

The Influence of Lead Suspension in Oil Lubricant on the Sliding Wear Behaviour of Cast Iron

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Abstract This investigation pertains to the analysis of the sliding wear response of a cast iron over a range of applied pressures in the presence of an oil lubricant. The effect of varying concentrations of lead particles suspended in the oil lubricant on the wear behaviour of the cast iron was also examined. The wear rate increased with pressure initially at a lower rate followed by a higher rate of increase beyond a specific pressure. Furthermore, the presence of suspended lead particles up to a specific concentration in the oil proved beneficial while the trend reversed at still higher concentrations. The extent of frictional heating increased with test duration at a high rate in the beginning of the tests. This was followed by a reduced rate of temperature increase at longer test durations. In some cases, the rate of temperature rise increased once again while it reduced in one case towards the end of the tests. The severity and extent of frictional heating also increased with pressure. Lead addition to the oil lubricant up to a specific concentration led to a reduced degree of heating while the trend reversed at still higher lead contents. Specimen seizure caused significantly high wear rate and frictional heating. The observed wear response of the samples has been explained in terms of specific characteristics like cracking tendency and lubricating and load bearing capacity of various microconstituents of the specimen material. Another important factor of concern affecting wear characteristics was observed to be lubricating film formation and its stability during sliding. The wear behaviour has also been substantiated through the characteristics of wear surfaces and subsurface regions.

Keywords Cast iron · Sliding wear behaviour · Oil · Lead solid lubricant · Material removal mechanisms

1 Introduction

Cast iron has been used as tribo-components in various engineering applications encountering sliding action [1–3]. Oil is a very common lubricant used in such applications. It contains a number of additives for improved performance. Solid lubricants constitute an important class of those additives incorporated in the oil that greatly influence the overall response of the lubricant system towards controlling the performance of sliding pairs [4–7].

There exists a variety of solid lubricants that are used in practice [4–7]. Amongst them, lead is a well-known solid lubricant added to several material systems, bearing bronzes constituting an important category of materials that find wide engineering applications [8–10]. Dry sliding wear studies on Cu-based alloys (bronzes) dispersed with lead have shown that substantial material ‘chip off’ observed at low speeds leads to poor performance of the alloys [11, 12]. It has been suggested that lead particles being soft produce weakening effect in the material system [11–13]. Furthermore, their existence practically as a mechanical mixture in view of very limited solid solubility in the alloy matrix imparts cracking tendency [11, 12, 14–16]. This leads to premature removal of the phase through chipping off action and hence adversely affects wear response [11, 12, 14–16]. On the contrary, higher sliding speeds cause the alloys to show improved wear performance in dry condition [11, 13]. This has been attributed to the effective formation of lead film on the sliding surfaces [11, 14]. Studies suggest that the cracking tendency of the material system gets suppressed in view of increased compatibility

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of the matrix material surrounding the lead particles under favourable conditions of sliding [11, 13, 14]. Better compatibility characteristics of the matrix with the dispersed lead particles arise from the high (optimum) frictional heating conditions that cause the matrix to become viscoplastic [11, 13, 14]. In such cases, the matrix effectively accommodates the lead particles offering the latter better opportunities for their effective smearing and formation of lubricating film on the sliding surfaces. Under the circumstances, the beneficial effects of lead particles dispersed in the matrix could be realized in terms of improved wear performance [11, 13, 14]. The quantity of lead and tin greatly affects the wear response of the leaded Cu-based alloys [16]. A comparative study of the sliding wear behaviour of the leaded copper-based alloys with that of zinc-based alloys revealed inferior wear response of the Cu alloys at slower speeds in view of the predominant adverse effect of cracking tendency due to lead while the trend reversed at higher speeds as a result of suppressed cracking tendency and more effective formation of lead film [11, 12, 14, 15, 17]. Lead particles have also been incorporated in aluminium alloy matrices and their sliding wear behaviour investigated [18–21]. It has been observed that lead dispersed in aluminium by stir casting technique helps to realize improved sliding wear resistance [18–20]. Higher stirring speed used during alloy synthesis enabled to improve the degree of homogeneity of distribution of lead in the alloy system and hence sliding wear resistance [18]. Smearing of lead helps to form a layer that is responsible for the improvement in wear response [18–20]. A comparison of wear response has shown the aluminium–lead alloys to attain higher wear resistance and lower friction coefficient than that of aluminium–tin alloys in sliding wear conditions [21]. Application of accelerated cooling under excess pressure enables to improve the quantity of dispersion, degree of homogeneity of distribution and refine the size of lead particles in the aluminium matrix making the alloys suitable as a lining material for journal bearing applications [21].

Recent investigations have shown that dispersion of solid lubricant particles like graphite and talc in an external base lubricant such as oil becomes more effective in improving the wear behaviour of cast irons and zinc-based alloy and composite [22–30]. It has been observed that addition of a critical content of a solid lubricant to the oil leads to the best wear performance of the materials, while quantities higher than that of the critical one produce a reverse effect [22, 23, 25, 28–30]. The critical content exhibiting the best wear performance has been observed to depend on factors like the nature of the solid lubricant [23, 29] and sliding pair material [22, 30]. The wear performance was also controlled by the applied load/pressure [24–28], sliding speed [24, 26, 27] and microstructural features of the samples

[22, 25, 30]. In a few investigations, 3–10% of graphite/talc in oil greatly affected the wear performance of the alloys and composite, while 3–6% of solid lubricant addition to the oil lubricant enabled the specimens to show the best wear performance [22, 25, 28, 29].

