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Effect of sliding speed on friction and wear of uni-directional aramid fibre–phenolic resin composite

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A previous study on the tribological performance of a compression-moulded aramid fibre–phenolic resin composite, containing 30% continuous fibre, showed that this composite provides a reasonable combination of the friction coefficient and wear rate to be used as a friction component, such as a brake shoe. In the present work, the effect of sliding speed on the friction and wear behaviour of this composite has been investigated. The sliding experiments were conducted in a speed range of 0.1–6 m s^{-1} at two normal pressure levels of 1.0 and 4.9 MPa. The coefficient of friction was found to be stable over a wide range of sliding speeds and normal pressures. The wear of the composite was found to be insensitive to changes in the speed in the higher speed range. The results have been supplemented with scanning electron micrographs to help understand possible friction and wear mechanisms.

1. Introduction

Synthetic polymers are attractive engineering materials because they offer good strength to weight ratio as components and often require little post-casting surface treatment, prior to use. The mechanical properties of common polymers when compared to metals are, however, not very good. This has prompted many attempts to cast the polymer with fillers. Considerable attention has thus been paid in the last 15 years to record the tribology of polymer composites. Reviews of such works may be found in articles by Briscoe and Tweedale [1, 2], Sinha and Biswas [3], Zum Gahr [4], Bijwe *et al.* [5] and Suh and Sin [6]. Recent works on aramid (Kevlar) fibre-filled resin [3] have shown that this material offers tribological properties (high friction and low wear rate) useful for a brake material. Detrimental health and environmental issues have severely constrained the use of asbestos as a brake material [7]. Past [3] and present work indicate that aramid fibre resin composite may have a future in replacing asbestos as an automotive brake material.

In automotive brakes, generally, a soft brake shoe is used against a steel drum for the generation of sufficient frictional forces. The desirable characteristics of a brake material may be listed as [7].

1. friction coefficient - 0.3 under dry conditions;
2. stable friction under various conditions;
3. low wear rate;
4. minimum damage or wear to the opposing material;
5. long endurance under heavy loads and high speeds; and
6. no brake noise.

As the composite microstructure lends itself to manipulation over a range, for a specific application the optimum microstructure may be selected on the basis of a wear model of the composite. The existing model [4, 8–10] includes the effects of the mechanical properties of the fibre, matrix and the fibre–matrix interface on wear and friction but pays little attention to the *in situ* development of a transfer film at the interface and its effect on the friction and wear of these materials. An earlier paper [3] by the present authors indicated the importance of this film on the tribology of these materials. The present work was thus devoted to changing the film morphology and thickness by changing the sliding speed and normal load and observing the effect of this change on friction and wear of these polymeric composites. The information generated will, it is hoped, have an important bearing on the tribological modelling of these composites.

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1.1. Friction materials

Automotive brake shoes are made up of a wide range of materials, namely cast iron, rubber, resins or a combination of rubber and resins, mixed with fillers such as asbestos, metal and metallic compounds, fibres, etc. However, the specific choice of the material appears to result from a trial-and -error experimentation during the process of the development of friction materials [11]. While the use of asbestos is prohibited on health and environmental considerations, other materials suffer either from the demerit of having damaging effects on the mating surface during the operation or from their poor tribological performances [12]. Hard materials such as metal compounds and glass fibres, which are used as fillers, can easily abrade the counterface which is commonly a grey cast iron drum or disc. The brake materials are also required to be sufficiently strong and stiff to cope with accidental severe conditions from the point of view of safety.

In comparing the brake performance of resin-based composites with cast iron, the conventional brake shoe material, Yamaguchi [7] records that the polymer brake shoes have higher coefficient of friction and significantly higher wear resistance. Yamaguchi's test resin was filled with inorganic particles. He shows that for phenolic resin-based composites the order of friction coefficient is 0.3–0.35, whereas that for diallyl phthalate, melamine, polyamide and silicone resin is 0.4–0.6. In a previous paper, the present authors [3] reported that when the phenolic resin is filled with an organic aramid fibre in the sliding wear test (at contact pressures an order higher and sliding velocity an order lower than that used by Yamaguchi) the stable friction coefficient falls in the regime of 0.2–0.4 and the wear rate is significantly lower than that reported by Yamaguchi for the inorganic particle-filled resin. The present investigation establishes the friction and wear behaviour of the phenolic resin-based aramid composites over a range of speed (0.1–6.0 m s^{-1}) similar to that used by Yamaguchi (0.5–20 m s^{-1}) and investigates the changes in the wear mechanism brought about by the changes in speed and load.

