DEVELOPMENT AND IDENTIFICATION OF A PROBABILISTIC TWO-SCALE MODEL FOR HIGH CYCLE FATIGUE PREDICTION

Cédric DOUDARD*, Sylvain CALLOCH*, Philippe CUGY**, André GALTIER** and François HILD*

* Laboratoire de Mécanique et Technologie
61, Avenue du Président WILSON
94235 CACHAN CEDEX - FRANCE

** IRSID
Voie romaine
BP 30320 – 57283 MAIZIÈRES-LÈS-METZ - FRANCE

INTRODUCTION

The present paper is concerned with the development of a probabilistic two-scale model for HCF that accounts for the failure of sample but also for the thermal effects during cyclic loadings. We assume that HCF damage is localized at the microscopic scale. So the microplasticity appears without affecting the behaviour of the material at the macroscopic scale. The development of the model is presented in three successive stages. In the first one, the model is deterministic and we show how to interpret the thermal effects by integrating the conduction heat equation. So we justify the empirical method proposed to estimate quickly the mean fatigue limit. We improve then the model by introducing a probabilistic characteristic at the microscopic scale. We assume that the number of active sites, i.e. a site whose the microplasticity appears, follows a Poisson process. We show that the new model represents better the thermal effects than the first model. With this approach the scatter can be determined but not the mean fatigue limit of a fatigue sample. A method of identification is also proposed. It is based on the analysis of the thermal effects for the scatter and is applied on a dual-phase steel. A first validation of the model is effected by predicting the scatter of the S/N curve. And a second validation is proposed by showing a good agreement between the experimental result and the predicted model for bending fatigue test.

BEHAVIOUR OF A DUAL-PHASE STEEL UNDER CYCLIC LOADINGS

The material studied is here in a ferrite-martensite dual-phase steel grade (around 15% of martensite). This steel offers a better combination of strength and ductility than other conventional steels.
To evaluate the fatigue properties of dual-phase steel, temperature measurements are used. It consists in applying successive series of 3000 cyclic loadings (Fig 1) for different increasing stress amplitudes Σ_0 (Fig 2). For each load amplitude, the change of the temperature $\theta = T-T_0$ (T, the temperature of the sample during the test obtained by a thermocouple and T_0 the initial temperature) is recorded (Fig 3). The mean temperature becomes stable after some cycles and equals $\bar{\theta}(\Sigma_0)$. Figure 4 shows the change of the steady state mean temperature $\bar{\theta}(\Sigma_0)$ with the load amplitude for a dual-phase steel for two different tests. We can see that the test is reproducible. This result is obtained by different authors [1, 2]. We observes that $\bar{\theta}(\Sigma_0)$ suddenly increases as the load level is close to the fatigue limit of the material. This evolution can be explained by the occurrence of the first slip bands on the surface [1].

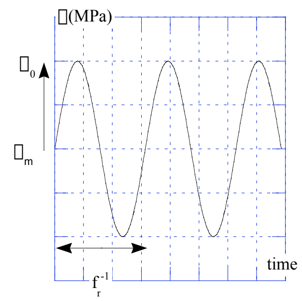

Figure 1. Cyclic loadings

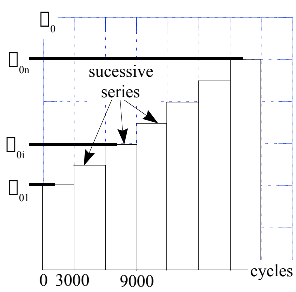

Figure 2. Loadings for different increasing stress amplitudes Σ_0

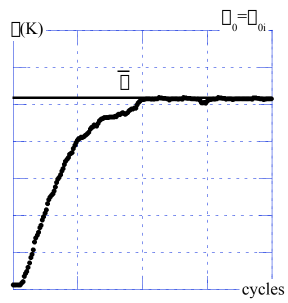

Figure 3. Change of the temperature during 3000 cyclic loadings

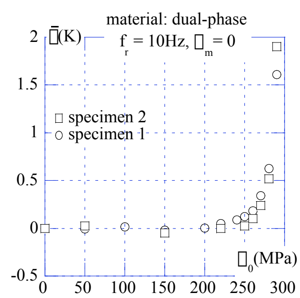

Figure 4. Steady state mean temperature versus load amplitude

A DETERMINISTIC TWO-SCALE MODEL

The two-scale model has been developed by Lemaitre and Doghri [4] in a deterministic way. It is based on the hypothesis that HCF damage is localized at the microscopic scale, whose dimensions are smaller than those of the representative volume element (RVE) associated to the mesoscopic scale. Consequently, two phases are considered in the model. The first one is an inclusion standing for grains where local plasticity is developed; the second one is the matrix describing the other grains whose behaviour remains elastic. We assume that the two phases have got the same elastic behaviour and that the yield stress of the elasto-plastic inclusion σ_y^μ is less than that of the surrounding material. The constitutive equations of the model are resumed by the following relations:

Strain decomposition in the inclusion: $\underline{\underline{\varepsilon}} = \underline{\underline{\varepsilon}}^e + \underline{\underline{\varepsilon}}^p$ Yield surface in the inclusion: $f = J_2\left(\underline{\underline{S}} - \underline{\underline{X}}\right) - \sigma_y^\mu \le 0$

Normality rule: $\dot{\underline{\underline{\varepsilon}}}^p = \dot{\lambda}\frac{\partial f}{\partial \underline{\underline{S}}}$ Kinematic hardening: $\dot{\underline{\underline{X}}} = \frac{2}{3} C \dot{\underline{\underline{\varepsilon}}}^p$

Law of localization: $\underline{\underline{\sigma}} = \underline{\underline{\Sigma}} - 2\mu(1-\beta)\underline{\underline{\varepsilon}}^p$ Dissipated energy for a loading cycle: $D = \frac{4 f_v \sigma_y^\mu}{h}\left\langle \Sigma_0 - \sigma_y^\mu \right\rangle$

The previous model is now used to analyse the heat transfer induced by the intrinsic dissipation D. The heat equation is deduced from the two first principles of thermodynamics. Let us assume that the convective terms of the material time derivative and the coupling between temperature and hardening variable are negligible and that the external heat supply r is time independent, the local heat conduction equation is given by [5]:

$$\rho c \dot{\theta} - k \Delta\theta = D + T \underline{\underline{\sigma}}_{,T} : \dot{\underline{\underline{\varepsilon}}}^e$$

and the mean steady state temperature is given by the following equation obtained by the resolution of local heat conduction equation:

$$\bar{\theta} = \frac{4 f_v f_r \tau_{eq} \sigma_y^\mu}{h \rho c}\left\langle \Sigma_0 - \sigma_y^\mu \right\rangle$$

Figure 5 shows the result of the identification of the model. The following section deals with an improvement of the present approach by considering that the microscopic yield stress are scattered.

A PROBABILISTIC TWO-SCALE MODEL

Let us assume that the microscopic yield stress is a probabilistic variable. An active site (in terms of fatigue mechanism) is defined as a site whose the applied stress is greater than the microscopic yield stress. These sites are assumed to be described by a Poisson point process. In this context, it can be shown that the mean state temperature is given by the following relation:

$$\bar{\theta} = \eta V_0 \frac{m}{(m+1)(m+2)} \frac{\Sigma_0^{m+2}}{V_0 S_0^m}$$

Figure 6 shows the result of the identification of the probabilistic two-scale model. We can see that the thermal effects are accurately reproduced by the model. The validation of the probabilistic two-scale model is based on the prediction of the scatter of the experimental fatigue result (Fig. 7).

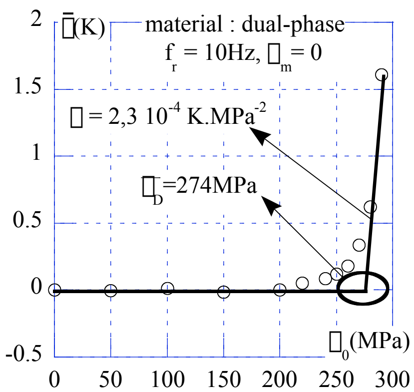

Figure 5. Identification of DTSM

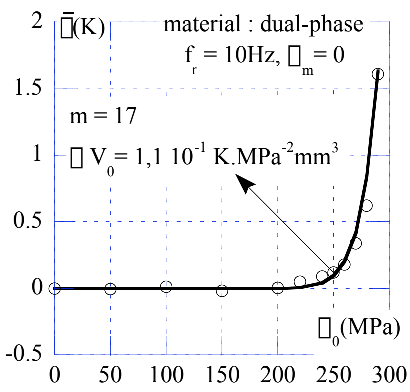

Figure 6. Identification of PTSM

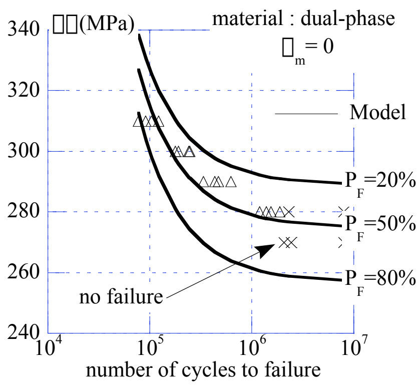

Figure 7. Validation of PTSM

References

[1] Galtier A., Bouaziz O. and Lambert A.: Influence de la microstructure des aciers sur leurs propriétés mécaniques. Méc. Ind., 457-462, 2002.

[2] Mabru C., Chrysochoos A.: Dissipation et couplages accompagnant la fatigue de matériaux métalliques. Photo-méca, 375-382, 2001.

[3] Lemaitre J., and Doghri F.: Damage 90: a post processor for crack initiation. Comput. Methods Appl. Mech. Engrg., **115**:197-232, 1994.

[4] Chrysochoos A., Louche H.: An infrared image processing to analyse the calorific effects accompanying strain localisation. Int. J. of Eng. Sc., **38**:1759-1788, 2000.