Lubricated Sliding Wear Behavior of a Cast Iron: Effect of Graphite and/or Talc Fraction in Oil

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The effects of suspended solid lubricant (graphite and/or talc) particles in oil on the sliding wear response of a cast iron have been studied in this investigation. The role played by the changing concentration of the talc and graphite particles added to the oil separately as well as in combination toward controlling the wear behavior of the cast iron has also been analyzed. The investigation strongly suggests beneficial effects of the solid lubricant particles suspended in lubricating oil in terms of decreasing wear rate, frictional heating, and friction coefficient. Interestingly, increasing concentration of the suspended lubricant particles in oil led to reduction in the mentioned properties initially followed by the attainment of the minimum at a specific concentration of the solid lubricants. At still higher concentrations, the trend reversed in the case of wear rate and friction coefficient while it remained unaffected as far as the influence on frictional heating is concerned. Formation of stable lubricating film/layer was noted to be responsible for the improved wear performance of the samples while rupture of the lubricant film led to deterioration in wear behavior.

Keywords	cast iron, graphite, oil, sliding wear behavior, talc

1. Introduction

Use of lubricants in applications involving sliding movement of cast iron components is quite common (Ref 1-3). There exists a variety of lubricants in liquid, semi-solid, and solid conditions. Oil is an important class of liquid lubricant while grease falls in the category of semi-solid ones. The lubricating characteristic of oil lubricants is very much controlled by the nature of the base oil and the additives therein (Ref 4-6). Solid lubricants are among the important constituents of additives (Ref 4-7).

From structural stand point, graphite has a hexagonal layered structure (Ref 8) containing parallel layers of hexagonal (basal) planes stacked 0.34 nm apart (Ref 4). With an interatomic distance of 0.1415 nm between the carbon atoms in the basal plane (Ref 4), the ratio of the interplanar to interatomic distances for graphite becomes 2.403, which is much greater than 1.633; the latter is the case of an ideal close packed hexagonal crystalline structure (Ref 9). This makes the bonds between the parallel layers, i.e., basal planes, relatively weaker (Van der Waals type) in contrast with covalent bonds in the basal plane (Ref 4). The key to solid lubricating characteristics of graphite lies in its layered structure and its ability to form strong chemical bonds with gases and water vapor (Ref 10-12). The latter are adsorbed on to the crystalline edges and thus weaken the interlayer bonding resulting in easy shear and transfer of the crystalline platelets to the mating surfaces

thereby providing solid lubricating properties (Ref 10-12). Graphite, both in natural and synthetic forms, is a popular solid lubricant (Ref 7) and has been used as an additive to base (liquid/semi-solid) lubricants (Ref 4, 7, 13).

The crystal structure of talc is monolithic (Ref 14). In this case, a layer of brucite $[Mg(OH)_2]$ is sandwiched between two silica [Si-O tetrahedral] sheets/layers (Ref 8, 15). These layers are bonded together with a weak Van der Waals force that allows them to slide over each other and create slippery property when shear force is applied (Ref 8). Talc in essence has the potential to be an ideal solid lubricant in view of its layered structure (Ref 15, 16) and very low hardness of Moh 1 (Ref 8). However, it is not very well known for this purpose and finds place only to a limited extent, e.g., as a solid lubricant (glidant) to regulate flow in talcum powder (Ref 17). In a sliding wear study, reinforcement of 3-5% talc in an Al-Si alloy matrix has been noticed to bring about a 20-30% reduction in wear rate despite a reduction in strength and hardness of the composite (Ref 16).

A comparison of the structural features of graphite and talc reveals that despite their differing crystalline structures (open hexagonal versus monolithic), there is one commonality between them in terms of their loosely bonded layered structure. The latter is one of the essential qualifications for a solid to act as (solid) lubricant. However, talc has been less talked about as a solid lubricant in terms of understanding its response in sliding condition (Ref 16) than graphite despite great scope. Further, available information suggests that the quantity of solid lubricant additive greatly affects the lubricating characteristics of oil lubricants. In the event of the additive being a mixture of two or more solid lubricants, the nature and fraction of various constituent materials are also bound to govern the overall response. Moreover, material and sliding conditions greatly influence the response of the oil plus solid lubricant mixture. No work seems to have been carried out pertaining to the influence of talc addition to oil lubricant as well as the role of solid lubricant mixture containing varying

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quantities of graphite and talc therein toward controlling the sliding wear response of materials like cast iron, which are used for several engineering applications involving lubricated sliding conditions. Partial metal-to-metal contact takes place between the sliding surfaces in the events of delayed lubrication in sparsely lubricated conditions and during starting and stopping operations in fully lubricated conditions in such applications.

