

MICROSTRUCTURAL CONSIDERATIONS ON FATIGUE CRACKS

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Abstract: The paper is concentrated on some micro-structural issues concerning the intimate behaviour of materials subjected to fatigue cycles. A manganese compounds diffusion process has been revealed. This diffusion process, as a consequence of the intimate behaviour an aluminium alloy subjected to fatigue, has been then analysed using a physical model for which the local temperatures have an essential role.

Keywords: fatigue, cracks, propagation laws

1. INTRODUCTION

The study of the fatigue cracks propagation laws occupies a very important place within the modern engineering design. The present-day fatigue research is concentrated on materials cracks behaviour, considering that such cracks are present to some degree in all mechanical structures.

They may exist as basic defects in the constituent materials – assimilated to material deficiencies in the form of pre-existing flaws – or they may be induced in a certain engineering structure during the service life. The whole life time of a certain structure subjected to fatigue cycles (or to static loads as well) depends upon the way in which material cracks do propagate until the final failure.

On the other hand, from the methodological study point of view, there is a big difference in studying short fatigue cracks (taking into consideration different micro-structural issues) and long fatigue cracks, applying to a certain extension the laws of *LEFM* – *Linear Elastic Fracture Mechanics*. In the engineering publications a large number of fatigue crack propagation laws have been proposed [1].

Most of them refer to long crack propagation, i.e. within the field of *LEFM*. On the other hand, at the level where the microstructural features become important for the material behaviour under fatigue, i.e. the field of short crack propagation, the fatigue crack propagation laws involving the field of *LEFM* cannot be applied.

For this last level, the interaction among short cracks and microstructural features becomes of a great importance. The crack length limiting the two distinct fields of fatigue investigations in engineering is approximately of 1 mm (Figure 1).

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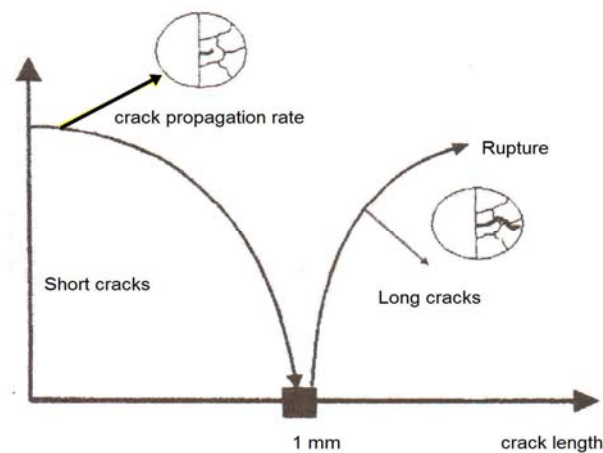


Fig. 1. Short cracks and long cracks propagation domains.

2. MICROSTRUCTURAL CONSIDERATIONS ON FATIGUE CRACKS

The modern theoretical and experimental investigations on fatigue of metals are now largely concentrated on three important areas: *fatigue crack nucleation*, *short crack growth* and *long crack propagation*. It is known that, from the very beginning of the fatigue cycles, short cracks develop inside the material. Some of these short cracks continue to propagate during the fatigue cycles, changing into long cracks while others stop propagating especially due to their interaction with microstructural features. Initiation and growth of fatigue cracks were found to be strongly dependent both on microstructural features (second phase particles, grain boundaries etc.) and on their changes during the fatigue cycles [1]. This paper analyses some investigations carried out to study certain structural changes in an aluminium alloy subjected to fatigue cycles. The material used for the experimental investigations – aluminium alloy 6061 T651, with the chemical composition shown in Table 1, was in form of rolled plates.

Table 1. Chemical composition of the aluminium alloy (wt%).

Element	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
min.	0.40		0.15		0.8	0.04			balance
max.	0.80	0.70	0.40	0.15	1.2	0.35	0.25	0.15	

Fatigue specimens, in form of elliptical section, (Figure 1), were subjected to a constant axial load and to a constant amplitude sinusoidal bending moment until fractures occurred. All tests have been performed in a laboratory environment at room temperature. After failure, the specimens fatigue fractures surfaces have been studied using a scanning electron microscope and a metallographic microscope. Thus, some relevant micrographies were obtained. We have found a lot of physical parameters changed by fatigue: material resistivity and acoustic properties, changes of the mechanical, electrical and magnetic behaviour of the material. From all these changes this paper presents some important conclusions concerning diffusion process of some manganese compounds under the action of fatigue cycles (Figure 2).

