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# La Tribologie : Fondamentaux et Applications Complexes

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## CONTACT PLASTIC ACCOMMODATION INFLUENCE ON THE FRETTING FATIGUE CRACKING RESPONSE OF STEEL

### *INFLUENCE DE L'ACCOMMODATION PLASTIQUE DU CONTACT SUR LA FISSURATION D'UN ACIER SOUMIS A DES SOLLICITATIONS DE FRETTING FATIGUE*

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#### Abstract

This work aims to quantify safe running fretting-fatigue condition for a severely plastic contact by predicting the crack nucleation condition. Experimental results show that the crack nucleation condition is stable despite increasing fatigue loading. Yet, the fatigue stress tends to increase the global stressing so that the related threshold fretting contact stressing is expected to be reduced. Simulations have been done and the crack nucleation condition was addressed by transposing the Crossland's multiaxial fatigue criterion at a critical distance to take into account the contact stress gradient. Contact plastic accommodation phenomenon is shown to explain the plateau evolution of the crack nucleation condition.

#### Résumé

*Ce travail a pour but de dimensionner la réponse en fretting-fatigue d'un contact sévèrement déformé plastiquement en prédisant la condition d'amorçage de fissure. Des essais expérimentaux montrent que la condition d'amorçage en fretting (force tangentielle) est stable malgré l'augmentation du chargement de fatigue. Or une augmentation de la sollicitation de fatigue est sensée augmenter le chargement global de sorte que la valeur seuil du chargement de fretting devrait être diminuée. Des simulations ont été réalisées, et la condition d'amorçage calculée en utilisant le critère de Crossland à une distance critique afin de prendre en compte les gradients de contrainte. L'accommodation plastique du contact apparaît être à l'origine de l'évolution en plateau de la condition d'amorçage.*

#### 1. INTRODUCTION

Fretting is defined as a small oscillatory movement between two bodies in contact which induce relative displacement between the two surfaces. Combined with cyclic bulk fatigue loading, the so called fretting-fatigue loading can induce catastrophic damages which critically reduce the endurance of assemblies.

To rationalize the prediction of crack nucleation risk induced by fretting-fatigue, a fretting-fatigue map concept which consists to plot the crack nucleation boundary as a function of the applied maximum fatigue stress  $\sigma_F$  (x-axis) and the fretting tangential force amplitude  $Q^*$  (y-axis) has been introduced [1].

In this study, we will focus on the crack nucleation process by transposing conventional multiaxial fatigue criteria [2,3]. Because of the contact stress gradient effects [4], a non-local approach is developed using the Crossland's multiaxial fatigue criterion.

Severe contact stress conditions will be applied inducing plastic deformations in the contact to study the influence of the plastic contact accommodation on the crack nucleation process.

## 2. MATERIALS AND TESTS

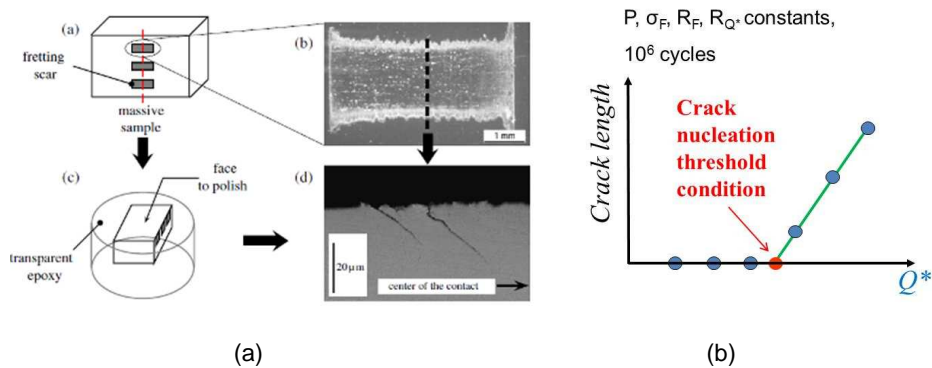
The fretting-fatigue response of a low alloyed industrial steel flat specimen (IS) fretted against a 35NCD16 steel cylinder pad (radius  $R=19\text{mm}$ ) is investigated. Their mechanical properties are presented in Tab. 1. IS properties are confidential but it is considered homogeneous and it is described by a monotonic elastic-plastic law determined by simple tensile test.