In view of the above, an attempt has been made to assess the influence of graphite and talc particles, when suspended in oil in varying quantities/fractions separately as well as in combination, on the sliding wear behavior of a cast iron. The observations have been substantiated through the characteristics of wear surfaces and subsurface regions.

2. Experimental Procedures

2.1 Material and Microscopy

The cast iron (3.25% C, 2.58% Si, 0.49% Mn, 0.09% P, 0.07% S, and remainder Fe) was prepared in the form of 20 mm diameter and 150 mm long cylindrical castings. Hardness of the cast iron was 220 HV. Microstructural studies were carried out using optical microscopy on 15 mm thick samples that were metallographically polished and etched with 2% nital solution. Wear surfaces and subsurface regions of typical wear tested samples were examined using scanning electron microscopy. The samples were sputtered with gold prior to their SEM examination. For subsurface examination, transverse sections of wear surfaces in the sliding direction were mounted in polyester resin, polished metallographically,

and etched with 2% nital solution prior to sputtering with gold for SEM examination.

2.2 Wear Tests

Lubricated sliding wear tests were conducted on 8 mm diameter, 30 mm long cylindrical samples using a pin-on-disc machine. Typical photographic views of the wear test apparatus in Fig. 1 show the basic machine, sample, control and display unit, and a magnified view of the pin-disc test assembly. The counterface (disc) was fabricated with a European standard steel En31 (1.02% C, 1.05% Cr, 0.3% Ni, 0.35% Mn, and remainder Fe) having a hardness of 746 HV. All the tests were carried out at an applied load of 20 kg (corresponding pressure being 3.92 MPa) and rotational speed of 1500 rpm (corresponding to a linear speed of 6.24 m/s). The samples were loaded against the disc using a cantilever mechanism. The lubricant consisted of 50-100 μm particles of talc and graphite mixed separately or in combination in the concentration range of 0-60% in SAE 40 oil. The ratio of graphite to talc particles in the case of adding them together in the oil lubricant was varied as 75/25, 50/50, and 25/75. Here the term 'concentration' in % of the solid lubricant particles corresponds to the weight of the solid lubricant(s) in g mixed with 100 cc of the oil lubricant. Similarly, a given graphite-to-talc ratio is with respect to the 'total content' of graphite plus talc in the solid lubricant mixture. For example, 60% solid lubricant content with a graphite-to-talc ratio of 25/75 in the oil means that the total content of the solid lubricant particles was 60 g in 100 cc of oil, and that the quantity of graphite in the mixture was 15 g and that of talc 45 g. The solid lubricant particles were added gradually to the oil and stirred vigorously therein simultaneously in a bid to make the lubricant
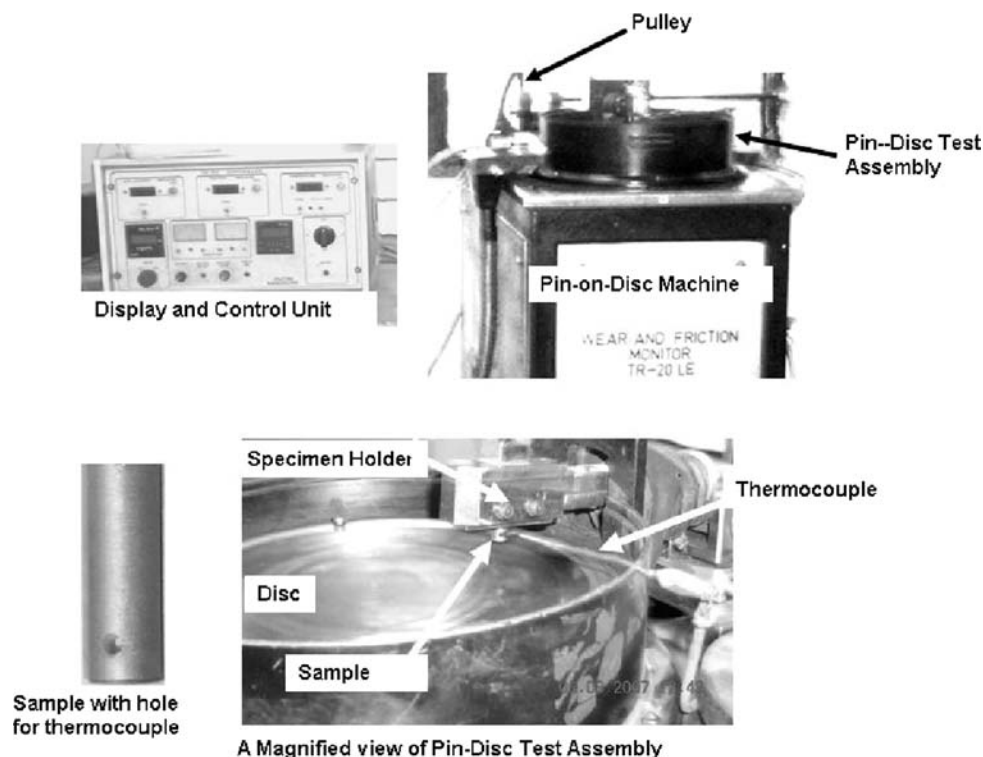

