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The influence of load and surface treatment on the corrosive wear of cast iron in oil–sulphuric acid environments

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An investigation into the influence of load and surface finish on the reciprocating corrosive wear of grey cast iron in oil–10 vol % sulphuric acid mixtures has been undertaken with particular respect to the contact between cylinder-lining and piston-ring materials from marine diesel engines. In mixtures containing acid of 10 vol % concentration, under loads of 1.5 to 3.5 kg, the hard-phase phosphide eutectic/alloy carbide material in the cast irons was able to support the load and aid in the retention of an oil film during sliding. However, at a load of 4 kg the hard-phase material was able to penetrate the oil film more effectively and contact the countersurface for long periods, giving considerably increased wear rates. In mixtures containing acid of 40% concentration, the wear rates were less than those of 10% concentration, due to formation of adherent, wear-protective corrosion-product films. These were particularly effective at loads of 1.5 to 2.0 kg, while at 2.5 to 4.0 kg such films were unable to be sustained on the hard-phase regions and wear rates were increased to some extent, although were still much less than in the 10% acid concentration mixture. During sliding in mixtures containing acid of 40% concentration, development of a wear-protective film was influenced very markedly by the surface finish of the cast-iron specimens. Corrosion-product films were able to develop more easily on rough surfaces (120 grit) than on smooth surfaces (1 μm), while hydrodynamic oil films could develop more easily on smooth surfaces. The overall result was that the wear rate increased with decreasing surface roughness from 120 grit to a maximum at an intermediate value (800 grit), and then decreased with further decrease in roughness to 1 μm.

1. Introduction

Although corrosive wear can account for over 5% of industrial wear damage [1], there have been relatively few studies of the synergistic effects of electrochemical corrosion and mechanical wear. One example where corrosive wear can cause considerable damage is in the cylinder linings and piston rings of marine-diesel engines. Here, the piston ring moves in reciprocating motion in close proximity to the cylinder-lining material and lubricating oil is used to minimize metal–metal contact by providing a hydrodynamic-lubrication layer between the surfaces in relative motion. However, there has been a recent trend to residual fuels rather than distillate fuels to drive such engines. These former fuels can contain high impurity levels, particularly up to 4 wt % sulphur. On combustion, acid vapours are produced which may condense on the cylinder liners. In particular, the formation of sulphuric acid can result in considerable corrosion and corrosive wear of the component surfaces. The sulphur burns to form SO_2, some of which combines with excess oxygen to give SO_3. In the presence of water vapour, the SO_3 in converted to sulphuric acid which condenses on the cylinder-lining surfaces if the temperatures are below the dew point for such condensation. The formation of SO_3 from SO_2 can be catalysed by the cylinder surface [2] and by the presence of V_2O_5, produced by the combustion of vanadium impurities in the fuel [3]. Approximately 0.1% of the sulphur in the fuel is converted to sulphuric acid, the remainder passing out as SO_2 in the exhaust gas [4, 5].

Many cylinder linings and piston rings are made from grey cast iron which performs well under conditions of lubricated sliding wear. During running-in, the graphite in the iron is reported to be removed and forms a surface coating with iron oxide debris [6]. This coating assists in wear protection during momentary contacts between the sliding surfaces if the lubricating oil film should break down. In the presence of sulphuric acid, it may assume a more important role if the acid causes significant breakdown of the oil film. In addition, since the coating develops over surface irregularities, it produces a smooth surface which allows higher loads to be carried by a fully hydrodynamic lubricant film.

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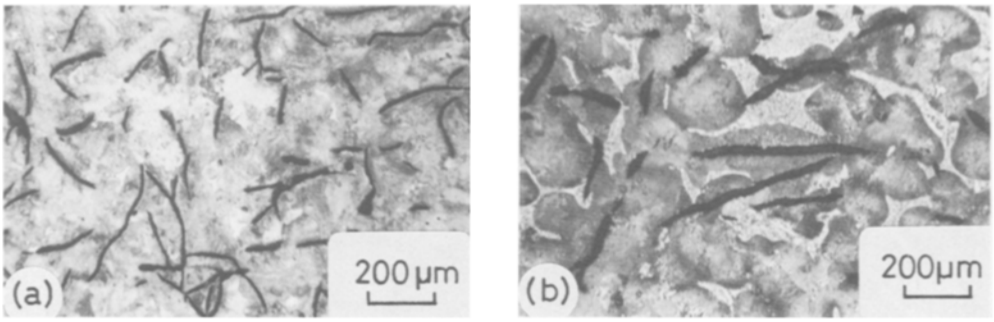

Figure 1 Microstructure of the wear-specimen materials: (a) pin material, (b) disc material C.

The present research programme has been a systematic study of the interaction of corrosion and mechanical wear during the reciprocating sliding of cast iron cylinder-lining and piston-ring materials in a base lubricating oil contaminated with various amounts of sulphuric acid of various concentrations. This paper describes the influence of applied load and specimen surface finish on the wear behaviour in two acid–oil environments, while other publications consider the influence of metallurgy and composition of the cast iron [7], of acid volume and concentration [8], and of temperature [9].

