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Fatigue Mechanisms of Aluminium Alloy Assemblies

H. Proudhon[1,2], J-Y. Buffière[1], S. Fouvry[2]

[1] GEMPPM, INSA de Lyon, 20 Avenue Albert Einstein 69621 Villeurbanne Cedex
[2] LTDS, Ecole Centrale de Lyon, 36 avenue Guy de Collongue 69134 Ecully Cedex

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Abstract

The microscopic crack growth mechanisms in a mechanical assembly involving the damage tolerant 2024 alloy have been studied from the short crack point of view. Fretting tests and fatigue tests on specimens with a central open hole have been performed. The experimental loading conditions leading to fretting crack initiation have been precisely determined. Crystallographic stage I cracks have been observed to grow in the region of the specimens submitted to a high stress concentration. A detailed analysis of the local crack paths reveals a strong correlation with the orientations of the grains encountered by the cracks.

1. Introduction

In spite of the efforts spent by the aeroplane industry to introduce novel methods for assembling aeronautical components, nowadays, the vast majority of assemblies in a plane still consists in mechanical joints (rivets). The fatigue resistance of such joints is therefore an old problem but still not completely understood because of its complexity. Indeed many factors can alter the fatigue life of such joints: short cracks effects (3D effects, scatter in the propagation rates and crack closure), contact between parts which may induce a complex stress state and change the crack nucleation conditions, multi-cracking, residual stress effects.

This study focuses on the short crack aspect of the problem. Indeed, it is generally believed that improved lifetime predictions could be obtained via a better understanding of the fatigue mechanisms of cracks with a size typically in the mm range which can initiate and propagate in the vicinity of a joint.

The effect of the complex stress state (resulting from the contact stresses between the different parts of the assembly) on crack initiation has been simulated through fretting tests. Besides, more classical fatigue tests on specimens with a central open hole have been carried out to investigate the microscopic crack growth mechanisms within a region of stress concentration.

The experimental conditions leading to fretting crack initiation in the damage tolerant 2024 alloy have been determined. The strong influence of the local crystallography on the growth of the short cracks is evidenced and a crystallographic criterion for determining the local crack path is suggested.

2. Experimental work

2.1. Material

The material used in this study is a damage tolerant 2024 aluminium alloy commonly used in assembled structure like aircraft fuselage panels.
The material was supplied in the form of a 25 mm thick rolled plate. The microstructure resulting from the rolling process exhibits the usual “pancake” grains with an average size of 0.50 mm x 0.16 mm x 0.13 mm in the Longitudinal, Transverse and Short transverse directions (L,T,S) respectively. The 0.2% yield stress of the material after a T351 heat treatment was found to be 320 MPa.

2.2. Fretting Tests

Fretting tests have been first carried out in order to determine the contact conditions leading to crack nucleation in partial slip conditions [1]. The principle of the fretting test is described on Figure 1a). Basically, the material to be tested is submitted to a constant normal force P applied the L direction using a counterboby. While maintaining this load constant, a cyclic tangential displacement with an amplitude δ^* and a sinusoidal shape is then imposed to the sample along the S direction. In this work, the counter body is a cylinder of 7075 T6 aluminium alloy. The normal load imposed to the surfaces as well as the tangential load induced by the contact (Q*) are recorded. After 50 000 cycles, the sample is cut in two halves with a slow speed diamond saw and optical micrographs of the material microstructure below the contact are recorded in the xy plane defined on figure 1a. Such a micrograph showing a fretting crack is presented in figure 1b. Crack nucleation was studied in partial slip for a smooth contact (R_a=0.1 µm) in a range of normal load from 200 N/mm to 700 N/mm, in order to bracket the possible contact conditions in an assembly like a rivet. For each normal load tested, several tests have been carried out with different relative displacements δ^* imposed. As this displacement increases, the tangential force induced in the contact increases and the crack nucleation risk too.

