Mild Wear Study on Running-in of Rolling-Sliding Contacts

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Abstract

Running-in, steady state wear and wear-out are three typical wear stages in a common wear system of mechanical components. In the running-in, there are two dominant mechanisms: plastic deformation in normal direction and mild wear. This paper reviews the proposed mild wear and the opportunity of predicting topographical changes of the surface on the rolling-sliding contacts due to mild wear. Elastic-plastic contact model has been used to predict the changes of surface topography on running-in wear. However, most of them are in a macroscopic / global approach. Based on this review, the topographical changes of the surface due to mild wear could be predicted by applying the elastic-plastic moving contact on the running-in of rolling-sliding contacts.

Keywords: Mild wear, Running-in, Rolling-sliding, Elastic-plastic contact.

Introduction

The study of surface interaction was started after the identification of friction by Amontons (1699), Coulomb (1785) and Morin (1833). They hypothesized that friction is resulted due to the interlocking of mechanical protuberances or asperities on the surface of contacting materials. Wear is the next phenomenon studied in surface interaction science however less than friction (ASM, 1992). Wear consist of the removal of material from solid surfaces as a result of the mechanical action (Rabinowicz, 1995). The progressive damage and material loss due to wear has economic consequences (Jost, 1966) which involves the cost of component replacement, machine down time and production lost.

Type of Wear

There are four basic mechanism of wear, namely adhesive wear, abrasive wear, corrosive wear and surface fatigue wear (Rabinowicz, 1995). When two smooth bodies are sliding over each other and fragments are pulled off of one surface and adhere to another is called adhesive wear. Abrasive wear takes place when a rough hard surface or a soft surface containing hard particles, slide over a softer surface and plough a series of grooves in it. On the surface of a material a thin layer is created in a corrosive environment. When these layers are removed due to mechanical interaction wear is referred to the corrosive wear. Fatigue wear occurs when repeated sliding or rolling over a surface cause the formation of surface or subsurface cracks. A combination of the basic wear mechanisms may result in another characteristic damage mode such as delamination (Suh, 1973), oxidation wear (Quinn, 1983), fretting, pitting, scuffing, galling, ploughing, etc. (Williams, 1999).

Wear stages

There are three types of wear-time behavior (Lin and Cheng, 1989). Majority of the wear time curves observed were of type I, in which the wear rate is initially high and then decrease to a lower value. Wear of type II is more usually observed under dry conditions and the wear rate is constant in time. Wear rate of type III increasing continuously with time which the example of this type is not numerous. Lin and Cheng (1989) and Jamari (2006a) developed the wear-time curve which consists of three wear regimes: running-in or break-in or wear-in, the steady state and accelerated wear or wear-out as is shown in Fig. 1. Each category has a different wear behavior. During running-in, the wear-time curve belongs to type I. The surface of the material surface gets adjusted to the contact condition and the operating environment. This regime is more beneficial instead of detrimental. Wear type II usually takes place in the steady state wear process. The wear-time function is linear. In the wear-out regime, the wear rate increases rapidly because of the fatigue wear that occur in the upper layers of the loaded surface. Breakdown of lubrication due to temperature increase, lubricant contaminant or environment factors are other causes of the increase of wear and wear rate in this regime (Lin and Cheng, 1989).

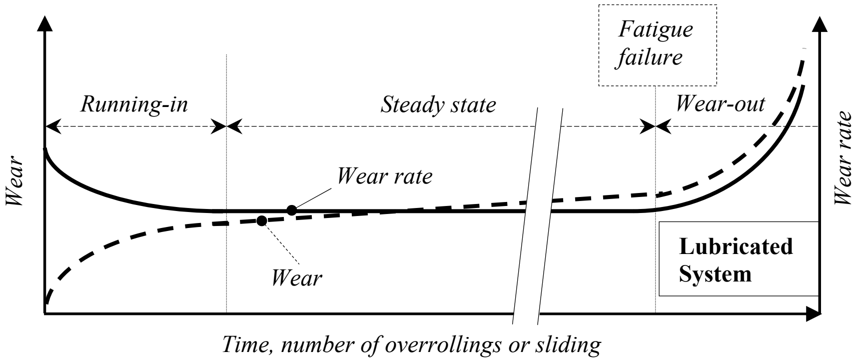

Figure 1: Wear and wear rate behavior as a function of time, number of overrollings or sliding distance, after Jamari (2006).