1.2. Effect of sliding speed

The influence of sliding speed on the tribological behaviour of polymer composites has been investigated by other workers [3, 12–21]. Working on thermoplastic (Nylon 66 and polyetheretherketon (PEEK)) matrix reinforced with short carbon and glass fibres, Lhymn [12] found the specific wear rate to decrease with sliding speed up to a speed of 0.314 m s^{-1} for carbon fibre composite, but, for glass fibre it shows an increasing trend up to 0.1 m s^{-1} sliding speed, and beyond this range the specific wear rate decreases with increasing speed. Voss and Friedrich [13] observed that the specific wear rate of PEEK increases with the increase of speed, while for its composite (carbon fibre) the specific wear rate decreases initially, but after a speed of 1.5 m s^{-1} it increases with sliding speed. On the other hand, the specific wear rate for its composite with glass fibre, continued to increase with sliding speed. Wear furrows in the matrix material and fibre pulverization were the characteristic features of the worn samples. No qualitative change in the wear mechanism was observed on changing the normal load and sliding speed conditions. Lhymn and Light [9, 10] reported that for polybutylene terephthalate (PBT)–glass fibre composite, the specific wear rate decreases exponentially with sliding speed up to 1.0 m s^{-1}. Beyond this sliding speed the specific wear continued to rise. There was not much change in the friction coefficient of PBT–carbon fibre and PBT–glass fibre composites with increase in sliding speed. They concluded that there were basically thermally induced changes at the interface with the change of sliding speed. In the region of low sliding speed, the temperature rise is not effective and the specific wear rate is inversely proportional to sliding speed. The medium speed range appears to promote the lubricating action of the molten polymer at the surface and finally at higher sliding speeds thermal heating induces weakening of the material leading to high wear rate. Reasons for the stability of the coefficient of friction were not clear in this study. Many other investigators [14–21] have also reported the influence of sliding speed on the wear and friction properties of polymer composites.

2. Experimental procedure

2.1. Sample preparation

The composite consisting of 30% (wt) fibre and phenolic resin samples was prepared in the laboratory; 30% fibre was used because this composition combines good tribological properties (friction and wear) with the bulk mechanical strength and integrity of the material. Phenolic resin was supplied by Bakelite Hylam Ltd, Hydarabad, India, and aramid fibre was supplied by the National Aerospace Laboratory, India. The samples were cast by the compression moulding method using a die and punch [3]. Alternate layers of weighed amounts of resin and fibre (30%) were laid unidirectionally over one other in the die cavity of dimensions 20 mm × 30 mm × 30 mm. The material was preheated for 30 min and then pressed at 65 MPa. The sample was cured for 30 h at 180 °C under the pressed condition. It was subsequently cooled in the furnace. Pins of length 20 mm and surface area 20 mm^{2} (4 mm × 5 mm) were machined out of the cast block such that the axis of the fibre was parallel to the pin axis. During experiments the pin axis was held vertical such that the fibres were normal to the counterface. The samples were found to be free of any macro-defects such as voids or cracks. The density of the composite specimen was 1.3 g cm^{-3}.

2.2. Experimental apparatus

Dry sliding experiments were carried out using a pin-on-disc apparatus. In this machine the sample is held vertically in a sample holder. A schematic sketch of the apparatus and the sample is given in Fig. 1. The counterface used was ground (0.05–0.1 μm CLA) EN-24 steel (hardness 55 R_c) disc. Friction was measured

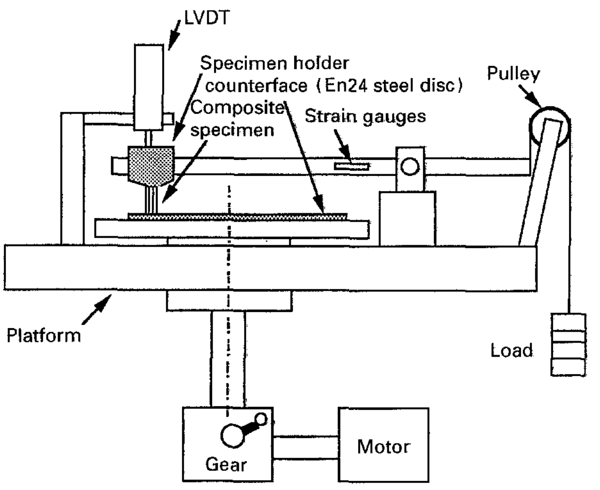

Figure 1 Schematic drawing of the pin-on-disc apparatus.

by strain gauges attached to the arm of the specimen holder and wear was measured, *in situ*, by recording the changes in the length of the pin specimen using a displacement measuring instrument (LVDT).

2.3. Surface temperature

The counterface surface temperature was measured at the end of each test. The temperature probe consisted of a small thermocouple bead protected inside a sheath from all sides except one end. The thermocouple was brought in contact with the surface of the disc after the test. The temperature data reported in the results thus represent an estimate of the counterface temperature only and not the actual interface temperature. The surface temperature measured in this work compares well with such measurements using a radiance trace by Tripathy and Furey [22]. For a specimen radius of 3.17 mm (area 31.6 mm^2) and surface speed up to 7 $m\,s^{-1}$, they measured a temperature rise up to 110 °C. They noted that the temperature of the counterface increases during the initial period of a test and gradually it attains a steady-state value. Probably the amount of heat generated at the interface balances the heat transfer taking place mainly through the machine structure and radiation. The frictional heat generation measured by them was about 7 W at 3.5 $m\,s^{-1}$ sliding speed and 14 W at 7 $m\,s^{-1}$.

