The relevance of wear-mechanism maps to mild-oxidational wear

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Abstract

The presence of oxygen in the environment in which a steel sliding system operates will promote a mild form of wear with wear debris consisting mainly of iron oxides. Of the oxidation-dominated mechanisms, mild-oxidational wear (the prefix describes the extent of oxidation and not the wear rate) has been most extensively investigated. In this paper, examples will be used to show that the wear-mechanism map for the unlubricated sliding of steels can adequately predict the occurrence of mild-oxidational wear and the trend of wear rates as well as describe the resultant features on the worn surfaces. It is also shown that this map is relevant to delamination wear and to test geometries other than the pin-on-disk configuration. It is suggested that the more-recently constructed wear maps for aluminium and magnesium alloys could similarly be used to predict the wear characteristics of these alloys during sliding.

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1. Introduction

In almost all sliding situations, some forms of interaction will occur between the environment and the surfaces exposed by the sliding actions. As the environment is normally the atmosphere (or some oxygen-containing fluid), it is therefore possible to obtain a mild form of corrosive wear known as oxidational wear.

While it was perhaps Eden et al. [1] who first observed the presence of oxide at steel surfaces in relative motion, it was Fink [2] who first identified oxidation as another essential component in the wear of metals. The advance of X-ray diffraction techniques allowed these oxidised wear debris from sliding steel surfaces to be analysed and the associated wear processes investigated (see for example the work of Kehl and Siebel [3]; Archard [4]; Nakajima and Mizutani [5]; Farrel and Eyre [6]; Quinn et al. [7]; Uetz and Sommer [8]). These findings have provided key experimental evidence of the role of oxidation during sliding. Although these observations were made in steel sliding systems, oxidation as a wear mechanism has also been observed to take place in aluminium alloys [9–13] and in magnesium alloys [14].

In this paper, it will be shown that the wear-mechanism map for steels [15] can be used to describe the outcome and predict the occurrence of oxidation-dominated wear, especially mild-oxidational wear, in steel sliding systems. In what follows, a brief description of the development of wear-mechanism maps will first be presented. This will be followed by a summary of how oxide layers are formed at the sliding interface and how this affects the wear of sliding steel components. Examples will be used to demonstrate how mild-oxidational wear and its relationship to sliding conditions could be readily understood using the wear-mechanism map for steels.

2. Wear-mechanism maps

Presenting wear data in a graphical form is not a new idea. One of the earliest presentations is the wear-rate surface constructed by Okoshi and Sakai for the sliding of steel components [16]. The next significant development is the wear-regime map for soft steels proposed by Childs [17], although there were a number of two- and three-dimensional representations of wear data (see for
example, Welsh [18] and Egawa [19]). The one factor that sets Childs’ map apart is his use of a wide range of sliding conditions, which allows the users to have a more global view of the wear characteristics of soft steels. Later on, Tabor [20] remarked that wear might be the result of interacting mechanisms with no single process dominating. He suggested that wear-mechanism maps—summarising data and models for wear, showing how the mechanisms interface, and allowing the dominant mechanisms for any given set of conditions to be identified—could be developed to explore this much broader pattern of wear behaviour.

Following this line of thought, the wear-mechanism map for steels in un lubricated sliding was constructed based on the experimental data (primarily from pin-on-disk tests) and theoretical models culled from a wide range of sources [15]. This map describes the un lubricated pin-on-disk wear behaviour of steels over a wide range of sliding conditions. It predicts the field of dominance of one wear mechanism and when its contribution becomes less important. Within each field, contours of predicted normalised wear-rates are superimposed. Expanding on the original map, a companion wear-mode map and a wear-transition map were proposed to provide additional information which the first map could not conveniently present [21]. The latter two maps summarise the sliding conditions associated with mild wear and severe wear and where transitions between them occur for steels. The wear-transition map also shows how the various wear transitions reported in the literature could be related and harmonised with one another.

Wear maps for other materials (such as polymers and ceramics) in sliding contact, or in different tribological interactions (such as erosion and fretting), or in different environments (such as in the presence of lubrication) have also been prepared. The same mapping methodology has since been extended to investigate the wear of both uncoated cutting tools and differently-coated tool inserts during turning operations. The concept of safety zone (where the tool experienced the lowest rate of wear) was proposed and the effects of machining conditions on the wear of tools were elucidated [22]. It has been established more recently that wear maps could be used to maximise the cost-effectiveness of the thin layers of coatings on tool inserts through the appropriate selection of machining conditions [23]. Readers interested in the developments in wear-mechanism maps may wish to refer to a recent review [24].

3. Oxidation-dominated wear in steels

The manner in which the oxide layers on steel sliding surfaces (and the properties of the steel surfaces supporting the oxide layers) influence the wearing process had earlier been described [21]. This is briefly summarised as follows.

