Studies on abrasive wear of carbon fibre (short) reinforced polyamide composites

U. S. Tewari, J. Bijwe, J. N. Mathur and Indu Sharma*

This paper reports the results of the abrasive wear investigations of various composites of polyamide (nylon 6,6) reinforced with increasing amounts of carbon fibre against various abrasive papers under dry conditions. The object was to study the influence of parameters such as: amount of fibre, its orientation, effect of solid lubricant (PTFE), and other experimental parameters eg load and abrading particle size. It was observed that wear rates increased rapidly with increasing fibre concentration. A combination of particulate filler (PTFE) and carbon fibre proved to be very detrimental to abrasive wear resistance. Load, abrading particle size and fibre orientation were observed to be important factors in these studies. Efforts are made to correlate wear behaviour with appropriate mechanical properties. Ratner/Lancaster plots did not show linearity. Instead, a proportional rise in wear was noticed with an increase in e^{-1}, where e is ultimate elongation, with the exception of one composite. Worn surfaces were studied with a SEM to give a greater insight into the wear mechanisms.

Keywords: *dry abrasion, wear, carbon fibres, scanning electron microscopy, (polyamide) composite*

Introduction

Innovations in modern technology are placing ever-increasing demands on advanced composite materials. Polymeric composites, especially fibre-reinforced thermoplastics (FRTPs), form an excellent class of tribo-materials because of their high specific strength and stiffness, properties available through controlled combination of fibre and matrix, combined with their excellent adhesive wear performance. FRTPs excel in highly abrasive systems such as: conveyor aids, vanes and gears for pump handling industrial fluids, sewage and abrasive contaminated water; chute liners in agricultural, mining and earth-moving equipment; roll neck bearings in steel mills subjected to heat, shock loading, water and mill scale; chute liners abraded by coke, coal and mineral ores; guides in bottle handling plants; bushes and seals in agricultural and mining equipment; and sluice gate bearings[1–3]. Large amounts of data are available concerning the wear performance of advanced composites in adhesive applications[4–6]. On the other hand, data regarding abrasive wear investigations of FRTPs are limited. Hence, a fundamental and comprehensive understanding is necessary of the abrasive wear mechanism of these composites.

Polyamide (nylon 6,6), an engineering thermoplastic and its filled and reinforced composites are being extensively used as a tribo-material in various applications such as in bearings, gears and the tyre related industries[7,8]. Very little has been reported on the effect of filler or reinforcement on the abrasive wear performance of nylon[9,10]. It is accepted that tribo-properties are not intrinsic material properties[11], rather these strongly depend on the tribo-system as shown in Fig 1. The influence of such parameters cannot always be predicted *a priori* and will be investigated in an actual tribo-system. In the present work nylon 6,6 and its various carbon-fibre-reinforced composites were selected. These composites are known to have excellent potential in adhesive wear applications[8]. Wear behaviour of these composites in abrasive conditions has not yet been reported.

During the process of abrasion, wear debris formation occurs due to microploughing, microcutting and microcracking mechanisms induced by the hard asperities of the counterface. The effective contribution of the three individual mechanisms to abrasive wear is a function of abrading surface properties such as: counterbody asperities, their shape, size, sharpness, hardness and grain density[12–14]. For investigating the influence of these parameters on the wear of composites, different grades of grinding paper are used for simulating the counterface properties with variations. In this work, polyamide and its composites were abraded under different loads against various sizes of abrasive paper.

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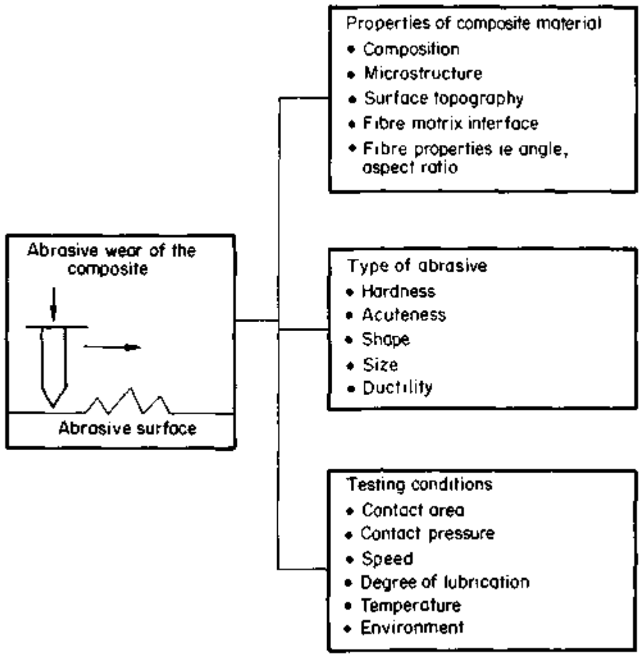

Fig 1 Dependence of abrasive wear on tribo-system

The effects on wear were studied of fibre concentration and orientation, load, and abrading particle size. Efforts were made to correlate wear performance to relevant mechanical properties.