Fig. 1 Typical photographic views of the pin-on-disc wear test apparatus showing the basic machine, its control and display unit, a magnified view of the pin-disc test assembly, and the specimen with a hole for inserting the thermocouple

mixture homogeneous. The pin and disc were polished to a roughness (Ra) level of 0.8 μm and cleaned well prior to testing. The test procedure involved fixing the polished and cleaned sample in position, spreading the lubricant mixture on to the disc, allowing the disc to rotate at 640 rpm for 5 s to spin off excess lubricant, loading the sample against the disc, and rotating the disc at the required speed of 1500 rpm. The sliding distance was fixed at 2500 m or until specimen seizure was indicated in terms of high rate of temperature increase, large material adhesion on to the disc, burning of the lubricant mixture, and abnormal noise in the pin-disc assembly. Wear rate was computed by weight loss method. The specimens were cleaned and weighed prior to and after wear testing. A Mettler microbalance was used for weighing the samples. The precision of measurement attained through the balance was 0.01 mg. Temperature near the specimen surface was monitored as a function of test duration with a chromel-alumed thermocouple that was inserted in a 1.5 mm diameter hole made at a distance of 1.5 mm from the contacting surface. Friction coefficient was recorded using a friction transducer fitted at the rear end of the specimen holder assembly. An average of three observations has been considered in this study.

3. Results

Microstructure of the cast iron is shown in Fig. 2. It revealed flakes of graphite in a matrix of pearlite plus a limited quantity of ferrite (regions marked by single arrow, A, and double arrow, respectively).

Figure 3 shows the wear rate of the cast iron plotted as a function of graphite/talc content in the oil lubricant for different graphite-to-talc ratios therein. The wear rate decreased with increasing concentration of the solid lubricant particles in the oil initially, attained the minimum at 5% talc for oil plus talc and 40% graphite with or without talc in rest of the lubricant mixtures, and increased thereafter at still higher contents. Addition of talc to the oil lubricant led to a decrease in the wear rate compared to that of graphite prior to attaining the minimum. A reverse trend was noticed beyond the minimum wear rate. Specimen seizure was observed in the case of oil and oil plus 20% talc environments, while no seizure was noted in rest of the lubricant mixtures. Increasing the fraction of talc in
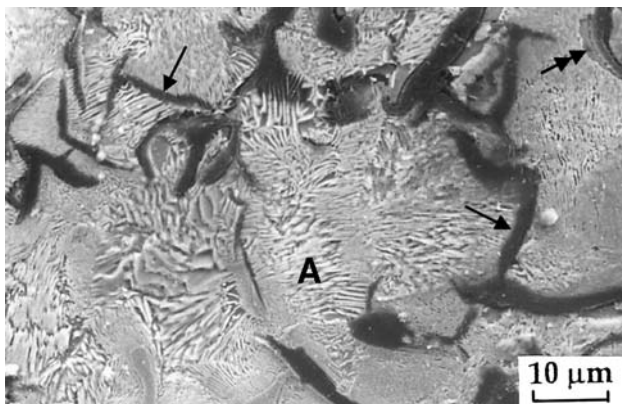
the graphite plus talc solid lubricant mixture (added to the oil lubricant) led to deterioration in the wear performance of the samples.

Temperature near the specimen surface is shown in Fig. 4 as a function of test duration for different graphite-to-talc ratios in the oil lubricant. The results of testing the samples in oil without solid lubricant particles are also shown in the figure for comparison. The temperature increased initially at a high rate with the test duration. This was followed by a lower rate of increase in temperature at longer test durations in general, with a few exceptions wherein the rate of increase became high once again toward the end of the wear tests. The presence of graphite plus talc particles in the oil lubricant led to less frictional heating in general. However, varying concentrations were noted to produce a mixed effect on frictional heating.

Maximum temperature near the specimen surface is plotted in Fig. 5 as a function of concentration and ratio of solid lubricants (graphite and talc) in the oil lubricant. Frictional heating decreased in the presence of graphite and/or talc particles in the oil lubricant. However, changing concentration/ratio of the solid lubricant in the oil did not produce appreciable effect on frictional heating except during seizure; substantially higher frictional heating was noticed in the case of specimen seizure.

