International Journal of Fatigue 78 (2015) 22–30

Contents lists available at ScienceDirect

International Journal of Fatigue

journal homepage: www.elsevier.com/locate/ijfatigue

Assessment of fatigue crack closure under in-phase and out-of-phase thermomechanical fatigue loading using a temperature dependent strip yield model

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ARTICLE INFO

Article history:
Received 5 November 2014
Received in revised form 20 March 2015
Accepted 25 March 2015
Available online 3 April 2015

Keywords:
Fatigue crack closure
Thermomechanical fatigue
Strip yield model
Lifetime prediction

ABSTRACT

In this paper fatigue crack closure under in-phase and out-of-phase thermomechanical fatigue (TMF) loading is studied using a temperature dependent strip yield model. It is shown that fatigue crack closure is strongly influenced by the phase relation between mechanical loading and temperature, if the temperature difference goes along with a temperature dependence of the yield stress. In order to demonstrate the effect of the temperature dependent yield stress, the influence of in-phase and out-of-phase TMF loading is studied for a polycrystalline nickel-base superalloy. By using a mechanism based lifetime model, implications for fatigue lives are demonstrated.

1. Introduction

Crack closure strongly affects the fatigue crack growth rate and, thus, the fatigue life of components. Accounting for crack closure in fatigue life prediction models allows the description of mean stress effects on fatigue life. In these models, the stress range $\Delta\sigma = \sigma_{max} - \sigma_{min}$ of a loading cycle is typically replaced by an effective stress range, which considers only that part of the loading cycle in which that crack is open: $\Delta\sigma_{eff} = \sigma_{max} - \sigma_{op}$ (σ_{min} and σ_{max} are the minimum and maximum stress in the loading cycle, respectively, and σ_{op} is the crack opening stress, i.e. the stress where the crack opens during loading).

Models for the estimation of the crack opening stress as function of stress range and mean stress are e.g. proposed by Schijve [1] and Heitmann et al. [2]. Newman proposes an advanced crack opening stress equation which additionally accounts for the ratio between the maximum stress σ_{max} in the loading cycle and the yield stress σ_Y of the material [3] and, thus, allows for the prediction of decreasing normalized crack opening stresses σ_{op}/σ_{max} with increasing σ_{max}/σ_Y, as it is observed in the transition regime from high-cycle (HCF) to low-cycle fatigue (LCF) [4–6].

In high temperature components, however, mechanical and thermal loads are acting at the same time during start-up and shut-down cycles resulting in thermomechanical fatigue (TMF) of the materials. Gas turbines are classical examples of such components where nickel-base alloys are used in the hot parts. The static and cyclic yield stress of polycrystalline nickel-base alloys such as MAR-M247 stay approximately constant up to 750 °C, but rapidly drop for temperatures above (Fig. 1).

As a consequence of the temperature dependent yield stress, the mean stress strongly changes with the applied phasing of thermal strains and mechanical strains: Under out-of-phase (OP) TMF, the compressive stresses arising during heating are according to amount lower than the tensile stresses arising during cooling (Fig. 2a). This results in positive mean stresses. Analogously, in-phase (IP) TMF can result in negative mean stresses (Fig. 2a).

While under isothermal conditions higher mean stresses usually lead to lower fatigue lives, IP-TMF tests can show lower fatigue lives than OP-TMF tests for the same mechanical strain amplitude and the same strain ratio, even though lower mean stresses are present in the IP tests (see Fig. 2a and b). This tendency is especially true for higher mechanical strain amplitudes. At lower mechanical strain amplitudes the tendency reverses (Fig. 2b and [9]).

Since fatigue crack growth in ductile metallic materials involves irreversible plastic deformations at least in a small zone around the crack-tip, plasticity-induced fatigue crack closure, which is the

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http://dx.doi.org/10.1016/j.ijfatigue.2015.03.022
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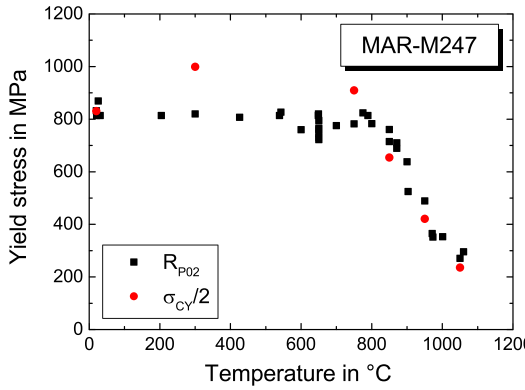

Fig. 1. Static (R_{P02}) and cyclic (σ_{CY}) 0.2%-offset yield stress as a function of temperature for the nickel-base alloy MAR-M247.

dominant mechanism for the explanation of mean stress effects, immediately becomes history dependent, too.

