and wear resistance, i.e. $(K_0)^{-1}$ of selected materials (L, 43 N; speed, 2.1 m/s except for sample A where L is 25 N).

3.2. Abrasive wear studies

3.2.1. Abrasive wear against SiC papers

Abrasive wear behavior of three materials in single pass condition [17] and multi pass condition [18] was studied in depth. Specific wear rate as a function of load in two types of conditions is shown in Fig. 4a and b, respectively. Wear property correlation (in single pass condition) is shown in Fig. 4c. Wear rates were in the range of 10^{-11} m^3/N m. K_0 in the single pass condition was higher than in the multi pass condition. The difference in the extent of wear in the single pass and the multi pass was because of clogging effect. In multi pass condition the crevices on the abrasive paper are clogged with the wear debris reducing abrasivity of the grits. Hence, the extent of wear decreases in further sliding. Interestingly, the performance order in both the conditions was exactly opposite to that observed in the adhesive wear mode. Composite C performed worst in the abrasive wear situation and this was explained on the basis of the reduction in Se factor as shown in Ratner–Lancaster plot (Fig. 4c) [21].

3.2.2. Abrasive wear studies on RWAT

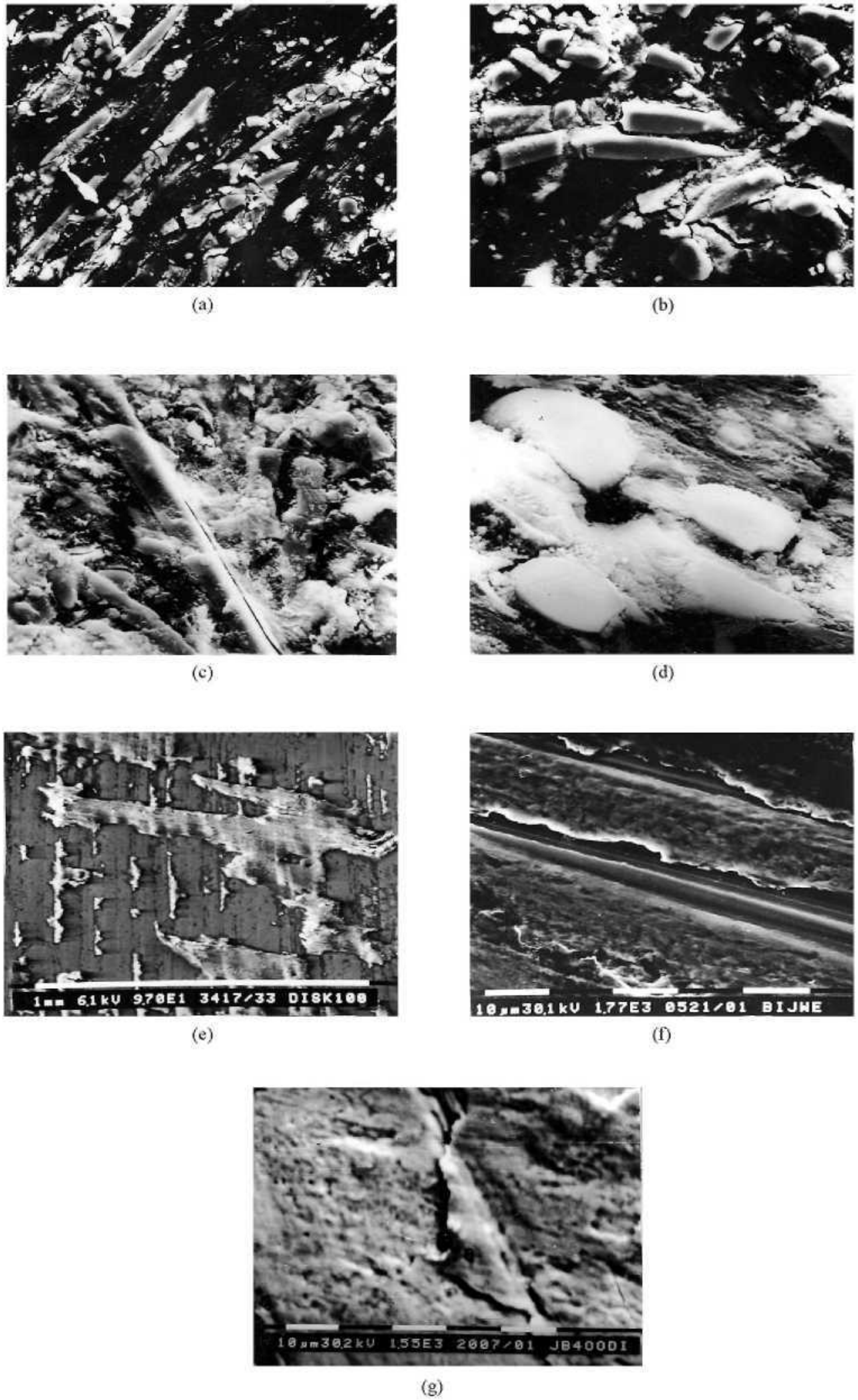
Specific wear rate as a function of load for the three composites is shown Fig. 5. In the third body abrasion also the performance order of the materials was same as in the case of two body abrasive wear. The third body abrasion was more severe because of the size of the abrasive particles was large ($\cong$300 μm). Overall, the K_0 was in the range of 10^{-11} m^3/N m for the materials A and B. For C, however, it was very high in the range of 10^{-10} m^3/N m. The performance ranking was in the order A>B$\ggg$C.