2.4. Testing procedure

Before each experiment the sample surface was prepared by sliding it over an abrasive paper (400 grade) at a normal pressure of 0.12 MPa to ensure good contact (during the actual experiment) between the specimen and the counterface. After this preparatory abrasion, the counterface and the sample surfaces were cleaned with acetone. The surface speed was varied between 0.1 and 6 $m\,s^{-1}$ at two normal pressure levels of 1.0 and 4.9 MPa. The reported characteristics are averages from three experiments. The standard deviation of results from three experiments was found to be 0.0489 for the friction coefficient and 6.14×10^{-8} $mm^3\,mm^{-1}$ for the wear rate. The worn specimens were sectioned parallel to the sliding direction, the exposed planes containing the full length of some fibres. These sections are referred to as parallel sections. Sections and worn surfaces were coated with gold and examined by scanning electron microscopy (SEM).

3. Results

Fig. 2 shows that the addition of continuous aramid fibres to the resin reduces the wear rate by 30–40 times. The experiments with resin could not be done at speeds more than 2.0 $m\,s^{-1}$ because the specimen ruptured and disintegrated at those speeds. Within this (0.1–2.0 $m\,s^{-1}$) speed range the wear rate of resin increases steadily with speed at high load while at the low load the wear rate decreases initially (< 0.5 $m\,s^{-1}$) with speed and then increases steadily with increasing speed. By contrast the wear rate of the composite decreases drastically with speed in the low-velocity regime (< 0.5 $m\,s^{-1}$), decreases gently in the intermediate speed regime (0.5–2 $m\,s^{-1}$) and remains relatively insensitive to speed in the high-velocity regime (2–6 $m\,s^{-1}$). At high load the wear rate shows a slight drop in the wear rate at speeds more than 4.0 $m\,s^{-1}$.

Fig. 3 shows that the addition of fibre lowers the coefficient of friction. For both test materials, the

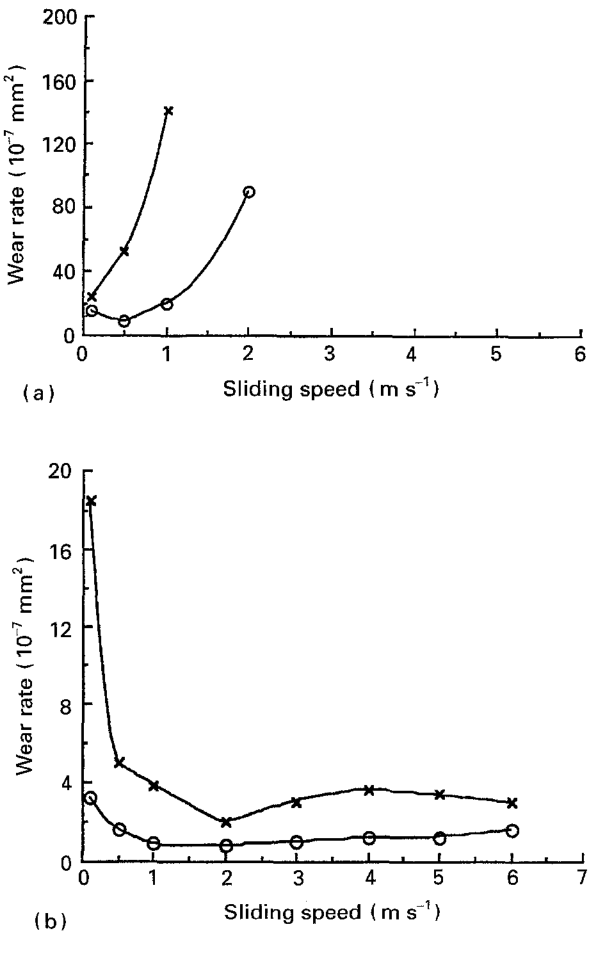

Figure 2 Wear rate as a function of sliding speed at (×) + 4.9 MPa and (○) 1.0 MPa for (a) resin, (b) composite.

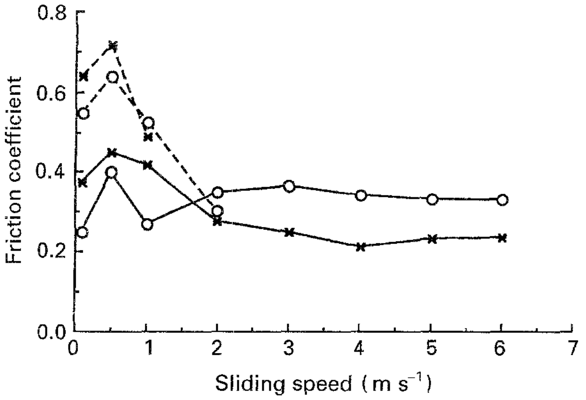

Figure 3 Friction coefficient as a function of sliding speed, at (×) + 4.9 MPa, and (○) − 1.0 MPa for (---) resin, (———) composite.

friction coefficient increases with speed in the low-speed regime, decreases in the intermediate regime and, not withstanding some subtle variations, remains more or less steady in the high-velocity regime.

SEM of the resin surface worn at low pressure (1.0 MPa) and very low speed (0.1 m s^{-1}) show gentle abrasion as well as asperity persistence (Fig. 4a). The asperities persist, though somewhat smoothened (Fig. 4b), at a higher speed (2.0 m s^{-1}) but the worn surface develops deep widespread cracks which join to give debris. Increasing surface speed at the high pressure introduces a stick–slip mode (Fig. 4c) which appears to aid the process of surface fracture.