2. Experimental details

2.1. The wear apparatus

The wear experiments were carried out in a reciprocating pin-on-disc apparatus described in detail elsewhere [7, 10]. Prior to operation of the apparatus, the pin specimen was placed perpendicular to, and in contact with, the fixed horizontal disc specimen which was located in a corrosion cell containing an oil–acid mixture. The wear motion involved traversal of the pin over the disc in a backwards-and-forwards movement with an amplitude of 7 mm and a frequency of 400 double traversals per minute. The load on the specimens could be varied between 1 and 5 kg. The temperature was maintained at 20° C during the tests.

The contact-resistance between the pin and disc specimens was measured continuously during the tests using a device described elsewhere [11]. In order to obtain meaningful measurements, the specimens were electrically isolated from the wear apparatus by PTFE seals. As clean metals in contact under low loads give contact-resistances of milliohms or less, then any positive readings on this device (which could measure values in the range 0.1 to $10^6\,\Omega$) would indicate the presence of oil, oxide or other insulating contaminant film between the contacting surfaces.

2.2. The wear specimens

The pin specimens were machined from a pearlitic, grey cast-iron piston-ring material containing significant quantities of relatively small graphite flakes and about 0.9 vol % of a light-etching, hard, phosphide eutectic/alloy carbide phase (Fig. 1a). The specimens were 12.5 mm diameter rods which had a hemispherical tip turned on to them by a lathe, giving the final surface finish. The disc specimens were machined from a cylinder-lining material, designated material C. This was a pearlitic grey cast-iron containing 2.83 wt % C, 1.25 wt % Si, 1.0 wt % Mn, 0.63 wt % P, 0.21 wt % V and 0.11 wt % S. A few relatively large graphite flakes were apparent in the matrix which also contained approximately 17.7 wt % of a hard phase (Fig. 1b). The discs were 30 mm in diameter by 20 mm thick. Prior to testing, the surface was polished down to 400 grit finish on SiC paper (standard procedure). Subsequently, some specimens were polished against one of the following surfaces: 120, 800 or 1200 grit finish SiC paper or 1 µm diamond paste-coated polishing cloth. Prior to testing, the non-contacting parts of the two specimens were protected from the corrosive environment by an epoxy resin coat. The exposed metal was washed and degreased in acetone.

2.3. Experimental procedure

The specimens were bolted into the wear apparatus, with the abrasion markings on the disc specimen being at 90° to the direction of motion of the pin, the load set to the appropriate value and the electrical connections made to the contact-resistance device. Appropriate volumes of a base lubricating oil (one used in formulated marine diesel engine oils but without any additives being present) and sulphuric acid (of the required concentration in water) were mixed for 1 h in a beaker using a mechanical stirrer and an air bubbler. The emulsified mixture was poured into the wear-apparatus cell and maintained at 20° C. The mechanical stirrer and air flow (35 ml sec^{-1}) were switched on. The wear run was commenced and allowed to continue for 24 h. The motor was switched off and the specimens removed rapidly and cleaned in acetone. Subsequently, the specimens were examined and analysed by various techniques. The wear volume of the pin was determined from measurement of the diameter of the wear scar on the hemispherical surface and calculation of the volume of material lost, assuming that the wear scar was flat.

3. Results

3.1. Pin wear volume measurements

3.1.1. The influence of applied load

The total wear scar volume after 24 h sliding against a disc of 400 grit finish in a 10 vol % acid-in-oil mixture (acid of 10% concentration) was relatively independent of load in the range 1.5 to 3.5 kg, but increased very considerably for a load of 4.0 kg. In acid of 40% concentration, the total wear volume was always less than in acid of 10% concentration. Here, the wear volume was independent of load in the region 1.5 to

