Time-dependence and exposure-dependence of material removal rates in fretting

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Abstract

Fretting generally results in either material removal or fatigue, or a combination of both. Although the term is rarely used now, in the early literature addressing this subject, fretting that resulted in material removal was sometimes termed "*fretting corrosion*" on account of the characteristic oxide debris that emanated from such contacts, with this description itself encapsulating the understanding that the material removal has both a mechanical and a chemical nature.

When the mechanical aspects of material removal in fretting dominate in the interpretation of the results, wear rates tend to be presented in terms of volume loss for a given exposure to wear (often measured by number of fretting cycles, total distance of sliding or energy dissipated). However, it is well understood that, in fretting, some aspects related to the formation of oxide-based debris are time-dependent (such as transport of species into and out of the contact and chemical reactions which take place at the contact surface) and this raises issues as to how to best present rate data associated with material removal. In this paper, recommendations are made as to how to be present volume loss data in fretting in a way that assists in the development of understanding of the rate-determining processes in material removal in fretting.

Keywords

Mechanisms; Modelling; Debris; Mapping

1 Introduction

Wear rates are commonly presented in terms of amount (mass or volume) of material removed from a system wear per unit of exposure to the agent which is causing wear. In fretting wear, the definition of wear rate typically follows the thinking that is embodied in Archard's work on sliding wear [1], which states that:

$$\frac{dV}{dS} = \frac{k\,P}{H} \qquad \text{Equation 1}$$

where V is the worn volume and S is the distance slid, P is the applied load and H the hardness of the softer material. When this is applied to fretting, the motion is defined by the slip amplitude, δ^*, with the total distance slid in a test being given simply by the product of the slip distance per cycle $(4\,\delta^*)$ and the total number of cycles in the test, N. Accordingly, Equation 1 is often presented as follows:

$$\frac{dV}{dN} = 4\,\delta^*\frac{k\,P}{H} \qquad \text{Equation 2}$$

In these formulations, it is assumed that the distance slid is known; however, in fretting testing, this requires a knowledge of the slip amplitude (δ^*), i.e. the local slip to the contact. The slip amplitude is not easily directly measured in a fretting test and requires the fretting loops of the type shown schematically in Figure 1 to be processed (the slip amplitude is defined as the displacement in the loop when there is no net tractional force, Q). In many tests reported in the literature, it is in fact the far-field displacement amplitude (Δ^*) which is measured and controlled (since this is straightforward to achieve reproducibly). One issue here is that it is assumed (specifically in the form presented in Equation 2) that δ^* does not vary throughout a test; however, this is not a good assumption in practice. By reference to Figure 1, it can be seen that the relationship between δ^* and Δ^* can be described by the following equation [2,3]:

$$\delta^* = \Delta^* - \frac{Q^*}{S} \qquad \text{Equation 3}$$

where Q^* is the maximum tangential force experienced in a fretting loop and S is the stiffness of the system (with includes the contact stiffness). The maximum tractional force, Q^*, may vary over the duration of a test (being dependent upon the evolving coefficient of friction and the evolving geometry of the contact during the test [4]) and therefore, although Δ^* may be held constant in a test, δ^* may vary. It is also noted that (i) δ^* and Δ^* are not directly proportional to each other; (ii) Q^* is strongly dependent upon the applied load, P, and therefore, for a fixed value of Δ^*, δ^* will be different for different values of applied load.

It should be noted at this stage that as control systems develop, on-the-fly control of slip amplitude (δ^*) is now possible, as seen (for example) in recent work of Dreano et al. [5]; it is expected that in time, all laboratory testing of fretting will move from one of displacement amplitude-control to slip amplitude-control as test systems are upgraded (although that it is noted that this on-the-fly control becomes more difficult as the fretting frequency increases).

