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Estimation of the coefficient of friction in partial slip contacts between contacting nickel superalloys

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ABSTRACT

Standard methods for measuring the coefficient of friction between two objects are not appropriate for partial slip contacts, since less damage occurs at the interface. A discussion on the different methods for measuring the coefficient of friction in partial slip contacts is carried out. Results of the coefficient of friction between Nickel superalloys, measured by a non-sliding technique, are presented. The effect of crystal orientation of single-crystals on the friction coefficient was found to be small. A study for using the energy dissipated in two-dimensional partial slip contacts is also presented. An approach for measuring the friction coefficient using the dissipated energy is proposed and the challenges and difficulties in measuring friction through the dissipated energy at the contact are discussed.

1. Introduction

Fretting fatigue occurs primarily in partial slip contacts. Although the surface wear in partial slip is not as significant as in gross sliding contacts, the small slip region in the contact may accelerate crack initiation and propagation, reducing the fatigue life of components. Vingsbo and Söderberg [1] have shown through their map of different fretting regimes that wear may inhibit crack initiation in gross sliding contacts, when material is removed before cracks can initiate. In partial slip contacts, on the other hand, cracks are more likely to initiate and propagate. One of the main difficulties in analysing partial slip problems is that the coefficient of friction is generally unknown inside the contact zone. Crack initiation is governed by the overall surface stress which is, of course, affected by the normal and shear tractions; and the latter are directly dependent on the coefficient of friction at the interface. Incomplete partial slip contacts generally have a central stick zone, where slip does not occur, and where the surface damage is often negligible. It is clear from experiments that the surfaces are significantly less damaged under partial slip when compared to gross slip cases. It has therefore been suggested that the coefficient of friction in a partial slip contact is different from that measured under gross sliding [2], and that in order to accurately predict the fretting fatigue life of components it is first necessary to obtain a good estimate of the coefficient of friction in the areas of partial slip.

The traditional method of measuring friction is by measuring the shear load necessary for sliding to occur. This assumes that the friction force depends on the normal force applied, P, and a coefficient of friction, μ, as given by Coulomb's law of friction, $Q = \mu P$. However, if a partial slip fretting contact is subsequently slid in this manner by applying a sudden overload, only the average friction coefficient will be obtained, rather than the slip zone value. Several methods have been suggested to estimate the coefficient of friction in partial slip contacts. Hills and Nowell [2] showed that by calculation of the evolution of the stick zone in a fretting experiment, it is possible to infer the coefficient of friction, μ_n, in the slip zones after n cycles from the measurable mean coefficient of friction, $\bar{\mu}$, during sliding. This gives

$$\bar{\mu} = \mu_n - \frac{2Q}{\pi P}\left\{-2\sin\alpha + 2\ln\left[\tan\left(\frac{\alpha}{2} + \frac{\pi}{4}\right)\right] + \frac{P\mu_n\alpha}{Q} - \tan\alpha\right\} \tag{1}$$

where $\cos\alpha = Q/\mu_n P$, P is the applied normal force and Q the applied shear force. This method has been used by several authors for Hertzian geometries and isotropic bodies [3,4]. Dini and Nowell [5] also extended this method to other geometries. However, Eq. (1) applies only when gross sliding takes place in the first few cycles. Hence some surface damage will occur everywhere within the contact. Vadivuchezhian et al. [6] used a similar technique to measure the effect of variable coefficient of friction on the contact traction. They assumed that the coefficient of friction is a function of the total distance slid by each surface point and used a small gross sliding test to predict the evolution of friction for each point in the partial slip contact. They have also shown that if the slip zone size does not change significantly during the test (e.g. Q/P remains constant), then accurate contact tractions are obtained by assuming a constant coefficient of friction

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throughout the contact. This coefficient is similar to the asymptotic value of the slip zone coefficient of friction. Several authors investigating the coefficient of friction in small amplitude reciprocating contacts have shown that it tends to converge to a value after a transient period of a certain number of cycles [6–8]. However, it is only adequate to use the asymptotic value of the coefficient of friction if the time scale of the asymptote is very small when compared with the time scale of crack initiation (i.e. the number of cycles for initiation is much greater than the number of cycles needed to obtain a converged value of the coefficient of friction in reciprocating gross sliding tests).

An alternative approach for measuring the coefficient of friction in partial slip contacts was suggested by Reina et al. [9]. This method consists of varying the location of the slip zone inside the contact, such that every point in the contact slips at some instant during the loading cycle, but at each instant there is a zone in the contact which is stuck. Hence, the contact is always in partial slip regime, but can be made to displace (or "walk") along the specimen. Less surface damage is observed in this approach than in the one suggested Hills and Nowell [2], since it is not necessary to reach the sliding limit of the contact pair. Instead, the coefficient of friction may be obtained from the shear force which causes transition from stationary behaviour to rigid body motion of the pad. Alternatively, and more practically, an estimate may be obtained from the displacement, Δs, of the pad during each load cycle. This approach has been used to measure the coefficient of friction between similar polycrystalline nickel superalloys and for single crystal Nickel superalloy pads pressed against polycrystalline specimens. The results are presented in this paper.