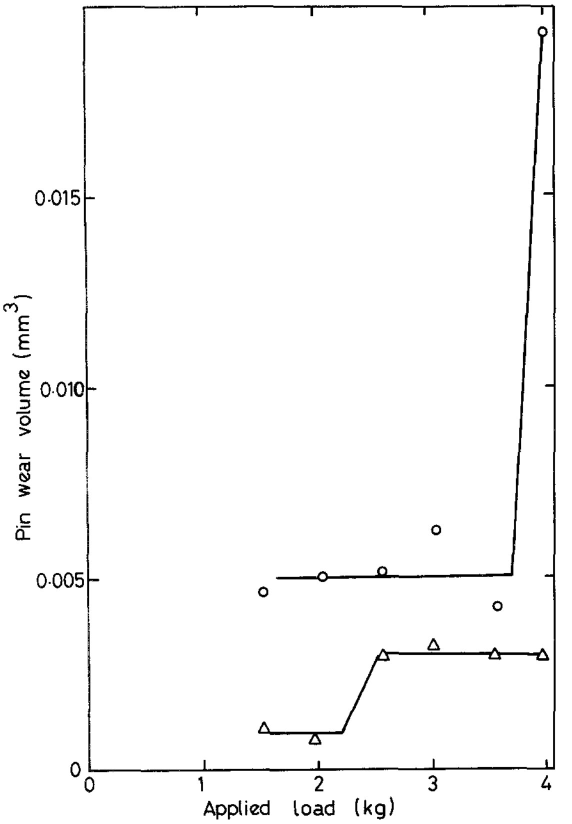

Figure 2 Plot of pin wear volume against applied load after wear of pin specimens against disc specimens for 24 h (10 vol % acid-in-oil mixtures). Disc specimens of 400 grit SiC paper surface finish. Acid concentration (○) 10%, (△) 40%.

2.0 kg, but then increased somewhat at 2.5 kg and remained reasonably constant with further increases in load to 4.0 kg (Fig. 2).

3.1.2. The influence of surface finish

The total wear scar volume after 24 h sliding under a load of 2 kg in 10% acid-in-oil mixture (acid of 40% concentration) was very dependent on the surface finish of the disc (Table I). As the surface finish was reduced in coarseness (from 120 grit to 800 grit), the pin wear volume increased very considerably. However, further reductions in the coarseness of the surface finish (from 800 grit to 1 μm) resulted in a progressive decrease in wear volume. The wear volume from sliding against the disc with 800 grit finish was much larger than those from sliding against discs of either coarser or finer surface finish.

3.2. Contact-resistance measurements

During each test, the instantaneous contact-resistance values fluctuated rapidly between maximum and minimum values, the rate of fluctuation being consistent with the rate of change of direction in the reciprocating sliding mode. The maximum values were recorded as the pin reached the centre of its traversal, while the minimum values were recorded as the pin came to a stop and the direction of motion was reversed. At this time, the oil film was at least partly collapsed before the pin started moving again and the oil film was redeveloped.

TABLE I Pin wear volumes after sliding against disc specimens of various surface finish for 24 h under a load of 2 kg in 10 vol % acid-in-oil mixture (acid of 40% concentration)

Disc surface finish	Pin wear volume (mm^3)
120 grit	0.00039
400 grit	0.00090
800 grit	0.00736
1200 grit	0.00138
1 μm	0.00041

3.2.1. Sliding in 10 vol % acid-in-oil environment (acid of 10% concentration)

3.2.1.1. The influence of applied load. During sliding under a load of 1.5 kg, maximum and minimum values of 0.15 and 0 Ω were recorded for the first 10 h. Subsequently, and for the next 6 h, these increased to 0.28 and 0.15 Ω, respectively. During the final 8 h of the test the maximum value increased to 1.6 Ω although the minimum value was unaltered.

Under a load of 2.0 kg the recorded contact-resistance was zero for the initial 3 h sliding. Positive maximum and, slightly later, positive minimum values were then noted. However, these maximum and minimum readings were very erratic and fluctuated a number of times during the sliding period. The maximum values fluctuated between 2.4 and 0 Ω while the minimum values fluctuated correspondingly, between 0.4 and 0 Ω.

Increasing the load to 2.5 kg resulted in a maximum resistance of 0.28 Ω which remained reasonably constant throughout the 24 h period, while at a load of 3.0 kg the maximum was maintained at 0.1 Ω. At 4.0 kg the maximum recorded value was similarly very low, often decreasing to zero during the sliding period. In all three cases, minimum values of zero were recorded at all times. However, under a load of 3.5 kg the contact-resistance profiles were slightly different. Here, during the first 7 h sliding, maximum values of 0.15 Ω and zero minimum values were recorded. Subsequently these increased to 0.28 and 0.15 Ω, respectively and, after a further 4 h they increased further to 0.52 and 0.17 Ω, respectively, at which they remained for the duration of the test.

3.2.2. Sliding in 10 vol % acid-in-oil environment (acid of 40% concentration)

3.2.2.1. The influence of applied load. Under an applied load of 1.5 kg, maximum and minimum contact-resistance values of 33 and 17 Ω, respectively, were established during the initial 20 min and maintained throughout the test period. Under a load of 2.0 kg, corresponding values of 300 and 60 Ω were established during the initial 40 min sliding. However, after 13 h these reduced sharply to 39 and 24 Ω, respectively. A further increase in load to 2.5 kg resulted in maximum and minimum values of 33 and 17 Ω, respectively, being established during the initial 20 min sliding. After a further 8 h these decreased to 17 and 6 Ω, respectively, and remained steady for the remainder of the test period.

