Tribology International 76 (2014) 23–34

Contents lists available at ScienceDirect

Tribology International

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

T-stress based short crack growth model for fretting fatigue

J. Bellecave [a,b,d,*], S. Pommier [b], Y. Nadot [c], J. Meriaux [d], J.A. Araújo [a]

[a] Departamento de Engenharia Mecânica, UnB, Brasília/DF, CEP 70910-900, Brazil
[b] LMT-Cachan, Bâtiment Léonard de Vinci, 61 avenue du Président Wilson, Cachan 94230, France
[c] Institut P, ISAE-ENSMA, 1 Avenue Clément Ader, Téléport 2, Futuroscope Chasseneuil 86961, France
[d] Snecma Villaroche, Rond Point René Ravaud, Réau, 77550 Moissy-Cramayel, France

ARTICLE INFO

Article history:
Received 6 July 2013
Received in revised form
16 January 2014
Accepted 20 February 2014
Available online 1 March 2014

Keywords:
Fretting-fatigue
T-stress
Short crack
Multiaxial
Ti–6Al–4V

ABSTRACT

The aim of this work is to model short crack growth under fretting fatigue loading conditions by considering a criterion based on linear elastic fracture mechanics quantities, which also accounts for the first non-singular terms of the asymptotic expansion, namely the T-stresses. The Modes I and II Stress Intensity Factors and the T-stresses were computed by the finite element method under plane strain hypothesis. To assess the model fretting fatigue tests were carried out using two cylindrical fretting pads, which were loaded against a flat dogbone tensile test piece, both made of a Ti–6Al–4V titanium alloy. The model was capable to correctly estimate short crack arrest and to find the threshold fretting conditions separating failure from infinite life (here defined by tests which reached one million cycles). An optimization technique was implemented to the numerical model so that it could also estimate crack path.

1. Introduction

Fretting appears when mechanical assemblies experience relative motion at contact interfaces under the action of an excitation force or vibration. Experimental evidence has shown that the conjoint action of fretting and fatigue may produce strength reduction factors varying from 2 up to 10 [1].

Fretting failure of components such as splines, the dovetail fixing between blade and disc in fans of aeroengines [2] and riveted skins of the aircraft fuselage [3] has become a major design concern. In these applications, components are usually subjected to high cycle fatigue involving high frequency type of loads, often superimposed on a high mean stress. Madge et al. [4] showed that minimum life corresponded broadly to the transition from partial slip to gross sliding. Indeed gross sliding can remove nucleating fatigue damage before propagation into cracks. In their work, they concluded that for partial slip cases and for low wear coefficients, partial slip failure is predicted at the edge-of-contact. Fouvry et al. [5] showed that under partial slip conditions the normal force has a low effect on the nucleation condition and that crack threshold can be associated to a constant tangential force.

Under fretting conditions, the loads involved generate a time varying non-proportional multiaxial stress field under the contact [6], which decays very fast from the surface to the interior of the component [7]. Therefore, non-local approaches, developed initially for predicting the fatigue endurance of notched specimens, have been applied by different authors to the fretting fatigue problem [8–10]. Araújo et al. [9] used the theory of critical distances (TCD) conjunction with the modified Whöler curve method (MWCM) and showed that it was capable of predicting the results of fretting fatigue experiments with a high degree of accuracy ($\pm$20%).

