DELAMINATION WEAR MECHANISM IN GRAY CAST IRONS

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Abstract An investigation of the friction and sliding wear of gray cast iron against chromium plated cast irons was carried out on a newly constructed reciprocating friction and wear tester. The tests were the first to be done on the test rig under dry conditions and at the speed of 170 cm/min, and variable loads of 20-260 N for a duration of 15 min. to 3 hours. The gray cast iron surfaces worn by a process of plastic deformation at the subsurface, crack nucleation, and crack growth leading to formation of plate like debris and therefore the delamination theory applies. No evidence of adhesion was observed. This could be due to formation of oxides on the wear surface which prevent adhesion. Channel type chromium plating 'picked' up cast iron from the counterbody surfaces by mechanically trapping cast iron debris on and within the cracks. The removal of the plated chromium left a pitted surface on the cast iron.

Key Words Wear, Delamination Wear, Gray Cast Iron, Chromium Plating

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INTRODUCTION

The delamination theory of wear has been presented as being dependent on the presence of a soft surface layer which is relatively free of dislocations [1]. The proposed theory by Suh is based on plastic deformation at the subsurface, leading to void and crack formations. The subsequent joining of cracks by shear deformation and its propagation to surface create flake like sheet debris. Further work by Suh and his associates [2,3,4], examined the fundamental mechanism of sliding wear postulated by the delamination theory of wear. They concluded that since the forces exerted at the surface control the crack nucleation and the propagation rates, it is clear that as the magnitude of the surface traction and the contact area of each asperity increase, the wear rate increases and the transition occurs from mild to severe wear. The transition occurs from the initial stage of wear involving the removal of surface asperities to a steady state. At this stage of wear, although the surface looks smooth, subsurface damage is being accumulated. When the damage reaches a critical level, wear sheets are generated in large quantities and the wear process reaches a steady state, Eyre and Williams [5] have also shown that deformation of the underlying metal is a critical factor in initiating severe (metallic) wear.

When wear particles are generated, a subsurface crack breaks through the surface. Since the propagating end of the crack is always situated behind the moving asperity, the crack reaches the surface after the asperity moves over the crack. Consequently, the wear particles always lift up from the surface so that the underside faces the direction opposite to the slider motion.

Rigney [6] advanced the study of near surface regions. The micromechanisms associated with the formation of debris in the form of plates were identified by following the development of cellular microstructure in the subsurface of crystalline materials under heavy localized deformation. He used the term cellular to describe a deformation microstructure containing regions which are relatively free of dislocations, separated by high tangled regions of dislocations which serve as cell boundaries. The wide cell boundaries are arranged so that a relatively large volume fraction in this region can behave as effective short-circuiting paths for diffusion, thus allowing migration of specific solutes at temperatures considerably below those required for measurable bulk diffusion. Moreover, the solubility of various species in the cell boundaries should be much higher that in the bulk material. Such changes in solubility could easily lead to changes in composition near the surface during wear.

Surface wear can be caused by either thermal stresses or fatigue failure in the sliding faces. These can be caused by a momentary overload due to dry running, as a result of failure of the coolant or by a large load or speed variation. Scuffing, or 'galling' are typified indication of these events or such a mechanism, the cause of which basically being the high temperature produced at points of intimate contact as a result of high load and sliding speed [7, 8, 9, 10].

The success of gray iron in resisting wear is attributed to the lubricating qualities of graphite. Yet, malleable iron containing the same amount of graphite as gray iron cannot be substituted successfully for gray iron in many engine parts. Hegh [11] indicated that the shape or form of graphite flakes in gray iron contribute to the material wear resistance. Coarse, thick graphite flakes of random orientation, meeting the designation of type A graphite, are preferred form of the graphite.

The lack of galling tendency combined with the oil-retaining ability and the actual lubricating action of graphite may also be responsible for excellent wear resistance of gray cast iron. These properties are the reasons for the large use of a cast iron by the automotive industry.

EXPERIMENTAL PROCEDURE

Materials The cast irons used for the investigation have a hardness of 252 HV and "A" type graphite, on the ASTM scale. SEM surface topography of cross-honed gray cast iron is shown in Figure 1. The chromium plated on cast irons has a channed type structure with a thickness of 0.2 mm and a hardness of 853 HV.

Wear Testing The rig consists of a primary drive unit and an intermediate reciprocating drive unit for converting rotory motion from the

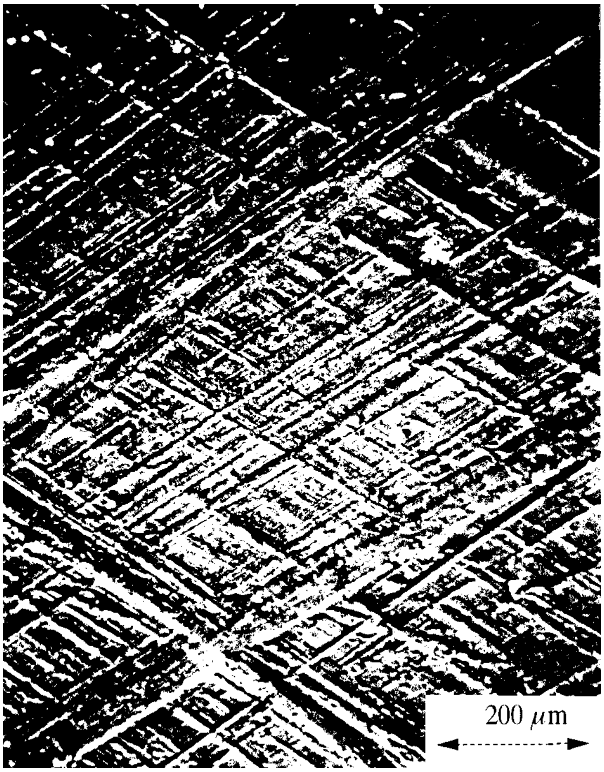


Figure 1. SEM surface topography of cross-honed gray cast iron (X100).

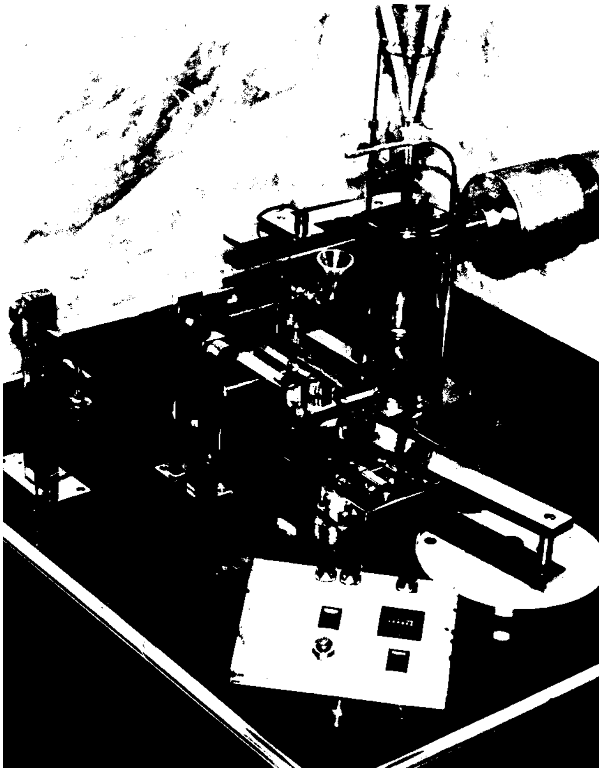


Figure 2. Test unit rail bed.