Plasticity-induced fatigue crack closure has been investigated in numerous studies using different numerical or analytical methods. In [10–13] discrete dislocation simulations were used to study crack closure in the near threshold regime, where the plastic zone only consists of few dislocations. The strip yield model (SYM) [14] has proven to be a powerful tool to explain load history effects such as fatigue crack growth retardation after overloads [15,16] and to predict fatigue lives under spectrum loading [14–17]. Even though yielding in the SYM (or similar boundary element models) is confined to a narrow yield zone in the crack plane, the quantitative agreement with finite element simulations of plasticity induced fatigue is found to be good, if the same material model (i.e. elastic perfect plasticity) is used [18–20]. The finite element method allows to use more complex material models (with isotropic and kinematic hardening), which are expected to give a more realistic description of the cyclic stress–strain evolution under fatigue loading. The effect of the material model was studied e.g. by [21–25] and was found to greatly affect plasticity-induced fatigue crack closure both under constant and variable amplitude loading. However, both the SYM and the finite element method predict decreasing σ_{op}/σ_{max} with increasing σ_{max}/σ_Y [19,21,22,26–28]. This common trend is independent of the specimen geometry and the material model being used. For an overview on the simulation of plasticity-induced fatigue crack closure using the finite element method the reader is referred to [26]. For a summary of the more recent discussions on the numerical aspects of simulating plasticity-induced crack closure an excellent overview is given by [29].

Recently, a strip yield model was applied by Schlitzer et al. [30] to investigate fatigue crack growth under TMF loading with temperature and stress gradients including a location dependent yield stress. Similar investigations were performed by Bauerbach [31] in studies with the finite element method. Here, it was shown that crack closure and opening under TMF loading does not occur at the same strain level in contrast to isothermal loading. In both studies, however, the phase relation between the thermal and mechanical load and its consequence on crack closure are not addressed. Indeed, no systematic studies are known to the authors of this paper in which crack opening stresses are assessed for cracks in homogeneous transient temperature fields under IP and OP loading, respectively. However, it has already been suspected in [32], that LCF and TMF loading will develop different crack closure effects due to the temperature dependence of the yield stress.

Thus, it is the aim of the paper to study the basic effects of a temperature dependent yield stress on plasticity-induced crack closure under IP- and OP-TMF loading. To this end, the SYM from [14] is extended to account for temperature dependent material properties. The usage of the SYM with perfect plasticity instead of the finite element method with more sophisticated cyclic plasticity models is justified, since the SYM describes the trends of plasticity-induced crack closure correctly. Moreover the computational costs are low and the required material properties can easily be determined. For more detailed studies with the finite element method, a viscoplastic model with kinematic hardening would be necessary along with the corresponding material properties up to large strains. Otherwise the deformations at the crack-tip cannot be predicted reliably [33]. At the current stage of knowledge, such a model complexity would seem to be inadequate in order to investigate the basic trends caused by TMF loading.

The paper is structured as follows: In the next section the SYM is presented while in Section 3 the results of the systematic studies under IP- and OP-TMF loading are shown. In Section 4 the results are discussed before the paper is concluded in Section 5.

2. A strip yield model for TMF-loading

In this section, the SYM for a center-cracked (infinite) plate with crack length $2a$ under mode I loading is derived (Fig. 3). For application under TMF, the history dependence is included by consideration of the loading history and the temperature dependent material properties. Thus, the externally applied stress σ_∞, the homogeneous temperature T of the plate and the material properties are functions of time t.

2.1. Temperature dependent Dugdale model

In the following, the basis equations of a temperature dependent Dugdale model are introduced and assigned in the next section into a discretized setting for the treatment of local crack face contact and crack growth. In the Dugdale model a stationary crack is considered and the extension of the plastic zone in y-direction normal

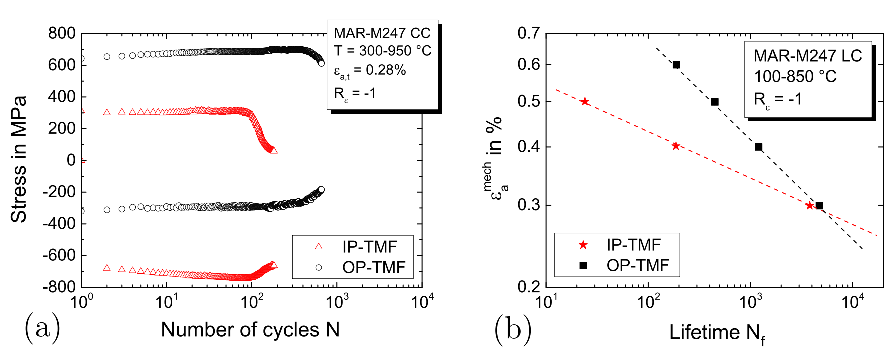

Fig. 2. (a) Stress evolution during IP- and OP-TMF loading from [7], (b) fatigue lives of IP- and OP-TMF tests for MAR-M247 LC from [8].