Experimental

Materials selected

Nylon 6,6 and its various composites, reinforced with short carbon fibres (see Table 1), were supplied by M/s Hysol Grafil Company, UK in the form of small bars. Square samples (12 mm× 12 mm) with a 4-mm thickness were cut from these bars while studying the effect of fibre orientation; however, the contact area of the samples was different. The data supplied by the manufacturer on composition and mechanical properties are presented in Table 1. Friction and wear properties in the adhesive wear mode are also included. Since the data were not supplied on ultimate tensile strength and ultimate elongation, these were generated on a universal testing machine, capacity 9.84 tonnes (10 tons), using the ASTM D638 method (Table 2). Waterproof silicon carbide (SiC) abrasive papers of

Table 1 Details of selected composites (supplier's data)

Property	ASTM	Unit	Nylon 6,6	Nylon 6,6 20% CF*	Nylon 6,6 + 30% CF*	Nylon 6,6 + 40% CF*	Nylon 6,6 + 30% CF* + 15% PTFE*
Designations			A	B	C	D	E
Density	D792	g cm^{-3}	1.14	1.23	1.28	1.34	1.33
Mechanical tensile strength (at 23°C)	D638	MPa	81	193	241	276	209
Tensile elongation	D638	%	10	3–4	3–4	3–4	3–4
Flexural strength		MPa	103	289	351	413	278
Flexural modulus	D790	GPa	2.8	16–5	20	23.4	15.2
Thermal heat distortion temperature	D648	°C	66	257	258	260	258
Continuous service temperature		°C	—	110	110	110	110
Thermal conductivity		W m^{-1} K^{-1}	0.24	0.79	1.05	1.22	0.95
Thermal expansion	D696	$\times 10^{-5}$ K^{-1}	8.1	2.5	2.6	1.4	2.6
Frictional coefficient (static)			0.2	0.16	0.16	0.13	0.11
Dynamic (μ)			0.28	0.20	0.20	0.18	0.15
Wear factor			200	40	20	14	10
Limiting PV							
(a) 0.05 m s^{-1}			3000	—	21 000	—	29 000
(b) 0.50 m s^{-1}			2500	—	27 000	—	42 000
(c) 5.00 m s^{-1}			2500	—	8 000	—	19 000

**Filler and fibre % are by weight. The figures quoted are specific to the standard moulding procedure and test method used and are intended only as a guide to the comparative material performance*

Table 2 Data on mechanical properties of the composites (generated in laboratory)

Property	ASTM	Unit	A (Nylon)	B (Nylon+ 20%CF)	C (Nylon+ 30%CF)	D (Nylon+ 40%CF)	E (Nylon + 30% CF + 15% PTFE)
Ultimate tensile strength (*S*)	D698	MPa	29.87	98.23	144.92	161.98	89.70
Ultimate tensile elongation (*e*)		%	92	9.67	6.93	6.6	10.33
$(e)^{-1} \times 10^{-2}$			1.08	10.3	14.4	15.2	9.7
$(S)^{-1} \times 10^{-2}$			3.35	1.02	0.69	0.62	1.11
$(Se)^{-1} \times 10^{-4}$			3.62	10.51	9.94	9.42	10.76

various mesh sizes (80, 100, 120, 180, 220, 320 and 400) were selected as abrading counterfaces for polymeric samples. All papers were selected from the same sample to avoid effects due to sample variations in the manufacturing process.

Abrasive wear studies

Studies were made using a pin-on-disc machine[10]. Abrasive paper was fixed onto the disc which rotated with a set speed (5 cm s^{-1}). Polymer samples fixed in a holder were abraded in a circular path (single pass condition) for a selected abrading distance (1.28 m). Dead-weights (8, 10, 12, 14 N) were applied on the sample while studying the effect of load on wear. Two fibre orientations were selected, normal and parallel to the abrading surface. Wear was measured by weight loss. Before and after the wear tests, pins were cleaned with acetone in an ultrasonic cleaner, dried, and then weighed. Pin surfaces were examined by an optical microscope to ensure no emery particles had stuck to the pin surface. The specific wear rate, K_0, was calculated from the following equation:

$$K_0 = V/Ld \tag{1}$$

where V is wear volume in cubic metres, L is load applied in Newtons and d is the distance abraded in metres.

SEM studies

Polymer pin and paper surfaces were silver sputtered to make them conductive and observed using a Phillips 515 scanning electron microscope (SEM).

Results and discussion

The effect of filler concentration on the abrasive wear of selected composites is shown in Fig 2. Wear property correlations are shown in Fig 3. Wear as a function of $(Se)^{-1}$ (Ratner-Lancaster plot) is shown in Fig 3 (S is ultimate tensile strength and e is ultimate elongation). Wear versus e^{-1} is also plotted in the same figure. Wear as a function of load and abrading particle size is shown in Figs 4 and 5, respectively. The effect of fibre orientation on wear is shown in Fig 6 and Table 3. The effect under the multi-pass condition[15] is also summarized in Table 3. SEM micrographs of pin and paper surfaces are shown in Figs 7–9.