prime mover into reciprocating motion of the test unit rail bed (Figure 2). For each test, agray cast iron specimen is clipped to the bed. The chromium plating is held by a specimen holder through which load can be exerted on its holding fixture. The specimen holder consists of two parts at its lower end where it has the same curvature as the chromium plating and the specimen can be clipped to an upper pat. A transducer measures the dimensional changes in the chromium plating and gray cast iron simultaneously to give the total wear. The gray cast iron wear is measured by a transducer which responds to the dimensional change in the height of a bar which is fixed to the test unit. At the other end of this bar, a wheel rotates as the bed reciprocates and change in the thickness of gray cast iron, affects the height of the bar. Another transducer is also used for measuring the chromium plating frictional (tangantial) forces on the gray cast iron. All three transducers are connected to a six-channel recorder for a continuous recording of wear and friction. The load on the chromium plating specimen holder can be varied from 20N upwards.

All the tests were carried out at laboratory environment with temperature in the range of 16-30ÜC and relative humidity of 60-91%.

Test duration varied from 15 minutes to a maximum of 3 hours. Wear was calculated from the transducer reading, indicating chromium plating and gray cast iron dimension changes which were continuously recorded and checked by weight loss of both gray cast iron segment and chromium plating specimen.

The coefficient of friction was determined by calculating tangantial force exerted on the surface from the force transducer reading and dividing it by actual force (weight).

Debris were collected and taken for Scanning Electron Microscope (SEM) examination.

Metallographic Examinations of Wear Products The following techniques were used to examine wear;

(a) Taper section
(b) Optical Microscopy
(c) Microprobe Analysis (EPMA)
(d) Scanning Electron Microscopy (SEM)

Taper Section Technique This was used to examine worn surface from the tests. This enabled features such as cracks, plastic deformation, separating debris and composition changes near the surface of wear tracks to be identified. In this evaluation, 11 degree tapered sections were prepared, giving an effective increase in surface layer thickness of five times. This also enabled the examination of separating debris projecting above the wear track to be studied.

The main stage of preparation involved the construction of a new jig which was tapered 11 degrees at the top surface.

The wear track was protected with epoxy resin, and then a wear specimen was placed into the taper section jig. As the transverse section being machined was parallel to the original 11 degree tapered top face of the jig, an 11 degree taper section transverse to the wear track was ultimately obtained. The epoxy resin gave a greater surface area to the wear specimen to be placed in the mounting cylinder, reducing any chance of tilting as well as protecting the wear track from deformation during grinding. The specimen was then placed into the cylinder, in which the tapered end lies at the bottom. The specimen mount was removed from the cylinder and the tapered surface was polished carefully. The specimen was then prepared for conventional metallographic examination.

Optical Microscopy Optical microscopy was used to investigate the nature and distribution of phases in the gray cast iron specimens, as well as to examine such features as cracks, plastic deformation, separating debris and compositional changes near surface of wear tracks at different magnifications.

Microprobe Analysis (EPMA) The technique was used for identifying and analysing iron pick on the chromium plating surface and chromium pick up in the region of the wear track of gray cast iron.

Scanning Electron Microscopy (SEM) The scanning electron microscope (SEM) was used to examine the surface topography of wear tests and three dimensional viewing of worn surfaces as related to the metallography of the substrate. The equipment was quite useful, because in this case it was difficult on a single photograph to differentiate between height differences on the wear track surface viewed by an optical microscope. This was particularly valuable in the examination of worn surfaces on which there was transferred material, oxide layers and cracks. The debris collected from the tests were also examined by SEM.

RESULTS AND DISCUSSION

Examination of Worn Gray Cast Iron Surfaces It is most convenient first to examine the wear of surfaces by SEM examination of representative samples of wear tracks to reveal some of the predominant wear mechanism.

In general, when a chromium plated gray cast iron slides on a gray cast iron, cast iron exhibites two regimes of wear. By analogy with the metallic processes, these may be described as 'mild' and 'severe' [12]. However, these two regimes were not distinct and they merged

Figure 3. Plastic flow and developed network of the cracks on the gray cast iron surfaces-load 8 kg (X200).

gradually into each other. At lower loads as shown in Figure 2, the worn surfaces were relatively smooth. When the surface was subject to higher stresses, these was a gradual transition towards severe wear (Figures 2 and 3). Therefore, in this particular case, Severe and mild wears can be defined as "when the density of the wear craters is high, it is called severe, whereas when density is low it is called mild". The transition occurs from the initial stage of wear, involving the removal of surface asperities to a steady production of craters (Figure 3a). The cast iron asperities either fractured immediately or deformed upon initiation of wear experiments (Figure 4) At this stage of wear, although the surface looks smooth, subsurface damage is being accumulated. Eyre et al [13] have suggested that heat built up at substrate. The surface is unable to support the oxide and plastic deformation and severe wear

