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Modern Tendencies in Fatigue Investigations

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Abstract
The paper presents several fundamental tendencies concerning the new investigations in fatigue phenomenon. The problem has been focused on the two fields of understanding this phenomenon and of trying to offer the most suitable and reliable methods to model fatigue in engineering: short crack and long crack propagation domains. A modern method to get a new crack propagation law has been proposed.

Keywords
crack, fatigue, linear elastic fracture mechanics, microstructural features

1. Introduction

The study of the fatigue crack propagation laws occupies a very important place within the modern engineering design. It is considered 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 an important 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*.

2. Short Cracks and Long Cracks

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 *Linear Elastic Fracture Mechanics* (*LEFM*). On the other hand, at the level where the microstructural features become important for the material behavior under fatigue, i.e. the field of short crack propagation, the fatigue crack propagation laws involving the field of *LEFM* can not 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 (Fig.1).

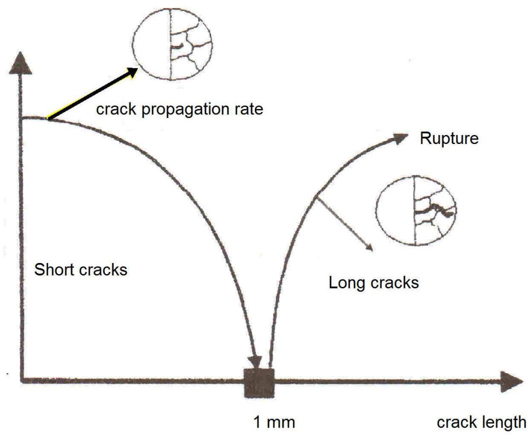

Fig. 1. The two fields of fatigue investigations

To investigate the field of short crack propagation the interaction between crack and microstructural features should be modeled, using different thermodynamic methods combined with the theory of dislocations. Such microstructural features are present to a certain degree in almost all engineering materials, (Fig. 2) [1]. The way in which these microstructural features does interact with cracks in propagation has very important consequences for the whole life time of a mechanical structure subjected to fatigue cycles.

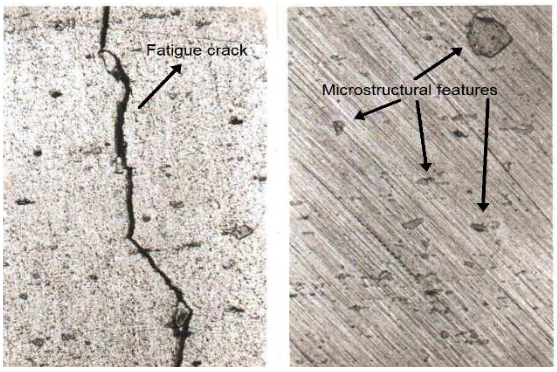

Fig. 2. Fatigue crack and microstructural features

3. Physical Aspects of the Mechanical Interaction between the Fatigue Cracks and the Mechanical Structure

The author have managed to make an analysis of the mechanical interaction between the microstructural components of an aluminium alloy (Al 6061 T 651) and the fatigue cracks, within an original fatigue testing program, using specialized specimens.

The specimens material used for the experimental investigations – aluminium alloy 6061 T651, with the chemical composition shown in Table 1, was in form of rolled plates with initial crack, with the width *b* and the thickness *h,* subjected to a bending moment M, having a sinusoidal variation in time, (Fig. 3).

Table 1. The studied aluminium alloy chemical components

Mg	**Si**	**Fe**	**Cu**	**Mn**
1.1	0.45	0.31	0.18	0.13
Cr	**Zn**	**Ti**	**Ni**	**V**
0.1	0.05	0.012	0.001	0.002
Al – balance				

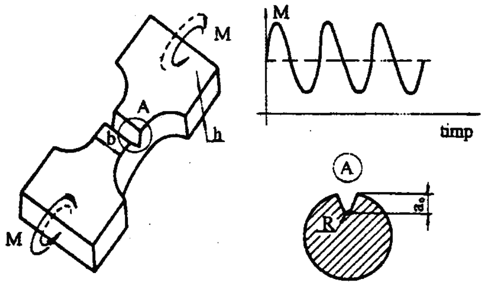

Fig. 3. Specimen used for investigations

One of the most important conclusion deriving from this analysis was that different chemical components of the specimen (here manganese compounds) did change their position within the material, migrating to the short crack during its propagation (Fig.4). 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. Under the action of the external forces, during the fatigue cycles, at a given moment a certain crystal of the material is stressed in a certain way.