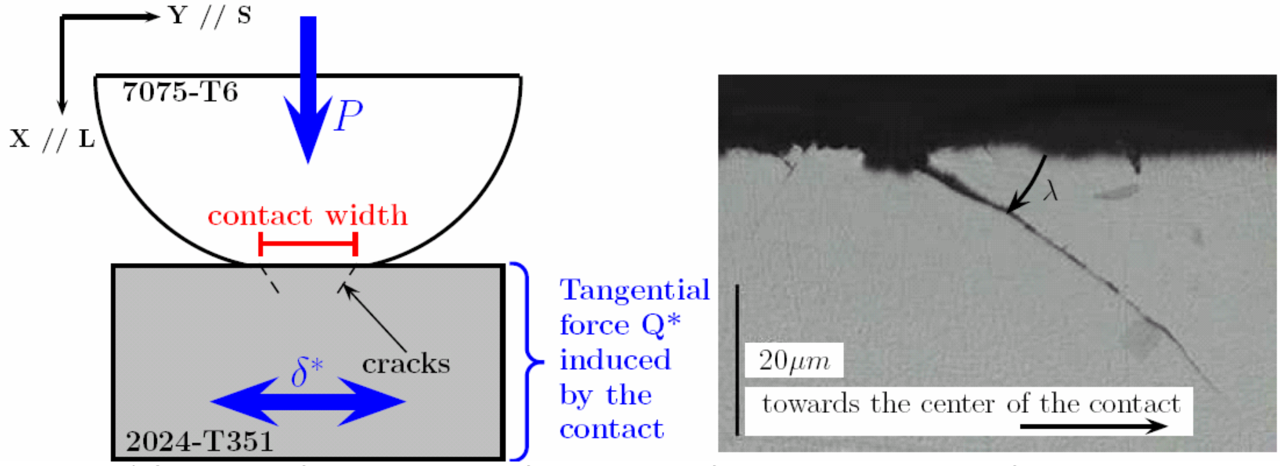

Figure 1: a) Schematic of the experimental fretting test configuration, the diameter of the counterbody is 49 mm, the fretting specimen is a small parallelepiped (14 mm x 12 mm x 25mm). b) Optical micrograph of a crack observed on the cross section of a specimen subjected to fretting loading, P = 500 N/mm and Q* = 300 N/mm.

2.3. Fatigue Tests

Fatigue specimens with a loading axis parallel to the L direction were extracted from the center of the plate to reduce scatter in material properties. The specimen dimensions were 150 mm x 30 mm x 3 mm in the L, T and S directions respectively with a central open hole of 10 mm diameter. The two surfaces of each sample were carefully mechanically polished down to diamond paste (1/4 µm) to enable in situ optical monitoring of the crack length *a* as a function of the number of cycles *N*. The specimens were loaded in the L direction with a constant amplitude (stress ratio 0.1) and a maximum stress σ_{max} of 200 MPa in the section with the hole. During cycling, the specimen is dismounted every 1000 cycles and optically observed to detect crack initiation (defined as a crack of a few microns long) and subsequent propagation. Four samples were cycled and a total of 28 cracks were monitored. The tests were interrupted before failure in order to further investigate the local microstructure at the vicinity of the cracks by the Electron Back Scattered Diffraction (EBSD) method. To do so, each sample was cut and then electro polished to remove the thin layer of strained material induced by mechanical polishing. A 840 JEOL Scanning Electron Microscope (SEM) fitted with an *hkl* camera and the Channel 5 software, were used for the crystallographic indexation. Finally fractographic analysis was performed in the SEM on different samples cycled to failure.

3. Results and Analysis

3.1. Determination of the Fretting Crack Nucleation Boundary

Figure 2 presents the result of all the fretting investigations; the dotted line is the fretting crack nucleation boundary for this couple of materials after 50000 cycles.

