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A generalized fretting wear theory

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ABSTRACT

Combined impact-sliding fretting wear is a complex phenomenon due to the random nature of the excitation force and the self-induced tribological changes. Available models, which relate wear losses to the process variables, are empirical in nature and bear no physical similarity to the actual mathematical and physical attributes of the wear process. A generalized fretting wear theory is presented to mathematically describe the fretting wear process under various modes of motion; impact, sliding and oscillatory. This theory, which is based on the findings from the fracture mechanics analysis of the crack initiation and propagation processes, takes into consideration the simultaneous action of both the surface adhesion and subsurface fatigue mechanisms. The theory also accounts for the micro-, and macro-contact configuration of the fretting tribo-system. The closed form solution requires the calibration of a single parameter, using a limited number of experiments, to account for the effect of environment and the support material. The model was validated using experimental data that were reported for Inconel 600 and Incoloy 800 materials at room and high temperature environment, and for different types of motion. The results showed that model can accurately predict wear losses within a factor of ± 3. This narrow range presents better than an order of magnitude improvement over the current state-of-the-art models.

1. Introduction

Accurate prediction of the fretting wear damage of mechanical components, e.g., aerospace engines and nuclear power plants is extremely critical for safe, reliable, and economical operation [1]. The fretting wear process is quite complex due to a number of factors; the competition between the wear and fatigue processes, the presence of sliding and impact motions, and the friction-induced thermo-mechanical effects resulting from the thermal constriction phenomenon introduced by the micro- and macro-contact configuration at the contact interface.

Available fretting wear models can be grouped into two categories; empirical and analytical models. In the empirical approach [2–6], the base function of the model bears no physical similarity to the actual mathematical and physical attributes of the wear process and does not reveal the internal relationship and interactions between the process variables. This deficiency makes the predictions unreliable outside the range of tested conditions. Following Archard's equation for adhesive wear of unidirectional sliding systems [7], the concept of work rate W was adopted to relate the volumetric wear losses to the integral effect of the applied load and the relative sliding distance at the interface [8–11]:

$$\dot{W}_{\mathrm{N}} = \frac{\int_0^t F_{\mathrm{N}}(t)\dot{L}(t)dt}{\int_0^t dt} \tag{1}$$

where $F_{\mathrm{N}}(t)$ is the normal contact force as a function of time t, $\dot{L}(t)$ is velocity of sliding during contact and t is total time over which the work rate is averaged. In relating the volumetric wear rate losses $\dot{V}$ to work rate

$$\dot{V} = K_{\mathrm{w}}\dot{W}_{\mathrm{N}} \tag{2}$$

The constant K_{w} is the specific wear coefficient that incorporates the effects of the surface flow stress σ_{f} (hardness) of the softer material and the environment.

2. Limitations of the work rate concept

2.1. Oscillatory sliding fretting wear

While Stowers et al. [12] confirmed the applicability of Archard's work rate approach for predicting oscillatory sliding fretting wear, contradictory conclusions can, however, be drawn from the experimental data reported in [13–15]. These data, which were obtained for different material combinations, showed a

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strong linear dependence of wear coefficient K_w on the slip amplitude. Söderberg et al. [16] have conducted accelerated fretting wear tests on 304 austenitic stainless steel against 304 austenitic stainless steel at a frequency of 20 kHz. The tests were conducted for normal contact forces $5.4<F_N<49.8$ N and slip amplitudes of $13<\delta<32$ μm. These test conditions provided work rates in the range of 2.8–65 Nm/s. Analysis of the results indicated that the specific wear coefficient K_w varies by a factor of approximately 15 (Fig. 1). Instead of being constant, the wear coefficient seems to assume a linear relationship with work rate. This leads to the conclusion that even with pure oscillating sliding motion, the validity of the work rate concept in its current form is questionable. An important conclusion that can be drawn from this analysis is that for the same change in work rate, the specific wear coefficient appears to be slightly affected by variation in a normal load as compared to the effect of displacement amplitude; a ten-fold increase in the normal load results in a change in K_w by a factor of <2, while as δ is increased by a factor of 2.5 only, the coefficient K_w increases eight-fold. Therefore, one can conclude that lumping these two variables in a single parameter, as in 'work rate', which assigns equal weights to sliding distance and normal load, may lead to a significant error in predicting wear rates.