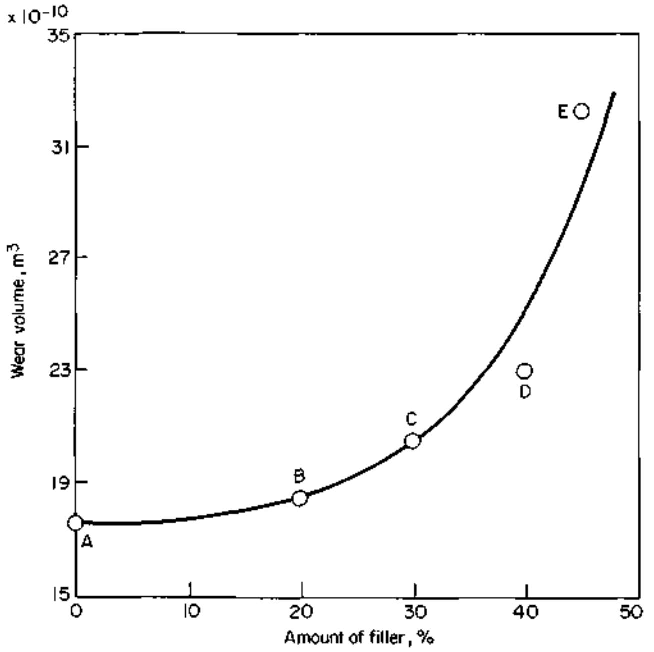

Fig 2 Wear as a function of concentration of carbon fibre (load = 8N; speed = 5 cm s^{-1}, abrasive paper mesh size = 220 and abraded distance = 1.72 m)

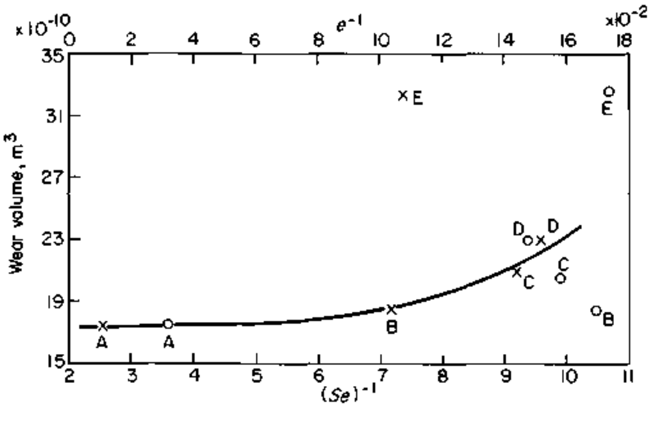

Fig 3 Wear as a function of $(Se)^{-1}$ (Ratner-Lancaster plot) and e^{-1}. Crosses signify e^{-1} points, circles signify $(Se)^{-1}$ points

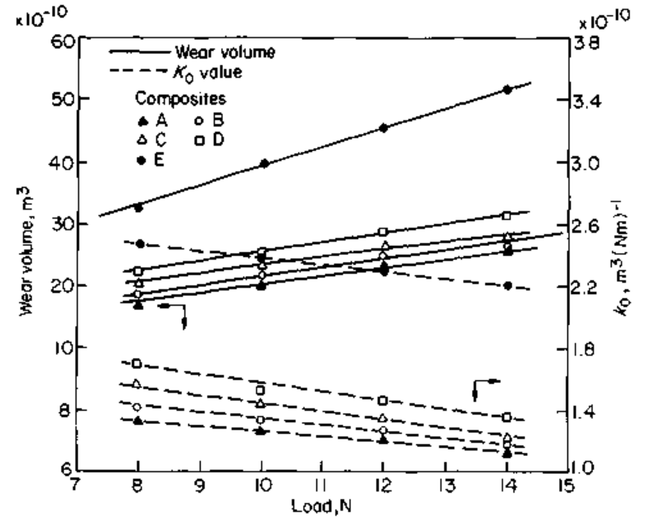

Fig 4 Wear and specific wear rate as a function of load (speed = 5 cm s^{-1}, abrasive paper mesh size = 220, and abraded distance = 1.72 m)

From Fig 2, under selected loading conditions, wear of the composites increased almost exponentially with respect to an increase in reinforcement. Excessive wear was exhibited by the composite E which contained a combination of two types of filler, particulate (PTFE) and fibrous (carbon). It is important to note that the same composite E showed its best combination of friction and wear properties in the adhesive wear mode (Table 1). Thus, fillers which are beneficial to a particular wear mode can be equally unsuitable for another type. Wear of these composites under various loads has shown a similar trend.

