Chapter 1
Comparison Between 0D and 1D Heat Source Reconstruction for Fatigue Characterization

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Abstract Material fatigue damage is associated with heat production leading to material self-heating. In this context, measuring temperature fields on a specimen's surface by infrared thermography is useful to analyze the fatigue response of the tested material. Calorific information can be also obtained by reconstructing the heat power density (heat sources) at the origin of the temperature changes. In particular, mechanical dissipation due to fatigue damage can be determined from the thermal response using specific temperature acquisition conditions. The processing is based the heat diffusion equation, whose different formulations have been proposed in the literature to perform heat source reconstruction. The present study compares two approaches for homogeneous fatigue tests, namely the zero-dimensional (0D) and one-dimensional (1D) approaches. The error generated by the 0D approach (compared to the 1D approach) was first determined from a model. For comparison purposes, experimental tests were performed on a copper specimen. Consequences of using the 0D processing for fatigue analysis are discussed.

Keywords Infrared thermography · Fatigue · Heat source · Mechanical dissipation · 0D approach

1.1 Introduction

Material fatigue is generally associated with a production of *mechanical dissipation* or *intrinsic dissipation*, leading to a "self-heating". The heat sources due to fatigue can be calculated from the temperatures measured on the surface of a specimen using infrared (IR) thermography. By "heat sources", we mean the heat power density (in $W \cdot m^{-3}$) which is produced or absorbed by the material due to a change in the material thermomechanical state. When heat sources are spatially homogeneous in the tested specimen, processing can be performed using a macroscopic approach, also named zero-dimensional (0D) approach. The latter consists in using the temperature changes averaged over the whole specimen's measurement zone to calculate the heat sources [1–6]. This approach is based on the fact that in the case of spatially homogeneous heat sources, the heat exchanged by conduction with the jaws of the testing machine is nearly proportional to the mean temperature change [7]. The 0D processing considers a "global" heat exchange with the outside of the tested specimen (jaws and ambient air), which is proportional to the mean temperature change. The present study analyzes the error generated by the 0D approach in the assessment of mechanical dissipation during a fatigue test. This error can be defined with respect to a one-dimensional (1D) approach, which is applicable to longitudinal specimens subjected to uniaxial loading [8–13]. Heat exchanges by conduction in the specimen and by convection with the ambient air are separately taken into account in the 1D approach.

The study was performed in two steps. First, a model was proposed to estimate the error generated by the 0D approach in the assessment of mechanical dissipation due to fatigue damage. Second, tests were performed on a specimen made of pure copper.

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1.2 Preliminary Analysis from a Model

Let us consider a longitudinal specimen with constant cross-section and placed in the jaws of a uniaxial testing machine: see Fig. 1.1. The temperature change $\theta(z, t)$ due to mechanical loading is given by the following 1D expression of the heat diffusion equation:

$$\rho C\left(\frac{\partial\theta}{\partial t}+\frac{\theta}{\tau}\right)-\lambda\,\frac{\partial^2\theta}{\partial z^2}=s \tag{1.1}$$

where s is the variation over time t in the heat source. The density ρ, specific heat C and thermal conductivity coefficient λ are assumed to be homogeneous in the specimen. τ is a time constant characterizing the heat exchanges by convection with ambient air. The specimen is clamped in the jaws of the machine. Considering that specimen and jaws are both metallic, the following boundary conditions are assumed:

$$\theta\left(\pm\frac{L}{2}, t\right)=0 \tag{1.2}$$

where L is the clear distance between the two jaws and $z = 0$ the mid-point of the specimen.

