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ORIGINAL PAPER

Embedding Wear Models into Friction Models

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Abstract Frictional behavior in dry or boundary-lubricated tribosystems is commonly time-dependent. Examples include phenomena like running-in, scuffing initiation, adhesive transfer, coating wear-through, and lubricant starvation. Fundamental models for the sliding friction coefficient usually focus either on determining a steady–state value or on predicting periodic behavior like stick-slip. They often neglect the details of long- and short-period frictional transients, some of which are quite repeatable. In addition to generating heat, frictional work is known to be dissipated in several ways, including roughness changes, wear particle generation, tribomaterial evolution, and microstructural alteration. Pairs of materials can display identical average friction coefficients but significantly different wear processes because frictional work is dissipated differently from one pair of materials to the next. The attributes of friction-versus-time behavior for combinations of metals, ceramics, and polymers can be comprised of stages whose understanding may require the development of piecewise friction models that include wear. This paper discusses past work on the subject, exemplifies embedding a simple wear model into a friction-versus-time model, and indicates how friction process diagrams can play a role.

Keywords Friction mechanisms · Unlubricated friction · Unlubricated wear · Running-in · Boundary lubricated friction · Non-ferrous alloys · Oxidative wear · Wear mechanisms

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1 Introduction

The relationship between sliding friction and wear depends upon the conversion and dissipation of kinetic energy. The larger the quantity of frictional work produced by sliding contact, the more energy must be dissipated. Well-lubricated tribosystems remain cooler and sustain less wear and surface damage because there is less frictional energy to be dissipated. As Czichos pointed out three decades ago [1], a tribosystem can be represented in terms of mechanical, thermal, and chemical planes. Each of these has a role in generating and dissipating energy. As the present author has noted [2], a set of sliding couples can have the same friction coefficient, yet exhibit much different wear characteristics because the energy is differently partitioned.

The following possibilities exist for dissipating frictional energy when solid bodies slide:

- Frictional heating
- Making or breaking adhesive bonds
- Ordering/disordering of molecular species at the surface
- Elastic deformation of one or both solids
- Generation of sound waves or vibrations
- Plastic deformation of one or both solids
- Fracture of one or both solids
- The creation of defects or phase transformations in one or both solids
- The promotion of surface chemical reactions
- Viscous losses in the interposed medium (if any)
- The compression or redistribution of interfacial wear debris

The energy partition is dependent upon the specific attributes of the tribosystem and materials, and cannot be generalized. In some tribosystems, there is a direct proportionality between friction coefficient and wear rate, yet in others there is not. Furthermore, the dissipation of frictional energy changes the nature of interface, and that in turn affects the sliding resistance. This recursive process forms the basis for the present discussion.

In 1995, Meng and Ludema [3] commented on the use of friction coefficients in wear models. They wrote as follows:

> "Since friction forces add to the stresses and temperatures imposed upon all substances in the interface, friction should be represented in some more fundamental and locally distributed manner than the coefficient of friction. The latter is a useful term for mechanical design purposes but not for research in wear."

The present discussion considers the inverse consideration; namely, wear in the context of friction, and it will be shown, by an example of running-in behavior, that the time-dependent changes in friction force can be modeled by embedding simple wear models into friction models.

2 Past Research on Wear-Friction Modeling Interrelationships

Attempts to incorporate considerations of surface damage on friction are not new. For example, the division of the friction force into adhesive and plowing components by Bowden and Tabor [4] implies that the work of deformation, a wear precursor, can raise the friction force. Similarly, other investigators have associated transitions in friction and wear with changes in dominant mechanisms like adhesion, cutting, or plowing, e.g. [5–7]. In 1963, Dobson and Wilman [8] considered the contribution of plowing and brittle fracture in the friction of sodium chloride. Three regimes wear versus friction were identified depending on the penetration depth of the abrasive. Furthermore, Godet [9] recognized that particles produced by wear or external contamination can influence the sliding resistance between surfaces.

Only in cases where the cumulative sliding distance is short, the contact pressure is low, or the materials are effectively lubricated does wear not influence frictional behavior. Sometimes, the highest wear occurs during running in, and after that the wear rate becomes lower. In other cases a transition to high wear or severe surface damage signals the failure of a coating or the end of a bearing's useful life. Studies by the author have shown that the time to reach steady–state friction is not necessarily equal to that to reach a steady–state rate of wear [10], further suggesting a need to embed wear models into certain types of friction models.

During the 1980s, the need to select materials for plain bearings prompted the development of what became known as "IRG transition diagrams." IRG transition diagrams combined friction-versus-time behavior with wear analysis to map safe and unsafe load and sliding speed combinations [11]. While it is common to investigate changes in the severity of sliding wear by monitoring frictional behavior, it is also useful to consider the role of wear when modeling friction.

