# FRETTING FATIGUE CRACK GROWTH ANALYSIS: EXPERIMENTAL PHOTOELASTIC METHOD COMBINED WITH NUMERICAL MODEL

V. Lamacq*, M.-C Dubourg*, B. Villechaise†

Cracking behaviour under fretting fatigue (FF) loading is here investigated. A transparent photoelastic specimen of epoxy is submitted to fretting fatigue conditions. Cracks initiated by fretting contact are shown to propagate up to several millimetres. Qualitative and quantitative informations on fretting crack initiation, location, inclination and growth rate are obtained. Cracks initiate near the edge of the contact. They generally show two principal inclinations. These orientations are related to different propagation stages identified during FF crack life. FF crack growth evolutions are analysed in terms of influencing external loading.

## INTRODUCTION

Fretting fatigue failures occur between contacting bodies submitted to oscillatory conditions. Hence, fretting loading still remains a significant concern in designing and maintaining industrial structures. A set of experiments (1) was carried out on three aeronautical aluminium alloys to study cracking phenomena under cumulative effects of contact and static external loading. Cracks were shown to nucleate under fretting and propagate up to several millimetres. This study permited to relate fatigue crack location and orientations with different fretting regimes. During these tests, crack extension could not be followed across these opaque alloys. In the literature, FF crack growth rates are rare, but they are a necessary tool to model FF crack propagation or failure. Endo and Goto (2) presented fretting fatigue crack growth rates for cracks $<500\mu m$. Here, a new set of experiments is proposed to follow complete fretting fatigue crack life. A transparent photoelastic specimen of epoxy with a high elastic modulus is used to allow the direct visualization of cracking phenomena occuring during fretting fatigue. A model is developped to analyse isochromatic fringe patterns and measure crack lengths and inclinations.

* LMC, UMR CNRS 5514, I.N.S.A. - Lyon, 69621 Villeurbanne Cedex, France.
† LMS, CNRS URA 861, Université de Poitiers, 86960 Poitiers Cedex, France.

## EXPERIMENTAL PROCEDURE

The apparatus was first proposed to complete the initial experiments on aeronautical aluminium alloys (2). The replacement of the aluminium alloy by an epoxy to answer to cracking phenomena under FF loading was, at the beginning, questionable. This pointed out the problem of the influence of the microstructure on crack nucleation and propagation. During these experiments, it appeared that the epoxy behaved, in terms of crack propagation, in a similar manner than aluminium alloy. This first experimental investigation was conducted to test the potentiality of the experimental apparatus. Even if the latter will have to be improved, the experimental results presented here are very promising.

The experimental apparatus and dimensions of pieces are presented in Fig. 1. A rectangular epoxy slab is submitted to a static traction, $\sigma_{0x}$. A cylindrical aluminium alloy pad is pressed against the slab through a constant normal force, P. The epoxy specimen is submitted to an oscillating displacement, d, and thus rubs (Q) against the cylindrical pad. A photoelastic system is used to obtain isochromatic fringe patterns. These patterns and the transparent epoxy specimen are then filmed by a CCD video camera. Temperature and humidity were not controlled.

A model was developed to analyse automatically the CCD camera images. Each image pixel was transformed in a grey level to dissociate fringes of the pattern and number them. Hence, at each fringe corresponded a set of experimental points (Fig. 5). In the same way, a crack was analysed in the transparent epoxy specimen as a single fringe (Fig. 4a). The model permited to determine the exact geometry and length of cracks (and not only crack depths) by providing the experimental constitutive crack points.

### Available experimental data.

Three kinds of experimental data were either imposed, recorded or observed. The loading parameters $\sigma_{0x}$, P, d and Q were statically imposed *at the beginning of each test*. An aluminium/epoxy contact was chosen to enable heat dissipation through the aluminium pad and prevent any epoxy melting. A condition of elastic adhesion prevails between the contacting bodies during all the tests. *During the test*, qualitative data were recorded. The crack length versus the number of cycles were recorded. Crack extension was followed. Hence, if crack branched in a new direction, the corresponding time and crack length were automatically known. Numerous data points on the stress field through the isochromatic fringe patterns were also collected at specific loading step. The exploitation of these last data will not be presented here. It is the subject of further study aiming at determining friction coefficient along crack faces, experimental stress intensity factor and experimental (da/dN, $\Delta K$) curves. *Once the test was achieved*, the contact zone was microscopically observed (Fig. 2). The contact zone size and the repartition of the sticking and sliding zones were determined. The crack localisation and geometry at the material surface was recorded. If failure took place, the crack rupture feature was observed by electronic microscopy (fig. 3a).

Even so, the perfectly plane/cylinder contact was a hard condition to reach. Actually, here, no device allows to get rid of any non-parallel condition between the specimen and the cylindrical pad. Hence, some cracks might have shown a more or less pronounced three dimensional profile induced by non-symetrical fretting loading. Nevertheless, the tests were reproducible in terms of location and inclination of cracks initiated by the fretting contact.

