Tribology International ■ (■■■■) ■■■–■■■

Contents lists available at ScienceDirect

Tribology International

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

Prediction of fretting fatigue crack initiation and propagation lifetime for cylindrical contact configuration

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ARTICLE INFO

Article history:
Received 14 June 2013
Received in revised form
4 February 2014
Accepted 20 February 2014

Keywords:
Fretting fatigue
Damage mechanics
Crack initiation
Crack propagation

ABSTRACT

A fretting fatigue failure scenario can be explained by accumulation of damage, which leads to formation of initial macro-cracks at the contact interface and propagation of macro-cracks to sudden rupture of bulk material. The main aim of this study is estimating these two portions by means of a numerical modelling approach. For this purpose, an uncoupled damage model based on a *thermodynamic potential function* is used to model the crack initiation lifetime. In order to model crack propagation part a linear-elastic fracture mechanics approach under mixed-mode loading conditions has been considered. The crack propagation direction is defined based on experimental observation and compared with some available criteria in the literature, which are usually used for proportional loading conditions. The estimated results are compared with observed experimental lifetime and show good agreement.

1. Introduction

Fretting fatigue damage occurs in contacting components while they are subjected to fluctuating loads and relatively small movement at the same time. There are many practical applications that are subjected to fretting fatigue, such as bolted and riveted connections, bearing shafts, blade-disk attachment in gas and steam turbines and aero-engine splined couplings [1]. The schematic view of experimental set-up of fretting fatigue for cylindrical contact is illustrated in Fig. 1. Two identical fretting pads are pushed against the fatigue specimen using constant load, *F*, which is called contact load and at the same time the specimen is subjected to oscillatory fatigue load. Therefore, in the presence of these two loads fretting fatigue failure occurs. Fretting fatigue failure evolution is caused by combination of several parameters, which can be related to a different mechanical response of material. These parameters can be divided into two sets of primary and secondary variables, which have more and less influence on fretting fatigue total lifetime. A fretting fatigue failure process can be divided into two portions of crack initiation and propagation. The primary variables also have different effects on each of these fractions of total lifetime. The number of cycles at which the macro-crack nucleates is called damage threshold. It is very difficult to separate the crack initiation and propagation portions of the total lifetime experimentally. On the other hand since tracking of crack under a fretting fatigue condition is a very challenging task, finding the damage threshold is almost impossible or very difficult. Therefore, in order to better understand each portion and estimate fretting fatigue total lifetime a numerical approach is a useful technique to model crack initiation and propagation lifetime separately.

There are many numerical approaches that have been used by researchers in order to model fretting fatigue crack initiation lifetime time based on multiaxial criteria such as critical plane approaches [2,3]. Some of these approaches have been reviewed in authors' previous works [4,5]. However, recently continuum damage mechanics (CDM) became more popular for modelling fretting fatigue damage [4–8]. In authors' previous works two different uncoupled damage models have been developed for elastic and elasto-plastic behaviour of material subjected to fretting fatigue cylindrical and flat contact configurations, respectively. In this study more information are given to clarify the difference between these two derived models and select the proper model for the right application. To this end, the uncoupled damage model, which has been developed by authors [4], was used in order to estimate fretting fatigue crack initiation lifetime for cylindrical contact configuration. The developed damage evolution model is based on the thermodynamics potential function, which was introduced by Lemaitre [9]. For this purpose, a parametric finite element (FE) model for fretting fatigue contact problem was modelled using the Python language along with the ABAQUS software. After verifying the FE model with analytical solution, which is given by Hills and Nowell [1], the crack initiation site was estimated based on dissipated energy during cyclic loading at the contact interface. The number of cycles to crack

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http://dx.doi.org/10.1016/j.triboint.2014.02.017
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Please cite this article as: Hojjati-Talemi R, et al. Prediction of fretting fatigue crack initiation and propagation lifetime for cylindrical contact configuration. Tribology International (2014), http://dx.doi.org/10.1016/j.triboint.2014.02.017

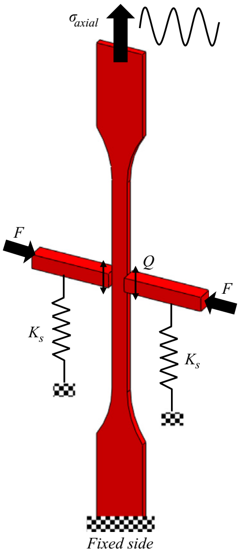

Fig. 1. Schematic view of the fretting fatigue experiments set-up.

initiation was estimated based upon the developed uncoupled damage model, which consists of the multiaxial stress state at the location of initial crack and the damage parameters, which were calibrated using the experimental results.