A survey of friction-versus-time (alternatively sliding distance or number of cycles) characteristics was conducted in the early 1980s [12] and revealed eight common forms. Each form can be characterized by its shape, the time to reach certain transition points, and the magnitude of the instantaneous fluctuations. Each of these three attributes provides clues to the operable processes and to the stability of the tribosystem. Unfortunately, none of the eight common forms has an unique origin, but rather depends on the materials, lubricants, and tribosystems involved. However, despite this limitation, friction curve analysis (FCA) has been used to establish the repeatability of tribotesting methods, the sequence of changes in surface states during sliding, and other phenomena of interest in both basic and applied studies. By dissecting the contributions to friction-time behavior, it is possible to understand better the evolution of sliding processes, to observe how the competition between processes varies on different size scales, and to monitor interfacial conditions such as the severity of wear [13].

3 An Example: Relationship Between Wear and Friction Preceding a Sliding Transition

By a simple illustration, one can show how wear can initiate a friction transition. The form of friction-time behavior in oxidized metals or coated surfaces, described in References [10, 12] as type "e", is shown schematically in Fig. 1. In the primary stage of sliding, the friction force is controlled by a thin film of ambient oxide (or a solid

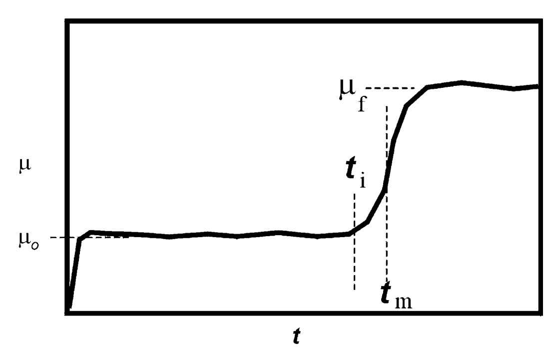

Fig. 1 Features of a break-in curve of type (e)

lubricant) that eventually wears off, exposing an adhesion-prone substrate, which in turn transfers to the counter face and elevates the friction in a short period of time. One can model the time-dependent friction coefficient $\mu(t)$ using the pre-transition friction coefficient (μ_o), the post-transition value (μ_f), and the time to the mid-point of the transition (t_m). An equation of the following form can be used:

$$\mu(t) = \mu_o - \left[\left(\mu_f - \mu_o\right)/2\right]G(t) \quad (1)$$

The transition factor $G(t)$, is expressed as:

$$G(t) = 1 + (t - t_m)/[(1 + \mathrm{abs}[t - t_m]^b)^{(1/b)}] \quad (2)$$

where b is the rate constant. Two curves with $b = 1$ and $b = 2$, and using given values for μ_o and μ_f, are plotted in Fig. 2. Assuming a linear wear rate for the film prior to the onset of the transition, one can derive the incubation time (t_i), which is defined as a 5% increase in μ_o.

Consider a pin-on-disk tribotest in which a pin of nominal contact area A_c is sliding on a circular track of total wear area of A_t. We shall assume that in order to initiate a friction transition like that shown in Fig. 2, a film of thickness z must be worn off completely the wear track on the disk. Using the definition of wear rate K as the volume removed (V) per unit applied force P and distance slid x, we can write:

$$K = \frac{V}{Px} = \frac{zA_t}{Pvt} \quad (3)$$

where, $v =$ the sliding velocity and $t =$ time. Note that K is the wear factor for the film, which can be also function of load, so K and P are not independent of one another. The nominal contact pressure p, is the applied force divided by the nominal contact area A_c. For convenience, let the ratio of A_t to A_c be called f. Then, Equ. (3) becomes

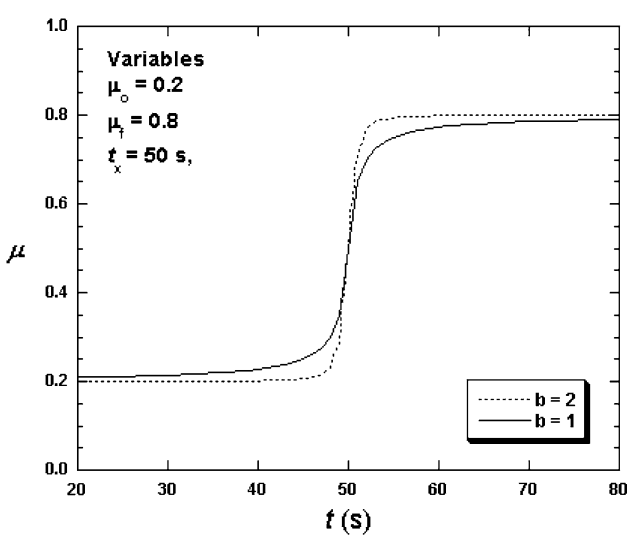

Fig. 2 Plot of Eq. 2 using two different rate constants

$$K = \frac{zfA_c}{pA_cvt} = \frac{zf}{(pv)t} \quad (4)$$

If the film is entirely worn through, in order to initiate the friction transition, then $t = t_i$ and

$$t_i = \frac{zf}{(pv)K} \quad (5)$$

The incubation time can therefore be expressed as a function of the contact pressure–velocity product (pv), the film thickness (z), the load-dependent volumetric wear rate of the film K, and the ratio of the wear track area to the nominal contact area (f). Equation 5 makes physical sense because: (a) the higher the contact pressure or speed, the shorter is the incubation time; (b) the thinner the film to be removed, the shorter is the incubation time, and (c) the higher the wear rate of the film, the shorter is the incubation time.

