THERMAL EMISSION FROM A FATIGUE CRACK

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Thermal emission is measured at several sites on the surface of a cracked Compact Tension specimen, subjected to sinusoidal loading. Spectral analysis is exploited to discriminate the non–linear component of the response, associated to the crack tip processes, from the dominant linear component, associated to the elastic strain field. Both components are consistently measured and quantitatively characterized. The non–linear source is localized in the crack tip zone. Non–linearities can be due to crack closure phenomena, to local microplasticity, and to the damage processes themselves.

INTRODUCTION

The deformation of materials generally causes temperature variations (thermal emission), which can be exploited to analyse the deformation processes. In this work the temperature is measured at the surface of a cracked metallic specimen subjected to low cycle fatigue.

In a metal undergoing elastic–plastic deformations, the temperature T obeys the Fourier equation (Landau and Lifshitz (1), Beghi et al (2))

$$\rho c\, \partial T/\partial t - k\nabla^2 T = W_{te} + W_d\,; \qquad (1)$$

W_{te} and W_d, which play the role of effective thermal sources, describe the thermoelastic and thermoplastic effects respectively. W_{te} is given by (Wallace (3))

$$W_{te} = -\rho c\,\gamma T\,\frac{\partial(\Delta V/V)}{\partial t} \simeq -\rho c\,\gamma T_0\,\frac{\partial(\Delta V/V)}{\partial t}, \qquad (2)$$

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where $\Delta V/V = \varepsilon^e_{xx} + \varepsilon^e_{yy} + \varepsilon^e_{zz}$ and T_0 is a mean temperature. W_d can be expressed as the fraction f of the specific plastic power W_p which is immediately dissipated into heat; the complement $W_p - W_d$ is stored as internal energy (stored energy of cold work).

LINEARITY AND STATIONARITY

Linear and non linear responses

The temperature field maps linearly the fields of the effective sources W_{te} and W_d, with the time (frequency) dependent distortion introduced by thermal conduction.

Except for large plastic strains, the temperature variations due to deformation are typically small; the approximate expression of W_{te} (Eq.2) is therefore accurate. W_{te} is thus proportional to the elastic strain rate, via a constant coefficient; in the absence of plastic strains ($W_d = 0$), the temperature field depends linearly on the elastic strain field, and therefore on the stress field. Thus, in the elastic regime, the relationship of the temperature to the applied load is generally linear; nevertheless, non–linearities can be introduced by boundary conditions. The two lips of a crack form a unilateral constraint, which transmits compressive stresses only: if crack closure phenomena occur, the relationship of the strain and temperature fields to the applied load can be non–linear. Similarly, a plastic zone imposes non–linear boundary conditions to the adjacent elastic part of the specimen.

The plastic strain instead, and the specific powers W_p and W_d, are non–linear functions of the local stress, and therefore of the applied load. More generally, non–linearities are introduced by inelastic behaviours, including damage processes.

Stationary and quasi–stationary responses

During cyclic loading, if a damage process like crack propagation is active, the state of the specimen is progressively modified, and the measurable signals are not stationary. However, if the damage process is slow enough, the signals are quasi–stationary, and the techniques for the analysis of stationary signals, like spectral analysis, remain applicable. In practice, the Fourier transform remains meaningful if, during the time interval required to perform a transform (typically a few tens of cycles), the modification of the spectrum of a signal remains of the order of the uncertainty in its determination. This condition turns out to be met for crack propagation rates up to at least 0.001 mm/cycle.

Sinusoidal loading

A cracked specimen under cyclic loading behaves elastically, except for a zone around crack tip, where non–linear phenomena are active. Measurements must detect and characterize the non–linear component of the signals. Sinusoidal excitation (load or displacement) is best suited: the excitation and the linear component of the response fall at the same frequency, while the non–linear component gives contributions at other frequencies. Non–linear phenomena can also give a contribution at the excitation frequency; however, this often causes only a minor modification of the linear response.

In the performed tests the spectral purity of the excitation is good, and the spectra of the responses (mechanical and thermal) differ from that of the excitation for the presence of a number of discrete peaks, at frequencies which are exact multiples of the excitation frequency (see Figure 2). This means that the signals can be expanded in a discrete Fourier series: they are therefore nearly perfectly stationary, and the non–linear component can be characterized by the weights of the harmonics of the excitation frequency.

