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# ENERGY DISSIPATION IN COPPER DURING VHCF LOADING

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**ABSTRACT:** This communication is dedicated to the presentation of an experimental setup developed to estimate the energy dissipated during high cycle fatigue tests (VHCF). VHCF tests are performed at very low stress ranges, generally under the conventional fatigue strength. To reduce the duration of tests, the cycling loading is performed at a frequency of about 20 kHz. The experimental set-up uses ultrasonic techniques to generate such a dynamic loading and an infrared thermographic system to capture the temperature fields at the flat specimen surface. An infrared image processing is proposed to estimate the heat evolved using inevitably under-sampled thermo-signals and taking into account the different heat exchanges between the specimen and the surroundings. The calorimetric analysis being associated with microstructural investigations, pure copper specimens are used, focusing on the development of slip bands considered as the main source of energy dissipation. The very first calorimetric results are shown and discussed.

## 1. CONTEXT

This paper presents a first contribution to a wide research project that aims at a deeper understanding of mechanisms leading to crack initiation in metals and alloys in Very High Cycle Fatigue (VHCF), with special focus on the role of some material parameters, microstructure and surface state (ANR Disfat project). The VHCF regime is associated with stress magnitudes lower than the conventional fatigue limit and as a result, numbers of cycles higher than  $10^8$ - $10^9$ . It is thus closely related to the question of the existence of a fatigue limit. The detection of dissipation, the identification of its nature and intensity are naturally crucial signs of irreversibility and should become helpful indicators to quantify the fatigue progress.

## 2. EXPERIMENTAL SETUP AND IR IMAGE PROCESSING

### 2.1 Mechanical arrangement

Figure 1 shows the mechanical testing machine. It essentially involves 3 components: (i) A power generator which transforms 50 or 60 Hz voltage signal into ultrasonic 20 kHz electrical sinusoidal signals. (ii) A piezoelectric (or magnetostrictive) transducer excited by the power generator, which transforms the electrical signal into longitudinal ultrasonic waves and mechanical vibration of the same frequency. (iii) An ultrasonic horn (in titanium alloy, portion EDC in Fig. 1) which amplifies the vibration coming from the transducer in order to obtain the required displacement in the upper edge of the specimen. Depending on the specimen loading, the horn is designed so that the displacement is amplified between E and C usually 3 to 9 times. The testing machine is also calibrated with a laser extensometer in order to obtain the relation between the displacement on the horn edge and the input electrical signal. The geometry of the specimen must be pre-determined using the finite element method in order to have a longitudinal vibration mode at a frequency of around 20kHz [1-2].

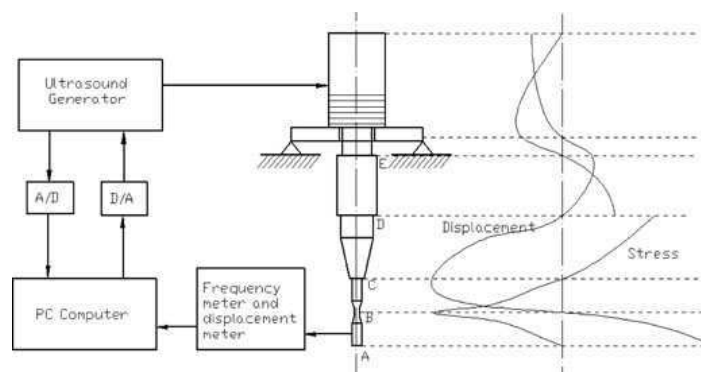


Figure 1- Scheme of the piezoelectric fatigue machine

It is worth noting that the copper specimen (part ABC) is screwed on the horn (C) and is free of stress at its bottom extremity (A). The stress in the middle section of the specimen is calculated with a finite element method, assuming an elastic behavior of the specimen.

However and despite the dynamic character of the loading, the horn-specimen alignment is designed to limit out-of-plane displacements. This point is of importance when thinking to the focal length of the IR camera. The asymmetry of mechanical boundary conditions also complicates the modeling of heat exchanges between the specimen and the surroundings.