3.3. Erosive wear studies

Erosive wear as a function of amount of erodent and impact angle is shown in the Figs. 6 and 7, respectively. Following are the salient observations.

- Performance ranking was in the order A>B$\ggg$C. Thus, incorporation of fibers deteriorated the performance of the neat polymer and the combination of fillers and fibers proved excessively detrimental. The trends were identical to the trends in the abrasive wear mode.
- Wear increased with increase in amount of erodent linearly.
- Performance of all the three materials was almost similar at an angle 75°, though it differed significantly for other angles
- Maximum was observed in the wear–impact angle relationship for all the three materials at 30°.

Though, polymers are extensively used in applications where erosive wear resistance is an essential criteria, a little is reported on erosive wear aspects of polymers and composites. In the case of PI and composites still less is reported [22–26]. Erosive wear behavior of PEI composites has not



(a) (b) (c) (d) (e) (f) (g)

Fig. 3. Worn surfaces of composite C (a–d) and disc (e–g). (a–d) *L*, 72 N, speed, 2.1 m/s; fibers parallel to sliding direction: (a) micro-cracking of fibers; (b) various stages of breaking, pulverization and removal of fibers; (c) deterioration in fiber-matrix bonding; (d) fibers normal to sliding direction — elliptical fiber tips buried in the matrix, severe melt flow of polymer; (e) worn disc against PEI showing transfer of molten polymer; (f) worn disc against composite B showing layer of transferred molten material on the disc; (g) worn disc against composite C showing thin film transfer of PTFE.

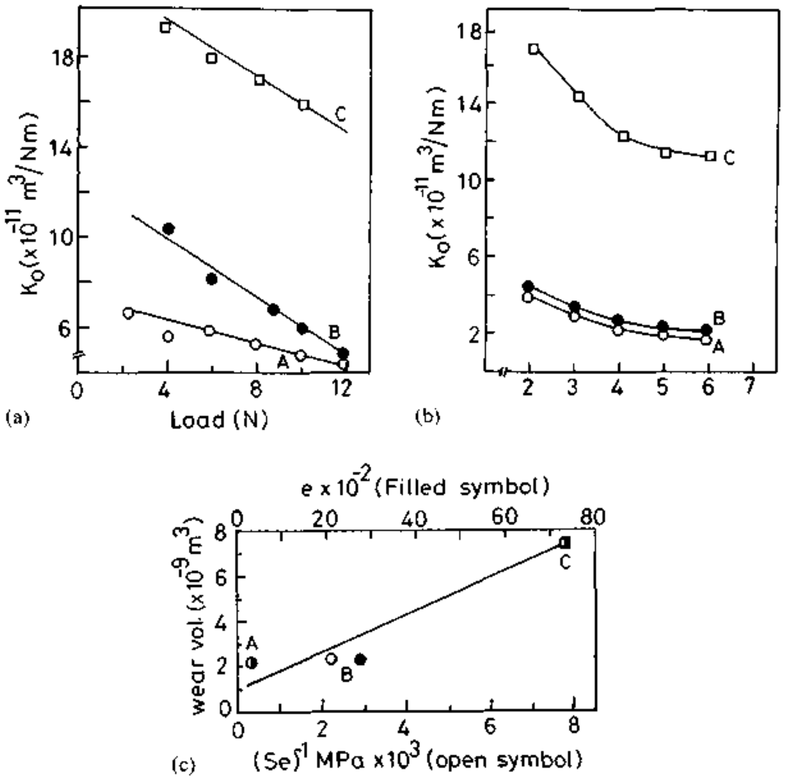


Fig. 4. (a) Abrasive wear in single pass condition: specific wear rate as a function of load (speed, 5 cm/s; grit size, 52 μm; distance abraded, 4 m). (b) Abrasive wear in multi pass condition: Specific wear rate of selected materials as a function of load (speed, 43 cm/s; grit size, 52 μm; distance abraded, 100 m); (c) Ratner–Lancaster plot: wear volume as a function of $(Se)^{-1}$ and e^{-1}(single pass condition).