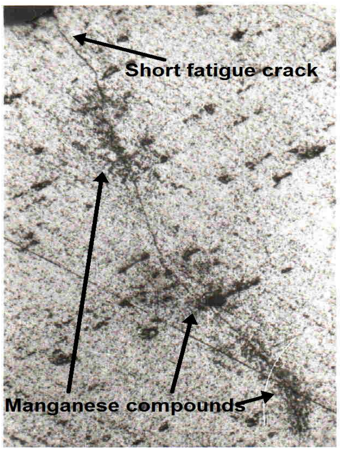

Fig. 4. Manganese compounds diffusion process

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:

$$Q = \alpha \cdot V \cdot \frac{\sigma_M^2 + \sigma_m^2}{2 \cdot E}, \tag{1}$$

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, determining in this way the migration of the manganese compounds, (Fig. 5) - scanning electron micrography of fracture surface showing the manganese segregation (dark) separated due to a diffusion process (x3000).

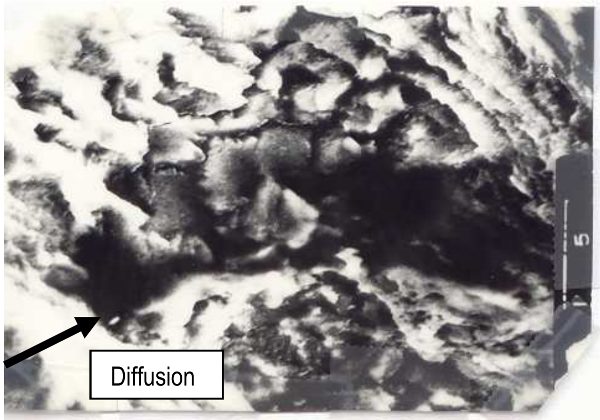

Fig. 5. Manganese segregation (dark)

4. An Original Method to Propose a New Crack propagation Law within LEFM

Due to the importance of materials cracks behavior during mechanical structures service life, the study of the crack propagation laws within the *LEFM* domain has become a very important point for the engineering research. This is the reason why a wide variety of crack propagation laws has been proposed by different researchers in the field (more than 100 cracks propagation laws). In [1] a general collection of *Linear Elastic Fracture Mechanics* crack propagation laws and the main advantages offered by each of them have been proposed. Although there are so many crack propagation laws, none of them has a good general applicability. Each one may be found reasonably satisfactorily only for particular cases and for limited sets of data. This is the reason why a general *LEFM* law (which to combine all advantages offered by each law separately) has become a very important issue. A general crack propagation law has three main regimes of growth rates (Fig. 6).

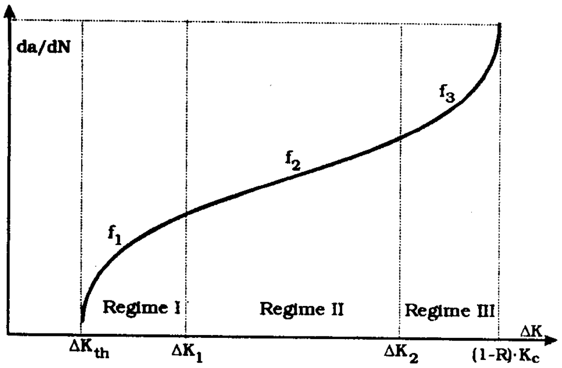

Fig. 6. Crack propagation law regimes

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

Regime I:

$$f_1 = \frac{da}{dN} = C_1 \cdot \left(\Delta K^{m_1} - \Delta K_{th}^{m_1} \right); \tag{2}$$

Regime II:

$$f_2 = \frac{da}{dN} = C_2 \cdot \left(\Delta K \right)^{m_2}; \tag{3}$$

Regime III:

$$f_3 = \frac{da}{dN} = \frac{C_3 \left(\Delta K \right)^{m_3}}{\left[\left(1 - R \right) \cdot K_c - \Delta K \right]}, \tag{4}$$

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:

$$F = \frac{da}{dN} = \sum_{i=1}^{3} f_i \cdot p_i , \tag{5}$$

where p_1, p_2 and p_3 represent moderation functions:

$$p_1 = \frac{1}{e^{\frac{\Delta K - \Delta K_1}{\beta_1}} + 1} \tag{6}$$

$$p_3 = 1 - \frac{1}{e^{\frac{\Delta K - \Delta K_2}{\beta_2}} + 1} \tag{7}$$

$$p_2 = 1 - p_1 - p_3 , \tag{8}$$

where: β_1 and β_2 are transfer parameters; ΔK_1, ΔK_2: extreme ΔK values of the second characteristic regime of a general crack propagation law.

