Non-isothermal low-cycle fatigue analysis of elasto-viscoplastic materials

Heraldo da Costa-Mattos [a,*], Pedro Manuel Calas Lopes Pacheco [b]

[a] Laboratório de Mecânica Teórica e Aplicada, Programa de Engenharia Mecânica, Universidade Federal Fluminense, Rua Passo da Pátria 156, 24210-240 Niterói, RJ, Brazil
[b] Departamento de Engenharia Mecânica, Centro Federal de Educação Tecnológica Celso Suckow da Fonseca, Av. Maracanã 229, Maracanã – 20271-110 Rio de Janeiro, RJ, Brazil

ARTICLE INFO

ABSTRACT

A non-isothermal elasto-viscoplastic model, developed within the framework of continuum damage mechanics, is proposed to investigate the influence of thermomechanical coupling on fatigue life of metallic materials. The numerical simulation of constant-amplitude low-cycle fatigue testing of a 316L stainless steel at room temperature shows that the hypothesis of isothermal processes may be inadequate when cyclic inelastic deformations are involved. The results show that the specific heat can decrease when the fatigue damage is high, causing a localized increase of the temperature even if the amount of heat generated is not so high and, hence, promoting a reduction in lifetime.

© 2008 Elsevier Ltd. All rights reserved.

1. Introduction

Inelastic cyclic deformation promotes heating of metallic structural elements. For high loading rates and/or high amplitudes of inelastic deformation, a considerable amount of heat can be generated (Simo and Miehe, 1992; Pacheco and Costa-Mattos, 1997; Stablere and Baker, 2000; Rosakis et al., 2000; Longère and Dragon, 2008). However, in traditional low-cycle fatigue models, the variation of the material temperature due to thermomechanical coupling is not considered and unreal life predictions may be obtained. Indeed, there are situations where such coupling cannot be neglected and a physically realistic model must consider it. Since temperature variation can interfere on the fatigue phenomena and most classical low-cycle fatigue models only take into account isothermal processes, the ASTM standard for low-cycle fatigue testing (ASTM, 1980) establishes that the gradient of temperature during the testing program must not exceed a range of ±2 K. For high inelastic amplitudes the standard recommends the use of cooling devices and low loading frequencies maintain the specimen temperature within the established range. However, this is a difficult condition to achieve in real mechanical components in operation. In this paper, a continuum damage mechanics model is proposed to study the thermomechanical coupling effects on the life prediction of metallic structures submitted to cyclic inelastic loadings. A thermodynamic approach permits a rational identification of the thermomechanical coupling in the mechanical and thermal equations. Numerical simulations of austenitic stainless steel (AISI 316L) bars submitted to cyclic loadings are presented and analyzed.

2. First and second laws of thermodynamics

To set up a general constitutive theory it is necessary to consider aspects of the first and second law of thermodynamics since heat transfer and dissipative behavior must be taken into account. Considering the hypothesis of small transformations

* Corresponding author. Tel./fax: +55 21 2629 5585.
E-mail address: heraldo@mec.uff.br (H. da Costa-Mattos).

and under suitable regularity assumptions it is possible to consider the following expressions as local versions of the first law (FLT) and second law of thermodynamics (SLT)

$$FLT : \rho \dot{e} = -div\underline{q} + \underline{\underline{\sigma}} : \dot{\varepsilon} + \rho\, r; \quad SLT : d = \underline{\underline{\sigma}} : \dot{\varepsilon} - \rho(\dot{\psi} + s\dot{\theta}) + q.g \geqslant 0 \tag{1}$$

where a dot denotes the material time derivative; ρ is the mass density; $\underline{\underline{\sigma}}$ the stress tensor; $\underline{\varepsilon}$ the total strain (the symmetric part of the displacement gradient); e the internal energy per unity mass, θd the absolute temperature; s the total entropy per unit mass; $\psi = e - \theta s$ the Helmholtz free energy per unit mass; q the heat flux vector and $g = -grad(\log \theta)$, $\log \theta$ standing for the logarithm of the absolute temperature. is the rate of energy dissipation per unit volume. The second law of thermodynamics makes a distinction between possible processes ($d \geqslant 0$) and impossible processes ($d < 0$). The possible processes may be reversible (the rate of energy dissipation d is always equal to zero) or not. This local version of the SLT does not exclude the possibility of unusual behaviors such as a decreasing temperature if heat is added to the medium. To exclude the possibility of such kind of unusual behavior, here we only consider fluids that always satisfy a further restrictive constraint:

$$d_1 = \underline{\underline{\sigma}} : \underline{\dot{\varepsilon}} - \rho(\dot{\psi} + s\dot{\theta}) \geqslant 0; \quad d_2 = \underline{q} \cdot \underline{g} \geqslant 0 \tag{2}$$

