A GEOMETRICAL MODEL FOR FATIGUE CRACK-CLOSURE

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This paper concerns the fatigue crack closure phenomenon and proposes a geometrical model which permits to describe the crack opening kinematics during a loading cycle and calculate the crack opening load value.

INTRODUCTION

In the litterature, the numerous results concerning the physical origin of the fatigue crack closure bring out three essential causes :

- the existence, in the wake of a fatigue crack, of a plastically strained material which presents a residual extension (Elber (1)).
- the presence of asperities on the fatigue cracked surfaces (Suresh (2)).
- when the cracking takes place under agressive environment (even in air), the existence of oxide layers on the cracked surfaces (Ritchie (3)).

Even if the intricate origin of the fatigue crack closure is not elucidated, neglecting its existence leads to overvalue the stress intensity factor amplitude effectively applied at the crack

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tip. The purpose of this study is to determine and model the relative influence of the plastically strained material and the crack surfaces roughness on the amount of crack closure.

EXPERIMENTAL CONDITIONS AND RESULTS

Fatigue tests with a decreasing stress intensity amplitude down to the threshold and load ratios equal to 0.1 or 0.5 were performed on CT specimens machined in a 7075 alloy sheet. Four aged hardening conditions of this alloy were studied, because of the great differences in the observed crack surfaces roughnesses. In order to avoid any oxidation effect, the tests have been carried out in a vacuum chamber ($p < 10^{-3}$Pa).

At each test end, when the crack propagation rate was less than 10^{-10}m/cycle, some closure loads values have been obtained :

i) the variations of the specimen compliance were measured by a back face strain gauge and amplified in order to obtain the **global** opening load value P_o.

ii) on the polished side of the specimen, the crack edges spacing (δ) was measured where the local crack path was normal to the loading axis, with an optical microscope (x425). A small device used to load the specimen on the microscope has permitted to obtain the variations of δ with the applied load P at different distances from the crack tip : Δa_s (not closer than 0.1 mm to the tip).

One can see on the figure 1, giving an example of such a curve, that no displacement between the two cracked surfaces is observed below the **local** opening load, P_{ouv} , which depends on the distance Δa_s. Numerous experimental results given elsewhere (M.C. Lafarie-Frenot and C. Gasc (4), (5), (6)) concerning these local measurements have shown that the values of the residual spacing observed at zero load and the local opening loads depend significantly on the different studied parameters : for example, they were found as high as the crack surfaces roughness was, and systematically higher when R = 0.5 than R = 0.1.

The opening kinematics of a fatigue crack can be represented in a diagram P_{ouv} vs Δa_s : two examples of such curves are given in figure 2. In these two cases, the material plastic extension along the crack contineously decreases as the crack advances (threshold tests). In the same time, the crack surfaces roughness increases in the underaged material (UA) and decreases in the hyperoveraged one (HOA). This difference induces very different ultimate opening point locations during a loading cycle : in the first case, the crack tip is the last point to be open, in the second case it is a point near the notch. At last, it was noted that, in all the cases studied, the global opening load value P_o corresponds to that entirely opens the crack (see fig. 2). All these results confirm that there exists an interaction between the "histories" of the plastically strained material and of the cracked surfaces roughness, that determines the opening load value.

RESULTS ANALYSIS - PLASTICITY/ROUGHNESS INTERACTION MODEL

On the figure 3 is given a schematic representation of a fatigue crack local opening curve (as obtained in figure 1) :

$$\begin{aligned} &\delta = \delta_R \text{ for } 0 < P < P_{ouv} \\ &\delta = \mathfrak{T}(\Delta a_s) \times P - \delta_{pl} \text{ for } P > P_{ouv} \end{aligned} \qquad (1)$$

with : P_{ouv} = local opening load
δ_R = residual spacing at $P < P_{ouv}$
$\mathfrak{T}(\Delta a_s)$ = slope of the opening straight line
P' = load value obtained at $\delta = 0$
δ_{pl} = absolute crack edges spacing at $P = 0$

Note that, in all cases studied, δ_{pl} was experimentally found to be negative.