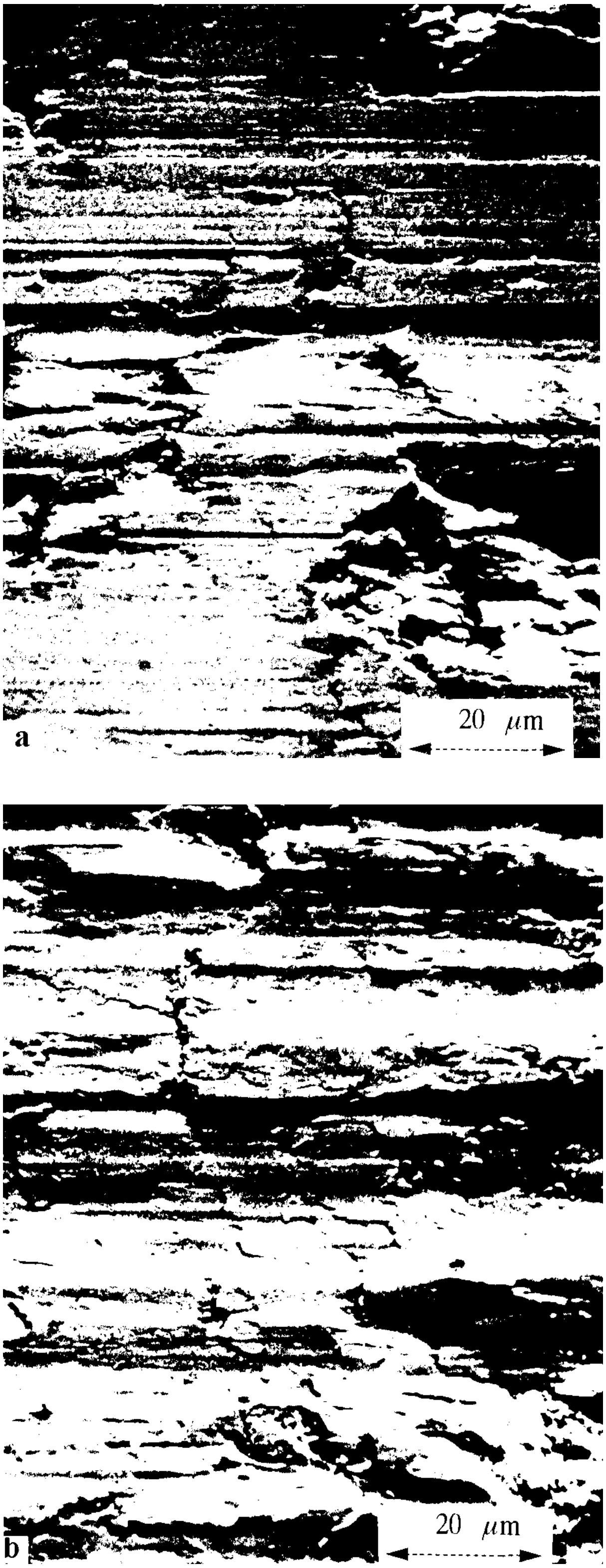


Figure 4. Plastic flow on the gray cast iron surfaces increases with load. (a) Worn at 10 kg load (X1000) and (b) Worn at 18 kg load (X1000).

Figure 5. SEM micrograph shows that the asperities on the wear tracks are completely smeared over. The surface and waviness of the surface is diminished-load 20 kg (X100).

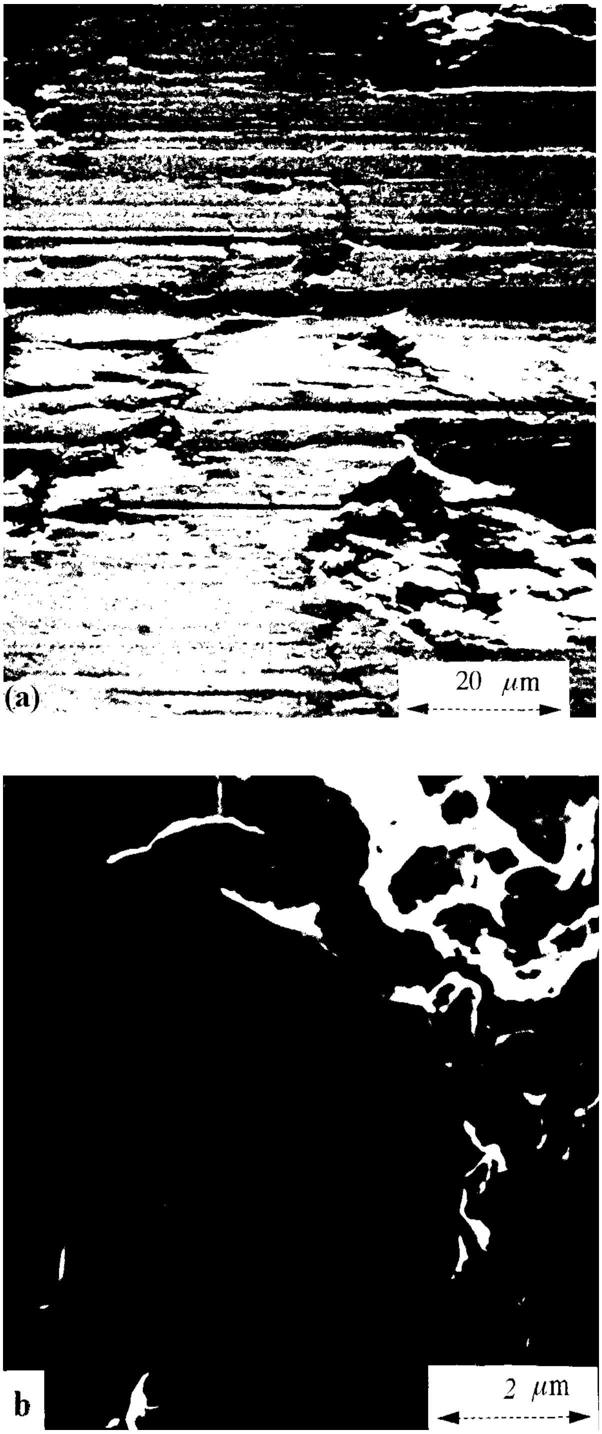


Figure 6. Surface of worn gray cast iron-load 20 kg. (a) Plastic flow and formation of particle islands (X1000) and (b) Formation of a particle island (X10K).

occurs. They have shown that the deformation of the underlying metal is a critical factor in the surface causes thermal softening of the initiating severe wear. On the other hand the stress distribution around a localized asperity contact depends on the shear stress imposed by the applied forces and this, in turn, influences the dynamics of fatigue wear. All these theories and suggestions plus the observations in the present investigation are substantiately the same as the delamination theory of wear for metal proposed by Suh [1]. During delamination wear, the immediate surface is under the influences of applied stresses and under these conditions considerable plastic flow is possible. Figure 5 shows that plastic flow increases with load. This could be justified by considering that the pressure exerted at the surface controls the crack nucleation and propagation rate. It is clear that increasing surface traction causes the contact area of each asperity to increase

Figure 7. Surface flow has occurred to cover underlying structure on the gray cast iron surface-16 kg (X2000).

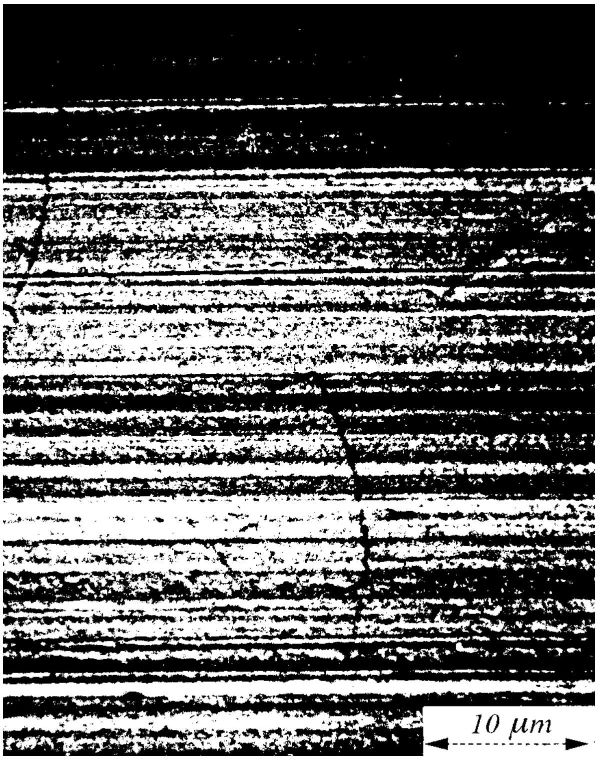


Figure 8. SEM micrograph shows that the asperities on the wear tracks are completely smeared over. The surface and waviness of the surface is diminished-load 20 kg (X100).

and thus the wear rate increases.