An appraisal of the above discussion suggests that addition of solid lubricants in externally added base lubricants like oil proves more beneficial in terms of the sliding wear response of materials [22–30] than when dispersed in the sliding material system [11–21]. Furthermore, no direct correlation exists amongst different controlling parameters like sliding speed, pressure, test environment and nature and characteristics of the sliding pair material system and the solid lubricants; and rather the parameters produce a synergistic effect on the wear behaviour. It is also evident from the discussion that lead has extensively been used as a solid lubricant in Cu-based alloys in various tribological applications [11–17] while it has shown potential in similar applications when dispersed in aluminium matrices [18–21]. In such cases, the beneficial effects of lead could be realized in selected conditions only with adverse effects on mechanical properties [11–17]. Finally, no information appears to be available on the response of lead when dispersed in an externally added base lubricant like oil in controlling the wear behaviour of materials despite a great scope.

In view of the above, an attempt has been made in this investigation to examine the influence of lead particle suspension in an oil lubricant on the wear behaviour of a grey cast iron over a range of applied pressures. The influence of the dispersoid content of the lubricant mixture has also been investigated on similar lines. The wear response of the samples has been discussed in terms of specific nature of material microconstituents such as cracking and smearing tendency, effective formation of lubricant film on the contacting surfaces and predominance of one set of parameters offering improved wear response over the other producing a reverse effect. The examination of wear surfaces and subsurface regions enabled to further substantiate the observed response of the samples and understand the operating material removal mechanisms.

2 Experimental

2.1 Material and Specimen Preparation, Hardness Measurement and Microscopy

The cast iron (Table 1) was prepared by liquid metallurgy route in the form of 20-mm diameter and 150-mm-long cylindrical castings. Samples for microstructural observations and sliding wear tests were prepared from the castings. The samples prepared for hardness measurement and

Table 1 Chemical composition of the experimental pin and disc materials

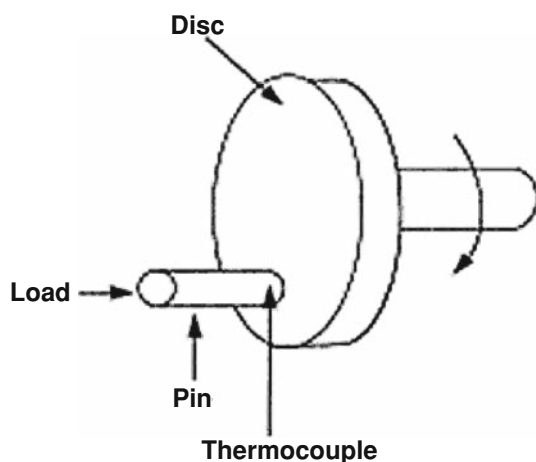
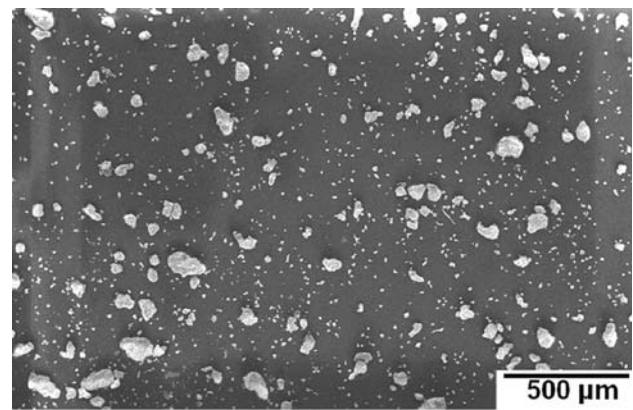
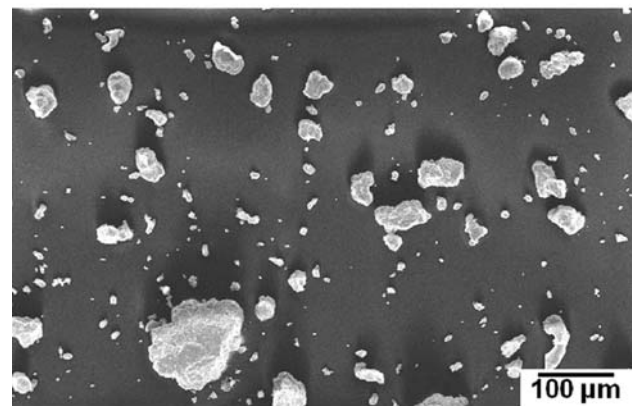
Material	Chemical composition (element wt%)						
	Fe	Si	C	Mn	Ni	Cr	Mo
Cast iron (Pin)	Bal.	2.58	3.25	0.49	–	–	–
EN25 (AISI 4340) steel (Disc)	Bal.	0.23	0.30	0.58	2.50	0.70	0.50

microstructural studies were 15 mm in thickness and 20 mm in diameter, whereas the specimens for sliding wear tests were 53 mm in length and 8 mm in diameter. The samples for microstructural investigation and hardness measurement were polished metallographically. Hardness of the samples was determined using a Vickers hardness tester at an applied load of 31 kg. An average of five observations has been reported in this study. For microstructural studies, the metallographically polished samples were etched with 2% nital solution, while optical and scanning electron microscopy was used for examining the samples.

Wear surfaces and subsurface regions of typical wear-tested samples were examined using scanning electron microscopy (SEM). The wear surfaces were mounted on brass studs and sputtered with gold prior to their SEM examination. For the subsurface studies, transverse sections in the direction of sliding wear prepared from the wear surfaces and mounted in thermosetting resin. The samples were then polished as per standard metallographic procedures and etched with 2% nital solution and sputtered with gold.