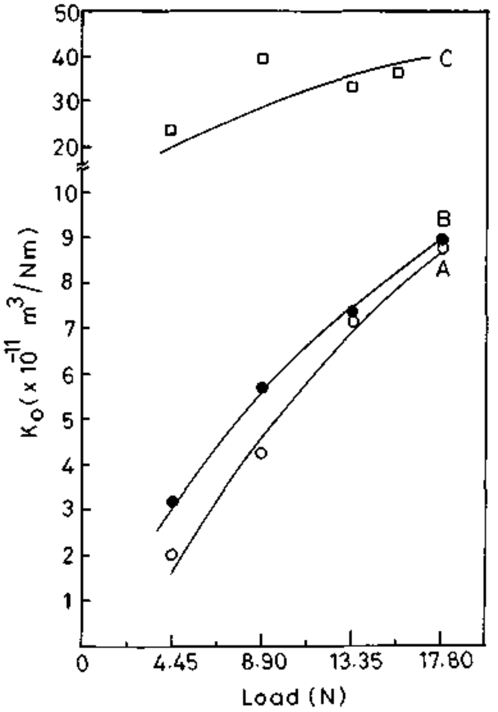


Fig. 5. Third body abrasion: specific wear rate of selected materials as a function of load (speed, 100 rpm; size of abrasives, ≅300 μm; abrading time, 2 min).

yet been reported. As per literature generally incorporation of fibers or fillers in polymers resulted in deterioration in erosive wear resistance of a parent polymer. In the present case also similar trend was observed.

In the case of erosive wear and impact angle relationship, angle at which maximum wear takes place (α_{max}) is very important since it reflects the mode of failure of material, for example ductile, semi-ductile or brittle [27]. Zahavi and Schimitt [22] studied composite of quartz-PI at various impact angles and α_{max} observed that at 75° erosion rate was maximum indicating brittle failure of the material. Mathias et al. [23] reported that the erosive wear resistance of long

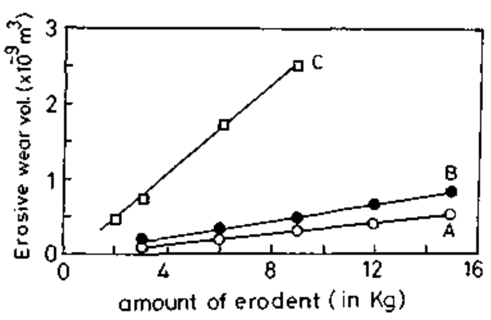


Fig. 6. Erosive wear as a function of mass of erodent (pressure, 45 psi; impact angle, 45°; impinging particle size, ≅80 μm).

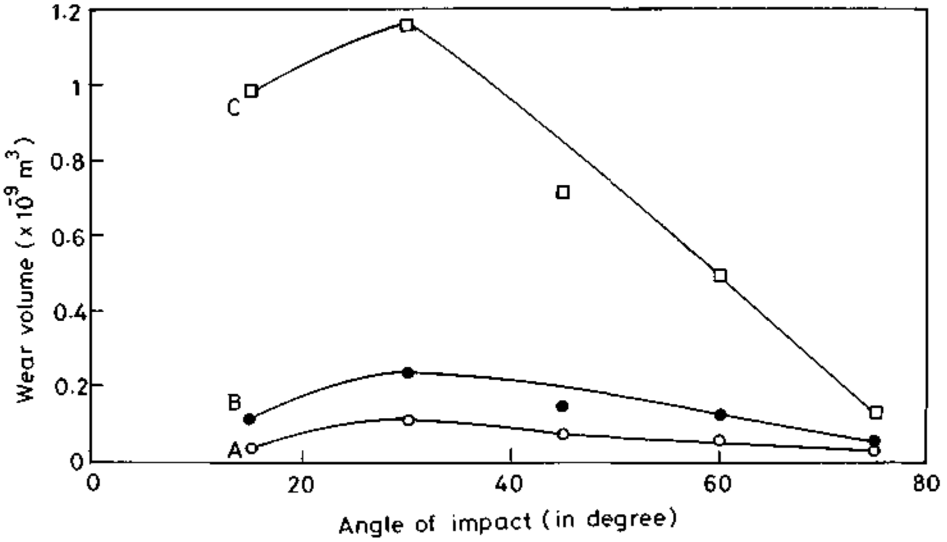


Fig. 7. Erosive wear as a function of angle of impact (pressure, 45 psi; amount of erodent, 3 Kg; impinging particle size, ≅80 μm).