Literature surveys indicate that the effect of filler on the abrasion of plastic is a complex and unpredictable phenomenon[16]. A comparison between the wear performance of parent polymers and composites has revealed in many cases a deterioration in wear resistance because of filler addition[12,17,19]. However, mixed trends[9–11,16] or an improvement in wear resistance[1,19], have also been reported for continuous fibre reinforcement.

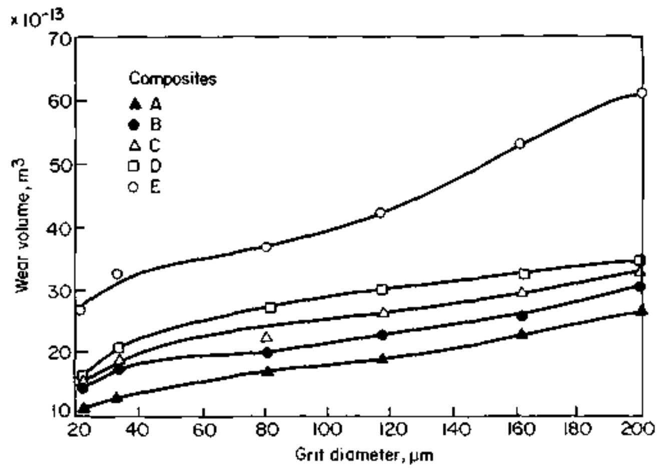

Fig 5 Wear as a function of abrading particle size (load = 10 N, speed = 5 cm s^{-1}; abrasive paper mesh size = 200, and abraded distance = 1.28 m)

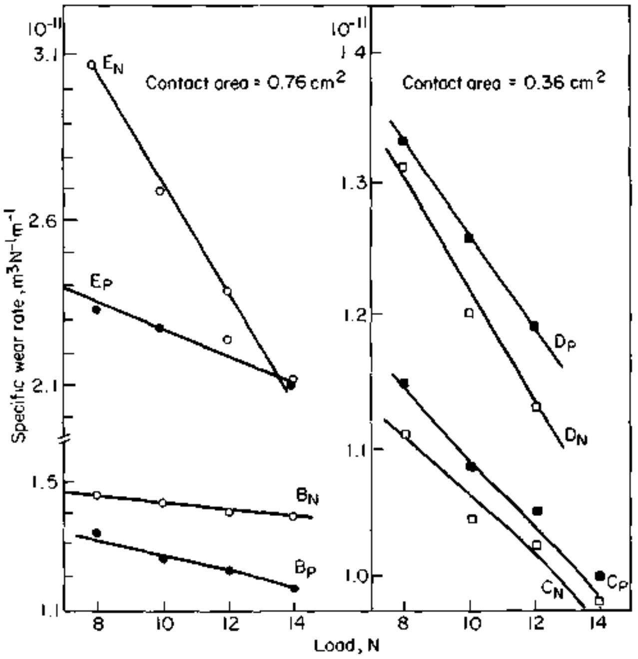

Fig 6 Wear as a function of load for the composites with different fibre orientation; (○—○) fibre normal to surface; (●—●) parallel to the surface (speed = 5 cm s^{-1}, abrasive paper mesh size = 220 and abraded distance 2.18 m)

Comparatively less effort has been directed towards the investigation of the effect of increasing amounts of particulate filler[16,17] and fibre[11,18] on the abrasive wear performance of composites. Small percentages of filler raise the wear resistance of plastics. Further increases or reductions in wear can occur with an increase in filler depending on the nature of the filler and polymer[16]. A continuous decrease in wear was noticed in the case of PP + TiO_2[15], an increase in the case of PEEK + PTFE[17] and minima at typical concentrations of filler[16].

From Table 2, it seems that *S* and *e* of the composites, showed a regular increase and decrease respectively, as the amount of filler increased, with the exception of composite E, whilst $(Se)^{-1}$ did not reveal any regular pattern. From Fig 3, wear versus $(Se)^{-1}$ (Ratner-Lancaster plot) did not show a proportional relationship. On the other hand, wear showed almost an exponential increase with respect to an increase in e^{-1}. Thus, elongation to break was observed to be a more prominent controlling factor in the case of the abrasive wear of these composites. Composite E showed disproportionate wear which could be because of a combination of two basically different types of filler (fibre and powder). In our earlier work[10] it was proved that such a combination of fillers was unsuitable for the abrasive wear resistance of composites.