2.2 Sliding Wear Tests

Lubricated wear tests were carried out using a Cameron-Plint make pin-on-disc machine. A schematic representation of the wear test configuration is shown in Fig. 1. The disc used was fabricated using an En 25 steel (Table 1) that

**Fig. 1** A schematic representation of the wear test configuration**(a)****(b)****Fig. 2** Micrographs of lead particles representing (a) a general view and (b) particle morphology

conformed closely to AISI 4340 and had hardness of 318 HV. The oil lubricant was SAE40 oil. Different quantities (3–10%) of lead particles in the size range of 5–75 μm (Fig. 2) were mixed with the oil to prepare the lubricant mixture. The content range of lead added to the oil lubricant in this study was based on our earlier observations that 3–10% of solid lubricants like graphite suspended in oil greatly influence the sliding wear response of materials [22, 25, 28]. It may be mentioned that much higher density of lead (11.34 g/cc) than that of the oil (0.89 g/cc) makes the former to tend to segregate in the suspension. Accordingly, the suspension was stirred well during mixing and just prior to adding onto the disc surface during testing to avoid/minimize the extent of possible segregation of lead in the lubricant mixture. In this study, the term % lead indicates the weight of the lead particles mixed with 100 cc of oil. The applied pressure was increased in steps until specimen seizure prior to negotiating the predetermined sliding distance of 2,500 m while the tests were performed at a sliding speed of 4.2 m/s. Specimen seizure was monitored in terms of burning of the lubricant, abnormal noise in the pin-on-disc assembly,

substantial adhesion of the pin material onto the disc surface and high rate of increase in frictional heating and wear rate. The pin and disc surfaces were polished and cleaned well prior to and after conducting the wear tests. The wear rate was computed by weight loss method. A Mettler microbalance having a precision level of 0.01 mg was used to measure the wear loss of the pin samples. Temperature near the specimen surface was monitored during the tests by inserting a chromel–alumel thermocouple in a hole made at a distance of 1.5 mm from the contacting surface of the samples. An average of three observations has been reported in this study, the range of variation being $\pm 3\%$.

The test procedure involved immersing the polished disc in the thoroughly mixed lubricant mixture, allowing the disc to rotate at a sliding speed of 2.68 m/s for 5 s in order to maintain sliding condition close to mixed lubrication through spinning off the excess lubricant. This was followed by pressing the polished sample against the lubricated disc with the help of a hydraulically operated loading mechanism and permitting the sample to negotiate the predetermined sliding distance of 2,500 m or prior to seizure.

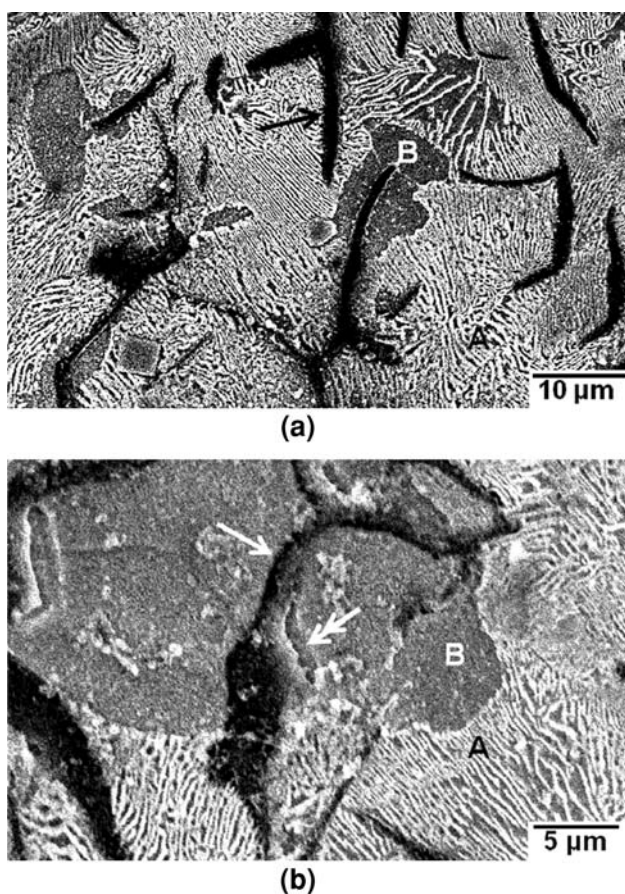


Fig. 3 Microstructural features of the cast iron revealing (a) different microconstituents and (b) occasional decohesion at graphite/ferrite matrix interface. *Single arrow* graphite, *A* pearlite, *B* ferrite, and *double arrow* decohesion

3 Results

3.1 Microstructure

Figure 3 shows microstructural features of the pin sample material i.e. cast iron. Graphite flakes in a matrix of mainly pearlite with a limited quantity of (free) ferrite may be seen in Fig. 3a (regions marked by single arrow, A and B). Occasional decohesion in the graphite/(ferrite) interfacial region in addition to the features mentioned in Fig. 3a is shown clearly in Fig. 3b (regions marked by double arrow, single arrow, A and B). The hardness of the sample was 220 HV.

3.2 Wear Behaviour

Figure 4 represents the influence of applied pressure and lead content in the lubricant mixture on the wear rate of the samples. The wear rate increased with pressure in general. The wear rate versus pressure plots showed two slopes. The slope was low up to a specific pressure followed by a larger slope at higher pressures. The wear rate decreased with increasing lead content initially and attained the minimum in the oil lubricant mixture containing 5% lead, while the maximum was delineated in the lubricant mixture containing 10% lead. Furthermore, specimen seizure was monitored at higher pressures in the oil plus lead lubricant mixture than in oil alone except the one containing 10% lead; the trend reversed in the latter case.

