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Wear mechanisms in polymer matrix composites abraded by bulk solids

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Abstract

An experimental study of the wear of polymer matrix composite materials subjected to abrasion from bulk materials has been conducted. Three examples of vinyl ester resin systems were considered: (a) unreinforced, (b) reinforced with glass fibres, and (c) reinforced with particles of ultra high molecular weight polyethylene (UHWMPE). Soft and hard bulk materials used for abrasion were granular forms of coal and the mineral ignimbrite. The bulk material was presented to the wear surface on a conveyor belt in a novel wear tester. While UHWMPE reinforcement enhanced the wear resistance to both hard and soft abrasives, the situation for fibre reinforcement was more complicated. With coal as the abrasive, it was found that glass fibre reinforcement reduced the wear rate, whereas in the case of the harder ignimbrite, fibre reinforcement increased the wear rate. Microscopy indicated significant differences in the mechanism of wear in each surface/abrasive combination. Wear textures, consistent with both two and three-body wear, were observed with, respectively, soft and hard abrasive particles.

Keywords: Wear mechanisms; Polymer marix composites; Bulk solids

1. Introduction

Polymer matrix composites are being increasingly used in industry because of their unique combination of mechanical, electrical, and thermal properties. Typically they have high specific strength and modulus, excellent fracture toughness and fatigue properties, and good corrosion, thermal and electrical resistance properties. This combination of properties, particularly their high strength/stiffness to weight ratio, make them very attractive materials for transport applications where there is commercial advantage in minimising vehicle weight. One such application is in the transport and handling of bulk solids. However, their use in this application is limited by an incomplete understanding of their abrasion wear resistance and the means by which this can be controlled and improved. The aim of the work described in this paper was to provide further understanding of the wear of polymer matrix composite materials when subjected to abrasive wear from bulk solids.

In addition to transport applications, there has also been growing interest in their abrasive wear performance in applications such as chutes in mining and agricultural equipment [1]. A number of studies on polymer matrix composites subjected to sliding and abrasive wear indicate that wear resistance depends on the detailed properties of the material as well as the external wear conditions such as applied pressure and contact velocity [2–5]. Furthermore, fibre addition to polymers does not necessarily improve their wear resistance [6].

Abrasive wear can occur as two-body abrasion, three-body abrasion, or a combination thereof [2]. In two-body abrasion, the two surfaces in contact are constrained to move in two dimensions and as such wear occurs through abrasive material on one surface sliding over the other surface. During three-body abrasion however, the abrasive material is trapped between the two constraining surfaces and is free to roll as well as to slide. Typically, wear rates obtained under two-body conditions are much higher than those actually observed in three-body wear, sometimes by as much as an order of magnitude [7] and the mechanisms of one cannot be modeled accurately from the other [8]. In reality, because of the complexity of the abrasion process,

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no single mechanism can completely account for all of the material loss.

This paper reports a study of the wear performance of three different surfaces with and without reinforcement during abrasion by both hard and soft bulk solids. The bulk solid abrasives were applied to the surface of the test surfaces under conditions common in industry in which there was limited constraint of the transport of the bulk solid particles. As such, both two and three-body wear was possible, depending on the abrasive/surface interaction. The purpose of this study was to shed light on the transition between these mechanisms, and to characterise wear damage arising from these mechanisms as a function of relative hardness and other properties of the wear system. The effects of the reinforcement and the wear media on the wear mechanisms involved were investigated through scanning electron microscopy (SEM) and weight loss measurements.

2. Experimental details

The abrasive wear of a relatively hard wear medium (ignimbrite) and a relatively soft wear medium (coal) on three different composite surfaces (vinyl ester resin, glass fibre reinforced plastic (GFRP), and ultra high molecular weight polyethylene (UHMWPE) particle reinforced resin) have been investigated. The choice of the two different wear media was dictated by intention to evaluate the effects of wear media hardness upon the wear rates of different materials. Coal mined from Bulga Colliery in the Hunter Valley was chosen as one abrasive wear medium. It was found that approximately 95% of coal particles were between 0.5 and 7.0 mm in diameter throughout the testing period, although the distribution changed through particle attrition throughout the experiment, as discussed below. The moisture content of the coal was measured to be $8.5 \pm 1\%$ by mass. The Vickers hardness of this and other materials used in this study is shown in Table 1. Values shown are for an indent load of 10 kg. Ignimbrite was chosen as a second representative abrasive wear medium due to its hardness and highly angular particle shape. Ignimbrite consists of vitric (glass) shards, variable proportions of pumice fragments and crystals, and a further variable proportion of lithic (stone) fragments.