An SEM topographic study of the gray cast iron wear track surface shows the destructive effects of delamination on the metal. Surface flow has occurred to cover the underlying structure and a network of cracks has developed. Figure 6 shows how delamination of the surface can produce a large quantity of plate-like metallic particles. These particles plough the surface as long as they remain trapped between the gray cast iron and chromium plating.

Figure 7 clearly indicates that at higher loads the process is mostly mechanical, with plastic deformation caused by friction and fatigue taking place. In this case the stress exceeding the strength of the gray cast iron and transveres cracks have developed within these surface and this leads to scuffing. The term used here as scuffing is not the same as the definition adopted by the Institution of Mechanical Engineers (1957). According to their defintion scuffing is "gross damage characterized by the formation of local welds between the sliding surface". But these observations showed no clear evidence of adhesion.

The catastrophic wear rate that is one of the characteristics of severe wear in this investigation is due to delamination.

Examination of Worn Chromium Plating Surface SEM examination of worn surface of chromium plating specimens shows that cracks tend to form at the chromium plating interface. The number of cracks increased as the load increased and was more predominant in the immediate vicinity of the channel cracks. Figures 8 and 9 show that the density of cracks

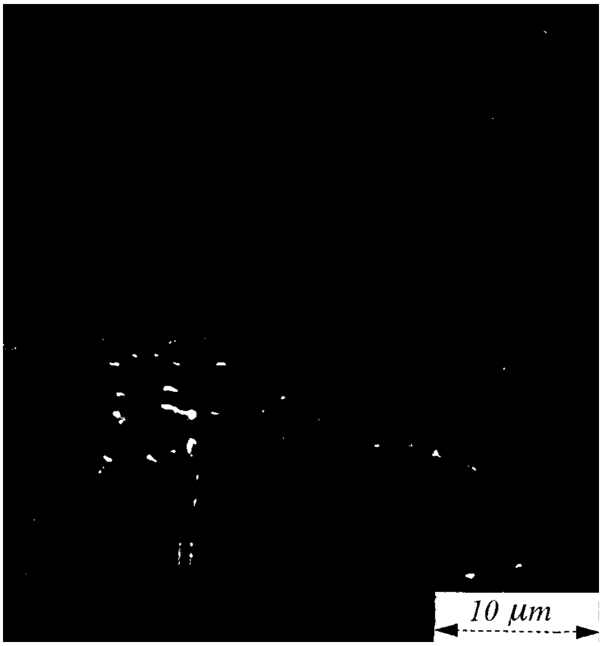
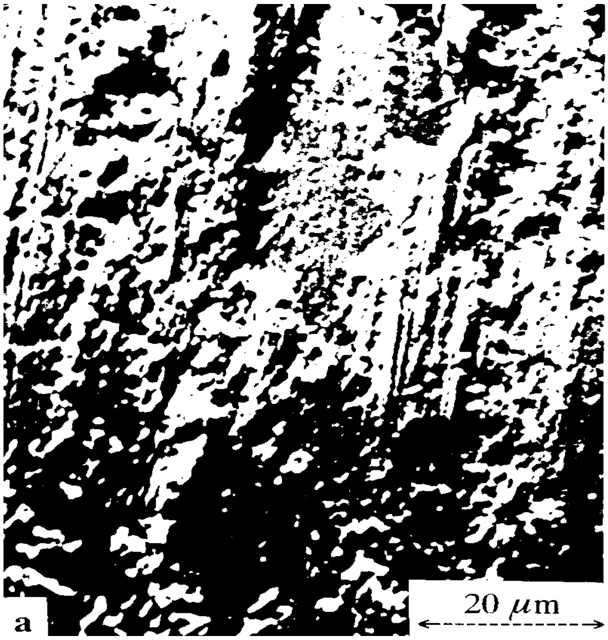
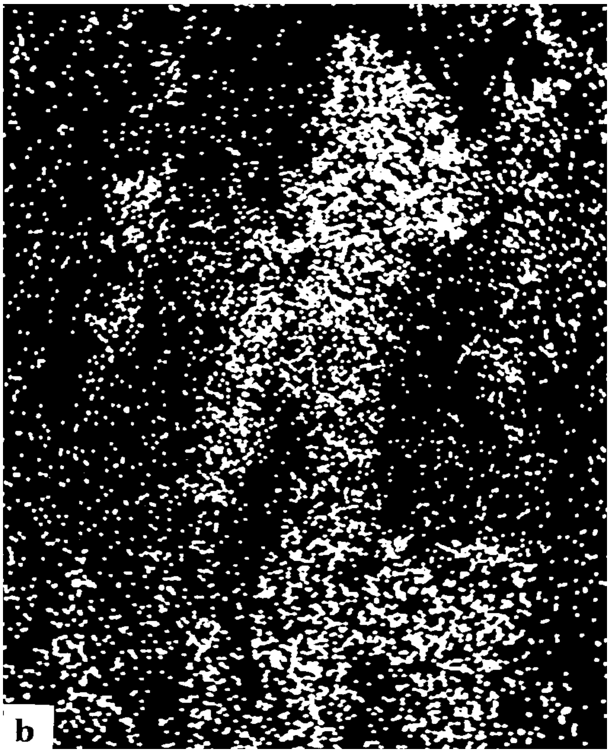


Figure 9. SEM micrograph shows that the asperities on the wear tracks are completely smeared over. The surface

increases as the applied load increases and these cracks are formed predominantly at right angles to the rubbing direction. This mechanism of failure is shown to be slightly distance and load dependent, and therefore, appears to be a fatigue mechanism.





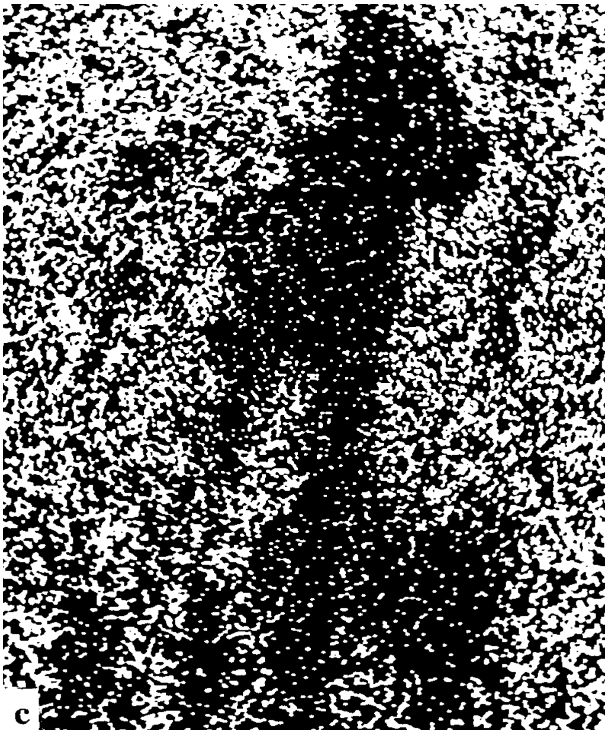


Figure 10. Particles of gray cast iron embedded on the chromium plating surface-load 8 kg (X1000). (a) Viewed in the SEM, (b) Micro probe analysis for iron and (c) Micro probe analysis for chromium.