Several efforts have been made to correlate abrasive wear to appropriate mechanical[12,19,20] or other physical properties[21]. According to Lancaster[9], the *Se* factor is of more importance. Although the addition of fillers and reinforcements increases the strength and stiffness of polymers, there is generally a corresponding reduction in elongation to break, *e*. The product *Se*

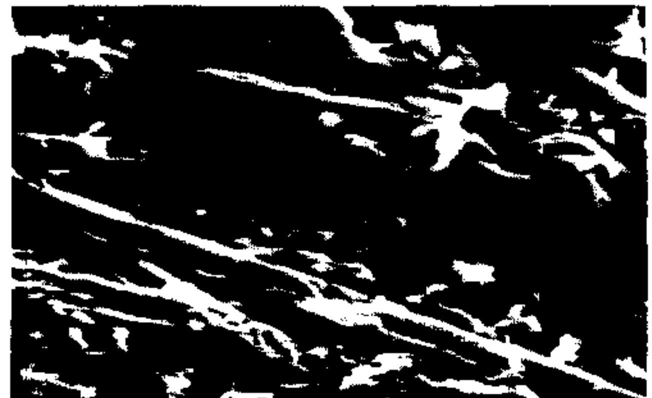

Fig 7 SEM micrographs of surface of composite D worn under different loads (a) 6 N; (b) 14 N

for a reinforced polymer may thus become smaller than that for an unreinforced one, with a consequent reduction in abrasive wear resistance. Ratner and Farberova[16] consider that the reduction in elongation to break is the concomitant factor influencing abrasive wear resistance and this is confirmed by the present results.

The effect of load on wear performance and specific wear rates of composites is shown in Fig 4. For all the composites, an increase in load resulted in a linear and slow increase in wear and a decrease in wear rates.

While studying the effects of normal load (F_N) on the specific wear rates (K_0) of fibrous polymer composites against SiC abrasive papers, Lhymn[22] proposed a mathematical model to account for crack propagation. According to him, the following equation is applicable when thermal activation is insignificant, as in the case of abrading at low speed:

$$K_0 = K_6 \cdot \frac{V_s}{EHC_f\mu_\alpha} \cdot V_c \cdot \frac{1}{F_N} \qquad (2)$$

where K_6 is the proportionality constant, V_s is the sliding speed, E is the elastic modulus, H is the hardness and C_f is wear failure strain, μ_α the friction coefficient, V_c is the crack growth velocity, and F_N is the normal load. This equation indicates that wear rate is inversely proportional to the normal load F_N. If F_N or V_s is large, thermal effects become significant and this relationship is not applicable.

Both F_N and V_s are small in this case so that Eq (2) is applicable and hence, wear rates decrease linearly with an increase in load.

The effect of abrading particle size on wear performance of composites is shown in Fig 5. Composites A, B, C and D showed a slow and almost linear increase in wear with an increase in the grit diameter of the abrasive paper. Composite E, however, showed a rapid increase in wear with larger grit diameter. The different behaviour of composite E again could be because of the combination of two different types of filler. In the case of metals many data have been reported on the wear-grit diameter relation[23]. Metals are known to exhibit a size-effect phenomenon in such a relationship. After the application of a typical size of abrading grit, the metal wear shows up as either a saturation effect or very little increase. Limited research efforts have been directed towards examination of this effect for polymers. Some polymers are observed to exhibit size effects similar to that of metals[24,25]. For polymer composites even less effort has been made in this area[10,13–15,25] and mixed trends have been reported[15]. No clear indication of size effect was observed in this study.

The effect of fibre orientation on abrasive wear performance of the composites is shown in Fig 6. Similar studies under multi-pass conditions[15] (speed 0.43 m s^{-1} and abrading distance 100 m) are also included for comparison in Table 3. Because of some experimental constraints, the contact area of all the samples could not be kept the same. When contact area was higher, resulting in lower contact pressure, composites B and E with normal fibres showed greater wear than those with parallel fibres, while the reverse trend was shown by composites C and D with smaller contact area.

In the literature, mixed trends have been reported on the effects of fibre orientation on wear. Generally fibres normal to the surface result in better performance[12,18]. However, there is some conflicting evidence[1,26]. The effect of alignment of fibres on wear varies depending upon the fibre type, aspect ratio, polymer matrix, and nature and type of abrading paper. The geometry of the contacting surface and area also plays an important role in such cases. For continuous carbon-fibre reinforcement in PEEK and epoxy resin, normal orientation gave greater wear than with parallel fibres, while glass-fibre and aramid fibres in epoxy and PEEK showed better performance in the normal direction[1,19]. Here, however, contact area proved to be an important factor in deciding the wear performance of composites with different fibre orientations.

Studies of SEM have been grouped, in Figs 7–9, in the form of micrographs. SEM micrographs of the pin surface of composite D abraded under two extreme