The principal effect of fibre addition to the resin appears to be, as has in fact been observed earlier [3], to develop a surface film. The surface coverage of this film increases consistently with increasing surface speed. At low pressure and low-speed regime, Fig. 5a shows disruption and cracking in the surface region, not covered by the film and light abrasion in the film itself (Fig. 5a). In the intermediate and high-speed ranges the film is no longer abraded and appears as discrete but smooth spots (Fig. 5b). The area not covered by the film is also not abraded but fails by fracture yielding flaky laminate-type debris (Fig. 5c). Increasing the normal pressure prolongs the abrasion and surface cracking in the low-speed regime (Fig. 6a). At high pressure the film coverage of the surface continues to increase with speed. The delamination type of failure observed in the intermediate and high-speed regime at low pressure (Fig. 5c) is observed only in the vicinity of 2.0 m s^{-1} speed. At high speeds the surface was found to be extensively covered by a smooth continuous film (Fig. 6b). The wear in this speed range occurred by the cracking of the film at the edges (Fig. 6b). The debris generated at this high-speed regime is small and spherical.

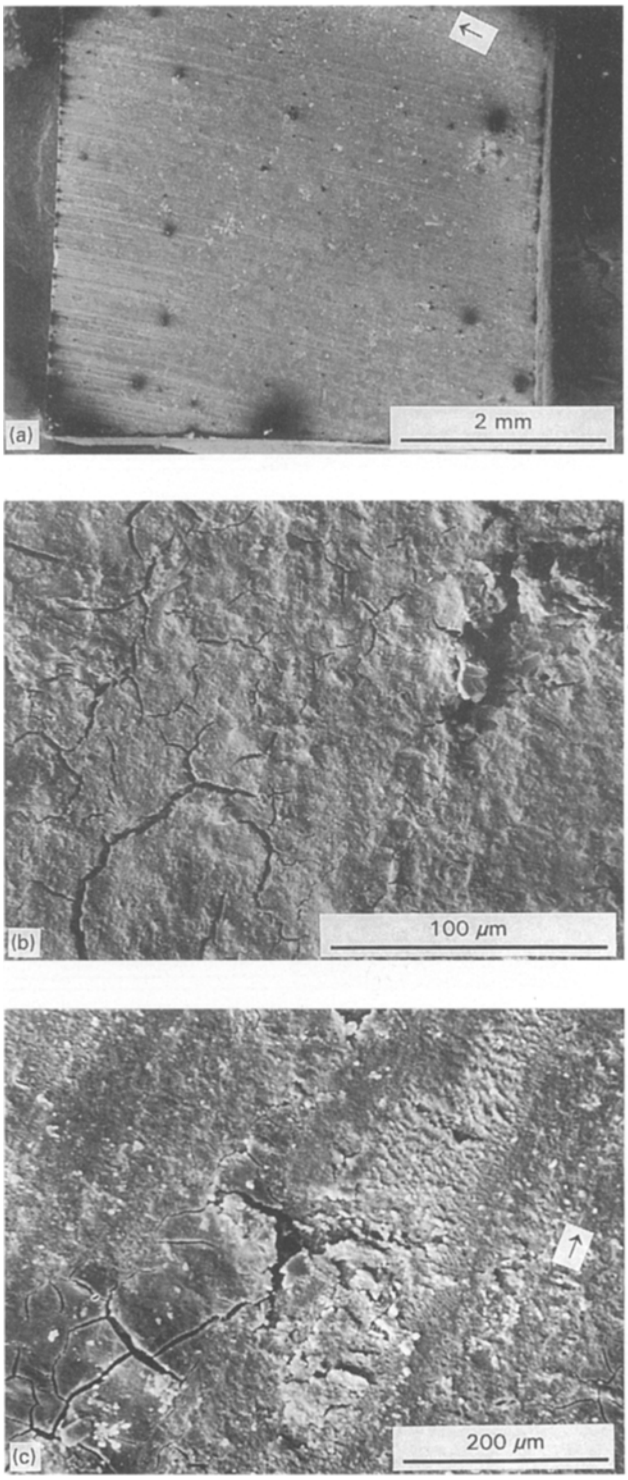

Figure 4 Scanning electron micrographs of the worn resin surface (arrow indicates sliding direction) at various speeds and pressures: (a) 0.1 m s^{-1} 1.0 MPa; (b) 2.0 m s^{-1}, 1.0 MPa; (c) 1.0 m s^{-1}, 4.9 MPa.

