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A comparative study of the wear resistance of thermoplastic and thermoset coatings

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Abstract

Thermoset and thermoplastic polymeric materials are used as coatings on the bore of downhole tubulars such as water injectors in the oil industry. Previous work has indicated that such coatings can fail by impact damage and by abrasion from the wire used to lower inspection tools down the tubular. The wire is commonly called "slickline" and the type of wear is called "wireline wear". However, the different wear mechanisms of thermoset and thermoplastic polymeric coatings under wireline wear conditions have not been clarified. Filler materials such as calcium silicate, calcium fluoride and alumina are often added to polymeric coatings to enhance the mechanical properties of the matrix materials; nevertheless, fillers can improve the wear resistance or exacerbate the wear rate of polymeric coatings depending on the characteristics of the filler material such as its shape, concentration, and the boundary condition between the filler and the matrix material. In this study, two types of thermoset polymeric coatings, a modified novolac containing calcium silicate fillers and a modified epoxy containing alumina as the filler, and one type of thermoplastic coating, a fluoropolymer with 2% calcium fluoride filler, were selected for wear tests. The disc specimen in a pin-on-disc (POD) apparatus was modified to enable embedding a circular loop of wire into its surface. That arrangement was used to study the effect of normal force and sliding distance on wireline wear of the three polymeric coatings. Detailed scanning electron microscopy (SEM) was carried out on the wear tracks produced to investigate the wear mechanisms. Energy dispersive X-ray (EDX) spectroscopy was used to X-ray map the wear scars so as to quantify the amount and size distribution of filler present in the wear scar compared to that in the bulk material and thus elucidate the role of fillers in the wear mechanism.

Keywords: Wireline wear; Polymeric coatings; Fillers; Wear resistance

1. Introduction

A water injection system, consisting of steel tubulars, is used in the oil industry to maintain pressure in the well by the injection of water into the reservoir. For several decades, plastic coatings have been used to prevent corrosion and lubricate the bores of these tubulars [1]. Historically, these plastic coatings have been primarily based on phenolic resins but recently various thermoset and thermoplastic materials such as novolac (a type of phenolic resin produced by the condensation reaction of phenol and formaldehyde using an acid catalyst), epoxy and polyamide, etc. have been applied as coatings to the downhole tubulars. In service, the inspection tools that are periodically lowered down the tubulars at speeds up to approximately $2\,ms^{-1}$ can mechanically damage these polymeric coatings resulting in exposure of the substrate steel and subsequent corrosion by the water environment. This mechanical damage is caused by the wearing action of the supporting slickline wire against the coating, called wireline wear, and by direct impact of the inspection tool against the coating [2]. Previous work on wireline wear has proved that the wear mechanism is predominantly that of two-body abrasion between the asperities on the surface of slickline wire and the coating surface [2,3]. The wear damage mechanisms are shown schematically in Fig. 1.

Several mechanisms, namely microploughing, microcutting, microfatigue and microcracking, have been proposed by Zum Gahr [4] to explain the processes of two-body abrasive wear that are possible when a single abrasive tip traverses a surface of a material. Because of the complexity of abrasion, no one mechanism completely accounts for the loss of material under any given condition. Generally, microploughing and microcutting are the dominant processes on ductile materials while microcracking becomes important on brittle materials. Microcracking was recognised by Evans and Lancaster as one of the important wear modes during the sliding wear of polymers against metals [5]. Microcracking can lead to sections of material detaching by spalling

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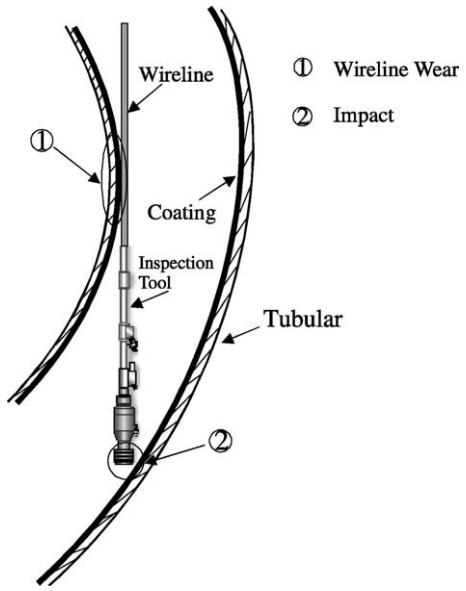


Fig. 1. Schematic diagram showing mechanical damage mechanisms in a downhole tubular.

as sub-surface cracks propagate during abrasive wear. This can produce far greater material loss in brittle materials than microploughing and microcutting [4].

Fillers, in the form of particulates and fibres, are often added to polymeric materials to improve their stiffness and strength [6]. This second phase filler material will influence the wear resistance of the composite material. There are many references that illustrate the influence of fillers and fibre reinforcement on the abrasive wear resistance of polymeric composites [7–9]. Under controlled testing a given phase shows a specific wear mode and wear rate, which is determined by its individual properties. Consequently, when various phases are combined to form a multiphase material, it is expected that the overall performance will be a function of the respective contribution of each phase [10]. Nevertheless, the influence of the structure of composites on abrasive wear is a complex function of the properties and interactions of the matrix, the reinforcing constituent, and the interface between them [11] and experimentally it is found that fillers can either enhance or degrade the wear resistance of polymeric composites [12].

Tanaka and Kawakami [13] studied the effect of different fillers on polytetrafluorethylene (PTFE)-based composites. They recommended a filler size ranging from several micrometres to about 30 μm as the most suitable for PTFE-based composites. Small fillers within PTFE result in poor wear resistance of the PTFE. This is due to the fact that small fillers on the frictional surfaces cannot prevent large scale destruction of the banded structure of the PTFE matrix and thus very small fillers are easily removed from the wearing surface together with the PTFE film and transferred onto the counterface. PTFE and polyetherimide (PEI) proved to be good wear-resistant materials in a study by Bijwe et al. [7]. However, adding fillers resulted in an inferior wear performance for both materials. Analysis of the pin surface by scanning electron microscopy (SEM) revealed that a number of deep cracks were present which propagated in a direction normal to the abrasion furrows. Poor adhesion of the filler to the matrix gave rise to the initiation of these cracks and hence increased the wear rate [7]. Microcutting and microploughing were found by Symonds and Mellor [2] in abrasive wear tests on ductile modified epoxy coatings while microcracking was found when brittle silica filled modified epoxy coatings were tested under similar conditions. Microcracks, initiating at the filler particles, resulted in the brittle coating exhibiting higher wear rates than the ductile coatings. Microcracking was also observed by Lhymn [14] during sliding wear tests carried out on carbon-fibre-reinforced PTFE. Microcracks were observed at the surface either at the fibre-matrix boundary or at weak spots in the matrix and eventually led to delaminatation of the matrix material.

In conclusion, wear of polymeric composites is influenced by the properties of the filler, of the matrix and of the interface, by the relative hardness of the filler to that of the abrasive grit or counterface, by the content, shape, size, distribution and orientation of filler, by the abrasiveness of filler against the matrix and last but not least by the loading conditions during abrasive wear.

In the present study, wireline wear tests have been carried out on three types of polymeric coatings (two thermoset and one thermoplastic) to determine wear rates, wear mechanisms and the effect of fillers. The coatings were supplied by commercial coaters and to maintain product confidentiality have been identified here as A, B and C.