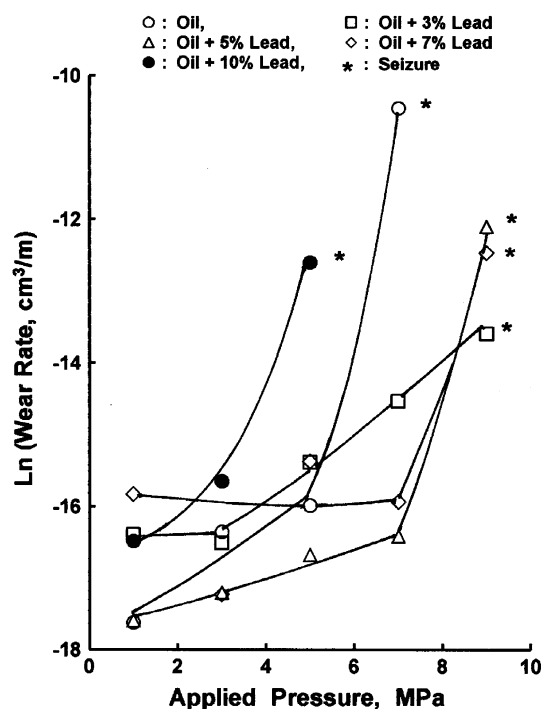


Fig. 4 Wear rate versus applied pressure plots of the cast iron tested in different environments

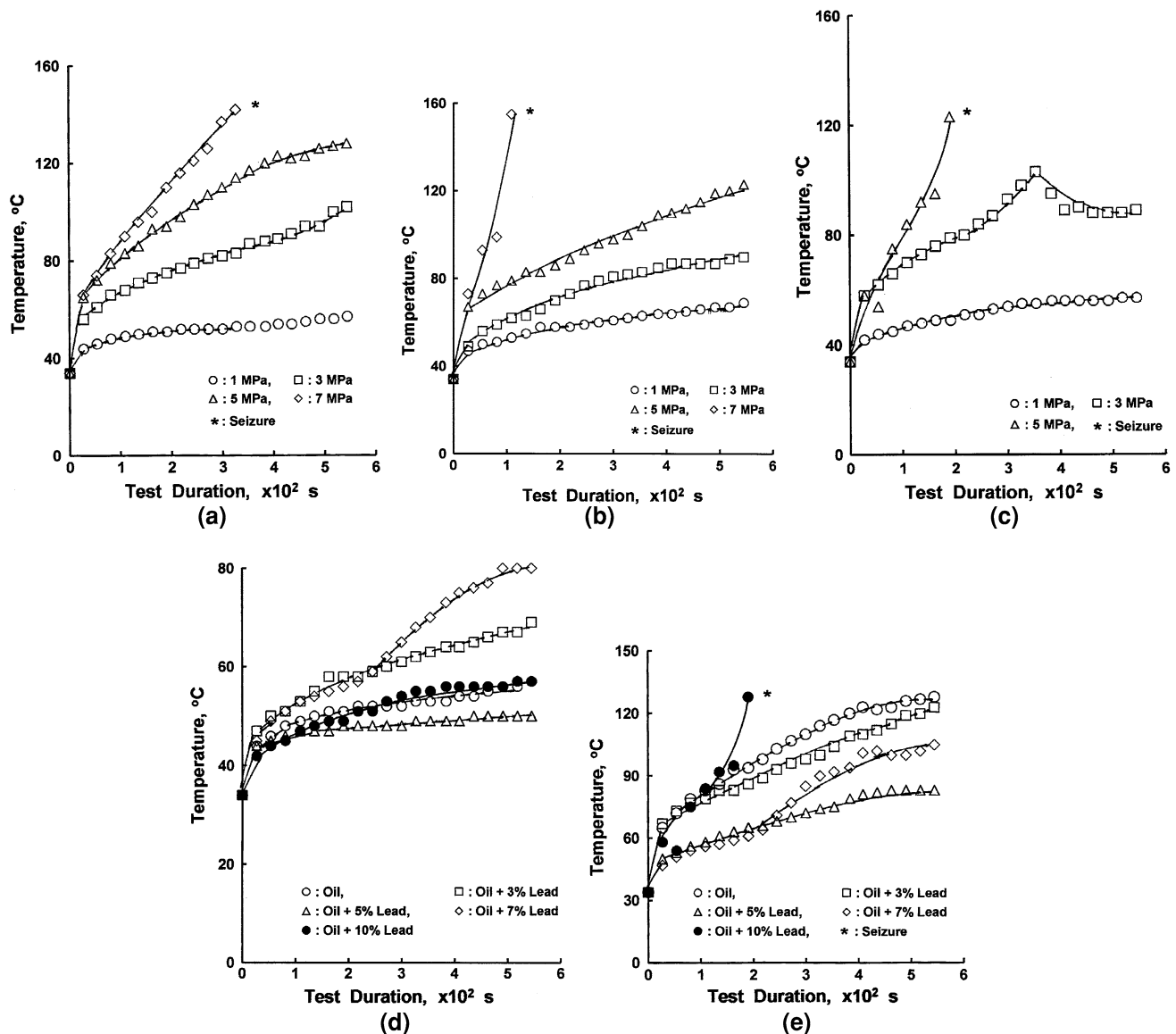


Fig. 5 Temperature near the specimen surface versus test duration plots for the cast iron tested at (a–c) different pressures in (a) oil, (b) oil + 3% lead, (c) oil + 10% lead, and in (d, e) different environments at (d) 1 MPa and (e) 5 MPa

Figure 5 represents the temperature near the specimen surface plotted as a function of test duration. The effects of pressure and test environment on the temperature are also shown in the figure. The rate of temperature increase was initially high followed by a lower rate of increase at longer test durations. In some cases, the rate of temperature increase became high once again (Fig. 5a, d, e) while it also tended to show a negative slope in one case (Fig. 5c) towards the end of the tests.

The maximum temperature near the specimen surface has been plotted as a function of applied pressure in Fig. 6. The effect of changing content of lead particles in the oil lubricant on frictional heating is also evident in the figure. The frictional heating increased with pressure. The presence

of lead particles in the oil lubricant caused the severity of frictional heating to reduce in general, the lubricant mixture containing 5% lead attaining the minimum. This was followed by a reversal in the trend at a lead concentration of 10% in the oil. The trend observed by the frictional heating with increasing pressure (Fig. 6) was practically identical to the one observed for the wear rate (Fig. 4).

