On the correlation between the Second-Harmonic of temperature and crack-closure

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Abstract. The work illustrates a new experimental approach to evaluate crack closure in metallic samples undergoing fatigue crack growing tests. The closing loads behind the crack tip create cyclically varying local elastic compression stresses which generate a thermoelastic temperature change. These compression stresses arise only during part of the load cycle, and the corresponding thermoelastic signal does not follow a pure sinusoidal mono-frequency modulation. The periodic rise and interruption of the crack-closure-induced compression stresses has a peculiar signature in the amplitude and phase of the Second Harmonic, that is here described and exploited.

Introduction

Materials undergoing linear elastic straining exhibit the Thermoelastic Effect, according to which temperature changes linearly with the first stress invariant [1]. When a pure sinusoidal load is applied, the temperature-change follows a sinusoidal modulation around the initial mean body temperature. In cracked samples subject to cyclic loading, under LEFM conditions, the maximum and minimum loads of the sinusoid, and all intermediate values, generate a self-similar singular stress field, proportional to the Stress Intensity Factor (SIF) [2–4]. The temperature harmonic amplitude at the load frequency, ΔT, is then proportional to a maximum stress change, $\Delta(\sigma_x+\sigma_y)$, that is correlated to ΔK, i.e. the range of variation of the SIF between the maximum and minimum load [5]. This rationale has proposed Thermoelastic Stress Analysis (TSA) as a full-field experimental stress analysis technique able to perform quantitative evaluations of fracture parameters such as the SIF or J-Integral [3]. This ability is, though, impaired when crack-closure arises. In this case, the minimum load does not generate a conventional singular stress field, due to the rise of compression forces on the crack flanks. Whenever crack closure develops, a certain portion of the external remote loading cycle is accompanied with the rise of compression loading behind the crack tip. Therefore, ΔT is no longer fully accounted by a self-similar proportional change of the singular stress field, and all the procedures based on fitting the thermoelastic signal with analytical models of ΔK are no longer applicable.
In TSA, Second-Harmonic (SH) maps are obtained by extracting the temperature harmonic at the frequency 2ω, where ω is the applied load frequency. A few works have shown maps of the SH in presence of crack closure and have evidenced the formation of a peculiar signal pattern, where a high signal is detected immediately behind and ahead of the crack tip [6–8]. The high SH signal around the crack tip usually forms a peculiar shape resembling that of a turtle, where the turtle's neck provides an estimation of the crack tip location (see Fig. 1a). This has allowed to exploit the SH to locate the crack tip and evaluate fatigue crack growth rates [6]. None of the works commenting on this typical SH shape have provided a comprehensive explanation of such signal pattern, and the correlation with crack-closure.
The present work shows that the rise of an SH signal behind the crack tip is a direct consequence of the presence of periodic compression stresses during the load cycle. As this compression stresses are null for a part of the load cycle, while follow a sinusoidal trend for the remaining part of the load cycle, they generate a thermoelastic effect induced temperature modulation that presents a marked component at twice the loading frequency. A close look at the modulated temperature from points positioned over the zone of crack-closure allows to detect the instants of crack opening and closing, thus permitting not only a direct observation of the zone interested by crack-closure, but also a quantitative estimation of the opening and closing loads.

Experimental setup

The description of the correlation between the SH and crack closure is here supported by tests on a Single Edge Notched Tension (SENT) sample made of AISI 304L steel (yield strength 210 MPa). The sample is subject to a sinusoidal cyclic load ranging from 1 to 10 kN with ratio R=0.1, with a loading frequency of 15 Hz. The temperature variations are sampled by a cooled sensor IR camera, over a time interval of 30 sec, at 200 Hz. The harmonic content of the thermograms has been filtered via Least Square Fitting algorithms [9], extracting the temperature amplitude and phase at twice the loading frequency (second harmonics).