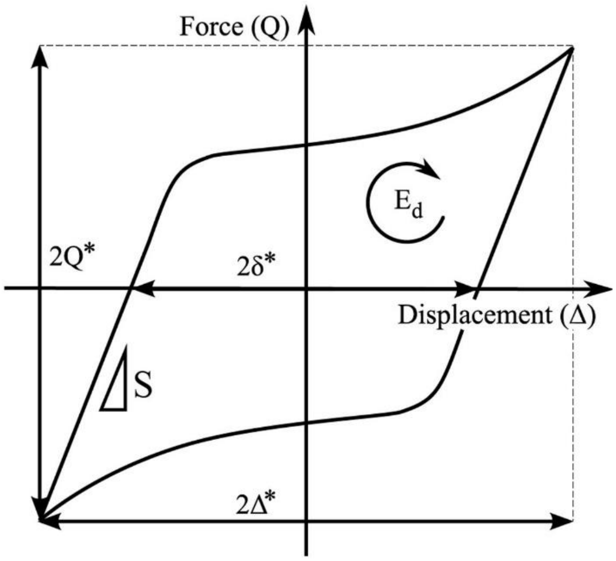


Figure 1 Schematic diagram of a fretting loop showing the relationship between the displacement amplitude, Δ^*, and the local contact slip amplitude, δ^* [4].

The complexities with defining the exposure to wear (i.e. the cumulative distance slid in a test) were ameliorated by the definition of the energy coefficient of friction, proposed by Fouvry and co-workers [6], which is now commonly used as a basis for describing the wear rate. The energy coefficient of friction, μ_E, is defined as follows:

$$\frac{dE}{dN} = 4\,\delta^*\,P\,\mu_E \qquad \text{Equation 4}$$

where E is the frictional energy dissipated in causing slip (the energy dissipated in a single fretting loop is indicated as E_d in Figure 1). Combining Equations 2 and 4 yields the now commonly employed definition of the wear rate:

$$\frac{dV}{dE} = \frac{k}{\mu_E H} \qquad \text{Equation 5}$$

Formulations such as these have been successfully employed over many years to allow wear rates in fretting tests to be defined (typically either a distance-based wear rate, $\frac{dV}{dS}$, or an energy-based wear rate, $\frac{dV}{dE}$) and in experimental test programmes, they have been used to analyse the effect of typically varied test parameters such as test duration (N), applied load (P), slip well as the nature of the materials that make up the contact.

The three main issues to be considered as surfaces slide against each other have been identified as follows [7]:

- Stresses and damage;
- Thermal effects
- Chemical reactions and interactions of the surfaces.

with these three exhibiting interdependence. The second and third of these can be classed as being having rates that are, at least in part, time-based (as opposed to being solely based upon slid distance or energy dissipated). When fretting is considered more specifically, the access of environmental species to the contact surface and the egress of debris from the contact may also have a dependence upon (i) time; (ii) numbers of cycles; (iii) distance slid (it is not the aim of this paper to discuss which of these is dominant, but merely to recognise that there is a time-dependence of the critical transport mechanisms in fretting). As such, it can be seen that the commonly-employed graphical representations (Figure 2) of the rate formulations presented in Equations 1, 2, 4 and 5 may not be the best ways of presenting data where the effects of processes where the rates are time-dependent need to be explicitly considered.

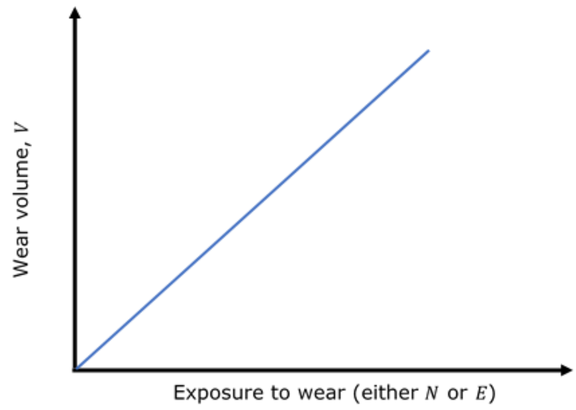


Figure 2 Form of the graphical presentation of fretting wear data commonly used in the literature, based upon Equations 2 and 4.

The effect of frequency on fretting is well established with a developed literature. In some of the earliest work in this area [8–10], it was shown that whilst the effect of frequency on wear rate was strong in an atmosphere containing oxygen, it was much weaker (or not observed at all) in an atmosphere which was predominantly nitrogen (i.e. with very small oxygen levels) where the formation of oxide debris in the contact was limited. As such, it is clear that there is a time-dependence associated with the oxygen – either in terms of its transport into the contact or in terms of rates of reaction to form the debris; it was later recognised that this time-dependence was not solely affected by the frequency, but also by the size of the contact [11]. In addition, it is also recognised that frequency of fretting also affects the temperature in the contact and this too will influence the basic physical processes associated with wear [12].

