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Structural Considerations on Fatigue Cracks

This paper has been focused on the modern theoretical and experimental investigations on fatigue of metals which are now largely concentrated on three important areas: fatigue crack nucleation, short crack growth and long crack propagation. The main differences concerning the short cracks and long cracks mechanical investigation analysis have been presented.

Keywords: *fatigue, short cracks, long cracks*

1. Introduction

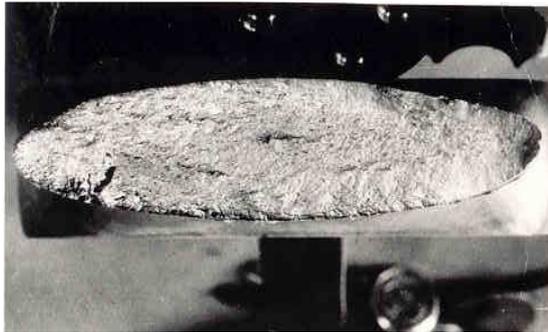
The study of the fatigue cracks propagation laws occupies a very important place within the modern engineering design. The present-day fatigue research is concentrated on materials cracks behaviour, considering that such cracks are present to some degree in all mechanical structures. They may exist as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

Within the above mentioned context, this paper is concentrated both on some micro-structural issues - concerning the intimate behaviour of materials subjected to fatigue cycles – and on macro-structural aspects of *LEFM*.

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.



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)

Figure 1. Fatigue fractures surfaces microstructural aspects showing a diffusion process induced by fatigue

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	

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.

Fatigue specimens, in form of elliptical section, (Figure 1a), 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 a diffusion process of some manganese compounds under the action of fatigue cycles, (Figure 1). 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 [4] 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 : the diffusion coefficient for foreign atoms, k : Boltzmann's constant, T : temperature, t : time, n_0 : the number of foreign atoms per unit volume, A : 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 [4]:

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

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.

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 cycles 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 : a constant, V : the volume of the material per number of dislocations, σ_m , σ_M : the maximum and the minimum value of stress, E : 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]:

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

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

For a homogeneous material, eq. (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

$$\chi = \frac{\xi}{c_v \rho_m} \text{ is the diffusivity.} \quad (6)$$

A solution for eq. 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

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

is Poisson's nucleus for Cauchy's problem in heat equation, having the following properties, [4]:

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

where \vec{r} is the position vector and \mathbb{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:

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

It follows therefore:

$$A_T = \frac{Q}{c_v \rho_m} = \frac{\alpha \cdot V}{c_v \cdot \rho_m} \cdot \frac{\sigma_M^2 + \sigma_m^2}{2E} . \quad (9)$$

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

$$T(x, y, z, t) = T_0 + \frac{\alpha_0 \cdot V_0}{c_v \rho_m} \cdot \frac{\sigma_M^2 + \sigma_m^2}{2E} \left(\frac{1}{4\pi\chi t}\right)^{3/2} \cdot e^{-\frac{x^2+y^2+z^2}{4\chi t}} . \quad (10)$$

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

$$T(x, y, t) = T_0 + \frac{\alpha_1 \cdot V_1}{L \cdot c_v \cdot \rho_m} \cdot \frac{\sigma_M^2 + \sigma_m^2}{2E} \left(\frac{1}{4\pi\chi t}\right)^{3/2} \cdot e^{-\frac{x^2+y^2}{4\chi t}} , \quad (11)$$

(for a linear dislocation with dimension L) and

$$T(x,t) = T_0 + \frac{\alpha_2 \cdot V_2}{S \cdot c_v \cdot \rho_m} \cdot \frac{\sigma_M^2 + \sigma_m^2}{2E} \left(\frac{1}{4\pi\chi t} \right)^{3/2} \cdot e^{-\frac{x^2}{4\chi t}}, \quad (12)$$

(for a bidimensional dislocation with area S).

The gradient of temperature created do play a very important part within the diffusion process observed on our specimens, (Figure 2).

