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SHORT RESEARCH COMMUNICATION

EXPERIMENTAL ANALYSIS AND MODELLING OF FATIGUE CRACK INITIATION MECHANISMS

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The present work is devoted to simulation of fatigue crack initiation for cyclic loading within the nominal elastic regime. It is assumed that damage growth occurs due to action of mean stress and its fluctuations induced by crystalline grain inhomogeneity and the free boundary effect. The macrocrack initiation corresponds to a critical value of accumulated damage. The modelling of damage growth is supported by Electronic Speckle Pattern Interferometry (ESPI) apparatus using coherent laser light.

Keywords: fatigue crack initiation, damage evolution, optical methods

1. Introduction

The process of fatigue damage development and structural degradation is of local nature. The mechanism responsible for damage accumulation during cyclic loading below the yield point remains elusive. The present paper concerns the fatigue crack initiation and evolution in metals subjected to loading at the stress level below the conventional yield strength. During the process of cyclic loading due to an inhomogeneous grain structure, the micro plastic effects develop and can be observed on the macro-scale. Sangid (2013) proposed a physically-based model for prediction of fatigue crack initiation based on the material microstructure. Using the potential offered by the novel experimental techniques, it is possible to identify physical phenomena and to describe mechanisms of degradation and fatigue damage development in modern structural materials. Their identification involves usage of damage detection methods, both destructive and non-destructive to evaluate material behaviour under different loads (Kowalewski *et al.*, 2008). Electronic Speckle Pattern Interferometry (ESPI) is a widely used technique to measure full-field deformation on surfaces of many kinds of objects. The shielding effect on fatigue crack growth at constant amplitude loading and during application of overloads was investigated using ESPI by Vasco-Olmo *et al.*, (2016). The analysis of the plastic processes that governs crack propagation was analysed using ESPI method by Ferretti *et al.*, (2011). However, its application to the study of fatigue damage mechanisms has not been yet explored extensively. Therefore, in this study, ESPI is applied to investigate the distribution of strain fluctuations.

2. Applications of ESPI method

Nowadays, the ESPI method seems to be very attractive in capturing damage growth. Primarily, optical methods are used to analyze strain fields and strain localization on the surface of a specimen. For instance, strain distribution map using ESPI for nickel alloys (C – 0.09%, Cr – 8.8%, Mn – 0.1%, Si – 0.25%, W – 9.7%, Co – 9.5%, Al – 5.7%, Ta+Ti+HF – 5.5%) is presented for an increasing number of load cycles in Fig. 1.

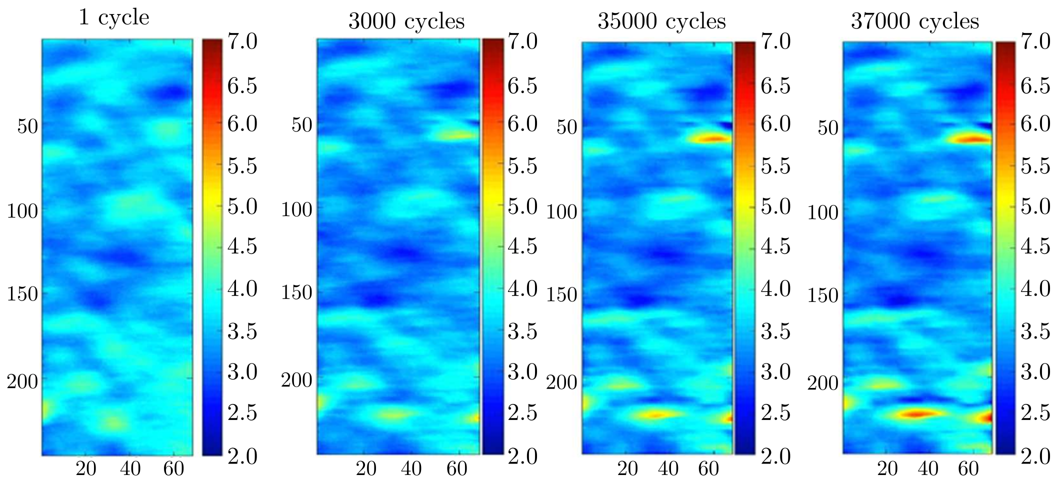

Fig. 1. Strain distribution maps on the plane specimen surface using ESPI for different stages of the fatigue process

