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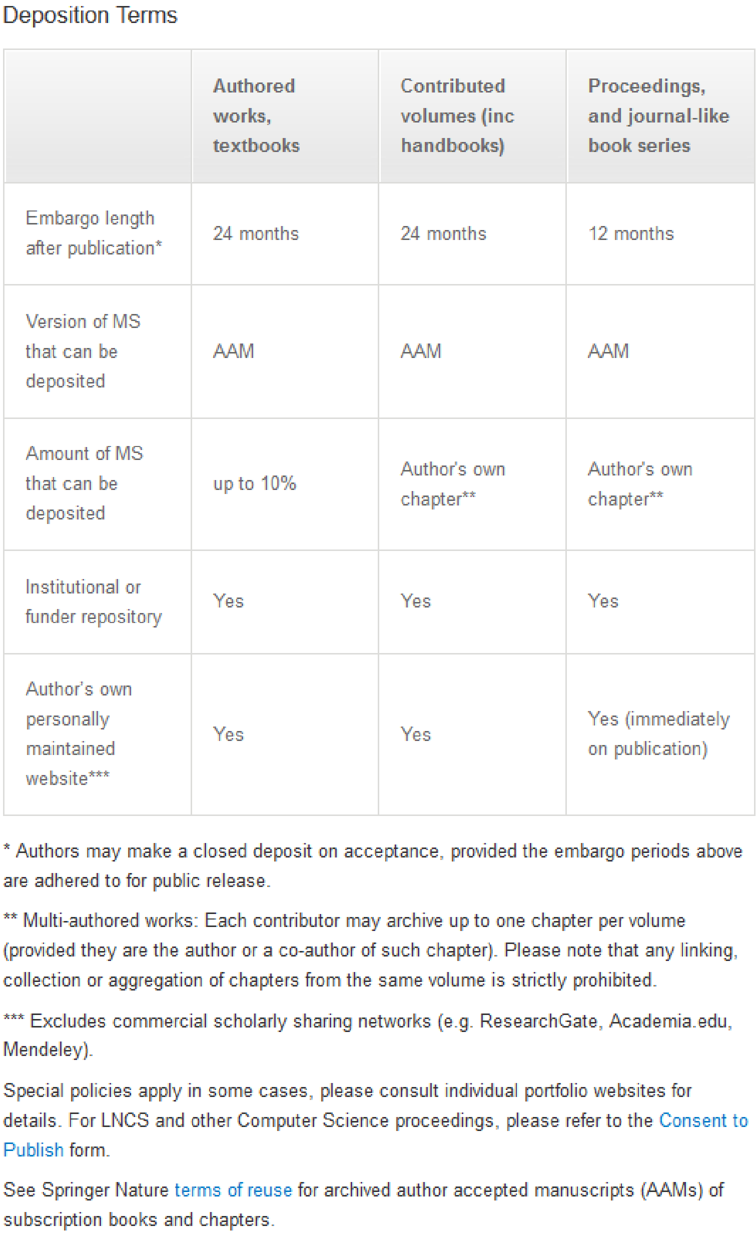

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Mechanics and Evaluation of Early Damage

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Abstract. This article describes the microstructural mechanisms leading to damage and formation of fatigue cracks as well as the methods available to monitor this process. The evaluation of early damage is especially important for structures with long service life spans, where the crack nucleation stage can dominate the total fatigue life.

Keywords: Early damage, Crack nucleation, Fatigue.

1 Introduction

A decomposition of the total fatigue life, N_T, is commonly represented by two main stages:

$$N_T = N_n + N_p, \tag{1}$$

where N_n is the number of cycles required to nucleate a crack and N_p is the number of cycles to propagate the crack to failure. N_p can be further divided into microstructurally small crack, physically small crack and long crack propagation stages. This paper is concerned with the crack nucleation stage only. From microscopic point of view, the crack nucleation is a complex process characterised by a transition from an uncracked to a cracked lattice, which can result into crack formation from 1 to 100 μm long in the high cycle fatigue (HCF) regime and to 0.1-1 μm in the low cycle fatigue (LCF) range. Crack incubation and crack formation are also often used interchangeably to describe this process [1]. The distinction between crack nucleation and early stages of propagation is difficult to make. N_n can also incorporate the number of cycles required to propagate the crack beyond the first few strong microstructural barriers that can restrict further crack advance. The latter might have a significant impact on fatigue limit and total fatigue life [2].