Table 1
Measured Vickers hardness for the abrasive wear media and composite surfaces

Material	Vickers hardness (10 kg)
Pure vinyl ester resin surface	21.0–26.9
Glass fibre reinforced resin surface	37.6–46.9
UHMWPE particle reinforced resin surface	Not measurable
Coal abrasive particles	27.0–59.6
Ignimbrite abrasive particles	255–295

The UHMWPE particles (Shamrock Chemicals, USA and supplied by Plastral Fidene, Australia) consisted of crystalline polyolefin which could be easily dispersed in a solvent or water-based system. Using the manufacturer's specifications, the average particle size was 40 μm, and the specific gravity was 0.93. The particle size measurement was confirmed using SEM. The solvent resistance of UHMWPE enables it to be compatible with vinyl ester resin systems and the particles were observed to readily disperse in the vinyl ester resin to produce test panels of a uniform texture. The vinyl ester resin used for manufacturing all the composites was Derakane 441-400 (Epoxy Vinyl Ester, Dow Plastics), which is a vinyl ester based resin containing about 7.5 wt.% of a carboxyl-terminated butadiene acrylonitrile (CTBN) liquid polymer reacted into the resin base. The resin was cured with 2 wt.% methyl ethyl ketone peroxide (MEKP). The glass fibre used in the manufacturing of wear specimen was 900 g/m^2 unidirectional E-Glass manufactured by ACI fibreglass and supplied by Fibre Glass International, Australia. The E-Glass fibre reinforced epoxy vinyl ester resin samples were made using the vacuum bag resin infusion (VBRI) process. Particle reinforced specimens were made by mixing the required amount of resin with the calculated quantity of particles for the desired volume fraction of the particle (37%). This mixture was then laid on the single sided mould and allowed to cure. Once the mixture was cured, layers of glass fibre were arranged on top of the cured coating and further vinyl ester resin was infused into the glass fibre layers (using the VBRI process) and then cured. The resulting structure consisted of a test specimen of particle reinforced vinyl ester resin material, strongly bound to a backing plate made of glass fibre reinforced resin. Glass reinforced specimens were made in a similar fashion with 57% volume fraction of glass laid up using unidirectional fibres. The thickness of the reinforced layers was typically 4–5 mm.

All of the abrasive wear testing was conducted using an open linear sliding abrasive wear tester for bulk materials that has been developed at the University of Newcastle, a schematic of which is shown in Fig. 1. In this apparatus, a bin and hopper arrangement delivers the abrasive particles onto a conveyor belt and under the test specimen and carrier. The carrier is loaded with steel weights allowing the normal load on the specimen to be varied. Shear load cells attached to the carrier allow continuous monitoring of the friction force. The conveyor belt has a variable speed hydraulic drive to allow the incident flux of abrasive particles to be altered. Approximately 0.5 m^3 of wear medium can be stored in bin and hopper and drawn out as the conveyor belt moves beneath the hopper exit creating a flow of wear media with a uniform bed depth of approximately 15 mm. After the media passes beneath the test specimen, it is circulated back to the bin and then hopper via a bucket elevator. For the experiments described here, the belt speed was set to be 0.54 m s^{-1} and the average

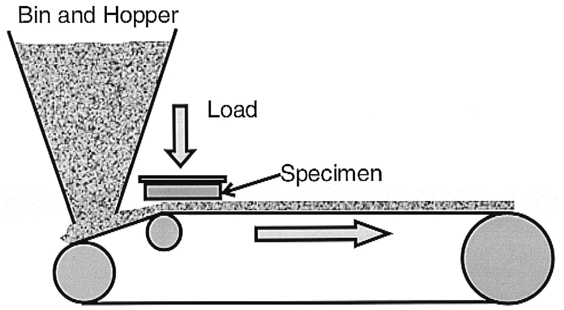

Fig. 1. Schematic representation of the bulk solids abrasive testing apparatus. The return circuit for the bulk solids has been omitted for clarity.

surface pressure was set to 5.4 kPa. A detailed description of the testing machine is given elsewhere [1].

Dimensionless wear rates were calculated according to Eq. 1 [9]. Cumulative and progressive wear rates have been calculated for a number of specimens and compared.

$$W = \frac{(M_1 - M_2)}{\rho AVt} \tag{1}$$

where M_1 and M_2 are the specimen mass before and after test respectively, ρ is the density of composite, A is the apparent wear surface area, V is the belt speed, and t is the running time. Measurements were taken every 15 min to monitor the kinetics of the wear process.