When the sliding velocity is much smaller than 1 m/s, the low sliding speeds do not generate a high enough flash temperature to make oxidation the dominant wear mechanism. Under such a condition, the very thin but tenacious oxide film effectively separates the asperities as long as the contact pressure at the asperities remains low. Fine oxide particles are produced and a condition of mild wear occurs [25,26]. These fine particles could also come from small metallic fragments which may occasionally be removed (most probably through a delamination mechanism [27]) and oxidised. The damaged surface quickly re-oxidises, preventing further direct metallic contact, maintaining the mild wear condition.

When the sliding speed exceeds about 1 m/s, frictional heating becomes considerable, resulting in a much higher rate of oxidation at the sliding surfaces. Oxidation therefore becomes an important mechanism through which wear particles are generated—the dominant mechanism of wear. However, the extent of oxidation could lead to major differences in wear characteristics. Two general groups of wear behaviour could be observed in steel sliding systems. These are mild-oxidational wear and severe-oxidational wear [15]. The pre-fixes of ‘mild’ and ‘severe’ refer to the extent of oxidation at the sliding surfaces (primarily as a result of the flash temperatures generated there), these are not a reflection of the rates of wear. In fact, the wear rates when severe-oxidational wear dominates are usually low.

3.1. Mild-oxidational wear

This takes place typically when the sliding speed exceeds 1 m/s (or about 0.5 m/s when the load is higher). Frictional heating at the contacting asperities becomes considerable, leading to a higher rate of oxidation, giving rise to a thick and brittle layer of oxide. These oxide layers usually appear as patches (or islands) on the sliding surfaces [28]. More oxidation replenishes the losses due to the breakaway of oxide fragments as wear debris. The effective separation of the sliding surfaces by the oxide layer results in mild wear.

When the load is high enough to penetrate the thicker but brittle oxide layers—generated by increased frictional heating—on a soft substrate (which is further softened by frictional heating), direct metal-to-metal contacts will result. Within a small range of sliding condition, severe wear occurs and this leaves behind much damages on the sliding surfaces.

With further increases in load and speed, a hard surface layer (most likely martensite) is formed on the steel surfaces because of the higher flash temperatures, followed by rapid quenching as the heat is conducted quickly into the underlying bulk material. At the same time, the higher flash temperatures also cause the local oxidation rate to increase. A thicker and more uniformly
distributed layer of oxide, now supported by the hardened substrate, is formed and is able to prevent further direct metallic contacts, despite the higher contact pressure at the asperities. Mild wear results with a significant reduction in wear rates.

3.2. Severe-oxidational wear

When the speed is increased beyond a certain threshold (typically 10 m/s), the amount of oxide formed on the steel surfaces has been found to increase from the isolated patches on the sliding surfaces to a plastically deformed continuous film of oxide covering the entire sliding surface [29–31]. It was concluded that the oxide formed under such conditions is thicker (than those formed under the condition of mild-oxidational wear), more continuous, and almost certainly hotter and more plastic (compared to the more brittle nature of the ‘colder’ oxide) [15]. The characteristics of the wear process are different and the rates of wear are generally lower. The mechanism is one of melting of the thick oxide formed under the much hotter environment resulting from the more severe sliding condition [15].

3.3. Development of the understanding of mild-oxidational wear

Much of the development work on the understanding of mild-oxidational wear (the main focus of this paper) originated from the work of Quinn [32]. His oxidational wear mechanism states that frictional heating causes an equal amount of oxidation to occur at each contact until a critical oxide thickness is reached, beyond which the oxide film becomes mechanically unstable and breaks away from the substrate to form wear debris. The film cracks up probably due to dissimilarities in their thermal expansion coefficients. Wear equations were developed by Quinn to describe and predict the oxidational wear rate. These were subsequently refined and improved upon by Quinn and his co-workers (see for example, Quinn [33,34]; Quinn et al. [35,36]). More recently, extensive computation and modelling work on oxidational wear was undertaken by Quinn [37–40]. While it is noted that external heating can also lead to similar extent of oxidation at the sliding surface when the sliding speed is lower, such as during slow reciprocating sliding when frictional heating is insignificant [41], the attention of this paper will be on mild-oxidational wear that occurs in the absence of external heating.

In the following sections, examples will be given to show how the wear-mechanism map for steels can be used to predict the occurrence of mild-oxidational wear in steel sliding components, and to describe the wear mode and wear features on steel sliding surfaces.

4. The relevance of the wear-mechanism maps to mild-oxidational wear

4.1. The wear map for steels can predict the occurrence of mild-oxidational wear

A series of unlubricated crossed-cylinders wear tests using AISI 1045 steels was carried out both in air and in vacuum by Venkatesan and Rigney [42]. When sliding took place in vacuum, they found wear debris which are irregular plates and flakes—similar to those found when the tests were done in air; no cutting chips were observed (more later). This is to be expected and this wear behaviour can be understood using the wear map for steels.