During the process of pulsating cyclic loading the material deforms heterogeneously and numerous strain concentration spots are visible. It is expected that the microstructure of the materials plays an important role in strain localization. The strain concentration occurs especially at grain boundaries. It can be expected that cracks start to nucleate in the zones containing large strain accumulation during cyclic loading. Apart from the density and distribution of defects in the volume of tested specimen, the specimen size and location of individual defects are important factors of fatigue damage initiation and its further evolution. The lateral profiles of maximal cross-sectional strain distribution for the increasing number of cycles are presented in Fig. 2. The results are shown for the nickel alloy.

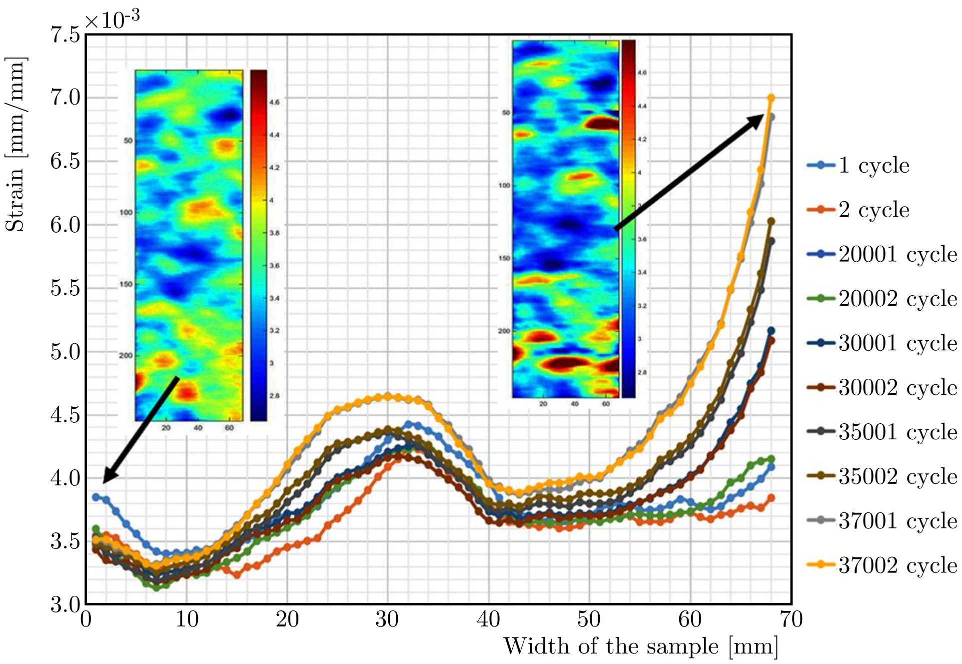

Fig. 2. The lateral profiles of maximal cross-sectional strain evolution

The distribution of strain across the sample at the place of crack initiation and its evolution during the cyclic loading process is shown in Fig. 2. Using ESPI, the strain distributions for the first and last cycle (at the moment of rupture) are included. The strain values evolve faster at the edge of the sample. Results will serve to verify and calibrate the mathematical description. The results of fatigue tests in the form of stress-strain diagrams exhibiting the permanent strain, stiffness modulus variation and hysteresis loops during selected cycles of fatigue are presented in Fig. 3.

