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Effects of fatigue damage and wear on fretting fatigue under partial slip condition

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ABSTRACT

The continuum damage mechanics model incorporating wear was developed in the previous paper by the authors [27] to predict the fretting fatigue crack initiation life for both cases of partial slip and gross sliding. In the present study, the effects of external parameters on the fretting fatigue crack initiation behaviour under partial slip condition are investigated systematically. Firstly, a different fatigue damage accumulation rule is used, which can predict a more reasonable damage process. Secondly, the effects of the relative slip amplitude and wear coefficient are evaluated based on the improved approach. It is significant to note that the impact of wear coefficient on the fretting fatigue life is non-monotonic, and the action mechanism of that is analysed in detail in this work. Finally, the combination and competition between fatigue damage and wear are presented. The results indicate that none of the fatigue damage and wear can be neglected in the fretting fatigue life prediction.

1. Introduction

Fretting fatigue is a process of damage accumulation that occurs when two bodies in contact experience small reciprocating motion. Depending on the relative slip status between the two contacting bodies, fretting fatigue can be classified into two different regimes: the partial slip regime and the gross sliding regime. In the partial slip case, relative slip only occurs in the portions of the contact zone and mainly results in crack nucleation. In the gross sliding case, all the contact surfaces experience relative slip and the main form of fretting damage is wear. The behaviors of the above fretting failure forms were widely investigated in the past decades.

Numerous efforts were undertaken to understand the behavior of fretting crack nucleation. The critical plane method based on the multi-axial fatigue model is widely used to predict the fretting fatigue crack initiation life, which looks for the maximum value of a predefined fatigue damage parameter over a number of planes and predicts the crack initiation life based on that maximum value. The location and orientation of the fretting fatigue crack are also obtained using the critical plane method [1–4]. Vázquez et al. [5] combined the finite element simulation and the critical plane method to investigate the effect of a textured surface on fretting fatigue. With the improved understanding of the behavior of fretting fatigue, further attention was devoted to the role of wear on the fretting fatigue. Two kinds of wear models, the Archard wear model and the energy wear model, were proposed by Archard [6] and Fouvry et al. [7] respectively to describe the wear mechanisms. Zeise et al. [8] proposed a novel comprehensive modeling approach to simulate the complex fretting wear process of assemblies including abrasion, corrosion, accumulation and transport of the produced debris during dynamic loading. The effect of wear is then combined with the critical plane method to predict the behavior of fretting fatigue crack initiation [9–12]. Recently, the effect of surface wear was investigated by the fretting-fatigue map concept [13] which was used to predict the crack nucleation and crack arrest boundaries [14]. However, there are two modelling simplifications in the critical plane approaches that need improvement. The first one is the Miner–Palmgren rule based on the accumulated fatigue damage, which ignores the effect of the loading sequence. The other one is the fatigue damage that is computed independently according to the stress and strain fields without accounting for the effect of fatigue damage on the stress and strain fields.

Actually, Fretting fatigue life consists of crack nucleation life and the crack propagation life. These two issues often need to be separately modelled, as in the literature [15–19]. An important aspect of the “nucleation-propagation” method is the initial crack length for the propagation period. It is difficult to define the

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macroscopic crack length, which is dependent on several factors. In the macroscopic approaches, such as the critical plane method, 10 μm is a common used value for Ti–6Al–4V [15], which means that the crack length is about 10 μm after the crack nucleation. In the work of McCarthy et al. [18,19], the micro-mechanical approach was used and a shorter initial crack with the length of 1.2 μm was used for 316 L SS. However, for some cases the crack propagation life is very short comparing to the crack nucleation life, in which the crack propagation can be neglected. This paper focuses on the crack initiation behavior of fretting fatigue, which means the research is mainly fit for the cases when the crack initiation life is the majority of the entire fatigue life.

The continuum damage mechanics (CDM) approach has been introduced in the fretting fatigue problem. A damage variable is defined as a measurement of micro-cracks and micro-voids in the material. The approach deals with the mechanical behaviour of a deteriorated medium at the macroscopic scale and evaluates progressive damage based on the damage evolution law derived from thermodynamics until damage reaches a certain critical value. Many CDM approaches have been used for the fretting fatigue problem, including uncoupled CDM approach [16,17,20], coupled CDM approach [21], and coupled CDM approach with micro-structural characterization [22]. However, the effect of wear, which is less severe than that in the gross sliding case but still exists in the partial slip case [23–26], is ignored. In the previous paper by Shen et al. [27], a coupled CDM approach with consideration of wear was developed to predict the fretting fatigue crack initiation life for both cases partial slip and gross sliding. The damage coupled Chaboche plasticity model and a combined fatigue damage model are implemented in the approach. Besides, the progressive change of the contact geometry caused by wear was considered by using the energy wear model [7] in which a constant wear coefficient was specified. The results of the literature [27] agree well with the experimental data. However, two aspects are worth studying further as outlined below.