Sliding of channel type chromium plating surface against a gray cast iron specimen had the effect of breaking up the chromium matrix between the channel cracks into smaller areas. Some of these particles then broke away leaving a pitted surface (Figure 9).

Figure 10a shows that the gray cast iron wears by removal of plate-like debris and some of these become embedded in the faces of the chromium plating. EMPA micrographs in Figures 10b and 10c show that there is metal transfer on the surface, these particles are iron which must have been removed from the gray cast iron. Figure 11a shows an abrasive wear process produced on the surfaces by the particles embedded in the rubbing surface of the chromium plating surface acting as abrader.

During the test at 200 N load, debris were

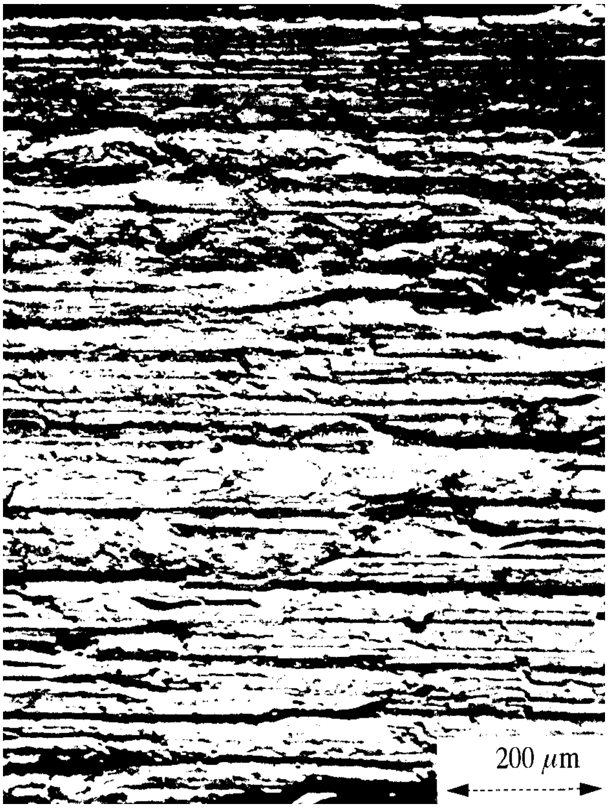


Figure 11. Iron embedded on the chromium plating surfaces causes gray cast iron wear by abrasive process-load 18 kg (X100).

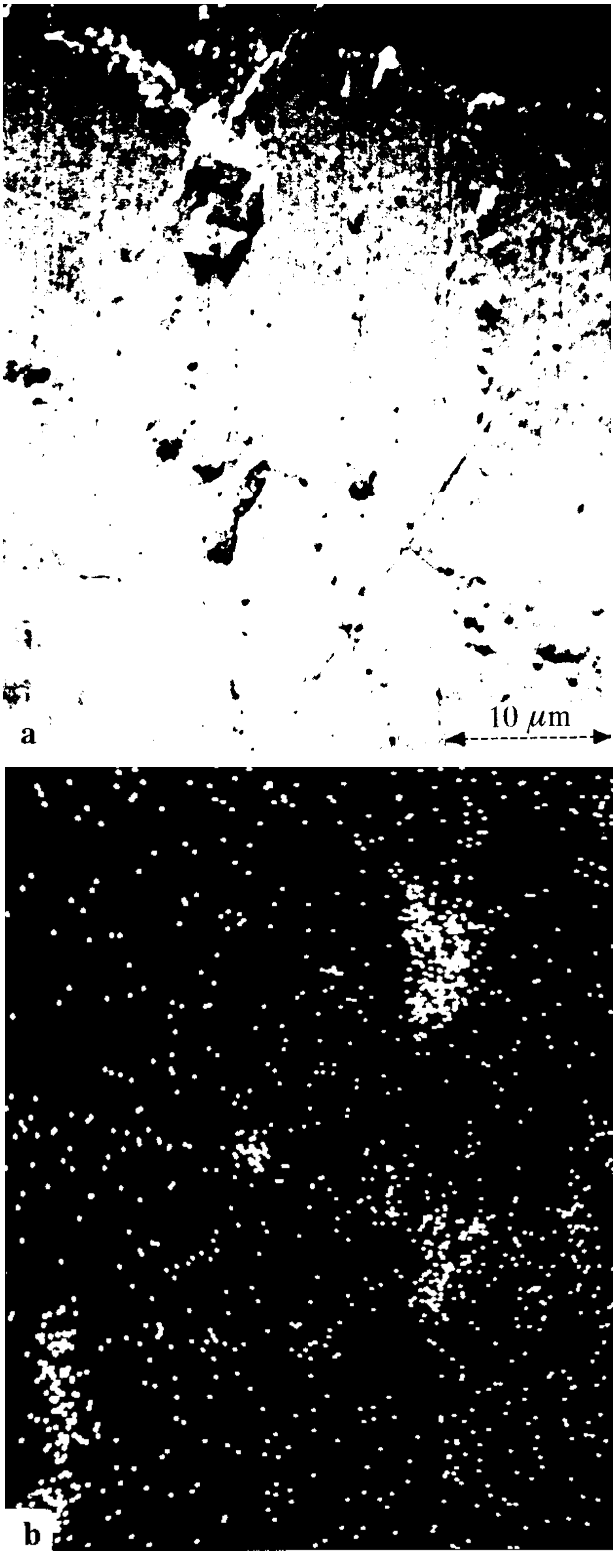


Figure 12. Iron transferred to chromium plating surface filling up the channel cracks-load 20 kg (X2000). (a) Viewed in the SEM and (b) EMPA for iron.

collected by a vacuum pump. Figure 12 shows that less particles were transferred and embedded in the chromium plated surface. Therefore, the abrasive wear process was diminished. The micrographs also show that the transferred iron has accumulated in the channel cracks on the chromium plating face. This is a good evidence that the transferred iron was trapped in the cracks in the chromium plating face. In other words, the a gray cast iron was worn by delamination process rather than adhesion.