During sliding under a load of 3.0 kg, maximum

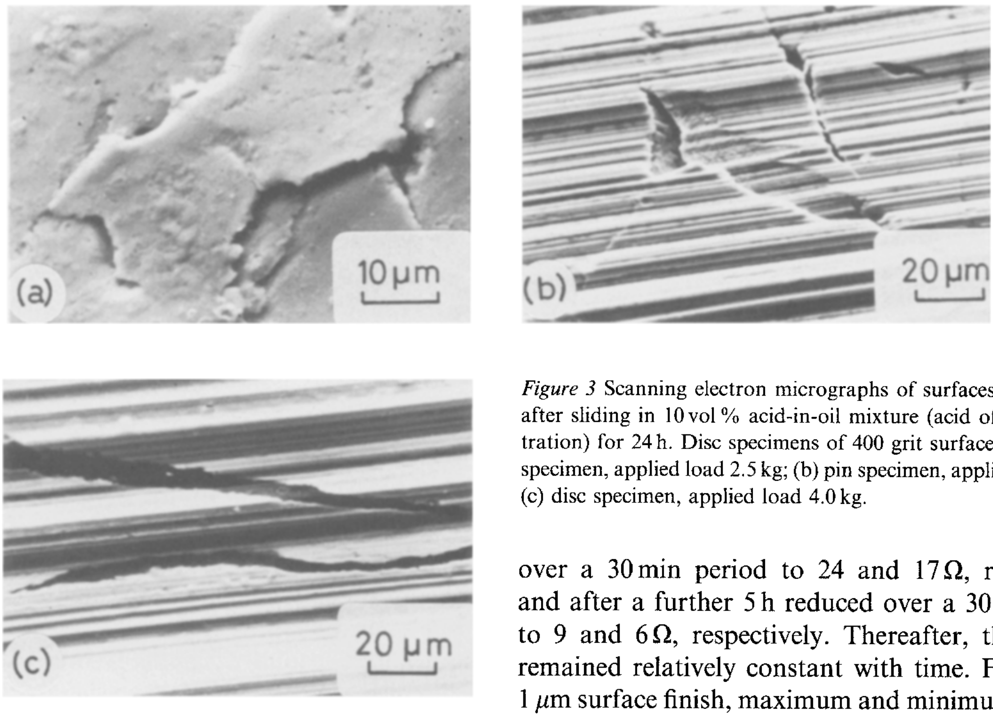

Figure 3 Scanning electron micrographs of surfaces of wear scars after sliding in 10 vol % acid-in-oil mixture (acid of 10% concentration) for 24 h. Disc specimens of 400 grit surface finish. (a) Pin specimen, applied load 2.5 kg; (b) pin specimen, applied load 4.0 kg; (c) disc specimen, applied load 4.0 kg.

and minimum values of 11 and 6 Ω, respectively, were established during the first 20 min sliding. These remained reasonably constant for 8 h when the maximum value increased to 17 Ω. After 21 h both values dropped to zero but quickly increased to 8 and 5 Ω, respectively, and thereafter remained reasonably constant. Under a load of 3.5 kg, maximum and minimum values of 60 and 24 Ω, respectively, were attained during the initial 20 min. However, these decreased progressively with time, reaching 11 and 6 Ω, respectively, after 9 h before increasing again to 17 and 11 Ω after a further 2 h. There was little further change for the remainder of the run. At the highest load, 4.0 kg, maximum and minimum values of 14 and 6 Ω, respectively, were recorded after 20 min and these remained constant for the next 9 h, at which time the values decreased to 6 and 3 Ω, respectively. These were maintained for the duration of the test.

3.2.2.2. The influence of surface finish. Steady maximum and minimum contact-resistance values of 77 and 33 Ω, respectively, were attained after 25 min sliding against discs of 120 grit surface finish. These values were maintained throughout the sliding period. For discs of 400 grit surface finish, maximum and minimum values of 300 and 60 Ω, respectively, were established after 40 min. These remained constant for 13 h but then decreased to 39 and 24 Ω, respectively, at which they remained steady for the remainder of the test run.

For pins sliding against discs of 800 grit surface finish, steady maximum and minimum values of 45 and 33 Ω, respectively, were attained after 35 min. Following a further 14 h, these values reduced gradually over a 40 min period to 20 and 9 Ω, respectively, which then remained reasonably constant with further sliding time. Similarly, for discs of 1200 grit surface finish, it required 35 min sliding to establish steady maximum and minimum contact-resistance values of 100 and 33 Ω, respectively. After 13 h, these reduced over a 30 min period to 24 and 17 Ω, respectively, and after a further 5 h reduced over a 30 min period to 9 and 6 Ω, respectively. Thereafter, these values remained relatively constant with time. For discs of 1 μm surface finish, maximum and minimum values of 100 and 60 Ω, respectively, were developed over the initial 30 min sliding. After 13 h, these values dropped rapidly to 17 and 6 Ω, respectively, for a 3 h period and then increased rapidly to 150 and 60 Ω, respectively. These values were maintained for the duration of the run.