CF reinforced bismaleimide (BMI) composite was less than the parent polymer and higher erosion at an angle 90° (indicating brittle behavior) than for 30°. For neat polymer, wear was independent on impact angle. Brandstadter et al. [24] and Karasek et al. [25] studied erosion behavior of BMI and its graphite FRCs at various impact angles and velocities and reported that the composite material was more susceptible to erosion damage rather than the parent polymer. Both the materials eroded in a brittle manner. Pool et al. [26] reported maximum wear of PI composite as compared to epoxy and PPS composites. They also reported maximum wear at $\alpha = 90°$ for graphite FRCs of PI indicating brittle behavior. For epoxy-Kevlar composite, however, α_{max} was observed in the range 34–45° indicating semiductile behavior. PPS composite with chopped graphite fibers showed best behavior and maximum shown at $\alpha = 25°$ indicating ductile behavior. In the present work also, maximum was observed at $\alpha = 30°$ indicating ductile behavior of PEI matrix.

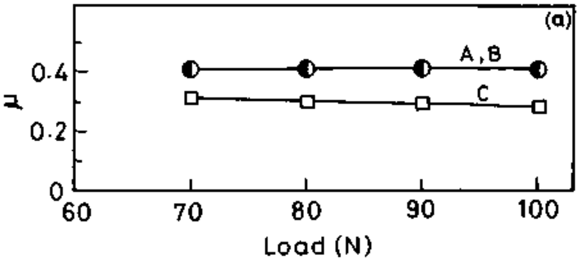


Fig. 9. Influence of load on friction coefficient of A, B and C (fretting wear mode).

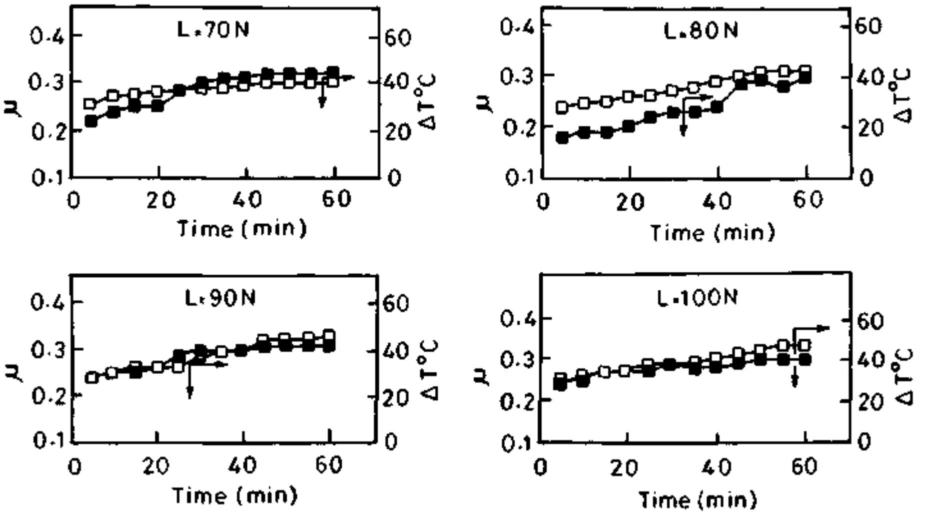


Fig. 8. Friction coefficient as a function of fretting time under various loads for composite C.

3.3.1. Fretting wear studies

Performance of materials in this wear mode is shown in the Figs. 8–10 while microscopic observations on worn surfaces are shown in Figs. 11 and 12. Friction coefficient as a function of sliding duration at various loads for composite C is shown in Fig. 8. Since materials A and B did not show any change in friction coefficient in this context the respective graphs for these materials are not shown here. Instead, average friction coefficient as a function of load for all the selected materials is shown in Fig. 9. Specific wear rates as a function of load for these three materials are shown in Fig. 10. Following were the salient features of the studies:

- Friction coefficient of materials A and B was constant (0.4) irrespective of variation in load and fretting duration.
- Inclusion of three lubricants in composite C affected the friction coefficient of neat PEI in a beneficial way. It reduced further from 0.40 to 0.28 with increase in load.
- With increase in fretting duration, under various loads it slowly increased from 0.2 to 0.3 (Fig. 8).
- Unlike friction coefficient, specific wear rates of all the materials very much depended on operating conditions.
- Both the materials A and B exhibited wear rates in the order 10^{-14} m^3/N m while wear rate of composite C was in the order of 10^{-15} m^3/N m. The friction and wear performance of the composite C was significantly better than the materials A and B. 20% GF in PEI improved the wear resistance of neat PEI by 6–7 times. Further inclusion of three solid lubricants along with 25% GF, improved the wear performance of the composite C almost by 18–20 times. Performance rankings among the materials, were the same in both the modes, adhesive and fretting; though