The dominant view on fatigue life in the past was that, in all materials, defects are present from the start so the cracks will propagate right from the first load cycle, and therefore, the crack nucleation stage is insignificant in the total fatigue life, or $N_n \ll N_T$. This view is often the case at relatively short life spans, or high levels of the applied cyclic stress, as well as in the case of many common engineering structures [3]. However, if the life span is long, the fatigue crack nucleation stage occupies an appreciable portion of the total fatigue life. For instance, N_n can range from 5 to 50% of the total lifetime, N_T, in the HCF regime, and can fully dominate the fatigue life in UHCF (Ultra High Cycle Fatigue). It is well known that the crack nucleation is also strongly affected by the loading spectra. However, there were few attempts to assess the effect of variable stress amplitudes on the crack initiation process [4,5].

The crack nucleation mechanisms can be very different in different materials and can be advanced or delayed depending on the applied loading. In single crystals of simple materials as well as in polycrystalline materials, the accumulation of irreversible plastic deformations is considered as one of the most common crack nucleation mechanisms. It involves the localisation of plastic micro-strains within slip bands that normally form intrusions/extrusions at surface grains or impinge on grain boundaries for non-surface grains. The crack nucleation is considered to be a result of progressive microstructural and topological changes due to the accumulation of the irreversible plastic micro-strains in a large number of repeated load cycles. These progressive microstructural and topological changes in the material during cyclic loading will be termed here as early damage.

The practical significance of the evaluation of early damage, which proceeds the crack propagation stage, is obvious, specifically for long life spans or in HCF and UHCF regimes. This evaluation is critical in situations when a subsurface crack nucleation and growth dominates failure life, as many traditional NDT techniques are rendered inappropriate or ineffective for internal defects. In these situations, a damage tolerance approach seems to be difficult or impossible to apply in order to predict fatigue life and address the structural failure risk with appropriate maintenance and inspection strategies.

2 Phenomena Associated with Progression of Early Damage

Cyclic strain localisation and strain accumulation has been proven to be the substantial feature of early damage accumulation. Several phenomena accompanying this process can be utilised for the detection and characterisation of its severity as well as the evaluation of structural integrity.

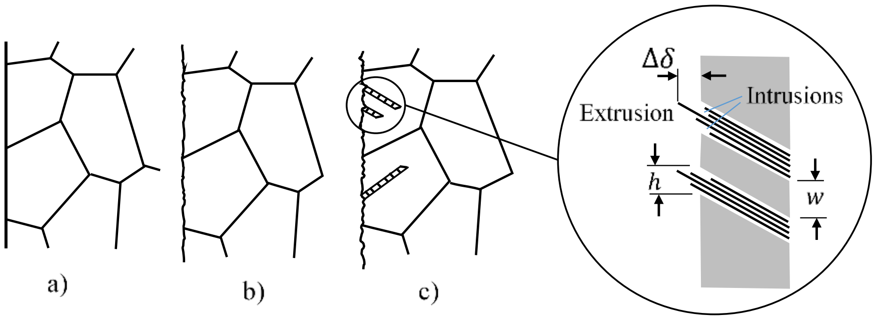

Fig. 1. Schematic illustration of surface roughness development [2, 5]: a) - initial stage; b) - early stage of surface roughening; c) - PSB formation. $\Delta\delta$ is the cycle slip displacement, h and w are the slipband width and spacing, respectively.

2.1 Surface Roughness

In ductile metals, the cyclic strain localisation in the form of Persistent Slip Bands (PSB) at the free surface frequently occurs and leads to crack nucleation. The PSB normally consist of a central extrusion and two parallel intrusions as illustrated in Fig. 1, producing a distinct surface morphology. Therefore, the fatigue-induced roughness, in principle, can be distinguished from the initial roughness or machined surfaces [2, 3]. The kinetics of extrusion and intrusions has been studied extensively over the past decade. It was reported in a number of studies that during cyclic loading, the w/h ratio increases with increasing fatigue cycles at a diminishing rate and the ratio normally saturates at about 0.5 - 1 at fatigue cycles greater than 10^4. Thus, the evolution of roughness of the surface during fatigue can potentially be utilised as an early damage parameter (Chan, 2010). Both experimental and numerical studies indicate that an area with high surface roughness may be a precursor of surface crack formation or transition to crack propagation stage. However, this approach seems to be inappropriate and ineffective for the evaluation of subsurface crack nucleation, specifically in the UHCF regime, which is dominated by interior crack initiation.

2.2 Temperature evolution

As mentioned above, fatigue damage of ductile materials is intimately related to some kind of irreversibility, which can be a result of a number of microscopic mechanisms, e.g. cross slip of screw dislocations or mutual annihilation of dislocations. A certain fraction of the work associated with irreversible plastic deformations and other damage mechanisms results in a heat generation and this process is often called intrinsic heat dissipation. After an initial shakedown stage of the first load cycles, the temperature rise, ΔT, or intrinsic dissipation are considered to be representative of a thermal equilibrium state, and can, therefore, be used for the damage evaluation.

