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FIELDS OF DISSIPATED AND STORED ENERGY ACCOMPANYING THE HCF OF STEELS

B. Berthel, F. Latourte, S. Pagano, B. Wattrisse, A. Chrysochoos
 Mechanical and Civil Engineering Laboratory, Montpellier II University
 CC048, Université Montpellier II, Pl. E. Bataillon, 34095 Montpellier, France
 berthel@lmgc.univ-montp2.fr, name@lmgc.univ-montp2.fr

1. CONTEXT

During high cycle fatigue of steel specimens, stress states remain traditionally within the mesoscopic elastic domain of the material. However, slight energy dissipation due to the irreversible evolution of the microstructure can be observed during the multiplicity of cycles performed at high loading frequencies. This dissipation is then superimposed on the classical thermoelastic coupling sources due to the thermal expansion of the crystalline network. This paper presents a protocol to locally estimate the different terms of the energy balance, namely the deformation energy, the dissipated and stored energies. The experimental setup involves two quantitative imaging techniques: digital image correlation (DIC) and infrared thermography (IRT).

2. EXPERIMENTAL PROTOCOL

On the one hand, DIC provides in-plane displacement fields u and after derivation, fields of small strain ε and strain-rate $\dot{\varepsilon}$. A variational method, associated with an energy functional, is used both to identify the field of elastic parameters and to determine the stress pattern σ [1-2]. The knowledge of stress and strain-rate fields then allows constructing distributions of deformation energy rate. The temperature variations $\theta = T - T_0$ remaining small ($|\theta| < 10K$, room temperature $T_0 \approx 293K$) throughout the tests, since we neglected their influence on the microstructural state (no self-annealing) and on the strain fields. We also neglected the influence of microplastic strains on stress distributions. In this framework, the deformation energy rate was approximated by a purely elastic one:

$$\sigma : \dot{\varepsilon} = E^{-1} : \sigma : \dot{\sigma} + \lambda \text{tr} \sigma \dot{\theta} \approx E^{-1} : \sigma : \dot{\sigma} \quad (1)$$

where E is the elastic rigidity tensor and λ the isotropic thermal expansion coefficient. Estimation of $\sigma : \dot{\varepsilon}$ was made as follows: during a test, the displacement field u is given by DIC. The load applied at its boundary is also known (load cell). The couple (E, σ) is then one solution of the identification problem if it satisfies the local equilibrium equations, the constitutive equations and the global equilibrium. We associated to this problem the energy functional F defined by [5]:

$$F(\tau, B) = \frac{1}{2} \int_{\Omega} (\varepsilon(u) - B : \tau) : B^{-1} : (\varepsilon(u) - B : \tau) d\Omega \quad (2)$$

where the stress field τ is statically admissible, and where the compliance tensor B is supposed to be symmetrical, non negative and definite. The functional $F(\tau, B)$ is separately convex and positive, and null if and only if the couple (τ, B) satisfies the constitutive equation. Therefore the identification is performed by numerically minimizing the functional $F(\tau, B)$. A minimisation over the first and second variable gives the stress field solution and the field of elastic parameters, respectively. The small micro-plastic effects are taken into account by identification performed at each loading step.

On the other hand, IRT provides thermal images which are used to estimate separately the distributions of thermoelastic source amplitudes Δs_{the} and the intensities of intrinsic dissipation \bar{d}_1 . To compute the heat sources, thermal image processing uses a local linear expression of the heat diffusion equation. Under several hypotheses detailed in [3-4], this local equation can be written in the following simplified form:

$$\rho C \left(\frac{\partial \theta}{\partial t} + \frac{\theta}{\tau_{\text{th}}} \right) - k \Delta_{x,y} \theta = d_1 + s_{\text{the}} \quad (3)$$

where ρ is the mass density, C the specific heat, τ_{th} a time constant characterizing the heat losses perpendicular to the surface of the specimen, k the isotropic conduction coefficient, $\Delta_{x,y} \theta$ the Laplacian term corresponding to the in-plane losses. We underline that the left-hand side of equation (3) is a differential operator applied to θ . To estimate the heat sources, a local least-squares fitting of thermal data was chosen. The local approximation function has the following form:

$$\theta^{\text{app}}(x, y, t) = \underbrace{p_1(x, y) t + p_2(x, y)}_{\text{"instantaneous" drift}} + \underbrace{p_3(x, y) \cos(2\pi f t) + p_4(x, y) \sin(2\pi f t)}_{\text{periodic response}} \quad (4)$$

The trigonometric time functions describe the periodic part of the thermoelastic effects (with a possible phase shift) while the linear part takes into account transient effects due to heat losses, dissipative heating and possible drifts of the equilibrium temperature. The functions $\rho(x, y)$, $i = 1, \dots, 4$, are second order polynomials of the in-plane coordinates x and y . The identification of the best fitting functions allowed us, for each approximation zone, to compute the amplitudes of the thermoelastic source and the mean intensity of the dissipation per cycle.

3. SOME RESULTS

The fatigue tests were carried out by imposing a series of loading blocks on thin, flat specimens. Each block was performed at constant loading frequency f_L , constant load ratio R_σ , and constant stress range $\Delta\sigma$. We chose loading blocks of $N_c=2\ 400$ cycles performed at different $\Delta\sigma$ with $R_\sigma = -1$ and $f_L=30\text{Hz}$. Between the 5th and the last five blocks, a block of 100 000 cycles was performed at the maximal stress range upper than the fatigue limit (Fig. 1). The short blocks were made to estimate the dissipation levels at different stress amplitudes and at relatively constant damage states. Conversely, the long block at maximal constant stress range aimed at speeding up fatigue development.

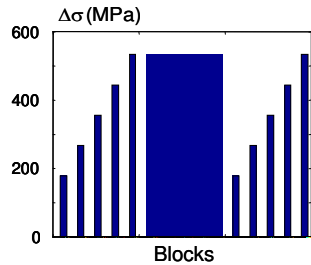


Figure 1- Series of blocks

To illustrate the potentialities of the developed protocol, we show in Fig. 2a the distribution of the mean deformation energy w_{def} per cycle averaged over the penultimate block of the test. Similarly, we show the mean dissipated energy per cycle w_d (Fig. 2b) and the mean stored energy rate w_s (Fig. 2c). Divided by ρC , these energy fields are expressed in mK.

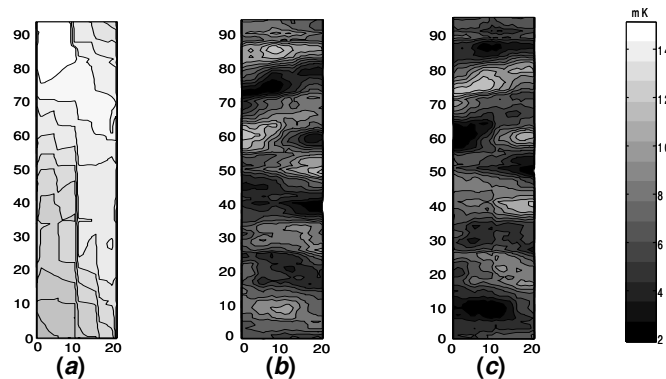


Figure 2- Energy fields: (a) w_{def} , (b) w_d , (c) w_s , $\Delta x \approx 0.2\text{mm/pixel}$

These results should enable us to better understand the localized development of fatigue kinetics through analysis of the time course of internal and dissipated energy fields.

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