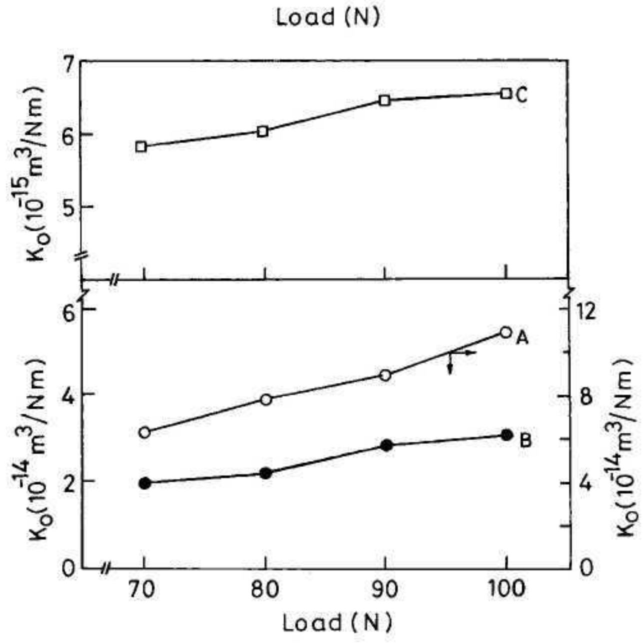


Fig. 10. Influence of load on specific wear rates of A, B and C (fretting wear mode).

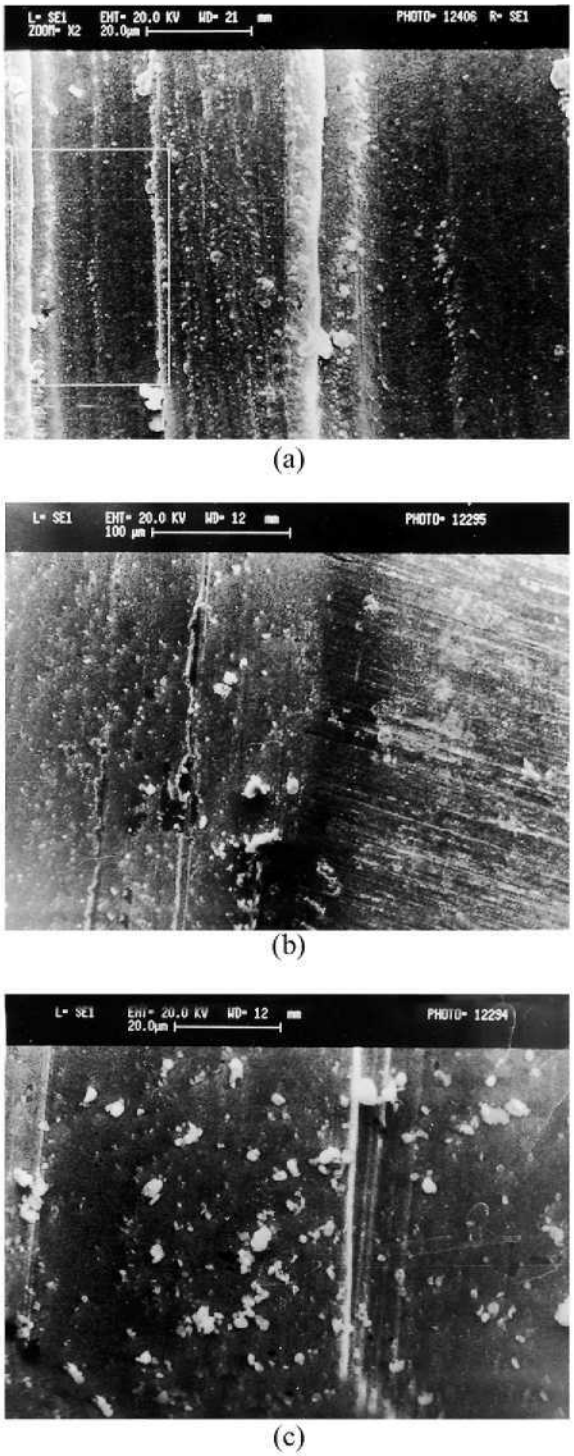
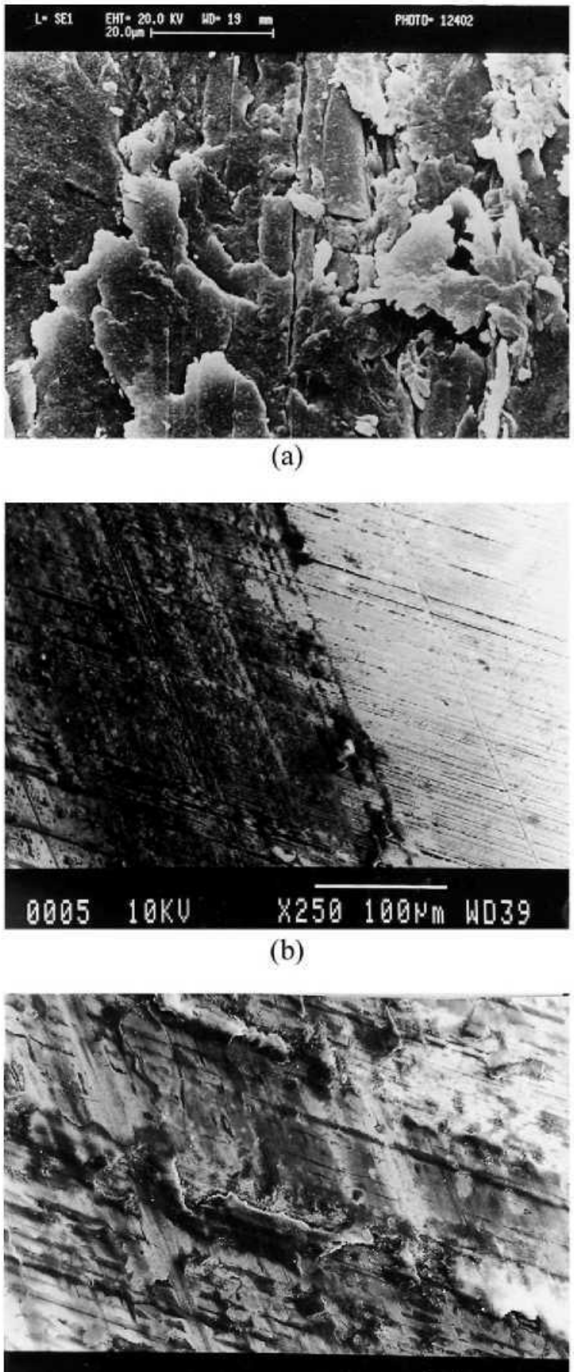