EXPERIMENTS

Tests are performed at room temperature on an austenitic stainless steel (AISI 316) Compact Tension specimen (Figure 1). The specimen is thin, the notch region being further thinned, to obtain plane stress conditions, in which strain and temperature are uniform across the thickness. The specimen is wide; a crack advancement of a few millimetres still represents a small fraction of the ligament: the stress field around crack tip and the propagation rate are not strongly modified during propagation. Temperature is measured by fourteen thermistors, glued on either side of the specimen, around crack tip (Figure 1). The sensors are small ($\sim$ 0.3 mm); in the measurement of small ($\sim$ 1 K) variations around an initial temperature T_0, the resolution can exceed 0.001 K (Beghi et al (4,5)).

The specimen is fatigue pre-cracked; a sinusoidal excitation (load or crack–mouth opening displacement) is then imposed, at frequency of 0.1 or 0.2 Hz. The relatively low frequency is needed to minimize the effect of the finite response time of the sensors; the effects of heat conduction are then unavoidably present. 10000 full amplitude ($\sim 9000N$) cycles are performed, and several smaller amplitude cycles; the specimen is then broken. The crack advanced by 4.5 mm, the propagation rate being always within the limits for the applicability of Fourier transform techniques; the initial and final positions of the crack tip are indicated in Figure 1.

RESULTS

The measurements under load control are mainly discussed here. A typical segment of a test is shown in Figure 3. The power spectra of the load and of one of the temperatures are shown in Figure 2; the "background" in the temperature spectrum is due to temperature fluctuations of the ambient air.

The linear part of the thermal response is the dominant one; it is best characterized by the load to temperature transfer functions, evaluated at the excitation frequency. A spatial pattern of amplitudes and phases is present: ahead of crack tip the amplitude is maximum, while along the lips of the propagated crack the amplitude strongly decreases and the phase is progressively delayed. This pattern is determined by the stress distribution around the crack: when the crack advances, the pattern reproduces itself at the shifted position. Due to thermal conduction and the low loading frequency, the quantitative characters of the spatial pattern are however frequency–dependent, and a quantitative stress analysis is not possible. The evolution of the thermal responses, which are sensitive to the local strains, is much more pronounced than that of a global response like CMOD.

Phenomena like crack closure and microplasticity at crack tip introduce non–linearities, which cause an amplitude dependance of the transfer function, also for the linear component. Loading histories can be devised which exploit this dependence to determine the onset of these phenomena. The non-linear thermal response can be characterized in a consistent and reproducible way by the weights of higher harmonics in the power spectrum, for signal amplitudes down to at least three orders of magnitude below that of the linear response. The evolution of these harmonics can be monitored (Figure 4). The weights of the harmonics, normalized to the amplitude of the linear component, are significantly higher at the sites close to crack tip, indicating a mainly localized non–linear source. Work is in progress to correlate quantitatively this part of the response with the crack tip phenomena.

SYMBOLS

γ = Grüneisen parameter (adimensional)

$\Delta V/V$ = relative volume variation (elastic)

$\varepsilon^e_{xx} + \varepsilon^e_{yy} + \varepsilon^e_{zz}$ = trace of the elastic strain tensor

f = W_d/W_p

k = thermal conductivity ($W\,K^{-1}\,m^{-1}$)

ρc = heat capacity per unit volume ($J\,K^{-1}\,m^{-3}$)

T = temperature (K)

W_d = specific power ($W\,m^{-3}$) dissipated into heat

W_p = specific mechanical power ($W\,m^{-3}$) associated to plastic strain

W_{te} = thermoelastic "effective source" ($W\,m^{-3}$)

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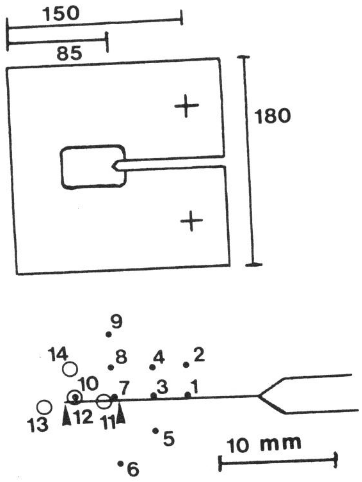
Figure 1. Specimen dimensions (mm); B=8mm; in the central zone B=5mm; thermistor positions around the crack; initial and final tip positions.



