EXPERIMENTAL AND THEORETICAL APPROACH TO FRETTING CRACK NUCLEATION ON PRE-STRESSED ALUMINIUM ALLOY

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Fretting tests on a pre-stressed specimen were performed on aluminium zinc alloy. Fretting cracks were shown to nucleate under fretting and propagate up to several millimetres. Cracking behaviour strongly depends on the fretting regime and external static traction. Here, crack nucleation is emphasized through metallographic examinations. Two fretting crack types are observed. A theoretical analysis is performed to determine crack initiation angles. The two crack initiation mechanisms experimentally observed are identified. The location of each of this fretting crack depends on the initiation mechanism.

INTRODUCTION

Cracks can nucleate in numerous tribological situations. Under fretting loadings, cracking is not only related to classical fretting-fatigue experiments for which a large drop of fatigue limit is often registered. In the case of fretting wear, mappings have identified cracking zones associated to the mixed fretting regime for which partial slip conditions prevail during greatest part of life nucleation. Crack nucleation and propagation have been widely studied for conventional fatigue but few analysis tended to a better description of the nucleation of cracks under fretting conditions. The main lack is experienced in the location of the first cracks in the contact area and in their orientation towards the surface as revealed on metallographic cross section. Orientation is an important parameter of the durability of the contact as it governs the nature of the damage. For instance, the inclination of symetric cracks controls the depth of spalls while perpendicular cracks can propagate up to a complete failure. This paper proposes a theoretical analysis of crack nucleation under fretting loadings. The theoretical orientations are

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compared to results obtained for aluminium alloys with a peculiar attention given to separate stress states due to contact loading and stresses induced by external loads.

EXPERIMENTAL FRETTING CRACK NUCLEATION BEHAVIOUR

Numerous tests were performed on a fretting rig (1) schematically shown in Fig. 1. An external static load was imposed on the specimen before testing. Fretting behaviours were analyzed through metallographic examinations and tangential load-displacement variations, also called friction-logs. Two essential degradation mechanisms were observed: detachment of particles and fretting cracking. Three degradation modes could be distinguished under different experimental conditions as indicated in Fig. 2 (2): wear damage occured in the gross sliding regime; only slight surface degradation was observed in the partial slip regime; mixed regime appeared as the most detrimental mode for cracking.

Multi-cracks were frequently observed on the specimen cross-section. Long and short cracks could simultaneously exist. Two principal crack types were observed: the first type (type I in Fig. 3.a) initiated at a small angle of about 25° with respect to material surface; the second type (type II) occured at an initiation angle of about 80° with respect to material surface (Fig. 3.b). Both nucleated cracks then extended under fatigue along a 65° direction. From a fretting crack nucleation point of view, no difference between the pre-stressed specimen and its counterface was observed on the initiation angles (Fig. 3.c). On the other hand, crack growth depths were smaller in the counterface. It may be concluded that the first orientation of fatigue crack was governed by the fretting contact only.

Crack nucleation took place in the early stage of fretting life (5.10^4 cycles compared to 10^6 cycles test). Under a normal load equal to 1000N, type I crack nucleation remained the most critical in the mixed fretting regime while type II crack nucleation appeared in the partial slip regime. It was also noted that the two previous nucleation modes could exist at the same time under experimental conditions lying at the boundary of mixed and partial slip regime.

THEORETICAL MODELS

The aim of this part of the study is to predict crack intitiation angles. Approaches concerned with microscopic analysis and more specifically with dislocation concepts were proposed to analyse cracking behaviour. Yamashita and Mura (3) considering the stresses influencing dislocation movements predicted crack initiation angles under repeated oblique force. In this study, an analysis of the stress field in the surface layer is conducted. Considering the movements of dislocations on persistent slip band (PSB), the crack initiation mechanism is identified either as a process of extrusion and intrusion of slip bands or as a tensile fatigue process.

Contact model

The repartition of stick and slip zones and normal and tangential pressure distributions in the contact area are results of a unilateral analysis with friction (4). Coulomb's law is used. These contact conditions hold at the interface of two contacting bodies submitted to a constant normal load, P, and an oscillating tangential traction, Q(t) (Fig. 4). Static traction, σs, is superimposed to stress field.

Dislocation model for crack initiation

The simple model for contact fatigue crack initiation proposed by Yamashita and Mura (3) is used here. Cracks are assumed to initiate by localization of plastic deformation. Plastic slip takes place on weak glide plane. Dislocation loops are piled up as a result of multiple slips. The slip plane (SP) is inclined by an angle α with respect to material surface. In figure 5, a schematic representation of the pile-ups of dislocation loops on a slip plane is represented. Two typical slip patterns are shown: (a) a rising pattern , (b) a sinking pattern. Figure 5.c shows the damage accumulated at the dislocation dipoles due to cyclic loading.