## 2.2 Infrared device and calorimetric analysis

The infrared focal plane array camera is placed in front of the flat specimen surface (see Fig.2). The thermographic system involves a Cedip camera (Titanium MWIR) with 320x256 elements. The camera is programmable up to 380 Hz in full frame mode that is widely less than the 20 kHz of the signal frequency. Moreover the loading frequency is not absolutely constant throughout the test. The determination of the dissipation time course within a loading cycle is then impossible. The mean dissipation per block of cycles (about  $10^3$  cycles) is then chosen to determine the progress of VHCF mechanisms. Note that given the high loading frequency and the lowness of the stress range, the thermoelastic effects are here out of reach which is not the case for standard HCF loadings [3]. For the sake of simplicity, the overall dissipation within the gauge part of the sample is finally estimated. To compute such dissipation, the thermal image processing uses a local linear expression of the heat diffusion equation. Under several hypotheses detailed in [4], this local equation can be written in the following simplified form:

$$\rho C \left( \frac{\partial \theta}{\partial t} + \frac{\theta}{\tau_{\text{eq}}} \right) = d_1, \quad (1)$$

where  $\rho$  is the mass density,  $C$  the specific heat,  $\tau_{\text{eq}}$  a time constant characterizing the overall heat losses. The temperature variation  $\theta$  is derived from the under-sampled thermo-signal using a convolutive filtering. If the definition of the mean dissipation  $d_1$  depends on the cutoff frequency of the chosen filter, the gradual progress of the fatigue mechanisms gives mean dissipation estimates that changes only slightly.

## 3. FIRST RESULTS AND DISCUSSION

Figure 2a shows the temperature variations associated with a block of  $10^7$  cycles performed at  $19.75 \text{ KHz} \pm 0.15 \text{ KHz}$ . The test is displacement controlled for a displacement ratio  $R_u = u_{\text{min}}/u_{\text{max}} = -1$  and a displacement range of  $\Delta u = 9.3 \text{ } \mu\text{m}$ . The associated stress range is about 100 MPa. At the end of the test, the thermal return is recorded to estimate constant  $\tau_{\text{eq}}$ .

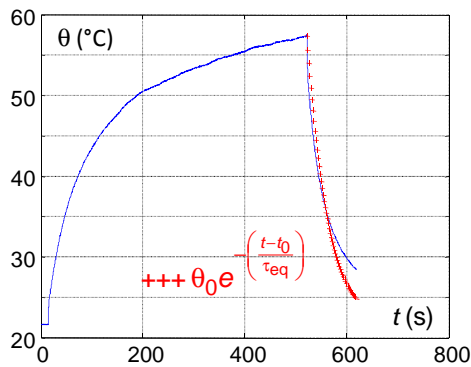


Figure 2a - Evolution of the temperature throughout the test.

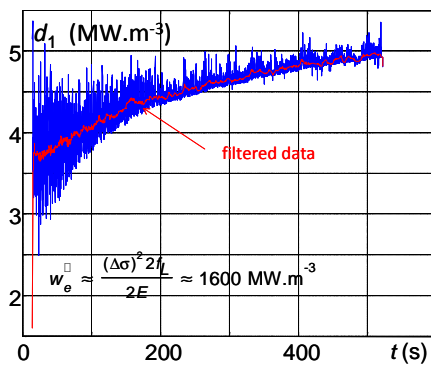


Fig2b. Dissipation: crude and filtered signals

The approximation of the thermal return by an exponential branch is fairly good despite the simplistic character of the heat exchange model. A more realistic thermal model is currently under construction and validation. It requires taking into account the temperature distribution within of the specimen.

Figure 2b shows the corresponding evolution of the averaged dissipation  $d_1$ . No stabilization of the temperature and of the dissipation can be observed. This indicates a continuous evolution of the fatigue state (i.e. no elastic or plastic shakedown). Finally an order of magnitude of the elastic deformation energy rate can be computed. It is about  $1600 \text{ MW.m}^{-3}$ . The dissipation is less than one percent of the deformation energy rate.

## 4. REFERENCES (\*)

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