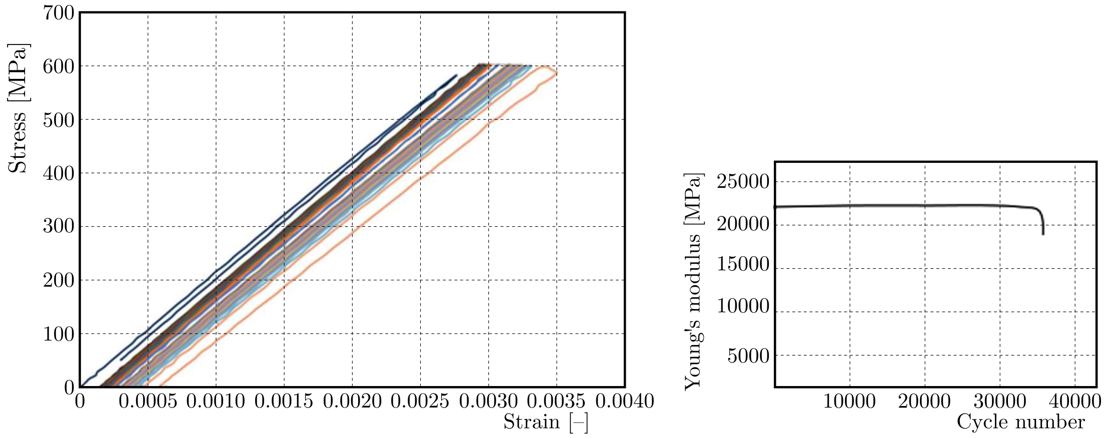

Fig. 3. Development of the fatigue hysteresis loop during selected cycles

The fatigue hysteresis loops are not measurable during the cyclic process indicating that the material globally deforms in the elastic state, and the macroplastic strain developed in the final phase of process is of order 0.1%. The microdamage can evolve within the local zones of strain concentration. The understanding of mechanical properties of materials plays an important role during the fatigue process.

3. Mathematical modelling of fatigue damage evolution, numerical implementation and comparison with ESPI results

In the present paper, the mathematical description of fatigue crack initiation and evolution is formulated. The problem of damage evolution for metals under cyclic loading inducing fatigue crack initiation and propagation within the elastic regime is discussed. The condition of damage accumulation is formulated after Mróz *et al.*, (2004). It is assumed that when the critical stress condition is reached on the material plane, the damage zone Ω is generated. Afterwards, the growth of the damage zone can be described. The mathematical model is applied to study damage evolution under cyclic tension and the predictions are compared with experimental data. The profile of normal strain $\varepsilon(x)$ and stress $\sigma(x)$ along the damage zone Ω is expressed as a sum of the mean $(\overline{\varepsilon}, \overline{\sigma})$ and fluctuation $(\widetilde{\varepsilon}(x), \widetilde{\sigma}(x))$ components

$$\varepsilon(x) = \overline{\varepsilon} + \widetilde{\varepsilon}(x) \qquad \sigma(x) = \overline{\sigma} + \widetilde{\sigma}(x) \tag{3.1}$$

The material is assumed to be linearly elastic, but exhibiting a damage process at the strain concentration zones. In order to illustrate the problem (Fig. 4), the potential damage zone Ω is selected with the largest strain and stress fluctuations.

Damage evolution rule (3.2) was originally formulated by Mróz *et al.* (2004) for brittle materials

$$dD = A\Big(\frac{\sigma - \sigma_0^*}{\sigma_c - \sigma_0}\Big)^n \frac{d\sigma}{\sigma_c^* - \sigma_0^*} \tag{3.2}$$

where A, n and p denote material parameters, σ_0 is the damage initiation threshold, σ_c denotes the failure stress in tension for the damaged material, σ_0^* and σ_c^* are the threshold values for the undamaged material and D denotes the scalar measure of damage $(0 \leqslant D \leqslant 1)$.

