Theoretical analysis, infrared and structural investigations of energy dissipation in metals under cyclic loading

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Abstract

The infrared and structural investigations of energy dissipation processes in metals subjected to cyclic loading have given impetus to the development of a new thermodynamic model with the capability of describing the energy balance under plastic deformation. The model is based on the statistical description of the mesodefect ensemble evolution and its influence on the dissipation ability of the material. Constitutive equations have been formulated for plastic and structural strains, which allow us to describe the stored and dissipated parts of energy under plastic flow. Numerical results indicate that theoretical predictions are in good agreement with the experimentally observed temperature data.

Keywords: Infrared thermography; Energy storage; Low-cyclic fatigue; Thermodynamics of cyclic loading

1. Introduction

The fatigue loading of a great number of modern structural materials is accompanied by the generation of small defects, which cannot be detected till the end of structure lifetime. This necessitates the development of new techniques for damage monitoring and forecasting the endurance and durability of materials. The infrared thermography is considered as one of the promising techniques for these purposes. The current progress in the development of infrared detectors makes the infrared thermography a powerful, non-destructive, non-contact technique for investigation of heat dissipation during different deformation processes. For instance, the infrared thermography has been successfully used for fast determination of the fatigue limit and shape of the Wőhler curve [1,2]. In spite of these successes, the modern applications of this technique and experimental works of the authors of this paper show a lack in the adequate theoretical models.

The present study is devoted to the development of a thermodynamic internal variable model for describing the plastic deformation localization in metals. Based on the results of the statistical approach, the plastic deformation is divided into two parts, of which only one is interpreted as a thermodynamical variable. By generalizing the Ginsburg–Landau approach, we represent the thermodynamic potential (free energy) as an expansion in terms of the introduced thermodynamical variables. Numerical simulation of crack initiation under cyclic loading shows good agreement with experimentally observed temperature evolution.

2. Experimental procedure

Experimental investigations of fatigue of metals were carried out in the LAMEFIP ENSAM (France) laboratory in collaboration with the LPFS ICMM (Russia). The materials studied were 35CD4 and 301L steels. A detailed description of experimental conditions and material properties are provided in ref. [3].

During experiments an infrared camera (CEDIP Jade III) was used to record the evolution of the temperature field of the specimen surface. The spectral camera range is 3–5 μm. The

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maximum picture size is 320×240 pixels. The minimum size of pixel is 10^{-4} m. The maximum framing rate is 500 Hz. The thermal sensitivity is <25 mK at 300 K.

Fig. 1 presents the thermal image of a 301L steel specimen subjected to cyclic loading ($R = 0.1$, maximum stress 1300 MPa). The lifetime was 11,000 cycles. Fig. 1b and c present the temperature evolution in the crack initiation point at the beginning and last stages of the test, respectively.

3. Thermodynamic consideration

Let us introduce the following notations: $T(x,t)$ is the absolute temperature field; ρ the volumetric mass; e the specific internal energy; $\tilde{\varepsilon}$, $\tilde{\sigma}$ the strain and stress tensor, respectively; r the heat supply; $\vec{q}$ the heat flux vector; F the specific Helmholtz free energy; $\tilde{\varepsilon}^{\mathrm{e}}$ the elastic strain tensor; $\tilde{\varepsilon}^{\mathrm{p}}$ the plastic strain tensor; $\tilde{p}$ the defect induced strain tensor; $\tilde{\beta}$ is the thermal expansion coefficient tensor. The media under consideration obeys the kinematical relationship $\tilde{\varepsilon} = \tilde{\varepsilon}^{\mathrm{e}} + \tilde{\varepsilon}^{\mathrm{p}} + \tilde{p} + \tilde{\beta}(T - T')$. The energy and entropy balance equations can be written as