Pannemaecker et al. [11] used a short crack arrest methodology. Such an analysis consisted in computing the stress intensity factor as a function of the crack length and assess whether this K-factor loading path intercepts the short crack arrest boundary given by the Kitagawa–Takahashi model. Indeed, within such a model the mode I threshold stress intensity factor is not constant. It tends asymptotically towards the long crack threshold for long cracks and to zero for short cracks. The threshold value is also the function of the stress biaxiality ratio, which is consistent with experiments from McEvily et al. [12]. In Pannemaecker's work, a kinked crack and an equivalent stress intensity factor (ΔK_{eff}) are considered. The coefficient of friction between the crack faces proved to be of utmost importance in the calculation of the mode II stress intensity factor (and consequently of the ΔK_{eff}), which plays a relevant role in the short crack stage. A reverse analysis was performed in order to establish the evolution of the crack arrest condition as a function of projected crack length. The direction of propagation of the slant crack was assumed based on the experimental observation of a cylinder/plane (TA6V/Al-alloys) contact configuration under partial slip conditions. However, to apply a save life criterion at the design

* Corresponding author at: Departamento de Engenharia Mecânica, UnB, Brasília/DF, CEP 70910-900, Brazil.
E-mail address: jbellecave@gmail.com (J. Bellecave).

http://dx.doi.org/10.1016/j.triboint.2014.02.016
0301-679X

stage, the crack propagation path must be defined *a priori*. In this setting, Giner et al. [13] used the extended finite element method (X-FEM) allowing for crack face contact for the simulation of a complete-contact fretting problem. The minimum shear stress range ($\Delta\tau$) and the maximum tangential stress (MTS) criteria, both applied ahead of the crack tip, were used to predict the crack propagation direction. Predictions of the crack path based on the minimum value of $\Delta\tau$ showed the best agreement with the experimental observations. On the other hand, Noraphaiphipaksa et al. [14] evaluated the stress and strain around crack tip in fretting fatigue and showed that the crack path can be successfully estimated based on the MTS range criterion using also a complete-contact but with SM430A steel material.

The aim of this work is to evaluate a *T*-stress based criterion [15,16] to model short crack growth under fretting fatigue conditions. This criterion is constructed as a generalized von Mises yield criterion and states that below the threshold value of a critical distortional elastic energy for the crack tip region, the crack should remain arrested. An elastic domain is thus defined which is function of two linear elastic fracture mechanics quantities: the stress intensity factor (SIF) and the first non-singular terms of the asymptotic expansion, namely the *T*-stress. The method was applied to the problem of fretting fatigue and shows that the high values of the *T*-stress encountered in this problem contribute to crack tip plasticity of short crack and may promote short crack growth. Fretting fatigue tests on Ti–6Al–4V have been carried out to evaluate the accuracy of the proposed methodology.

2. Experimental results

2.1. Fretting fatigue apparatus and specimen

Fretting fatigue tests were carried out using two cylindrical fretting pads, which were loaded against a flat dogbone tensile test piece. The pads used in the experimental and numerical work have a radius of 20 mm, and a cross section of 13 mm × 15 mm, 13 mm being the out of plane thickness. The tests were performed for a Ti–6Al–4V titanium alloy. Specimens and pads were supplied and manufactured by Snecma from a fan disc of an aeroengine. Table 1 contains a list of static and fatigue material properties for this alloy, which are relevant for the analysis in this work, viz. Young's modulus, E, Poisson's ratio, ν, fully reversed fatigue limits under push–pull and torsion, $\sigma_{f_{R=-1}}$ and $\tau_{f_{R=-1}}$. These data were collected from the literature [17]. For the threshold value of the mode I SIF, $\Delta K_{th_{R=-1}}$, data were found to vary from 4.5 MPa m$^{1/2}$ [9] to 6.5 MPa m$^{1/2}$ [18]. Therefore, a mean value in this range was adopted for this study.

Before testing, pads and specimen were chemically degreased and, to assure the alignment of the contact between the cylindrical pads and the flat specimen was correct across the width of the specimen, a Pressure Measuring Film (Fuji Prescale Film – Medium Pressure – Mono Sheet Type) was selected. Fig. 1 depicts a photograph of a pair of pads together with impressions made on the pressure sensitive paper after a correct alignment was performed.

Tests were carried out using a fretting apparatus which can be considered as an enhanced version of a device initially proposed by Nowell [19]. This apparatus is well detailed by Martins et al. [20] and only an overview of it is provided here. The apparatus is

Table 1
Ti–6Al–4V properties used for the analysis.

