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Application of the Microstructural Finite Element Alternating Method to assess the impact of specimen size and distributions of contact/residual stress fields on fatigue strength

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ABSTRACT

This paper shows an implementation of the Microstructural Finite Element Alternating Method (MFEAM) to calculate fatigue strength of engineering components subjected to complex loading conditions. These conditions include combination of primary cyclic loading and residual stress fields or localised stress distributions due to the contact of two solids. The alternating method uses the finite element method (FEM) to solve the boundary value problem of the un-cracked body, allowing treatment of arbitrary shaped components, in conjunction with a short crack model to account for the interaction of the crack with the microstructural barriers, implemented within the distributed dislocation technique (DDT) to assess the crack problem in an infinite medium. An iterative scheme between the FEM and the DDT solutions is proposed in order to predict the required applied load to propagate the crack in the finite size body. Comparisons of results with reported data in the literature show that the MFEAM can be used effectively to analyse finite size components and that it is capable of capturing the effect of localised stress concentration features on cyclic behaviour.

1. Introduction

Advances in manufacturing processes make possible the release to market of smaller, lighter and more powerful micro-machines and sensors, permit the implementation of innovative tools and components in medical applications, and allow the use of electronic devices made of a few number of crystals, among other applications. These advances also allow a major reduction in the number of manufacturing macroscopic defects in components. In addition, if these defects are present in the component, with the developments in defect detection technologies, quality control may lead to rejection of the part. As a consequence, in some industries only the presence of microscopic defects, of the size of the microstructure of the material is possible. During operation, many of these components are subjected to cyclic load or vibrations, thus facing potential fatigue failure.

Microstructural Fracture Mechanics provides a theoretical foundation for the evidence observed in the early stages of fatigue crack growth tests [1–5], where the Linear Elastic Fracture Mechanics hypothesis is not valid. Some theories have been proposed, seeking to extend fracture mechanics to the regime where cracks have the size of the microstructure.

The understanding and proper modelling of short fatigue crack growth is of great importance for example in micro-components with dimensions of the order of 100 μm or less, and in components under High Cycle Fatigue (HCF), where micro-crack initiation and propagation involves about 90% of the component's total life, among other cases. Hobson [6], Chan and Lankford [7], de los Rios et al. [8], Navarro and de los Rios [9–11] and Hussain et al. [12], have presented pioneering models to tackle the short crack growth behaviour of plain specimens. However, in-service mechanical parts and structures present stress concentrators of different nature.

Several models, based on microstructural fracture mechanics, have been proposed for the analysis of notch components, as proposed by Tanaka and Mura [13], Chapetti [14], Vallellano et al. [15,16] and Chaves and Navarro [17,18].

Most applications of MFM involve cracks that are small compared to the dimensions of the bodies containing them and this allows the use of infinite or semi-infinite solutions, which simplifies the analysis enormously. There are, however, examples of

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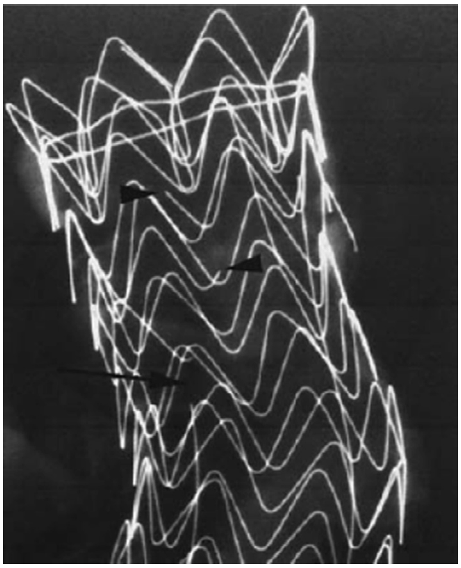

Fig. 1. X-ray image of a stent [19]. Arrows show broken filaments.

practical interest in which the influence of the 'far' boundaries cannot be neglected. Coronary stents (Fig. 1), microelectronic contacts, micro-moulds and micro-gears, in which at least one of the dimensions is of the order of a few hundred microns, are examples of micro-components that are susceptible to fatigue failure. Residual stress distributions or contact stress fields play a major role in the integrity of these components. These fields are induced either during fabrication, installation or operation and considering their effect in the analysis is paramount for conservative fatigue assessments.