3.3. Morphological features of the wear scars

3.3.1. Sliding in 10 vol% acid-in-oil environment (acid of 10% concentration)

3.3.1.1. The influence of applied load. The wear scars on the pin slid against material C under a load of 1.5 or 2.0 kg were generally smooth, but some ridges were evident, caused by smearing of the material. No graphite-flake sites were visible. The wear scars on the corresponding disc specimens were also relatively smooth, with graphite sites being visible in the surface, although the graphite flakes had generally been removed from them. Only a few areas of hard phase were distinguished within the wear scars and these had been slightly etched. The surrounding pearlite matrix had been heavily etched. In a few areas the wear scars contained pits.

The pin wear developed under a 2.5 kg load contained many ridges due to metal smearing and a number of holes due to the removal of material. Fig. 3a shows an area of the wear scar which is raised. It appears that material had been forced under this raised area, possibly along an interface associated with a graphite-flake site. Further sliding would have resulted in removal of this material. The corresponding wear scar in the disc specimen was generally smooth, with graphite sites being exposed in the surface, but the flakes having been removed during the sliding period. No hard-phase regions could be distinguished above the matrix although such regions were usually lightly etched. The surrounding pearlite matrix was more heavily etched. A number of pits were also observed in the wear scars.

The wear scar on the pin specimen after sliding

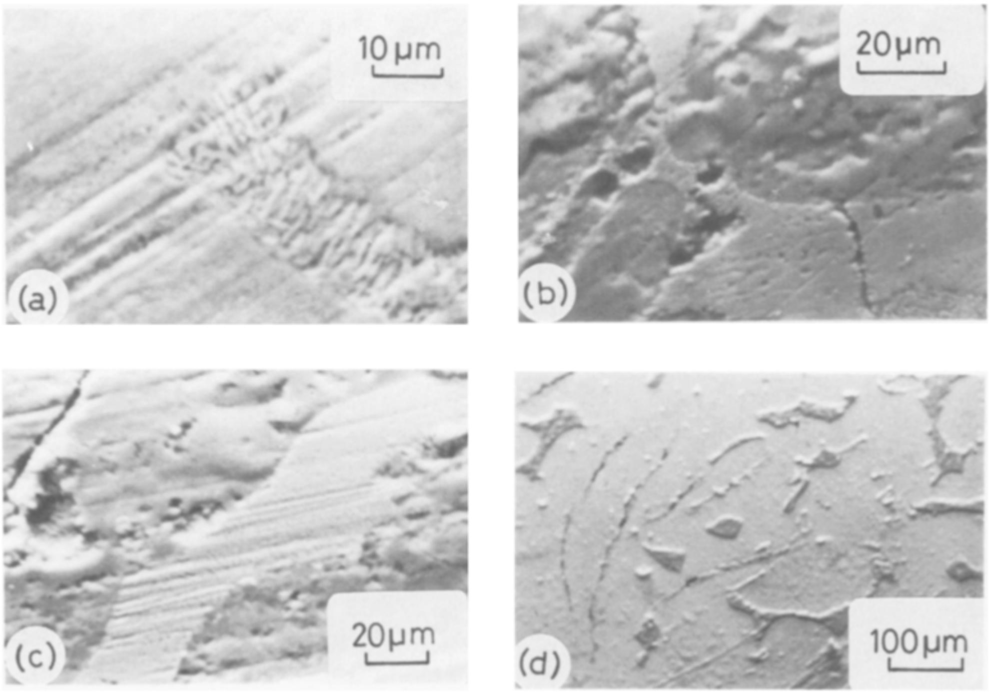

Figure 4 Scanning electron micrographs of surfaces of wear scars after sliding in 10 vol % acid-in-oil mixture (acid of 40% concentration) for 24 h. Disc specimens of 400 grit surface finish. (a) Disc specimen, applied load 2.0 kg; (b) disc specimen, applied load 2.5 kg; (c) disc specimen, applied load 4.0 kg; (d) disc specimen, applied load 4.0 kg (non-contacting area).

under a load of 3.0 kg was similar to that developed under a load of 2.5 kg. The corresponding disc wear scar was lightly scored in some regions. The pearlite matrix was etched, revealing hard phase which was sometimes lightly etched. Many of the graphite sites in the surface had been sealed over by the flow of deformed metal although this had not created ridges.

Examination of the pin wear scars developed under a load of 3.5 kg revealed areas of cracked material and some areas where material had been removed completely. No graphite sites were visible and no ridges due to smearing were evident. The corresponding wear scar on the disc was generally pitted, with the graphite sites being visible in the surface and the graphite flakes intact within them. Areas of lightly-etched hard phase were surrounded by heavily-etched pearlite matrix.

The wear scar on the pin specimen under a load of 4.0 kg was heavily scored and, generally, graphite-flake sites were visible with the flakes being intact within them. Fig. 3b shows an area where a graphite-flake site has been partially sealed and a piece of material has been removed. The area from which material has been lost is associated with a graphite flake. The wear scar on the corresponding disc was also heavily scored, with graphite-flake sites being apparent and the flakes being intact (Fig. 3c). No hard phase could be identified in the wear scar.