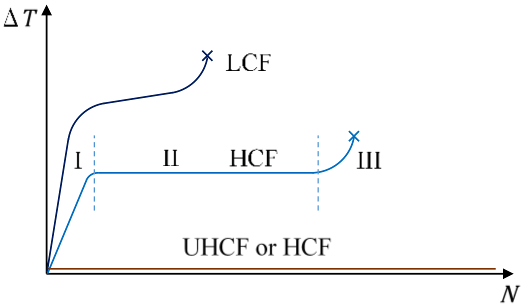

Fig. 2. Temperature evolution in different fatigue regimes (constant amplitude of loading)

Extensive studies have demonstrated that there are normally three stages of temperature evolution during fatigue loading if the applied stress range is above fatigue limit, see

Fig.2 [6]. In the initial stage I, the temperature of specimen surface increases very quickly until an equilibrium is reached between the heat generation and heat losses. It leads to a stage II largely characterised by a stable temperature in HCF regime or a slight increase of the temperature, specifically, in LCF regime. In the final stage III before failure, there is normally a rapid temperature growth associated with propagation of a macro-crack. The temperature rise depends strongly on the applied stress range and the frequency of loading. In laboratory tests conducted at 1 to 100 Hz, the temperature rise is typically in the range of 1 - 50 ^{0}C, so, these changes can be easily detected by a standard infrared camera.

Experimental observations UHCF regime or in HCF regime at the stress ranges below fatigue limit demonstrate a much smaller magnitude of the temperature variations, largely due to a cessation of cyclic micro-plasticity. Therefore, temperature measurement techniques can be quite effective in the establishment of fatigue limit for different materials working in HCF region. But at the same time, it is difficult to apply $\Delta T(N)$ diagrams for the evaluation of progressive damage, because in stage II, which dominates fatigue life, there might be no detectible change in the temperature or heat dissipation. An alternative approach for damage evaluation would be to utilise the initial fatigue stage with rapid temperature change, i.e., the stage I. However, this approach needs a relatively high frequency of the applied loading, which might not be possible in practical situations [6].

2.3 Change of Material Constants with Damage Accumulation

It is well known that the total strain tensor, $\bar{\varepsilon}_{ij}$ in the homogeneous solid material of volume, V, containing an arbitrary shear slip system can be written as

$$\bar{\varepsilon}_{ij} = \varepsilon_{ij} + \frac{1}{2V}\sum_{r}\int_{S_r}\left(u_i n_j + u_j n_i\right)ds \quad , \quad (2)$$

where ε_{ij} is the microscopic strain tensor, V is the volume of the solid, S_r is the surface of the r-slip band, u_i and n_j are the displacement and normal vector components at the slip surface, S_r.

Different procedures and methods can be applied to evaluate the effective elastic properties of the solid in the presence of the shear slip bands. For uniaxial loading, these averaging procedures normally result in the following equation:

$$E = E_0/(1+\kappa\rho), \quad (3)$$

where E is the effective elasticity modulus of the solid, E_0 is the elasticity modulus of the solid without presence of defects (e.g. slip bands), κ is a constant related to the shape and intensity of the slip bands and ρ is the density of the slip bands. Parameter κ has to be a function of the applied strain, which initiates shear deformations at slip bands and ρ is the function of the accumulated damage, i.e. $\rho = 0$ for undamaged material. In the case of weak changes of elastic constants, using the expansion of Eq. (3), the effective elasticity modulus can be written as

$$E = E_0(1 + \kappa_0 \rho) - E_0 \kappa_1 \varepsilon \rho + O(\varepsilon^2), \tag{4}$$

where κ_0 and κ_1 are constants.

The link between the uni-axial stress and strain can now be written as

$$\sigma = E_0(1 + \kappa_0 \rho)\varepsilon - \beta \varepsilon^2 + O(\varepsilon^3). \tag{5}$$

Experimental observation demonstrate that the change of the elastic moduli (the second-order elastic constants) in HCF and UHCF are negligible, i.e. $\kappa_0 \rho \ll 1$. The constant β is the non-linearity constant, which is related to the third-order elastic constants, is much more sensitive to damage. It can be decomposed as a sum: $\beta = \beta_0 + \beta_d$, where β_0 is the virgin non-linearity (mainly due to the anharmonic response of the lattice) and β_d is the nonlinearity due to damage. Therefore, by monitoring the evolution of the non-linearity constant (or, more generally, the third order elastic constants) during fatigue loading, it is possible to link these changes to damage [7-10].

The non-linearity constant (or third-order elastic constants) cannot be determined from the ordinary stress-strain diagram due to very small changes in the linear response for most structural materials. However, there are two methods based on the generation and sensing of high-frequency ultrasonic waves, which can be utilised for the evaluation of β, and, subsequently, progression of fatigue damage [9].