Many authors have also correlated the energy dissipation concept with damage. Fouvry et al. [10] have associated the energy dissipation in gross slip contact problems with the wear rate. It has been shown that axi-symmetric contact problems, e.g. two spheres in contact, have a finite constant displacement at any point sufficiently far from the contact region [11]. Following the work of Mindlin, Fouvry et al. [12] have obtained an analytical solution for the ratio between the energy dissipated and the total energy available. Using the analytical solution for the energy dissipated in a spherical contact problem given by Fouvry et al. [13], Pasanen et al. [14] have presented an energy approach for calculating the energy dissipated that works for the three slip regimes; partial, mixed and gross slip. The approach used in [13,14] depends largely on the fact that for a contact between two spheres, or a sphere on a plane, the displacement at any point far enough from the contact region is finite and converges to a value which can be obtained analytically. In a two-dimensional half-plane problem this is not the case. The solution of the displacement has a logarithmic form and tends to infinity as the distance from the contact centre increases. However, the work done by each point at the interface due to the slip and shear tractions ought to match the total energy dissipated. Therefore, a study of the energy dissipated at the contact interface of 2D Hertzian contacts will also be presented, together with a discussion of possible energy based methods for plane contact problems.

2. The "walking pad" friction test

2.1. Experimental procedure

The "walking pad" tests were conducted using the fretting fatigue experimental rig with two in-line actuators, as illustrated in Fig. 1a. An LVDT sensor was used to measure the relative net displacement between the centre of the contact and the pads. The armature was attached to the specimen at the centre of the contact and the body was attached to the pad holder (Fig. 1b). During the test, the pads are pressed onto the specimen with a constant normal force P=2.5 kN, resulting in a peak contact pressure $p_0 \approx 80$ MPa which is below 1/10 of the yield limit of Nickel superalloys. Hence, no plastic deformation due to the normal contact pressure occurred. Then, a cyclic bulk tension, σ, is applied to the specimen. The range of the bulk tension cyclic load is raised to a specified amplitude and then kept constant throughout the test. Using the second (small) actuator, the shear force between the pads and the specimen is incrementally increased in a "staircase" fashion. Schematic representations of the loading history and of the applied loads are displayed in Fig. 2a and 2b. In each shear force step, the test ran for about one minute, equivalent to 15 cycles of the bulk tension. The pads remain in partial slip regime at all times and, as the shear load increases, reverse slip starts to occur at the edges of the contact. After a certain value, the stick zone moves from one side to the other in the contact, such that the pads start "walking" along the specimen without ever fully sliding. The higher the coefficient of friction the slower the rate of displacement. During the experiments, the shear loads and displacement data were recorded. With this information, it is possible to calculate an average displacement, Δs, per load cycle for each shear force increment and, hence, the coefficient of friction...

The solution of the rate of displacement for the "walking" problem can be obtained by quadratic programming [9]. By comparing the quadratic programming solution for different values of coefficient of friction with the experimental data, it is possible to infer the value of the coefficient of friction by interpolation of the experimental results. The coefficient of friction can also be obtained by the shear load limit at which the pads start to walk. However, it is extremely hard to define experimentally the precise moment in which the pads start accumulating a net displacement at the end of each cycle. Examples of the graph that were used to interpolate the coefficient of friction are presented in Figs. 3 and 4. The solid lines represent the displacement per cycle obtained from the quadratic programming solution for each coefficient of friction μ as the ratio Q/P increases from 0 to 1. The blue cross points are the displacement per cycle obtained experimentally, with an appropriate normalization. This normalization takes into account the peak pressure, p_0, the contact semi-width, a, and the elastic compliance between the materials, A[1]. Note that for the nickel single-crystal superalloy pads, these variables were obtained by solving the anisotropic contact solution presented by [15]. In the case of the elastic compliance, it can be shown that the constant, A, used in isotropic solutions is equivalent to $\mathrm{Re}(\gamma)$ in the equation for the contact pressure of anisotropic bodies given in [15]. Finally, the green circular points (right hand axis) represent the values of the coefficient of friction - obtained by matching the experimental data and the quadratic programming solution for the rate of displacement.

As second measurement of the coefficient of friction was carried out using the standard gross sliding test. At the end of each "walking" test, the cyclic bulk loading was interrupted and the shear load reduced to zero. Then, the pad carriage actuator was changed to displacement control. A displacement ramp was then applied (i.e. constant actuator velocity), inducing the pad to slide along the interface of the specimen. As the pad was sliding, the shear force, Q, was measured, from which the sliding coefficient of friction can be calculated, by averaging the load ration Q/P throughout the sliding phase. Problems associated with this method include the fact that the pad surfaces are significantly damaged during the test. One of the problems of using this method to partial slip contacts is the fact that the pad surfaces are significantly worn out during the test, which does not happen in partial slip. Furthermore, at the beginning of the gross sliding tests, the surfaces of the pad were already slightly damaged, since the tests were carried after the "walking pad" test. Hence, the coefficient of friction measured at the early stages of the gross sliding tests are also not representative of the undamaged partial slip contact where the central slip zone does not experience any surface damage. Note that, although the partial slip test always had a central stick zone, in the "walking pad" test, the stick

[1] For isotropic contacts, the contact elastic compliance is given by $A = (\kappa_1 + 1)/4G_1 + (\kappa_2 + 1)/4G_2$, where κ_i is the Kosolov's constant, defined as $\kappa = 3 - 4\nu$ for plane strain, and G_i is the shear modulus of body i=1,2.