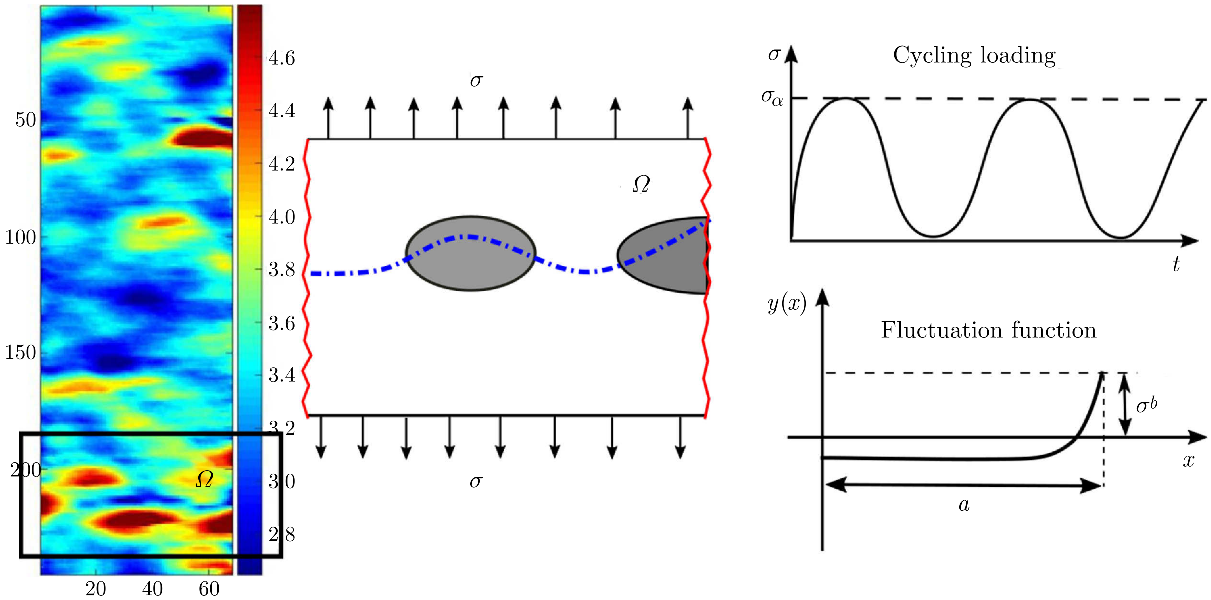

Fig. 4. Damage zone Ω with the major stress fluctuation

The stress value σ increases but the values of σ_0 and σ_c decrease. Both σ_0 and σ_c depend on the damage state according to the formula

$$\sigma_c - \sigma_0 = (\sigma_c^* - \sigma_0^*)(1-D)^p \tag{3.3}$$

The process of cyclic loading is described by the time variation of stress in the following form

$$\sigma(t) = \frac{1}{2}\sigma_a[1+\sin(\omega t)] \qquad \omega = \frac{2\pi}{T} \tag{3.4}$$

where σ_a is the stress amplitude. Substituting σ from Eq. (3.4) into Eq. (3.2) and integrating, the equation for the damage increase in one cycle $\Delta D_s = D_{s+1} - D_s$ is expressed as follows

$$\int\limits_{D_s}^{D_s+\Delta D_s} (1-D)^{np}\,dD = \frac{A\omega\sigma_a}{2(\sigma_c^* - \sigma_0^*)^{n+1}} \int\limits_0^T \Big(\frac{1}{2}\sigma_a(1+\sin(\omega t)) - \sigma_0^*\Big)^n \cos(\omega t)\,dt \tag{3.5}$$

Finally, the damage evolution law for one cycle reads

$$\Delta D_s = \frac{1}{(1-D_s)^{np}} \frac{A}{(\sigma_c^* - \sigma_0)^{n+1}} \frac{1}{n+1}\Big[\Big(\frac{1}{2}\sigma_a(1+\sin(\omega T)) - \sigma_0^*\Big)^{n+1} - \Big(\frac{1}{2}\sigma_a - \sigma_0^*\Big)^{n+1}\Big] \tag{3.6}$$

The free edges of the sample due to surface irregularities act as a kind of stress concentrators. The influence of edge defects on the damage evolution and crack propagation is significant (see Fig. 2).

