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Modelling of fatigue thresholds for small cracks in a mild steel by "Strip-Yield" model

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ABSTRACT

The fatigue of mechanical components can be explained by the growth of very small fatigue cracks, which lead to the final fracture of the component. It is, therefore, essential to try to describe the growth and the thresholds of small cracks. In this paper, the Strip-Yield model is used to analyse the fatigue thresholds of a mild-steel widely used for manufacturing railway axles. Furthermore, the need for a precise definition of the constraint factor, under cyclic, non-linear response of the material, is addressed, together with the choice of an appropriate constraint formulation. This results in good fatigue threshold predictions at $R = -1$ for long cracks (obtained from SE(B) specimens), whereas the description of the Kitagawa diagram (obtained by fatigue tests on specimens with artificial defects) is relatively poor.

The analysis of the cyclic stress ahead of small cracks enables us to compare the results with the threshold models for small cracks by McEvily, Usami and Shida.

1. Introduction

One of the main requirements in the design of many mechanical components is the ability to resist a large number of stress cycles under service loads. Fatigue life can be defined as the number of cycles involved in the growth of a crack from dimensions of the order of grain size up to final fracture of the component [1]. This definition highlights that defects or inhomogeneities (manufacturing defects, inclusions or pits), which are larger than the material's inherent micro-structural dimensions, are hugely detrimental to fatigue life and strength. In light of this, the extreme importance of analysing the growth of small cracks and the dependence of fatigue thresholds on crack size with general crack growth algorithms is clear. Among the existing algorithms, one of the most useful is the Strip-Yield model (SY) [2], a bi-dimensional analytical tool for simulating K_{op} in fatigue crack propagation under constant and variable amplitude loading. The SY model is based on Dugdale's one [3] and assumes that near-tip yielding occurs in thin strips. With this model, crack opening displacements (COD) and crack advance are then calculated in a discretized form, thus allowing to simulate the formation of the plastic wake and to obtain an estimation of the opening load. The three-dimensional constraints at the crack tip are introduced via a "global constraint factor" α_g [2]: the material at the crack tip is then assumed to deform plastically above a yield stress equal to $\alpha_g \cdot \sigma_o$ (Fig. 1b), where σ_o is the flow stress of the material, i.e. the average between the monotonic yield stress and the ultimate strength of the material. Fatigue crack growth can then be described as ($\Delta K_{eff} = K_{max} - K_{op}$):

$$\frac{da}{dN} = f(\Delta K_{eff}) \tag{1}$$

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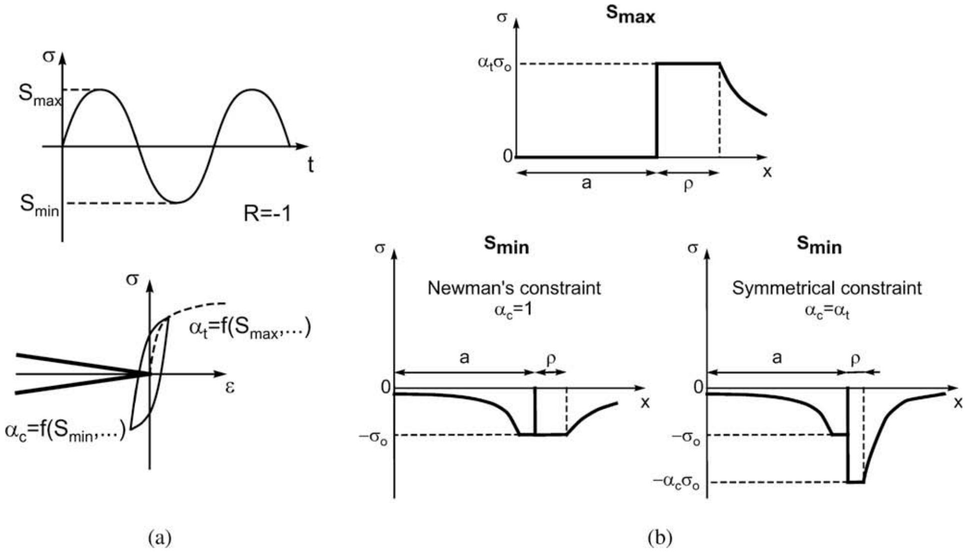

Fig. 1. Constraint formulations at crack tip: (a) cyclic plasticity; (b) Newman's and *symmetrical* formulations.