2 Plotting of wear data to facilitate identification of time-based effects in fretting

The issue at hand here is how to best represent a time-dependence graphically, and to do this in a way that illustrates the time-dependence without necessarily introducing new parameters (inferred or explicit) into the equations. The process will be illustrated by development of equation 5 although it is recognised that the method would be equally applicable to any of the other formulations presented (Equations 1, 2 and 4). With no further assumptions related to the time-dependence of any processes (i.e. maintaining the basic principle underpinning the equation that wear volume is proportional to the energy dissipated), Equation 5 can simply be rewritten as follows:

$$\frac{\left(\frac{dV}{dt}\right)}{\left(\frac{dE}{dt}\right)} = \frac{k}{\mu_E H} \qquad \text{Equation 6}$$

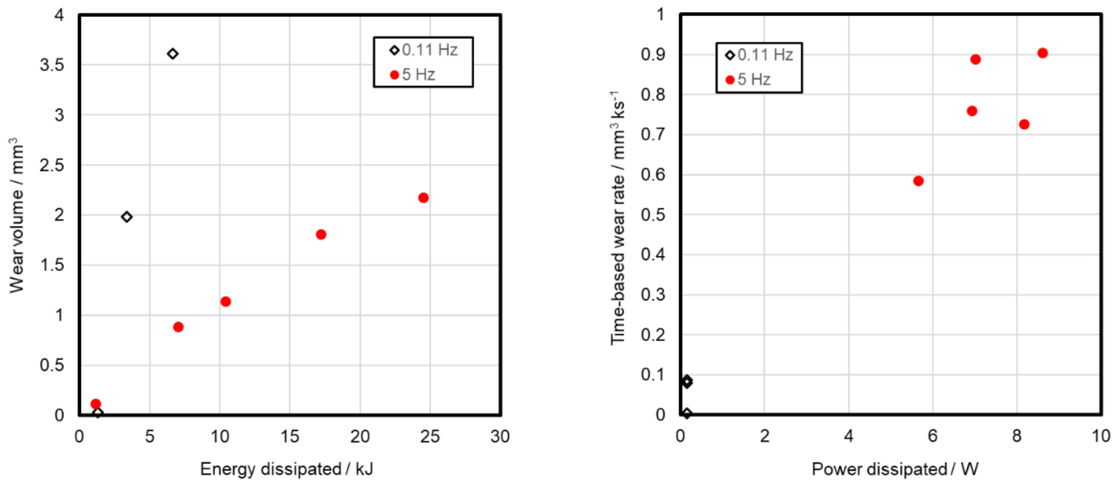
This graphical representation of this requires the plotting of the time-based wear rate $\left(\frac{dV}{dt}\right)$ against the rate of frictional energy dissipation $\left(\frac{dE}{dt}\right)$ (i.e. the frictional power dissipation). To explore this, the data from two papers published by Fouvry and co-workers [13,14] will be examined; both papers concern the same basic system, namely that of laboratory fretting of Ti-6Al-4V couples in a cylinder-on-plane geometry.

In the first of these papers [13], work is described where a series of tests were conducted over a range of cycles with both a constant displacement amplitude and load, with these test series being conducted with fretting frequencies of both 0.11 Hz and 5 Hz. Figure 3 shows the data, presented in both their traditional form (as presented in the paper itself) and in the form indicated by Equation 6. In Figure 3a, a clear reduction on the energy-based wear rate (i.e. the gradient of the data) is observed as the fretting frequency is increased from 0.11 Hz to 5 Hz (a feature commonly observed in the literature). In discussing this, the authors clearly ruled out temperature effects (associated with the different rates of power dissipation) as the cause, and identified instead the time required for oxygen to react with the titanium as the underlying cause, stating [13]:

> “Hence, the most plausible explanation related to this sharp increase of the energy wear rate with the frequency reduction is that, by increasing the time that oxygen can react with the native titanium metal, a thicker titanium oxide layer is formed on the surface. Consequently, the amount of material removed during each cycle significantly increases.”