$$-F_{\tilde{p}} : \dot{\tilde{p}} + \frac{1}{\rho}\tilde{\sigma} : (\dot{\tilde{\varepsilon}}^{\mathrm{p}} + \dot{\tilde{p}}) \geq 0; \tag{1}$$

$$c\dot{T} = Q^{\mathrm{e}} + Q^{\mathrm{p}} + r - \nabla \cdot \vec{q}. \tag{2}$$

where $Q^{\mathrm{e}} = TF_{T\varepsilon^{\mathrm{e}}} : \dot{\tilde{\varepsilon}}^{\mathrm{e}}$ is heat production due to thermoelasticity; $Q^{\mathrm{p}} = TF_{Tp} : \dot{\tilde{p}} + (1/\rho)\tilde{\sigma} : \dot{\tilde{\varepsilon}}^{\mathrm{p}} + ((1/\rho)\tilde{\sigma} - F_{\tilde{p}}) : \dot{\tilde{p}}$ represents the inelastic contribution to heat production; $c = -TF_{TT}$ is the specific heat capacity.

Inequality (1) determines the plastic deformation and damage kinetics. It was shown [4] that F_p can be represented as $F_{\tilde{p}} = F_{\tilde{p}}(\tilde{p}, \delta)$, where δ is the dimensionless material parameter proportional to the ratio of a mean size of the defect nuclei and the distance between defects.

Considering δ as an additional thermodynamic variable describing the scaling characteristic of the defect ensemble, we can write inequality (1) as

$$-F_{\tilde{p}} : \dot{\tilde{p}} - F_{\delta} : \dot{\delta} + \frac{1}{\rho}\tilde{\sigma} : (\dot{\tilde{\varepsilon}}^{\mathrm{p}} + \dot{\tilde{p}}) \geq 0, \tag{3}$$

which leads to the following kinetic equations

$$\begin{aligned} \dot{\tilde{\varepsilon}}^{\mathrm{p}} &= 1_{\varepsilon^{\mathrm{p}}} F_{\varepsilon^{\mathrm{e}}} + 1_{\varepsilon^{\mathrm{p}} p}(F_{\varepsilon^{\mathrm{e}}} - F_p), \\ \dot{\tilde{p}} &= 1_{\varepsilon^{\mathrm{p}}}(F_{\varepsilon^{\mathrm{e}}} - F_p) + 1_{\varepsilon^{\mathrm{p}} p} F_{\varepsilon^{\mathrm{e}}}, \\ \dot{\delta} &= -1_{\delta} F_{\delta}. \end{aligned} \tag{4}$$

where the functions F_p, F_δ can be determined from the solution for the statistical model of a solid with mesodefects [4].

4. Results and conclusions

The defect accumulation kinetics in the one-dimensional cyclic test and its influence on the change of scaling characteristics of the material are described by Eq. (4). To close the system of equations, it is necessary to determine approximations for functions F_p, F_δ. Based on the available results [4], the