2. Coating characterisation

Samples from each type of coating were prepared using standard metallographic methods and studied using SEM. The basic microstructural characteristics of the coatings are listed in Table 1. Details of the primer layer present on these coatings are not given, as the primer plays no role in determining the wear resistance.

Coating A was a modified novolac thermoset polymeric coating filled with nominally 9% calcium silicate by volume with a particle size of 10–30 μm. This was powder coated onto mild steel by means of electrostatic spraying. Fig. 2 shows a transverse section of coating A. The fillers are seen to be well bonded with the coating matrix. However, a number of gaps were apparent at the filler/matrix interface, in addition cracks were also present within the fillers. These were believed to have been caused by metallographic preparation of the sample.

Thermoset coating B was a modified epoxy-phenolic coating filled with nominally 20% alumina by volume with a particle size of 10–30 μm. Note this is approximately double the filler volume fraction of that present in coating A. Fig. 3 presents a transverse section of coating B, the fillers are slightly proud of the matrix indicating that during the

Table 1
Details of the three types of polymeric coatings tested

Coating	Generic name	Resin type	Filler type	Filler size (μm)	Filler percentage	Coating density (kg m^{-3})	Coating thickness (μm)
A	Thermoset	Modified novolac powder	$CaSiO_3$	10–30	~9	690	345–360
B	Thermoset	Modified epoxy-phenolic	Al_2O_3	10–30	~20	740	250–260
C	Thermoplastic	Fluoropolymer powder	CaF_2	20–40	~2	1380	1500

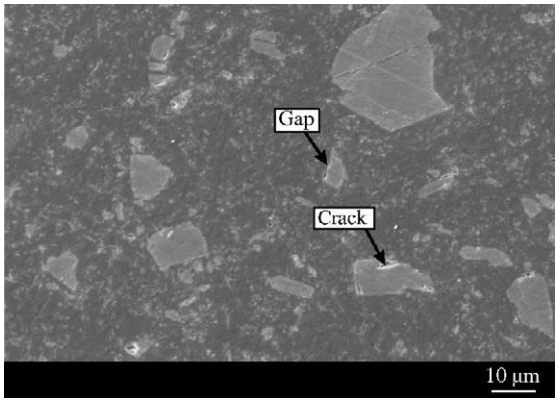


Fig. 2. Transverse section of thermoset coating A showing the good bonding between fillers and matrix. Note a number of gaps at the filler/matrix interface and cracks within the fillers, which were caused by metallographic preparation of the sample.

metallographic preparation procedure the matrix material was more easily removed. Additionally, the cavity shown in the coating matrix is the result of a filler particle detaching from the matrix due to loss of matrix around it and poor adhesion between the filler and matrix.

Coating C was a thermoplastic fluoropolymer coating filled with 2% calcium fluoride by volume with a particle size of 20–40 μm. Fig. 4 shows a transverse section of coating C. Note there was a high volume fraction of fillers in the primer layer matrix but these are irrelevant to the wireline wear resistance of this material.

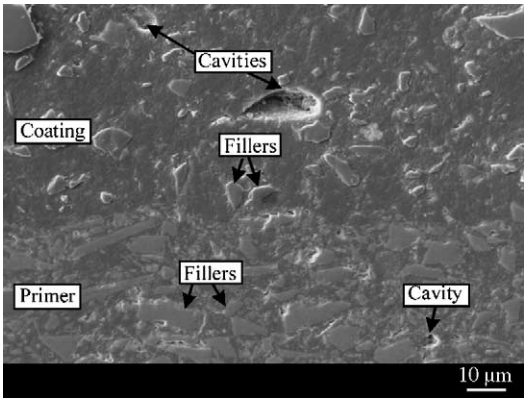


Fig. 3. Transverse section of thermoset coating B, note the matrix material was preferentially removed by the metallographic process leaving the fillers proud of the matrix. Note also the cavities on the surface resulting from filler detachment.

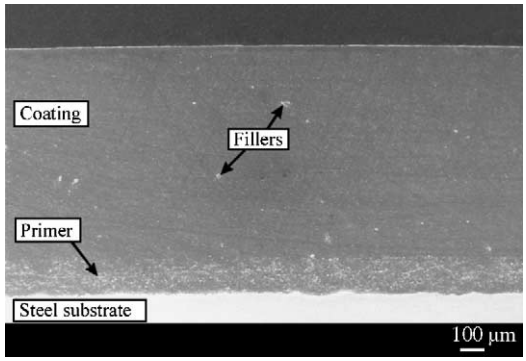


Fig. 4. Transverse section of thermoplastic coating C, note the very small amount of filler (2%) present within the matrix.

3. Wireline wear tests

3.1. Experimental apparatus

Wireline wear is produced by the linear motion of slickline wire against a polymeric coating. To replicate this relative motion in the laboratory under controlled conditions a length of slickline wire was embedded on a stainless steel disc of a pin-on-disc (POD) rig. The slickline wire itself was 3.2 mm in diameter and was formed into a circular loop of 80 mm radius. The surface roughness of the slickline wire was Ra = 0.35 μm along the axis of the wire. Its Vickers hardness, 30 kg load, was 435. Coating samples were cut from the polymeric coated plates to form square pins with dimension of 10±0.5 mm, which were then loaded against the revolving circular loop of wire. Fig. 5 shows a photograph of the

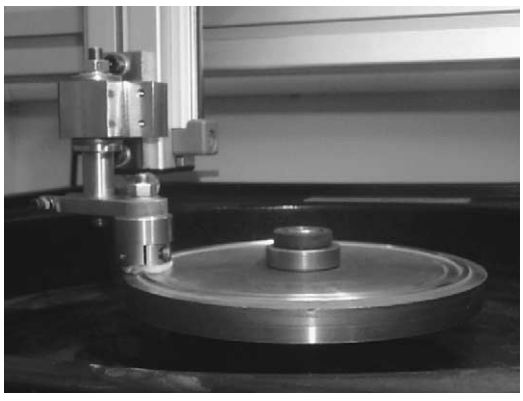


Fig. 5. Modified POD apparatus for wireline wear tests.

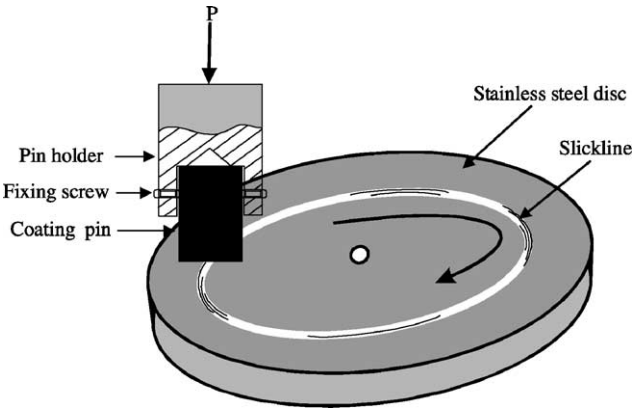


Fig. 6. Schematic diagram of wireline wear tests.

modified POD experimental apparatus and Fig. 6 presents schematically the polymeric coating pin clamped in a pin holder with the slickline wire sliding beneath it.

3.2. Experimental procedure and conditions

Two types of comparative experiments have been carried out on the polymeric coatings in this study—firstly an investigation of the influence of applied load on wear rate and secondly an investigation of the influence of sliding distance on volumetric loss. For the study on the influence of load, the load applied to the sample pins was varied from 80 to 220 N, while the sliding distance was maintained constant at 500 m. These line loads were selected as they are in the range of line loads seen in service. To study the influence of sliding distance, the load applied to the coatings was fixed at 150 N and the sliding distance was varied from 250 to 1250 m. For both types of experiments the rotational speed of the disc was 100 rev/min and tap water coolant was supplied during the experiment to prevent the temperature rising from the sliding action of the coating pin against the slickline wire. The experimental conditions are detailed in Table 2.

During the wear test the coating and the wire will wear. Wear of the asperities on the wire might result in a lower wear rate of a coating subsequently tested against this "worn" wire. In order to eliminate the influence of wear of the wire in the two types of comparative study carried out on the three different polymeric coatings, a new slickline wire loop was used for each polymeric coating for both types of experiment. Additionally, in order to study quantitatively the influence of the "worn" wire on the wear rate of the polymeric coatings, the "worn" wire was finally used to repeat the wear test carried out first with the lowest applied load.

Table 2
Experimental conditions for the wireline wear tests

	Tests at various loads	Tests at various sliding distances
Load (N)	80, 115, 150, 185, 220	150
Sliding distance (m)	500	250, 750, 1250
Rotational speed of disc (rev/min)	100	100
Testing time (min)	10	5, 15, 25
Volume of coolant water (l min^{-1})	1	1

4. Experimental results and discussion

4.1. Wear rates of polymeric coatings from wireline wear tests

The mass loss of each specimen after wear testing was determined and converted into volume loss in order to calculate volumetric wear rate (m^3 h^{-1}) of the polymeric coating. Fig. 7 shows the volumetric wear rate of the three polymeric coatings A, B and C as a function of the load applied. Error bars are included for the data where duplicate tests were carried out. The thermoplastic polymeric coating C showed, in general, the highest wear rates of the three polymeric coatings tested. Fig. 7 shows an increase in wear rate for all three polymeric coatings with increasing applied load. However, the wear rate of the thermoplastic coating C showed little increase in wear rate with loads above 150 N. The thermoset coating with the highest percentage of filler particles, B, exhibited a linear increase in wear rate with load while the wear rate of the thermoset coating A with fewer filler particles showed a sudden increase in wear rate between loads of 150 and 185 N. Fig. 8 indicates that volumetric loss increases with sliding distance. Note only the data from coating A would seem to extrapolate in a linear manner through the origin of the plot. This is discussed in Section 4.4.

4.2. Wear mechanisms

Wearing the slickline wire against the surface of a specimen of polymeric coating produced a scar that contained features of the wear mechanisms for each coating. When studying the wear scar using scanning electron microscopy, it was noted that the key evidence on the wear mechanism

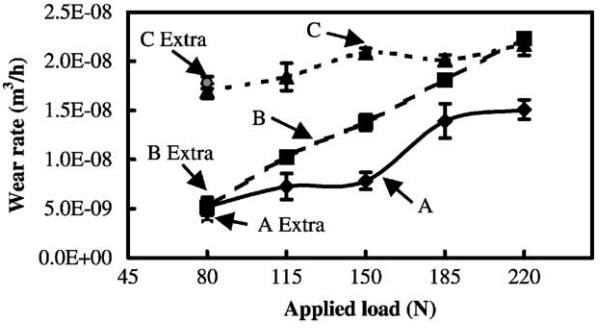


Fig. 7. Wireline wear rates of the three polymeric coatings tested as a function of applied load.

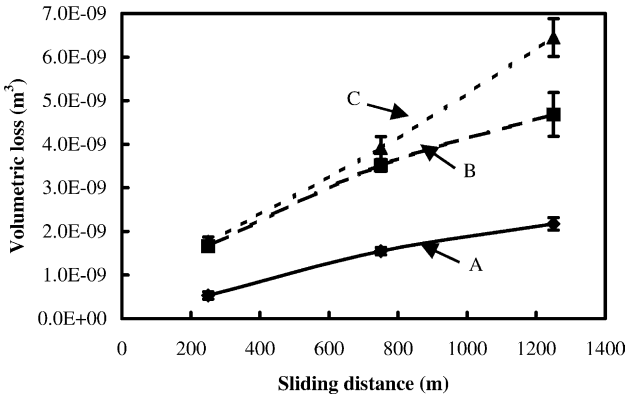


Fig. 8. Volumetric loss of the three polymeric coatings tested as a function of sliding distance.

operative was not only to be found at the bottom of the wear tracks themselves, but also at the areas close to the edges of the scars. The slickline wire had a curved surface, so the coating was worn in an ever widening and deepening track until the diameter of the wire was reached or the test finished. Therefore, the edge of the track was the last area of virgin surface to be worn.

Fig. 9, a SEM micrograph of the wear scar of coating C tested at a load of 80 N, shows both microploughing and microcutting wear mechanism are operative at this low load. These features were found on all specimens of the thermoplastic coating C tested. Fig. 10 shows the debris left at the edge of the wear scar on the thermoplastic coating C tested under a higher load of 185 N. This debris appears to have been produced by an extrusion mechanism. Examination at high magnification indicated that this extrudate did not derive from a third body trapped and spread in the contact. This behaviour was also found at lower loads but to a more limited extent. Microploughing furrows were also present on this wear scar. These mechanisms of material loss are responsible for the high wear rate exhibited in Fig. 7. Fig. 11 shows the bottom of the wear scar of coating C tested under the highest applied load, 220 N. Microcracking can be seen in the direction normal to the microploughing furrows. High friction force between the slickline wire and the coating surface under this high applied load was the main reason for microcracking. Additionally, higher loads forced the water coolant out from the contact area increasing the friction force dramatically. However, as can be appreciated from Fig. 7 microcracking at loads above 150 N did not produce an increase in wear rate because coating C was not removed by this mechanism due to the tough, ductile nature of the thermoplastic matrix.

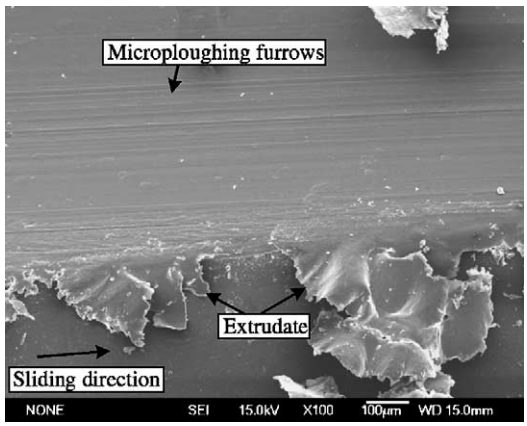


Fig. 10. Wear scar on the thermoplastic coating C under a load of 185 N, note the extrudate left on the edge of the wear scar and the microploughing furrows.

Fig. 12 shows a wear scar on the thermoplastic coating A tested under an applied load of 80 N, microcracking and microploughing can be seen as the main wear mechanisms at the bottom of the wear scar. Microcracking initiated from the filler particles and the cracks propagated into the matrix; the microploughing furrows were shallower than the furrows found in the wear scar of the thermoplastic coating C. Under the applied load, stress was concentrated around the filler particles causing cracks between the fillers and

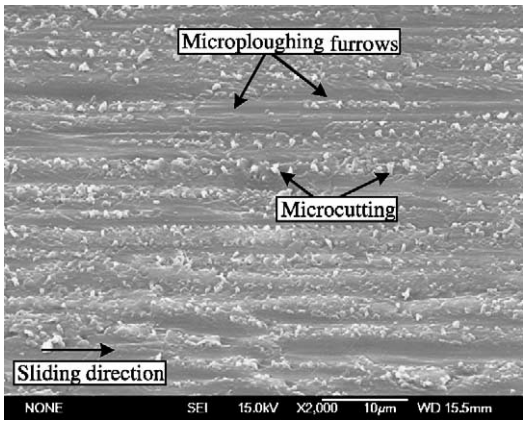


Fig. 9. Wear scar on the thermoplastic coating C under a load of 80 N, showing microploughing and microcutting to be the dominant wear mechanisms causing loss of material.

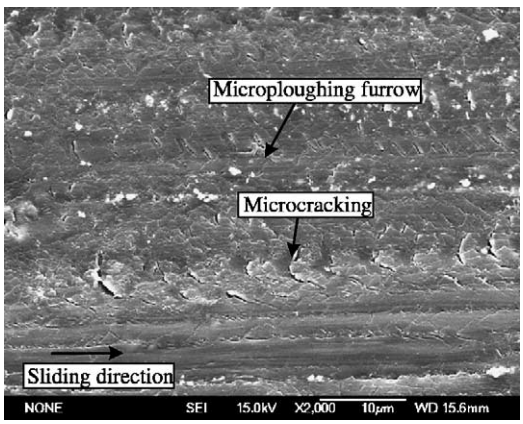


Fig. 11. Bottom of the wear scar on thermoplastic coating C. Note the microcracking occurring under a load of 220 N. However, the microcracks did not propagate leading to material removal.

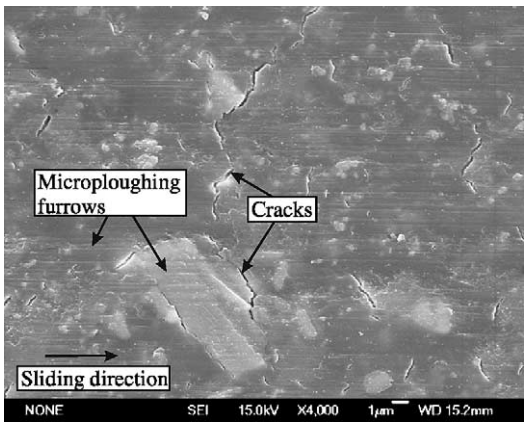


Fig. 12. Wear scar on the thermoset coating A under a load of 80 N. Note the cracks initiating from the fillers and propagating into the matrix. Microploughing furrows were also found on the surfaces of both fillers and matrix indicating that the fillers supported the load applied from the slickline wire.

matrix. However, the filler particles were not detached from the matrix material under this low load due to the good bonding between the fillers and matrix. Fig. 13, a SEM micrograph close to the edge of the wear scar on A under a 80 N load, shows microcracks around the fillers and large fillers which have been fractured and fragmented but which are still held in the matrix material. This indicates that the filler particles have good bonding with the matrix and that they can support part of the load in the wireline wear tests. Fig. 14 shows that under a higher load of 150 N large filler particles were fractured into fragments and many small filler particles were detached from the matrix material leaving cavities in the matrix. These cavities were themselves stress concentrations and resulted in more cracks in the matrix and a higher wear rate as was seen in Fig. 7. At an even higher load (185 N), Figs. 15 and 16 show that severe microcracking took place around the edge of the wear scar and at its bottom. Large sections of matrix were removed

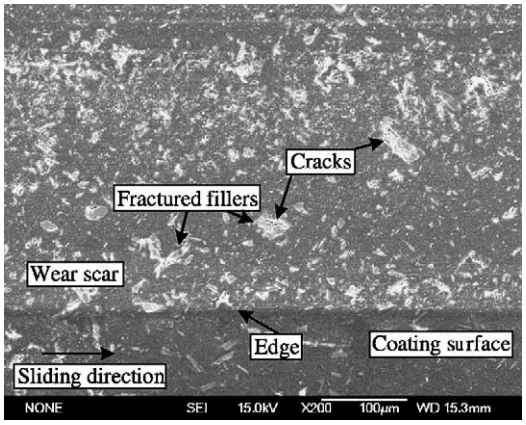


Fig. 13. Wear scar on coating A under a load of 80 N, note the fillers fragmented but the fragments were retained in the matrix to support part of the load applied from the slickline wire.

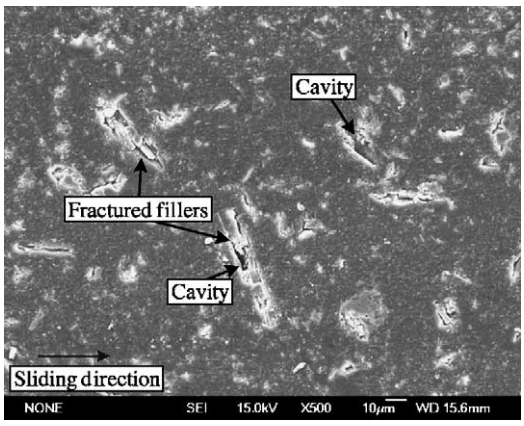


Fig. 14. Wear scar on coating A under a load of 150 N, note the fillers were fragmented and detached from the matrix with this higher load.

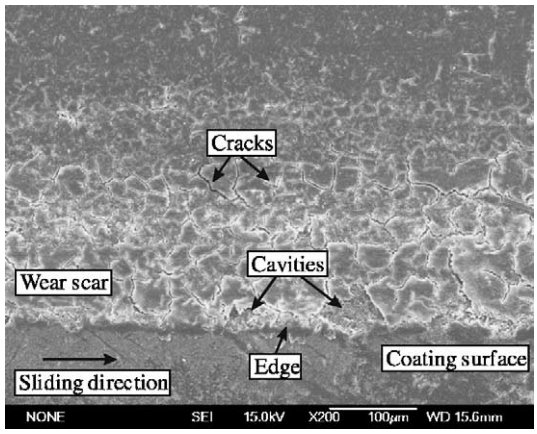


Fig. 15. Wear scar on coating A under a load of 185 N, note severe microcracking of the coating matrix along the edge of the wear scar.

causing even larger filler particles to be detached from the matrix. Thus the fillers do not now support the load resulting in a sudden increase in the wear rate as shown in Fig. 7.

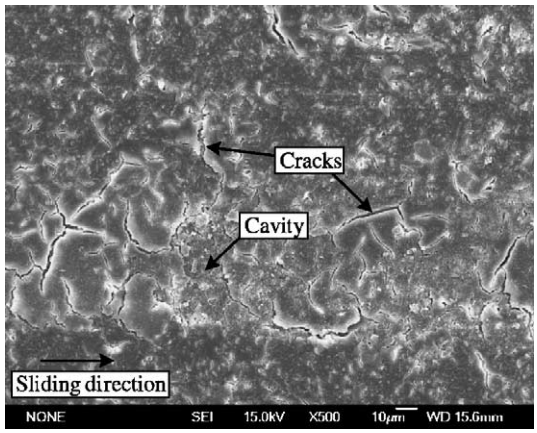


Fig. 16. Wear scar on coating A under a load of 185 N, note large cracks were found at the bottom of the wear scar and contributed to matrix removal.

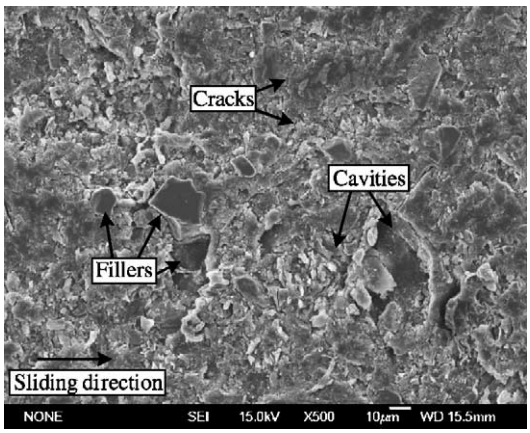


Fig. 17. Wear scar on coating B under a load of 80 N, note the poor wear resistance of the matrix material. The matrix material was fractured and removed from the coating surface leaving the fillers proud of the matrix; the fillers then detached leaving the cavities in the matrix.

Figs. 17 and 18 show wear scars on the thermoset coating B after testing under a low load of 80 N and a high load of 220 N. Very similar wear features were found for all the loads applied to this coating. Microcracking of the matrix material was the main wear mechanism operative. The matrix material exhibited very poor wear resistance in wireline wear tests as it was fractured and removed even before the filler particles were detached from the matrix. This is in agreement with that shown in the SEM micrograph of the metallographically prepared cross-section of coating B shown in Fig. 3, where many fillers are observed to be proud of the coating matrix after the metallographic polishing process. Fig. 19 shows poor bonding between the filler and the matrix; the fillers were easily detached from the matrix under a low load of 80 N leaving cavities whose boundaries were the same shape as the filler particles removed. Many cavities within the matrix material structure lead to many stress concentrations in the matrix resulting in higher local stresses, microcracking and in consequence a high wear rate. Additionally, the high percentage (20%) of fillers in coating B degraded the wear resistance of the coating because the fillers themselves caused stress concentrations in the matrix. Furthermore, the detachment of fillers causes the adjacent matrix to be poorly supported and hence is subjected to greater stress and thus more susceptible to fracture. Fig. 20 shows a large crack in the matrix, normal to the sliding direction, which formed after neighbouring fillers had been detached. This would give rise to a high volume loss of matrix.

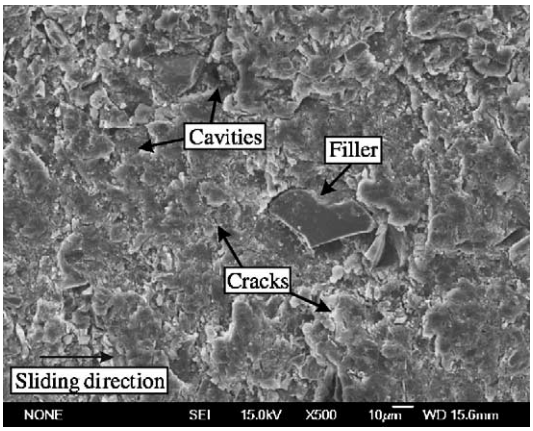


Fig. 18. Wear scar on coating B under a load of 220 N, note the similarity of features found on samples tested at both 80 and 220 N.

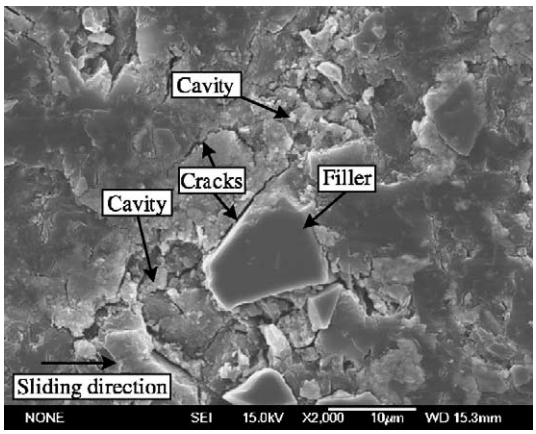


Fig. 19. Wear scar on coating B under a load of 80 N, note the poor bonding between the fillers and matrix causing the fillers to detach easily.

The above results for wireline wear of polymeric coatings containing fillers are thus similar to those reported in the literature for the abrasive wear resistance of polymers and reviewed in Section 1 [2,4,7,14], where it was highlighted that microcracking and subsequent spalling of material is an important wear mode for filled polymeric materials. The wear rate itself depends on the properties of the filler, of the matrix and of the filler/matrix bond strength. In addition the relative hardness of the filler to that of the counterface, the content, shape, size, distribution and orientation of filler, and the abrasiveness of filler against the matrix are important parameters. This will now be addressed.

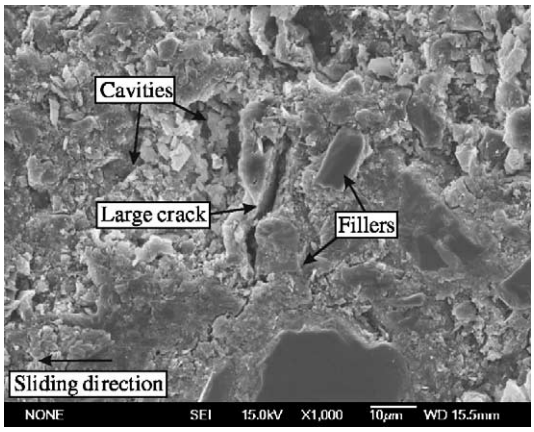


Fig. 20. Wear scar on coating B under a load of 80 N, note the large crack in the matrix normal to the sliding direction formed after neighbouring filler particles had detached.

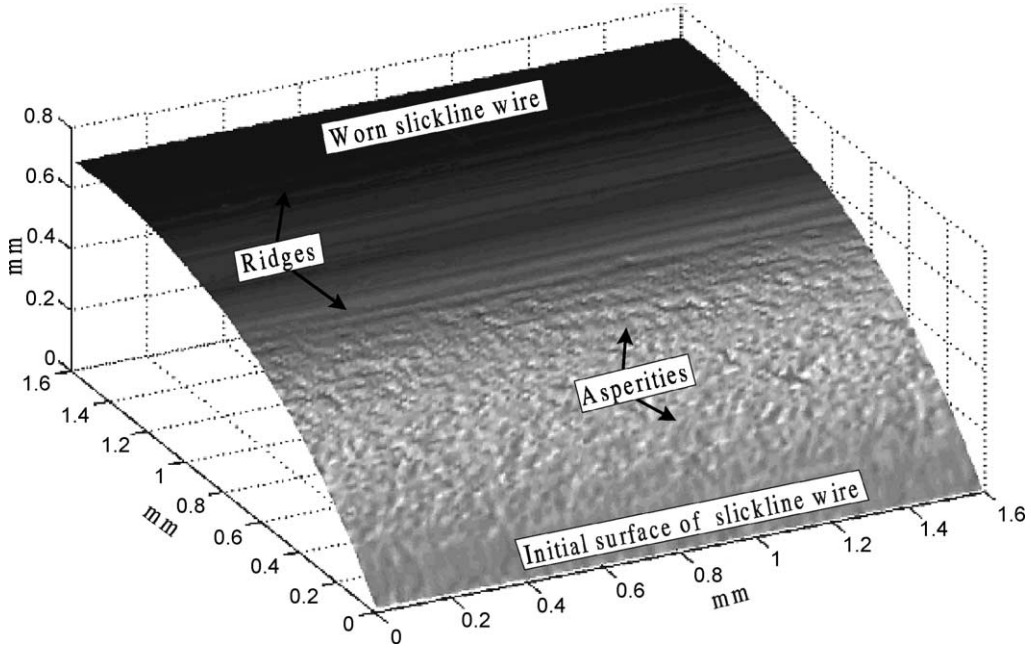


Fig. 21. A section of the slickline wire loop after concluding the wireline wear tests under various loads for coating A. Note the difference between the surface of the "new" slickline wire and the "worn" slickline wire; asperities on the wire surface have been polished, however ridges can still be seen running along the longitudinal sliding direction.

4.3. Influence of the topography of the slickline wire on the wear of polymeric coatings

During the wear test the slickline wire itself will wear somewhat especially when the polymeric coating contains abrasive filler particles. Fig. 21 shows the geometry of part of the surface of the slickline wire loop determined by a Taylor Hobson form Talysurf 120L after concluding wear testing at various loads for coating A. This clearly reveals the difference between the "worn" wire and the wire which has not been in contact with the filled polymeric coating. The asperities on the surface of the slickline wire in contact with the coating have polished somewhat (Ra $= 0.21\,\mu$m as compared to the original value of Ra $= 0.35\,\mu$m), however longitudinal ridges and grooves are still present on the "worn" wire.

The wear rates of the three polymeric coatings using the "worn" slickline wire and conditions of 80 N load and 500 m sliding distance are also shown in Fig. 7 (identified as "extra"). The wear rate of A by the "worn" slickline wire was approximately 21% less than that by the "new" slickline wire. Thus, although some asperities are removed from the slickline wire during this wear test its microploughing ability is maintained by the longitudinal ridges still present on the "worn" wire. It should be noted that the "worn" wire used for the repeat experiments and that shown in Fig. 21 was that corresponding to after all the experiments with varying load had been concluded on that coating type. Therefore, the difference in wear rates between any two adjacent tests carried out on coating A attributable to the different condition of the slickline wire should be much less than 21%.

The wear rates of coatings B and C using the "worn" slickline wire were 11 and 5% higher than that by the "new" wires, however, these values are within the experimental error range which suggests for these coatings less polishing of the asperities on the slickline wire is taking place. In the case of the filled polymeric coating B it was noted that the filler particles were readily removed from the matrix and thus did not support the applied load appreciably. Hence they would be expected to abrade the slickline wire less.

4.4. The influence of load and sliding distance on wear rate

A simple model of abrasive wear, based on the Archard equation, predicts that the volume of material removed by two-body abrasion should be directly proportional to the normal load and also directly proportional to the sliding distance [15]. Fig. 7 shows that, in general, the wireline wear rate of the three polymeric coatings increases as the load increases but the three coatings exhibit different relationships between wear rate and load. Little increase in wear rate with load was observed for the thermoplastic coating C above a load of 150 N. Microcracking was found at loads above 185 N in this material. As these microcracks did not propagate, this wear mechanism did not lead to additional material removal and an increase in wear rate with load. A large amount of microcracking was found on the thermoset coating A at loads of 185 N and above. However, these microcracks propagated resulting in a sudden increase in wear rate as large filler particles were removed from the matrix material. No change in wear mechanism with load was

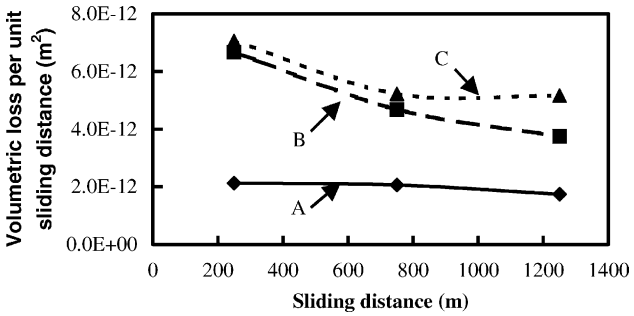


Fig. 22. Volumetric loss per unit sliding distance as a function of sliding distance for the three polymeric coatings tested.

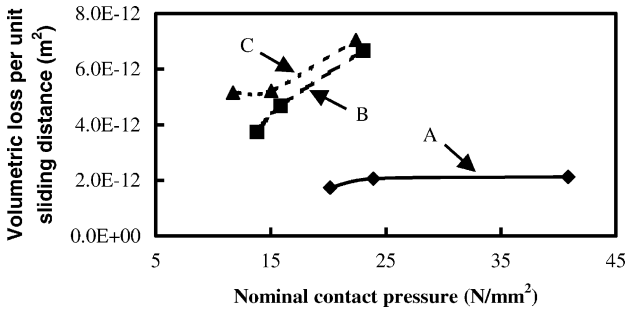


Fig. 23. Volumetric loss per unit sliding distance as a function of nominal contact pressure for the three polymeric coatings tested.

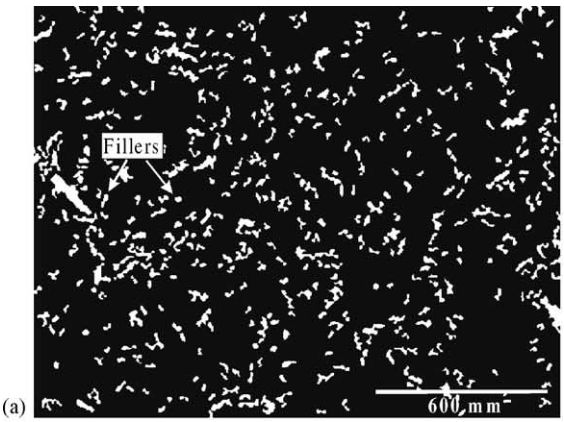
detected for the thermoset coating B, therefore the wear rate of this coating increased in a constant manner with load as shown. As noted above wear rate should be directly proportional to load. Fitting a power law relationship to the data in Fig. 7 for coating B and to the data for loads less than or equal to 150 N for coatings A and C gives power law exponents equal to 1.4, 0.89 and 0.27, respectively. Only the data for coating A give an exponent close to 1 suggesting that the simple wear model does not hold for coatings B and C.

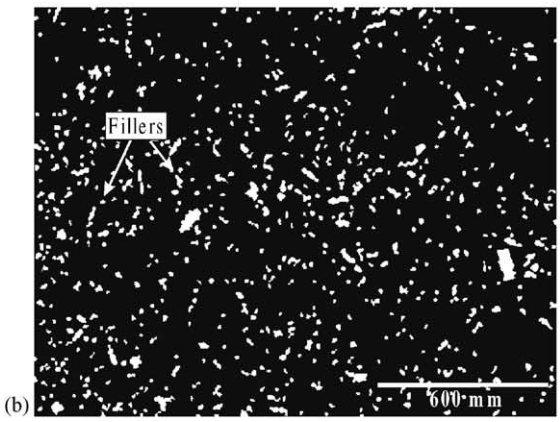
As noted above the simple abrasive wear model would predict that the volume of material removed should be directly proportional to the sliding distance, i.e. the volumetric loss per unit sliding distance should be a constant. Fig. 22 presents the volumetric loss per unit sliding distance as a function of sliding distance. This figure indicates that the volumetric loss per unit sliding distance of the thermoplastic coating C and particle filled thermoset coating B decreased by approximately 25% as the sliding distance increased from 250 to 750 m, while for sliding distances between 750 and 1250 m the volumetric loss per unit sliding distance did not changed significantly. The volumetric loss per unit sliding distance of the thermoset coating A did not change appreciably for all the three sliding distances tested. Indeed, reference to Fig. 8 reveals that that the volumetric loss for this coating extrapolates to approximately zero at zero sliding distance implying that the volumetric loss per unit sliding distance is constant even at very low sliding distances. The rate of wear-in of the coatings thus varies but at longer sliding distances (times) the cumulative wear rates of individual coatings are comparable.