4. Discussion

4.1. Performance as a brake material

While no attempt has been made here to assess the overall performance of the aramid fibre phenolic resin composite as a brake material in terms of braking time, braking torque and under water-lubricated sliding conditions, the friction coefficient and wear characteristics recorded under sliding conditions point to its potential as a good brake material. In a normal pressure range of 1.0–4.9 MPa the friction coefficient is in the range of 0.2–0.4, at speeds more than 2.0 m s^{-1}. Both Yamaguchi [7] and Briscoe [23] reported the same order of friction for their polymer based brake materials. In terms of wear rate, Yamaguchi reported a specific wear rate of 0.1×10^{-4} $mm^3 N^{-1} m^{-1}$ at a constant pressure of

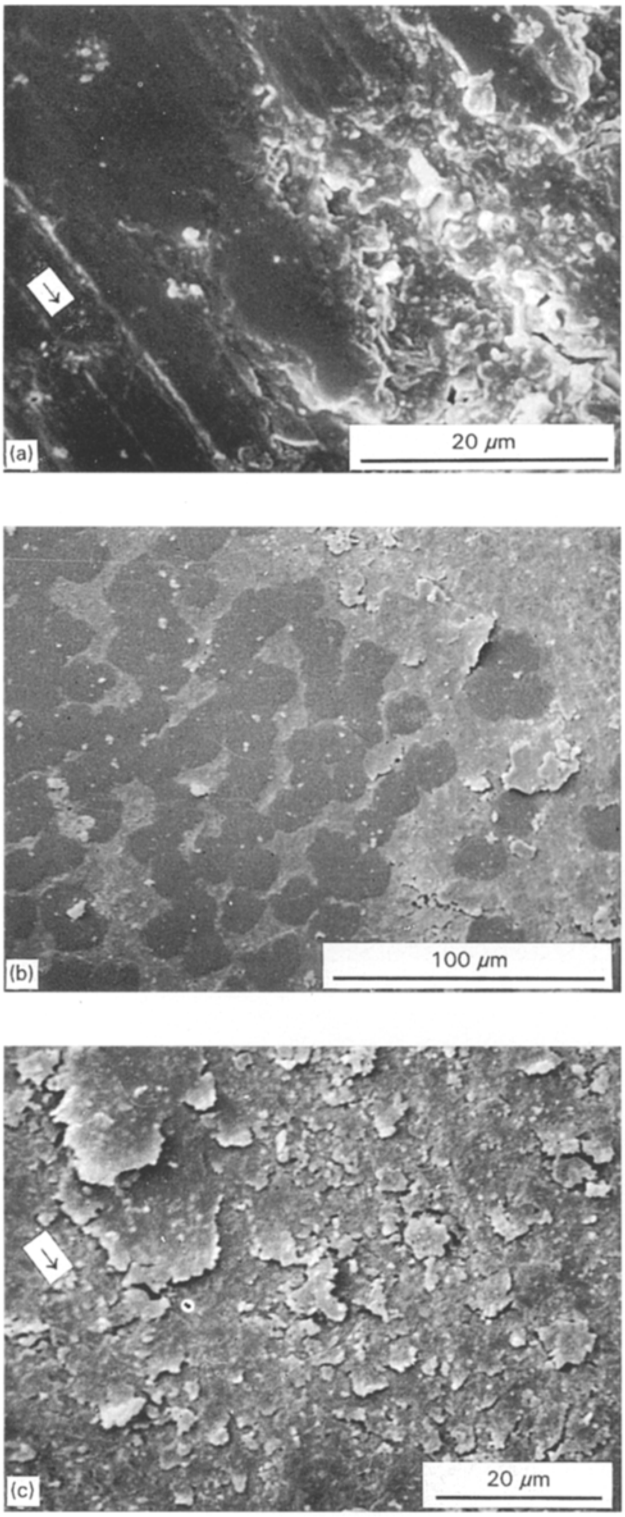

Figure 5 Scanning electron micrographs of the worn composite surface at various speeds and pressures. (a) 0.1 m s^{-1} 1.0 MPa; (b) 6.0 m s^{-1}, 1.0 MPA; (c) 6.0 m s^{-1}, 1.0 MPa.

0.4 MPa and sliding speed of 10 m s^{-1}. The present material, in contrast, records a specific wear rate of 0.02×10^{-4} mm^3 N^{-1} m^{-1} at a constant pressure of 4.9 MPa and a sliding speed of 6.0 m s^{-1}. Further, Yamaguchi recorded a specific wear rate which is insensitive to contact pressure and directly proportional to speed. The present material shows a slight fall in the specific wear rate with contact pressure and a marked insensitivity to speed, at speeds more than 2.0 m s^{-1}.

