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Fretting fatigue crack nucleation: A review

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ABSTRACT

This study aims to provide an overview of numerical and experimental work, related to crack nucleation under fretting fatigue conditions. In fretting fatigue, multiaxial loads and severe stress gradients are present at the contact interface, which can lead to failure. The damage process, in general, is considered as a two-phase phenomenon, namely, nucleation and propagation. Various damage models and approaches are available in literature to model each phase. In the present work, different criteria, related to nucleation phase, are classified based on the approach used to define failure. These approaches include, critical plane approach, stress invariant approach, fretting specific parameters and continuum damage mechanics. Apart from theoretical background, the work related to the applications of these approaches to fretting fatigue problems is also presented. It is observed that, to analyse various aspects, intricate details near the contact interface and mechanisms involved in fretting fatigue, the strength of finite element method can be employed. In the light of numerical and experimental observations, comparison between different approaches, common sources of errors in prediction and generalized conclusions are presented.

1. Introduction

Fretting occurs at the junction of contacting bodies due to the presence of oscillating force, which generates small relative displacement. The contact surface generally involves slip regions where relative displacement occurs at the edges of the contact and is complemented by stick region in the middle. This relative displacement causes surface degradation and heat at the expense of frictional energy [1]. The form of surface degradation depends largely on the material properties and geometry of contacting bodies, stress state, surface and environmental conditions, magnitude and sequence of loads. The amplitude of slip plays an important role under fretting conditions. At higher slip amplitude (gross sliding regime), wear causes severe surface damage, while crack formation is limited. This phenomenon is known as fretting wear [2–6]. On the other hand, at lower slip amplitude (partial slip regime), wear effects are small and the development of crack is dominant, which can be termed as fretting fatigue [7,8]. For estimation of life in fretting fatigue problems, the failure process is usually divided in two phases, namely, crack nucleation [9–11] and crack propagation [12–16]. The proportion of life taken by each phase significantly depends on the type of failure mode and definition of initiation crack length. Damage in a material may be considered as a continuous physical process, which leads to the failure of material. On physical basis, damage is related to plastic or irreversible strains either on microscale or mesoscale. Considering the microscale, this process involves the accumulation of micro stresses in the vicinity of defects and breaking of bonds. At mesoscale, it represents the coalescence of micro cracks or voids, which together can initiate one crack [17]. Therefore, the start of nucleation phase may be termed as damage initiation and end as crack initiation. In general, the initiation refers to formation of flaw, which encompasses a few grain sizes in length. In contrast, the propagation is often considered as the proportion of life, where crack behaviour can be described by fracture mechanics. Fretting fatigue can cause an early damage as it affects both nucleation and propagation phases of crack life.

The process of fretting fatigue involves multiple loads in different directions, which give rise to multiaxial and non-proportional stresses [18]. At the contact interface, severe stress gradients are present due to frictional and tangential loads [19]. Various approaches have been used by researchers to predict initiation location and life. Some approaches are based on empirical laws and physical observations, while others are based on thermodynamics principles. One such approach is known as critical plane approach (CP), which uses certain preferential planes to

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define failure parameters [20]. Based on CP approach, different multiaxial criteria have been developed by researchers that can characterize nucleation behaviour. The other popular approaches include continuum damage mechanics (CDM) approach, stress invariant (SI) approach and fretting specific parameters. In general, to estimate crack initiation life, these parameters are equated to fatigue strength limit (in fully reversed tension/torsion) or to Manson-Coffin and Basquin type relation [21]. The CDM approach employs mechanical variables to describe nucleation process inside a representative volume element (RVE) of mesoscale [22]. There are some other numerical techniques for crack analysis, which are based on cracking particles method [23,24] and dual-horizon peridynamics method [25,26], however applications of these methods are not proven under fretting fatigue crack nucleation.

In the present study, various aspects of damage or crack nucleation under fretting fatigue conditions have been reviewed. The sequence of the paper includes a generalized classification of crack initiation criteria, then a brief theoretical background and application of damage parameters to fretting fatigue problems. To review each approach, summary is presented at the end of each approach. For ease of understanding and review purposes, similar works are combined depending on the focus of the study and are not presented in strict chronological order. The last part of the paper provides a comparison of each approach, reasons of error in prediction and finally conclusions.

2. Classification of damage models

Researchers have used different approaches and damage parameters to study various aspects under fretting fatigue conditions. On conceptual basis, these approaches can be classified as Critical Plane approach, Stress Invariant approach, Fretting Specific parameters and CDM approach. Fig. 1 provides an overview of this classification. Although there are other parameters, the most popular ones are presented here, which has been successfully applied for fretting fatigue problems.