However, in the case of a wear test in which the nominal size of the wear contact increases with sliding distance, it is not at all obvious that the wear volume per unit sliding distance should necessarily remain constant [16]. During the wireline wear tests the nominal area of the wear contact is continually increasing and consequently the nominal contact pressure is continually decreasing. For a constant asperity density on the wireline surface this would imply that the load on the individual asperity decreases as the nominal contact pressure decreases [16]. In order for the volumetric loss per unit sliding distance to be independent of the sliding distance, it must also be independent of the load per asperity. Whereas some wear models predict this to be the case [17], ball cratering wear tests have shown that the load per abrasive particle actually influences the wear rate [16]. Fig. 23 shows the volumetric loss per unit sliding distance as a function of the nominal contact pressure based on the projected area of the wear scar. This figure would seem to suggest that above a certain nominal contact pressure, or load per asperity, the volumetric loss per unit sliding distance is independent of nominal pressure but below a certain value the volumetric loss per unit sliding distance decreases as the nominal contact pressure decreases.

4.5. Role of the filler in wireline wear of polymeric coatings

Filler particles play an important role in determining the wear rates of the filled polymeric coatings, therefore it is important to study how the number and size of these filler particles evolve during wireline wear. Fig. 24(a)–(c) shows the Si Kα X-ray maps of the surface of coating A before the wireline wear tests and of the wear track after tests at 150 and 185 N. A suitable magnification was chosen so that the whole width of the wear scar was included in the map. The same magnification was used for all X-ray maps. Similarly, Fig. 25(a)–(c) shows the Al Kα X-ray maps of the surface of coating B before the wireline wear tests and of the wear track after tests at 150 and 185 N. These X-ray maps were subject to standard image analysis techniques to determine the number of filler particles present in a given area and their size distribution. Fig. 26 gives the area percentage of fillers present initially and in the wear track after tests at loads of 150 and 185 N. This confirms that fillers are more easily lost for coating B than for coating A. After testing at 150 N load coating A had only lost 18% of the fillers originally present while coating B had lost 58%. After testing at 185 N the corresponding values are 37 and 61%. Figs. 27 and 28 show the number of filler particles in various size ranges present in coatings A and B initially and after wireline wear testing at loads of 150 and 185 N. Wireline wear of coating A produces a large number of smaller particles by fragmentation of larger particles. At a load of 150 N these smaller filler particles are retained while at 185 N these particles have





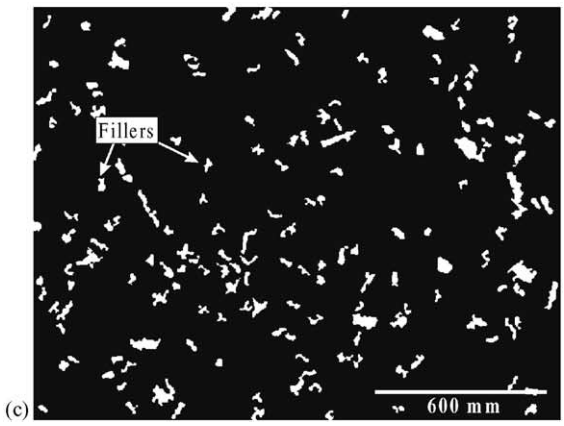
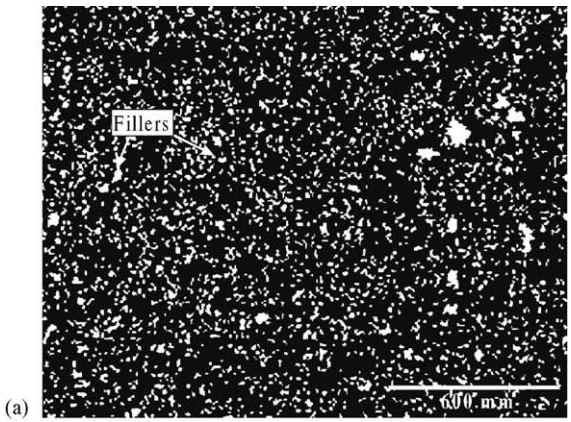
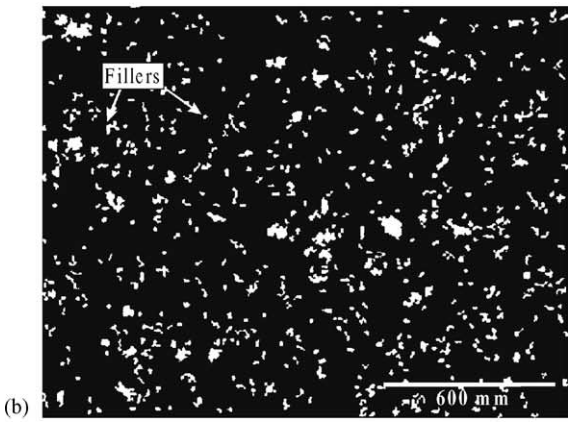


Fig. 24. Si Kα X-ray map from coating A. (a) Initial surface of coating A containing 9.5% $CaSiO_3$ fillers. (b) Wear track produced by a load of 150 N, note the large fillers in the initial surface have fragmented into smaller ones and some of these have been removed. Area of filler equals 7.8%. (c) Wear track produced by a load of 185 N, note many fillers particles have been removed. Area of filler equals 6.0%.





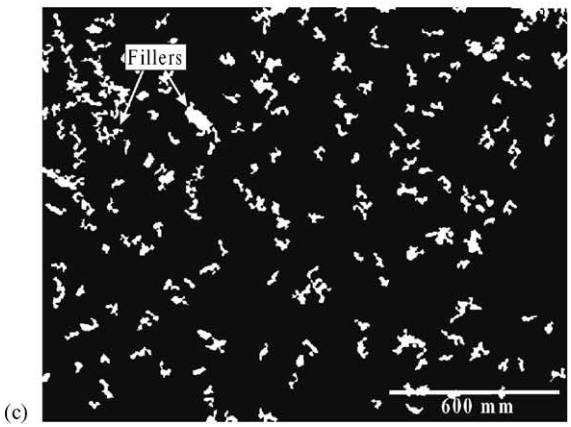


Fig. 25. Al Kα X-ray map from coating B. (a) Initial surface of coating B containing 18.5% Al_2O_3 fillers. (b) Wear track produced by a load of 150 N, note both small and large fillers have been detached. Area of filler equals 7.8%. (c) Wear track produced by a load of 185 N, note the number and size of filler particles are very similar to that seen in (b). Area of filler equals 7.1%.

detached and are no longer present to help support the load. The drop of filler content from 7.8% after testing at 150 N to 6.0% after testing at 185 N (a 23% change) combined with the detachment of the smaller filler particles would appear to be responsible for the sharp increase in wear rate of this coating noted in Fig. 7.