In order to account for the edge effect, the stress fluctuation function (see Fig. 4) is introduced and the total stress expressed as follows

$$\sigma(x) = \overline{\sigma} + \widetilde{\sigma}(x) = \overline{\sigma} + \overline{\sigma}y(x) = \overline{\sigma}\Big(1 + \alpha + \beta\Big|\frac{x}{a}\Big|^m\Big) \qquad y(x) = \alpha + \beta\Big|\frac{x}{a}\Big|^m \tag{3.7}$$

where $y(x)$ denotes the fluctuation function, a is width of the sample, β and m are material parameters. The integration of stress fluctuation on $[0,a]$ makes it possible to establish the parameter α

$$\int\limits_0^a \widetilde{\sigma}(x)\,dx = 0 \quad\rightarrow\quad \int\limits_0^a \Big(\alpha + \beta\Big|\frac{x}{a}\Big|^m\Big)\,dx = 0 \quad\rightarrow\quad \alpha = -\frac{\beta}{m+1} \tag{3.8}$$

The boundary condition at the external edge allows one to specify parameter β, thus

$$\widetilde{\sigma}(x=a)=\sigma^b \qquad \rightarrow \qquad \beta=\frac{\sigma^b}{\overline{\sigma}}\frac{m+1}{m} \tag{3.9}$$

The value of σ^b is assumed to correspond to the measured boundary fluctuation, here $\sigma^b=1.1\overline{\sigma}$.

Finally, the stress distribution is expressed in the following form

$$\sigma(x,t)=\overline{\sigma}\Big(1+\alpha+\beta\Big|\frac{x}{a}\Big|^m\Big)\Big(\frac{1}{2}+\frac{1}{2}\sin(\omega t)\Big) \tag{3.10}$$

According to the mathematical description, numerical analysis of damage evolution (3.2) under mechanical loads (3.10) in elastic-plastic solids has been made. The evolution of damage during the growing number of cycles is shown in Fig. 5. The macro-crack initiation is assumed to occur at the critical value of damage $D_c=0.3$.

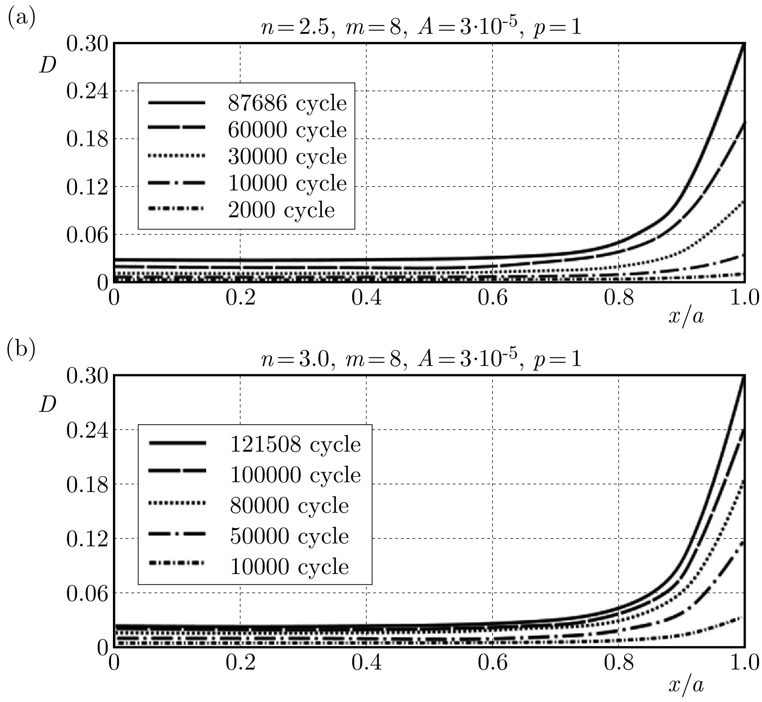

Fig. 5. Damage evolution related to the number of cycles for different values of the parameter n

4. Conclusions

The present paper concerns the damage evolution in elastic-plastic materials subjected to cyclic loading. The mathematical description of crack initiation and propagation under cyclic loading is presented. This model is supported by optical methods of stress and strain monitoring (ESPI) for early detection, localization and monitoring of damage in materials under fatigue loading. The numerical prediction and the experimental results indicate a good correlation.

Acknowledgement

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