While the use of a simple relationship such as that in Eq. 5 can be enticing, it has a number of short-comings; specifically:

- It assumes that the wear of the film alone determines the pre-transition incubation time.
- It assumes that the film wears off at an uniform rate from full thickness to zero thickness.
- It fails to account for spallation (contact fatigue) or the possibility that a friction transition can be initiated when only a fraction of the substrate is exposed.
- It assumes that sliding-induced changes in the pin do not affect the wear of the film.
- It makes no accounting for the initial surface roughness of either the pin or the disk.
- It requires preliminary knowledge of the film wear rate and the initial and post-transition friction coefficient.
- It makes no accounting for adhesive transfer from one surface to the other as a possible initiator of friction transitions.
- At best, it is applicable only to the frictional response prior to the onset of the transition and does not model the effect of wear on friction after the transition period.

With its dependence on so many experimental factors, the simple model expressed by Eqs. 1 and 5 is not a fundamental, first-principles model. Yet it serves to show how wear models can become a means to understand the contributions to frictional transitions.

With case-specific modifications, an approach like this can be used to model frictional behavior of other kinds. Since the contributory factors in friction change during a transition, different wear models will be required for the initial friction and longer-term friction stages. Therefore, the challenge in embedding wear models into friction models is to identify the applicability of several possible wear models to each stage of the sliding process and to develop appropriate criteria that trigger the transition between an early-stage wear model and a later-stage wear model.

The foregoing example used a linear wear equation to model one attribute of FCA; namely the incubation time prior to transition. There are other attributes of friction-time behavior, such as the instantaneous level of fluctuations in friction force that would also benefit from the consideration of wear processes. For example, the state of wear could be used to estimate the range of friction forces during a post-running-in period. A knowledge of not only the nominal value of the friction force, but also their range would help engineers to develop condition monitoring systems and aid in the selection of motors and drive systems to accommodate such fluctuations over the course of operation.

In the author's earlier work [10] friction process diagrams (FPD) were introduced as a means to depict transients in sliding friction for those tribosystems in which several contributions, related to the state of wear, could be operating in parallel. Figure 3 shows a FPD for sliding metals, similar to the foregoing example, in which the contributions to interfacial sliding resistance varied from surface film domination to film loss and the onset of transfer, and then to the accumulation of third bodies. The dominant wear models corresponding to each apex of the FPD in this case could be scaled proportionately within the friction model to enable the history of the tribosystem to be portrayed.

A similar approach was exemplified in a study of the running-in of a cast aluminum silicon alloy (C390) against bearing steel in which the aluminum alloy surface had been etched such that the Si particles dominated the friction initially. As wear continued, the Si particles were worn down to the point that ductile Al matrix smearing dominated the friction [14]. Using tests on pure Si and on an aluminum alloy with a composition similar to the Al matrix within C390, it was demonstrated that the running-in behavior could be modeled by a rule of mixtures in which the relative area fraction of Si exposed during sliding decreased from 1.0 to that typical of the bulk C390 alloy. Therefore, two quite different wear models, one based on the fracture of silicon particles and one based on the ductile shearing of an aluminum, would be required to effectively model time-dependent frictional behavior.

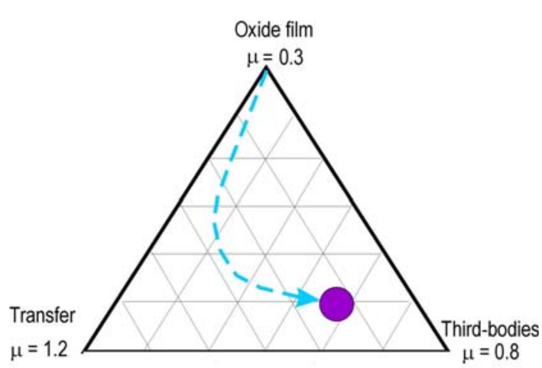

Fig. 3 Friction process diagram for steel sliding on copper, adapted from reference [10]

4 Summary

Kinetic friction behavior, under both dry and boundary-lubricated conditions, is commonly observed to vary with the time. Wear can be a contributor to such behavior, especially in cases like running-in or the wear-through of coatings. Wear models may usefully be embedded into friction models in such cases. To ignore wear when attempting to model the friction of many practical systems, especially those in which fluid films fail to separate the surfaces, can distance the modeler from physical reality. While the added variables and assumptions required in this more rigorous approach compounds the difficulty of friction model development, A. Einstein supposedly said: "Everything should be made as simple as possible, but not one bit simpler."

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