Materials	35NCD16	Industrial steel
Young's modulus $E$ (GPa)	210	190
Poisson's coefficient $\nu$	0.3	0.29
Yield stress $\sigma_Y$ (0.2%) (MPa)	1127	$\sigma_Y$
Ultimate stress $\sigma_{UTS}$ (MPa)	1270	$\sigma_{UTS}$

**Tab. 1** Mechanical properties of the tested materials  
*Propriétés mécaniques des matériaux étudiés*

The contact is tested in plain fretting and fretting-fatigue. In both case, a high static normal force  $P$  is applied so that severe plastic deformations are induced in the flat:  $p_0/\sigma_Y = 2.5$  ( $p_0$  maximum pressure in the flat). The fatigue and fretting stress ratios are kept constant at respectively  $R_F = 0.94$  and  $R_{Q^*} = -1$ .

The crack analysis is restricted to the flat specimen. The dimensions chosen allow plane strain conditions along the central axis of the fretting scar. All the fretting scars were analyzed following a method developed by Proudhon *et al.* [5]. The main steps of this method are depicted in Fig. 1a.



**Fig. 1** (a) Optical analysis method, (b) crack nucleation threshold determination methodology  
(a) méthode d'analyse optique, (b) méthode de détermination du seuil d'amorçage de fissure

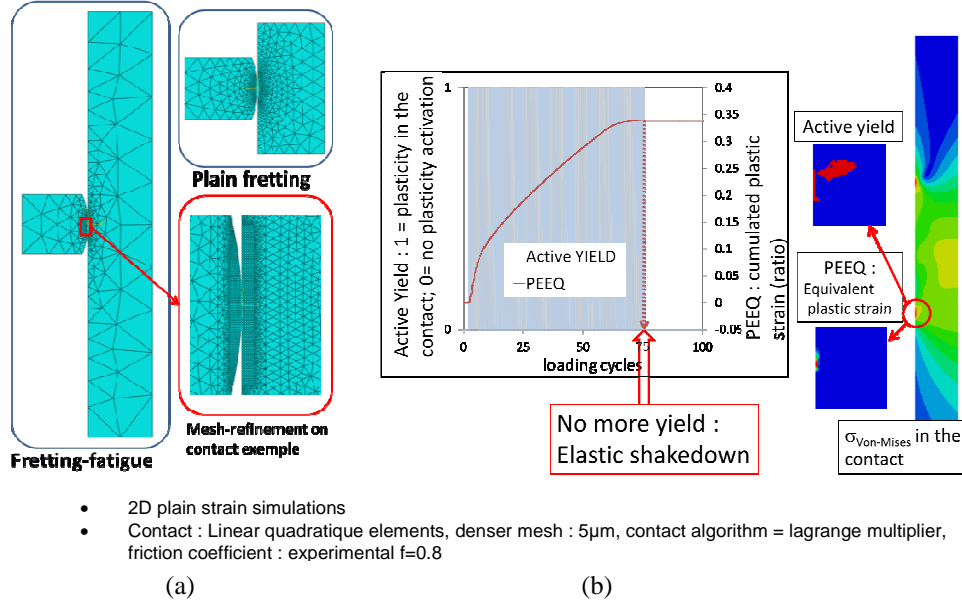
For each experimental test, the maximum projected crack length is considered and plotted as a function of the tangential force amplitude. The crack nucleation condition is defined for the tangential load at which no crack can be observed. To determine this value a linear evolution of the crack length with the tangential load is assumed as plotted in Fig. 1b.