3. Critical plane approach (CP)

Critical plane approach refers to the calculation of damage parameters on specific planes, which are prone to cause failure. Depending on the failure mechanism, these planes are considered as maximum shear planes or planes perpendicular to maximum principal stress. The concept of critical plane was first introduced by Findley et al. [27] and Findley [28], by using stress components, under plain fatigue loading. For better understanding of critical plane concept, it is important to mention here the crack formation stages. According to Forsyth [29], the failure process can be divided into two stages; i.e. stage I, in which crack orientation coincides with maximum shear plane, and stage II, in which crack orientation coincides with planes perpendicular to maximum principal stress direction. It is generally believed that crack initiates along persistent slip bands in material crystals, which are aligned at or near to maximum shear planes. Later, various damage models were developed for multiaxial plain fatigue application, where critical planes were identified by stress based, strain based and strain energy density based concepts. Brown and Miller [30] analysed multiaxial fatigue by using state of strain on plane of maximum shear strain. Other promising work was contributed by Socie [31,32] and proposed two parameters one for shear mode failure and the other for tensile mode failure. Socie equated the damage parameters to Smith-Watson-Topper equation [33] to compute total failure life. According to Socie, the characteristic failure behaviour of the material should be known in priori, to select the suitable damage parameter for life estimation. The other multiaxial fatigue parameters, which were originally developed for plain fatigue and later adopted for fretting fatigue includes, Fatemi-Socie [34], McDiarmid [35] and Liu [36] parameters.

For fretting fatigue, the concept of critical plane was first adopted by Szolwinski and Farris [20] by using the concept proposed by Socie. They combined damage parameter with stress components to predict crack nucleation site and fretting fatigue life. The concept of critical plane as proposed by Szolwinski and Farris is shown in Fig. 2. Later, many other damage parameters, which were originally proposed for plain fatigue, were applied to fretting fatigue cases to predict crack nucleation location, initial crack orientation and crack initiation life. Based on the formulation, critical approach can further be classified as stress based, strain based and strain energy density based parameters. Although there are many damage parameters in literature [37,38], this article presents the

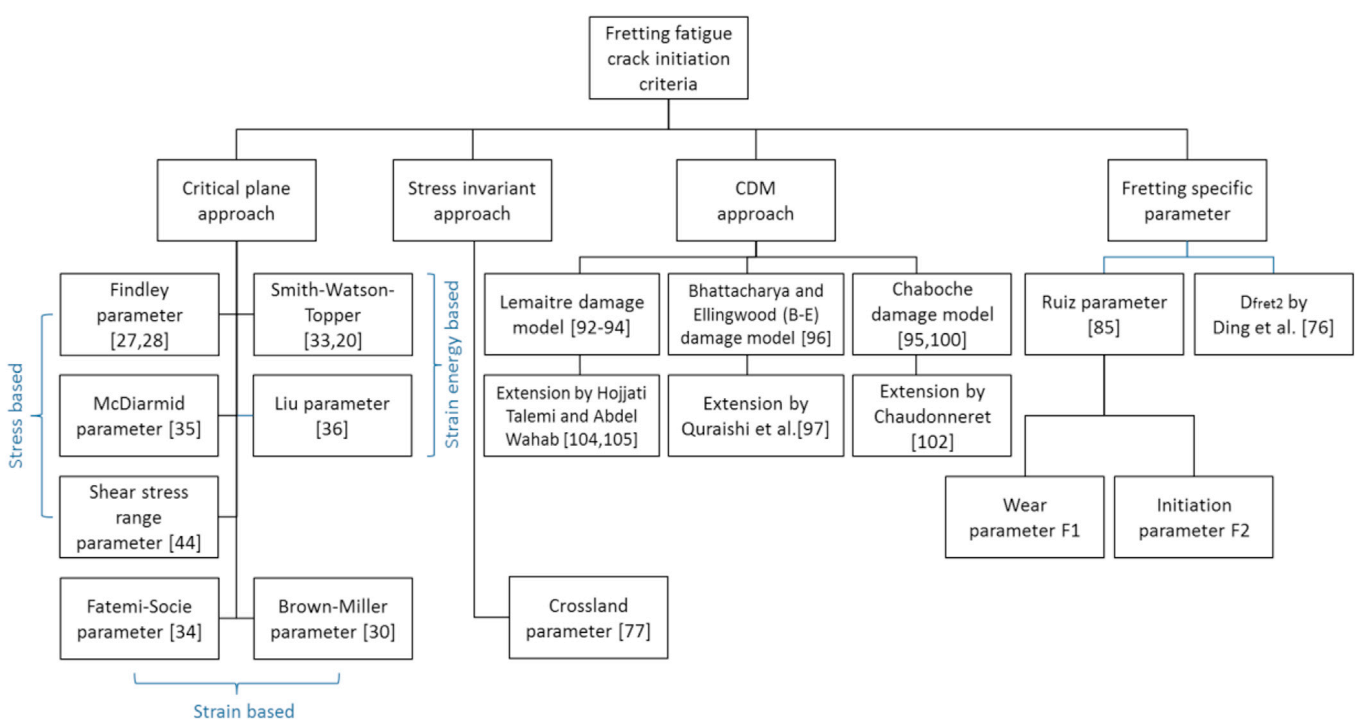

Fig. 1. Generalized classification of crack initiation criteria, applied to fretting fatigue.