Residual plastic extension

The schematic representation given in the figure 4 shows that the direct measurement through a microscope of the spacing between the two cracked surfaces for different values of the load, permits to determine the residual plastic extension of the material near the crack. At a point located at Δa_s from the crack tip this spacing can be represented by the relation :

$$\delta(P) = u_y(P,a) - \delta_{pl} \qquad (2)$$

where u_y (P,a) is the C.O.D. at this point, **elastic** displacement due to the load P applied to a crack, the length of which is a. The linear part of the local opening curve **experimentally** obtained for $P > P_{ouv}$(see fig. 3) and for $\Delta a_s > 0.1$ mm agrees with the relation (2). More, the values of $\mathfrak{T}(\Delta a_s)$ have been found, in all the cases studied, very close to that given by Irwin (7) :

$$\mathfrak{T}(\Delta a_s) = \frac{4(1-\nu)}{\sqrt{2\pi}\, G} \sqrt{\Delta a_s}\, \frac{K_I}{P} \qquad (3)$$

Then, we can assume that the value δ_{pl}, determined as indicated on the figure 5, **is the value** of the residual plastic **extension** at the considered point of the crack.

On the figure 5, have been plotted different values of δ_{pl} determined for the four microstructures, the two R values, and many Δa_s, vs the local values of $(K_M^2/E\sigma_y)$ (K_M is the value of the maximal stress intensity factor applied when the crack tip was at the considered point, E the alloy Young modulus and σ_y its yield strength). In this same basis have been drawn some theoretical laws giving δ_{pl} as proposed by Dill & Saff (8), Seeger (9) and Budiansky-Hutchinson (10). It can be seen that the experimental data are in good agreement with the theoretical models.

Local opening loads

On the schematic diagram given in figure 3, the value of the load noted P', obtained at $\delta = 0$, corresponds to the local opening load value only due to the residual plastic extension : imagine a fictitious crack, with no surfaces roughness at all ; during an unloading, there would be contact between the two crack edges at Δa_s for the load P' which verifies :

$$\delta = u_y(P') - \delta_{pl} = 0 \qquad (4)$$

In fact, we experimentally found that a real crack is never absolutely flat and that the contacts are always observed along the most misoriented surfaces with respect to the near crack propagation plane. At the same time, we found that the real opening load value P_{ouv} is always greater than P', the differences observed being very important when the crack surfaces were rough.

Plasticity/Roughness interaction model

The geometrical model we propose is given in figure 6. At a point located at Δa_S from the tip, the angle between the local crack path and the mean propagation plane is $\overline{\theta}$. We assume that :

i) the plastic deformation and fracture mechanisms are the same whatever the crack path orientation is.

ii) the length of each crack segment is so short that the imposed K_M value is the same all along it.

These two conditions induce that the residual plastic extension of the material, perpendicular to the cracked surfaces, is constant all along the considered crack length. Then, during an unloading cycle, the contact between the two cracked surfaces first takes place along the steep ones, at P_{ouv}, higher than P', which verifies the equation (5) :

$$u_y(P_{ouv},a) - \delta_{pl}/\cos\overline{\theta} = 0 \qquad (5)$$

(1) and (5)→
$$\cos\overline{\theta} = \delta_{pl}/(\delta_{pl} + \delta_R) \qquad (6)$$

The parameter $\overline{\theta}$ is not physically significant, the crack surfaces roughness geometry being three dimensional. However a good correlation is oberved on the figure 7, between the values of $\overline{\theta}$ so determined and a measured characteristic roughness parameter. Thus, we can assume that the roughness influence on the amount of crack closure can be modelled with the single parameter $\overline{\theta}$.

Opening kinematics of a fatigue cracks

The plastically strained material thickness left in the wake of a fatigue crack, (δ_{pl}) and the crack surfaces roughness ($\bar{\theta}$) depend on the applied K_M value and the alloy microstructure (with regard to the plastic deformation and fracture mechanisms it induces). The model we propose assume that, at a distance Δa_s from the crack tip, the thickness of the "plastic strained and rough" band of material can be characterized by the single parameter $(\delta_{pl}/\cos\bar{\theta})_{\Delta a_s}$.

Thus, the crack will be locally open at Δa_s for the load values P which imply that :

$$u_y(P,a,\Delta a_s) > (\delta_{pl}/\cos\bar{\theta})_{\Delta a_s} \qquad (7)$$

The crack opening kinematics during a loading cycle is then determined by the successive advent of points where this inequation is verified. The very different opening kinematics experimentally observed and presented in fig. 2, can be explained by the schematic diagrams given in figure 8.

a) In the case of the HOA alloy, the crack surfaces are very flat ($\cos\bar{\theta} \simeq 1$), the plastic deformation is intense because of the low value of its yield strength. The test being conducted with decreasing K_M values down to the threshold, the evolution of $(\delta_{pl}/\cos\bar{\theta})$ with Δa_s induces that the crack opens from its tip to the notch. Note that the opening kinematics would be opposite, if the test had been performed with a constant load amplitude.

b) In the case of the UA alloy, the roughness is high, and increases as the crack velocity decreases (i.e. in these tests, is higher near the tip than near the notch) ; the plastic deformation is very low and decreases as the crack advances. So, in such a case, the term ($\cos\bar{\theta}$) becomes preponderant in the threshold range, and the crack ultimately opens at its tip.

CONCLUSIONS

- The microscopic crack edges displacements measurements permit to determine with a good precision the values of the local residual extension of the material all along the crack. These values, in the case of tests in vacuum, are in good agreement with those obtained theoretically.

- A geometrical model is proposed for the determination of the local crack opening load value, which depends on the "plastically extended and rough" band of material left in the wake of the fatigue crack : $(\delta_{pl}/\cos\bar{\theta})$

- The comparison between the local and global crack closure measurements made our model valid and have permitted to describe the crack opening kinematics during a loading cycle.

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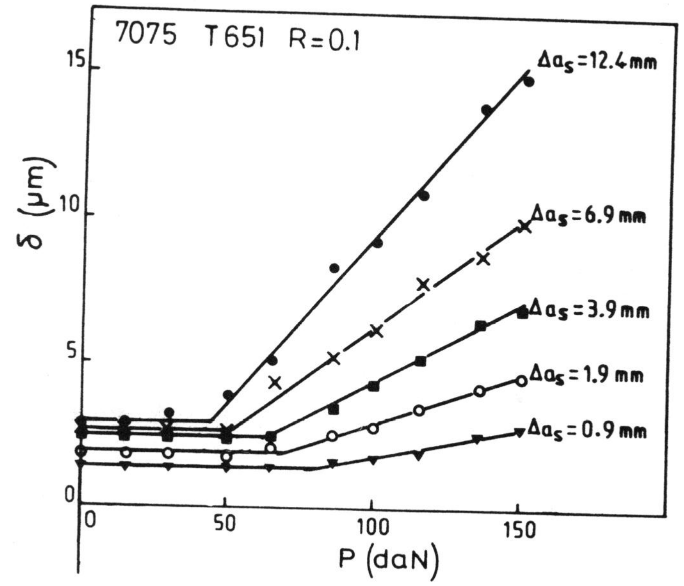

Figure 1 Example of local crack opening curves, obtained by microscopic measurements.

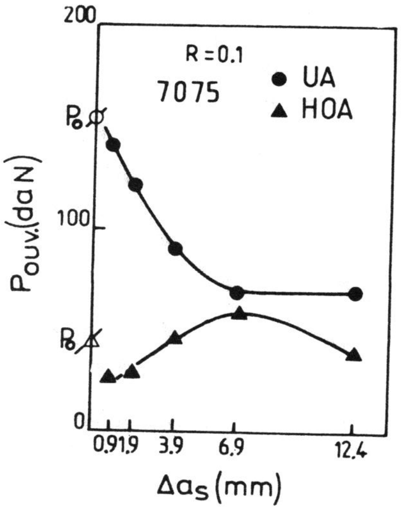

Figure 2 Examples of crack opening kinematics (P_O, plotted on $\Delta a_S = 0$, is deduced from compliance measurements).

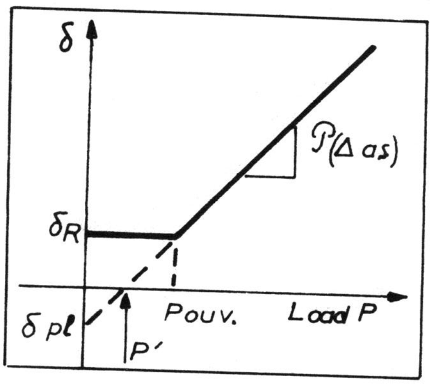

Figure 3 Schematic representation of a fatigue crack local opening curve.

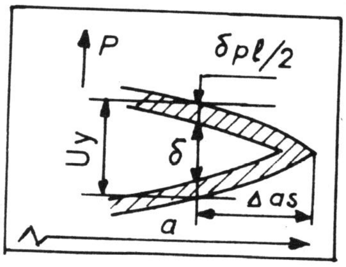

Figure 4 Schematic representation of a fatigue crack with a plastic wake characterized by its residual extension δ_{pl}.