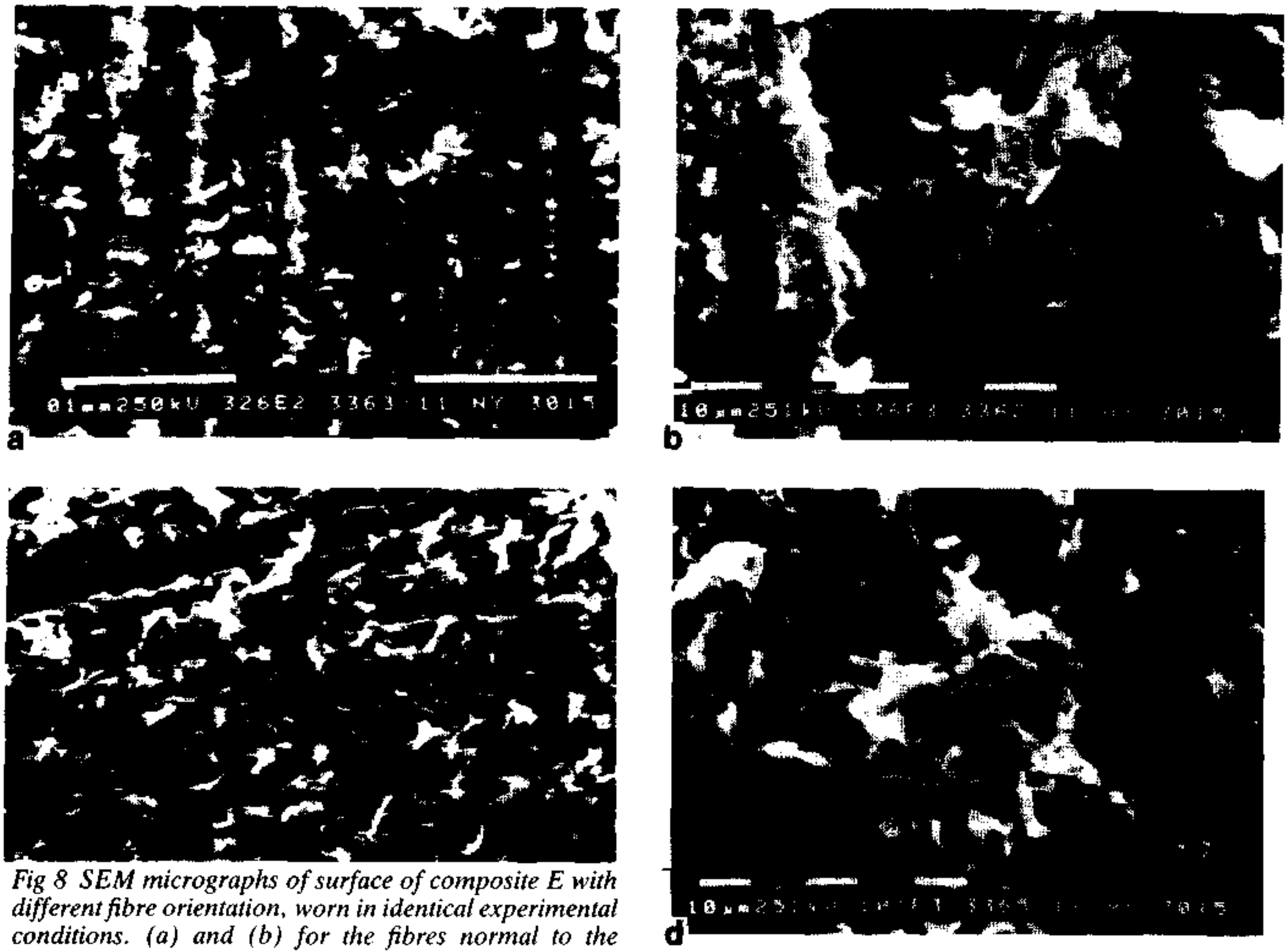

Fig 8 SEM micrographs of surface of composite E with different fibre orientation, worn in identical experimental conditions. (a) and (b) for the fibres normal to the surface and (c) and (d) for fibres parallel to the surface. Figure 8(a) × 326; 8(b) × 1360; 8(c) × 341 and 8(d) × 1010

loads are shown in Fig 7. Fibre orientation was in the direction parallel to the sliding surface. Comparatively less damage occurred to the surface when the load applied was small (Fig 7(a)). Carbon fibres seem to be intact. However, microcracks initiated in the fibres (the middle section of the micrograph) are also visible. This is the first stage of pulverization, or breakage, of the fibre. Brittle fracture of the polymeric material and plastic deformation because of the cutting action are apparent on the surface. Similar features were observed on the polymer surface (composite D) abraded under higher load (14 N, Fig 7(b)). The extent of damage to the fibres, however, is severe. Some of the fibres are broken and pulled out from the polymeric surfaces. Thus, higher loads damage fibres to a larger extent, which in turn results in higher wear.