## RESULTS

Three kinds of behaviours were observed during the experiments. When the displacement amplitude $\Delta d$ was small no significant surface degradations appear even after $10^6$ cycles. When $\Delta d$ was too high or combined to a high static traction unstable propagation took place just after crack initiated. In the following sections, fretting fatigue propagation is considered. The previous behaviours are not studied.

### Crack nucleation

The initiation of FF crack was difficult to determine. The nucleation time was fixed when a visible crack emerging from the contact shadow was detected. Crack initiated as a point in the contact area (fig. 3). It propagated then in two directions: perpendicular to the material surface in the specimen interior, and/or perpendicular to the fretting displacement direction at the specimen surface. As shown in fig. 3, crack initiated along a "semi-elliptical" plane inclined with respect to the surface. This corresponds to stage I propagation as described by Forsyth (4). This stage was not directly visible due to the crack length during this period ($<60\mu m$, fig. 3a). Crack is located at the boundary of the stick and slip zone near the edge of the contact (Fig. 2). This zone corresponds to high tangential stresses and important $\sigma_{xx}$ fatigue. The first detectable crack inclination is about 70-80° with respect to the surface (fig. 4a). This kind of crack was also observed on the Aluminium Alloy specimen. A previous study (3) showed that this kind of crack initiate by a traction fatigue mechanism and more likely near the edge of the contact, when partial slip condition holds in contact area.

### Fretting fatigue crack propagation

Figures 4b and 6 present FF crack growth rate curves obtained during three tests. Test n°1 curve is slightly different from the two others. Actually, the first detectable crack length equaled 100$\mu m$ for test n°1, 320$\mu m$ for test n° 2 and 200$\mu m$ for test n°3. An increase of crack growth rate was observed at the beginning of test n°1 until the crack length equaled 400$\mu m$. This may be a short-crack propagation period. Then as for the other tests, crack growth rate decreased abruptly to reach a plateau. During this period, crack propagated oblique to the surface under the contact zone (fig 4a). It was influenced by combination of fretting contact and static traction. Then started a period of stable propagation. At this depth, the fretting action was less effective. Furthermore, crack remained in the compression zone of fretting contact and then static traction was not optimal. Alternative opening and closing movements were directly observed along crack faces all along a fretting cycle. Due to its inclination, crack was undergoing mixed mode I+II at its tip. At a given depth, crack branched perpendicular to the static bulk. It was observed that the branched part of the crack remained open all along a fretting cycle whereas the oblique part was still undergoing opening and closure. This branch was a pure mode I one. Under this mode, crack growth accelerated abruptly to lead to failure of specimen. Unstable propagation took place. It thus appeared that superposition of mode II to mode I slowed down crack propagation.

## CONCLUSION

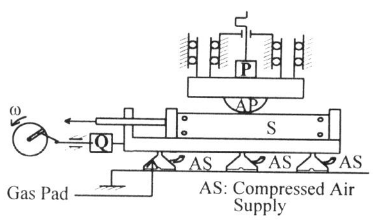
Fretting fatigue (FF) tests were performed on a photoelastic specimen. FF crack growth rates were obtained and different FF crack extension periods were identified during crack life. Initiation period was influenced by fretting contact. A slow down of crack growth rate then took place corresponding to stable propagation. During this period crack propagated obliquely to the surface under Mode Mixte I+II, and was influenced by combination of fretting contact and static traction. The final crack life was only influenced by static traction. After branching, crack accelerated to lead to failure by pure Mode I unstable propagation. FF crack propagation showed a specific behaviour and must be considered apart from Mode I propagation.

(1) Reybet-Degat P. and Vincent L., NordTrib'94, Vol.1, pp. 121-128, 1994

(2) Endo K. and Goto H., Wear, Vol. 38, pp. 311-324, 1976

(3) Reybet Degat P., Lamacq V., Dubourg M.-C., Zhou R.Z., Vincent L.,ESIS 1996

(4) Forsyth P.J.E., Fretting Fatigue, Elsevier Applied Science, London, pp 99-125,1981.




***AP*: Alumium pad** ; R= 25 mm
***S*: Epoxy slab**
HxLxP= 40x80x3.2 mm
E = 3150 MPa
$\nu$ = 0.36
C = 10,7 MPa/(Fringe/mm)