On the other hand, Fig. 28 indicates that for coating B small filler particles of area centred on 30 μm^2 are readily detached even at a load of 150 N, due to their poor bonding to the matrix, and thus cannot contribute to support the load. The drop of filler content from 18.5% initially to 7.8% (58% decrease) after testing at 150 N together with the detachment of a large number of small filler particles after testing at 150 N would appear to be responsible for the higher wear rate of this coating at this load compared to A.

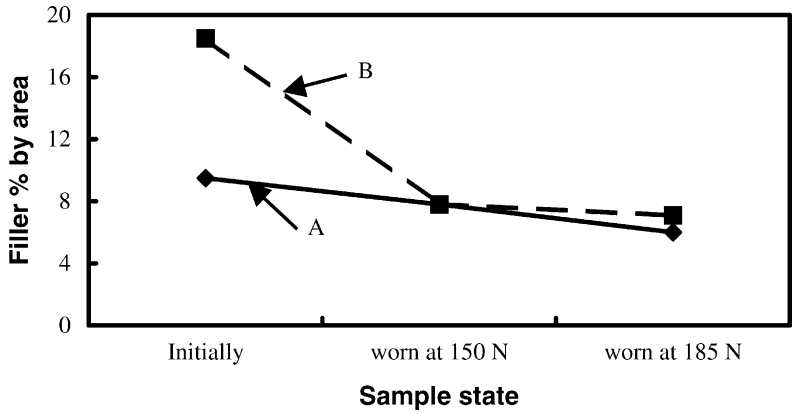


Fig. 26. Area percentage of fillers present initially and after wireline wear testing under applied loads of 150 and 185 N for coatings A and B.

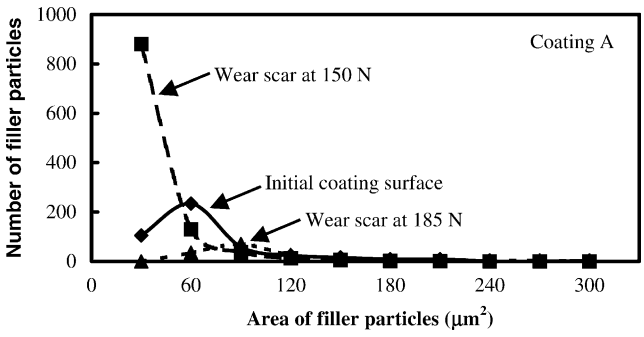


Fig. 27. Number of filler particles in various particle size ranges present in coating A initially and after wireline wear testing at loads of 150 and 185 N.

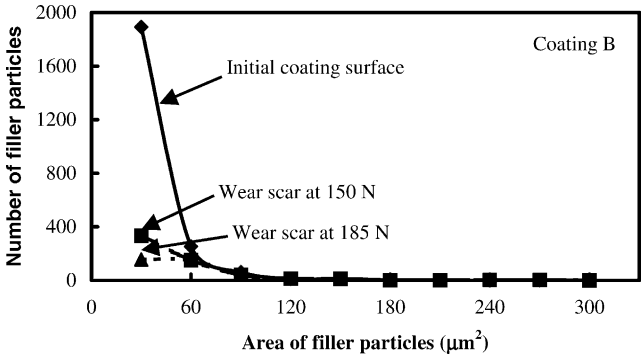


Fig. 28. Number of filler particles in various particle size ranges present in coating B initially and after wireline wear testing at loads of 150 and 185 N.

5. Conclusions

Wireline wear tests have been carried out on three polymeric coatings under different applied loads and for different sliding distances. The wear rates of the specimens tested have been calculated and the wear mechanisms of wireline wear analysed. The load applied during the tests influenced the wear mechanisms and wear rates of these polymeric coatings significantly. The rate of wear-in of the coatings varies but at longer sliding distances (times) the cumulative wear rates of individual coatings are comparable. Microcutting and microploughing were the main mechanisms causing the wear of the thermoplastic coatings, microcracking was found at higher applied loads. However, this did not change the wear rate significantly because the microcracks did not propagate and thus did not lead to material removal. Microcracking was the dominant wear mechanism for the thermoset coatings because the cracks on the wear scar propagated detaching segments of the matrix resulting in material loss. The fillers in thermoset coating A had good bonding to the matrix and supported the load from the slickline wire under moderate applied loads although the larger filler particles fragmented but these fragments were retained. However, they were detached from the matrix under higher applied loads resulting in a sudden increase of wear rate. The fillers in coating B detached very easily due to their poor bonding with the matrix. The cavities produced by filler detachment acted as a stress concentration causing more cracking and material removal. The slight wear of the slickline wire during the wireline wear test did not affect the wear mechanisms operative nor did it have a significant effect on the wear rates, especially for coatings B and C. Image analysis on X-ray maps of the wear tracks was found to be a useful tool in elucidating the role of fillers in wireline wear as it allowed filler particles and matrix to be easily differentiated and generated quantitative data on the evolution of the number and size of these filler particles during wireline wear.

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References

[1] R.H. Davis, The use of internal plastic coatings to mitigate CO_2 corrosion in downhole tubulars, NACE International, Corrosion 94, Paper No. 23.

[2] N. Symonds, B.G. Mellor, Polymeric coatings for impact and wear resistance, Wear 225–229 (1999) 111–118.

[3] Y.M. Xu, B.G. Mellor, The effect of fillers on the wear resistance of thermoplastic polymeric coatings, Wear 251 (2001) 1522–1531.

[4] K.H. Zum Gahr, Formation of wear debris by the abrasion of ductile metals, Wear 74 (1981) 353–373.

[5] D.C. Evans, J.K. Lancaster, The wear of polymers, Treatise Mater. Sci. Technol. 13 (1979) 85–139.

[6] S.L. Rosen, Fundamental Principles of Polymeric Materials, Wiley/Interscience, New York, 1982, pp. 303–311.

[7] J. Bijwe, C.M. Logani, U.S. Tewari, Influence of fillers and fibre reinforcement on abrasive wear resistance of some polymeric composites, Wear 138 (1990) 70–92.

[8] S.V. Prasad, P.D. Calvert, Abrasive wear of particle-filled polymers, J. Mater. Sci. 15 (1980) 1746–1754.

[9] A.C. Mcgee, C.K.H. Dharan, I. Finnie, Abrasive wear of graphite fibre-reinforced polymer composites materials, Wear 114 (1987) 97–107.

[10] W. Simm, S. Freti, Abrasive wear of multiphase materials, Wear 129 (1989) 105–121.

[11] K.H. Zum Gahr, Microstructure and Wear of Materials, Elsevier, Amsterdam, 1987, pp. 513–524.

[12] J.M. Thorp, Abrasive wear of some commercial polymers, Tribol. Int. 15 (1982) 59–68.

[13] K. Tanaka, S. Kawakami, Effect of various fillers on the friction and wear of polytetrafluoroethylene-based composites, Wear 79 (1982) 221–234.

[14] C. Lhymn, Effect of normal load on the specific wear rate of fibrous composites, Wear 120 (1987) 1–27.

[15] I.M. Hutchings, Tribology, Friction and Wear of Engineering Materials, Edward Arnold, London, 1992, p. 143.

[16] R.I. Trezona, D.N. Allsopp, I.M. Hutchings, Transitions between two-body and three-body abrasive wear: influence of test conditions in the microscale abrasive wear test, Wear 225–229 (1999) 205–214.

[17] E. Rabinowicz, L.A. Dunn, P.G. Russell, A study of abrasive wear under three-body conditions, Wear 4 (1961) 345–355.