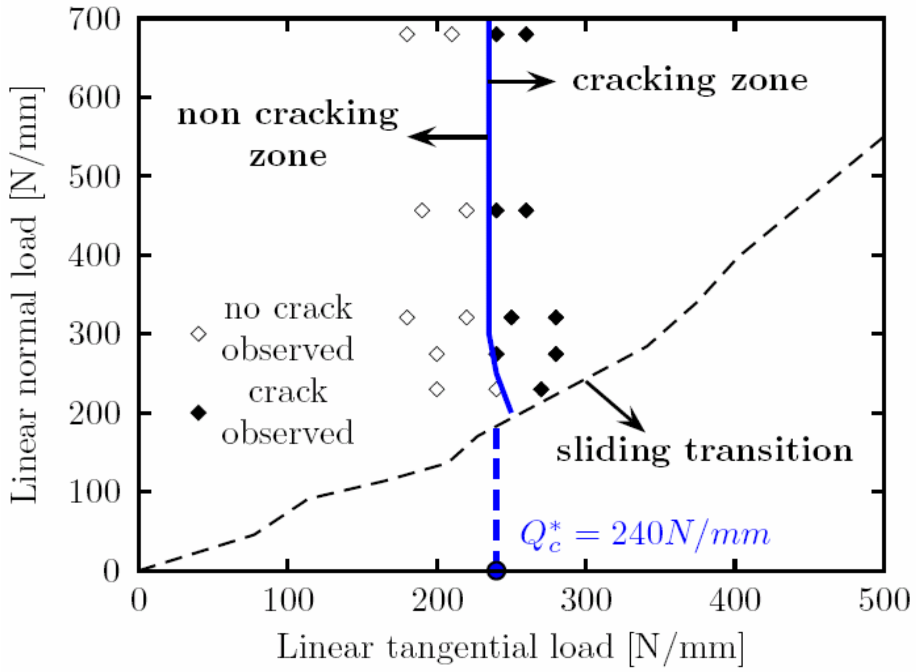

Figure 2: Experimental determination of the critical tangential load for crack nucleation during fretting of 2024T351 vs. 7075T6 Al alloys after 50000 cycles.

The observation of figure 2 clearly shows a crack nucleation boundary driven by the tangential load and therefore independent of P. This is consistent with the fact that the fretting cracks are found to initiate at the trailing edge of the contact were the pressure field vanishes. In addition, it was found that, in the early stages of propagation, the crack/surface angle λ defined on figure 1 is always smaller than 45°, showing a predominant crack growth in shear mode. The critical tangential load is determined to be Q^*_c=240N/mm.

3.2. Crack Propagation in Fatigue Specimens with a Central Hole

All the observed cracks grow predominantly in the T direction. Figure 3a shows typical a=f(N) curves recorded during the tests. Two main behaviours can be distinguished. Some cracks initiate, grow up to an average size of 100 microns and stop, such cracks will be called *non propagating cracks* hereafter. The other cracks, called *propagating cracks*, are still growing when cycling is stopped (*i.e.* near final rupture).

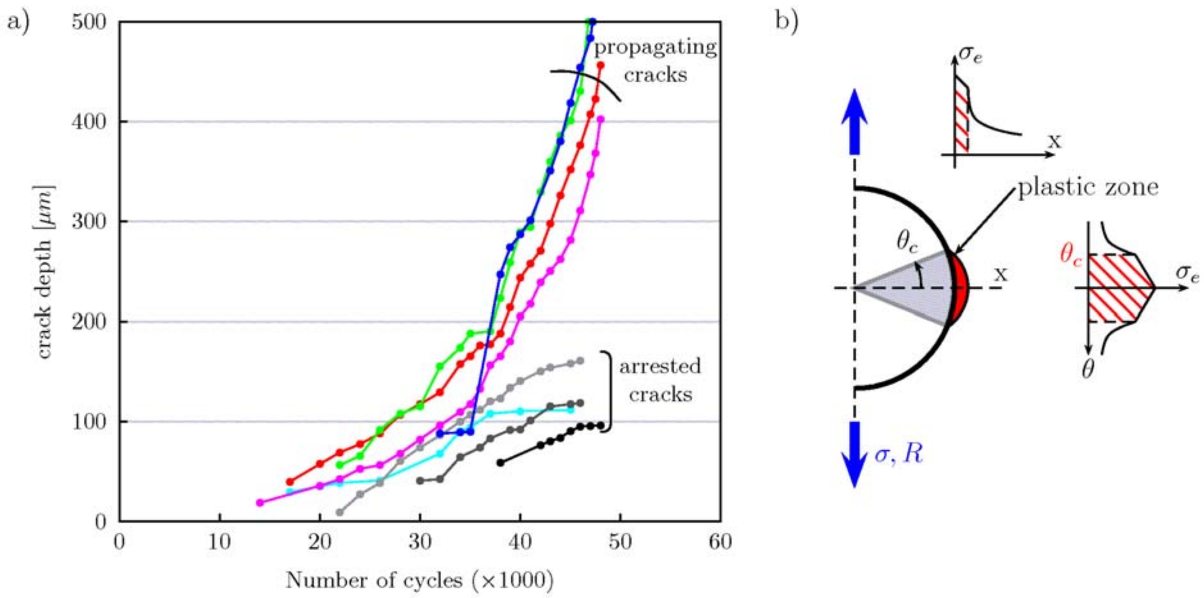

Figure 3: a) Typical a=f(N) curves obtained in 2024T351 samples with a central hole loaded in the L direction at constant stress amplitude σ_{max} = 200 MPa and R=0.1. b) Schematic drawings of the stress distribution of the Von Mises equivalent stress σ_e at the vicinity of the hole.