P = 200 N
$\sigma_{0x}$ = 19 MPa
Frequency = 10 Hz

Figure 1: Experimental apparatus and conditions

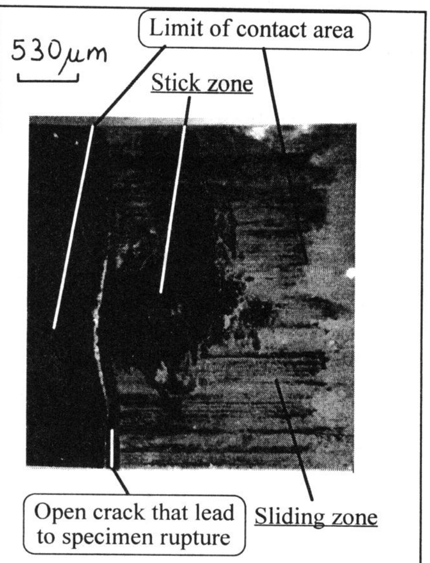
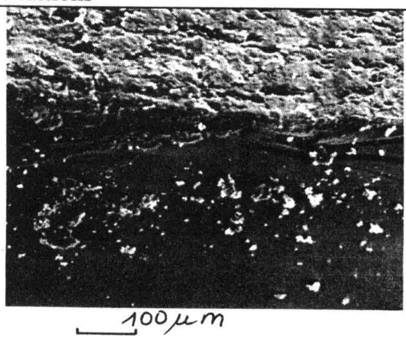
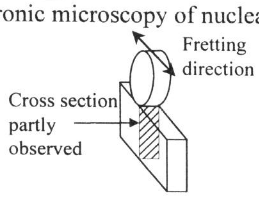
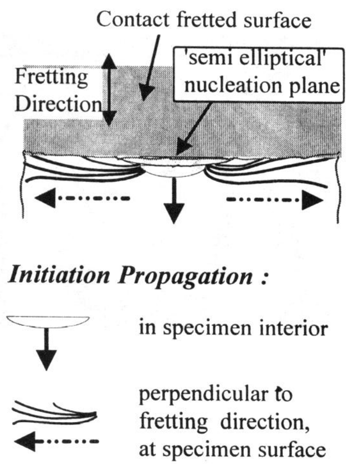



Figure 2: Microscopic surface contact view




(a)Electronic microscopy of nucleation site




(b)Schematic view of nucleation site and propagation

Figure 3: (a) Scanning electron microscopic view of a nucleation site and crack propagation directions; (b) Schematic representation of (a).

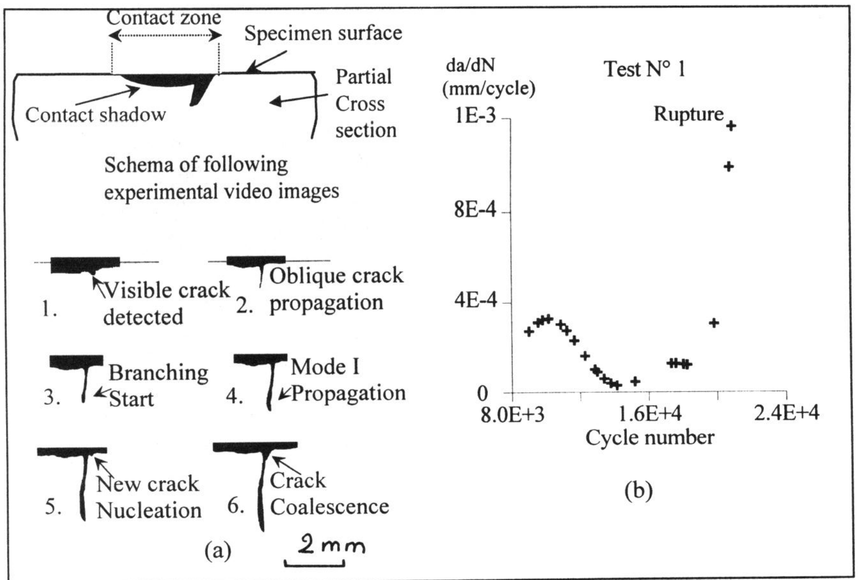
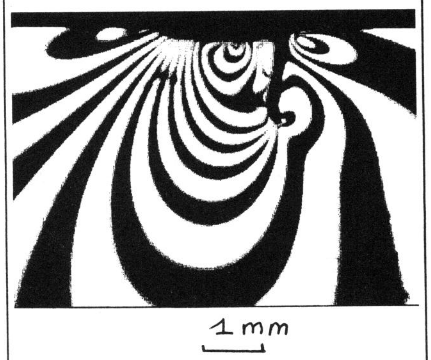



Figure 4: (a) Experimental video images of crack extension; (b) Corresponding experimental fretting fatigue crack growth rate curve




Experimental conditions:

Normal force, P = 210 N
Tangential force, Q = -102 N
Static traction, $\sigma_{0x}$ = 19 MPa

Figure 5: Experimental isochromatic fringe patterns of cracked specimen.

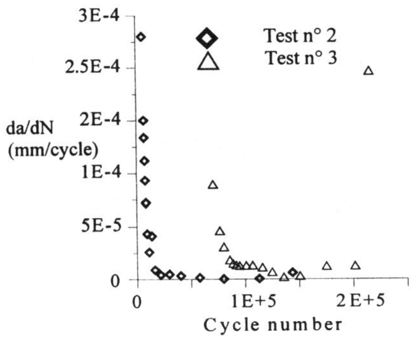



Figure 6: Experimental fretting fatigue crack growth rate curve.