On the one hand, in the literature [27], the total fatigue damage is the sum of two components, the elastic damage caused by the cyclic stress and the plastic damage due to the plastic strain during each cycle. The accumulation method of fatigue damage gives reasonable prediction of the fretting fatigue life. However, a limitation of the method is that it is inappropriate for the cases with large plastic deformation. For such cases, the accumulation of fatigue damage is overestimated, resulting in significant error for the prediction of the fatigue life. Since higher wear coefficient is employed in this study compared to the literature [27], plastic strain induced by wear will be greater. A more general method was employed to investigate the fatigue damage evolution of notched specimens [28], in which the total fatigue damage is the greater one of the two components. Based on the similarity of the mechanical behaviour at the notch tip and the critical contact position such as the contact edge (the edge of whole contact zone) or the stick-slip interface (the interface between the central stick zone and outside slip zones), the improved accumulation method is adopted to predict the fatigue damage evolution of fretting fatigue.

On the other hand, the effects of external parameters, including relative slip amplitude and wear coefficient, to the fretting fatigue crack initiation behaviour under the partial slip condition need to be investigated systematically using numerical implementation. The effect of the relative slip amplitude was studied experimentally by Jin and Mall [29]. The fretting fatigue life decreases in the partial slip regime but increases significantly in the gross sliding regime as the applied relative slip amplitude increases. Numerical simulations were carried out by combining the wear model and the critical plane method to describe the effect on the fretting fatigue life in the literature by Ding et al. [30] and Madge et al. [10]. However, the effect on the contact stress and subsurface stress was discussed without consideration of the fatigue damage. Wear coefficient is the other important parameter influencing the fretting fatigue life. In these numerical investigations, the wear coefficient used in the wear model was usually determined based on the wear experiments. However, the conditions of the fretting fatigue simulated numerically do not match exactly with the wear experiments, such as the heat treatment of materials or the level of loading. Thus it is necessary to identify the sensitivity of the fatigue life to the wear coefficient. In this study, the effects of the relative slip amplitude and wear coefficient to the fretting fatigue crack initiation behaviour are investigated numerically by the coupled CDM approach with consideration of the fatigue damage and wear, in which a series of slip amplitudes and several wear coefficients are employed.

Besides, the competition between the fatigue damage and wear are described empirically according to the failure form of the fretting fatigue [10]. When the contact status changes from the partial slip to the gross sliding, the corresponding failure form also changes, from the initiation of fretting fatigue crack to the wear of the contact components. In this study, a more detailed description is studied using the evolution of the contact stress and subsurface stress along the contact surface which are affected by both the fatigue damage and wear.

In the present study, a different method of fatigue damage accumulation is employed to investigate the fretting fatigue crack initiation behaviour under the partial slip condition. The effects of the relative slip amplitude and wear coefficient are evaluated based on the improved approach. The progressive evolution of the fatigue damage and wear scar are simulated under several simulation conditions including five relative slip amplitudes and four wear coefficients. The combination and competition mechanism of fatigue damage and wear to the fatigue life is also identified.

2. Theoretical models

The coupled CDM approach includes three types of theoretical models: damage coupled constitutive model, fatigue damage model and wear model, which are briefly described in this section.

2.1. Damage coupled Chaboche plasticity model

Damage mechanics based model in solid materials is the creation and growth of micro-voids or micro-cracks which are discontinuities in a medium considered as continuous at a larger scale. A damage variable is introduced to estimate the progressive deterioration of the material due to fatigue loading. In this study the case of isotropic damage is assumed with a scalar damage variable D. Strictly speaking, fatigue damage is anisotropic even for the initial isotropic materials. However, in the framework of CDM, anisotropic damage models [31–33] are much more difficult to be adopted in the fatigue damage analysis due to the inconvenience in parameter calibration, the complexity of fatigue damage evolution and the huge time requirement for calculations. Therefore, the assumption of isotropic damage is still adopted for an approximation of the real situation, which can also provide an acceptable predicted result of fretting fatigue life [20,22].

In fretting fatigue, the elasto-plastic constitutive model is more appropriate to use as one calculates the stress and strain in the contact zone where plastic deformation may occur due to stress concentration. The Chaboche plasticity model [34] is adopted in this study due to its simplicity and ease of use. In the case of fatigue damage, the damage variable is coupled into the Chaboche plasticity model by using the effective stress in lieu of the stress used in the elasticity law and in the Mises yield criterion, which is based on the hypothesis of strain equivalence. The basic equations