Mild and severe wear criteria

There are several criteria which contribute to distinguish mild and severe wear, namely coefficient of friction (Hsu *et al*, 1997) and specific wear rate (Williams, 1999; Adachi, 1997; Metselaar, 2001; Pasaribu, 2005). Hsu *et al.* (1997) used the coefficient of friction to determine mild or severe wear and classified wear of ductile materials in three conditions: mild wear, severe wear and ultra-severe wear. From practical engineering point of view, mild wear might well be considered as acceptable whereas the transition to severe condition often represent a change to commercially unacceptable (short life time, short maintenance interval, etc.). The transition of mild to severe wear is recognized by the rapid increase of the wear rate. Williams (1999) summarized the differences between mild wear and severe wear in Table I.

Table I: The distinction between mild and severe wear, after Williams (1999).

Mild Wear	Severe Wear
Result in extremely smooth surfaces- often smoother than the original.	Result in rough deeply torn surfaces much rougher than the original surface.
Debris extremely small typically less than 100 nm diameter.	Large metallic wear debris up to 0.01 mm diameter.
High electrical contact resistance.	Low contact resistance true metallic junctions formed.

Wear Model

Over the years, many researchers have carried out the study in modeling wear which resulted in many models for many different situations. There are 32 parameters found and nearly 200 wear equations, involving enormous material properties and operating conditions that have been identified by various authors (Meng and Ludema, 1995). There is no simple and universal model available that can predicts wear on the basis of mechanical properties and contact information only.

A starting point in the analysis of wear is conducted by Holm (1938) and followed by Archard (1953) in asserting an important wear model in a simple form. Archard's wear equation postulates that the wear rate, i.e. the volume worn away per unit sliding distance is proportional to the load and the material combination. The depth of wear, *h*, is used in Eq. (1) instead of wear volume as follows:

$$h = \frac{K}{H} sp \tag{1}$$

The wear coefficient is denoted by K, H is the hardness of worn surface, s is the sliding distance and p is the pressure. This model has lead to both theoretical and the experimental approaches in that period although some observation not always followed this model (Dorison *et al*, 1961; Richard, 1967; Hirst *et al*, 1956) but until recent time, the (modified) Archard's wear equation is still widely used by many researchers in numerical simulations, especially for the mild wear situation, with satisfactory results (Hugnel *et al*, 1996; Flodin *et al*, 2000; Olafsson *et al*, 2000; Oqvizt, 2001). The Archard's wear equation was developed in exponential equation according to the wear mechanism (Bayer, 1991, Zhu *et al*, 2007).

A wear map is one of the solutions of the wear quantification, where a single wear equation will be insufficient to cover the entire range of wear process. Welsh (1965) was as a pioneer in studying the wear map idea which depicts the wear mechanism and wear rate as a function of contact load and sliding velocity. Lim and Ashby (1987) continued the study by combining the wear map founded by Welsh (1965) and Quinn's theory (1984) about oxidation wear and proposed the wear mechanism map of steel under unlubricated conditions. Asperity temperature and some chemical constants are considered to be the important factor to the various types of wear.

Another map is developed by plotting of a wear mechanism, experimentally and theoretically. Some wear mechanism maps which successfully have been plotted are steel vs. nitrided steel (Kato *et al*, 1994), aluminum alloys vs. aluminum alloys (Liu *et al*, 1991; Zhang and Alpas, 1997), and grey cast iron (Riahi and Alpas, 2003). An alternative maps called mechanical wear maps were developed by (Kayaba *et al*, 1981; Kayaba *et al*, 1986; Kato *et al*, 1986; Hokkirigawa *et al*, 1987). The map is consist of three wear modes: ploughing, wedge forming, and cutting which correspond to the relation of Dp, degree of penetration and ξ, degree of wear was introduced. The ploughing regime can be recognized by the displaced material from wear track to ridges on both sides of the wear (Stroud and Wilman, 1962; Zum Gahr and Mewes, 1983; Kato and Hokkirigawa, 1985; Kato, 1990). Hokkirigawa *et al.* (1988) validated Challen and Oxley (1979) experiments and introduced the dimensionless parameter, the degree of penetration D_p as a severity index of sliding which is calculated by dividing h, depth of the groove with a, the radius of contact as shown in Fig. 2.

de Rooij (2005) uses in agreement with Hokkirigawa *et al* (1988), Challen, and Oxley (1979) three different wear regimes. The attack angle of the sliding asperity, θ, and dimensionless shear strength, f_{HK} was proposed to complete the previous explanation as follows:

$$f_{HK} = \frac{\tau}{k} \tag{2}$$

where k is the shear strength of the softest contact partner and τ is the shear strength of the interface. Childs (1988) also used k and τ to develop his wear model. Masen *et al* (2005 and 2007) investigated degree of wear in several experiments.