Results and discussion

Second Harmonic amplitude and phase maps are shown in Figure 1a and b. In both maps, a peculiar "signature" is found. The amplitude resembles the shape of a turtle, where the "head" is positioned in front of the crack tip, the "body" develops along the crack flanks, where crack-closure occurs, and the physical crack tip is located on the "neck" of the turtle. The phase resembles the shape of a butterfly, with the crack tip separating the two butterfly wings characterised by a 180° phase shift.

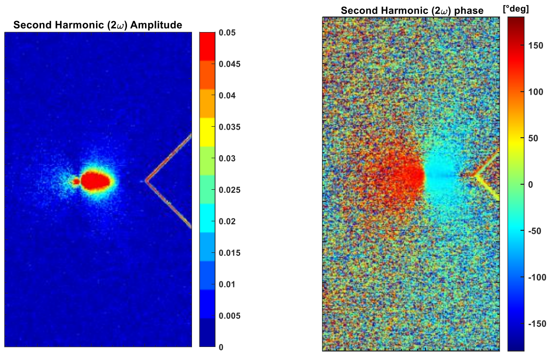

Fig. 1: Second harmonic a) Amplitude map, with the peculiar *turtle* shape due to the thermoelastic signal, and b) phase map, with the *butterfly* shape, due to the 180° phase shift between the crack tip.

An explanation of such a peculiar behaviour is provided in Fig. 2, where the signals experienced in the areas of the crack tip and on the flanks of the crack are simulated and analysed. In Fig. 2a the signals experienced in the crack tip area (blue) and wake of the crack (red) are reported, when a purely sinusoidal load at a 5 Hz frequency is applied. The blue signal has flat values as it approaches zero, due to a residual traction at the crack tip; while the signal on the flanks of the crack is equal to zero when the crack is completely open. In Figure 2b the Fourier transform of such signals is presented, it is shown that both have a complex harmonic content, with significant component at twice the loading frequency (10 Hz), that justify the presence of the turtle (Fig. 1a). In Figure 2c, the phasegram shows how a 180° phase shift is found between the second harmonics of the two signals, explaining the 180° phase shift encountered in the experimental data (Fig. 1b).

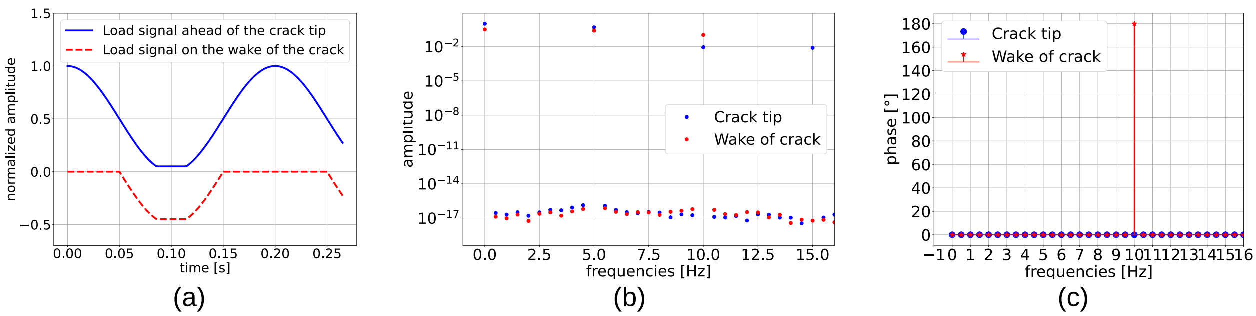

Fig. 2: a) numerically simulated load signals ahead of the crack tip (blue) and behind (red); b) spectrum of the loads and c) phasegrams.

Conclusions

The second Harmonic of the surface temperature, sampled over a time interval during fatigue loading, is a sensitive indicator of the presence of crack-closure. A direct visualisation of the area interested by crack-closure is obtained, based on the peculiar pattern of the second harmonic amplitude and phase maps near the crack tip. Also, the experimental evidence has been explained using synthetic data. The method provides an in-line monitoring of the presence and extension of crack-closure, that in terms of sensitivity and straightforwardness is unrivalled by other actual full-field experimental techniques.

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