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On the onset of steady state during transient adhesive wear

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ABSTRACT

An experimentally verified transient wear model is developed for determining the onset of steady-state t_s. The model does not require any unknown constants. It is shown that the transient wear behavior during the running-in phase is strongly dependent on the initial surface roughness. The efficacy of the transient wear model and the methodology for determining the onset of steady state is demonstrated by analyzing several case studies from the literature and performing series of additional pin-on-disk experiments with various surface roughness parameters.

1. Introduction

Wear of newly machined surfaces of a tribo-pair in relative sliding motion, is broadly characterized by a nonlinear transient running-in wear regime followed by linearly increasing steady-state wear. During the running-in period the initial irregular asperities are gradually polished and the process continues until the surface roughness, steady friction, and the wear rates stabilize [1–4]. It has been postulated that the transient process influences the steady-state performance of the components due to complex alteration of many intertwined parameters such as contact stresses, surface topography, contact temperature, etc. [5–12]. Therefore, the transient wear behavior as, a whole, and its duration until it reaches steady state plays a significant role in defining the component's long-term performance.

Satisfactory working “wear life” of a tribological component operating in steady state regime under the dry condition is epitomized in terms of the Archard's wear coefficient K, a parameter that is directly proportional to measured wear rate volume ($\dot{w}_v$), the hardness (H) of the softer of the two materials, and inversely proportional to the applied load (N) and sliding velocity (V). Archard's wear coefficient is mathematically represented in Eq. (1).

$$K = \frac{\dot{w}_v H}{NV} \tag{1}$$

The parameter K applies only to steady-state wear and its value can deviate by several orders of magnitude if it is determined at or by including the wear prevailing in running-in regime [13]. Hence, the determination of the time to reach the steady-state wear regime is critical in assessing the useful life of tribo-pairs, particularly when operating under dry conditions. To address these shortcomings, Yang [14] proposed a predictive wear model and an evaluation procedure involving three steps (*i*) transient wear tests, (*ii*) prediction of the steady-state wear coefficients using the transient wear tests, and (*iii*) validation test to confirm the steady-state prediction. This procedure yielded predictions with 20% accuracy while saving 40% time in performing tests. It is worthwhile to point out that in this model the effect of surface roughness is not taken into consideration. Kumar et al. [15] developed a methodology to characterize running-in and steady-state wear processes by considering load, temperature, and surface roughness. They concluded that the steady-state wear is significantly influenced by the initial surface roughness. More recently, Mortazavi and Khonsari [1] presented a wear model for predicting the behavior of the running-in process by determining a relationship between the wear loss and surface roughness during the running-in stage. They observed a linear relationship between the transient dimensionless wear, initial surface roughness, and running-in time.

In the present work, an attempt is made to develop a comprehensive methodology to predict the time to reach the steady-state wear regime t_s for any operating conditions and surface roughness.

2. Wear models

Kumar et al. [15] developed the following transient volumetric wear rate based on the wear volume equation provided by Queener et al. [5] (Fig. 1) is employed.

$$\dot{w}_v(t) = (\dot{w}_0 - \dot{w}_s)e^{(-bt)} + \dot{w}_s \tag{2}$$

It can be observed that the determination of volumetric wear rate in Eq. (2) requires the knowledge of the steady-state wear rate $\dot{w}_s$. The initial wear rate constant $\dot{w}_0$, and the system's time constant τ. Eq. (2)

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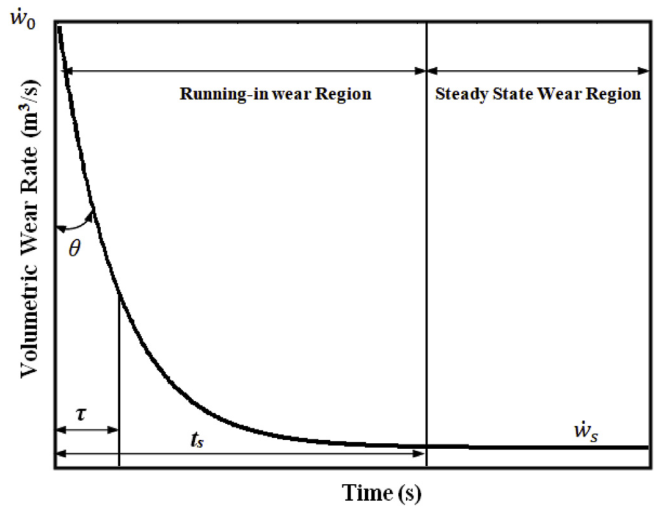


Fig. 1. Volumetric wear rate vs. Time.

can be rewritten as

$$\dot{w}_v(t) = \dot{w}_s\left[1 + \left(\frac{\dot{w}_0}{\dot{w}_s} - 1\right)e^{\left(-\frac{t}{\tau}\right)}\right] \tag{3}$$

where τ represents the time taken from the starting wear rate $\dot{w}_0$ to reach the 63.2% of the difference in steady state and starting wear rate values, i.e. $\tau = t[\dot{w}_0 - 0.632(\dot{w}_0 - \dot{w}_s)]$. This method is commonly applied to estimate the time constant in sensors like thermocouples, RC circuits, etc. The equation to estimate τ is:

$$\tau = t[\dot{w}_0 - 0.632(\dot{w}_0 - \dot{w}_s)] \tag{4}$$

The angle θ in Fig. 1 represents the slope of the wear rate $\dot{w}_0$ at the beginning of the experiment, i.e. $\theta = \frac{\partial \dot{w}_0}{\partial t}\Big|_{t=0}$ can be employed to determine the starting wear rate $\dot{w}_0$, if the value of τ and the wear rate at τ are known.

3. Characterization of the transient wear

To establish a relationship between the variables characterizing the transient wear behavior $\dot{w}_0$, $\dot{w}_s$, τ and θ, three cases from literature [5,16,17] are analysed followed by performing a experimental test using a pin-on-disk test setup. In Cases 1 and 2 the results reported by Zhang et al. [16] and Yang [17] for a range of the applied loads is considered. In Case 3 experiments were performed for different sliding speeds on pin-on-disk tribometer and in Case 4 the experimental results of Queener et al. [5] are used where in the initial surface roughness of the pins is varied. Based on the observations from these studies, a simple procedure is proposed to determine t_s by accounting the (*i*) starting wear rate $\dot{w}_0$, (*ii*) steady-state wear rate $\dot{w}_s$, and (*iii*) the time constant τ from the experiment performed at different operating conditions.

3.1. Case 1: Zhang et al. [16].

Zhang et al. [16] performed experiments with pin-on-disk test setup under the dry condition with 100 N, 150 N, 200 N loads using a pin made of 2014 Al matrix composites reinforced with 20 vol% SIC particles sliding at 1 m/s on a carbon steel disk (hardness = 450 kgf/mm^2). The experiments were performed for the total sliding distance of 500 m. The extracted wear volume data from the literature [16] is shown in Fig. 2a. An equation was developed using a curve fitting method by considering the transient wear volume equation provided by Yang [14].

$$w_v = A[1 - exp(Cx)] + Dx \tag{5}$$

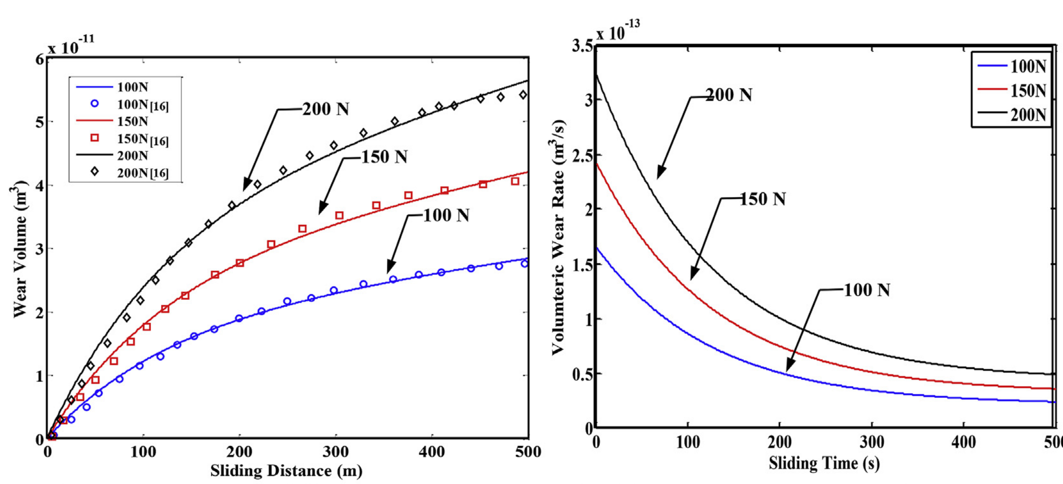
The values of coefficients *A*, *C,* and *D* are determined using the least square method. The obtained wear volume values using Eq. (5) for different loading conditions are superimposed on the experimental data extracted from Ref. [16] and shown in Fig. 2a. The corresponding volumetric wear rate is plotted in Fig. 2b from which it can be observed that the volumetric wear rate has not reached to its steady state for a sliding distance of 500 m. Therefore, the wear volume and volumetric wear rate were theoretically extended to 1000 m and plotted in Fig. 3a and Fig. 3b, respectively.

The wear coefficient *K* is determined using Eq. (1) for the extracted experimental data [16] and the results are provided in Table 1. The starting and steady-state wear rate from Fig. 3b, and the values of the volumetric wear rate at $t = \tau$ i.e. $\dot{w}_\tau = [(\dot{w}_0 - 0.632\,(\dot{w}_0 - \dot{w}_s)]$ for different loads are also given in Table 1.

The estimated time constant. τ was found from Fig. 3b for different cases are: 130 s, 132 s, and 128 s. *Interestingly, the values of τ is found to be approximately constant for all the loading conditions, implying that τ do not depends on the load variation.*

Note that direct substitution of $\dot{w}_v(t) = \dot{w}_s$ in Eq. (2) will lead to the steady state time t_s equal to infinity. Therefore, as suggested by Yang [14], the length of time to reach steady state wear is determined at $\dot{w}_v(t) = 1.01\,\dot{w}_s$. Substituting this in Eq. (3) we obtain Eq. (6).

$$1.01 = 1 + \left(\frac{\dot{w}_0}{\dot{w}_s} - 1\right)e^{\left(-\frac{t_s}{\tau}\right)} \tag{6}$$



(a) Wear volume vs sliding distance (b) Volumetric wear rate vs sliding distance

Fig. 2. Wear volume and volumetric wear rate vs. sliding distance [16].