When the same data are presented in the form of Equation 6 (Figure 3b), it can be clearly seen that the data collect into two distinct groups (data which perfectly fit the form of Equation 5 would in fact collapse onto two distinct points on a graph of this type, one point for each frequency). Specifically, it can be seen that the time-based wear rates associated with the tests conducted at 5 Hz are much higher than those associated with tests conducted at 0.11

Hz and therefore it is clear that whilst the reduction in energy-based wear rate with the higher frequency may be associated with a reduced time for the processes to occur, there is within these data no indication that any process (such as rates of transport of species or rates of reaction of species with the surface) is actually rate-determining (i.e. is acting as an upper limit on the time-based rate of wear that can be achieved).



(a) (b)

Figure 3 Fretting data from Van Peteghem et al. relating to fretting of a Ti-6Al-4V couple over a range of cycles at two different fretting frequencies [13]; (a) presented as wear volume as a function of energy dissipated; (b) presented as a time-based wear rate as a function of power dissipated.

It is recognised that the presentation of the data in the form suggested in Figure 3b does not in this case provide the clarity of insight that is expected of any design for graphical presentation of data (and that perhaps the form of Figure 3a is preferred). However, the value of presenting the data in this way can be seen via the data presented by Fouvry et al. [14]; in this work, a particular series of tests was reported where all the test parameters (contact geometry, applied load, slip amplitude, number of cycles) were held constant with the fretting frequency being varied over two orders of magnitude, from 0.05 Hz and 5 Hz (the respective test durations ranged between 100 000 s and 1000 s). In the original paper, the data were presented in the form shown in Figure 4 with the authors describing this as an exponential relationship.

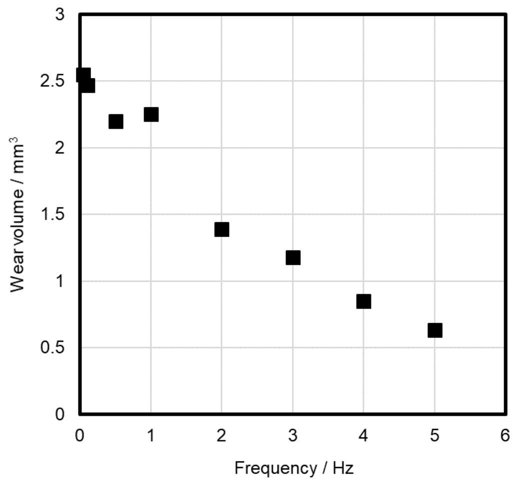
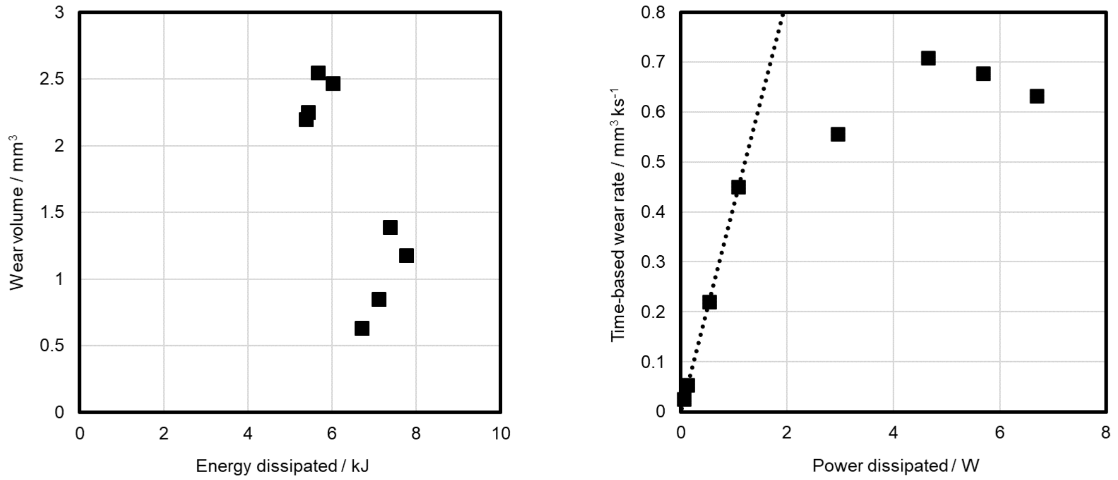


Figure 4 Fretting data from Fouvry et al. relating to fretting of a Ti-6Al-4V couple under a fixed set of parameters (contact geometry, applied load, slip amplitude, number of cycles) over a range of frequencies [14].