Figure 6 shows friction coefficient of the samples plotted as a function of test duration for different concentrations/ratios of the solid lubricant mixture in the oil. The presence of solid lubricant (graphite/talc) particles in the lubricant mixture caused the friction coefficient to reduce compared to that in

Fig. 2 Microstructure of the cast iron [A: pearlite, single arrow: graphite flakes, double arrow: ferrite]
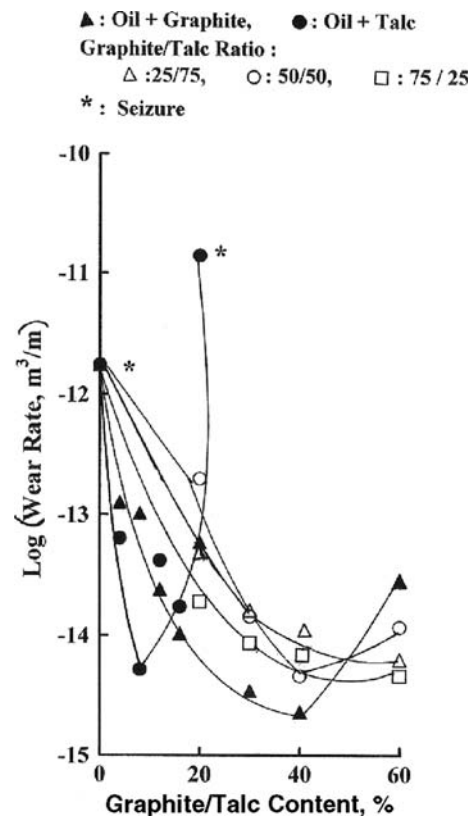

Fig. 3 Wear rate as a function of solid lubricant content in oil at different concentrations/fractions of the solid lubricant(s) in the (solid lubricant) mixture
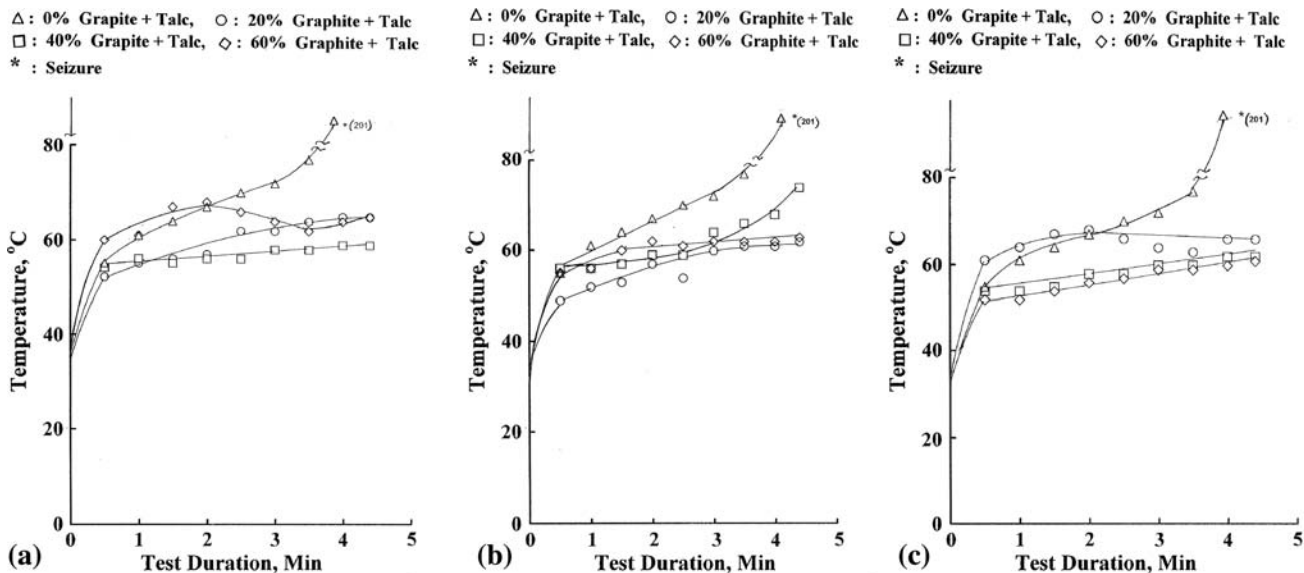
Fig. 4 Temperature near the specimen surface plotted as a function of test duration in oil and oil-graphite-talc mixtures for a graphite-to-talc ratio of (a) 75/25, (b) 50/50 and (c) 25/75
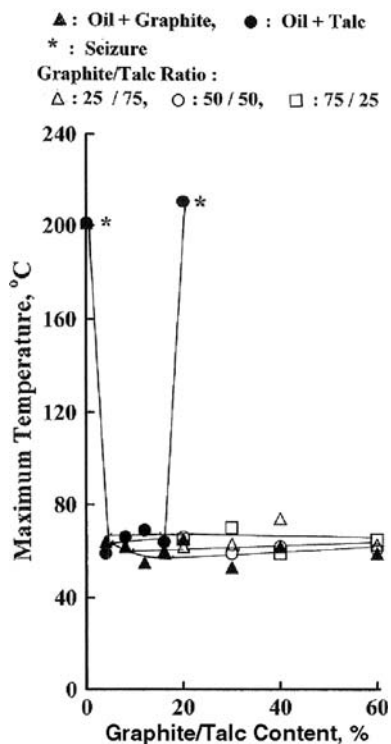