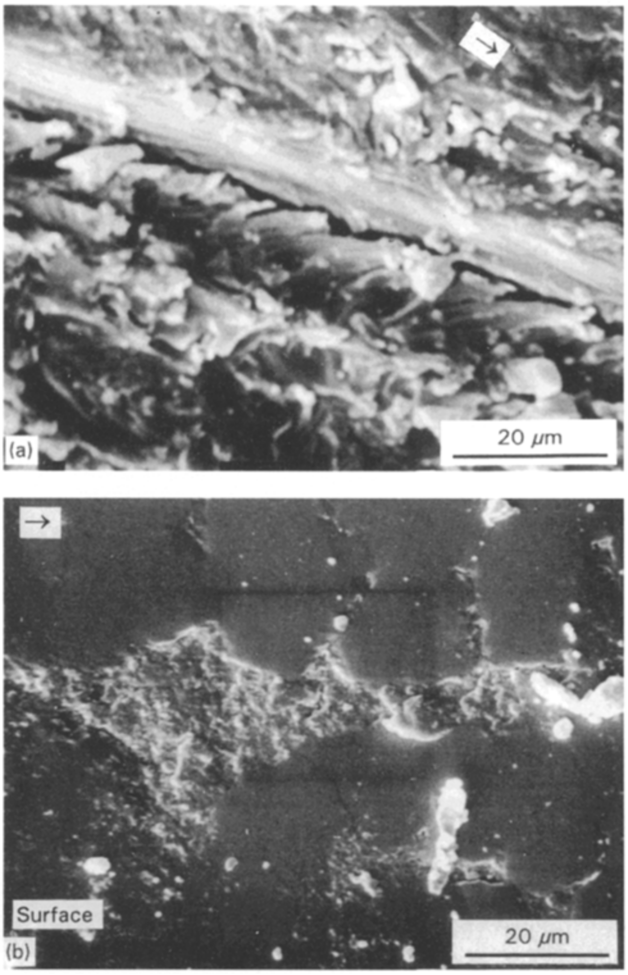

Figure 6 Scanning electron micrographs of the worn composite surface at (a) 0.1 m s^{-1} 4.9 MPa; (b) 6.0 m s^{-1}, 4.9 MPa.

4.2. Mechanisms of wear and friction

4.2.1. Wear

Sliding friction and wear experiments were conducted using the single-phase resin polymer with a view to provide a quantitative reference for the composite wear data. The Young's modulus and strength [24] as well as the fatigue strength [25] of a resin has been reported to be substantially enhanced by the addition of aramid fibres. Enhancement of these properties have generally been considered to influence the wear resistance of a polymer, favourably [6]. While this may indeed be true in the present case, there may be an additional reason for this dramatic enhancement of 30–40 times in wear resistance achieved by the addition of fibres. In a previous paper [3] it was shown that the fibre ends exposed at the interface trap the debris and help to form a smooth interfacial film. It is likely that it is this *in situ* formation of the film which is responsible for a substantial reduction in the tangential traction (Fig. 3) and consequently of the subsurface stresses. The subsurface fracture process is impeded and the wear resistance is enhanced.

Fig. 7 shows the specific wear characteristic of the composite. At the same orders of speed, Lhymn and Light [10] have observed similar behaviour for PBT glass-fibre and PBT carbon-fibre composites. This

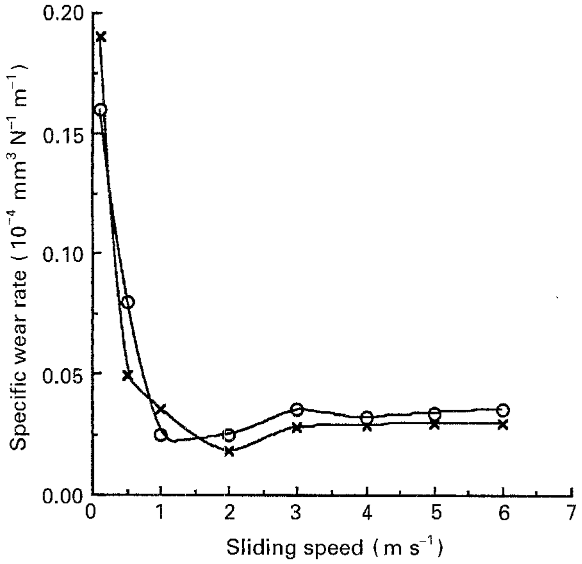

Figure 7 Specific wear rate of the composite as a function of sliding speed, at (×) + 4.9 MPa, and (○) + 1.0 MPa.

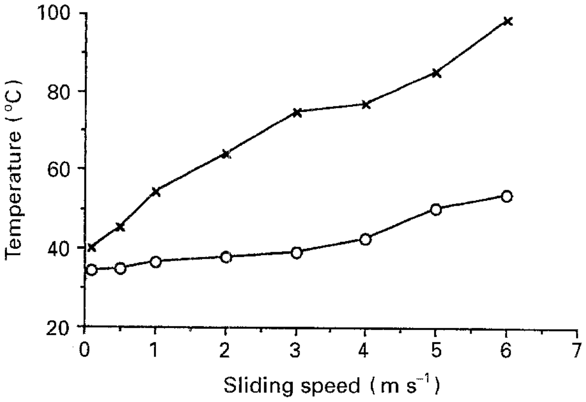

Figure 8 Temperature of the disc at the trailing end of the composite pin measured by a thermocouple tip placed at the pin–disc junction, at (×) 4.9 MPa and (○) 1.0 MPa.

figure shows that the specific wear-rate characteristics could be classified into three velocity regimes:

1. $V_s < 0.5\ \mathrm{m\,s^{-1}}$ – the specific wear rate in this regime increases with pressure;

