Modelling sliding wear: From dry to wet environments

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Abstract

Corrosive species in various forms exist widely in the environment and can significantly affect wear behaviour of materials, usually accelerating wear. Under conditions where the environments are seemingly non-deleterious in terms of corrosivity, some species from the environment can still affect the tribological behaviour of materials. It is thus extremely important to recognise the roles of reactive species in affecting the tribological processes and to understand the processes of tribo-corrosion interactions. In this paper, the mechanisms of wear debris generation and the roles of reactive species in the generation of wear debris during sliding wear in gaseous or aqueous environments are discussed. The effect of environment on the development of wear-protective layers is described. Based on the proposed mechanisms, mathematical models for sliding wear in both dry and aqueous environments are outlined, and the validity of the models is assessed against experimental data in sliding conditions.
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Keywords: Tribo-corrosion; Corrosive wear; Dry sliding wear; Wear debris; Modelling

1. Introduction

Damage to materials and mechanical components due to wear has a significant impact on the economics of engineering systems both directly and indirectly in terms of material loss and associated equipment downtime for repair and replacement of worn components. In the last half-century or so, great efforts have been made in understanding the mechanisms of wear to improve the wear performance of materials. Sliding wear involves the formation of wear debris particles and their subsequent removal from the rubbing interface. Most of the existing wear theories, such as the adhesion wear theory [1,2], the delamination theory [3], the low cycle fatigue theory [4,5] and the oxidational wear theory [6,7], are mainly concerned about the generation of wear debris, ignoring the commonly observed phenomenon that wear debris particles can get involved in the wear process and significantly affect the wear of materials [8–15]. Once formed, the wear debris particle is assumed to be removed from the rubbing system to cause material loss. Meanwhile, most of the existing theories do not directly incorporate the effect of environment on the wear process, except for the oxidational wear theory. In the

latter case, the wear loss is exclusively attributed to the cyclic formation and removal of oxide on the rubbing surfaces and is mainly applicable to the mild wear conditions [6,7].

In recent years, increasing interest has been noticed in the literature in the investigation of tribo-corrosion [16–22], which can be defined as the chemical–electrochemical–mechanical process leading to a degradation of materials in sliding or rolling contacts immersed in a corrosive environment. Such research has significant practical importance because in many engineering systems, materials forming tribological contacts are exposed to a corrosive environment in various forms and therefore are subjected to both mechanical and chemical–electrochemical solicitations. Typical examples are orthopaedic implants, chemical pumps and food processing or mining equipment. Under some other situations, the occurrence of tribo-corrosion is not always recognised in field practice, such as the accelerated corrosion of steel conveyors exposed to ambient air of high relative humidity and increased saw wear when cutting wet lumbers. Under the corrosion–wear conditions, material loss is usually accelerated as a result of synergistic interactions between the mechanical action of wear/rubbing and the corrosion reactions occurring on the wear surfaces [23–32]. Currently, the understanding on wear of metals in corrosive environments is very limited. Modelling of such complicated processes is even more challenging. Some modelling of tribo-corrosion has been carried out [33–36]; how-

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ever, it is mainly concerned with the corrosion and wear-induced corrosion aspects of the process.

In order to improve the performance of materials in engineering systems, there is a constant demand to better understand the mechanisms of wear under various conditions. Modelling is one of the effective tools in helping this understanding. In this paper, the concept of low cycle fatigue as a basic mechanism for the generation of wear debris particles is presented. Based on such a concept, the roles of reactive species in the generation of wear debris during sliding wear are discussed and mathematical models for sliding wear in both gaseous and aqueous environments are outlined. The validity of the models is assessed against experimental data.