Fig. 5 Frictional heating as a function of solid lubricant content in oil at different concentrations/fractions of the solid lubricant(s) in the (solid lubricant) mixture

oil. This trend was noticed irrespective of the graphite-to-talc ratio within the solid lubricant mixture added to the oil. The friction coefficient increased with test duration initially at a high rate. This was followed by a lower rate of increase at longer test durations except that the rate of increase became

high once again during specimen seizure while a reduction in friction coefficient was observed in some cases. Moreover, the presence of 60% graphite plus talc (graphite-to-talc ratio 50/50 and 75/25) and 40% graphite plus talc (graphite-to-talc ratio 25/75) led to minimum friction coefficient (Fig. 6a, b, and c, respectively).

Average friction coefficient recorded toward the end of the tests has been plotted in Fig. 7 as a function of solid lubricant (graphite and/or talc) concentration/ratio in the oil. The friction coefficient decreased in the presence of graphite and/or talc particles except during specimen seizure. Further, the friction coefficient decreased with the increasing concentration of talc and/or graphite in the oil initially, say, up to 5% talc and 20-40% graphite and graphite plus talc. This was followed by an increase in friction coefficient once again at higher concentrations of the solid lubricants. In some cases, the friction coefficient decreased once again at still higher concentrations of the solid lubricant mixture. Moreover, the least friction coefficient was observed prior to specimen seizure in the oil plus talc mixture.

Figure 8 represents the wear surfaces of the samples tested in different environments. The wear surfaces were smooth with dark appearance in general when tests were conducted in oil plus 40% graphite lubricant mixture (Fig. 8a). Similar observations were also made in the case of oil plus 5% talc mixture (Fig. 8b). Specimen seizure led to significantly increased surface damage and rupture of the dark patches/regions (Fig. 8c and d, regions marked by A and B, respectively). Further, graphite also got exposed on to the specimen surfaces (Fig. 8a-c, black regions).

Subsurface regions of the specimens are shown in Fig. 9. Substantial wear induced plastic deformation was observed in general. Flow of microconstituents including that of graphite from within the matrix is evident from Fig. 9(a) (regions marked by A and single arrow, respectively). The region in the nearest vicinity of the wear surface got most severely deformed and as a result comprised very fine microconstituents (Fig. 9b, region marked by B). A region in the process of being separated
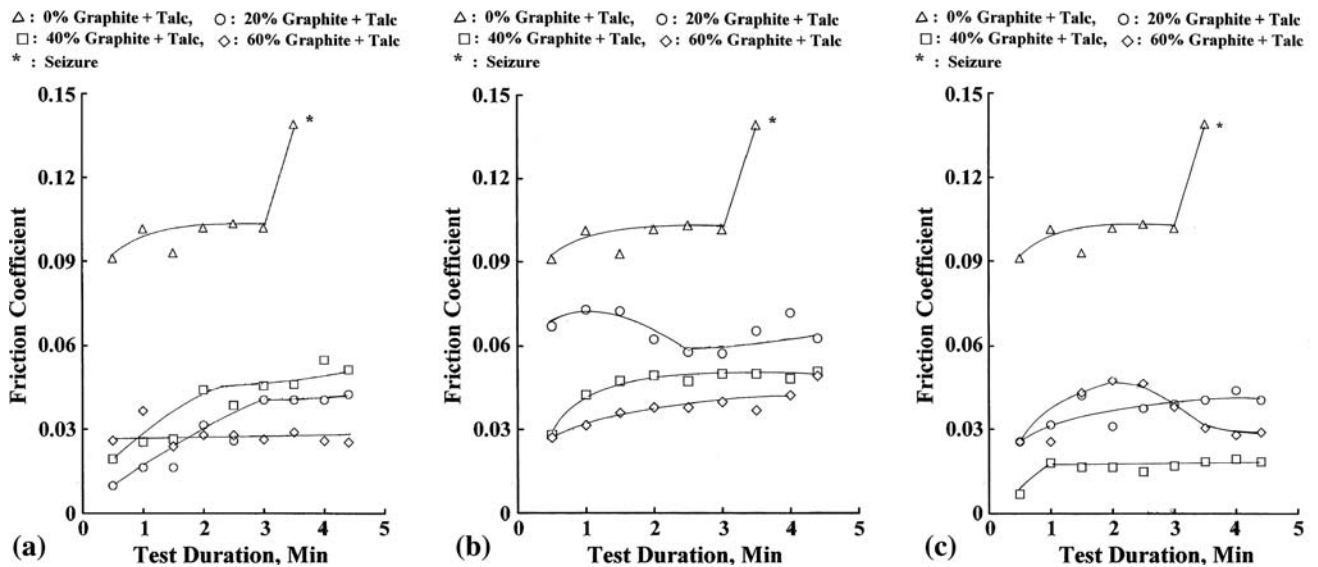
Fig. 6 Friction coefficient plotted as a function of test duration in oil and oil-graphite-talc mixtures for a graphite-to-talc ratio of (a) 75/25, (b) 50/50 and (c) 25/75
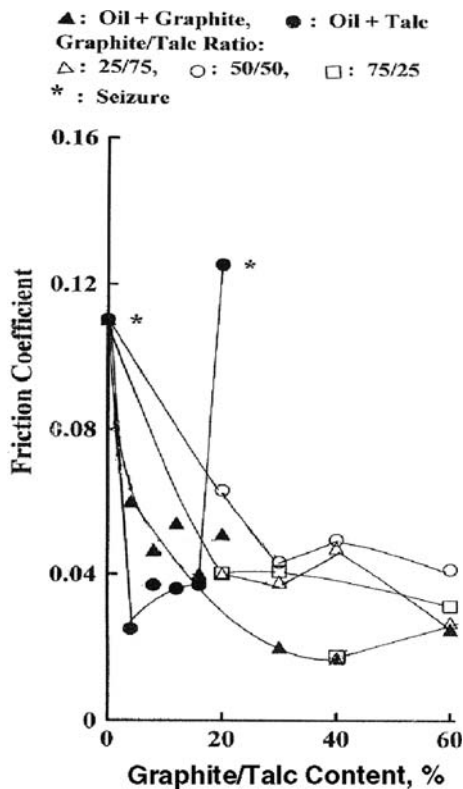

Fig. 7 Friction coefficient as a function of solid lubricant content in oil at different concentrations/fractions of the solid lubricant(s) in the (solid lubricant) mixture

from the bulk and microcracks were also noticed (Fig. 9b, regions marked by C and double arrow, respectively). The unaffected region far below the wear surface (Fig. 9, regions marked by D) revealed its microstructure to be identical to that of the normal bulk structure (Fig. 2).

4. Discussion

Decreasing wear rate with initially increasing concentration of graphite and/or talc particles (Fig. 3) could be attributed to the more effective formation of the lubricating film with greater stability (Fig. 8a and b). It has been suggested that the presence of oil lubricant changes the characteristics of sliding surfaces through producing triboinduced reaction products after interaction with the contacting surface materials and environment. Self-generating oxide films (Ref 18) produced during the process of sliding adhere firmly on to the contacting surfaces, increase the resistance of the contacting asperities against crumbling, reduce direct metal-to-metal contact, and thereby lead to better wear performance (Ref 18). Addition of solid lubricant (graphite/talc) particles to oil enables the formation of more stable lubricant film by smearing on the contacting surfaces (Ref 16, 19, 20). To form lubricant film effectively on the contracting surfaces, it becomes essential that the film firmly adheres in place. This characteristic is imparted through wetting of the film with the contact surfaces. In an oil plus solid lubricant mixture, the oil lubricant provides this additional characteristic enabling the suspended solid lubricant particles to effectively smear and form stable lubricating film. Needless to say, an optimum combination of the oil and solid lubricant contents would most effectively serve the purpose. Initially increasing concentration of solid lubricating particles in the oil lubricant enables to form stable lubricant films (Fig. 8a and b) on a larger contacting surface area leading to better wear behavior (Fig. 3, 5, and 7). However, this trend continues only up to a specific concentration of the solid lubricant. A reversal in the trend at higher concentrations of the solid lubricant particles (Fig. 3 and 7) was due to the rupture of the film (Fig. 8c and d) after attaining large thickness and becoming dry in view of insufficient oil content in the lubricant mixture. Concentrations of the solid lubricant higher than the optimum make the lubricant mixture more viscous. There is also the danger of agglomeration of the solid lubricant particles in the (oil) lubricant mixture. Under the circumstances, the (solid)
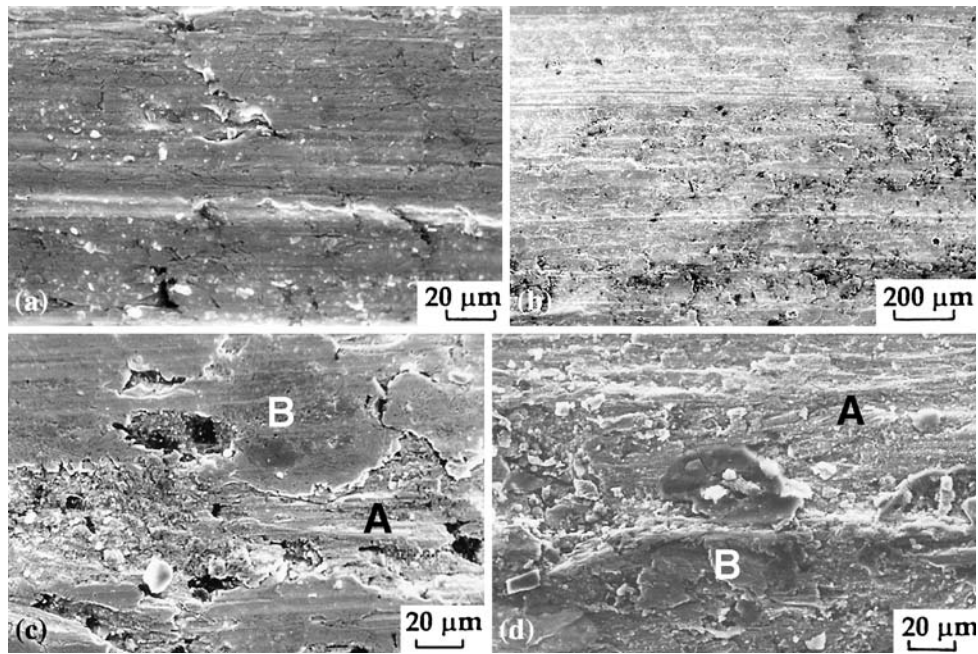
Fig. 8 Wear surfaces of the samples tested in oil containing (a) 40% graphite, (b) 5% talc, (c) 20% talc, and (d) no solid lubricant [A: damaged region, B: dark region, black regions: exposed graphite]
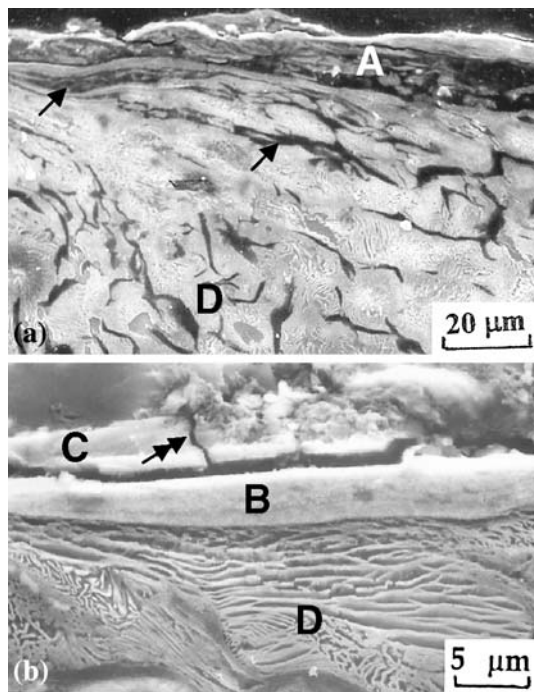

Fig. 9 Subsurface regions of the cast iron tested in oil containing 40% graphite [A: flow of microconstituents in sliding direction, single arrow: flow of graphite present in the cast iron matrix, B: severely deformed region containing very fine microconstituents, C: region in a process of separation from the bulk, double arrow: microcracks, D: unaffected bulk structure]

lubricant particles are not able to spread and adhere on to the contacting surfaces uniformly and effectively. The loosely held solid lubricant particles get thrown out of the contacting surfaces due to the presence of insufficient quantity of the oil lubricant thereby adversely affecting the stability of the film by facilitating its rupture through abrasion. Further, deteriorating wear performance with increasing talc content, i.e., decreasing graphite-to-talc ratio, in the solid lubricant mixture indicates that monolithic crystalline structure of talc (Ref 14) in combination with the open hexagonal structure of graphite (Ref 4) produces an adverse effect on the performance of the oil toward controlling the wear response of the cast iron. Interestingly, the same talc up to 5%, when added to the oil separately, proved to be the best but it also led to specimen seizure at 20% talc in oil. Further research is needed to dwell into the reasoning for the same. That the effects of changing concentration of talc and/or graphite and the graphite-to-talc ratio in the lubricant on friction coefficient (Fig. 7) were practically identical to those of wear rate (Fig. 3) suggests that the lower wear rate was corroborated with reduced friction coefficient while frictional heating also became less (although it stabilized beyond a specific level), Fig. 5. Specimen seizure was associated with higher wear rate (Fig. 3), larger rate of frictional heating (Fig. 4 and 5), greater friction coefficient (Fig. 6 and 7), and severely damaged wear surfaces (Fig. 8c and d, regions marked by A). Improved wear response of the samples in the presence of up to 5% talc, 40% graphite, and 40% graphite plus talc in different graphite-to-talc ratios in oil suggests that addition of graphite independently or along with talc could be more beneficial than talc alone from economic as well as scientific standpoints.