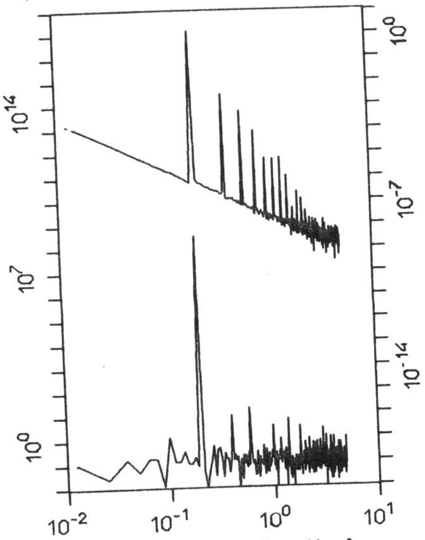


Figure 2. Power spectra of the load (N^2/Hz, lower curve, left scale) and of temperature 12 (K^2/Hz, upper curve, right scale)

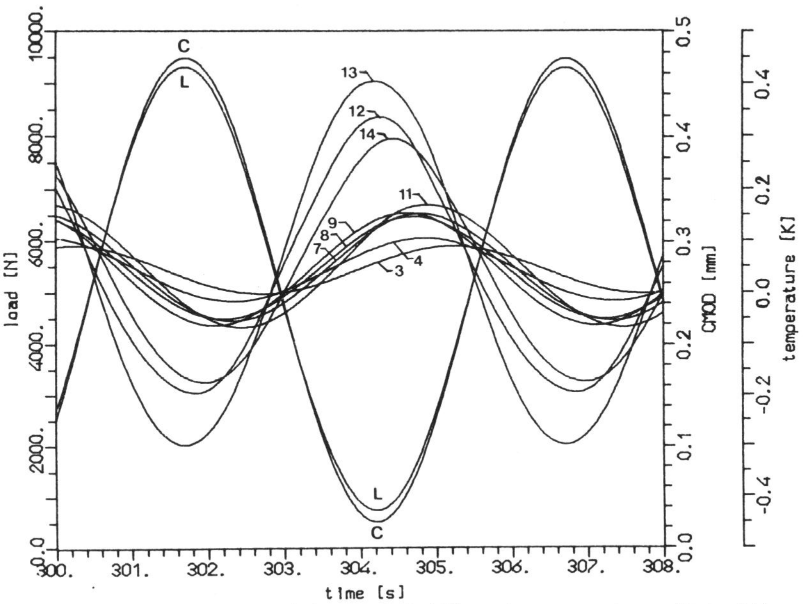


Figure 3. Measured load (L), CMOD (C) and temperatures (3 to 14).

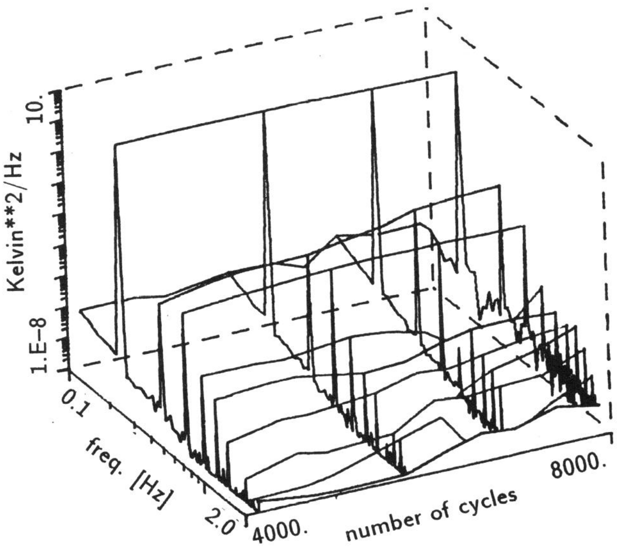


Figure 4. Evolution of the power spectrum of temperature 12.