Depending upon the values of the transfer parameters, the transition between two distinct regimes can be done slowly or quickly (Figs. 7, 8, 9, 10). In this way, with a single function but with different values for the transfer parameters, all the existing crack propagation laws can be modeled.

The new crack propagation law has been also compared with the experimental investigations performed on the propeller blade of a helicopter (Fig. 11, 12).

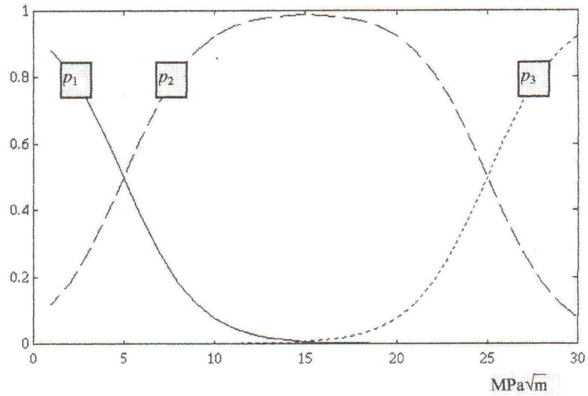

Fig. 7. Moderations functions for: $\alpha_1=\alpha_2=2$

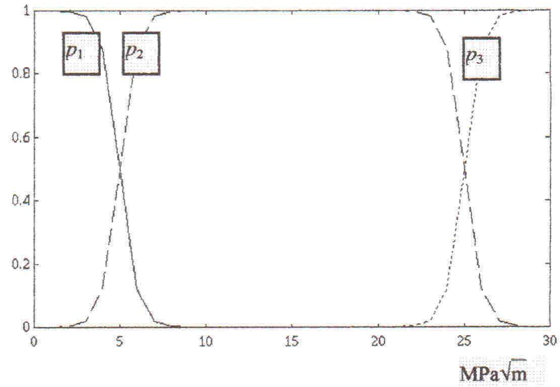

Fig. 8. Moderations functions for: $\alpha_1=\alpha_2=1$

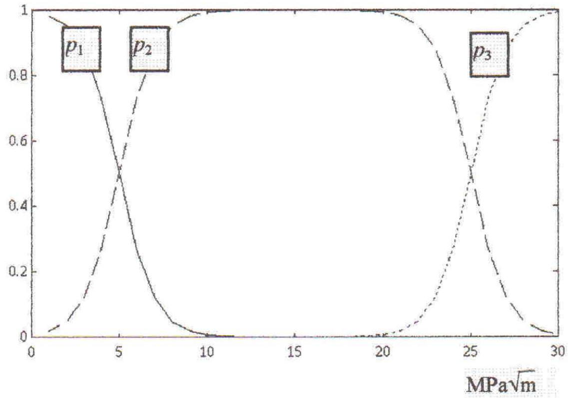

Fig. 9. Moderations functions for: $\alpha_1=\alpha_2=0.5$

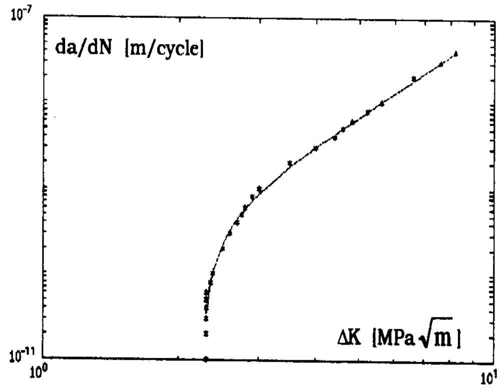

Fig. 10. Experimental data and the new crack propagation law

Fig. 11. Cross section of the propeller blade subjected to fatigue

5. Conclusions

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 behavior.

Fig. 12. Fracture surface detail (x3000)

References

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