A recent analysis, based on Eq. (1) by McEvily et al. [4], showed that it is possible to describe the typical thresholds for small cracks (the so-called Kitagawa–Takahashi diagram) on the basis of an approximate formulation for the opening load σ_{op}.

In this paper, these concepts are applied by utilising a SY model to analyse fatigue thresholds in a mild steel, widely used for manufacturing railway axles. This application is extremely significant because: (i) the propagation lifetime (for long cracks) of railway axles is generally calculated by SY models [5,6]; (ii) the usual constraint formulations do not allow accurate FCG predictions to be obtained when using SY models on mild steels and negative R ratios [7,8]; (iii) the life of railway axles is characterised by the growth of small defects or corrosion pits [9,10]. Therefore, good descriptions of crack growth and thresholds are needed when establishing the frequency of inspections during component service life. Since the α_g factor plays an important role in thresholds [11], this study attempted, first and foremost, to provide a precise definition of the constraint factor under the cyclic, non-linear response of the material. Secondly, it investigated which of the different constraint formulations gives the most appropriate results. This led to good predictions of the crack growth rate at $R = -1$ for long cracks (obtained on SE(B) specimens). Further analyses of the constraint ahead of small cracks allowed us to discuss the application of a SY model to the description of the Kitagawa diagram, obtained with experiments on micro-notched specimens. The results regarding the cyclic state of stress ahead of small cracks allowed for further comparison with the threshold models by McEvily [4] and Usami and Shida [12–14].

2. Experiments

2.1. Material

The material analysed in this study is a mild carbon steel, known as A1N, which is widely used for manufacturing railway axles [15]. The mechanical properties of A1N are [6]: ultimate tensile strength UTS = 591 MPa, monotonic yield strength $\sigma_{y,monotonic}$ = 388 MPa. Cyclic properties are: 0.2% cyclic yield stress $\sigma_{y,cyc0.2}$ = 364 MPa, cyclic linear elastic limit $\sigma_{cyc,el} = \sigma_{y,cyc0.005}$ = 195 MPa (0.005% cyclic yield stress) and the parameters of the cyclic Ramberg–Osgood relationship are equal to E_{cyc} = 200,000 MPa, n = 0.168472, H = 1036.24 MPa.

2.2. Crack growth properties

The crack growth properties of A1N steel were extensively studied by the authors of this paper [6]. Furthermore, some crack growth, ΔK-decreasing and CPCA ("compression pre-cracking constant amplitude" [16]) tests were carried out using different stress ratios on SE(B) specimens taken from three different steel batches. Fig. 2 shows crack growth data at $R = -1$. The data, relevant to the present research are: (i) the average propagation threshold at $R = -1$, obtained by CPCA, is: $\Delta K_{th,R=-1}$ = 10.34 MPa $\sqrt{m}$; (ii) the average propagation threshold at $R = -1$, obtained by ΔK-decreasing, is: $\Delta K_{th,R=-1}$ = 14.1 MPa $\sqrt{m}$; (iii) the effective threshold is identified at $R \geqslant 0.85$ (obtained by an average of the threshold data obtained at K_{max} = const. with $R_{fin} \geqslant 0.85$): $\Delta K_{th,eff}$ = 2.95 MPa $\sqrt{m}$. It is possible to note (Fig. 2) that the data at $R = -1$ can be fairly described by the da/dN–ΔK_{eff} curve considering a closure ratio $U = \Delta K_{eff}/\Delta K$ = 0.34 (i.e. the value suggested by Schijve for $R = -1$ [17]).