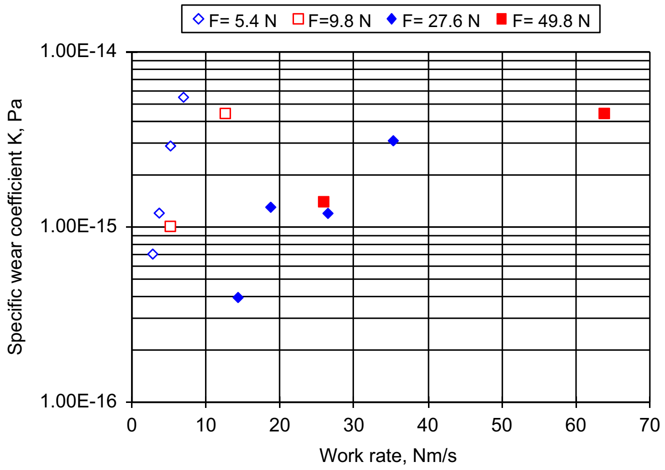

Fig. 1. Variation in the specific wear rate coefficient K_w with work rate, in oscillatory sliding fretting, for different normal loads F and slip amplitudes $13<\delta<32$ mm (materials: 304SS/304SS. Specimens geometry: crossed cylinders).

From the author's experience, the frequency contents of the forcing function that excites most mechanical components undergoing fretting wear damage is mixed and contains more than one frequency component [1]. The experimental results reported by Leheup et al. [17] were produced under the simultaneous action of two different excitations: (a) high wear component characterized by high slip amplitude of 250 μm and low frequency of 15 Hz, and (b) low wear component characterized by low slip amplitude of 40 μm and high frequency of 50–250 Hz. The results of the fretting wear tests indicated that higher work rates associated with the mixed-frequency mode may result in lower wear rate coefficient K_w.

2.2. Normal and oblique (compound) impact

The author has analyzed and examined the data available in the open literature [18–24] and a large number of classified research reports that pertain to the wear rate–work rate relationship various materials used in the nuclear power plants [25]. A sample of this data is presented in Fig. 2 for Inconel I-600 and Incoloy I-800 fretted against carbon steel and stainless steel at 200–285 °C. The support geometry includes drilled holes (DH), broached holes (BH), wires, threaded rods (TR), welding rods (WR) and knife edge (KE). The relative orbital motions between the contacting bodies include oscillatory sliding, normal impact and oblique impact. Fig. 2 shows clearly that the $\dot{V}\{\dot{W}\}$ relationship is not unique and may result in two to three orders of magnitude error in wear rate predictions. This is attributed to the fact that the work rate concept does not appropriately characterize the

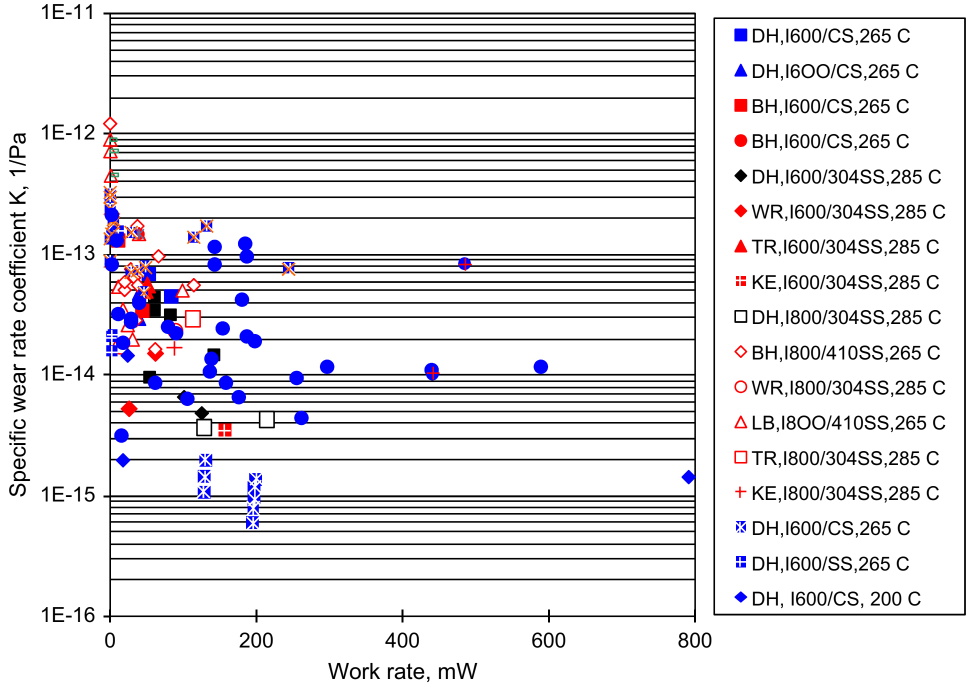

Fig. 2. Compiled data on the relationship between the specific fretting wear coefficient and work rate for I-600 and I-800 alloys against supports of different materials, geometries and temperatures.