Residual stresses are the result of non-recoverable strains (plasticity), and as a result permanent stresses are induced in the material. Tensile residual stresses, such as those due to machining or welding processes are detrimental as they increase the mean stress value of the fatigue cycle, whereas compressive residual stresses are generally considered beneficial as they generally reduce mean stress values. Shot peening, laser shock peening, autofrettage and other methods inducing compressive stress on structural surfaces have been demonstrated to be effective for improving the fatigue life and endurance limit of metallic alloys even in the presence of geometrical discontinuities. For example, the fatigue resistance to FOD (Foreign Object Damage) of turbine blades and airfoils is highly influenced not only by the geometry of the notch produced by the impact, but also by the residual stress field produced due to impact and removal of material. The resistance to FOD can be significantly improved by means of one of the techniques mentioned above.

Fretting fatigue, on the other hand, is caused by nucleation and propagation of cracks under the combined action of a cyclic global stress and local stress resulting from contact between two elements. Predicting fretting fatigue crack nucleation and propagation is of great interest in applications where security is critical, such as aircraft, railways and nuclear power plant components. This mechanism drastically reduces the fatigue resistance of engineering structures and mechanical parts [20]. Residual, thermal and contact stresses result in stress gradients in localised areas within the material. The fatigue behaviour of components subjected to these mechanisms can be analysed using methodologies similar to those employed to predict notch fatigue.

This paper deals with the characterization of fatigue failure of components containing very small defects (e.g. cracks). A MFM formulation recently presented by the authors in [21,22] is used to perform fatigue limit calculations of components in which the effects of residual stresses and fretting in the behaviour of finite size components should not be neglected. Comparisons with experimental data and other assessment methods are performed in order to validate the tool for these applications.

2. Micromechanical model for short crack growth

For the sake of completeness, the Navarro and de los Rios (NR) microstructural model for short crack fatigue growth assessment is briefly described in this section, although a general and detailed description of the model can be found in [9–11].

In the NR-model, the growth of a small crack is described in terms of successive blocking of the plastic zone at grain boundaries, Fig. 2. Cracks are assumed to be nucleated in second-phase inclusions or particles by the effect of the fracture of particles or their detachment from the matrix. A crack opened in Mode I by a stress $\sigma_{yy} = \sigma$ can be represented by a distribution of edge dislocations with its Burgers vectors normal to the crack plane, as shown in Fig. 3. Each dislocation in the slip plane sees forces due to (1) the applied stresses, (2) the interaction with other dislocations in the same plane and (3) the interaction with other dislocations in parallel planes and with precipitates, second phase particles, etc., which gives rise to friction stresses that oppose the movement of dislocations. A freely-slipping crack is modelled by putting the friction stress σ_1 equal to zero. The friction stress σ_2 in the plastic zone has a value different from zero which is supposed to be a characteristic property of the material. However, within the framework of this work, that is, for the calculation of fatigue limits, σ_2 does not play any role. The reason behind this is that the plastic slip zone ahead of the crack vanishes when the condition giving the maximum required load is reached, i.e. the crack tip has reached the microstructural barrier. Therefore, the particular value assigned to σ_2 is of no consequence for the outcome of the procedure. The friction stress σ_3 in the barrier zone is calculated as part of the solution. For more details the reader should refer to [17,18].

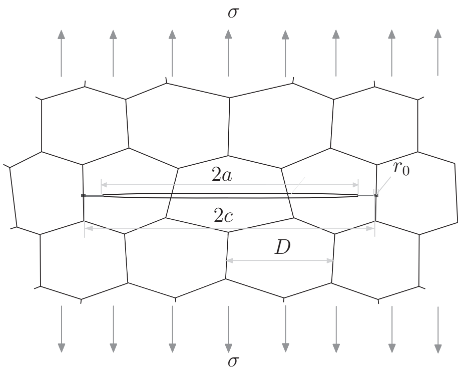

Fig. 2. Crack, plastic zones and barriers in a 2D polycrystalline infinite plate.

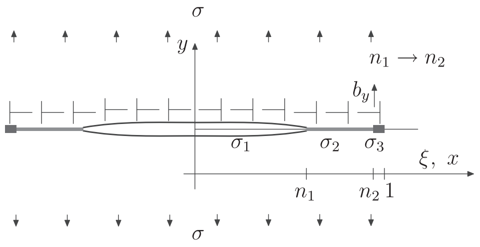

Fig. 3. Dislocation based model by Navarro and de los Rios.