Table 3 Effect of fibre orientation in the composite on abrasive wear

Composite	Contact area, cm^2	Trend in wear	
		Single pass	Multi pass
B (20% CF)	0.76	N > P	N > P
C (30% CF)	0.36	N < P	N < P
D (40% CF)	0.36	N < P	N < P
E (30% CF + 15% PTFE)	0.76	N > P	N > P

N – Fibre normal to the abrading surface. P – Fibre parallel to the abrading surface

In Fig 8, micrographs of two abraded pin surfaces are shown having two different fibre orientations. Figures 8(a) and (d) are of the composite with parallel fibres. Micrographs at lower magnifications (Fig 8(a): ×326; Fig 8(c) ×341) show a general pattern of the surfaces. Furrows can be seen caused by ploughing of the abrasive particles. Since the composite contains PTFE filler, which is more ductile than nylon, different features on the surfaces were seen. PTFE particles in an elongated form pulled out from the furrows can be seen on the surface (Figs 8(a) and (c)). Figures 8(b) and (d) are for the two pin surfaces with two fibre orientations at higher magnifications (Fig 8(b): ×1360, Fig 8(d): ×1010). Fibre tips can be seen in the furrows (Fig 8(b)), while in Fig 8(d), some long fibres are broken. Some are intact but peeled off from the polymer matrix (extreme right position). Such fibres can be broken easily in successive abrasions. Figure 9

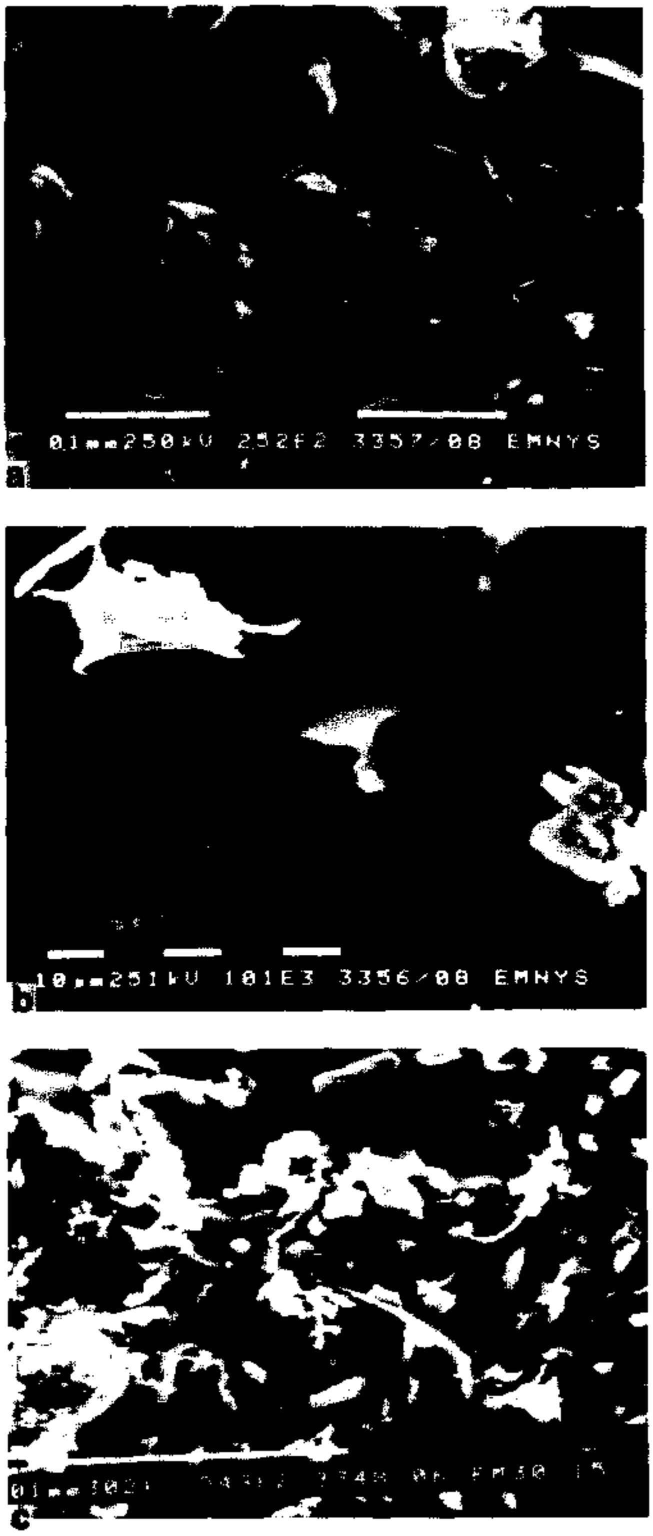

Fig 9 SEM micrographs of worn paper surface against different materials (abrasive paper mesh size = 200): (a) × 252 and; (b) × 1010 against neat nylon; (c) × 549 against composite E

is for micrographs of paper surfaces (220 mesh size) covered with wear debris after abrasion. Figures 9(a) and (b) are of paper abraded against neat nylon with two different magnifications. Shape, size of abrasive particles and nylon wear debris can be seen. Debris in flake form is cut from the polymer surfaces after brittle fracture caused by abrasion. In Fig 9(c), wear debris of composite E can be seen on the paper. A larger amount of debris results because of a high degree of composite wear. Fibrous debris is caused by PTFE filler which has higher ductility than that of nylon.