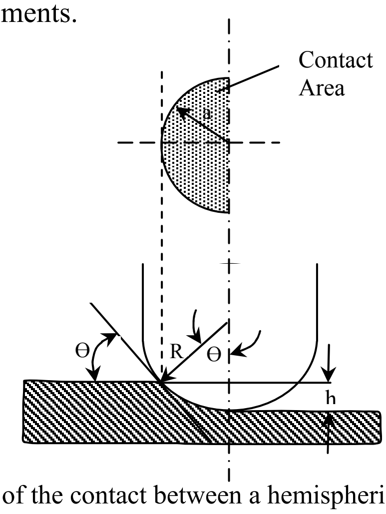

Figure 2: Schematic illustration of the contact between a hemispherical pin and a flat surface during sliding, after Hokkirigawa (1988).

Static and Moving Contact Model

Depending on the operational condition (load, velocity, temperature, (micro) geometry, etc.) a rolling-sliding contact may, at asperity level, deforms elastically and/or plastically. Moving two surfaces to each other, any motion can be described as a combination of sliding, spinning and rolling (Johnson, 1985). Sliding or slip is the relative velocity between two bodies in the contact in the tangent plane. Spinning is relative angular velocity between the two bodies about the common normal through contact, and rolling is the angular velocity of the two bodies about an axis lying in the tangent plane.

The study to predict the deformation in elastic, elastic-plastic, and fully plastic regime has been conducted for many years. Initially, Hertz (1882) introduced the model of elastic contact between ellipsoid and followed by Greenwood and Williamson (1966). Abbot and Firestone (1933) proposed the basic plastic contact model, which is known as surface micro-geometry model. Experimental studies of fully plastic contact have been conducted, for example, Jamari (2006b) investigated the fully plastic contact of sphere against hard flat.

The elastic-plastic contact regime is defined as the regime in which, due to the contact loading condition, the deformation of the contacting asperities stay in between the pure elastic and fully plastic condition. Many researchers have proposed the elastic-plastic contact model (Chang *et al*, 1987; Zhao *et al*, 2000; Kogut and Etsion, 2002; Jackson and Green, 2005). Recently, Jamari (2006a and 2006c) proposed an elastic-plastic contact model which has been validated experimentally and showed excellent agreement between model and test. The model uses the elliptical contact situation to model the elastic-plastic contact between two asperities. The mean effective radius R_m is defined as:

$$\frac{1}{R_m} = \frac{1}{R_x} + \frac{1}{R_y} = \frac{1}{R_{x1}} + \frac{1}{R_{x2}} + \frac{1}{R_{y1}} + \frac{1}{R_{y2}} \tag{3}$$

R_x and R_y denote the effective radii of curvature in principal x and y direction; subscripts *1* and *2* indicate body *1* and body *2* respectively. After considering models that has been proposed in literature, Jamari defined the elastic-plastic contact area A_{ep} and the elastic-plastic contact load P_{ep} as:

$$A_{ep} = 2\pi R_m \omega \frac{\alpha}{\beta} + (2\pi\sqrt{R_x R_y \omega} - 2\pi R_m \omega \frac{\alpha\beta}{\gamma}) \left[3\left(\frac{\omega-\omega_1}{\omega_2-\omega_1}\right)^2 - 2\left(\frac{\omega-\omega_1}{\omega_2-\omega_1}\right)^3 \right] \tag{4}$$

$$P_{ep} = A_{ep}\left[c_h H - H\left(c_h - \frac{2}{3}K_v\right)\frac{\ln\omega_2 - \ln\omega}{\ln\omega_2 - \ln\omega_1} \right] \tag{5}$$

where ω is the interference of an asperity, subscripts *1* and *2* indicate body *1* and body *2* respectively, α and β are the dimensionless semi-axis of the contact ellipse in principal x and y direction respectively, γ is dimensionless interference parameter of elliptical contact, c_h is the hardness factor, H is the hardness of material and K_v is the maximum contact pressure factor related to Poisson's ratio v. Another elastic plastic contact models are given by Nélias *et al.* (2006) and Hao and Keer (2007).

Running-in

Running-in is defined as the change in geometry (micro and macro) of rolling/sliding surface and the change in phsycomechanical properties of the surface layers of the material during the initial sliding period, which generally manifest it self, assuming constant external condition, in a decrease in the frictional work, the temperature and the wear rate (Kraghelsky *et al*, 1982). Running-in has been investigated experimentally by many researchers (for example: Blau, 1989; Wang and Wong, 2000; Wang *et al*, 2000; Jamari, 2006).