3.3 Wear Surfaces

Figure 7 represents the wear surfaces of the samples tested in oil. The wear surface was smooth in general with the presence of dark patches when the tests were conducted at lower pressures (Fig. 7a, region marked by A). Exposure of

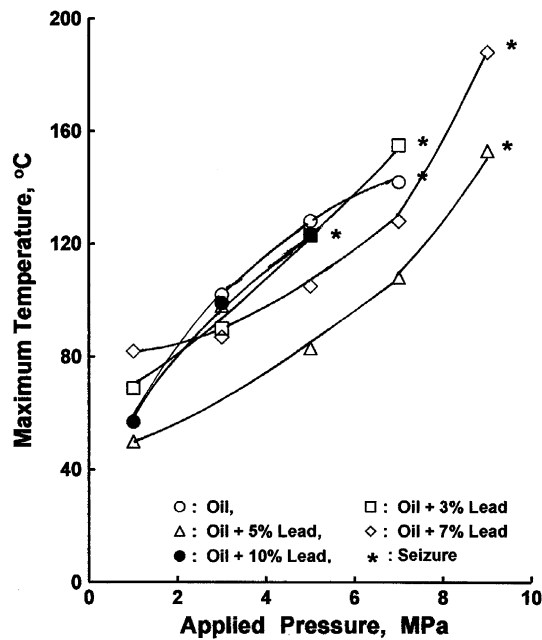


Fig. 6 Maximum temperature near the specimen surface versus applied pressure plots for the cast iron tested in different environments

graphite phase from within the material system along with decohesion at graphite matrix interface was also observed (Fig. 7b, regions marked by B and single arrow). The severity of surface damage increased with increasing applied pressure (Fig. 7c vs. 7a). Smearing of graphite on the wear surface may be seen in Fig. 7d. The graphite phase also tended to flow in the sliding direction (Fig. 7e, region marked by double arrow). Sticking of debris particles on the sliding surface was also noticed (Fig. 7e, region marked by triple arrow).

The wear surfaces of the samples tested in the oil lubricant mixture containing lead are shown in Fig. 8. The wear surface at lower pressures revealed dark patches (Fig. 8a, region marked by A). Figure 8b represents cracks on a typical dark patch (region marked by single arrow). The severity of surface damage increased with pressure (Fig. 8c vs. 8a). Graphite tended to flow on the wear surface (Fig. 8d, region marked by double arrow). Sticking of debris was also noticed (Fig. 8e, region marked by B). The solid lubricant phase (lead particles) mixed in the oil lubricant was also observed to stick and/or smear on the wear surface (Fig. 8f, region marked by C). Accordingly, the wear surfaces in this case generally tended to be covered with dark patches to a greater extent and relatively smoother than that in the oil lubricant without lead (Fig. 8 vs. 7).

3.4 Subsurface Regions

Figure 9 shows microstructural features of the regions below the wear surface (top). Three distinct regions were

observed based on their microstructural characteristics. The region in the nearest vicinity of the wear surface revealed the finest microconstituents (Fig. 9b, c, regions marked by A). This was followed by the ones representing flow of microconstituents in the sliding direction and unaffected bulk structure far below the wear surface (Fig. 9a, b, regions marked by double arrow and C). A magnified view clearly showed very fine microconstituents in the regions revealing flow lines (Fig. 9d). Microcracks and regions in a process of being detached from the wear surface were also noticed (Fig. 9e, f, regions marked by single arrow and D). The microstructural features of the subsurface regions of the samples tested in oil were similar to those of the ones in the oil plus lead lubricant mixture.

4 Discussion

From microstructural stand point, ferrite in the cast iron is soft and ductile and accommodates other microconstituents like hard pearlite and the weak and soft graphite [24–28, 31]. Strengthening in the material is imparted by the hard and strong pearlite. However, sharp tips and edges of cementite within pearlite offer stress raiser points thereby providing potential sites for the nucleation and propagation of microcracks during sliding [13, 15, 22, 25, 32]. Graphite/matrix interface also facilitates microcracking despite the precipitation of graphite from within the matrix during solidification of the alloy melt [31]. This is also evident from the occasional decohesion observed in the graphite/(ferrite) matrix interfacial regions (Fig. 2b, region marked by double arrow). This tendency of graphite makes the material crack sensitive, leading to inferior wear resistance [24–28]. However, under sliding conditions leading to an optimal level of frictional heating, the softer part of the matrix like ferrite accommodates graphite more effectively by developing better compatibility with the latter. This ultimately results into the smearing of graphite particles followed by the formation of solid lubricant film on the sliding surfaces [22–29]. The presence of an external lubricant like oil brings about improved wettability to the lubricant film with the sliding surfaces making the film more effective and stable [15, 22–30]. Cracking tendency of the material also gets suppressed in the presence of an oil lubricant thereby providing the graphite phase a better opportunity to smear on the sliding surfaces and form lubricant film. Self-generating oxide films (SOFs) also form in such cases as a result of tribochemical reaction of the lubricant with the material in contact and that of the environment [33]. The SOFs increase the resistance of the contacting asperities against crumbling [33] and improve the wear response. Addition of a solid lubricant phase (like lead particles in this investigation) in the oil enables the