## 3. STRESS FIELD ANALYSIS

### Abaqus modeling description

Finite element analysis (FE) was carried out using Abaqus 6.9 to formalize the experimental results. Two dimensional modeling of the plain fretting and fretting fatigue tests

have been generated following the sketches shown in Fig. 2. As we use an elastic-plastic law for the flat, each time enough cycle to reach elastic shakedown and thus a stable state were applied before the post treatment.



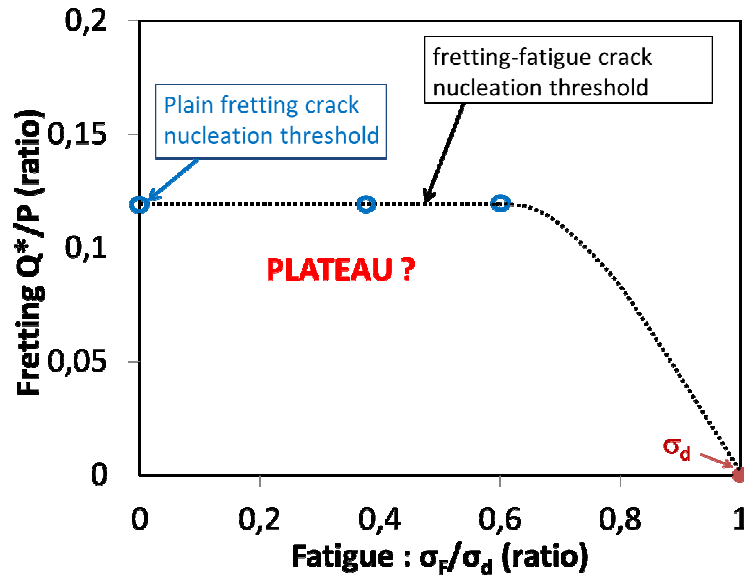
**Fig. 2** (a) Abaqus models of the experimental tests, (b) Elastic shakedown in contact  
(a) Modèles Abaqus des essais expérimentaux, (b) Accommodation élastique du contact

#### Validation of the elastic-plastic law

Prior to any numerical computation, a dedicated FE simulation-experimental analysis has been performed to verify if the given monotonous elastic-plastic law is representative of high compressive conditions. For this purpose, experimental sphere on plane macro indentation tests were performed and then simulated. The mean measured experimental radius was  $2a_{exp}=2.24$  mm whereas the simulated contact radius was  $2a_{th}=2.16$  mm. The standard deviation between the two radiuses is only  $4\% < 5\%$ . The monotonic elastic-plastic law of the plane gives a good reproduction of the experimental test so its use is justified to simulate the plain fretting and fretting fatigue tests.

#### 4. EXPERIMENTAL RESULTS

The experimental crack nucleation boundary determined from three fatigue conditions is plotted in Fig. 3. The three experimental crack arrest condition are determined from several tests as explained in Fig 1b. The experimental crack nucleation boundary can then be defined by linking those conditions. Then the boundary is extrapolated until  $\sigma_F = \sigma_d$  by considering the experimental fatigue limit of the material  $\sigma_d$  at the studied stress ratio :  $R_F=0.94$ .



**Fig. 3** Experimental crack nucleation fretting-fatigue map ( $P$ , 12Hz,  $10^6$  cycles,  $R_F=0.94$ ,  $R_Q=-1$ )  
*Carte expérimentale d'amorçage de fissure en fretting-fatigue ( $P$ , 12Hz,  $10^6$  cycles,  $R_F=0.94$ ,  $R_Q=-1$ )*

At this stage of the analysis, it is surprising to note that the threshold fretting loading presents a plateau response while a significant increase of the fatigue stress is imposed. Assuming an elastic analysis, the addition of fatigue stressing will imply a significant reduction of the threshold  $Q^*/P$  fretting loading [1]. The influence of plasticity on the crack nucleation prediction is thus investigated through a FE computation analysis.