For all specimens, the non-contacting but exposed areas were similar in appearance, being covered by a corrosion-product film.

3.3.2. Sliding in 10 vol% acid-in-oil environment (acid of 40% concentration

3.3.2.1. The influence of applied load. The pin wear scars formed under loads of 1.5 and 2.0 kg were generally smooth and the graphite sites had been almost completely sealed over, with only thin lines visible where material from each side had met when flowing over them. Very little corrosion product was observed on the wear scars. However, the corresponding scars on the disc specimens were largely covered by a smooth corrosion product and only a very few graphite flakes or hard phase could be distinguished. Fig. 4a shows one region of hard phase which had been etched and was not covered by a corrosion-product film.

The pin wear scar developed under a load of 2.5 kg was smooth with some areas of it being covered by a corrosion product. No graphite flakes could be observed. The corresponding disc wear scar was generally covered by a corrosion product. Lightly etched hard-phase regions, together with graphite sites containing graphite flakes, were apparent within the scar. In one area, cracking across a piece of hard phase was observed (Fig. 4b). The edges of this crack were not sharp, suggesting that fracture had occurred some time prior to the end of the test and small fragments of the edges had since fractured. Several areas where material had been lost from the wear scar were observed. These were associated with graphite-flake sites located just below the disc surface. Under the application of the sliding stresses, the material above such sites fractured (as the graphite was compressed) and was subsequently removed.

The wear scar on the pin after sliding under a load of 3.0 kg contained two wide grooves running its full length. The rest of the scar was smooth with no graphite sites being exposed and some metal smearing being apparent. A small quantity of corrosion product was present in the wear scar. The corresponding disc wear was covered by a thick coating of corrosion product, with smooth, unetched hard-phase areas and graphite sites containing graphite flakes being

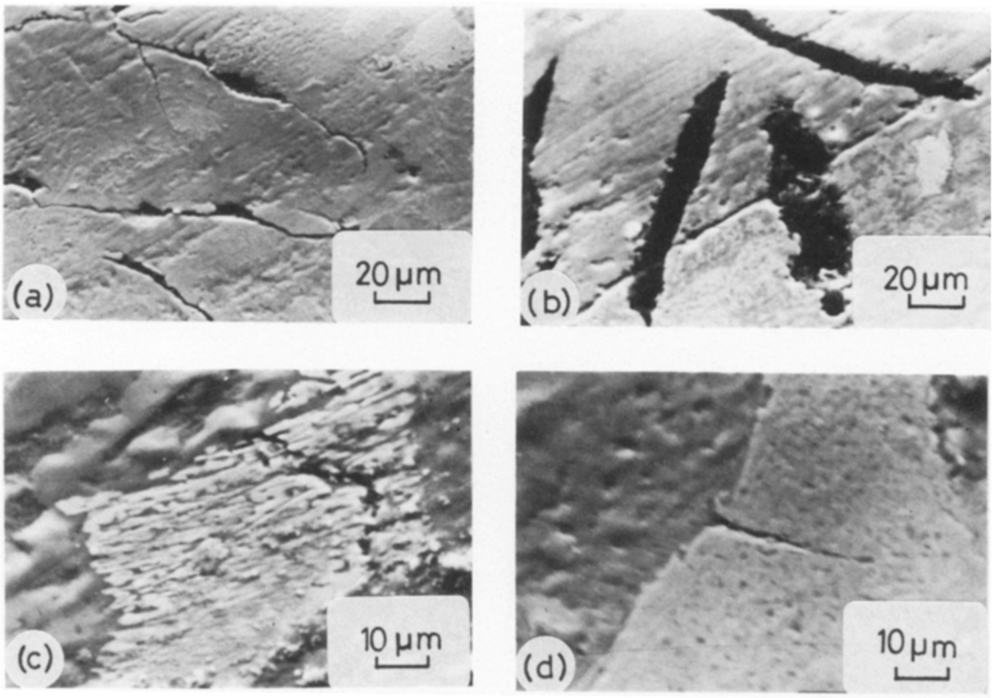

Figure 5 Scanning electron micrographs of wear scars after sliding in 10 vol % acid-in-oil mixtures (acid of 40% concentration) for 24 h under a load of 2 kg. (a) Disc specimen, 120 grit surface finish; (b) disc specimen, 800 grit surface finish; (c) disc specimen, 1200 grit surface finish; (d) disc specimen, 1 μm surface finish.

observed, on a level with the surrounding corrosion product. Several small areas of material had been removed from the wear-scar surface. These presumably created the deep grooves in the pin surface as they were being loosened prior to removal, since no features corresponding to the grooves could be seen in the disc surface.