2. $0.5 < V_s < 2\ \mathrm{m\,s^{-1}}$ – as an interfacial film develops with increasing speed the wear rate drops dramatically (Fig. 7). The wear rate is also inversely proportional to the pressure. Considering the fact that the initial part ($0.5 < V_s < 1.0$) of this regime is linear and the interface temperature rise (Fig. 8) is small, $V_s = 0.5\ \mathrm{m\,s^{-1}}$ may be considered to commence a regime of non-thermally activated subsurface failure-dominated wear process. Fig. 9 shows a crack nucleated at the fibre matrix interface propagating out into the surface. With increasing speed the temperature rise at the interface increases. It is possible that at $1.0 < V_s < 2.0\ \mathrm{m\,s^{-1}}$ a secondary thermally activated effect, where the specific wear rate is directly proportional to velocity, is introduced. This introduces a non-linearity in the characteristics and at $V_s = 2.0\ \mathrm{m\,s^{-1}}$ a minimum in the wear rate is reached;

3. $V_s > 2.0\ \mathrm{m\,s^{-1}}$ – in this regime the composite shows insensitivity of the specific wear rate of velocity and an inverse relationship with pressure.

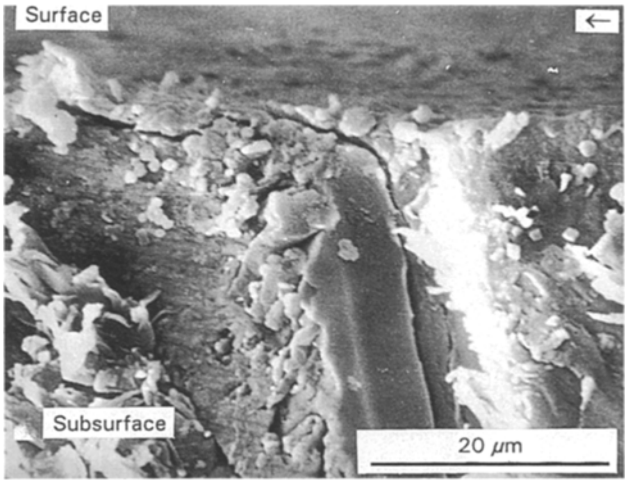

Figure 9 Scanning electron micrograph of a parallel section of the composite, at 2.04 MPa and 0.5 m s^{-1}.

The reason for this may be related to the self-lubricating nature of the contact in this regime. The interfacial temperature rise at the high pressure (Fig. 8) is substantial enough to soften the film and spread it extensively over the surface (Fig. 6a). Owing to a reduction in the interfacial shear strength, the tangential traction (Fig. 3) is lowered and crack growth is impeded. At the low pressure where the interfacial temperature rise is marginal, the film strength is retained and only a limited surface coverage by the film is achieved (Fig. 5b). The tangential traction (Fig. 3) at this pressure is relatively high and the specific wear rate registered is also, therefore, slightly higher than that obtained at the high pressure. In this situation it is possible that the bulk of the material loss does not occur by subsurface fracture but through losses from the film. The film material may recirculate between surfaces in a dynamic but steady state process, and, the net loss occurs from the continuously forming and deforming film. The present experimental results thus show that the tangential traction which is determined by the process parameters plays a very important role in determining the mode of wear of continuous fibre polymer composites.

4.2.2. Friction

One of the most important features of this composite, as far as its use as a friction material is concerned, is its relatively high and stable friction coefficient. As observed in Fig. 3, the friction coefficient for the composite remains between 0.2 and 0.4 even at high speeds (and consequently at high counterface temperatures). One of the common ways of assessing the performance of a friction contact is its so-called PV factor, which is the product of the applied contact pressure, P, and the sliding velocity, V. This factor determines a combined effect of pressure and speed acting at the interface or, in other words, it represents the rate of work being done per unit area. Typical figures of the PV factor for actual brake material are 2–24 MPa m s^{-1} at contact speeds of 2–3.2 m s^{-1} and pressures of 1–6 MPa [26]. These values in the present case were 0.1–29 MPa m s^{-1} at a maximum velocity of 6 m s^{-1} and a maximum pressure of 4.9 MPa. Fig. 10 shows friction coefficients for the composite plotted against the

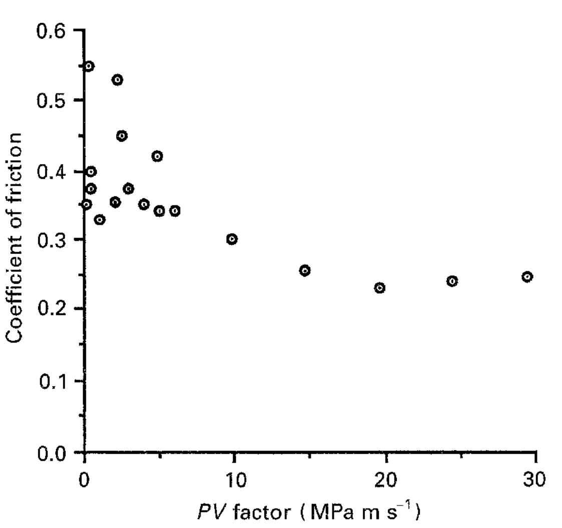

Figure 10 Friction coefficient plotted against the *PV* factor for the composite.