Conclusions

Abrasive wear studies in dry conditions of nylon 6,6 and its four composites showed that their wear resistance deteriorated because of fibre reinforcement. With an increase in carbon fibre percentage, elongation to break decreased, which is a controlling factor for abrasive wear performance.

Composite E, which contained heterogeneous fillers (fibres and powdery filler), showed exceptional behaviour. Load, fibre orientation, and abrading particle size were observed as important influencing parameters in abrasion studies. SEM studies indicated the existence of fibre pulverization, microcracking, peeling off or pulling out from the polymer surface as a result of abrasion, and the extent to which these factors depended on experimental parameters.

References

1. **Cirino M., Pipes R.B. and Friedrich K.** The abrasive wear behaviour of continuous fibre polymer composites. *J. Mat. Sci., 1987,* **22**, *2461–2492*
2. **Friedrich K.** *in Friction and Wear of Polymer Composites* Composite Material Series 1, (**ed. Friedrich K.**) *1986, Elsevier, Amsterdam, Ch. 8, 133–285*
3. **Thorp J.M.** Abrasive wear of some commercial polymers. *Tribology Int. 1982,* **15**, 59–68
4. **Briscoe B.J.** Wear of polymers: an essay on fundamental aspects. *Tribology Int. 1981,* **14**, *231–243*
5. **Watanabe M. and Yamaguchi H.** The friction and wear properties of nylon. *Wear 1986,* **110**, *379–388*
6. **Lee L.H.** Various approaches in controlling wear of polymers. *in Polymer Wear and its Control.* (**ed. Lee L.H.**) *ACS Symposium Series 287, Washington D.C., 1985; 77–87*
7. **Clauss F.J.** *Solid Lubricants and Self Lubricating Solids. Academic Press, New York and London, 1972*
8. *Technical Service Bulletin, product data sheet on TPI, Hysol Grafil*
9. **Lancaster J.K.** Friction and Wear. *in Polymer Science: a Material Science Handbook,* (**ed. Jenkins A.D.**) *North Holland, Amsterdam, 1972, 959–1046*
10. **Bijwe J., Logani C.M. and Tewari U.S.** Influence of fillers and fibre reinforcement on abrasive wear resistance of some polymer composites. *Wear, 1990,* **138**, *77–92*
11. **Gahr K.H.Z.** *Microstructure and Wear of Materials. Tribology Series 10, Elsevier, Amsterdam, 1987*
12. **Friedrich K. and Cyffka M.** On the wear of reinforced thermoplastics by different abrasive papers. *Wear, 1985,* **103**, *333–344*
13. **Bijwe J., Logani C.M. and Tewari U.S.** On the size effect in abrasive wear studies on polymers and their composites. *Proc. 5th Int. Cong. on Tribology, Eurotribe'89, Helsinki, Finland, 12–15 June 1989, 328–333*
14. **Tewari U.S., Bijwe J. and Vasudevan P.** On the abrasive wear of some polyimides and their composites. *Tribology Int. (in press)*
15. **Mathur J.N.** *Abrasive wear of nylon and its short fibre reinforced composites. M. Tech. Thesis, Indian Institute of Technology, Delhi, 1988*

16. **Bartenov G.M. and Lavrentov V.V.** *Friction and wear of polymers. Tribology Series 6,* (**eds Lee L.H. and Ludema K.C.**) *Elsevier, Amsterdam, 1981*
17. **Briscoe B.J., Yao L.H. and Stolaraski T.A.** The friction and wear of poly(tetrafluoroethylene)-poly(etheretherketone) composite: an initial appraisal of the optimum composition. *Wear, 1986,* **108**, *357–383*
18. **Voss H. and Friedrich K.** On the wear behaviour of short fibre reinforced PEEK composites. *Wear, 1987,* **116**, *1–18*
19. **Cirino M., Friedrich K. and Pipes R.B.** Evaluation of polymer composites for sliding and abrasive wear applications. *Composites, 1988,* **19**, *383–392*
20. **Czichos H.** Influence of adhesive and abrasive wear mechanisms on the tribological behaviour of thermoplastic polymers. *Wear, 1983,* **88**, *27–48*
21. **Giltrow J.P.** A relationship between abrasive wear and cohesive energy of materials. *Wear, 1970,* **15**, *71–78*
22. **Lhymn C.** Effect of load on the specific wear rate of fibrous composites. *Wear, 1987,* **120**, *1–27*
23. **Misra A. and Finnie I.** On the size effect in abrasion and erosion. *Wear, 1981,* **65**, *359–373*
24. **Suh N.P.** *Tribophysics. Prentice Hall, Englewood Cliffs, New Jersey, 1987*
25. **McGee A.C., Dharan C.K.H. and Finnie I.** Abrasive wear of graphite fibre reinforced polymer composite materials. *Wear, 1987,* **114**, *97–107*
26. **Tsukizoe T. and Ohmae N.** Tribo-mechanics of carbon fibre reinforced plastic. *Ind. Lub. and Tribol., 1976,* **28**, *19–25*