Young's modulus	ν	$\Delta K_{th_{R=-1}}$	$\sigma_{f_{R=-1}}$	$\tau_{f_{R=-1}}$
119.4 GPa	0.29	5.5 MPa m$^{1/2}$	583 MPa	411 MPa

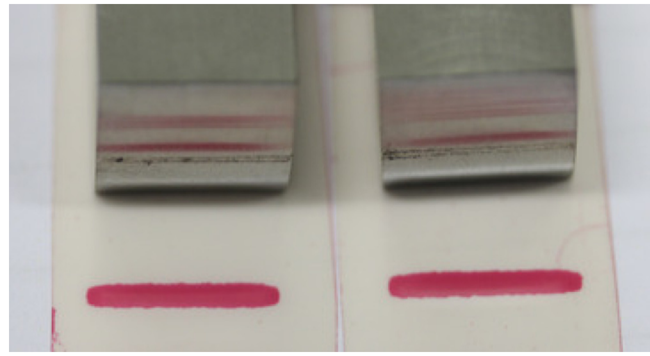

Fig. 1. Set of pads with their respected prints on the pressure sensitive paper.

attached to a servo-hydraulic fatigue test frame and works as a spring that reacts to the motion of the pads, which are pressed by a static force against the dogbone fatigue specimen. This motion arises when the specimen is subjected to a cyclic bulk load and then experiences a deformation that the pads do not. Due to the interfacial friction and to the fact that the pads are attached to the apparatus/spring, material points in the pads contact surface are not allowed to displace together with their counterparts in the specimen surface. The reaction of the spring results in the cyclic tangential load, which is hence proportional and iso-frequency to the bulk load. Fig. 2 depicts a photo of a test showing the apparatus, a zoom of the specimen/pads mounted on it and a scheme of the contact configuration.

2.2. Load configuration and test results

A schematic diagram of the loading cycle applied to the fretting configuration is depicted in Fig. 2d. After the specimen was mounted on the servo-hydraulic machine, the first step in the loading program was to apply the mean bulk load, so that the load ratio was set to 0. The fretting pads were then clamped by a constant normal contact load per unit thickness, P. The pads used here have a radius of $R = 20$ mm. This procedure means that the mean load/stress provokes no disturbance on the contact setting. The sinusoidal (fatigue) bulk load, B, was finally applied in small steps until the prescribed value for each test. The gradual increase of the bulk load and its frequency is necessary to avoid the pads sliding at the beginning of the test when the coefficient of friction, f, is still very low. Therefore, as the shear load is proportional to the bulk load, its increase in steps will allow the slip zones to grow smoothly together with f.

To obtain the coefficient of friction, f, under the partial slip regime, subsidiary tests were carried out using the methodology presented by Nowell and Hills [21,22]. The predictions for the slip zone friction coefficient were between 0.45 and 0.55. A value of 0.5 was used in the analysis.

The aim of these tests was to find the threshold fretting conditions separating failure from infinite life (here defined by tests which reached 10^6 cycles). To achieve this, the pick pressure, p_0, was fixed for all tests at 700 MPa (as P and the pad radius are constants), and an initially high fatigue load was decreased from test to test until the run out condition was achieved. Test frequency was fixed to 10 Hz. Here, it should be remarked that the fretting apparatus and the position of the pads along the specimen (the shear load depends not only of B and of the stiffness of the apparatus, but also on the length of the specimen above the contact line [20]) were defined so that the ratio between the bulk and the tangential force B/Q was set to be around 10. Fig. 3 contains the experimental points in a $\sigma_B/p_0 \times Q/fP$ diagram. Notice that the threshold loading is somewhere between $0.121 < \sigma_B/p_0 < 0.129$ and $0.48 < Q/fP < 0.53$. Also worth of