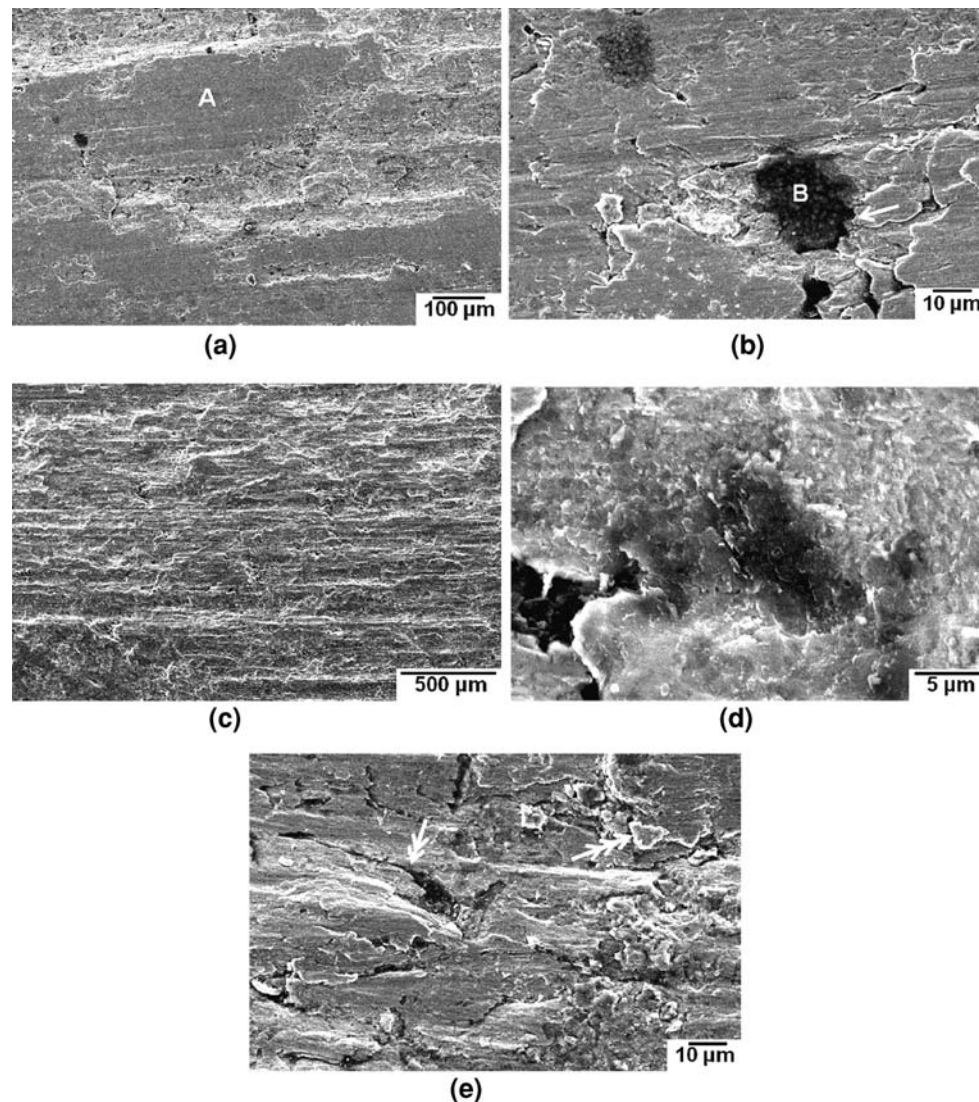


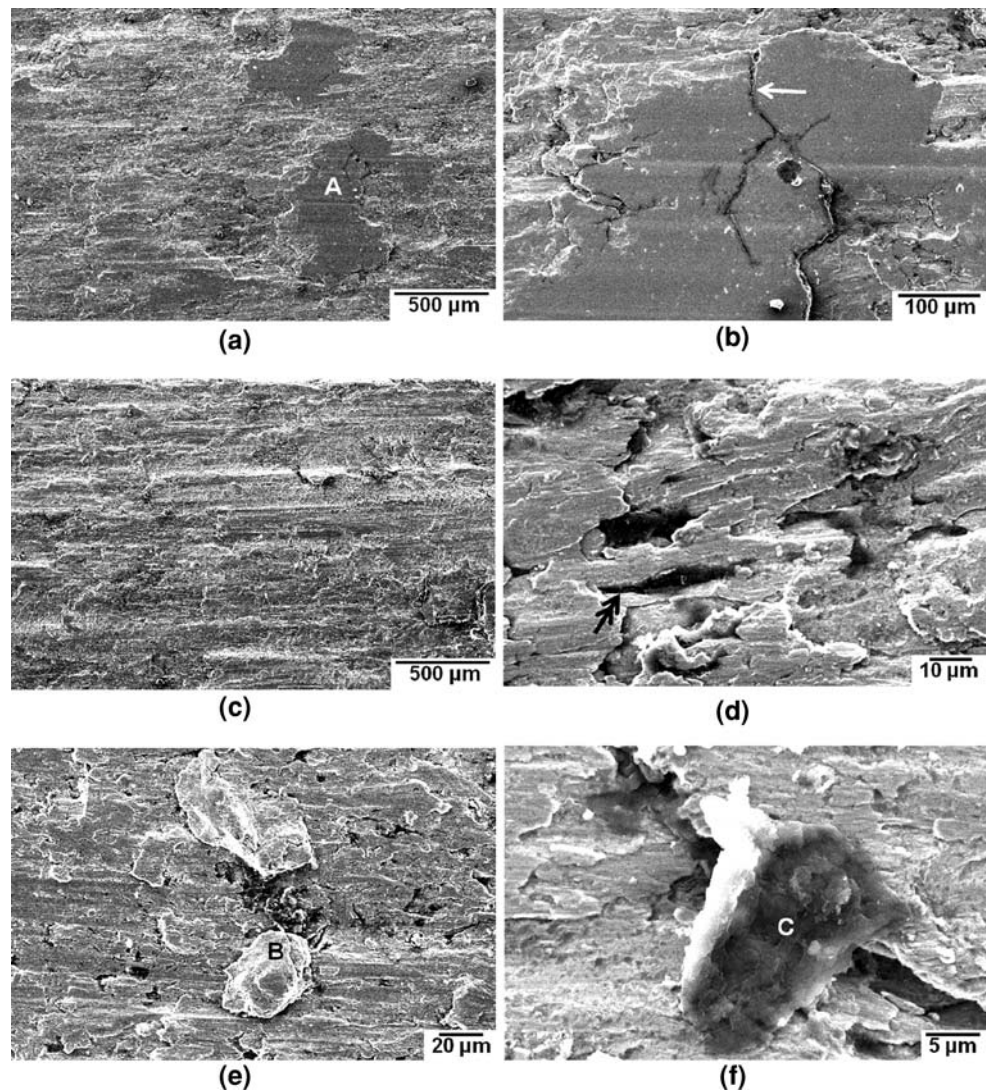
Fig. 7 Wear surfaces of the cast iron tested in oil at the applied pressure of (a, b) 1 MPa, (c, d) 10 MPa and (e) 7 MPa. A dark patch, B exposed graphite, *single arrow* decohesion of graphite, *double arrow* flow of graphite, *triple arrow* sticking of debris