Obviously, if the above relations are satisfied, then the local version of the SLT presented in (1) will also be satisfied. It is also simple to verify that (2) leads to the classical heat conduction inequality $-\underline{q} \cdot \underline{grad}(\theta) \geqslant 0$ since the absolute temperature θ is a positive quantity. This relation implies that heat flows in the direction of decreasing temperature when $\underline{q}$ is parallel to the temperature gradient. The quantity d_1, defined in (2), is usually called the intrinsic dissipation and the quantity d_2, the thermal dissipation. From the definition of the Helmholtz free energy per unit mass ψ and of the intrinsic dissipation d_1 it is possible to obtain the following alternative local form for the first law of thermodynamics which will be useful to analyze the thermomechanical couplings in the next sections:

$$-div\underline{q} + \rho\, r = -d_1 - \rho\theta\frac{\partial\dot{\psi}}{\partial\theta} \tag{3}$$

3. Elasto-viscoplastic model

The model used in this paper is developed within the framework of the thermodynamics of the irreversible processes. Such model is a generalization of the classic elasto-viscoplastic model proposed by Lemaitre and Chaboche (1990) for isothermal processes. For an elasto-viscoplastic material, the thermodynamic state is completely determined by a finite set of state variables, also called thermodynamic or independent variables. The state variables are the so-called observable variables – the total strain $\underline{\varepsilon}$ and the absolute temperature - and a set of internal variables related to dissipative mechanisms – the plastic strain variable $\underline{\varepsilon}^p$, the isotropic hardening variable p, the kinematic hardening variable $\underline{c}$ and the damage variable D. The macroscopic quantity D ($0 \leqslant D \leqslant 1$) represents the material local degradation. When $D = 0$ the material is in a virgin state and when $D = 1$ the material is completely damaged. In this model, the damage variable can be interpreted in terms of energy or as a measure of the link between material points and is not related to a volume fraction of voids. A further discussion about this interpretation of the damage variable can be found in Costa-Mattos et al. (1992). No matter the interpretation of the damage variable, the analysis of the different possibilities the free energy can be affected by the damage variable (which is the goal of this paper) is crucial to define how it can affect the specific heat $\mathbb{C}$ and provides a rational methodology to understand the adequate form of free energy and specific heat in coupled thermo-elasto-viscoplasticity with isotropic damage.

The elasto-viscoplastic behavior is characterized by two thermodynamic potentials: the Helmholtz free energy ψ and the potential of dissipation ϕ^*. The Helmholtz free energy is expressed as:

$$\rho\psi(\underline{\varepsilon}, \underline{\varepsilon}^p, p, \underline{c}, D, \theta) = (1 - D)[W_e(\underline{\varepsilon} - \underline{\varepsilon}^p, \theta) + W_p(p, \theta) + W_c(\underline{c}, \theta)] - W_\theta(\theta) \tag{4}$$

where the energy densities W_e, W_p, W_c and W_θ have the following form:

$$W_e(\underline{\varepsilon} - \underline{\varepsilon}^p, \theta) = \frac{E}{2(1 + v)}\left[(\underline{\varepsilon} - \underline{\varepsilon}^p) : (\underline{\varepsilon} - \underline{\varepsilon}^p) + \frac{v}{(1 - 2v)}[tr(\underline{\varepsilon} - \underline{\varepsilon}^p)]^2\right] - \frac{\alpha E}{1 - 2v}(\theta - \theta_0)tr(\underline{\varepsilon} - \underline{\varepsilon}^p) \tag{5}$$

$$W_p(p, \theta) = b\left(p + \frac{1}{d}e^{-dp}\right); W_c(\underline{c}, \theta) = \frac{a}{2}(\underline{c} : \underline{c}); W_\theta(\theta) = \rho\int_{\theta_0}^{\theta}\pi_1\log(\xi)d\xi + \frac{\rho}{2}\pi_2\theta^2 \tag{6}$$

E, v, α, b, d and a are temperature-sensitive material parameters, $\pi_1\psi$ and π_2 are positive constants and θ_0 a reference temperature. The so-called thermodynamic forces ($\underline{\underline{\sigma}}, B^p, \underline{B}^o, B^D, s$), associated to the state variables ($\underline{\varepsilon}, p, \underline{c}, D, \theta$), are defined from , as follows (a discussion about the role of the thermodynamic forces can be found in Lemaitre and Chaboche, 1990):

$$\underline{\underline{\sigma}} = \rho\frac{\partial\psi}{\partial\underline{\varepsilon}}; \ B^p = -\rho\frac{\partial\psi}{\partial p}; \ \underline{B}^c = -\rho\frac{\partial\psi}{\partial\underline{c}}; \ B^D = -\rho\frac{\partial\psi}{\partial D}; \ s = -\frac{\partial\psi}{\partial\theta} \tag{7}$$

An additional set of constitutive equations, called the evolution laws, which characterizes the evolution of the dissipative processes, is obtained from the potential of dissipation ϕ^*: