Engineering Fracture Mechanics 76 (2009) 2344–2358

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

journal homepage: www.elsevier.com/locate/engfracmech

Fracture mechanics assessment of stress concentrations in incomplete fretting contacts

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ARTICLE INFO

Article history:
Received 25 February 2009
Received in revised form 29 April 2009
Accepted 1 July 2009
Available online 7 July 2009

Keywords:
Singular stress field
Stress intensity factors
Contact stress concentration
Fretting fatigue
Sticking friction
Slipping friction

ABSTRACT

Life assessment of fretting fatigue has been studied for decades. Crack-analogy methods have been proposed for analyzing fretting fatigue of flat contact pairs. In the present work we re-consider the stress field near fretting contact pairs and study the feasibility of using known fracture parameters to assess incomplete fretting contact problems. Both analytical and FEM analysis reveal that the stress field near the discontinuous round corner of a friction pad, in which the round surface has been idealized without contacting the workpiece, is the same as that of crack tip. The stress field is described by the known stress intensity factors, K_I and K_{II}. For sticking contact these two fracture parameters are independent, whereas for the slipping contact K_{II} is linearly correlated with K_I. Therefore, the stress field around the slipping contact can be characterized only by one fracture parameter, together with friction coefficient. For the continuous contact pairs with finite round contact surface, the local stress concentrations near the contact edge are finite and can be characterized by K_I and K_{II}, either, in analogy to the blunting crack tip due to finite strains. Detailed computations confirm that using the fracture parameters to characterize the fretting contact failure is affected by both loading condition and friction pad geometry. The dominance zone around the pad corner decreases more significantly with vertical press load than the horizontal friction load. In the bi-material contact friction pair the stress field can be described by K_I and K_{II} in the same form.

1. Introduction

In engineering fretting fatigue is responsible for a large number of service failures [1]. Numerous experiments display that the fretting will reduce the life of components more than 50% under the same operation loading [2]. The problem of fretting fatigue, however, is related to high stress gradients, non-proportional multiaxial loading, and surface effects, which is difficult to be characterized by conventional fatigue criteria. In past decades a significant progress has been made in understanding fretting phenomena. Experimental observations in flat friction pairs confirm that cracks initiate directly near the edge of the friction pad [1,3,4]. The fatigue crack is related to stress concentrations in a small region near the pad edge. The published life assessments assume that the life of fretting fatigue can be expressed by the local stresses and local strains [2,3,5,6]. Due to sensitive contact conditions in test fixtures, the local stress fields near the friction pad edge may significantly vary with loading configurations and with loading cycles. It follows that the experimental results generally show large scattering and cannot give a reliable prediction of fretting life. No consensus has been achieved in assessing fretting fatigue.

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0013-7944/$ - see front matter
doi:10.1016/j.engfracmech.2009.07.004

Nomenclature

A	loading area of the pad
E	young's modulus
H	the shear load for fretting on the friction pad
K_I	stress intensity factor for mode I crack
K_{II}	stress intensity factor for mode I crack
K_n	the amplitudes of stress expansion in asymptotic analysis with $n = 0, 1, 2, \ldots$
m^p	the mode mixity after Shih [19]
m^T	the mode ratio of mode II to mode I ($m^T = K_{II}/K_I$)
P	the vertical load on the friction pad
(r, θ)	the polar coordinate system centered at the corner of contact pad. r is the distance to the tip. $\theta = 0$ denotes the contact surface; $\theta = \pm\pi$ stands for the free surface behind the contact zone
R_0	the rounding radius of the friction pad corner
r_{in}	the characteristic size of the zone where finite strains and nonlinear effects dominate
r_{out}	the characteristic size of the K dominance zone
s	the leading singularity of stress fields around the tip
u_i	displacement vector, $i = (r, \theta)$ for polar coordinate system and (x, y) for cartesian coordinate system
$\tilde{u}_i$	the angular function of the displacement vector
β	open angle of a V notch. $\beta = 0^\circ$ denotes a crack and $\beta = \pi$ stand for a smooth surface
ϵ_{ij}	strain tensor. $i, j = (r, \theta)$ for polar coordinate system and (x, y) for cartesian coordinate system
$\tilde{\epsilon}_{ij}$	the angular function of the strain tensor $i, j = (r, \theta)$ for polar coordinate system and (x, y) for cartesian coordinate system
μ	friction coefficient in the Coulomb's friction law
σ_0	nominal yield stress of the material ($\sigma_0 = E/300$). The variable is just introduced for non-dimensionalize the variables
σ_{ij}	stress tensor. $i, j = (r, \theta)$ for polar coordinate system and (x, y) for cartesian coordinate system
$\tilde{\sigma}_{ij}$	the angular function of the stress tensor. $i, j = (r, \theta)$ for polar coordinate system and (x, y) for cartesian coordinate system

Based on asymptotic analysis for the rigid orthogonal indenter pressed against a frictionless flat surface, Giannakopoulos et al. [7,8] suggested a new fretting model, which was further developed by other research groups [3,9,10]. They confirmed that there are some similarities between the asymptotic stress fields close to the edge of a flat pad corner and those around an elastic crack tip. The singularity of the stress field is exactly equal to 1/2 as a crack. The original results of Giannakopoulos et al. [7,8], however, are rather restrictive in terms of the specimen geometry. The premise for such kind of crack analogy is that the friction pad is rigid, orthogonal contacting incompressible elastic substrates. The application to practical fretting situations is therefore not entirely straightforward.

A systematic work [11,12] indicates that the stress singularity around a sharp corner of indenter, Fig. 1c, varies with both finite friction coefficient and angle of the friction pad, β in Fig. 1c. More curious is that the stress singularity is to exceed 1/2 for the case of higher friction coefficients and $\beta = 90^\circ$ [11,12]. That is, the stress field around the fretting pad would be more singular than the elastic crack solution. This prediction would physically mean a singular fracture energy release rate for fretting crack propagation. It raises doubts in relevance and applicability of the singular stress fields to the real fretting problems. More asymptotic analysis for various friction contact cases, e.g. complete contact, almost complete contact and incomplete contacts, has been published [3,9–11,13] to establish a new framework for assessing fretting frictions. However, the asymptotic solutions are based on postulates which are not consistent to practical applications. On the other side, the real fretting contact is generally the *incomplete contact* as shown in Fig. 1a, in which the round surface of the friction pad will contact the workpiece and the contact area depends on loading configuration and material stiffness. Generally it is a geometrically nonlinear problem. The stress singularity has to vanish in the near field around the contact tip. Ciavarella [14] predicted that one may not directly use the fracture parameters to assess fretting fatigue.

In engineering applications the friction pad is rounded to avoid high stress concentration and to keep manufacturing tolerances. Generally the fretting contact can be represented by the model in Fig. 1a. From above discussions the following questions for the round friction pad are remained to clarify: (1) Which singular stress fields are more related to a realistic fretting contact pad, even for the problem of complete contact (Fig. 1b)? (2) How should dominance of the singular stress fields in the incomplete contact, s. Fig. 1a, be quantified? Both questions are related to characterization of the fretting friction contact.

The fretting fatigue problem is highly nonlinear and sophisticated because of the moving stick-slip boundary, cyclic plastic deformations and the oscillatory loading. The problem addressed in the present work is just characterization of stress concentration for a special contact mechanics problem that is relevant to fretting fatigue. Generally, one may assume that the material failure is dominated by the local stress field, that is, the fretting fatigue can be clarified only if the local stress field is understood. In this sense the fretting fatigue of the present work is limited to contact mechanics analysis.