Fig. 11. Micrographs of worn surfaces of PEI (a) and corresponding disc (b and c) fretted under 100 N load: (a) pin surface showing embedded wear debris (both PEI and metal) from the third body interface; (b) disc surface showing transferred thin layer of PEI along with the wear debris (left portion) and unworn disc surface (right portion); (c) enlarged view of the disc showing details of debris and material transfer.



(a)

(b)

(c)

Fig. 12. Micrographs of worn surface of composite C and corresponding disc fretted under 100 N load: (a) pin surface showing array of broken glass fibers, deterioration in fiber-matrix adhesion, wear thinned and elongated sheets of graphite (left portion) and PTFE (right portion); (b) corresponding disc surfaces showing thin layer of material transfer; (c) enlarged view indicating coherent film transfer due to lubricants.

extent of improvement due to fillers and fiber was different. In the case of adhesive wear mode the extent of improvement was significantly large, i.e. by the order of three while in the fretting wear mode it was by 20 times for composite.

- With increase in load, performance of neat PEI deteriorated significantly while that of composites B and C deteriorated marginally.

Few papers are available on fretting wear performance of PIs and composites [28–30]. However, a little is reported on fretting wear performance of PEI and composites. Reinicke et al. [13] studied fretting wear behavior of PEI + 30% GF and PEI + 30% GF + 15% PTFE composites on SRV Optimol tester under different operating conditions with a view to examine the effect of PTFE on fretting wear performance of GF composite. They observed that PTFE incorporation in 30% GF + PEI composite reduced the friction coefficient marginally from 0.5 to 0.45 and was effective in all the conditions of temperatures and loads. However, PTFE was not very effective in enhancing wear properties of PEI + GF composite. It reduced K_0 from 5×10^{-14} to $4 \times 10^{-14}\,\mathrm{m^3/N\,m}$ at low load (10 N) and room temperature. At high temperature (150°C) and low load (10 N), PTFE reduced K_0 from 7×10^{-14} to $6 \times 10^{-14}\,\mathrm{m^3/N\,m}$. At higher load (30 N), however, it increased the wear rate from 8×10^{-14} to $14 \times 10^{-14}\,\mathrm{m^3/N\,m}$ indicating unsuitability of PTFE for high load applications. In the present case, interestingly combination of three lubricants in PEI + GF (25%) composite worked very well. It improved both friction and wear performance of GF+PEI composite significantly under all loads and temperatures confirming that the combination of lubricants was more effective than a single lubricant.

Friction and wear mechanisms in fretting wear are significantly different from that in adhesive wear mode. In the case of fretting wear of polymers, wear debris is generated both from base polymer, fibers, solid lubricants (if any) and metallic counterface and get entrapped in contact region. This debris then form a "third body interface" and the wear mechanism changes from solid body friction to a kind of either third body abrasion or dry lubricated friction depending on the nature of debris. Thus, fretting friction is significantly different from the friction in unidirectional sliding condition (adhesive wear mode) [31]. In the present case, wear debris in the case of each material was different. In first, it was that of PEI and metallic powder due to abrasion of mild steel by hard PEI[3] while in the second it contained more additional debris of GF. Third type of debris contained still additional particles viz. that of three solid lubricants and this was responsible for bringing down friction coefficient from 0.4 to 0.25.

Incorporation of fibers, generally reduces wear rates because of increase in load carrying capacity, resistance

---

[3] Counterface also showed measurable wear and crater of observable size.

to creep, thermal conductance and, hence, wear resistance. When solid lubricants are also present in the debris, it gets transferred on the counterface and abrasion action by the third body interface reduces significantly leading to low friction and wear [31]. This was observed in the microscopic studies on the counterface as discussed in the later section. K_0-values of FRC (composite C) increased with the load because of following reasons. Probability of fiber cracking increased with the increase in load. Since fibers are the main constituents to inhibit wear of matrix; their cracking, pulverization and subsequent transfer in the third body interface leads to the increase in wear. With increase in load, subsequent flash temperature increases leading to the following. Fiber-matrix adhesion deteriorated and pulling out or peeling off of pulverized fibers from the matrix became easy and, hence, wear increased with increase in the load. In the case of neat polymer also wear increased with the increase in load and temperature because polymers lose their mechanical strength at elevated temperatures leading to high wear.

Effect of solid lubricants on performance of a composites has been most unpredictable in fretting wear mode. Bill [28] reported about the detrimental effect of MoS_2 in the selected PI while Abarou and Play [29] reported on the benefits endowed by incorporating solid lubricants such as CF_x and graphite in PI, but not PTFE. These were claimed to be due to film transfer on metal during fretting. Chievers and Gordelier [30] reported on the positive effect of graphite in PI and epoxy composites.

Microscopic studies on various surfaces of pin and discs are shown in Figs. 11 and 12. Surfaces of PEI pin (Fig. 11a) and disc (Fig. 11b and c) worn under 100 N load showed the following features. Pin surface is embedded with different types of the wear debris probably of metal and polymer transferred from the third body interface formed during fretting [28]. Disc surface also showed thin transferred layer of PEI along with the wear debris (Fig. 11b and c).

Worn surfaces of composite C and corresponding disc are shown in Fig. 12. Micrograph in Fig. 12a is for the pin surface fretted under 100 N load and showed elongated sheets of PTFE, graphite flakes (left bottom portion), cracked/broken fibers, and enhanced fiber-matrix de-bonding. Micrographs in Fig. 12b and c show the details of the material transferred on the disc especially due to the three solid lubricants.

4. Conclusions

Three materials viz. neat PEI (A), PEI + 20% short GF (B) and PEI + 25% short GF + 15% PTFE + 15% (MoS_2 and graphite) (C) were examined for their performance in various wearing modes. These were adhesive, abrasive (three types), erosive and fretting wear. Various operating parameters such as loads, speeds, counterface roughness, etc. were selected as operating conditions. It was concluded that performance of materials very much depended on type of wear mode. Following was the performance ranking observed in these wear modes:

- Adhesive wear mode against mild steel — wear performance was in the order $C \gg B \gg A$ and the friction behavior was in the following order $C \gg A > B$.
- Erosive wear mode — wear performance order was $A > B \gg C$.
- Fretting wear mode — wear performance order was $C \gg B > A$ and the friction performance order was $C \gg A \geq B$.
- Abrasive wear mode, wear performance order was

  against SiC paper : single pass condition $A > B \gg C$

  against SiC paper : multi pass condition $A > B \gg C$

  against rubber wheel : three body abrasion $A > B \gg C$

Thus, composite C, commercially established bearing grade material, performed very well in adhesive and fretting wear modes. Inclusion of GF and three solid lubricants improved the wear performance of neat PEI by the order of three in adhesive wear mode and friction performance by three times. In fretting wear mode, approximately 20 times improvement in wear resistance could be achieved due to reinforcement and solid lubrication while improvement in friction was by two times. Operating parameters such as load, speed, temperature, sliding duration influenced the performance of materials significantly. The same fillers proved detrimental in the case of abrasive and erosive wear performance.

Acknowledgements

The authors gratefully acknowledge the financial aid by Council for Scientific and Industrial Research (CSIR), New Delhi, India for carrying out part of the research work in this paper. The authors are also thankful to GE Plastics Inc., USA for supplying materials for this research work.

References

[1] A.M. Hager, M. Davies, Short fiber-reinforced high temperature resistant polymers for a wide range of tribological application, in: K. Friedrich (Eds.), Advances in Composites Tribology, Composite Materials Series, Vol. 8, Elsevier, Amsterdam, 1993 (Chapter 4).

[2] J. Bijwe, M. Fahim, Tribology of high performance polymers: state of art, in: Handbook of Advanced Functional Molecules and Polymers, Gordon and Breach, London, 2000.

[3] J.C. Anderson, P.K. Williamson, Relating laboratory wear testing to the in-service wear of polymers, in: L.H. Lee (Eds.), Polymer Wear and its Control, ACS Symposium Series, Vol. 287, American Chemical Society, Washington, DC, 1985, pp. 315–331.

[4] S. Bahadur, D. Gong, J. Anderegg, Investigation of the influence of CaS, CaO and CaF_2 fillers on the transfer and wear of nylon by microscopy and XPS analysis, Wear 197 (1996) 271–279.