All the cracks initiate in a narrow angular sector of the hole circumference corresponding to the angle θ_c on figure 3b. The analysis of the stress distribution in this zone has been calculated by elasto-plastic FE analysis (using Abaqus V6.3). For the maximum normal load used, when θ varies from 0 to θ_c, the Von Mises stress σ_e in the uncracked specimen decreases from 430 MPa to 320 MPa (which is exactly the elastic limit at 0.2%) ; and a plastic zone approximately 1 mm wide is formed near the hole. However, a correlation between this local stress distribution and the fact that a crack does or does not propagate was not observed. In other words, cracks initiated at a low value of the angle θ (ie at a high value of the σ_e stress) can stop, while cracks initiated at higher value of θ can propagate and cause the failure of the sample. Hence it was concluded that the propagation / non propagation behaviour was not directly related to the local stress level but rather due to a strong interaction of the cracks with the local crystallography.

The in situ monitoring of crack development near the hole edge gives clear evidences for this strong interaction. Figure 4a gives an example of a crack path observed in this work. Such a crack path is typical of stage I cracks following crystallographic planes. The grain boundaries can often be observed on the optical images as some plastic deformation appears at the surface of the samples. The crossing of such grain boundaries is often accompanied by a strong deflection of the crack path (detail A on figure 4a). The crack path also follows the slip bands observed near the crack tip. In addition, fractographic observation shows a lot of crystallographic facets near the hole edge which further supports the idea of a crystallographic propagation of the cracks (figure 4b).