In the running-in period, there are two dominant mechanisms: plastic deformation in normal direction and mild wear (Whitehouse, 1980). Plastic deformation due to normal loading, known as

Phase I in running-in, is an important factor in changing the surface topography. The higher asperities are truncated in this phase, the coefficient of friction strongly decreases, the center line average roughness, R_a decreases, average contact area increase and temperature of the surface decrease. Jamari (2007) has modeled the asperity change due to plastic deformation in running-in of rolling contacts and a good agreement was found with the perform experiments. A deterministic elastic plastic contact model, which is stated in the previous section, was proposed to determine the run-in surface topography of a rolling contact during the running-in phase.

Phase II, which is a result of mild wear, is considered due to continuous removal of boundary layers formed by reaction of additives and oxygen in the lubricant and the contacting surfaces. The micro-hardness increases by selective work hardening and there is only a slight decrease of the coefficient of friction in this phase (Whitehouse, 1980)

Running-in of Rolling Contacts

A proper running-in period is often desirable for prolonging the lifetime life of a system. Predicting the wear rate and wear volume in running-in become an important matter. Zhang (1996), Lin and Cheng (1989) have studied the wear volume prediction by developing Archard's wear model. Kumar *et al* (2002) developed an empirical relation for the running-in wear rate, running-in period and steady state wear rate on the basis of mathematical model. The determination of the change of surface topography during running-in due to wear with a statistical model, in assuming the surface, has been used by many researchers (Stout *et al*, 1980; Sugimura *et al*, 1986; King *et al*, 1997; Shirong and Gouan, 1999; Jeng *et al*, 2000; Jeng *et al*, 2004). The models stated above are considered running-in with respect to wear during sliding motion. The macroscopic wear volume or change in standard deviation of surface roughness is studied extensively rather than the change of surface topography locally during running-in process.

Jamari (2006) has developed a model to predict the change of surface topography due to plastic deformation during running-in of a rolling contact. In example no sliding present the change of the surface topography during running-in for a rolling contact was modeled on the basis of the elastic-plastic contact model and the deterministic contact model of rough surfaces. Experimental tests were performed to investigate the contact area and the change of the surface topography due to plastic deformation. The correlation between the proposed model and the experimental data was excellent. Based on the aforementioned points, 1) the ploughing or plastic deformation and 2) the surface layer formation and breakdown mechanism are dominant for mild wear. However, it is challenging to develop a model for ploughing and corrosive action on asperity level in a deterministic way.

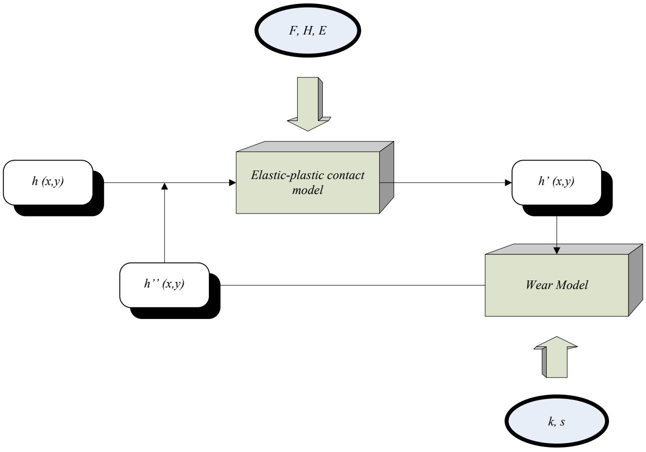

Figure 3: Schematic illustration of the proposed running-in of rolling-sliding contact model.

Closure

From this literature review, many investigations of mild wear have been conducted and some models have been proposed in macroscopic or global scale. The mild wear study during running-in of rolling-sliding contact in asperity level deterministically can be conducted by using the elastic-plastic contact model of Jamari (2006a, 2006c and 2007). To simulate the mild wear process and its contribution to the running-in process, the model as depicted in Fig.3 can be proposed. In this model, *h (x,y)* is the initial surface topography, which is obtained by measuring the surface, will be defined as an input. By applying the elastic-plastic contact model of Jamari, the deformed surface topography *h' (x,y)* is calculated. The applied load *P*, the material hardness *H*, the elasticity modulus *E*, etc are needed in elastic-plastic contact model calculation. The study can be extended with a mild wear model by considering some parameters such as the specific wear rate, sliding distance, sliding velocity, etc. With the mild wear model, the modified surface topography *h" (x,y)* is calculated. This calculation routine is repeated until the steady state condition is reached. The second step is to predict a reliable value for the specific wear rate for the system defined.

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