## 5. QUANTIFICATION OF CRACK NUCLEATION

In order to formalize the crack nucleation boundary, a technique using the Crossland's multiaxial fatigue criterion at a critical distance so as to take into account the stress gradient effect has been followed.

### Crossland's criterion at a critical distance

The Crossland's multiaxial fatigue criterion expresses the crack risk as a linear combination of the maximum amplitude of the second invariant of the stress deviator  $\sqrt{J_{2,a}}$ , and the maximum value of the hydrostatic pressure  $\sigma_{h \max}$  [6].

The non-cracking condition is expressed by

$$\sqrt{J_{2,a}} + \alpha \cdot \sigma_{h \max} < \tau_d \quad (1)$$

Where

$$\alpha = \frac{\tau_d - \sigma_d / \sqrt{3}}{\sigma_d / \sqrt{3}} \quad (2)$$

With,

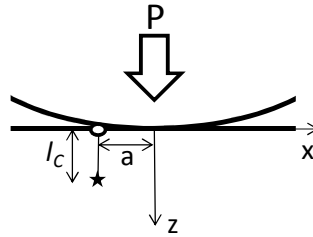
$\sigma_d$  : alternating bending fatigue limit,

$\tau_d$  : alternating shear fatigue limit.

The cracking risk can also be formalized considering a scalar variable:

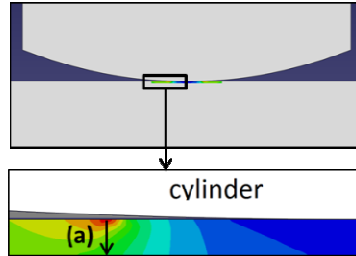
$$d_c = \frac{\sqrt{J_{2,a}}}{\tau_d - \alpha \cdot \sigma_{h \max}} \quad (3)$$

The non-cracking condition is then expressed by  $d_c < 1$ . If  $d_c$  is greater than or equal to 1, there is a cracking risk. In this study, we will use this scalar variable to quantify the cracking risk. The contact configuration creates a strong stress gradient below the surface. A point stress analysis on the surface greatly overestimates the cracking risk. Therefore a non-local criterion is applied. The critical distance method has been chosen here being the easiest one to implement. Fig. 4 describes its principle.



**Fig. 4** Critical distance method with  $l_c$  : critical length  
Principe de la méthode de distance critique avec  $l_c$  : distance critique

This method is equivalent to the point stress analysis but instead of considering the surface "hot spot" stress at the contact border, the fatigue analysis is performed considering the stress loading path at a critical distance below the surface ( $x=-a, z=l_c$ ).

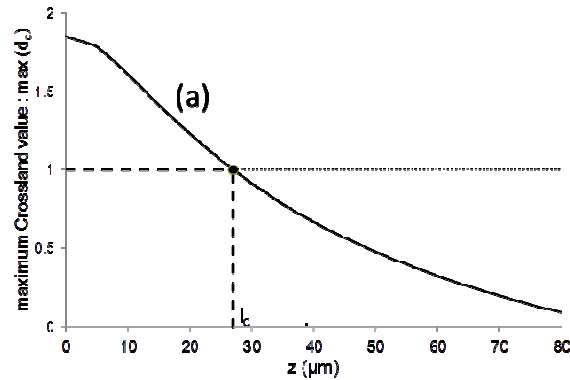


**Fig. 5** Crossland cracking risk on abaqus computation  
Calcul abaqus du risque d'amorçage par le critère de Crossland

The non-local Crossland criterion is extracted along the expected perpendicular crack path using FE analysis combined with a python subroutine (Fig. 5).

#### Calibrating of the optimal critical distance

The critical distance is calibrated on the plain fretting nucleation threshold. The experimental plain fretting nucleation threshold condition is reproduced using FE simulation. The critical distance is defined as the distance to the border contact for which the cracking risk  $d_c=1$  as shown in Fig. 6.

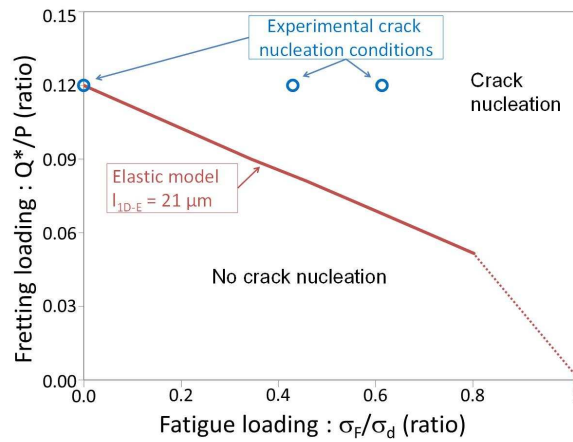


**Fig. 6** Calibration of the critical length in elastic-plastic computation. Extraction of the cracking risk along the path  $(x=-a, z)$   
*Calibration de la distance critique pour une simulation élastoplastique. Extraction du risque d'amorçage suivant le chemin  $(x=-a, z)$*

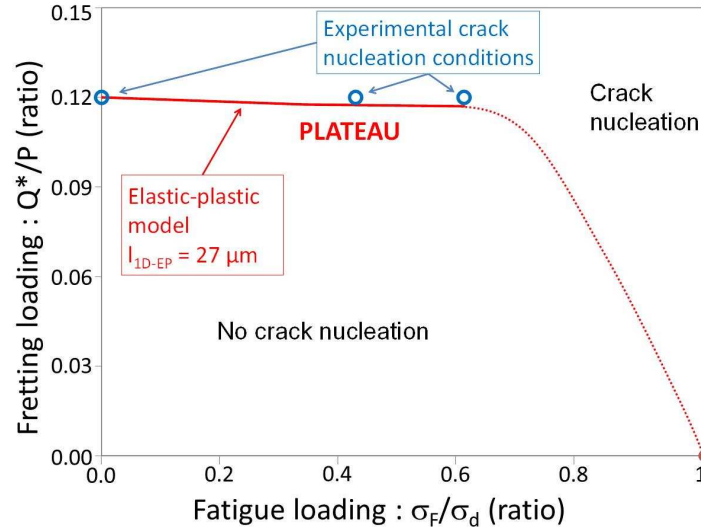
For a purely elastic simulation, the critical length calculated is  $l_{C-E}=21 \mu\text{m}$ . When the flat is described with its monotonic elastic-plastic law, the critical length is  $l_{C-EP}=27\mu\text{m}$ .

#### Predicting the crack nucleation risk under fretting-fatigue

The theoretical crack nucleation condition is calculated at three fatigue levels by iterations for both elastic and elastic-plastic models. The obtained boundaries are plotted in Fig. 7 for elastic simulations and in Fig. 8 for elastic-plastic simulations.



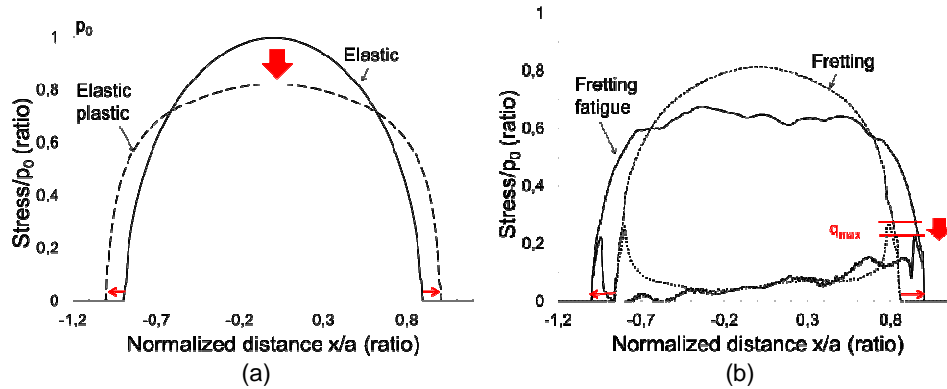
**Fig. 7** Elastic crack nucleation fretting-fatigue map ( $P, 12\text{Hz}, 10^6\text{cycles}, R_F=0.94, R_Q=-1$ )  
*Carte d'amorçage élastique de fissures en fretting-fatigue ( $P, 12\text{Hz}, 10^6\text{cycles}, R_F=0.94, R_Q=-1$ )*



**Fig. 8** Elastic-plastic crack nucleation fretting-fatigue map ( $P$ , 12Hz,  $10^\circ$ cycles,  $R_F=0.94$ ,  $R_Q=-1$ )  
*Carte d'amorçage élastoplastique de fissures en fretting-fatigue ( $P$ , 12Hz,  $10^\circ$ cycles,  $R_F=0.94$ ,  $R_Q=-1$ )*

The elastic boundary decreases linearly with the rise of the fatigue stress. For  $\sigma_F/\sigma_d = 0.6$ , the standard deviation to the experimental result is 44 %. The elastic analysis is not pertinent to capture the crack nucleation condition for such severe plastic strain conditions. Unlike the elastic boundary, the elastic-plastic boundary shows really good correlation between experiments and simulations: for  $\sigma_F/\sigma_d = 0.6$ , the standard deviation to the experimental result is only 2.5 %. In addition we demonstrated that the experimental plateau comes from a generalized contact plastic accommodation of the interface.

The normal and tangential loads as well as the fatigue stress create a contact plastic accommodation process. The plastic strain in the contact leads to a reduction of the maximum contact pressure  $p_0$  and the maximal shear stress  $q_{max}$  in the contact which can be considered as the driving factor of the cracking process (Fig. 9). Hence an additional increase of the fatigue will increase the tensile state but also will extend the plastic accommodation of the interface reducing both  $q_{max}$  and  $p_0$  values. These two opposite effects of the fatigue loading compensate each other until the global tangential loading is enough to nucleate thus creating a plateau evolution of the crack nucleation boundary in the fretting-fatigue map representation.





**Fig. 9** (a) Contact plastic accommodation process. elastic/elastic-plastic peak pressure comparison, —:elastic contact pressure; ...:elastic-plastic contact pressure.  
 (b) Fatigue influence on contact plastic accommodation process. ...: Plain fretting pressure and shear contact profile. —: Fretting-fatigue pressure and shear contact profile.  
 (a) *Processus d'accommodation plastique du contact, comparaison des pics de pression élastique et élastoplastique ; —: pression de contact élastique; ...: pression de contact élastoplastique*  
 (b) *Influence de la fatigue sur le processus d'accommodation plastique du contact ; ...: profiles de pression et de cisaillement en fretting simple ; —: profiles de pression et de cisaillement en fretting-fatigue*

## 6. CONCLUSION

This investigation underlines that an elastic-plastic model is necessary to simulate accurately the fretting fatigue response of a severely plastic contact. The combined hypothesis of the plasticity and gradient stress consideration with a multiaxial fatigue analysis (Crossland) enables the crack nucleation risk under severe plastic fretting fatigue condition to be conservatively determined.

The plateau response is explained with a contact plastic accommodation phenomenon: the plastic strain of the contact increases with the fatigue loading which softens the contact pressure and shear stress profiles.

There is a competitive effect between the tensile state imposed by the fatigue loading and the plastic accommodation of the interface. So the linear decreasing evolution of the crack nucleation boundary defined from an elastic modeling leads to a more representative plateau evolution if elastic-plastic analysis is considered.

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