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Energy based approach for the evaluation of damage under partial slip and gross sliding condition

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ABSTRACT

Three possible contact conditions may prevail at a contact interface depending on the magnitude of normal and tangential loads, that is, stick condition, partial slip condition or gross sliding condition. Numerical techniques have been used to evaluate the stress field under partial slip and gross sliding condition. Cattaneo and Mindlin approach has been adapted to model partial slip condition. Shear strain energy density and normalized strain energy release rate have been evaluated at the surface and in the subsurface region. It is apparent from the present study that the shear strain energy density gives a fair prediction for the nucleation of damage, whereas the propagation of the crack is controlled by normalized strain energy release rate. Further, it has been observed that the intensity of damage strongly depends on coefficient of friction and contact conditions prevailing at the contact interface.

1. Introduction

Dynamic responses are generally analyzed by representing the friction that occurs at contact surfaces by means of single point contact coulomb friction model. By using coulomb friction model, it is effectively assumed that the bodies in contact are rigid, and the friction force at the interface is proportional to the corresponding normal force [1]. Experimental studies [2,3] have shown that this idealization of the problem may be acceptable, only if shear force at the contact interface exceeds the product of coefficient of friction and normal load. However, under high normal load or high coefficient of friction, partial slip condition may occur. Partial slip condition results in microscopic movement at the contact interface, in an annular region, without the inception of gross sliding, and is thus, sometimes also referred to as pre-sliding condition. In partial slip or pre-sliding condition, the center of contact remains stationary while the edges reciprocate with lower amplitude resulting in more wear damage in the annular region [4]. Such conditions resulting in small amplitude oscillatory movement between two contacting surfaces for a large number of cycles are generally characterized under fretting.

Mindlin [5] has given an elegant analysis of relative displacement of two normally loaded elastic bodies, under the action of a monotonically increasing tangential force and extended the analysis to an oscillatory tangential force. In his analysis, it was assumed that under gross sliding or micro slip condition, the shear stress on the surface would be everywhere proportional to the normal stress and the constant of proportionality being the same as the coefficient of friction. The main emphasis in the analysis was made on the estimation of surface traction and surface compliance under partial or pre-sliding condition. The experimental investigations carried out by Johnson [6] for micro-displacement between two contacting bodies, under the action of tangential forces less than that of limiting friction, show good agreement with the elastic model as regards the displacement at incipient slip. Experiments were performed on unlubricated contact of a hard steel ball with hard steel flat under both steady and oscillating tangential forces. The quantitative results of the experiments provide considerable support for Mindlin theoretical elastic analysis.

Effects of friction on the stress field under gross sliding condition have been studied by various authors [7–9]. Explicit equations for surface and subsurface stress distribution for normally loaded circular hertzian contact under gross sliding condition were given by Hamilton [7]. Experimental results illustrating the effect of these stresses were obtained by Gilroy and Hirst [10]. From these studies, the effect of friction is quantified on the basis of an increase in the tensile stress at the trailing edge of the contact and shift of maximum von Mises yield parameter ($\sqrt{J_2}$) from depth of $0.48a$ (under normal load) to the surface. The effect of friction was found very substantial for coefficient of friction greater than 0.3.

Various numerical analyses [11–14] based on finite element methods have been carried out to simulate partial slip condition for the estimation of elastic stress field and prediction of fretting

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damage. Ketan et al. [15] in his studies used explicit expressions for stress field as given by Hamilton [7] and adopted the superposition approach for the evaluation of stress induced by a spherical indenter, under partial slip condition. His study shows that the maximum normal tensile stress at the trailing edge increases significantly under partial slip condition compared to gross sliding condition.

Macroscopic failure criteria may be classified into four different types, that is, stress or strain failure criteria, energy type failure criteria, damage failure criteria, and empirical failure criteria. Nucleation or initiation of fretting damage can be predicted either based on stress criteria or on the basis of damage parameter having some empirical basis. Stress based criteria consider either the von Mises yield parameter ($\sqrt{J_2}$), or the occurrence and distribution of maximum principal stress. In stress based criteria, the effect of slip amplitude is not taken into account. In order to account the effect of slip amplitude, Ruiz and Chen [16] as part of their experimental investigation on fretting of dovetail roots of turbine blades, proposed a damage parameter, $\tau\delta$, where τ is maximum shear traction and δ is local value of microslip among the contacting surfaces. Later, they recognized that the presence of tensile stress at trailing edge parallel to the surface would promote crack formation, whereas a compressive stress at leading edge would inhibit it. Thus, damage parameter revised to $\sigma\tau\delta$, where σ is tensile stress parallel to the surface.