The manganese compounds observed at the level of the investigated fatigue surfaces - could be the result of a diffusion process involving different one-dimensional faults (interstitial atoms, foreign atoms, second-phase particles etc.) with very important consequences for the fatigue crack propagation and short crack growth. Even if the material is not loaded, there does also exist a certain interaction between dislocations and one-dimensional faults. Cottrell and Bilby [2] have shown that, the number of foreign atoms migrating in a time t towards the length unit of a dislocation is given by:

$$n(t) = 3 \cdot \left(\frac{\pi}{2}\right)^{1/3} \cdot \left(\frac{A \cdot D \cdot t}{kT}\right)^{2/3} \cdot n_0 \quad (1)$$

where D are the diffusion coefficient for foreign atoms, k is the Boltzmann's constant, T are the temperature, t is the time, n_0 are the number of foreign atoms per unit volume, A are the an elastic interaction parameter.

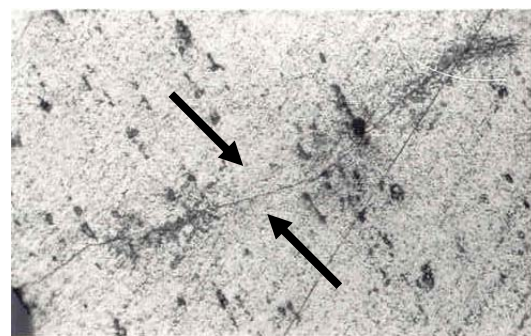
On the other hand it is known that the one-dimensional faults concentration is not uniform in a material, determining the development of a flux with particles, in accordance with Fick's law [3]:

$$i = D \cdot \text{grad}(N) \quad (2)$$

where N represents the concentration of the foreign particles while i is the number of foreign particles passing through the unit area in an unit time.



a. Cross section of the specimens subjected to fatigue.



b. Metallographic micrograph showing different manganese compounds developed within the immediate area of the fatigue crack (x400).



c. Scanning electron micrograph of fracture surface showing the manganese segregation (dark) separated due to a diffusion process (x3000).



d. Fracture surface detail. The direction of crack growth at the level of material grains is evident (x3000).

Fig. 2. Fatigue fractures surfaces microstructural aspects showing a diffusion process induced by fatigue.

It is also to be mentioned that both the interaction between dislocations and foreign atoms and the migration of particles due to a gradient of concentration are strongly dependent on temperature. Returning to the starting problem the following model has been considered: under the action of the external forces, during the fatigue cycles, at a given moment a certain crystal is stressed in a certain way. At every fatigue cycle there exists a probability for this crystal to emit (because of stress), discreetly, a local quantity of energy at the level of dislocation, which may be written as:

$$Q = \alpha \cdot V \cdot \frac{\sigma_M^2 + \sigma_m^2}{2 \cdot E} \quad (3)$$

where: α is a constant, V are the volume of the material per number of dislocations, σ_m , σ_M is the maximum and the minimum value of stress, E are the material modulus in simple tension and compression.

This energy determines the increase of temperature at the level of the involved dislocation. In order to find out the variation of temperature in space and time we have to use the equation of heat propagation [1]:

$$\text{div}(\xi \cdot \text{grad}T) = c_v \cdot \rho_m \cdot \frac{\partial T}{\partial t} \quad (4)$$

where: ξ is the thermic conductivity of the material, c_v are the specific heat for constant volume, ρ_m are the mass density.

For a homogeneous material, equation (4) can be written as follows:

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = \frac{1}{\chi} \cdot \frac{\partial T}{\partial t} \quad (5)$$

where:

$$\chi = \frac{\xi}{c_v \rho_m} \quad (6)$$

is the diffusivity.

A solution for equation (5) is:

$$T = T_0 + A_T K(x, y, z) \quad (7)$$

where: T_0 is the ambient temperature, A_T : an amplitude constant, while

$$K(x, y, z) = \left(\frac{1}{4 \cdot \pi \cdot \chi \cdot t} \right)^{n/2} \cdot e^{-\frac{\|\vec{r}\|}{4\chi t}} \quad (8)$$

is Poisson's nucleus for Cauchy's problem in heat equation, having the following properties [3]:

- $\left(\Delta - \frac{\partial}{\partial t} \right) \cdot K(\vec{r}, t) = 0$ for $t > 0$;
- $K(\vec{r}, t) > 0$ for $t > 0$;
- $\lim_{t \rightarrow 0} K(\vec{r}, t) = 0$, the convergence being uniform;
- $\int_{R^n} K(\vec{r}, t) dx = 1$ for $t > 0$.

where: \vec{r} is the position vector and R^n is the n -dimensional space.