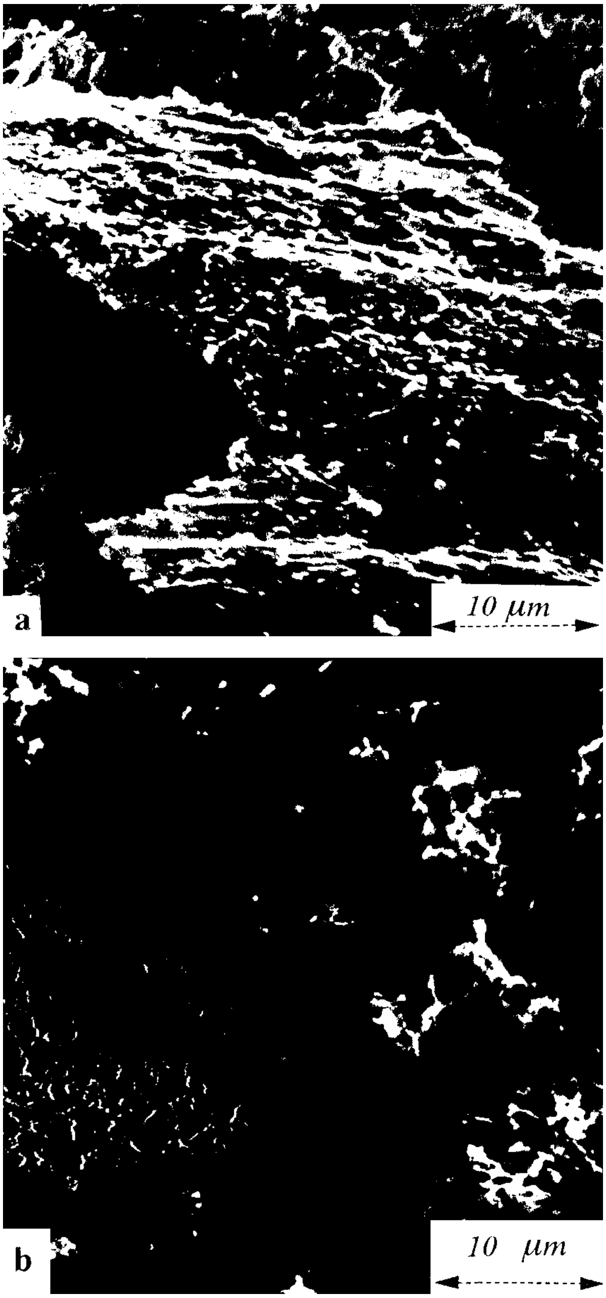


Figure 13. SEM examination of gray cast iron wear particles: (a) Elongated crack on a single plate like particle representing the cracks grown by the linking of holes as the metal undergoes further loading-load 20 kg (X2000) and (b) Holes on a single large wear particle, representing the cracks partly grown at different time-load 12 kg (X2000).

Gollogan et at [14] have studied the wear and friction behavior of Al bronze, P bronze and gray cast iron against hard chromium plating. They concluded that gray cast iron wears satisfactorily against channel type chromium plating and also exhibits a much lower coefficient of friction which is consistent with the lower wear rates for this material. Their conclusion are in agreement with the findings in the present investigation.

Examination of Wear Debris The metallic wear particles are in the form of thin sheets rather than spherical particles, especially those particles which are formed by the linking of cracks through shear deformation (Fig 13a). The surface of a single wear particle (Figure 13b) shows voids primarily by plastic flow of matrix and with time and load, the voids coalesce by growth or shearing of the metal.

Voids line up parallel to the sliding direction. Eventually the voids become elongated as the metal undergoes further deformation and join together forming a large crack (Figure 13b) parallel to the wear surface. This observation indicates a large number of cracks must be created before a loose particle can be formed. Therefore, in the absence of a large shear deformation along a given direction, wear particles may not form until additional cracks are nucleated. When these cracks finally shear to certain weak positions of the surface, long and thin wear sheets "delaminate".

Transverse Taper Microsections Wear track microsections in the transvers direction showed good correlation with both debris and SEM surface track observations.

All worn surfaces showed plastic deformation and the production of a wear particle by fracture along a graphite flake.

The sliding action of a chromium plating imposes a cyclic state of loading on the gray cast iron near the surface. Under this cyclic loading the matrix can undergo plastic deformation and fatigue along shear bands in the direction of sliding creating a heavily deformed layer (Figure 14a). A characteristic feature of the transition from mild to severe wear is in the appearance of this layer. It would appear that bulk plastic flow of the surface layers has taken place, facilitated by the greatly increased deformation of bulk material. It is fairly easy to see from the microsection in Figure 14a why the metallic debris which break away from the surface is plate like. The section through the wear surface shows the cracks associated with the graphite. This is a further illustration which shows that the plastic deformation of both the matrix and the graphite to produce the oriented structure.

Saka et al [15] suggests as deformation accumulates cracks will be nucleated when two conditions are simultaneously satisfied: (a) the tensile stress at the interface should be equal to the strength of particle-matrix interface and (b) the elastic energy released upon decohesion of the interface should be enough to overcome the surface energy of the void.

Figure 14a also shows that the cracks nearest to the surface are propagated in the transverse direction owing to the fatigue loading, because the direction and the magnitude of the normal stress are proportional to the radius respectively [20]. The micrograph clearly shows that significant crack growth is due to the linking up of separate cracks.

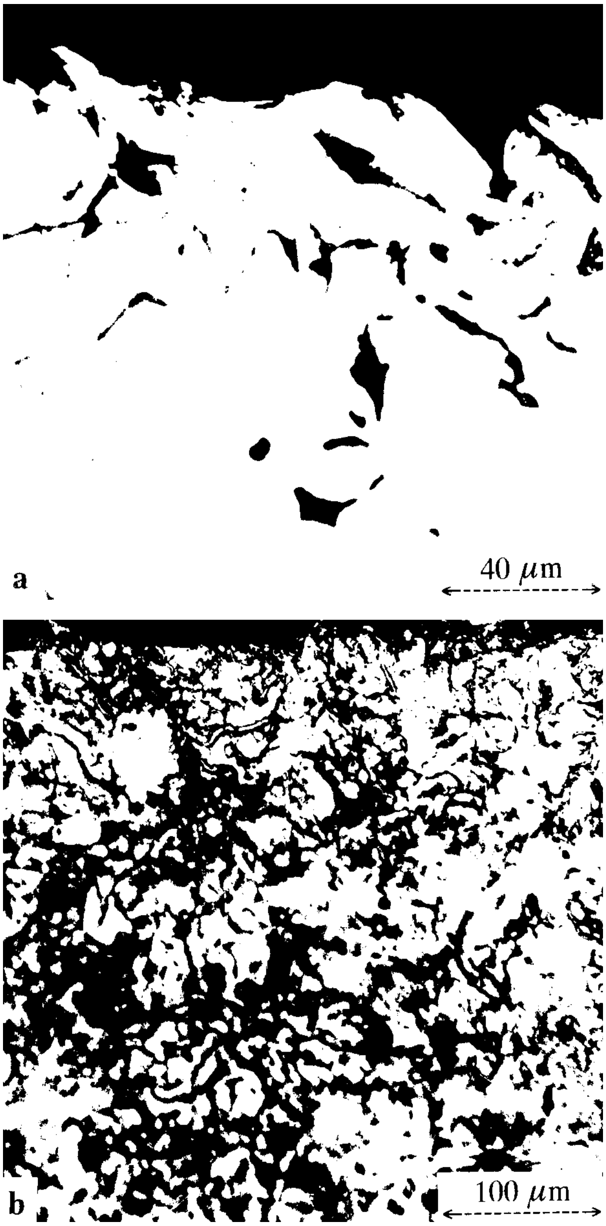


Figure 14. Transverse taper section of worn gray cast irons viewed in the optical microscope. (a) Plastic deformation-load 8 kg (X500) and (b) Etched by 2% Nital. No evidence of "white layer"-load 16 kg (X200).