In terms of crack propagation, the initial crack was inserted in the contact model and advanced up to the final rupture of specimen. For fretting fatigue crack propagation, there are numerous studies [10–20] that have used a fracture mechanics approach to calculate fretting fatigue crack propagation lifetime. In this study the crack propagation part was modelled by means of the linear-elastic fracture mechanics (LEFM) approach under mixed-mode loading conditions. From an initial crack length, whose size is related to the microstructure of material, the advance of crack was modelled using the FE method. Recently a new FE mesh independent formulation, i.e. extended finite element method (XFEM) [18], became more popular due to its capability to model the crack inside the mesh without any remeshing technique. However, it has been shown by Hojjati-Talemi et al. [19,20] that, in the case of fretting fatigue 2-D model, both conventional FEM and XFEM approaches almost have the same accuracy, however, the conventional FE approach was easier to programme using the Python programming language and converges faster. Because, up to now XFEM implementation in ABAQUS has some drawbacks such as strong discontinuity issues, which lead to longer solver time. Despite, its longer solver time in the case of 2-D crack propagation, the XFEM approach is suitable for applications such as thin coated layers, which are difficult to be modelled using the conventional FEM technique. Moreover, in general the XFEM approach is developed to be a mesh independent method, while this is not the reality with the implementation in ABAQUS. According to authors' previous work [20], it was found that the mesh should be refined at crack tip to capture singular stress and strain field around it and to achieve an accurate result the mesh size at crack tip has to be at least below 3% of the crack size. Nonetheless, the conventional FEM is still promising approach as recently implemented to study fretting fatigue behaviour by Mohd et al. [21]. Therefore, in this investigation the conventional FE method including the remeshing technique was chosen to model fretting fatigue crack propagation.

Since fretting fatigue is highly non-linear and subjected to the non-proportional loading condition, finding the right crack propagation trajectory is an issue, when dealing with fretting fatigue crack propagation. Recently Giner et al. [22] have tried to propose a new approach for fretting fatigue problem under the complete contact condition. The model they proposed was based on the minimum value of shear stress range evaluated ahead of a crack tip during a full cyclic loading. Nevertheless, they validated their results under complete reverse cyclic loading in which the crack is closed during the majority of cyclic loading. However, in this study a positive stress ratio was used and the crack was opened during the majority of cyclic loading. Therefore, three different conventional crack propagation direction criteria, which are usually used for the proportional loading condition, were selected to propagate the initial crack and their results were compared with a predefined crack propagation trajectory based on experimental observation.

This paper is organised as follows: Firstly a description is presented for the fretting fatigue experimental test rig along with a brief description about using a digital image correlation (DIC) technique to measure the frictional properties of cylindrical contact configuration. Secondly, the numerical modelling technique for fretting fatigue contact model, crack initiation and propagation is elaborated. Next, the estimated results are discussed and validated against the preformed experimental observations and results from the literature. Finally, the major conclusions are summarised.

2. Experiments

2.1. Experimental set-up and material

The fretting fatigue test rig has been designed and constructed as an additional fixture to a 100 kN ESH servo hydraulic load frame. The additional fixture is rigidly fixed on the upright poles of the load frame. The 100 kN hydraulic cylinder of the load frame is used to apply the axial dynamic force in the dog-bone specimen. The normal force, F, is applied with a single servo-hydraulic actuator. A C-beam construction, which is mounted on ertalon blocks and floated on the base plate, ensures that there are two equal and opposite normal forces. The tangential force, Q, between the dog-bone specimen and the pads is generated by means of leaf springs. The compliance of the leaf springs and the elastic deformation of the dog-bone specimen generates the tangential force, which is proportional to the fatigue load. A lateral load cell is attached to the C-beam, which measures the contact load directly. The induced tangential load is measured by attaching a strain gauge to the compliance springs. Data acquisition is done entirely on the control computer at a sample frequency of 1024 Hz. The schematic view and the picture of fretting fatigue test rig are illustrated in Figs. 2 and 3, respectively.

The tested material was aluminium 2024-T3, a tempered aerospace aluminium with good fatigue properties. All the test specimens, i.e. dog-bone specimen for tensile test, fatigue test specimen and fretting pads for fretting fatigue test, were produced from a single sheet of aluminium 2024-T3. The material compositions from the specification sheet are tabulated in Table 1. The measured yield strength σ_y and ultimate tensile strength σ_{ult} are given in Table 2. Dimensions of fatigue specimen and fretting pad which were used in this study are shown in Fig. 4.

2.2. S–N curve

The fretting fatigue experiments were performed using parameters such as $N_f \approx 10^5 \ldots 10^6$, axial stress ratio $R_s = 0.1$, tangential load ratio $R_Q = -1$, test frequency $f = 10$ HZ, and surface roughness $R_a \leq 0.3$ μm. The additional adjustable parameters for fretting fatigue experiments were kept constant for all the experiments: $F = 543$ N; pad radius $R = 50$ mm. The total lifetime of the

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