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Prediction of fretting crack propagation based on a short crack methodology

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Abstract

Fretting tests have been conducted to determine the maximum crack extension under partial slip conditions, as a function of the applied tangential force amplitude. An analytical elastic model representing a fretting-induced slant crack has been implemented and combined with the Kitagawa–Takahashi short crack methodology. This approach provides reasonable qualitative agreement between experimental and predicted maximum fretting crack lengths as long as the global response of the interface remains elastic. It confirms the stability of the crack arrest approach to predict the fretting fatigue endurance. It is, however, observed that the model is systematically conservative when significant plastic deformations are generated in the interface. A discussion of the appropriate fundamental parameters when dealing with steep stress gradients such as those present in fretting, and which are difficult to interpret in the context of the Kitagawa–Takahashi method, is presented. It is also shown that the maximum crack length evolution under plain fretting wear test conditions can be used to calibrate fretting fatigue predictions.

Keywords: Crack arrest; Fretting cracking; Kitagawa–Takahashi diagram; Short cracks; AISI 1034 steel

1. Introduction

Fretting is a small amplitude oscillatory movement, which may occur between contacting surfaces subjected to vibration or cyclic stress. Fretting is therefore encountered in assemblies of components subjected to vibration, and thus concerns a wide range of industries (e.g., helicopters, aircraft, trains, ships, trucks and electrical connectors) [1]. Fretting *damage* on the contacting surface is critically controlled, under sliding conditions, by the amplitude of slip displacement [2,3]. Under large amplitude gross slip conditions, where the whole surface is fretted and wear processes associated with debris formation and ejection dominate, friction energy wear models have been introduced [4]. Under partial slip conditions, initiation of fatigue cracks is generally a more significant concern than wear. Fretting fatigue tests, which combine a fretting contact and bulk fatigue

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loading, are classically used to investigate this regime [5]. The fretting and bulk fatigue loading are interdependent, and this feature complicates the investigation of their respective impacts. Fretting fatigue has a strong influence on both crack nucleation and early propagation, whereas bulk loading controls subsequent 'long crack' propagation [5]. Hence, a sequential strategy involving crack nucleation, short crack propagation and long crack propagation approaches has been developed [5–7].

Because of the very severe stress gradients imposed on the contact surface, a direct application of a fatigue analysis based on a stress *at a given point* is not appropriate. Therefore, approaches which take a length scale into account need to be considered, combining either a stress-averaging process volume [8,9] or an equivalent notch similitude description [10]. Prediction of subsequent crack propagation, and conditions for potential crack arrest, is less well understood [7,11]. Crack propagation is generally affected by the contact loading as well by the bulk remote load. If a linear elastic fracture mechanics approach is adopted, most of the literature suggests that the crack will arrest if the stress intensity range ΔK falls below a threshold value (ΔK_{th}) [12]. The critical question then becomes: 'What is the threshold value?'. It has been extensively reported that short cracks propagate at nominal stress intensity levels below the long crack threshold [13]. Araújo and Nowell [7] applied a method based on the Kitagawa–Takahashi diagram [13] to resolve the paradox of propagating short fretting cracks. An alternative starting point, employing a 'short crack correction', was developed by El Haddad et al. [14] and may be used to predict fatigue thresholds. It may be shown that the two approaches are essentially similar: the former modifies the threshold, whereas the latter modifies the crack driving force. However, as noted in [7], a definitive validation of the concept will require a comparison of the experimental and predicted maximum crack extension beneath a contact. The purpose of the research reported here is therefore to investigate this aspect by combining well-defined fretting experiments with a detailed model of crack evolution, taking into account crack location and orientation.

A second aspect concerns the stability of this crack arrest methodology versus the stress–strain loading range and more particularly the impact of plastic contact deformation on the crack arrest prediction. To simplify the analysis, a single 2D cylinder/plane fretting geometry has been chosen, under purely alternating load. This allows a systematic crack arrest condition to be investigated, and simplifies the stress analysis. By comparing the experimental crack propagation with the evolution of the calculated mixed mode stress intensity factor, the stability of the short crack arrest methodology has been evaluated. The experiments were carried out using a well-defined low carbon steel under low elastic and high elastoplastic pressure configurations.

2. Experimental

2.1. Test system

The experimental setup used in this study is based on a fretting device rigidly mounted on to a servo hydraulic test machine (Fig. 1). Further details of this setup and the experimental methods used can be found in [8,15].

A partial-slip cylinder-on-flat contact configuration was used. Fretting was applied by imposing a nominally static normal force, F_n, followed by a purely alternating cyclic displacement amplitude (δ^*). As a consequence an alternating cyclic tangential load (F_t) was generated on the contact surface. During a test, F_n, F_t and δ were recorded, from which the δ–F_t fretting cycle can be plotted; this cycle is characterized, respectively, by the tangential force (F_t) and slip displacement (δ^*) amplitude. The radius of the 52100 steel cylinder is $R = 40$ mm and the pad length $L = 5$ mm, giving plane strain conditions near the central axis of the fretting scar (Fig. 1b). Two linear normal loads are applied: $P = F_n/L = 227$ N/mm and $P = 540$ N/mm. The lowest normal loading induces a maximum Hertzian pressure of $p_{0H} = 450$ MPa and a Hertzian contact half-width of $a_H = 321$ μm. The highest infers $p_{0H} = 700$ MPa and $a_H = 500$ μm, respectively. Fretting tests were performed under constant-amplitude displacement at a frequency of 40 Hz. Note that under stabilized (steady state) partial slip conditions, a quasi-linear relationship exists between the displacement and tangential force amplitude. By exploiting this behaviour, the imposed displacement amplitude was adjusted to monitor constant tangential force amplitudes ($Q^* = F_t$/L).