In our case we have $n = 3$ for point-dislocation, $n = 2$ for linear dislocation and $n = 1$ for bidimensional dislocation.

For $n = 3$, using the property (d) it follows that:

$$\begin{aligned} Q &= \int_0^Q dQ = \iiint_V c_v \cdot \rho_m (T - T_0) dx dy dz = \iiint_V c_v \rho_m A_T K(x, y, z, t) dx dy dz = \\ &= c_v \rho_m A_T \iiint_V K(x, y, z, t) dx dy dz = c_v \rho_m A_T . \end{aligned} \quad (9)$$

It follows therefore:

$$A_T = \frac{Q}{c_v \rho_m} = \frac{\alpha \cdot V}{c_v \cdot \rho_m} \cdot \frac{\sigma_M^2 + \sigma_m^2}{2E} \quad (10)$$

The temperature at the level of a certain point (x, y, z) from the involved dislocation is:

$$T(x, y, z, t) = T_0 + \frac{\alpha_0 \cdot V_0}{c_v \rho_m} \cdot \frac{\sigma_M^2 + \sigma_m^2}{2E} \left(\frac{1}{4\pi\chi t} \right)^{3/2} \cdot e^{-\frac{x^2+y^2+z^2}{4\chi t}} \quad (11)$$

In the same way, for $n = 2$ and $n = 1$ we have:

$$T(x, y, t) = T_0 + \frac{\alpha_1 \cdot V_1}{L \cdot c_v \cdot \rho_m} \cdot \frac{\sigma_M^2 + \sigma_m^2}{2E} \left(\frac{1}{4\pi\chi t} \right)^{3/2} \cdot e^{-\frac{x^2+y^2}{4\chi t}} \quad (12)$$

(for a linear dislocation with dimension L) and

$$T(x, t) = T_0 + \frac{\alpha_2 \cdot V_2}{S \cdot c_v \cdot \rho_m} \cdot \frac{\sigma_M^2 + \sigma_m^2}{2E} \left(\frac{1}{4\pi\chi t} \right)^{3/2} \cdot e^{-\frac{x^2}{4\chi t}} \quad (13)$$

(for a bidimensional dislocation with area S).

The gradient of temperature created does play a very important part within the diffusion process observed on our specimens (Figure 3).

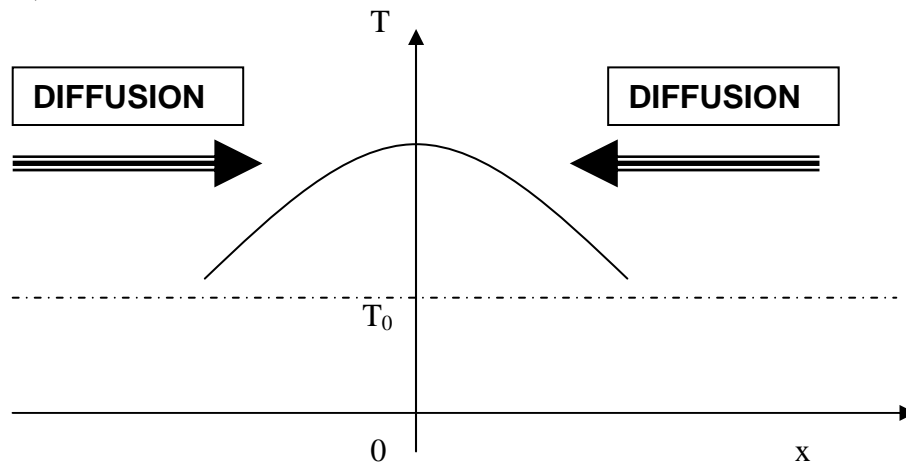


Fig. 3. The gradient of temperature determining the diffusion process.

3. CONCLUSIONS

At the level of the microstructure of a material subjected to fatigue cycles the structural changes have an important part in the fatigue strength and fatigue crack propagation. Different physical and chemical reactions do accompany the short cracks within their propagation, the temperature playing an important role in this matter. On the other hand the macrostructure fatigue behaviour obeys to other types of fatigue laws. This is why a general fatigue law is required to combine both the microstructural and the macrostructural specific behaviour.

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