As stresses in the surface layer change steeply, the average value of stresses on SP is used. In the following discussion, it is now assumed that the amplitude of the average shear stresses, $\Delta\tau m$, on a plane and the maximum value of the average normal stress, σm, on the same plane are the governing parameters for crack initiation during one loading cycle.

RESULTS AND DISCUSSION

In figure 6.b it is observed that σm reaches a maximum value depending on the contact point considered. For the point lying at the edge of the contact, x=-1.785mm, the inclination of the maximum-σm-plane equals 90°. This value equals 80° for points in the fretted area (x=-1.65 mm or x=-1.45 mm). The crack experimentally observed, inclined to 80° to the surface, are thus initiated by a mechanism of fatigue traction. They are more likely to initiate near the contact edge where σm maximum reaches its maximum value.

Figure 6.a shows that $\Delta\tau m$ reaches a maximum value on two planes inclined to 90° to each other, at each contact point. Figure 8 represents the variation of τm at point x=-1.65mm. $\Delta\tau m$ is maximum on 120°-plane and 30°-plane. Figure 7 represents the slip induced on these planes and the normal contact displacement. As can be

observed, the slip induced by τm on the 120°-plane is opposite to the contact displacement due to normal imbalance over the contact zone. It can be concluded that the slip on this plane is not physically acceptable. Movement and pile-ups of dislocations are thus prevented along this direction. Hence, at each contact point, two initiation planes are theoretically predicted. But one of them is physically inconsistent with contact displacements. In figure 8, the evolution of σm and τm, at point x=-1.65mm, for Q=+/-Qmax, is represented versus plane angle. Along the 30°-plane corresponding to $\Delta\tau m$ maximum, dislocations are submitted to alternative reverse slip and traction compression. Hence, a process of rising and sinking slips takes place. This process was already described as an extrusion-intrusion mechanism. As this mechanism is induced by localization of plastic deformation, it prevails in the fretted contact area were contact stresses are the most critical for plastic deformation (4).

As shown in figure 6.a, the crack initiation angles vary with contact location. In the fretted area, cracks are likely to initiate by an extrusion-intrusion mechanism along 25-35°-plane. Near the contact stick zone, crack initiated by this mechanism will arise along 0°-5°-plane. The former correlate with the fretting crack experimentally observed. The latter can lead to spall detachment in the contact stick zone. They are rarely observed but wear due to spall detachment near the contact stick zone is of experimental evidence.

CONCLUSION

Two crack nucleation modes were observed during fretting tests conducted on a pre-stressed specimen. Type I crack nucleation took place at a small angle (25°) with respect to the surface while type II appeared nearly perpendicular to material surface (80°). Two crack nucleation mechanisms were then theoretically proposed through a simple dislocation model. Hence, it was concluded that type I nucleation was related to a sliding (extrusion-intrusion) mechanism in the fretted area while type II nucleation was induced by a tensile fatigue at the edge of the contact.

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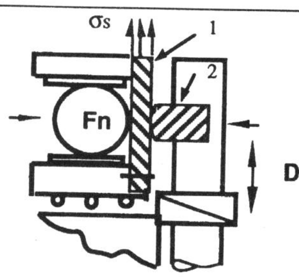
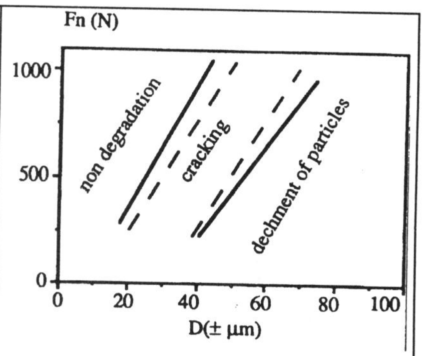


Relative humidity	50% +/-20
Temperature	23 °C
Imposed amplitude,D	+/-15 - +/-75 μm
Normal load, Fn	1000 N
Static stress, σs	230 MPa
Frequency	1 - 5 Hz
Number of cycles	$5.10^4 - 10^6$
Radius of sample (2)	0.3 m
Surface roughness	0.4 μm
Elastic limit	460 MPa

Figure 1: Scheme of the FPSS test and experimental conditions.



Dotted lines in the figure symbolyze the frontier between fretting regimes :

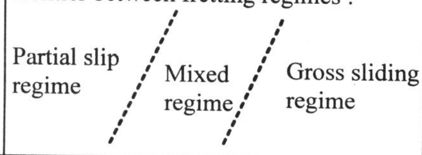
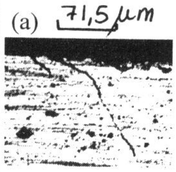
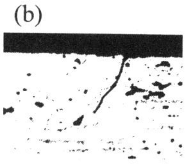


Figure 2: Fretting Map of the Aluminium alloy 7075 T7351

(a)



(b)



(c) Spherical counterface (up) on plane pre-stressed specimen (down)

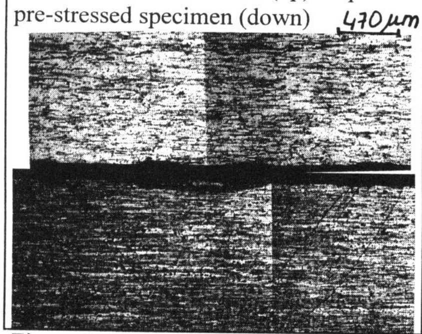
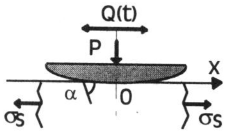
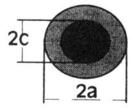


Figure 3: Crack initiation (a) type I; (b) type II; (c) in two contacting bodies



Normal force, **P** = 900 N
Tangential force **Q**= +/-950 N
Global friction coefficient μ = 1.2
σs = 230 MPa
Experimental contact zone, **2a**=3.57mm
Experimental stick zone, **2c**=2.30mm

(a)



(b)

Figure 4: (a) Experimental conditions
(b) Contact zone repartition

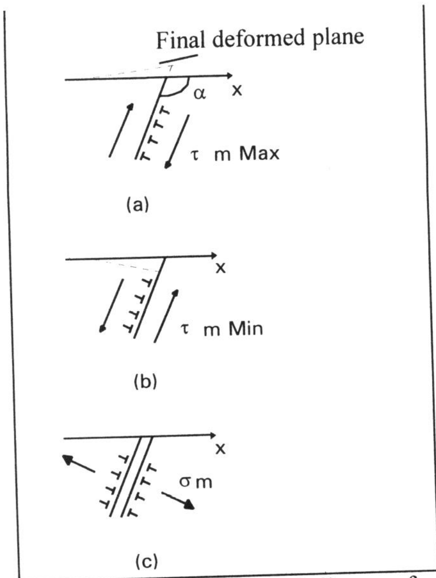


Figure 5: Representation of pile-ups of dislocation loops on inclined plane (3)

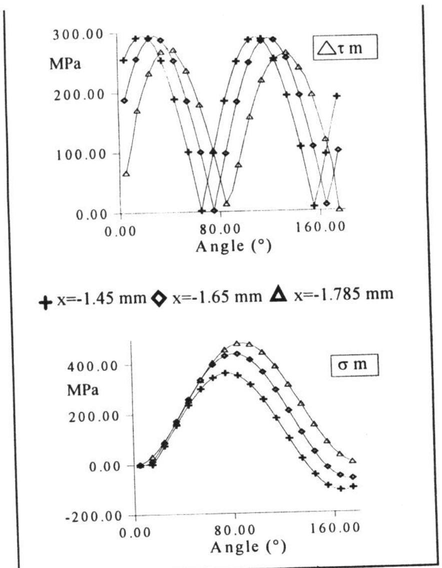


Figure 6: Evolution of (a) $\Delta\tau m$ and (b) σm versus initiation plane inclinationα

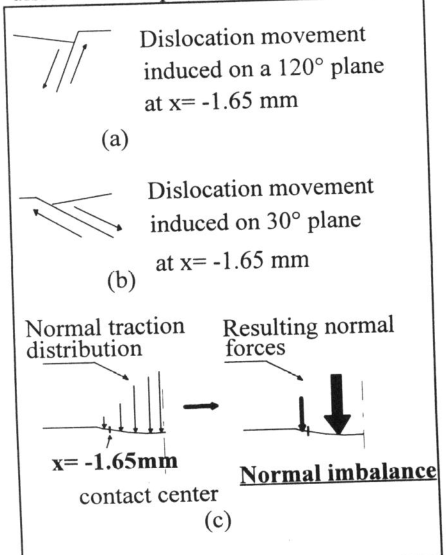


Figure 7: (a), (b) Slip band movement, (c) normal contact displacement

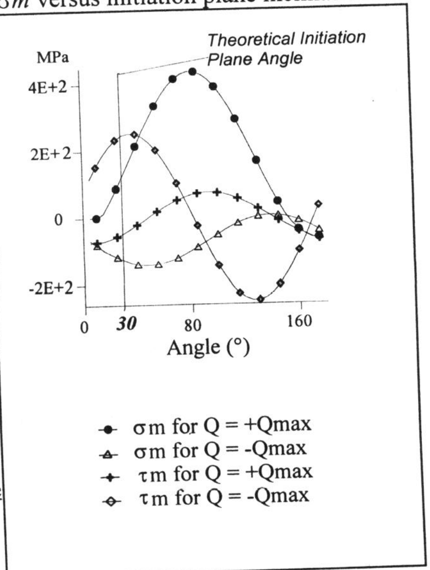


Figure 8:Evolution of τm and σm at point x=-1.65mm, vs. plane inclination