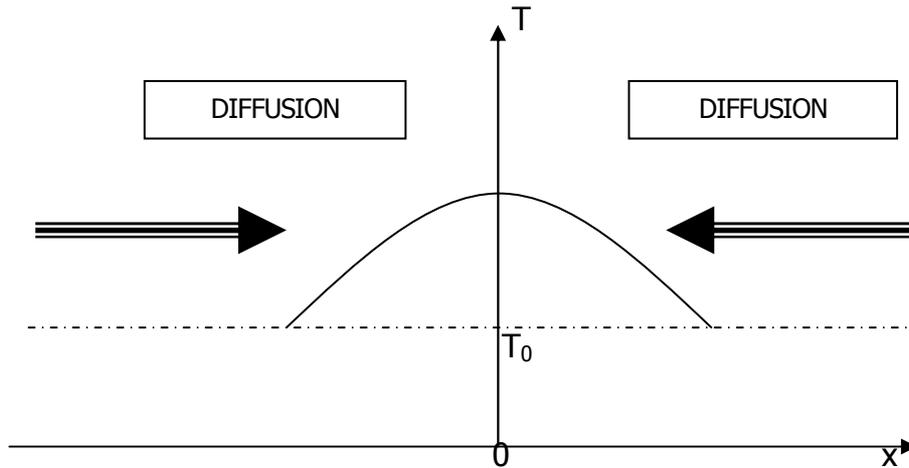


Figure 2. The gradient of temperature determining the diffusion process

It has followed that, at the level of the material microstructure and under the action of fatigue cycles, different structural changes may occur, with important consequences on the propagation of the short fatigue cracks. The diffusion processes accompanying these changes show a continuous movement of the matter inside the specimen subjected to fatigue. On the other hand all the above mentioned changes become less important when the fatigue crack has a certain

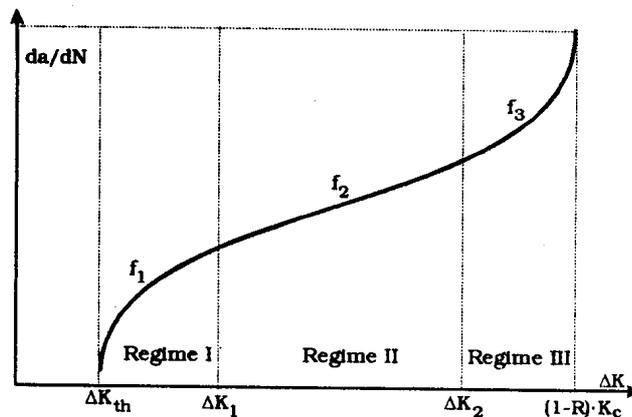


Figure 3. Regimes of growth rates [1]

dimension, changing from a short crack into a long crack. At the level of macrostructural stage, a general crack propagation law has three main regimes of growth rates, (Figure 3), [1].

In [1] there has been concluded that each of these regimes can be satisfactorily described by the following functions respectively:

- Regime I:

$$f_1 = \frac{da}{dN} = C_1 \cdot (\Delta K^{m_1} - \Delta K_{th}^{m_1}); \quad (13)$$

- Regime II:

$$f_2 = \frac{da}{dN} = C_2 \cdot (\Delta K)^{m_2}; \quad (14)$$

- Regime III:

$$f_3 = \frac{da}{dN} = \frac{C_3 (\Delta K)^{m_3}}{[(1-R) \cdot K_c - \Delta K]}; \quad (15)$$

where $C_1, C_2, C_3, m_1, m_2, m_3$: material constants; ΔK_{th} : threshold value of ΔK below which fatigue cracks do not grow; K_c : plain strain critical stress intensity factor; da/dN : crack propagation rate. As a result of a large number of computer aid investigations and data analysis, a new crack propagation law has been proposed, combining in a proper way the advantages offered by the functions f_1, f_2 and f_3 :

$$F = \frac{da}{dN} = \sum_{i=1}^3 f_i \cdot p_i, \quad (16)$$

where p_1, p_2 and p_3 represent moderation functions:

$$p_1 = \frac{1}{e^{\frac{\beta_1}{\Delta K - \Delta K_1}} + 1}, \quad p_3 = 1 - \frac{1}{e^{\frac{\beta_2}{\Delta K - \Delta K_2}} + 1}, \quad p_2 = 1 - p_1 - p_3, \quad (17)$$

where: β_1 and β_2 are transfer parameters; $\Delta K_1, \Delta K_2$: extreme ΔK values of the second characteristic regime of a general crack propagation law.

In Figure 4 a comparison between experimental data of 7075-T651 Al-Zn alloy [1] and the new proposed analytical function has been represented.

3. Conclusion

Since at the level of the microstructure of a material subjected to fatigue the structural changes have an important part in the fatigue strength, the macrostructure fatigue behavior obeys to other types of fatigue laws. A general

fatigue law is required to combine both the microstructural and the macrostructural specific behaviour.

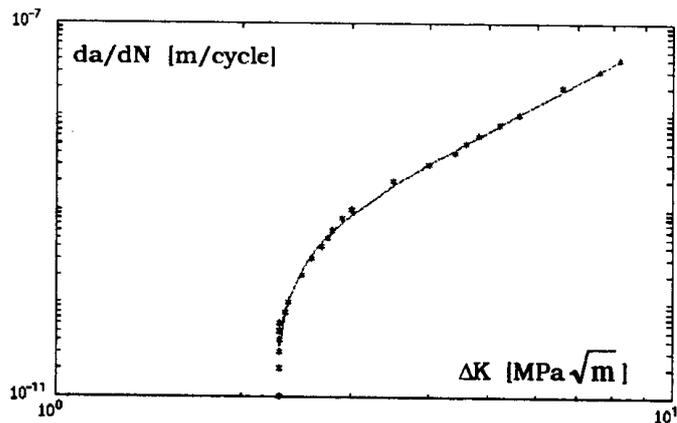


Figure 4. A comparison between experimental data

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