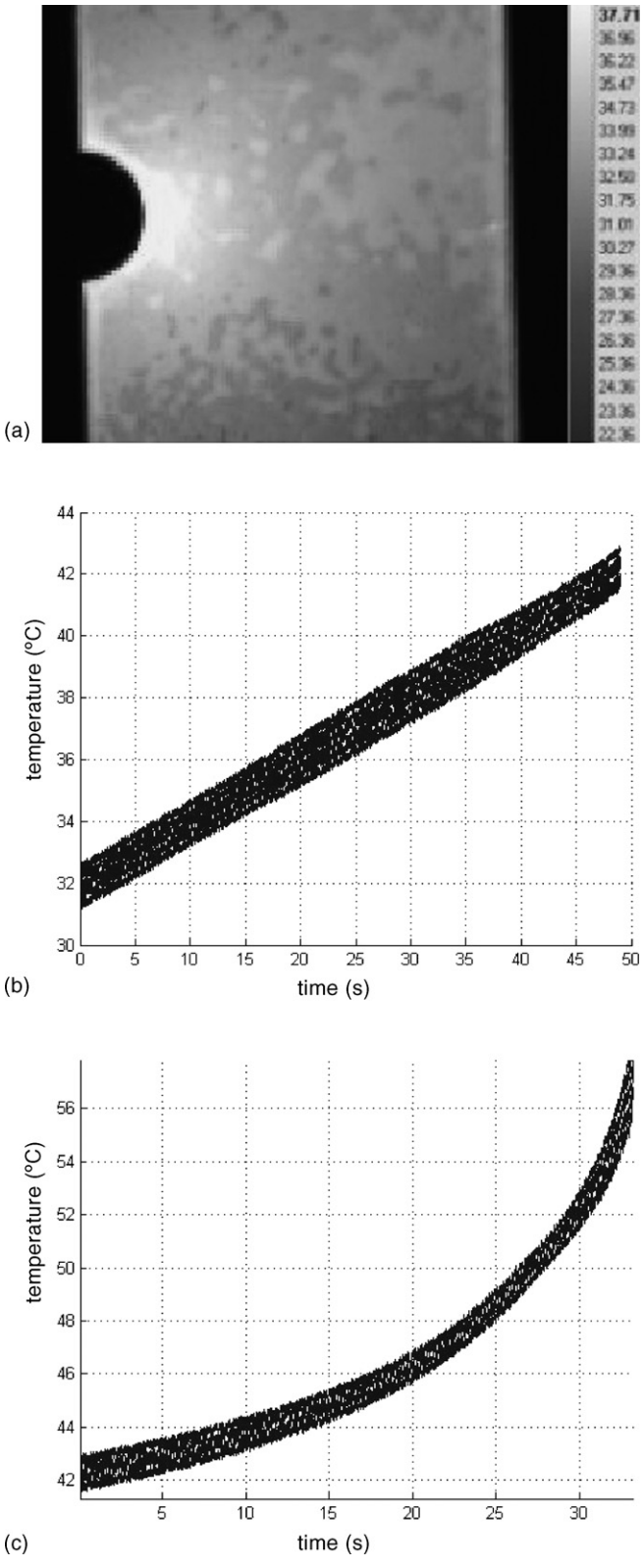

Fig. 1. (a) Temperature distribution on the notched specimen surface before fatigue crack initiation. Temperature vs. time (b) in the middle of the test, and (c) the moment of crack initiation.