Metallographic observations of the surface (Figure 4), of the subsurface (Figure 14), and of wear particles (Figure 13) clearly show that wear occurs by processes of subsurface

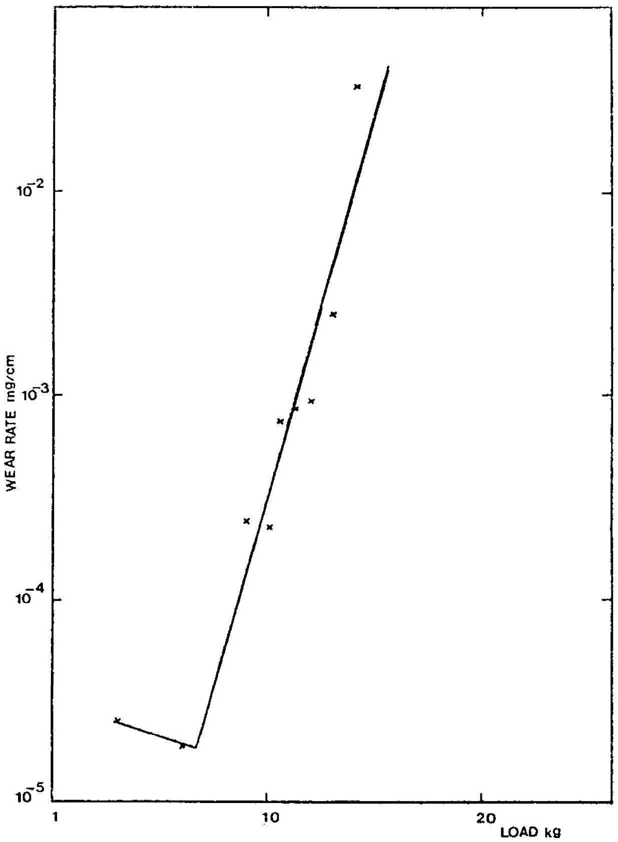


Figure 15. Gray cast iron wear as a function of load (Logarithmic scale).

deformation, crack nucleation and crack propagation.

These results are consistent with the reasoning of the delamination theory of wear that a layer of soft metal can continuously "delaminate" without much work hardening if the layer is so thin that the dislocations are not stable. It should be emphasised that the delamination theory of wear in its present state is applicable only for this case (low speed sliding) where the temperature rise at the contacting surface was so low that diffusion and transformation were not involved in the wear process. Figure 14b shows no sign of "white layer" formation on the gray cast iron after etching with 2% nital. This eliminates surface phase transformation as a contribution to scuffing wear under low speed conditions.

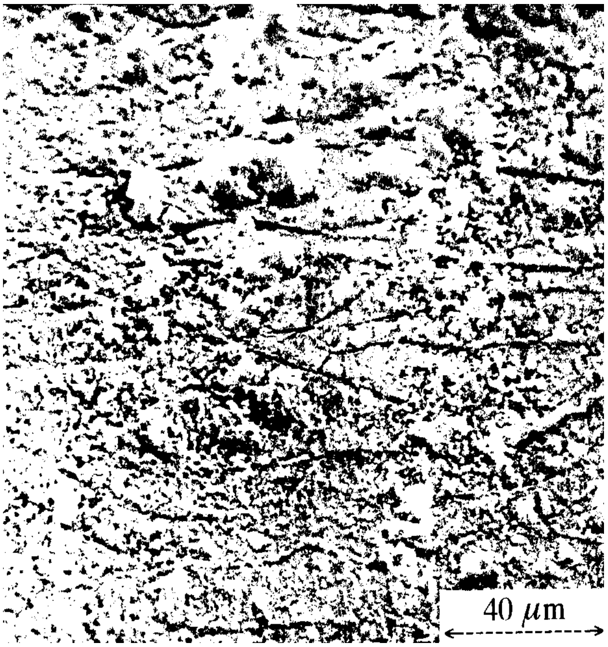


Figure 16. Worn chromium plating surface covered with patches of smooth iron oxide-load 22 kg (X500).

Wear Rate Figure 15 shows all of the wear rates are obtained for unlubricated wear tests??. There is a local peak in wear rate at 20 N. At the higher loads used in this investigation metallic particles were always detected in the debris (Figure 13). Local peak means that any change in the wear mechanism is not global and it does not indicate any general trend. In contrast to steel, gray cast iron surface examined in this research does not exhibit a mild to severe transition. From 40 N onwards, the wear rate is directly proportional to the load on semi-logarithmic scale.

(logarithmic scale). Figure 16 shows oxide forming on the surface. This is due to the rise in contact temperature that would be expected to occur during metallic wear. Oxide protects the surface and prevents welding.

At the loads used in this investigation metallic wear particles were always obtained.

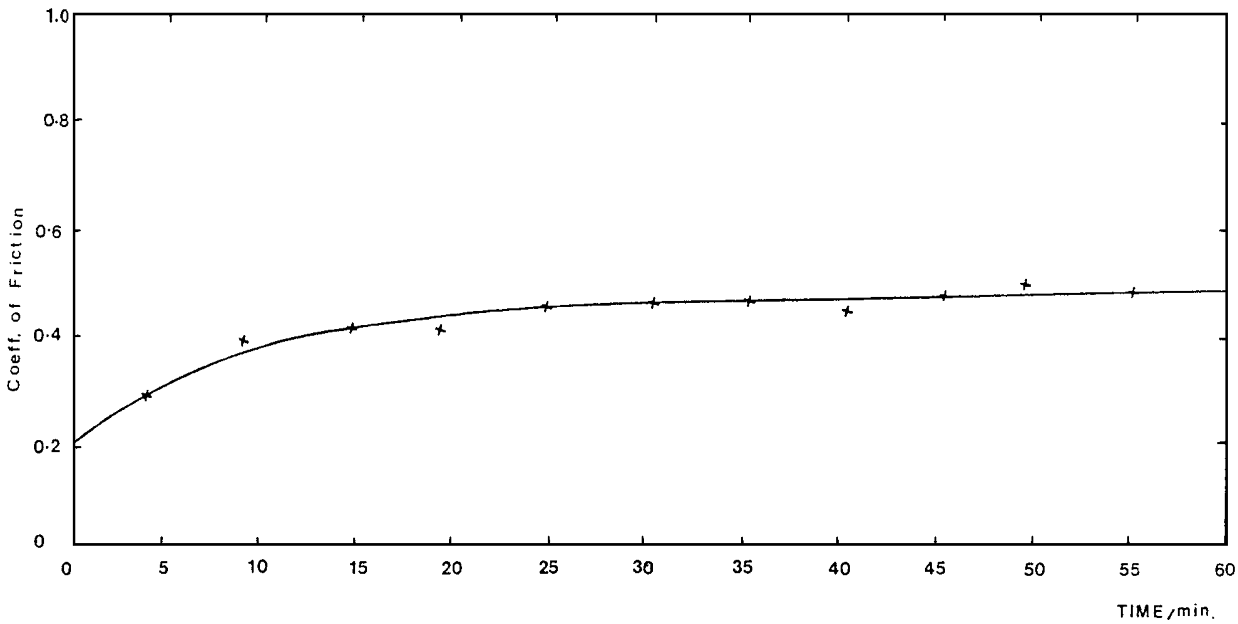


Figure 17. Friction coefficient as a function of time.