The heat source $s(t)$ corresponds to the heat power density produced or absorbed by the material itself. Heat sources due to thermoelastic coupling are negative when the stress increases, and positive when the stress decreases. Heat sources due to irreversible phenomena are always positive. They are named *mechanical dissipation* or *intrinsic dissipation*. Let us consider a fatigue test at constant frequency, maximum force and force ratio. The heat due to thermoelastic coupling is null over a mechanical cycle. As a consequence, it is possible to write an averaged version of Eq. (1.1) in steady-state regime as follows [14]:

$$\rho C\frac{\theta}{\tau}-\lambda\,\frac{\partial^2\theta}{\partial z^2}=d_1 \tag{1.3}$$

where d_1 is the mean mechanical dissipation per cycle, assumed to be constant along the test. The solution to Eqs. (1.2) and (1.3) writes as follows [15]:

$$\theta\,(z, \text{steady})=\frac{d_1}{\lambda\,\beta^2}\left[1-\frac{\cosh\left(\beta\,z\right)}{\cosh\left(\beta\,\frac{L}{2}\right)}\right] \tag{1.4}$$

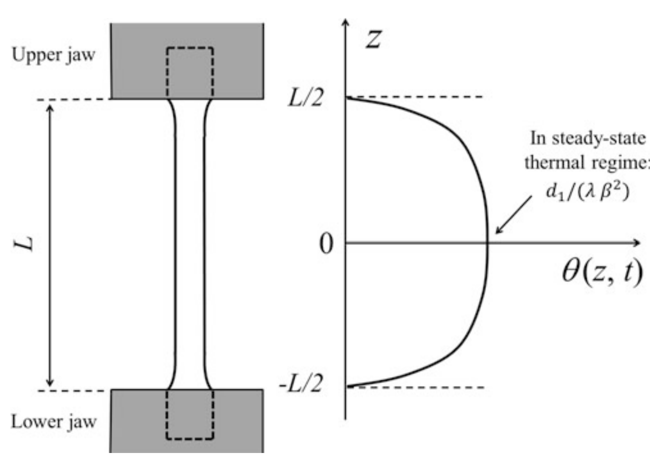

Fig. 1.1 Schematic view of a metallic specimen subjected to uniaxial fatigue loading

where

$$\beta = \sqrt{\frac{\rho\, C}{\lambda\, \tau}} \tag{1.5}$$

The temperature change to be considered for the 0D approach is defined by:

$$\Theta_{0D}\,(\text{steady}) = \frac{1}{L}\int_{-L/2}^{L/2} \theta\,(z, \text{steady})\ \mathrm{d}z \tag{1.6}$$

Then it gives from Eqs. (1.4) and (1.6):

$$\Theta_{0D}\,(\text{steady}) = \ \frac{d_1}{\lambda\,\beta^2}\left[1 - \frac{2}{\beta\, L}\ \tanh\left(\beta\ \frac{L}{2}\right)\right] \tag{1.7}$$

A numerical model was developed to find an empirical expression for the global time constant τ_{0D} characterizing the global heat exchanges with the outside of the specimen (by contact with the jaws and by convection with ambient air). An implicit Euler scheme of Eq. (1.1) was implemented to obtain synthetic values of $\theta(z, t)$ during a natural return to ambient temperature ($s = 0$) after homogeneous heating. Numerical results showed that the value of τ_{0D} can be written as follows for pure copper [14]:

$$\tau_{0D} \approx 61.7\ L^{1.65}\ \tau^{0.373} \tag{1.8}$$

with τ_{0D} and τ are expressed in [s], and L in [m]. The mechanical dissipation can be then estimated by using the 0D version of the heat equation in the steady-state regime:

$$(d_1)_{0D} = \rho C\,\frac{\Theta_{0D}\,(\text{steady})}{\tau_{0D}} \tag{1.9}$$

It gives from Eqs. (1.7), (1.8) and (1.9):

$$(d_1)_{0D} = \frac{1 - \frac{2}{\beta\, L}\ \tanh\left(\beta\ \frac{L}{2}\right)}{61.7\ \ L^{1.65}\ \tau^{-0.627}} \times d_1 \tag{1.10}$$

The relative error in per-cent generated by the 0D approach in the evaluation of mechanical dissipation can be then expressed as follows:

$$E\% = \left[\frac{1 - \frac{2}{\beta\, L}\ \tanh\left(\beta\ \frac{L}{2}\right)}{61.7\ \ L^{1.65}\ \tau^{-0.627}} - 1\right] \times 100 \tag{1.11}$$

1.3 Experimental Analysis

Fatigue test was performed on a specimen made of pure copper. Figure 1.2a, b present the specimen geometry. Two reference samples were also employed to track variations in the specimen's environment [14]. The references were clamped in the jaws of the machine. They were made of the same material as the tested specimen. The test was performed using a hydraulic ±15 kN MTS testing machine, see Fig. 1.1. To maximize the thermal emissivity of the specimen and the two references, surfaces were painted in a matte black color. Black curtains were also placed around the immediate environment to reduce reflections.