2. Low cycle fatigue as a basic mechanism for the generation of wear debris

In sliding wear, the real area of contact that carries the applied load is usually a very small fraction (<10%) of the apparent area of contact. As a result, high contact pressures exist at the real area of contact. For metals, the higher asperities will almost always deform plastically even under very low apparent loading conditions. Repeated contact at these real areas leads to the generation of wear debris particles. Essentially, this process of wear debris generation fits the definition of low cycle fatigue which is a material failure mode that incorporates a cyclic plastic strain component. Wear theories based on the concept of low cycle fatigue have been presented by several groups of researchers [5,37–40]. Arnell et al. [41] set out a qualitative description of sliding wear by invoking fatigue as the dominant wear mechanism. Challen and Oxley [5] calculated the magnitude of plastic strain increments during sliding of metals and evaluated wear rates on the basis of low cycle fatigue wear theory. Experimental results and the calculations agreed well [38]. Tangena [39] also presented a low cycle fatigue wear model and experimentally verified that the low cycle fatigue wear theory produces more reasonable predictions on wear rate of metals than the classical Archard's wear equation based on the adhesion theory. Broadly speaking, the other existing theories on the generation of wear debris can also be covered by such a low cycle fatigue wear concept. For example, in the delamination theory of wear [3,42], microcracks/voids are assumed to initiate and to propagate underneath the surface due to plastic deformation to generate wear debris. In the light of low cycle fatigue failure, a wear debris particle is generated when the fatigue life is reached under a given plastic strain amplitude. The classical adhesion wear theory can essentially be regarded an extreme situation of the low cycle fatigue model where the material at the cold weld junction reaches its fatigue life in one cycle of contact (breaks at the weak point upon each contact).

Despite the apparent agreement between the wear theories based on low cycle fatigue and experimental observations, so far, no direct measurement is available to assess the material fatigue properties under sliding wear conditions. By re-analysing the data obtained by Hokkirigawa and Kato [43] from single particle scratching test, the nature of low cycle fatigue in the process of generating wear debris can be more clearly illustrated.
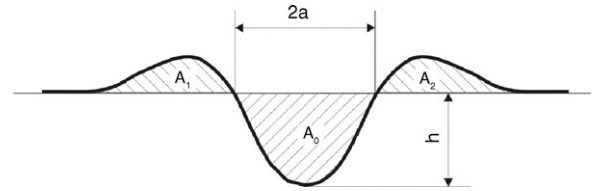

Fig. 1. Schematic diagram showing the cross-section geometry of the groove formed in the scratching test using a hard particle.

Using a single particle scratching test rig fitted in an SEM, Kato and co-workers [43–45] systematically studied material removal and the transitions in mechanisms of the material removal as a function of particle penetration into the specimen surface. In the rig, a round tip made of hard material was used to scratch the specimen surface to produce a groove, which has a cross-section geometry as shown in Fig. 1. In the groove, the volume of material being displaced is proportional to the area, A_0. A fraction of this displaced material, β, is removed/detached from the specimen surface to form a wear debris particle while the remaining material corresponding to the areas, A_1 and A_2, is displaced to the sides of the groove to form ridges. The material removal fraction, β, is calculated by

$$\beta = \frac{A_0 - A_1 - A_2}{A_0} \tag{1}$$

The experimental results for SUJ 2 bearing steel (containing 0.95% C and 1.3% Cr) treated to different hardness values (250–750 HV) from ref. [43] are reproduced in Fig. 2. The heat-treatment conditions included water quenching from 860 °C with or without further tempering at temperatures from 200 to 750 °C. The fraction of material removed, β, is determined by the "degree of penetration", D_p, which is defined as the depth of penetration, h, divided by the half-width, a, of the groove (Fig. 1),

$$D_p = \frac{h}{a} \tag{2}$$

Direct SEM observations [45] showed that the degree of penetration, D_p, also controls the modes of the material removal. Below some critical penetration value, D_{p1}, the dominant wear
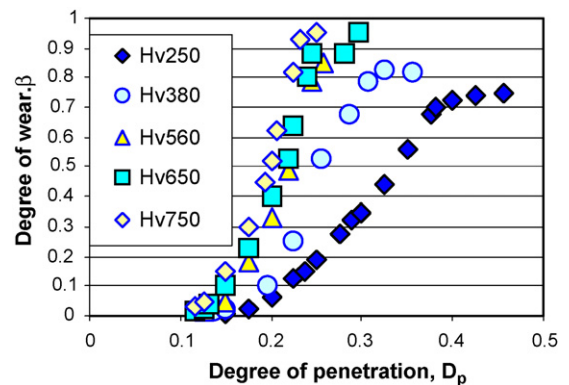

Fig. 2. The variation of the fraction of material removed, β, as a function of the degree of penetration, D_p, observed with heat-treated steels of various hardnesses in a single particle scratching test [43].