The pin wear scars formed under loads of 3.5 and 4.0 kg were generally smooth but a small number of light score marks were visible. Smearing had occurred, resulting in small cracks where material had flowed over and almost sealed graphite-flake sites. No areas of corrosion product were observed. The corresponding disc wear scars were mainly covered in corrosion product. Scored and etched hard-phase regions were visible amongst the corrosion product and level with it (Fig. 4c). Graphite-flake sites were mainly covered by corrosion product.

The non-contacting but exposed material around the wear scars was covered in corrosion product. This was particularly thick over the hard-phase regions, which had the effect of highlighting their location (Fig. 4d). Graphite-flake sites could also be observed since corrosion product had not formed over these areas.

3.3.2.2. The influence of surface finish. The wear scar on the pin slid against the disc of 120 grit finish was generally smooth, with no evidence of metal smearing even though no graphite flakes were visible. A few small areas of corrosion product were noted. The wear scar on the disc was generally covered in corrosion product, with a few lightly-etched hard-phase regions being apparent within it and on a level with it. The graphite-flake sites had been partly closed over (Fig. 5a).

The pin wear scar formed after sliding against a disc of 800 grit surface finish contained a number of partly sealed graphite-flake sites where metal had been smeared over them. Smooth, unetched hard-phase regions and graphite sites containing graphite flakes were visible in the disc wear scar surface. A few areas of the surrounding matrix were covered by a corrosion-product film, resulting in an overall smooth surface (Fig. 5b). However, these were less extensive than in the previous case.

Sliding against a disc with a 1200 grit finish resulted in a pin wear scar which contained many deep ridges due to the smearing of metal over graphite sites. There was little indication of corrosion product in the pin scar. However, part of the disc wear scar was covered with a corrosion-product film. Etched hard phase could be seen between the filmed regions (Fig. 5c). Many of these hard phases appeared cracked. Graphite sites were usually partly closed over by overgrowth of corrosion product from adjacent sites.

The pin wear scar developed during sliding against discs of 1 μm finish was generally smooth with some smearing of metal over graphite sites. A corrosion product was present over all the pearlite matrix of the disc wear scar, surrounding lightly-etched hard-phase regions which were often cracked (Fig. 5d). Again, the graphite sites were partly covered by overgrowth of corrosion product.

4. Discussion

The general mechanisms of corrosive wear in these 10% acid-in-oil mixtures have been considered elsewhere [7, 8]. For the environment in which the aqueous phase is 10% acid concentration, the wear process involves deformation and some abrasive wear of the metal surface and active dissolution of the deformed surfaces. Periods of metal-to-metal contact during which mechanical damage occurs are interspersed with periods in which the oil film is able to separate the metal surfaces, allowing the corrosion process to proceed. For the environment consisting of 40% acid concentration as the aqueous phase, development of adherent corrosion-product films on the metal surface results in reasonably low wear, the films acting as effective solid lubricants.

4.1. The influence of load

The current study has enabled the influence of load on the wear process during sliding in the 10% acid-in-oil mixture (the aqueous phase being 10% and 40% acid concentration) to be investigated.

As expected for sliding in the 10% acid concentration, as the load was increased there was an increasing mechanical contribution to the wear process. At the lowest load (1.5 kg) contact-resistance measurements indicated that metal-to-metal contact was rarely attained and corrosion of the metal surfaces was able to predominate. There was some deformation of the surface but the matrix was heavily etched. As the load was increased to 2.0 kg, metal-to-metal contact was recorded much more frequently, with periods of such contact occurring throughout the sliding period, particularly at the end of each cycle but also during the full course of some cycles. Positive contact-resistance values were not recorded at all during the first few hours of sliding. At higher loads of 2.5 to 4.0 kg, similar results were obtained.

However, as shown in Fig. 2, the wear of the pin was reasonably independent of load from 2.0 to 3.5 kg, but then increased very markedly at 4.0 kg. There was no obvious correlation between this observation and the contact-resistance data. However, examination of the wear scars indicated little difference between those developed under loads of 2.0 to 3.5 kg. The worn surfaces were generally deformed while evidence of pitting and etching was obtained, consistent with a corrosion process. Under a load of 4 kg, much more extensive scoring and deformation of the surfaces were observed. It is thus concluded that the hard-phase material in the specimen surfaces was able to support the load up to 3.5 kg and aid in the retention of the oil layer between the sliding surfaces. At 4.0 kg, the higher load resulted in the mechanical removal of metal becoming more dominant in the corrosive-wear process, and the wear rate increased considerably. Here, the hard phases in the disc surface were able to protrude completely through the oil layer and contact the pin surface for long periods in the test. The relatively small volume percentage of acid in the acid–oil mixture was insufficient to give significantly increased corrosion of the more heavily-deformed pin material as the applied load was increased.