Making reference to Fig. 1 where the sliding conditions of their tests are re-plotted onto the skeletal wear-mechanism map for steels [15]. (Much of the details of the map has been removed to allow the points indicating the sliding conditions to be clearly shown.) It is clear that all the initial and final sliding conditions (the contact geometry of the test specimens changed during the tests) fall outside the field of dominance of mild-oxidational wear. In fact, the sliding conditions are all within the field where delamination wear dominates. In the presence of oxygen, a thin and tenacious oxide film would be formed on the sliding surfaces. Depending on the contact
pressure at the asperities, this film might be able to prevent direct metallic contact (giving rise to mild delamination wear and producing fine flake-like wear debris, which could easily be oxidised) or it might not, giving rise to severe delamination wear—the production of larger flake-like wear debris. When tested in vacuum, the lack of oxygen would prevent the formation of even this thin oxide film. Even if the final sliding conditions are moved (by reducing the contact pressure) towards the region of mild delamination wear, there is very little or no oxide film to prevent direct metallic contact—severe delamination wear would have persisted throughout the tests in vacuum. Their vacuum wear tests therefore produced larger flake-like wear debris compared to similarly conducted tests in air—mild wear (oxidation assisted) was never allowed to occur in the vacuum tests. This is consistent with the wear map.

It would be interesting to see if significant changes to the wear mechanism could be observed when the sliding condition is altered—that is, to move out of the field of dominance of delamination wear and enter into another field. An attempt was therefore made to conduct wear tests in vacuum at a higher sliding speed, so that the sliding condition now falls within the field of mild-oxidational wear. The wear tests were carried out using a vacuum wear rig, capable of running pin-on-disk tests at a vacuum level of about \(3 \times 10^{-3}\) mbar. Pure iron pins were used to slide against mild-steel disk at a speed of 1 m/s at a load of 10 N. Further details of the test rig and experimental procedures are described elsewhere [43].

Results obtained from the present series of vacuum wear tests were significantly different from those reported by Venkatesan and Rigney [42]. Instead of flake-like wear debris, cutting-chip-like features were observed to protrude from the pin specimen at the sliding interface. Fig. 2 shows a close-up view of such a cutting-chip-like feature. This is indicative of the greater extent of plastic deformation experienced at the sliding interface where direct metallic contact occurred at a higher sliding speed. More interestingly, when tests were carried out in the presence of ambient air using the same test rig at exactly the same sliding condition, the wear mechanism reverted to one where fine powdery wear debris was observed (indicative of the operation of mild-oxidational wear) with no sign of cutting-chip-like feature to be found on the pin specimen. This complete change should be expected as sliding took place where mild-oxidational wear would have been the dominant mechanism had there been a continuous supply of oxygen to the sliding interface. When oxygen was re-introduced, mild-oxidational wear was again allowed to be the dominant mechanism of wear, as suggested by the wear map. It is also interesting to note that the map was able to correlate the results of tests carried out using two different test geometries (crossed-cylinders and pin-on-disk) as long as the appropriate normalised pressure values were used to locate the sliding condition on the wear map.

\[4.2.\text{The wear maps for steels can interpret observed wear results}
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A series of unlubricated washer-on-disk, steel-on-steel wear tests was carried out recently by Lin et al. [44]. Using AISI 1045 steels as specimen material, they observed the formation of oxide films on the sliding surfaces. They have attributed this to the operation of oxidational wear. It would be interesting to see how the wear-mechanism map for steels could be used to explain and interpret their results.

Translating their loading and contact conditions into the appropriate normalised pressure values, the range of sliding conditions used is given by the box defined by broken lines superimposed onto the wear-mechanism map for steels [15] as shown in Fig. 3. It is immediately clear that the series of tests was carried out within the field of mild-oxidational wear, confirming their observation that oxidational wear had occurred. This again supports the proposition that the wear-mechanism map for steels is able to predict the operation of mild-oxidational wear, as long as the sliding conditions (correctly converted into the normalised parameters) fall within the field of dominance of mild-oxidational wear.

Further, the wear map is also able to explain the various changes in wear characteristics. Take for example, Lin et al., reported that the wear rates underwent a transition to lower values with increasing load, and this transition took place at a lower load when the sliding speed was increased. Turning back to Fig. 3, it is clear that this harmonises with the general shape and orientation of the transition region (shaded area) between mild wear
and severe wear within the field of mild-oxidational wear.