formation of solid lubricant films/layer to a much greater extent causing a further improvement in wear behaviour [18, 22–30]. Initial increase in the quantity of the suspended solid mass in the oil lubricant mixture makes the film formed more and more stable and effective up to a critical content of the solid mass. However, as the solid content exceeds the limit, the film formed becomes too thick and dry to stick properly onto the sliding surfaces [22, 23, 25, 28–30]. Also, the possibility of segregation of the particles in the lubricant mixture increases, thus making the film inhomogeneous and unstable [22, 23, 25, 28–30]. This adversely affects the wear behaviour.

Increasing wear rate with pressure (Fig. 4) could be attributed to the increased severity of wear condition as also evident from higher frictional heating (Figs. 5, 6), greater surface damage and less formation and stability of

the lubricant film/dark patches (Figs. 7c vs. 7a, 8c vs. 8a). Initially, lower slope of the wear rate versus pressure plots (Fig. 4) could be attributed to mild wear condition, while higher slopes represent severe wear regime. Mild wear condition arises due to a more effective formation and greater stability of lubricating films of the triboinduced reaction products of the oil and solid lubricant phase and that of the sliding material pair and environment [15, 26, 33]. Formation of layers/films as a result of the smearing action of solid lubricant phases helps to improve the wear response of the samples further. This continues as long as the film/layer adheres firmly onto the sliding surface [34]. The thickness of and extent of protection provided by the film/layer increases with the progress of sliding and a condition comes when the film becomes too dry and too thick to adhere onto the specimen surface well leading to

Fig. 8 Wear surfaces of the cast iron tested in the oil lubricant mixture containing (a–e) 3% lead and (f) 5% lead at the applied pressure of (a, b) 1 MPa, (c, d) 5 MPa, (e) 7 MPa, and (f) 9 MPa. A dark patch, *single arrow* crack, *double arrow* flow of graphite, *B* sticking of debris, *C* sticking and smearing of solid lubricant particle



its fragmentation [15, 26, 33, 34]. Under the circumstances, fresh metal-to-metal contact takes place and the fragmented mass also abrades the surface leading to the onset of severe wear regime. This is finally followed by the occurrence of specimen seizure in view of the generation of excessive frictional heating and mass fusion and adhesion of the specimen material onto the disc leading to very high wear rates [15, 34]. A reduction in the wear rate of the samples due to the presence of lead in the oil lubricant mixture (Fig. 4) resulted from the formation of more stable solid lubricant films (Fig. 8a, region marked by A; and 8b). This was further substantiated through a corresponding decrease in frictional heating (Figs. 5, 6). The least wear rate at a critical content of lead in the oil lubricant could be due to the most stable lubricant film formation, while a deterioration in the wear behaviour with a further increase in the lead content was thought to be due to the possible segregation of the lead particles in the oil lubricant mixture, drying out followed by peeling off of the formed

lubricant film owing to less oil present therein, throwing out of the excess suspended solid mass from the lubricant mixture at the initial stage of sliding and abrasive action caused by the entrapped debris/constituents on the sliding surfaces [22–30, 34].

Flow of graphite in sliding direction (Figs. 7e, 8d, 9a, b, regions marked by double arrow) and smearing of the phase on the wear surfaces (Fig. 7d) indicate the formation of graphite film thereon leading to improved wear performance. On the other hand, the exposed graphite also tended to show occasional decohesion even on the wear surface (Fig. 7b, region marked by single arrow). Initiation and propagation of cracks from around the graphite phase indicates limited opportunity for the phase for smearing and forming solid lubricant film, thus adversely affecting wear performance. Sticking of debris (Figs. 7e, region marked by triple arrow; 8e, region marked by B) and the lubricant phase (Fig. 8f, region marked by C) on the wear surface reduces the extent of direct metal-to-metal contact

