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A Fatigue Damage Propagation Model Based on Locally Periodic Micro-crack Growth

Oumar Keita, Vincent Velay, Remi Lacoste, and Farhad Rezai-Aria

Abstract

This paper develops a new micro-mechanical damage model for fatigue crack propagation in tensile (Mode I) cyclic loading. The double-scale fatigue damage model is entirely obtained through small-scale yielding descriptions of micro-crack propagation. Based on the Paris fatigue crack growth law, the stress intensity factor range is expressed thanks to an appropriate micro-mechanical energy release rate analysis coupled with asymptotic homogenization developments. The macroscopic fatigue crack evolution law is established. Numerical simulations are presented. The reliability of the model to reproduce stress-strain shielding is demonstrated. The influence of the microstructural length on fatigue damage evolution is illustrated. The numerical results are compared with fatigue crack propagation tests performed on Ti-6Al-4V titanium fashioned by additive layer manufacturing (ALM). Through the calibration process, the model agrees with the experimental results.

Keywords

Micro-cracks • Fatigue • Asymptotic homogenization • Damage evolution • Size effects • Ti-6Al-4V titanium ALM

1 Introduction

Fatigue micro-crack growth generally occurs very early in the components' life, particularly when cyclic loading ranges between low cyclic fatigue (LCF) and high cyclic fatigue (HCF) regions. The fatigue limit is defined as classically a stress level below which a fatigue failure does not occur. However, the very high cyclic fatigue investigation has opened new windows concerning the existence or non-existence of fatigue limits.

Several phenomenological models of fatigue damage evaluation exist in the literature. One is the Nonlinear Continuous Fatigue Damage model (Manson and Hirschberg, 1964; Lemaitre and Chaboche, 1985; Chaboche and Lesne, 1988).

These phenomenological models mask inherent variability because they represent average behaviors at the continuum scale. It is shown that fatigue damage and life are strongly influenced by the tail ends of the defect distributions, which are often related to the microstructural-feature distributions, such as particle size, crystallography, grain boundaries, grain size, and shape distributions (Elias et al., 2010; Mingyang et al., 2019). Despite these observations, a few research dealing with fatigue damage modeling in a multiscale framework exists in the literature.

The present paper is in the tradition of these multiscale fatigue damage models. Assuming a locally periodic distribution of micro-cracks, double-scale fatigue damage is developed using a mathematical homogenization method based on asymptotic developments (Sanchez-Palencia, 1980). Furthermore, the model can predict the effect of the material microstructural length on fatigue damage evolution.

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2 Settings and Methods

2.1 Fatigue Crack Propagation

In linear elastic fracture mechanics (LEFM) (Paris & Erdogan, 1963), fatigue crack propagation power law is generally expressed as

$$\frac{dl}{dN} = C(\Delta K)^m \quad (1)$$

Considering the relationship between the stress intensity factor and the macroscopic energy release rate G , the following relationship can be established (Eq. 2) for plain strain condition, with

$$\frac{dl}{dt} = f \cdot C \left(\Delta \left(\frac{EG}{1-\nu^2} \right)^{\frac{1}{2}} \right)^m \quad (2)$$

where ν is the Poisson ratio and E is the Young modulus.

2.2 Two-Scale Approach for Local Periodic Distribution of Micro-cracks

This contribution addresses the evolution of the elastic field ahead of a long crack containing many micro-cracks. It is assumed that the head of the crack is constituted of a periodicity of cells containing each micro-crack. It is so considered that the micro-crack distribution is locally periodic (see Fig. 1a). The size cell is denoted ε and represents a material-dependent scale. It is equivalent to the distance between the centers of neighbor micro-cracks. The micro-crack length is l . It is assumed that the crack length has very small spatial variations. Therefore, the consideration that micro-crack distribution is periodic locally is relevant. Each crack is considered to lie horizontally along the x_1 -axis of the plan of the long crack (mode I loading). The damage variable is defined as the ratio between the micro-crack length l and the cell size (Eq. 3):

$$D = \frac{l}{\varepsilon} \quad (3)$$

So damage variable, D , varies between nil (undamaged material) and 1 (entirely damaged material).

2.3 Fatigue Damage Evolution Law

The damage energy release rate G expresses the rate of energy per crack length change corresponding to a small crack growth dl per unit surface. A relationship based on the micro-mechanical analysis is established in (Dascalu et al., 2008) for micro-cracks evolution:

$$\frac{\mathcal{G}_c}{\varepsilon} = \frac{1}{2} \frac{dC_{ijkl}^{\pm}(D)}{dD} e_{kl}^x(\mathbf{u}(0)) e_{ij}^x(\mathbf{u}(0)) \quad (4)$$

where $Y_d \equiv \frac{1}{2} \frac{dC_{ijkl}^{\pm}(D)}{dD} e_{kl}^x(\mathbf{u}(0)) e_{ij}^x(\mathbf{u}(0))$ is the macroscopic damage energy release rate.

By substituting Eq. 4 into Eq. 3, one can achieve the new expression for damage evolution law for fatigue crack propagation as follows:

$$\frac{dl}{dt} = f \cdot C \left(\Delta \left(\frac{-E\varepsilon \frac{1}{2} \frac{dC_{ijkl}^{\pm}(D)}{dD} e_{kl}^x(\mathbf{u}(0)) e_{ij}^x(\mathbf{u}(0))}{1-\nu^2} \right)^{\frac{1}{2}} \right)^m \quad (6)$$

In the present model, the variation of macroscopic damage energy release rate used for cyclic loading will come from the imposed macroscopic strain terms $e_{kl}^x(\mathbf{u}^{(0)}) e_{ij}^x(\mathbf{u}^{(0)})$ in (Eq. 6).

$$\frac{dD}{dt} = f \cdot C \left(\frac{E}{\varepsilon^{\frac{2}{m}-1} (1-\nu^2)} \right)^{\frac{m}{2}} \left(\left(-\frac{1}{2} \frac{dC_{ijkl}^{\pm}(D)}{dD} e_{kl}^x(\mathbf{u}(0)) e_{ij}^x(\mathbf{u}(0)) \right)^{\frac{1}{2}} \right)^m \quad (7)$$

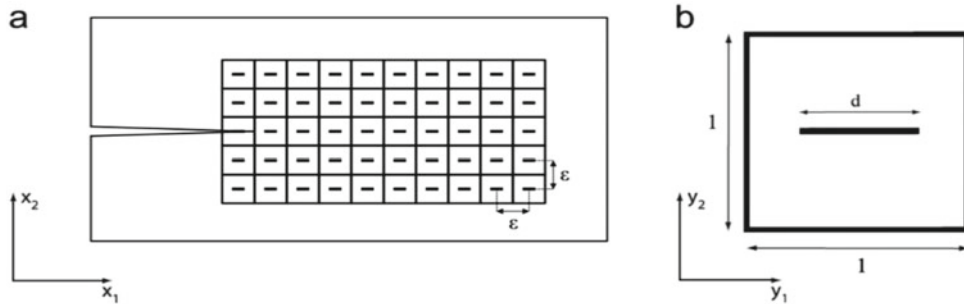


Fig. 1 **a** Ahead of a long crack containing locally periodic micro-cracks distribution, ε is the size of a period, and l is the local micro-crack length. **b** Unit cell with a rescaled crack of length D

Table 1 Parameters used in the simulations

E [Pa]	ν [-]	ε [m]	f [Hz]	C [-]	m [-]	D_0 [-]
2.10^9	0.3	$10 - 3$	0.1	$10 - 16$	2.11	0.05

3 Results

3.1 Local Macroscopic Response

The local macroscopic elastic damage response is simulated by considering a normal tensile strain-controlled loading along the direction perpendicular to crack lips. In contrast, the horizontal direction is free of stress. Plane-strain condition is considered, so the strain in the third direction is

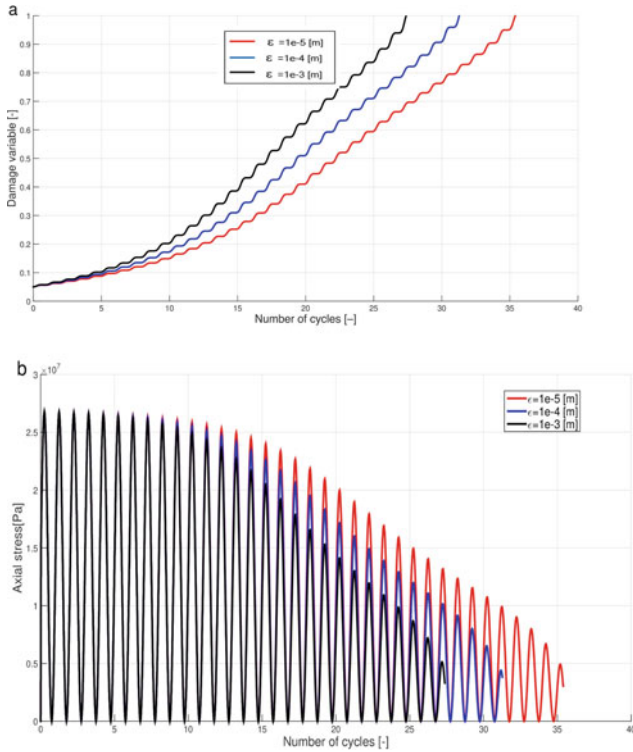
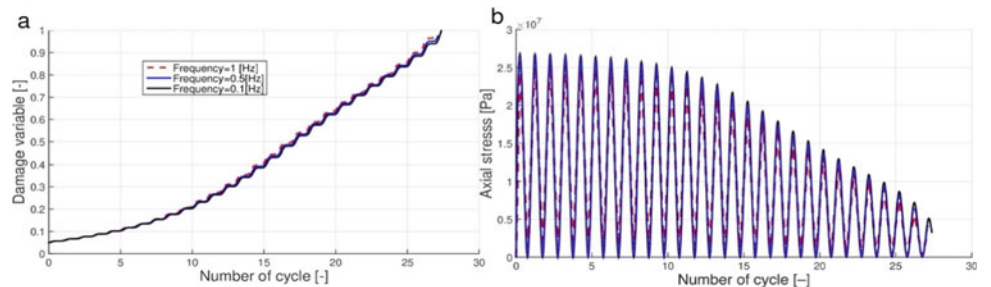


Fig. 2 Effect of microstructure lengths on the damage (a) and the stress (b) evolutions with the number of cycles

Fig. 3 Effect of the load frequency f on the damage evolution with time



neglected. The numerical values of the parameters used in the simulations are given in Table 1.

3.2 Influence of Microstructure Length E

Figure 2 shows the evolution of the damage variable with the number of cycles for several microstructure lengths. The decrease in the microstructure length leads to increased material resistance to damage (Fig. 2a). Also, several crack propagation investigations reveal that by decreasing the grain size, the fatigue crack propagation (FCP) resistance increases.

This known trend is also observed in the dynamic damage models (François & Keita, 2015; Keita et al., 2013) and quasi-static models of damage (Dascalu, 2009; Dascalu et al., 2008; Francois & Dascalu, 2010).

3.3 Influence of the Load Frequency

Figure 3 illustrates damage evolution with the number of cycles for different load frequencies. As expected, for the f range studied, slight difference is observed.

4 Discussion

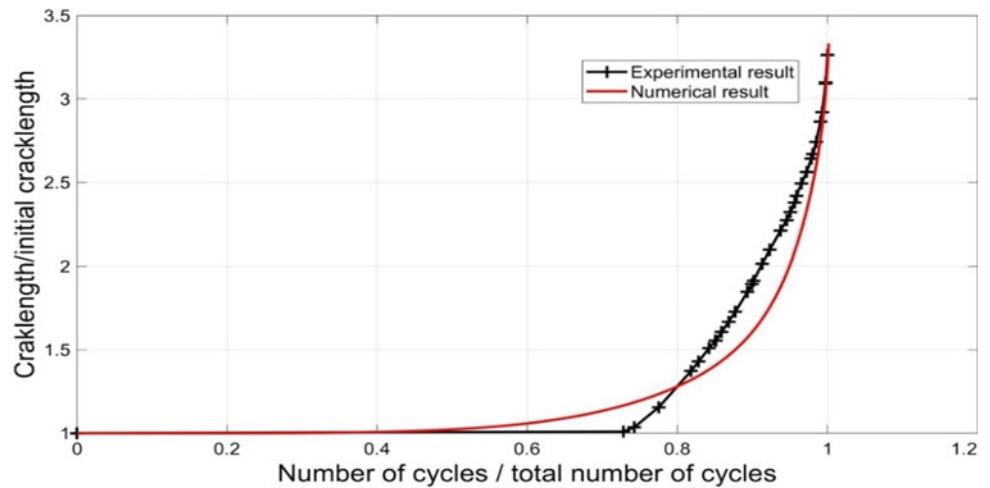
4.1 Model Validation

This section aims to validate our fatigue damage model. For this purpose, numerical simulation results provided by the model are compared with experimental fatigue tests. These tests are performed on Ti-6Al-4V titanium SLM alloy. The elastic parameters of the material are given in Table 2. The strain amplitude of $e_{kl}^x(\mathbf{u}^{(0)})_a = 0.002$ and a frequency of $f = 2$ Hz.

Table 2 Parameters of the Ti-6Al-4V alloy used in the simulations

E [Pa]	ν [-]	ε [m]	f [Hz]	C [-]	m [-]	D_0 [-]
$114 \cdot 10^9$	0.3	$2 \cdot 10^{-3}$	2	$2 \cdot 10^{-12}$	3	0.2

Fig. 4 Relative crack length evolution as a function of the normalized number of cycles: comparison of the model response with experiment



The parameters C and m given in Table 2 are determined using the results of fatigue tests performed in the present investigation.

The relative crack length evolution is a function of the normalized number of cycles with the corresponding experimental results on the Ti-6Al-4V SLM alloy. Because of the lack of experimental data on the microstructural characteristics of the material, a calibration by considering several microstructural lengths ε is performed. As a result, the model agrees well with the experimental results.

For an initial damage value of $D_0 = 0.3$ and a microstructural length of $\varepsilon = 10^{-3}$ m, the model agrees with the experimental result, as illustrated in Fig. 4.

5 Conclusion

Phenomenological fatigue damage models often give average material behaviors at the continuum scale. However, they cannot predict the effects of the internal micro-crack distribution on the global response. A new fatigue damage model depending on the internal material length is developed. The damage evolution law is deduced from Paris and Erdogan's locally periodic micro-cracks growth law (1963) combined with the asymptotic homogenization coupled with microscopic energy analysis. The model shows that the small-scale's period size of the micro-crack distribution controls the macroscopic fatigue damage. Furthermore, the influence of load frequency on damage evolution at a local macroscopic point is studied. Validation of the model is done by comparing.

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