Sliding in the 10 vol % acid-in-oil (acid of 40% concentration) mixture produced lower wear volumes than in the corresponding acid of 10% concentration mixture for all loads. The wear volume against load curve showed a step up at 2 to 2.5 kg and was reasonably independent of load at higher and lower values (Fig. 2). The contact-resistance values generally fluctuated during sliding, but higher values were recorded under loads of 1.5 and 2 kg than under the higher loads. The examinations of the wear scars did not show evidence for increased metal-to-metal contact with increasing load. At loads of 1.5 and 2.0 kg, the wear scars on the disc were generally smooth with graphite-flake sites being sealed over and corrosion-product film covering much of the surface. This indicates the tendency of the acid of 40% concentration to form adherent films. It is also consistent with the corrosion-product film being able to produce the surface in situations where the oil film breaks down. At higher loads, the wear scars were again coated with a corrosion-product film, but hard-phase material was now exposed. Here, the pins were able to remove some of the film and were supported on the hard phase. However, the corrosion-product film surrounding the hard-phase regions prevented substantial wear of the contacting pin surfaces, as indicated by the generally deformed appearance of the pin surfaces.

4.2. The influence of surface finish

The surface roughness of the disc had a considerable effect on wear of the pin in the 10% acid-in-oil (acid of 40% concentration) mixture, with the amount of wear being reasonably low for 120 grit finish and increasing with decreasing roughness to a maximum at 800 grit finish. Thereafter, the wear decreased with decreasing roughness to 1 μm finish. These values correlated reasonably well with contact-resistance measurements, since the higher wear values were generally associated with the lower contact-resistance measurements. To some extent, these observations were not expected since it might have been anticipated that a smoother disc would lead to reduced wear, as there was less disturbance to the formation of a stable oil film in the early stages of sliding. However, examination of the pin wear scars in the scanning electron microscope indicated increasing amounts of deformation and smearing of the metal with decreasing surface roughness from 120 grit to 1200 grit finish. All the disc surfaces were covered with corrosion-product film, with hard-phase regions between the filmed areas. These hard-phase surfaces were generally etched, except for the disc with 800 grit finish.

In all cases, the hard-phase regions eventually supported the load and aided the retention of corrosion-product film on the surrounding metal matrices. There were significant amounts of cracking of the hard-phase regions for the disc surfaces with the smoother surface finish (1200 grit and 1 μm), presumably due to a fatigue process under the reciprocating motion of the contacting surfaces.

From the studies of the wear process, it is apparent that the surface finish of the disc had two main effects on the extent of wear of the pin. These relate to the ease of development of the two kinds of film which can reduce metal-to-metal contact, namely the corrosion-product film and the oil film. For rough surfaces, corrosion-product films were able to be established most easily because, in the early stages, the load was carried on the protruding ridges, enabling corrosion to proceed uninterrupted and solid films to develop in the corresponding troughs. As the ridges were worn down, the substantial films in these troughs together with any exposed hard-phase regions were able to carry the load. The voluminous nature of the corrosion product helped to prevent metal-to-metal contact with the pin surfaces and thus high wear. For initially smooth surfaces, a stable oil film was able to develop more easily than for a rough surface, again reducing metal-to-metal contact. This had the additional effect of facilitating the formation of corrosion-product film on the metal surfaces without disruption by a wear process. Thus, the relatively low wear rates of the pin against the rough disc surface were associated with the easy development of corrosion-product films, while the low rates against the smooth disc surface were associated with the easy development of oil films. The disc of intermediate roughness (800 grit) thus gave the largest wear since neither film could develop as effectively or as rapidly as in the two more extreme cases.

5. Conclusions

1. Load and surface finish have significant effects on the wear of cast-iron piston-ring material during reciprocating sliding against a cast-iron cylinder-lining material in 10 vol % acid-in-oil mixtures.

2. In such mixtures of 10% acid concentration, the wear was relatively independent of load in the range 1.5 to 3.5 kg but increased markedly at 4 kg. At the lower loads, the hard-phase material in the cast irons was able to support the load and aid in the retention of an oil film during sliding; thus the wear rates were reasonably low. However, increasing the load to 4.0 kg resulted in increased mechanical damage as hard-phase regions in the disc surface were able to penetrate the oil film and contact the pin surface for long periods.

3. In mixtures of 40% acid concentration, the wear rates of the pin were less than in those of 10% acid concentration due to the formation of protective, adherent films of corrosion product which were able to protect the surface against wear damage if the oil film broke down. The wear rates under loads of 1.5 and 2.0 kg were less than those under loads of 2.5 to 4.0 kg. At the lower loads, corrosion-product films were able to develop over most of the wear scar surfaces, while at the higher loads such films were unable to be established on the hard-phase regions of the wear scars. These exposed regions were able to cause increased wear of the opposing surfaces.

4. In mixtures of 40% acid concentration, the surface finish on the disc influenced the development of the oil films and the corrosion-product film. The latter was able to form on the contacting surfaces more easily on the rougher surfaces, while oil films could develop more easily on very smooth surfaces. This resulted in reasonably low wear rates against discs of 120 grit and 1 μm diamond surface finish, but considerably higher rates against those of intermediate surface finish (e.g. 800 grit).

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