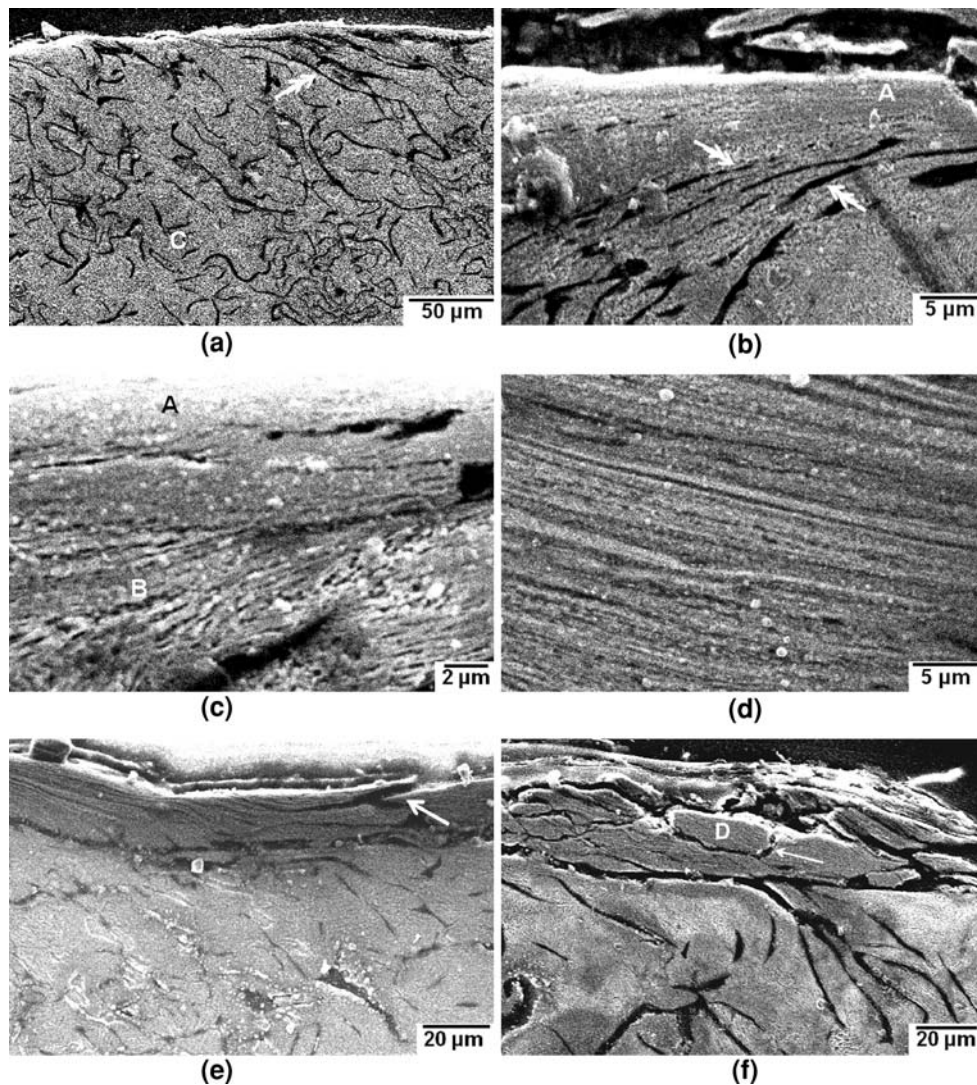


Fig. 9 Subsurface regions of the cast iron tested in the (b, c) oil lubricant and the lubricant mixture containing (a, d, e) 3% lead, and (f) 5% lead at the applied pressure of (a) 7 MPa, (b, c) 3 MPa, (d, e) 1 MPa, and (f) 9 MPa. A heavily deformed region in the nearest

vicinity of wear surface, *single arrow* crack, *double arrow* flow of graphite, *B* flow of microconstituents in general, *C* unaffected bulk structure, *D* regions being detached from the surface

and improves the wear resistance (inverse of wear rate). The presence of microcracks in the subsurface regions (Fig. 9e, f, regions marked by single arrow) and on the wear surfaces (Figs. 7b, 8b, regions marked by single arrow) suggests delamination to be one of the mechanisms of material removal. That adhesion is another important wear mechanism which is evident from wear-induced plastic deformation in the near vicinity of the wear surface (Fig. 9) and flow of microconstituents in sliding direction (Figs. 7, 8, 9, regions marked by double arrow).

The presence of deep grooves on the wear surface (Fig. 7c) results from the abrasive action caused by hard microconstituents/debris that get entrapped in between the sliding surfaces subsequent upon their removal [22–30, 34]. Specimen seizure led to severe most surface damage in

view of mass adhesion of material onto the disc surface [19]. This is in view of localized fusion of the contacting material due to high frictional heat generated as a result of severe sliding condition. It may be mentioned that localized flash temperature of the contacting surfaces is much higher than the measured average temperature near the specimen surface [34, 35]. This brings about localized fusion of highly stressed asperities. The extent of fusion becomes more severe in the due course of sliding leading to substantial material adhesion on the counter surface. Once the fused mass grows in size beyond a limit, it causes high loss of material (Fig. 4) as well as large frictional heat generation (Figs. 5, 6).

Initially, high rate of frictional heating (Fig. 5) during the wear tests emerges from the abrasion caused by

fragmented hard debris that get entrapped into on their removal from the sliding surfaces [22–30, 34]. It has been reported that initially contacting asperities constitute only a minor fraction of the total apparent contact area [36]. The total applied force is carried by the asperities; the effective stress far exceeds their yield stress. Accordingly, the asperities yield, fragment and work harden under the influence of thermomechanical events occurring therein [37]. Some of the fragmented mass gets entrapped in between the contacting surfaces and abrades the surface [22–30, 34]. With the progress of sliding, the effective surface area of contact increases as more and more number of asperities establish contact and the initially contacting asperities flatten. Under the circumstances, the asperities become less stressed and the wear condition becomes mild [36, 37], causing the severity of temperature increase to reduce at latter stages (Fig. 5). An increase in the rate of friction heat generation towards the end of the tests (Fig. 5) could be attributed to destabilization of the mild wear condition and substantial adhesion of the specimen material onto the disc. On the contrary, a decrease in the extent of frictional heat generation towards the end of the test (Fig. 5c) has been reported to be a result of material chipping off [17, 19, 22–30, 34] in view of the predominant effect of material cracking tendency (Figs. 7b, 8b, 9e, f, regions marked by single arrow).

5 Conclusions

1. The cast iron revealed graphite flakes in a matrix containing mainly pearlite along with a limited quantity of free ferrite. Occasional decohesion at the graphite/(ferrite) matrix interface was also noticed.
2. The wear response of the samples was controlled by factors like pressure and the presence of lead and its content in the oil lubricant mixture. The wear rate and temperature of the specimens increased in general with increasing applied pressure. The addition of lead particles to the oil lubricant up to a specific quantity led to better wear response in terms of lower wear rate and frictional heating. However, still higher concentrations of lead proved detrimental that came to be comparable to or even worse than that of the oil only environment.
3. The observed wear response of the samples could be corroborated with the specific characteristics of wear surfaces. For example, higher wear rate and frictional heating led to more severe surface damage and less effective formation of lubricant film. Material adhesion and smearing of the solid lubricant phase were noted to be important wear mechanisms, while abrasion and cracking also contributed to material loss.

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