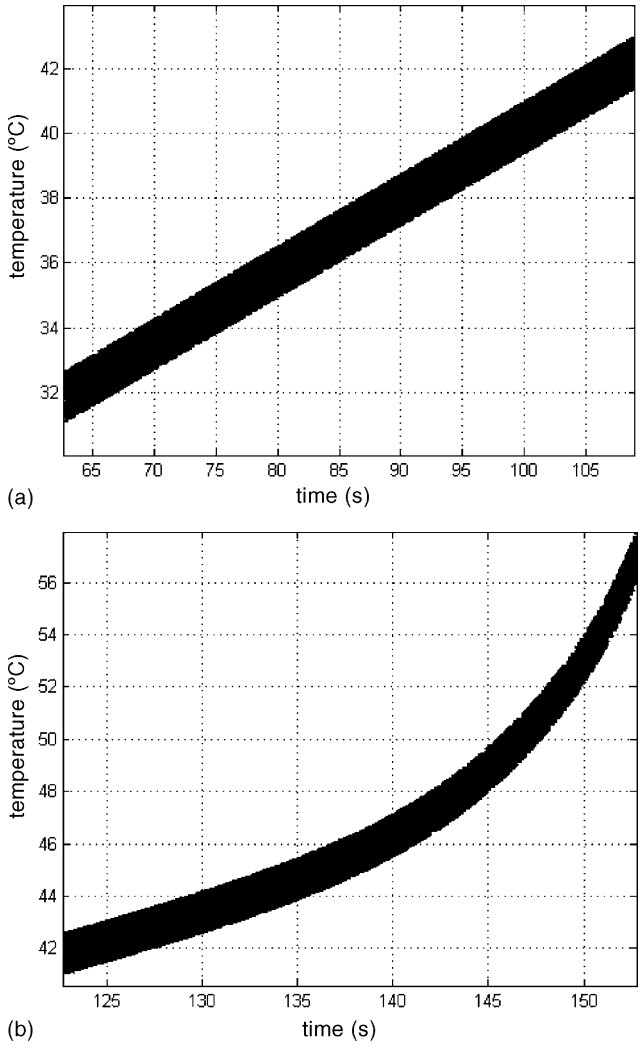

Fig. 2. Temperature evolution during numerical calculation (a) in the middle of the test and (b), at the moment of crack initiation.

following approximations can be proposed

$$F_p = (A_1(\delta) - A_2\mathrm{erf}((p_a p)^n))p + A_3(\delta)\mathrm{erf}((p_a p)^n), \tag{5}$$

$$F_\delta = \int_0^t F_p \dot{p}\, \mathrm{d}t. \tag{6}$$

where A_1, A_2, A_3, p_a, n are materials constants. (In our calculations we have used the following values: $A_1 = 14.2 \times 10^{11}$ J/m^2, $A_2 = 9.5 \times 10^{11}$ J/m^2, $A_3 = 8.0 \times 10^8$ J/m^2, $p_a = 400$, $n = 1.4$.) The values of these constants were determined based on the quasi-static stress–strain curve for material under investigation.

Materials constants (volumetric mass, specific heat, elastic modulus) are $\rho = 7870$ kg/m^3, $c = 420$ J/(kg K), $E = 2.0 \times 10^{11}$ Pa.

Eq. (2) for the one-dimensional geometry can be simplified as

$$c\rho\dot{T}(z,t) = Q^{\mathrm{e}} + \tilde{\sigma} : (\dot{\tilde{\varepsilon}}^{\mathrm{p}} + \dot{\tilde{p}}) - F_{\tilde{p}} : \dot{\tilde{p}} + k\frac{\partial^2 T'(z,t)}{\partial z^2}. \tag{7}$$

To solve (4)–(7) we introduce the following kinetic coefficients

$$1_{\varepsilon^p} = 0.7 \times 10^{-11}(\mathrm{Pa\,s})^{-1}, \quad 1_{\varepsilon^p p} = 0.01 \times 10^{-11}(\mathrm{Pa\,s})^{-1},$$
$$1_p = 0.035 \times 10^{-11}(\mathrm{Pa\,s})^{-1}.$$

These coefficients represent two mechanisms of plastic deformation incorporated in the model: viscous flow and defect ensemble rescaling. The plastic flow corresponds to the heat dissipation in the medium. The value of this dissipation depends on the coefficient 1_{ε^p} that can be considered as the effective viscosity of the medium. The peculiarities of the defect ensemble evolution rate can be described by the value 1_p. The characteristic time of defect evolution can be estimated as $\tau \approx (A_1 1_p)^{-1}$. The relatively large value of τ leads to the fast elastic accommodation of the material structure (material grains, mesodefects) and, as a consequence, to generation of the low internal structural stress and rather high heat dissipation.

The system of equations has been solved numerically. Fig. 2 presents temperature evolution in the course of the numerical test. It has been found that the theoretical results demonstrate good qualitative agreement with experimentally observed temperature signals.

Thus, we can conclude that the developed model (4) can adequately describe the influence of cold work accumulation on characteristic responses of the material subjected to loading. Eq. (6) describes the effect of energy storing process on the changes in the characteristic scales of the defect ensemble (defect ensemble rescaling), which decreases the material resistance to defect growth and, finally, initiates the fatigue crack. The process of crack initiation is manifested by non-linear temperature increase on the specimen surface.

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