3. Results and discussion

The particle size distributions of the wear media were measured to monitor the particle degradation during the testing in accordance with Australian Standard 1141.11-Particle Size Distribution by Dry Sieving. Particle size distributions of the wear media before and after the wear experiments are given in Fig. 2 and Fig. 3 for the ignimbrite and coal particles, respectively. These images show that while the ignimbrite does not show any significant degradation, the coal particles degrade gradually during the wear experiment. In addition, the mean size of the particles

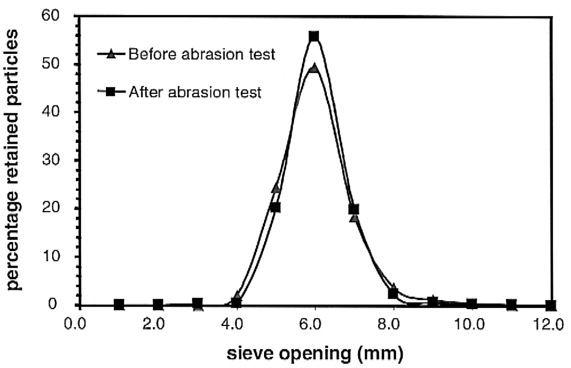

Fig. 2. Particle size distribution of the ignimbrite abrasive particles before and after abrasion testing.

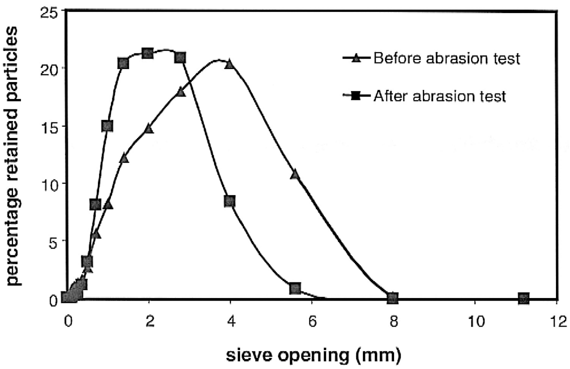

Fig. 3. Particle size distribution of the coal abrasive particles before and after abrasion testing. The mean abrasive particle size changes from approximately 4 mm before testing to approximately 2 mm after testing.

is larger for ignimbrite (2–8 mm) compared with that of coal (0.5–7 mm). A comparison of the ignimbrite particles before and after abrasion (Fig. 4) indicates that the angularity of the ignimbrite particles does not alter after abrasion. However, the wear of coal media during the experimental process leads to significantly rounded coal particles, as shown in Fig. 5.

It was found that the initial stages of abrasive wear for all of the surfaces are characterised by a time-dependent wear rate. As an illustration, the typical variation of dimensionless wear rate as a function of wear time for the three surfaces (vinyl ester resin, GFRP, and UHMWPE

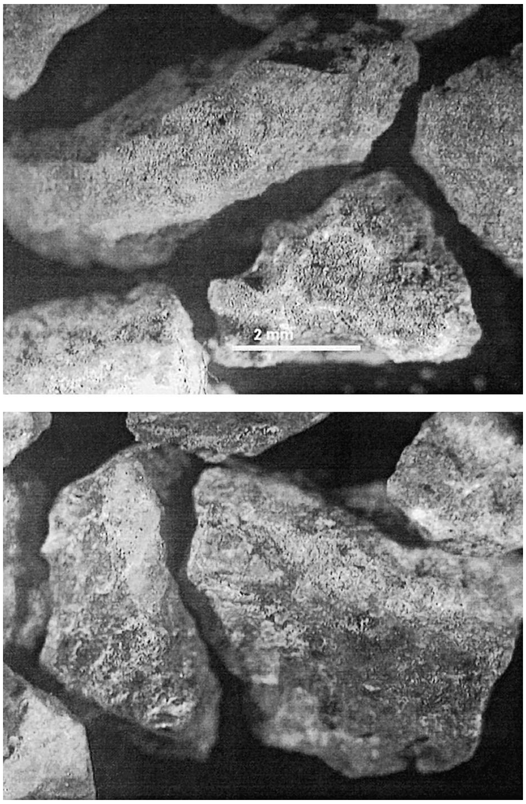

Fig. 4. Optical micrograph images of ignimbrite particles before abrasion (upper image) and after abrasion (lower image).

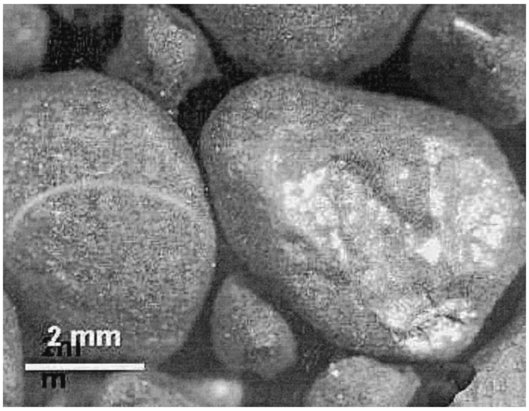

Fig. 5. Optical micrograph image of the coal particles after abrasion. The image demonstrates the rounded nature of the abraded coal particles.