This indicates that the mild/severe transition load is less than 20 N. As oxides prevent welding and were present at all loads there was no evidence of adhesive wear. Gray cast iron wear occurred by a "delamination" process. Under these conditions gray cast iron did not exhibit a mild/severe transition. It has been shown by Beagley [17] that with steel in a normal environment a transition from mild to severe occurs as subsurface deformation of the whole contact becomes plastic. Therefore the situation described by Suh [1] applies to these asperity interactions.

Friction Coefficient The law of "dry" friction by Coulomb was used to calculate the fundamental principle of friction coefficient. The tangential force resisting relative sliding of the chromium plating on the gray cast iron was obtained by transducer readings on a strip chart.

The relatively smooth and chemically clean surfaces of the specimens were covered by a film of absorbed water molecules because the relatively high humidity of the surrounding environment (70-90%) which lowered the coefficient of friction considerably at the start of each test.

By plotting values of friction coefficient against time (Figure 17), it is seen that friction coefficient is increasing during the running-in period.

Figure 14 shows evidence of oxide forming on the surface of the cast iron, therefore, they wear as a consequence of subsurfaces deformation of the bulk of metal. As the surface of the gray cast iron flows sufficiently (Figures 3, 6 and 7), asperity contact occurred over large areas. The friction coefficient fluctuated less (steady state).

Referring to Figure 18, friction is highest over the load range up to 140N and then it drops from 0.69 and this coincides with a change at noise level. Therefore, a lower coefficient of friction was obtained under high pressure. Apart from the development of plastic flow and vibrating islands of separating sheet particle which lower the friction force, there is aggregation of loose wear debris onto the

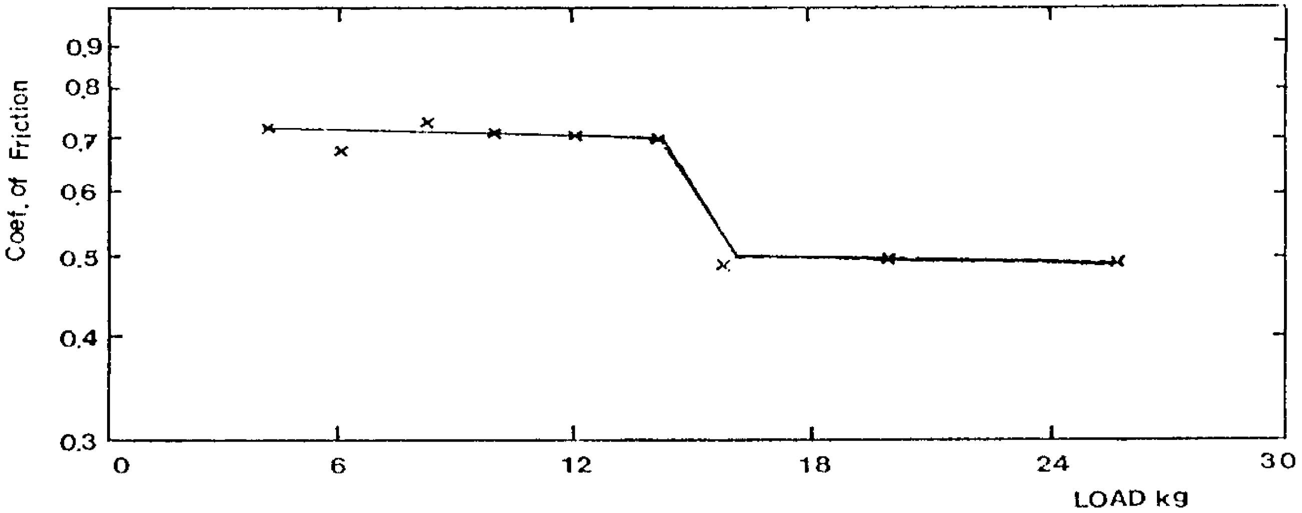


Figure 18. Friction coefficient as a function of load (Logarithmic scale).

surface on one or both of the gray cast iron and chromium plating surfaces. It is also possible that properties of these surface films determine the magnitude of the friction coefficient.

CONCLUSIONS

1. An oxide film was developed on the gray cast iron surface throughout the test. This prevented welding, therefore, adhesive wear did not occur.
2. Under the conditions used in this investigation gray cast iron surface did not exhibit a mild/severe transition.
3. Wear occurred by a process of delamination, the delamination wear theory is strictly applicable only for low speed sliding conditions where the temperature rise is low, so diffusion and phase transformation are not involved. No phase transformation was observed in these experiments.
4. Although the channel structure may be desirable from a lubrication point of view, the use of the SEM showed that the presence of channel cracks also caused areas of weakness from which failure was initiated to cause wear of the chromium plating.

REFERENCES

1. Suh, N. P., ***Wear***, 25, pp 111-124, (1973).
2. Suh, N. P., ***Wear***, 44, pp 1-16, (1977).
3. Suh, N. P. and Jahanmir, S., ***Wear***, 44, pp 17-38, (1977).
4. Suh, N. P. and Fleming, J. R., ***Wear***, 44, pp 39-56,(1977).
5. Eyre, T. S. and Williams, P., ***Wear***, 24, (1973).
6. Rigney, D. A., ***Wear***, 46, (1978).
7. Eyre, T. S. and Baxter, A., ***Met. Mater.***, pp 435-439, (1972).
8. Rogers, M. D., ***Tribology***, 2, pp 123-127, (1969).
9. Rogers, M. D., ***Wear***, 50, pp 105-116, (1970).
10. Prac., M.J., Inst. Mech. Eng.,London, 185, pp 21-32 (1971).
11. Bountorabi, S. M. A., Salehi, M. and Kondic, V., ***Wear***, 165, pp. 19, (1993).
12. Salehi, M., Ph. D. Thesis Universtiy of Birmingham, 1990.
13. Mahdavi, H., M.Sc. Dissertation, Iran University of Science and Technology, 1995.
14. Oberle, A. B., ***A. F. A. Trans.***, 56, pp 166-193, (1948).
15. Hegh, C., Brooklyn Chemical Publication Co., pp 145-168, (1949).
16. Archard, J. F. and Hirst, W., Pro. Roy-Soc., London, pp 236-297, (1965).
17. Eyre, T. S. and Wilson, F., ***Wear***, 14, pp 107-117, (1969).
18. Gologan, V. and Eyre, T. S., ***Wear***, 28, pp 49-57, (1974).
19. Saka, N., Pamies-Teixeira, J.J. and Suh, N. P., ***Wear***, 44, pp 77-86, (1977).
20. Nagato, T., Pamies-Teixeira, J. J. and Suh, N. P., ***Wear***, 44, pp 101-108, (1977).
21. Beagley, T. M., ***Wear***, 36, P 317, (1975).