At the sliding condition represented by the lower left corner of the box (point A)—in the wear transition region—Lin et al., observed both a smooth and heavily oxidised surface with the metallic surface clearly visible. This is a typical feature of the mild-oxidational wear: patches of oxidised plateaux or islands on the metallic surfaces. As we move towards point B (with increasing load), the sliding condition is now clearly in the severe wear region. Here, Lin et al. reported that the surface became sparsely covered with oxides and the worn surface appeared very rough and metallic. In this situation, the brittle oxide layers were broken up under the increased load, allowing direct metallic contact to take place, resulting in severe wear. At point C, Lin et al. reported that the surface features were very similar to those see at point A. This is not surprising as both points A and C are within or near to the wear transition region.

More interestingly is point D where the highest load and speed were used. This is clearly in the mild wear region. Lin et al. reported that the wear rates were significantly lower and the worn surfaces were found to have a thick and uniformly distributed oxide layer. Under this sliding condition, the higher flash temperatures generated not only contributed to the greater extent of oxidation at the sliding surface (hence the thicker oxide), it also led to the formation of a hard (possibly martensitic) surface layer. This hard layer in turn supported the thick oxide layers well, allowing them to more effectively protect the sliding surfaces, resulting in a mild wear condition with accompanying low wear rates.

The wear map again demonstrates its ability to predict such a significant change in wear characteristics over a relatively small change in sliding condition. It should also be noted that the reduction in wear rate reported (at point D) is not as large as those obtained under the classical severe wear to mild wear transition reported by Welsh [18] for medium-carbon steels. This is to be expected as the span of load and speed used by Lin et al. was much narrower than that used by Welsh. A different response is to be expected.

Turning back to Fig. 3, the condition of highest load and speed (at point D) is very near to the field boundary between mild-oxidational wear and severe-oxidational wear. When the latter operates, the hotter and more plastic oxide film tends to cover the entire sliding surface because of the higher flash temperatures generated. To have a thick and uniformly distributed oxide layer on the sliding surface (at point D) is to be expected.

4.3. Wear maps can also predict and explain oxidation-dominated wear in other metallic sliding systems

In the wear-mechanism map for aluminium alloys proposed by Liu et al. [12], oxidation was identified as a dominant wear mechanism at low load and speed. In the more-recent map prepared by Zhang and Alpas [13] for the same alloys, oxidation was not identified as a dominant mechanism, although the authors acknowledged that surface oxidation took place during sliding in the group of aluminium alloys investigated. The aluminium oxide formed nevertheless contributed to the mild wear observed as one of the two mild-wear mechanisms suggested is the formation and delamination of mechanically mixed surface layers consisting of fine aluminium, iron, and aluminium oxide particles [13]. Interestingly, this mild-wear mechanism (as identified by Zhang and Alpas) dominates within approximately the same range of sliding condition as the oxidation wear suggested earlier by Liu et al. [12]. It is therefore reasonable to conclude that there is general agreement that within this range of sliding conditions, oxidation plays an important role in the wear of aluminium alloys.

Oxidation was also found to be a dominant wear mechanism even when silicon carbide whiskers were
added to the aluminium alloy matrix. Two regions, namely severe oxidation and mild oxidation, were included in the wear-mechanism map for Al(6061)–SiCw composites proposed by Wang et al. [45]. For this group of composites, oxidation dominated the wear process at sliding speeds close to 1 m/s. This is also near to where oxidation is important during the sliding wear of aluminium alloys, suggesting that it is the matrix material that is more important to the triggering of the oxidation mechanism than the reinforcement phase. More recently, Chen and Alpas [14] proposed a wear transition map for magnesium alloys where both oxidation and delamination are described as the dominant mechanisms when mild wear occurs. The availability of wear maps for aluminium and magnesium alloys should enable a better understanding of oxidation-dominated wear and a more accurate prediction of its occurrence in these metallic sliding systems. It is further suggested that these maps could be used to predict the broader wear characteristics of these alloys during sliding.

5. Conclusions

The range of sliding conditions within which mild-oxidational wear occurs in steel sliding components can be adequately predicted through the wear-mechanism map for steels. The trends of wear rate and the associated transitions between mild wear and severe wear could also be estimated from the map. The features on the resultant worn surfaces could be predicted with confidence. This predictive ability has been shown to go beyond the field where mild-oxidational wear dominates.

Although the wear-mechanism map for steels was constructed primarily based on data from the pin-on-disk configuration, it can be applied to other test geometries after the sliding conditions have been appropriately converted to their pin-on-disk equivalent. This expands the applicability of the map.

The wear-mapping methodology has been extended to aluminium alloys and their composites, and to magnesium alloys. It is suggested that not only are these maps able to describe adequately the behaviour of these alloys when oxidation is the dominant mechanism contributing to most of the wear, they could also be used to predict the broader wear characteristics of these alloys during sliding.

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References