reinforced material) abraded with ignimbrite are shown in Fig. 6. Typically, the composite surfaces exhibited relatively high initial wear rates, when the surfaces were new, which decreased gradually to an asymptotic value. This is a typical ''bedding in'' behaviour seen in most materials at the outset of abrasion [10]. This transient wear is due to asperities and inhomogeneities being rapidly worn until a uniform wear surface is produced and the wear rate approaches an asymptote. Although all of the samples eventually reach an asymptotic wear rate, known as the equilibrium wear rate, the nature of the wear rate variation prior to equilibrium does depend on the surface. In particular, whilst the wear rate of the pure vinyl ester resin and UHMWPE samples decreases systematically to equilibrium, in contrast the wear of GFRP with ignimbrite can be seen to gradually increase to a steady state value. In this case, the initial wear removes the resin rich layer from the surface exposing the fibre to the abrasive. As the hard ignimbrite particles remove the fibre through brittle fracture, the rate of surface removal increases ultimately forming a (high) steady state value. Evidence for this mechanism is discussed further below.

In order to compare the wear rates of the three different surfaces, the samples were worn initially to remove these resin rich surfaces and to establish the steady state wear surface. Fig. 7 shows a comparison of the equilibrium wear rates for each of the three surfaces abraded by coal and ignimbrite. In general, it is clear that, for all the materials tested, the wear rate for ignimbrite is systematically higher than that of coal. As expected, the harder abrasive material is more effective at removing material from the surface. Furthermore, it is known that decreasing the abrasive particle size decreases the wear rate. Friedrich found that the wear rate of short fibre composites decreased fivefold after decreasing the Al_2O_3 abrasive size [10]. Moore found that the wear of homogeneous metals decreases with decreasing abrasive particle size [11]. Wang and Hutchings also demonstrated the similar phenomenon on ceramic/metal matrix composite materials [12]. Thus, as the size of the coal particles decreases during the wear test, it is expected that their effectiveness as an abrasive will be reduced.

Two aspects of Fig. 7 indicate that the wear mechanism depends strongly upon the hardness of the wear media. Firstly, the difference in wear rate between coal and ignimbrite varies with the surface material. Secondly, whereas in the case of the coal abrasive, the wear rate is reduced by glass fibre reinforcement and UHMWPE particles in the resin, for ignimbrite, glass fibre reinforcement was not able to protect the resin surface and the wear rate is higher than that of unreinforced resin. Using the UHMWPE particle reinforcement wear rate was reduced marginally when ignimbrite was used as abrasive. These results indicate that glass fibre and UHMWPE particle reinforcement provide protection against softer abrasives, like coal, but are less effective for harder abrasives like ignimbrite. The increase in wear rate with ignimbrite abrasive may be attributed to a number of factors, such as hardness, retained severe angularity of particles, and particle size.

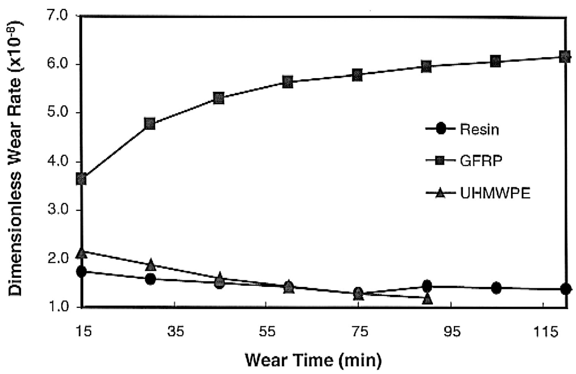

Fig. 6. Variation of cumulative dimensionless wear rate as a function of wear time for the three surfaces tested (pure vinyl ester resin, GFRP, and UHMWPE particle reinforced resin) undergoing abrasive wear from ignimbrite particles.

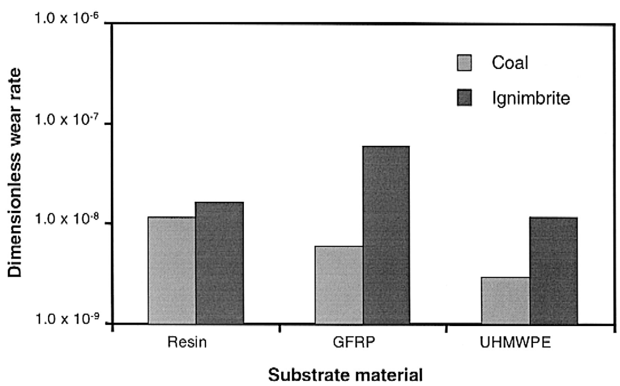

Fig. 7. A comparison of the dimensionless wear rate of the three surfaces tested (pure vinyl ester resin, GFRP, and UHMWPE particle reinforced resin) abraded by ignimbrite and coal abrasive particles.