There is a clear dependence of the wear volume on the test frequency, despite the fact that the total energy dissipated in each test is similar. Presentation of these data in the traditional form (as shown in Figure 5a) affords very little insight into the processes that may be influencing the variation of wear volume with frequency. However, a plotting of the same data in the form of Equation 6 (Figure 5b) shows that the time-based wear rate initially increases with increasing power dissipation (i.e. with the rate of frictional energy dissipation). Moreover, at the lower levels of power dissipation, a direct proportionality is observed (as indicated in Figure 5b); this indicates that the energy-based wear rate for tests conducted with power dissipation below ~ 1 W (covering the test frequencies of 1 Hz, 0.5 Hz, 0.11 Hz and 0.05 Hz) is constant. However, this direct proportionality between the time-based wear rate and the power dissipated is not sustained for power dissipation > ~ 3 W (test frequencies between 2 and 5 Hz); specifically, it is seen that the time-based wear rate reaches a plateau of ~ 0.6 – 0.7 mm^3 ks^{-1} for a dissipated power of above ~ 3 W. Previous work [15] has suggested that there are a number of critical sub-processes involved in the process of wear in fretting, and it will be the process with the smallest rate which controls the overall wear rate (i.e. there is a rate-determining process); for example, a competition between debris formation and debris ejection is illustrated in Figure 6, where it is suggested that debris formation is rate-determining when the wear scar is small in size, but debris ejection becomes rate-determining as the scar size increases. In the same way, the presentation of the data of Fouvry el al. [14] in Figure 5b suggests that there exists a process which can only proceed at a given maximum time-based rate; process is likely to be associated with the formation of oxide debris, and is likely to be a process either involved in oxygen transport into the contact or with the rate of reaction of the metal exposed by the wear processes [11,16–18].



(a) (b)

Figure 5 Fretting data from Fouvry et al. relating to fretting of a Ti-6Al-4V couple under a fixed set of parameters (contact geometry, applied load, slip amplitude, number of cycles) over a range of frequencies [14]; (a) presented as wear volume as a function of energy dissipated; (b) presented as a time-based wear rate as a function of power dissipated. In the second format, the direct proportionality between the time based wear rate and the power dissipated at the lower values of power dissipation is indicated.

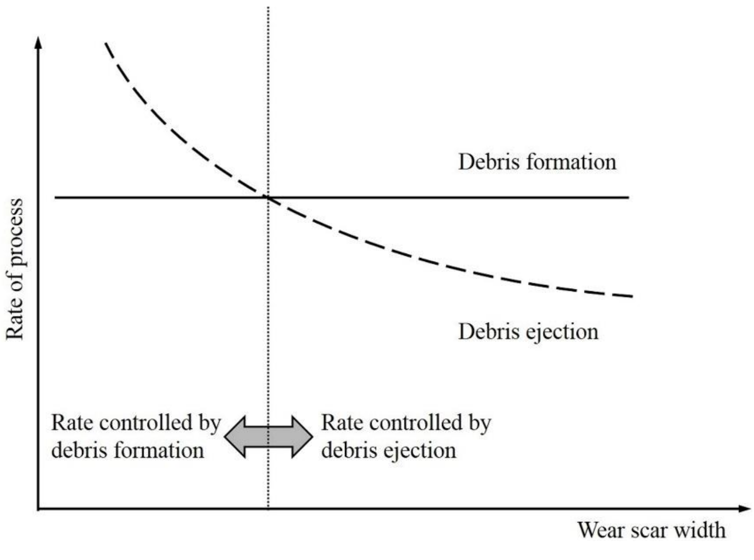


Figure 6 Schematic diagram illustrating the dependence of rates of wear and debris ejection on wear scar width, with regions identified where debris formation and debris ejection are the rate-determining processes (i.e. the process with the lower of the two rates at any scar width) [15].

3 Conclusions

In this work, it is suggested that a simple extension to the normal presentation of wear data (typically wear volume as a function of unit of exposure) to its presentation as a time-based rate of wear as a function of rate of exposure is useful in facilitating an understanding of the role of processes which may govern the overall rate of wear in fretting which have rates which are time-dependent (rather than being dependent upon either the rate of frictional energy dissipation or the rate of sliding displacement in the contact). The value of the approach is illustrated using data from the literature associated with investigations into frequency effects in fretting.

4 References

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