The increasing rate of frictional heating in the beginning of the wear tests (Fig. 4) could be attributed to the abrasive action (Ref 21) of the initially contacting asperities that get oxidized, work-hardened, fragmented, and entrapped in between the contacting surfaces in due course of sliding (Ref 22, 23). It has been suggested that sliding contact between the interacting surfaces initiates through highly protruding asperities that are quite less in number and constitute only a minor fraction of the total apparent area of contact (Ref 22, 23). Accordingly, they become highly stressed even beyond their yield stress. This

leads the asperities to yield and deform followed by their oxidation and work-hardening under the influence of thermo-mechanical effects produced by the sliding action (Ref 22, 23). The effective area of contact increases gradually with the yielding, deformation, and fragmentation of the asperities. As a result, the sliding conditions tend to become mild in view of the reduced effective stress and more effective formation of lubricating film leading to the generation of mild wear conditions (Ref 22, 23). Under the circumstances, relatively less rate of frictional heating takes place at longer test durations (Fig. 4). Moreover, increasing rate of frictional heating toward the end of the wear tests could be attributed to the destabilization/fragmentation of the lubricant film (Fig. 8c and d). The view gets strengthened further from the fact that this happened during specimen seizure (Fig. 4) wherein mass adhesion of the pin material takes place on to the counterface (disc) thereby adversely affecting the stability of the lubricating film formed. Practically identical effects of test duration on friction coefficient (Fig. 6) to those of frictional heating (Fig. 4) suggest that decreasing friction coefficient resulted from reduced frictional heating.

The varying microstructural features of the subsurface regions with depth below the wear surface (Fig. 9) result from the changing severity of wear-induced plastic deformation that they undergo during sliding (Ref 24-26). The region in the nearest vicinity of the wear surface experiences most severe plastic deformation and hence reveals extremely fine micro-constituents (Fig. 9b, region marked by B). It has been reported that such a fine microstructure results from the fast rate of thermal cycling (Ref 27) and phase transformation like austenite to martensite and back in ferrous alloys in quick succession (Ref 28-30). Added to this are high rate and degree of straining (Ref 31) experienced by the region leading to high dislocation density therein (Ref 32). The region basically consists of oxides of the contacting surface materials and reaction products of the surroundings through transfer and back transfer events and mechanical alloying (Ref 22, 23). Such a region produces lubricating effect and reduces the extent of direct metal-to-metal contact causing improved wear performance (Ref 22, 23, 26). The presence of such a deformed layer suggests adhesion to be the dominant mechanism of material removal. The region next to the topmost one shows flow of microconstituents in sliding direction (Fig. 9a, region marked by A) due to a relatively less severity of deformation. The region still below the wear surface (Fig. 9d, region marked by D) remaining unaffected during sliding possesses normal bulk structure similar to Fig. 2. Flow of graphite in the sliding direction (Fig. 9a, regions marked by single arrow) and exposure of graphite on the wear surfaces (Fig. 8b and c, black spots) indicate that the graphite flakes present in the cast iron also participated in forming the lubricating film (Ref 33) on the contacting surfaces (Fig. 8c and d, regions marked by B) and thereby improving the wear response. Formation of dark patches on the wear surfaces (Fig. 8, region marked by B) results from the smearing action of the lubricant and leads to improved wear response.

5. Concluding Remarks

An appraisal of the observations made in this study suggests definite improvement in the wear response of the cast iron as a result of mixing up to specific concentrations of graphite and talc solid lubricant particles, e.g., 5% for talc alone and 20-40% in the cases of graphite alone and graphite plus talc combinations, in the oil lubricant. Talc, when added separately to the oil, performed the best. This of course was true only for up to a lower talc concentration, e.g., 5%, as compared to 20-40% for graphite separately or in combination with talc. Improved wear performance was corroborated with the generation of smooth wear surfaces with dark regions. Concentrations of the graphite and/or talc in the lubricant mixture greater than mentioned above caused the wear response to deteriorate because of increasing severity of surface damage that resulted into rupture of the lubricating film (dark regions). Realization of the best wear performance at larger concentrations of graphite and graphite plus talc mixtures than talc alone in oil suggests the former ones to be more effective from economic (oil saving) point of view. Frictional heating increased at a higher rate in the beginning of the tests followed by a lower rate of increase at longer test durations in general. Friction coefficient also was affected by the test duration in a manner similar to that of frictional heating. Changing concentration of the solid lubricant particles in oil affected the wear rate and friction coefficient in an identical manner indicating that less wear rate was supplemented with reduced friction coefficient and vice versa associated with lower frictional heating.

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