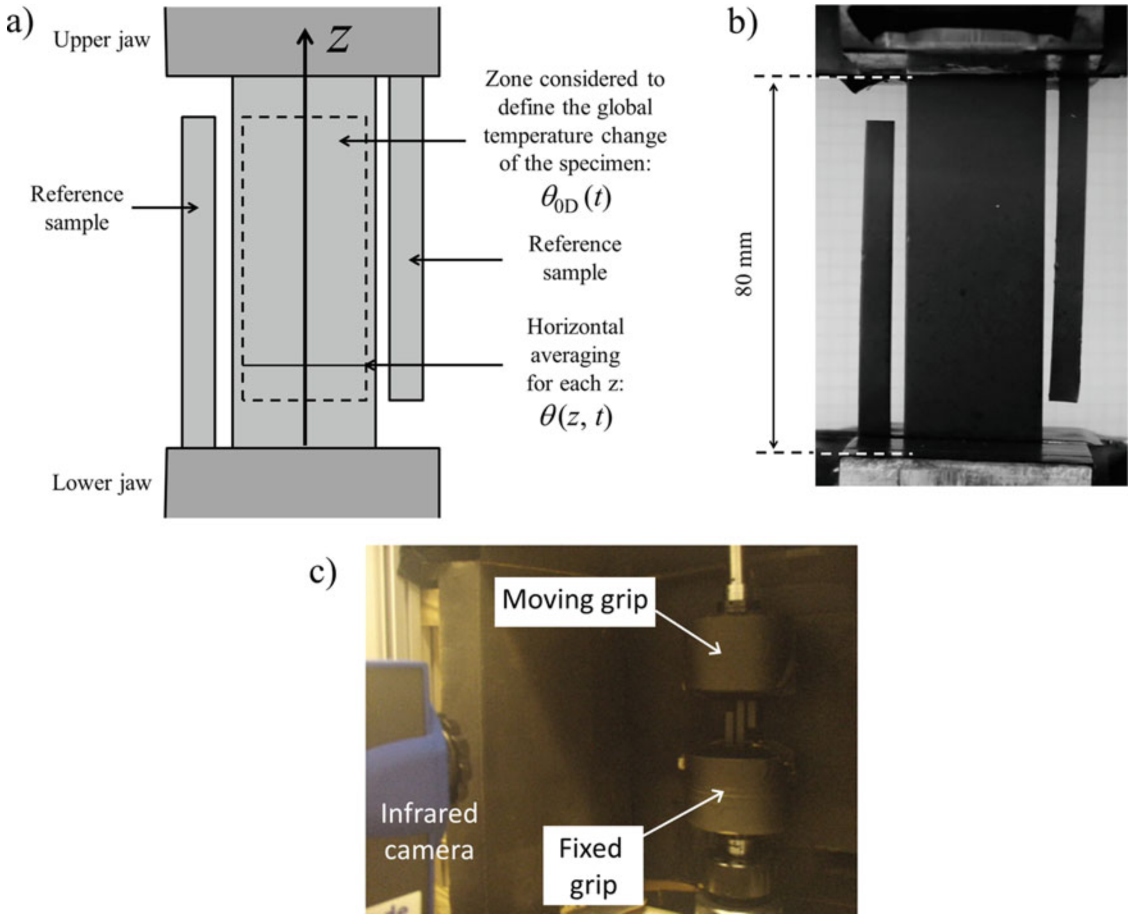

Fig. 1.2 Experimental set-up: (**a**) schematic view of the specimen with two reference samples, (**b**) specimen and reference samples painted in black to maximize the thermal emissivity, (**c**) photo of the experimental set-up