The role of fibre reinforcement in modifying wear rate is in broad agreement with related studies reported in the literature. Cirino et al. [5] investigated the wear resistance of composites with respect to fibre configuration and sliding direction. They found that the wear rate was strongly dominated by the wear mechanisms associated with the fibres rather than those associated with matrix. Kukureka et al. [13] investigated the friction and wear of Polyamide 66 (PA 66) reinforced with short fibres of aramid, carbon, and glass in rolling-sliding contact. The wear of the aramid and carbon reinforced composite was found to be 10 times greater than that of the unreinforced polymer. However, in the case of glass fibre reinforcement, the wear rate remains similar to that of the unreinforced polymer for some time and then reaches a value slightly higher than that of the other reinforced polymers. The observed increased wear rate of fibre reinforced composites was attributed to the removal of fibres from the surface.

Abrasive wear occurs mainly by three mechanisms: micro-ploughing, micro-cutting, and micro-cracking [10]. In order to understand the details of the wear mechanisms operating on each composite material, SEM was used to probe the morphology of the worn surface. SEM images of the unreinforced vinyl ester resin at relatively low magnifications (Fig. 8) clearly show the presence of wear marks on the surface along the direction of the flow of coal. At higher magnification (Fig. 9), long cracks may be observed, predominantly along the wear direction. Other than these features, the resin surfaces worn by coal have a smooth appearance with very little wear debris present. The deep longitudinal cracks observed on the surface are consistent with a repeated ploughing mechanism causing surface fatigue. Material is plastically deformed under load through ploughing and with subsequent applications of load, micro-cracks are created along the deformed material, which are eventually removed by brittle fracture. Thin scratch like grooves along the wear direction present on the surface are formed by micro-cutting by the abrasive particles. This pattern of wear for coal on pure vinyl ester resin is consistent with a predominantly two-body abrasion process.

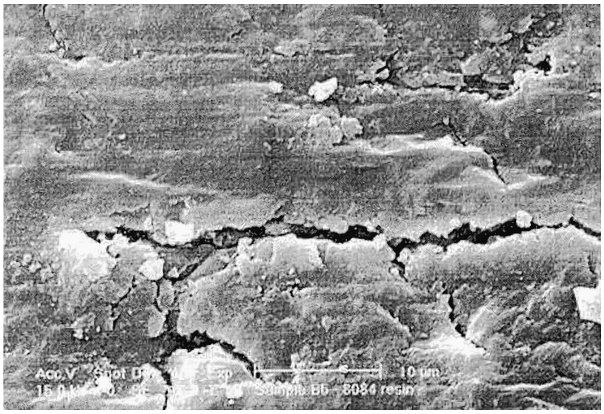

Fig. 9. High magnification scanning electron microscope image of a pure vinyl ester resin sample after abrasion by coal particles. The coal flow direction runs from right to left.

In contrast, vinyl ester resin surfaces abraded by ignimbrite (Fig. 10) do not show the texture arising from long wear marks present in case of coal. Instead, although some (short) scratch-like grooves are present, most surface damage is in the form of pits left in the surface after localised removal of surface material (Fig. 11). The evidence suggests that this spall type failure is caused by surface fatigue failure without the strongly oriented crack network seen in the case of coal. It is thought that this failure mechanism arises from the fact that the highly angular ignimbrite particles have a rolling component to their motion across the specimen surface, creating repeated point contact loading on the surface. These indentations lead to localised fatigue damage leading to spalling.

Low magnification electron micrographs (Fig. 12) of the GFRP samples worn by coal reveal that material is primarily removed by micro-cutting. Evidence for fibre

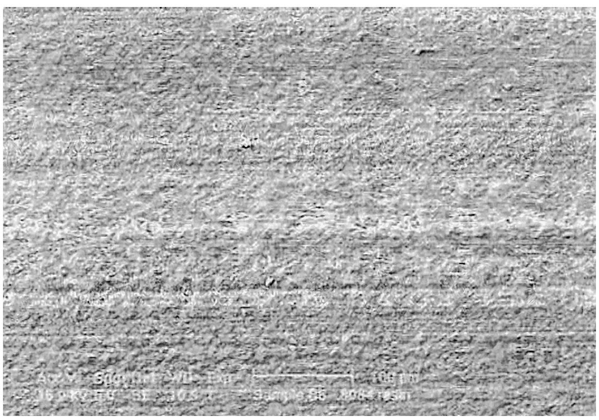

Fig. 8. Low magnification scanning electron microscope image of a pure vinyl ester resin sample after abrasion by coal particles. The coal flow direction runs from right to left.

Fig. 10. Low magnification scanning electron microscope image of a pure vinyl ester resin sample after abrasion by ignimbrite particles. The ignimbrite flow direction runs from top to bottom.

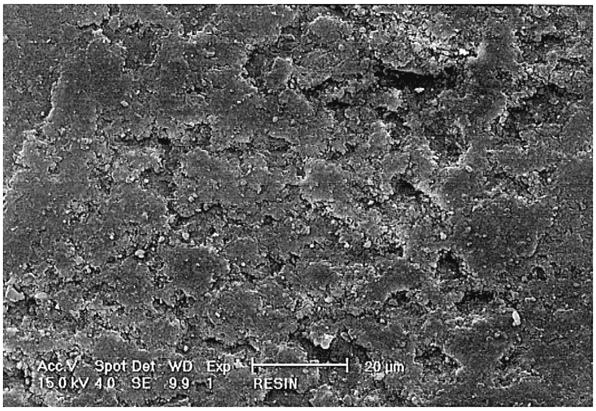

Fig. 11. High magnification scanning electron microscope image of a pure vinyl ester resin sample after abrasion by ignimbrite particles. The ignimbrite flow direction runs from top to bottom.

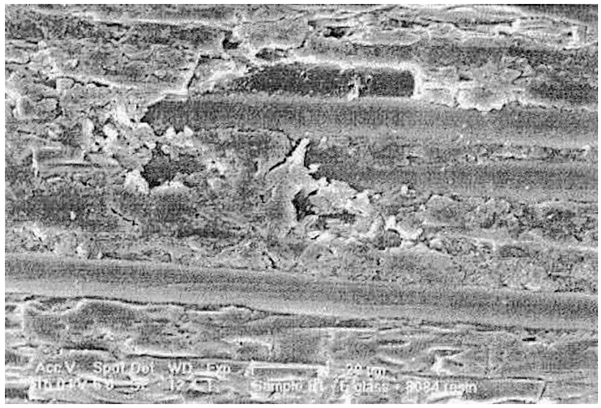

Fig. 13. High magnification scanning electron microscope image of a glass fibre reinforced resin sample after abrasion by coal particles. The coal flow direction runs from right to left.

breakage and voids left by debonded fibres are observed in the micrograph. At higher magnifications distinct evidence of fibre cutting and fatigue damage of the vinyl ester resin matrix can be seen on the surface (Fig. 13). It is thought that the observed damaged fibres are the result of surface fatigue due to repeated abrasion by coal particles. Voids caused by the removal of broken fibres are also seen on the surface and appear to be due to the abrasion of coal particles on the debonded fibres. Layers of resin seem to be removed by micro-cracking resulting again from surface fatigue. Fig. 14 and Fig. 15 show SEM images of the GFRP surface abraded by ignimbrite particles. The low magnification image shows regular banding of the surface, with some bands dominated by the presence of resin while other bands are dominated by the presence of glass fibres. These images reveal that the fibre is removed primarily through direct fracture since no sign of abrasive wear marking is observed on the fibres. It is clear that the high relative hardness and severe angularity of the ignimbrite particles result in the cleavage of exposed fibres. At higher magnifications, the presence of fibre breakage and fine wear debris are observed. The geometry and distribution of these fines suggests that they are produced through a micro-cracking rather than a micro-cutting process. Both of these observations are consistent with a wear mechanism that is dominated by abrasive particle rolling and subsequent fatigue damage. It is also evident from the undulations in topology observed in Fig. 14 that material removal from the glass fibre surface follows a cyclical pattern arising from the layered architecture of the composite with alternating resin rich and fibre rich regions. This was also recognised by Yen and Dharan [14] in their studies of the wear of fibre reinforced composites perpendicular to the fibre direction. In their quasi-steady abrasive wear model, initially the fibres are fully supported by the matrix. With continuing wear, fibres are gradually exposed as the less wear resistant vinyl ester resin recedes. Exposed fibres are then debonded and/or fractured from the surface as a consequence of inadequate matrix support. At this stage, fibres show minimum resistance to removal through wear. This process explains the observation that, of all the surfaces studied, fibre reinforced surfaces abraded by ignimbrite show the least resistance to abrasive wear.

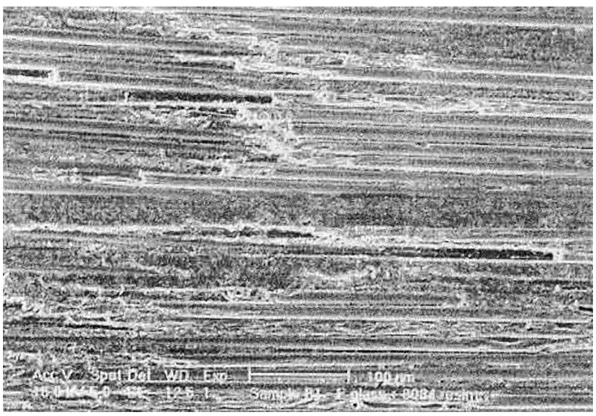

Fig. 12. Low magnification scanning electron microscope image of a glass fibre reinforced resin sample after abrasion by coal particles. The coal flow direction runs from right to left.

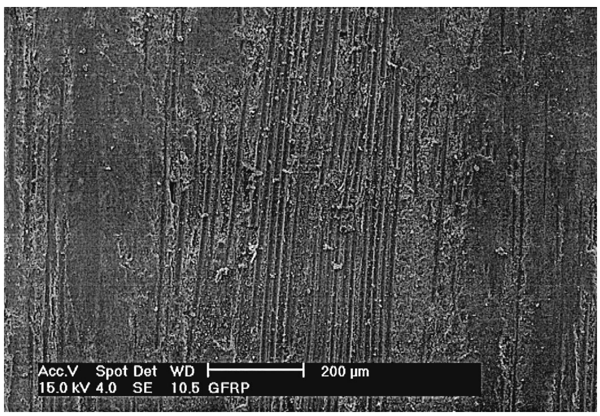

Fig. 14. Low magnification scanning electron microscope image of a glass fibre reinforced resin sample after abrasion by ignimbrite particles. The ignimbrite flow direction runs from top to bottom.

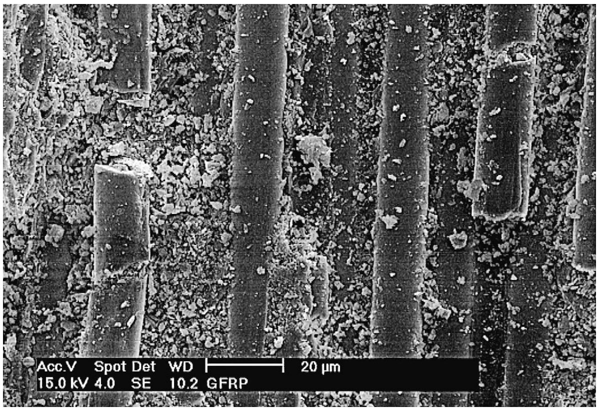

Fig. 15. High magnification scanning electron microscope image of a glass fibre reinforced resin sample after abrasion by ignimbrite particles. The ignimbrite flow direction runs from top to bottom.

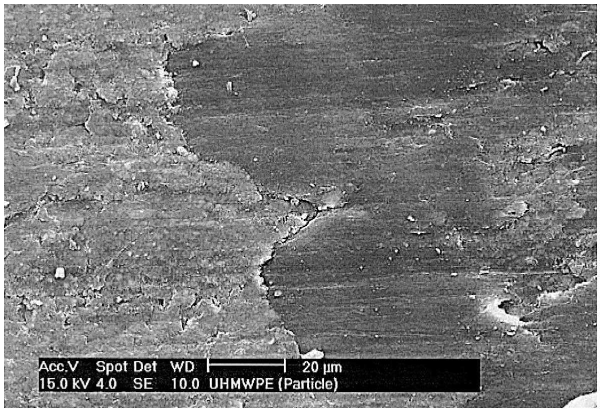

Fig. 17. A scanning electron microscope image of an ultra-high molecular weight polyethylene particle reinforced resin sample after abrasion by ignimbrite particles. The ignimbrite flow direction runs from left to right.

SEM analysis of the UHMWPE particle reinforced surfaces reveals that the predominant wear mechanisms for these surfaces are significantly different from those observed for the other two surfaces. As shown in Fig. 16 and Fig. 17, the UHMWPE particles appear to be well bonded within the vinyl ester resin matrix, since the particles are observed to be dispersed uniformly throughout the surface with little evidence of surface delamination. Although there appear to be some areas of weak bonding between the particles and matrix, these areas do not appear to be critical with respect to wear pattern of the surface. Indeed, no indication of particle debonding is observed for either coal or ignimbrite abrasion. Fig. 16 illustrates the flake like patterns that are commonly observed on the UHMWPE particle reinforced surfaces worn by coal. The surface shows evidence for feathering along the trailing edges of areas of the surface topology. The SEM images indicate that micro-cracking is significantly inhibited by the introduction of UHMWPE particles into the vinyl ester resin matrix. Indeed, cracks initiated in the resin are observed to terminate at the resin-particle interface, thus reducing the wear by micro-cracking and surface fatigue. Although the feathering wear features observed by coal abrasion on UHMWPE reinforcement surface are not observed in case of ignimbrite abrasion (Fig. 17), the scratch like patterns observed on the surface are shallow and clearly limited to thin layers only. The composite surface does not show any sign of particle debonding from the matrix indicating that a strong adhesive bond has been formed between resin and particle. Unlike the wear surface worn by coal, very little sign of micro-cracks and surface fatigue is observed on the surface worn by ignimbrite. Thus, it would appear that the effect of UHMWPE particle reinforcement dramatically improves the wear resistance of the composite surface whether coal or ignimbrite is used as the abrading medium. The observation that UHMWPE particle reinforcement improves the wear resistance of vinyl ester resins is unsurprising given that UHMWPE is a well-known abrasion resistant material. Indeed, work by Budinski [15] using a primarily three-body abrasion test (ASTM G 65) reconfirmed that UHMWPE has a better abrasion resistance to silica sand than most other plastics and elastomers. The results presented here show that while the nature of the abrasion resistance of UHMWPE reinforced resins depends upon the micro-mechanics of the wear process, it is present for both two-body and three-body wear regimes.

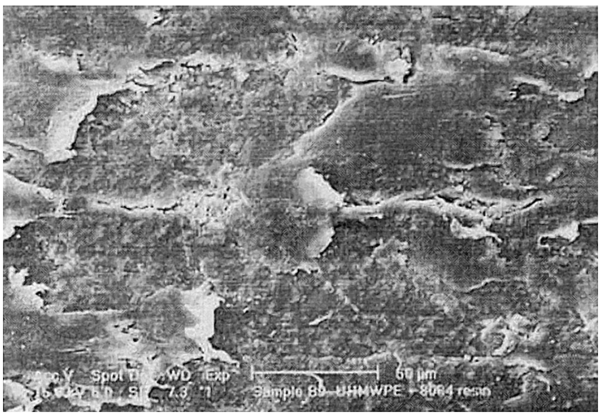

Fig. 16. A scanning electron microscope image of an ultra-high molecular weight polyethylene particle reinforced resin sample after abrasion by coal particles. The coal flow direction runs from left to right.

Finally, one of the main aspects of this study was to investigate the effects of abrasive particle hardness upon the wear mechanisms for fibre and particle reinforced composite surfaces. During two-body abrasion, the hardness of the particles involved in abrasion is known to have an important influence on the rate of wear [7]. In general, the harder the abrasive particle, the greater the wear rate is. For particles significantly harder than the surface, the exact value of their hardness becomes less significant. In fact, the wear rate becomes much more sensitive to the ratio of abrasive hardness (H_a) and the surface hardness (H_s) when $H_a/H_s \approx 1$. The measured hardness values of the materials used in this study are summarised in Table 1. The elastic nature of the UHMWPE particle reinforced surface meant that it was not possible to obtain a plastic deformation, and hence a hardness measurement, of this surface. Although coal is the softer of the two abrasive particles (by an order of magnitude), it does contain some relatively hard constituents, like quartz and iron pyrite, and variations in the relative content of these materials is likely to give rise to the measured variation of coal hardness [7]. For a hard abrasive, like ignimbrite, it appears that the dominant material removal mechanism occurs through surface fatigue. Localised surface fatigue in the vinyl ester resin samples revealed that this damage is consistent with a three-body mechanism whereby there is a rolling component of motion for the hard and angular particles. However, for a softer abrasive like coal, it seems that micro-cutting and ploughing and subsequent micro-cracking are the dominant wear mechanisms. The effect of reinforcement is then highly dependent upon the hardness of the wear medium. Although fibre reinforcement is effective in reducing the wear of a softer abrasive, the brittle fibres deteriorate rapidly under the action of hard particles that are free to undergo three-body abrasion. In the case of UHMWPE particulate reinforcement, the increased toughness of the reinforcing particles appears to dramatically reduce fatigue failure of the surface and thus material removal by both plastic deformation and brittle fracture is decreased.

4. Conclusions

Specimens of three different composite materials, vinyl ester resin, glass fibre reinforced resin, and UHWMPE particle reinforced resin, have been abraded using hard (ignimbrite) and relatively soft (coal) bulk solids. In general terms, lower wear rates were obtained for surfaces abraded by coal than for surfaces abraded by ignimbrite. These lower wear rates, in the case of coal, were a consequence of both lower particle hardness and decreasing particle size during abrasion.

The abrasion resistance of reinforced composite materials is a consequence of the micro-mechanics that occur during abrasive wear, which in turn, are strongly dependent upon the hardness of the wear media. Both two-body and three-body wear patterns are possible with bulk solids sliding across polymer matrix composites. The transition between two-body and three-body wear depends on the hardness of the abrasive particles. In this work, hard particles lead to spall type failure consistent with micro-cracking of the surface caused by fatigue. In contrast, two-body wear patterns involving cutting and ploughing were observed with soft particles.

Micro-cracking of the matrix caused by surface fatigue is the dominant mechanism of abrasive wear of polymer matrix composites caused by bulk solids. In the two-body wear process, this micro-cracking occurs predominantly as a result of ploughing. In the three-body case, this micro-cracking is the result of cyclic point loading as abrasive particles roll. In the case of both mechanisms, this surface fatigue failure can be inhibited by the use of a suitable reinforcement. Indeed, it is the nature of the reinforcement, rather than the matrix material, which dominates the wear rate. For fibre reinforced surfaces, the brittle fibres are highly vulnerable to fracture by harder abrasive particles, even though these materials offer protection against softer abrasives. Increasing the toughness of the reinforcing materials (as is the case for UHMWPE particles) increases the wear resistance of the materials to both soft and hard abrasives. Thus, the selection of an appropriate reinforcing material for enhancing the abrasion resistance of a composite surface is strongly governed by the material properties of both the abrasive particle and the reinforcement.

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