The first method exploits the change of the wave speed with the applied strain (i.e. acoustoelastic effect). Bulk, Rayleigh or Lamb waves can be used for accurate evaluation of the non-linearity constant under incrementally applied strains. However, the incremental or well-controlled loading is not always possible in real-world applications.

The second method makes use of nonlinear phenomena generated by a strong ultrasonic pulse, e.g. higher harmonic generation. The incident wave front becomes distorted by the non-linear response, so that higher harmonics are generated as illustrated in Fig. 3. The theory predicts that the non-linearity constant $\beta \sim x\, A_2 / A_1^2$, where x is the distance between the transducer and sensor, and A_1 and A_2 are the amplitudes of the fundamental and the second harmonics. The outcomes of the measurements are normally presented in terms of the ratio of β / β_0 as a fraction of fatigue life. There is substantial evidence that this ratio can monitor microstructural evolution leading to macroscopic damage [7,8].

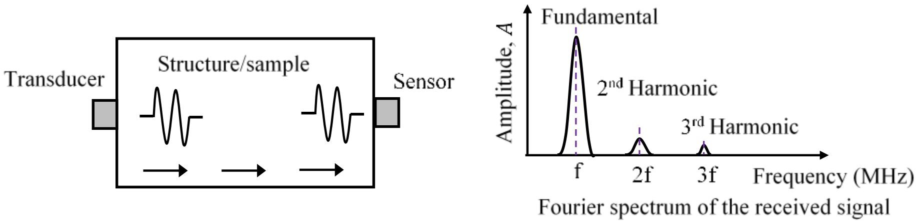

Fig. 3. Distortion in the harmonic wavefront during propagation in weakly-non-linear elastic solid

The experimental evaluation of β / β_0 is very challenging since the amplitude of the second harmonic is several orders of magnitude smaller than the amplitude of the fundamental frequency. This ratio is also affected by the surface roughness, diffraction and attenuation of the ultrasonic wave in the propagating medium. Recent studies report that the application of non-contact excitation and sensing systems, based on air-coupled ultrasonic transducers and lasers, has considerably improved the signal to noise ratio of the measurements and reduced the scatter in the experimentally evaluated dependence of β/β_0 upon fatigue damage accumulation. However, it seems that models for predicting the remaining fatigue life or damage based on non-linear ultrasonic measurements are yet to be developed [8].

3 Conclusion

The paper provided a very brief overview of methods available to detect and monitor early damage, i.e. damage which proceeds the crack propagation stage. These methods are essential for safe and efficient operation of machines and structures working in HCF and UHCF regimes. Various physical phenomena can be utilised to monitor early damage. It can be stated that all these methods are currently on the initial stages of their development. The greatest potential have methods utilising the evaluation of higher-order elastic constants, which are quite sensitive to mechanical damage, as well as measurements of surface roughness, which is directly linked to the accumulation of irreversable plastic deformation at the surface. However, the latter method might not be efficient in UHCF regime, where fatigue cracks are formed below the surface.

References

1. McDowell, D.L., Dunne, F.P.E. Microstructure-sensitive computational modeling of fatigue crack formation. Int. J. of Fatigue 32, 1521–1542 (2010)
2. Mughrabi, H. Microstructural fatigue mechanisms: Cyclic slip irreversibility, crack initiation. Int. J. of Fatigue 57, 2–8 (2013).
3. Polák, J., Mana, J. Experimental evidence and physical models of fatigue crack initiation.
4. non-linear elastic damage analysis. Int. J. of Fatigue 91, 294–303 (2016).
5. Chan, K. S. Roles of microstructure in fatigue crack initiation. Int. J. of Fatigue 32, 1428–1447 (2010).
6. Meneghetti G., Ricotta, M. The use of the specific heat loss to analyse the low- and high-cycle fatigue behaviour of plain and notched specimens made of a stainless steel. Eng. Fracture Mech. 81, 2–16 (2012).
7. Kim, J.-Y., Qu, J., Jacobs, L. J., Littles, J. W., Savage, M. F. Acoustic nonlinearity parameter due to microplasticity. J. of Nondestructive Evaluation 25(1), 29-37 (2006).
8. Torello, D., Thiele, S., Matlack, K. H., Kim, J.-Y., Quc, J., Jacobs, L.J. Diffraction, attenuation, and source corrections for nonlinear Rayleigh wave ultrasonic measurements. Ultrasonics 56, 417–426 (2015).
9. Mohabuth, M., Kotousov, A., Ng C.T. Effect of uniaxial stress on the propagation of higher-order Lamb wave modes. Int. J. of Non-Linear Mechanics 86, 104-111 (2016).
10. Mohabuth, M., Kotousov, A., Ng, C.T., Rose L.R.F. Implication of changing loading conditions on structural health monitoring utilising guided waves. Smart Materials and Struct. 27 (2), 025003.