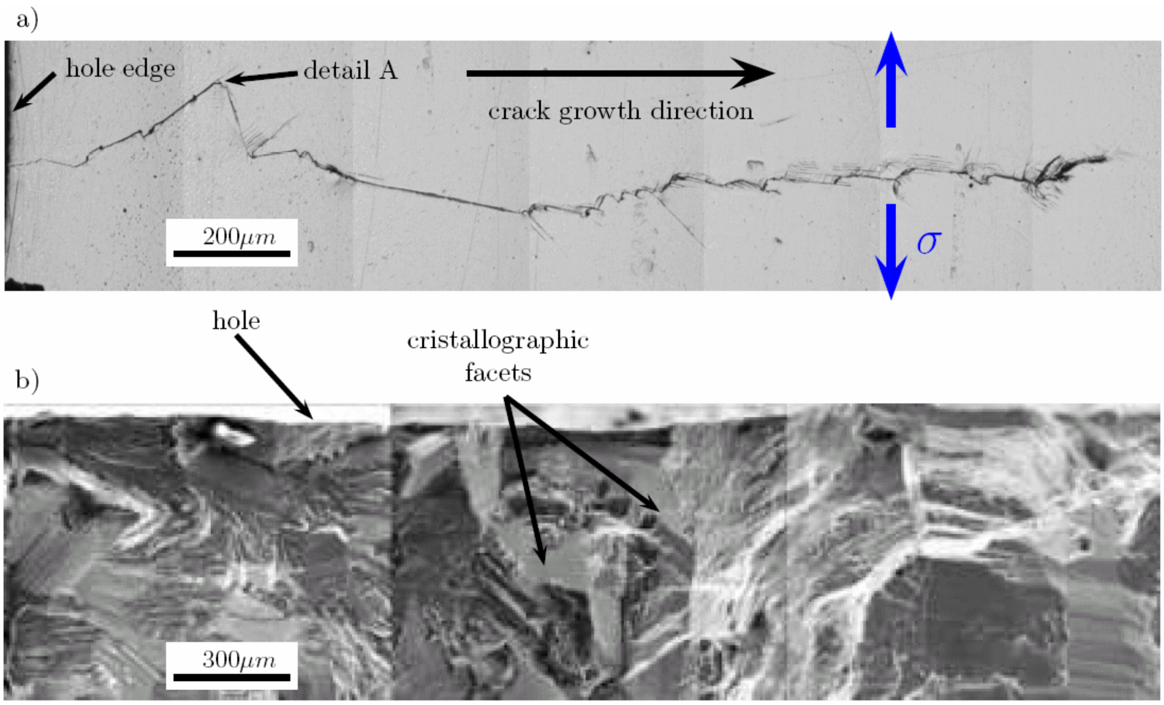

Figure 4: Illustration of the observed short crack crystallographic behaviour: a) Optical micrograph showing propagation from a hole in a fatigue sample, N = 4.10^4 cycles, σ_{max} = 200MPa, R = 0.1. b) SEM image of a fracture surface showing crystallographic propagation of the crack.

Zhai et al. [2] have recently shown the influence of local crystallography on fatigue crack paths in a rolled Al-Li alloy. Following this work, we have analysed by EBSD the local microstructure at the vicinity of several cracks in our material. Figure 5 shows an example of the results given by this analysis. On this figure, the local crack path has been compared to the trace of local {111} planes on the sample surface. It was found that the crack plane does match the relevant primary slip system in grain 1 and 2. Moreover, when crossing the grain boundary, the crack follows the plane giving the lowest twist angle (called α on the figure 5b) between the two local crack planes, as suggested by Zhai et al.. For the experimental conditions investigated here, it was found that nearly 46 % of the crack paths studied were in agreement with such a mechanism (see for example [3]). However, deviations from this criterion could also be observed which are likely to stem from specific grain boundary configurations.

Indeed, it must be remembered that in this model it is assumed that each grain boundary crossed is parallel to the loading direction and perpendicular to the surface. Since our material presents a pancake grain structure loaded in the L direction, this assumption is often verified but some deviations from this configuration cannot be excluded. Although the 3D shape of the grain boundaries cannot be obtained by EBSD, a recently developed technique combining gallium infiltration and high resolution micro-tomography can be used to check locally the grain boundary configuration in the interior of the material [4]. This work is currently being carried out to further test the model predictions.

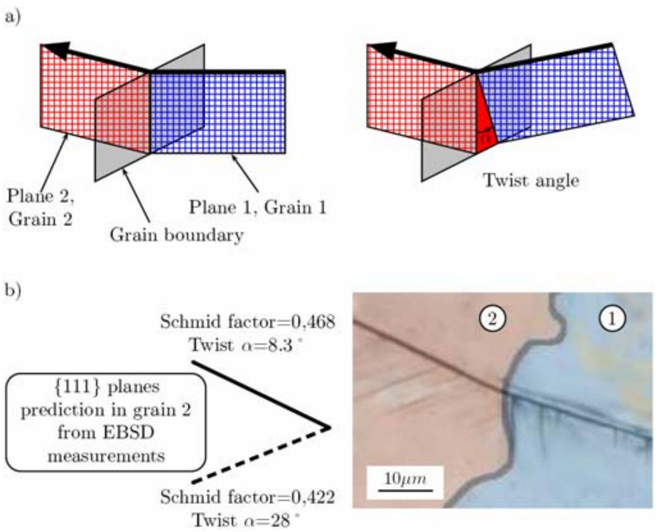

Figure 5: Illustration of the correlation of the crack path with local microstructure. a) Schematic drawings of the crystallographic mechanism for grain boundary crossing (left: simple tilt of the crack plane, right: tilt plus twist, α represents the twist angle). b) Illustration of this mechanism with a grain boundary deflection which minimises the twist angle.

4. Conclusion

The conclusion of this work can be summarised as follow:

- Fretting crack nucleation conditions for a 2024 Aluminium alloy have been determined experimentally in terms of loading conditions. The critical tangential load is determined to be Qc =240N/mm. For the experimental conditions investigated, no effect of the of the normal load P is observed.
- Fatigue crack growth in samples with a central hole has been studied quantitatively. Short cracks show different propagating/non propagating behaviours which cannot be accounted for by the local stress state but rather by the local crystallography.
- EBSD measurements have been carried out and a crystallographic propagation model has been successfully applied to predict the observed tortuous crack paths.

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