[5] J. Bijwe, J.N. Mathur, U.S. Tewari, Influence of reinforcement and lubrication on abrasive wear performance of polyamide, J. Synth. Lubric. 8 (3) (1991) 177–195.

[6] J. Bijwe, S. Neje, J. Indumathi, M. Fahim, Friction and wear performance evaluation of carbon fiber-reinforced PTFE composite, J. Mat. Sci., submitted for publication.

[7] I.W. Sarfaty, Polyetherimide: a versatile processable thermoplastic resin, J. Polym. Sci. Polym. Symp. 70 (1983) 129.

[8] The Comprehensive Guide to Material Properties, Design Processing and Secondary Operation — ULTEM Polyetherimide Resin, A catalogue by General Electric company.

[9] J.H. Yoo, N.S. Eiss, Tribological Behavior of Blends of PEEK and PEI, Wear 162–164 (1993) 418–425.

[10] J. Hanchi, N.S. Eiss, The tribological behavior of blends of PEEK, PEI at elevated temperatures, Tribol. Trans. 37 (1994) 494–504.

[11] L.K.E. Templemeyer, P.K. Davies, The abrasive wear of short fiber composites, Composites 16 (2) (1985) 127–136.

[12] J.W.M. Mens, A.W.J. de Gee, Friction and wear behavior of 18 polymers in contact with steel in environments of air and water, Wear 149 (1991) 255–268.

[13] R. Reinicke, F. Haupert, K. Friedrich, On the tribological behavior of selected injection moulded thermoplastic composites, Composites (Part A) 29A (1998) 763–771.

[14] J. Bijwe, Friction and wear of engineering polymers: studies on polyimides/composites, Ph.D. thesis, Indian Institute of Technology, Delhi, 1989.

[15] J. Bijwe, U.S. Tewari, P. Vasudevan, Friction and wear studies of polyetherimide composites, Wear 138 (1990) 61–76.

[16] U.S. Tewari, J. Bijwe, Recent developments in tribology of fiber-reinforced composites with thermoplastic and thermosetting matrices, in: K. Friedrich (Eds.), Advances in Composites' Tribology, Composite Materials Series, Vol. 8, Elsevier, Amsterdam, 1993 (Chapter 5).

[17] U.S. Tewari, J. Bijwe, On the abrasive wear of some polyimides and their composites, Tribol. Int. 24 (1991) 247–253.

[18] J.BijweC.M. Logani, U.S. Tewari, Influence of fillers and fiber-reinforcement on abrasive wear of some polymeric composites, Wear 138 (1990) 77–92.

[19] R. Benzing, I. Goldblatt, V. Hopkins, W. Jamiason, K. Mecklenburg, M. Peterson, Friction and Wear Devices, 2nd Edition, ASLE, Park Ridge, USA, 1976.

[20] N.P. Suh, Tribophysics, Prentice-Hall, Englewood Cliffs, NJ, 1986.

[21] J. Lancaster, Abrasive wear of polymers, Wear 14 (1969) 223–239.

[22] J. Zahavi, G.F. Schmitt Jr., Solid particle erosion of reinforced composite materials, Wear 71 (1981) 179–190.

[23] P.J. Mathias, W. Wu, K.C. Goretta, J.L. Routbort, Solid particle erosion of a graphite fiber-reinforced bismaleimide polymer composite, Wear 135 (1989) 161–169.

[24] A. Brandstadter, K.C. Goretta, J.L. Routgort, D.P. Groppi, K.R. Karasek, Solid particle erosion of bismaleimide polymers, Wear 147 (1991) 156–164.

[25] K.R. Karasek, K.C.GorettaD.A. Helberg, J.L. Routbort, Erosion in bismaleimide polymers and bismaleimide–polymer composites, J. Mater. Sci. Lett. 11 (1992) 1143–1144.

[26] K.V. Pool, C.K.H. Dharan, I. Finne, Erosive wear of composite materials, Wear 107 (1986) 1–12.

[27] I.M. Hutchings, Tribology: Friction and Wear of Engineering Materials, Edward-Aronold, UK, 1992.

[28] R.C. Bill, Selected fretting wear resistant coatings for Ti–6%Al–4%V alloy", Wear 106 (1985) 283–301.

[29] S. Abarou, D. Play, Wear transition of self-lubricating composites used in dry oscillating applications, ASLE Trans. 30 (3) (1987) 269–281.

[30] T.C. Chievers, S.C. Gordelier, Fretting fatigue palliatives: some comparative experiments, Wear 96 (1984) 153–157.

[31] K. Schulte, K. Friedrich, O. Jacobs, Fretting and fretting fatigue of advanced composite laminates, in: K. Friderich (Eds.), Advances in Composites Tribology, Composite Materials Series, Vol. 8, Elsevier, Amsterdam, 1993.