A Jade III-MWIR camera was employed to capture the temperature fields during the test. A force-controlled sinusoidal loading was applied to the specimen for 150 s. The temperature acquisition conditions were such that each recording image corresponded to an average over several mechanical cycles. As the heat due to thermoelastic coupling is null over a cycle, the heat sources that are calculated from Eq. (1.1) thus correspond to the mean mechanical dissipation. Prior to fatigue testing, the time constant τ characterizing the heat exchanges with ambient air was identified from a natural return to ambient temperature while the specimen is not clamped in the jaws of the machine (it was merely suspended in air).

The 0D version of the heat equation writes as follows

$$\rho C \left(\frac{\partial \Theta_{0D}}{\partial t} + \frac{\Theta_{0D}}{\tau_{0D}} \right) = s \tag{1.12}$$

The calculation of $(d_1)_{0D}$ thus requires the knowledge of the time constant τ_{0D} characterizing the global heat exchanges with the outside of the specimen (ambient air and jaws of the machine). In practice, τ_{0D} was estimated from a natural return to ambient temperature while the specimen is clamped in the jaws.

Figure 1.3 presents a temperature change profile in the thermal steady-state regime of a cyclic loading. The mean temperature change was obtained by spatial averaging over the specimen surface. This quantity enabled us to calculate the mechanical dissipation $(d_1)_{0D}$ from Eq. (1.9) with the experimental data. Equation (1.3) was used to determine the mechanical dissipation d_1 from the 1D approach. In practice, calculation was done at the mid-point of the specimen, i.e. at $z = 0$: see red curve in Fig. 1.3, employed to estimate the two terms in the left-hand side of Eq. (1.3). Numerical application led to a relative error $E\%$ of -8% in the estimation of the mechanical dissipation by the 0D approach compared to the 1D approach. The theoretical value from Eq. (1.11) is of -15%. This quantity actually strongly changes as a function of the

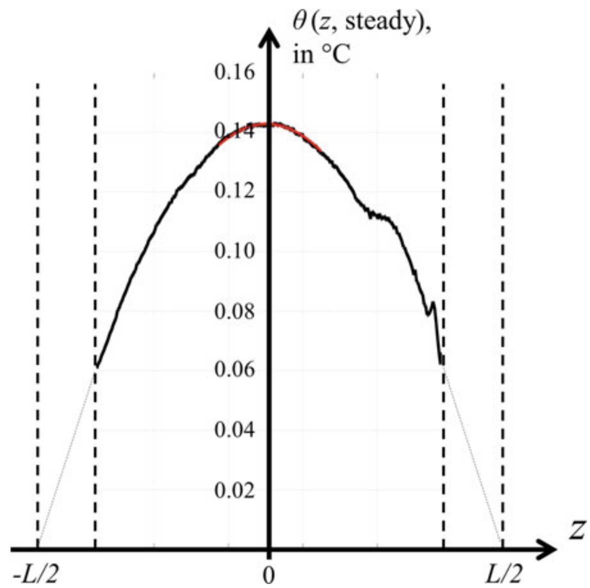

Fig. 1.3 Fatigue test of copper: temperature change profile in steady-state regime

specimen's length L and of the time constant τ characterizing the heat exchanges by convection with air [15]. Considering all the modeling hypotheses, it can be said that the experimental and simulated results are here in fair agreement. It must be noted that, although the relative error $E\%$ may seem small, it is important for quantitative fatigue analysis.

1.4 Conclusion

The present study aimed at analyzing the error generated by the 0D approach in the evaluation of mechanical dissipation due to fatigue damage. A copper specimen was subjected to cyclic loading while temperatures were measured by IR thermography. A model was also developed to provide a theoretical expression of the error generated by the 0D processing. The results showed that this error may not be negligible. It can be concluded that the 0D approach is a powerful and quite simple tool for thermomechanical analysis of materials, at least when heat sources are spatially homogeneous, but attention must be paid on its application for quantitative fatigue analysis.

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