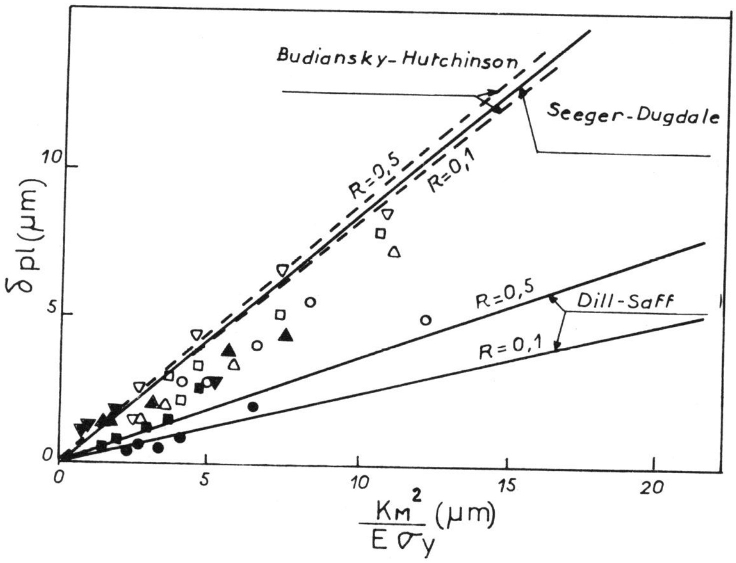

Figure 5 Plastic residual extensions along fatigue cracks, compared to different models.

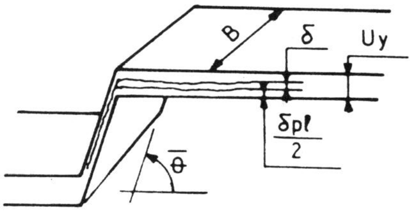

Figure 6 Equivalent asperity, characterized by $\overline{\theta}$ (disorientation) and δ_{pl} (plastic residual extension).

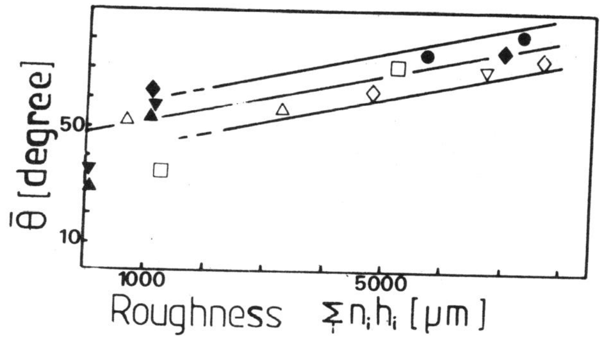

Figure 7 Equivalent disorientation $\bar{\theta}$ related to a measured characteristic roughness parameter.

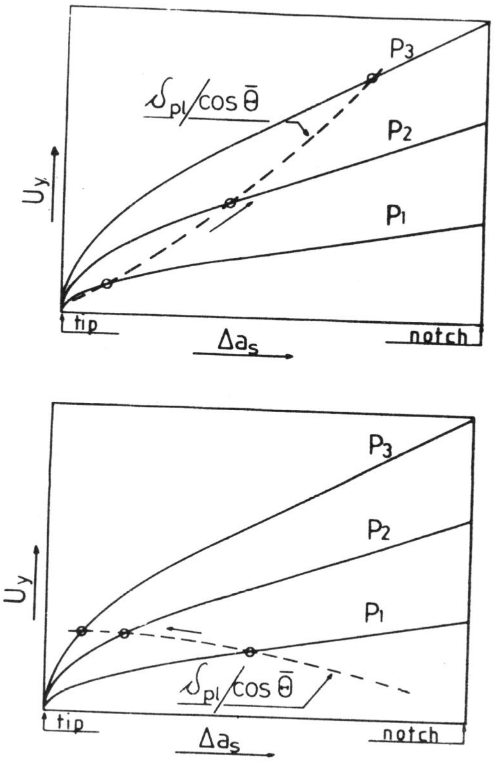

Figure 8 Schematic representation of different crack opening kinematics :
a) Opening from the tip to the notch.
b) Opening from the notch to the tip.