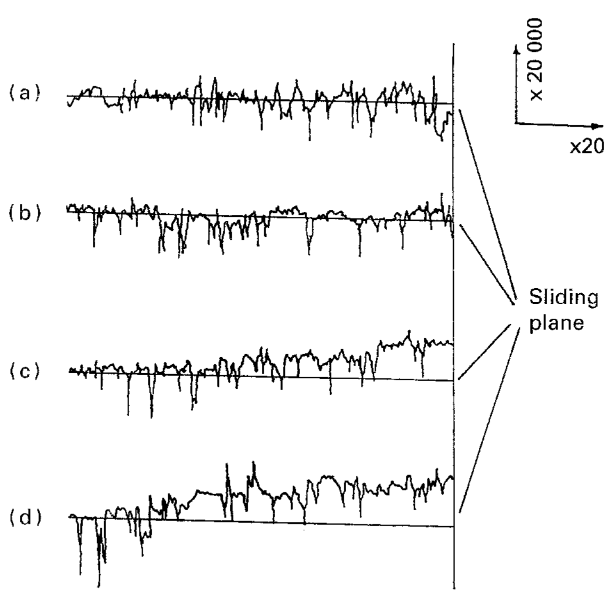

Figure 11 Profilometric traces showing topographical changes with sliding time at the same location of the counterface. Each trace shows part of the slid and part of the unslid wear track at a normal pressure of 3.77 MPa and a sliding speed of 0.5 m s^{-1}: (a) original surface, (b) 10 min sliding, (c) 30 min sliding, (d) 60 min sliding.

PV factor. The ability of the present composite to smoothly slide at high values of *PV* with a high friction and a low wear rate does indicate the superiority of this material over other available friction materials.

The origin of high friction in an aramid fibre–phenolic resin system against a steel counterface lies mainly in the adhesive interaction between transformed layers. A profilometric study of the wear track on the counterface (Fig. 11, also see [3]) indicates deposition of a thin film as the specimen continues to trace the same path. This relatively thin layer has strong adherence to the surface of the track. As the rubbed specimen of the composite sample also shows the presence of a covering film, the main tribological interaction during the course of the sliding process is between these two deposited films. The main constituent of these layers is the softer phase, i.e. resin, which comes out of the specimen during initial abrasive actions of asperities of the counterface. As the rheology of the film is expected to be a strong function of the prevailing temperature, the film, in fact, should become weaker, progressively leading to lower frictional force and low values of coefficient of friction. However, this is not observed when operating at high normal pressure and sliding speed (Fig. 3). This might be because, at high temperatures, the resin debris particles degrade and char followed by a rejection from the film. New film is continuously deposited giving rise to a balance of steady friction and wear rate. Because aramid fibres can withstand relatively high temperatures (150 °C) with no degradation, they continue to provide mechanical strength to the specimen and stability to the film on the exposed surface. Attainment of a thermal balance in the steady process [22] impedes any further deleterious effects of temperature on the polymeric matrix (resin) and fibre (aramid). The effects of fibre orientation may be substantial in achieving optimum friction and wear levels in a tribological test. The normal orientation, which was used in the present study, has been found to give a lower friction in the medium velocity regime (4–7 m s^{-1}) for a carbon–PEEK composite [22] when compared with other orientations such as parallel and anti-parallel. However, the virtue of the normal fibre orientation is that it provides a good thermal conduction in the composite, and hence minimizes the effects due to thermal heating of the interface. This gives relatively lower wear rate [27] compared to similar data for other orientations of fibres.

A final comment may be made about the effects of environment (such as the presence of water) on the tribological performance of this material. In the previous study [3] experiments were carried out using water as lubricant. A continuous stream of water was poured into the trailing edge of the pin specimen. Even under this condition the coefficient of friction was observed to be 0.21 at a normal pressure of 4.25 MPa and a sliding speed of 0.5 m s^{-1}. In those experiments also, the film was observed on the wear track of the counterface. The rubbed surface of the specimen showed the presence of pits on it. The wear rate was observed to be in the range 0.2–0.25 × 10^{-6} mm^3 mm^{-1} in the steady state of sliding.

5. Conclusion

Aramid fibre–phenolic resin continuous fibre composite was slid against an EN-24 steel disc in a pin-on-disc machine in a speed range of 0.1–6.0 m s^{-1} and at two normal pressures; 0.1 and 4.9 MPa. Addition of the fibre lowered the wear rate of the resin by 30–40 times. At speeds less than 2.0 m s^{-1} the wear of the composite was considered to be caused by surface fatigue and abrasion initially (speed < 0.5 m s^{-1}) and by a non-thermally activated micro-fracture process in the higher speed range ($0.5 < V_s < 2.0$ m s^{-1}). At speeds more than 2.0 m s^{-1} a continuous self-lubricating film develops at the interface. The consequent reduction in tangential traction renders the specific wear rate low and to be practially insensitive to velocity. It is conjectured that in this velocity regime the wear occurs principally through losses of material from the recirculating dynamic film and not by a process of subsurface fracture. This material gives a stable coefficient of friction between 0.2 and 0.4 even at high operating *PV* factor (29 MPA m s^{-1}) at high sliding speed and pressure.

The present experimental results indicate that in the context of application as a brake material, the performance of the aramid fibre–phenolic resin composite is good and possibly superior to other resin-based inorganic filler composites.

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