Various studies [15–17] have been carried out for determining stress intensity factor driving subsurface crack propagation under fretting fatigue condition. The difference between fretting and fretting fatigue condition is that in addition to surface normal and tangential loads, bulk cyclic loading also drives fretting fatigue. A possible mechanism of initiation of fatigue cracks was explained based on the formation of slip bands at the trailing edge due to cyclic normal stress [18]. Lamacq et al. [19] carried out detailed studies on the prediction of crack nucleation and their growth under fretting fatigue condition based on surface and subsurface stress field. Dubourg et al. [20] carried out a detailed study on the crack initiation and propagation under fretting fatigue condition, and discussed various stages involved in crack nucleation and their growth. Recently, Talemi et al. [13] carried out detailed numerical modeling of fretting fatigue in turbine dovetails. From all these studies, it can be concluded that crack initiation is primarily governed by local contact stresses, whereas propagation is more related to the far field, or bulk stresses. It has also been observed [13, 20] that the shear cracks nucleate at a shallow angle to the specimen surface, ranging from 15° to 35°, while tensile cracks due to bulk stress grow in a direction close to 90°. Fretting fatigue lives are generally predicted using multiaxial plain-fatigue parameters such as Smith–Watson Topper (SWT), Fatemi–Socie, McDiarmid, and Crossland [21]. These parameters have produced reasonable predictions of fretting fatigue life under partial slip condition. Yamashita and Mura [22] carried out a detailed study on contact fatigue damage under repeated oblique force. Their investigations mainly emphasized on the effect of repeated application of a one directional tangential load in stationary line contact. Test results identified cracks normal to the axis of the specimen, and propagated towards the center of the contact zone at an angle of 40–50° to the surface. Recently, experimental studies carried out by the authors [23] for self-mated stainless steel under seizure or presliding condition show subsurface damage in the form of multiple cracks and are found to propagate toward the center of the contact zone at an angle of 45–54° to the surface. Recently, Zhang et al. [24] adopted a more general fatigue damage approach to unify wear and fatigue prediction for fretting.

Till date the concept of crack growth explicitly from contact stress field is not very well understood. The stress field induced by the contact has a predominant effect on crack growth and this aspect is detailed in this paper. An important aspect discussed here is to propose the criteria for damage nucleation and crack propagation. Energy based approach has been adopted to study these aspects, and the influence of coefficient of friction and contact conditions prevailing at the contact interface is investigated in detail. Further, fracture mechanics approach has been adopted to quantify the influence of the stress field on the propagation of the cracks under different contact conditions prevailing at the contact interface.

2. Mathematical formulation

Mindlin [25] developed the stress field for point loadings on the surface of a semi infinite body. The coordinate system used in the evaluation of stress field is shown in Fig. 1. Under normal load, the hertzian pressure distribution at the contact interface can be expressed as

$$p(x,y) = p_o\left\{1-\left(\frac{x-x_0}{a}\right)^2-\left(\frac{y-y_0}{b}\right)^2\right\}^{1/2} \tag{1}$$

where a and b are the major and minor axes of the contact ellipse, x and y are the coordinates with origins at the center of the ellipse, x_0 and y_0 are the locations at the point load relative to the center of Hertz ellipse and p_o is the maximum Hertz pressure. A general approach for determining the nine components of the stress tensor at any given point can be written as [26],

$$\sigma_{ij} = p_o\int_{x_1}^{x_2}\int_{y_1}^{y_2}\left[\frac{\sigma_{ijN}}{P_N}+\frac{\mu_T\sigma_{ijT}}{P_T}+\frac{\mu_A\sigma_{ijA}}{P_A}\right]p(x,y)dxdy \tag{2}$$

where limits can be defined as, $x_1=x_0-a$ and $x_2=x_0+a$, and $y_1=y_0-b\ \sqrt{1-(x-x_0/a)^2}$ and $y_2=y_0+b\ \sqrt{1-(x-x_0/a)^2}$. In the present study, the above equation has been solved using numerical integration for each individual stress state. The accuracy of the above solution strongly depends on the integration method adopted for solving double integration. Numerical integration has been carried out using 61-point Gauss–Kronrod quadrature. Gauss–Kronrod quadrature is a variant of gaussian quadrature, in which the evaluation points are chosen so that an accurate approximation can be computed by re-using the information produced by the computation of a less accurate approximation. The difference between these two approximations is used to estimate the calculation error of the integration [27].

Evaluation of stress field at surface and subsurface region has been carried out by integrating Eq. (2), where σ_{ijN}, σ_{ijT}, and σ_{ijA} are stress tensors obtained from point loadings on the surface in normal, tangential and axial direction, respectively. The stress field due only to hertzian pressure distribution (Eq. (1)) has been evaluated by neglecting friction, that is, $\mu_A=\mu_T=0$ (Eq. (2)). Von Mises shear stress distribution under normal loading has been compared and found to be in good agreement with analytical

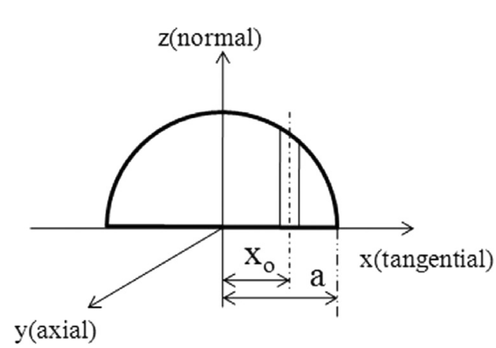

Fig. 1. Coordinate system used for stress field computations [24].