Monitoring intrinsic heat dissipation in metals by measuring the second-harmonic phase of temperature

R. Cappello[1a], G. Meneghetti[2], M. Ricotta[2] and G. Pitarresi[1a]

[1] Dipartimento di Ingegneria, University of Palermo, Viale delle Scienze, 90128 Palermo, Italy
[2] Department of Industrial Engineering, University of Padova, via Venezia 1, 35131 Padova, Italy
[a] riccardo.cappello@unipa.it, giuseppe.pitarresi@unipa.it

Abstract. The work investigates the possibility to detect intrinsic heat dissipation since the earlier stages of fatigue loading, from monitoring features of the harmonic content of temperature. The temperature signal is acquired over a time interval, during fatigue cycling, and analysed in the frequency domain. Attention is in particular focused on the harmonic of temperature at twice the load frequency (Second Harmonic), that is evaluated at growing load amplitudes. The work exploits the prediction of the higher order Thermoelastic Effect theory according to which the phase of a thermoelastic Second Harmonic is shifted by 180° with respect to the phase of the Second Harmonic correlated to dissipative heat sources.

Introduction

Several works have attempted to predict information on the fatigue strength of metals from the surface temperature [1]. Infrared cameras are generally used, allowing relatively simple, full-field, non-contact, high resolution and high frame-rate measuring setups. A wealth of quantitative and qualitative approaches have been proposed, trying to correlate the measured temperature to the underlying heat sources and infer the intrinsic heat dissipation aliquot [1]. This is then correlated with the irreversible onset of damage eventually leading to fatigue failure, that is therefore predicted after a relatively short fatigue cycling time.
A typical evaluation scheme requires measuring temperature-related metrics at gradually increasing values of cyclic load amplitude (stepwise approach). Several metrics have been proposed [1-3]. It is observed that those based on the interpretation of the absolute temperature may suffer the intrinsic low accuracy of IR cameras and environmental effects. Metrics based on fast temperature variations have a potential to better exploit the high resolution of cooled IR sensors [2-4], while filtering environmental influences. Therefore, metrics such as the amplitude, *A*, and phase, *P*, of harmonics at the load frequency, ω, and at twice the load frequency, 2ω, have been considered [2]. A_ω and P_ω are correlated to the Thermoelastic Effect, and their ability to reveal intrinsic dissipation relies on the gradual departing from the linear trend of the thermoelastic signal at increasing stress amplitude [2,3]. $A_{2\omega}$ and $P_{2\omega}$ describe the so called Second-Harmonic. $A_{2\omega}$ is associated to irreversible temperature changes, introduced twice in a cycle, due to non-linear hysteresis loops and cyclic plastic deformation [2,3,5,6]. Regarding $P_{2\omega}$, only a few studies have considered this matric [4].
The present work exploits the prediction that the second harmonic wave may have two different relative positions with respect to the loading wave, according to two existing theoretical models: one purely thermoelastic and one considering the presence of dissipative heat.

Theoretical framework

Let's assume a tensile sample under fatigue loading, and the uniform stress field given by $\sigma=\sigma_m+\Delta\sigma\sin(\omega t)$. In this case, the higher order thermoelastic effect theory leads to [7,8]:

$$\Delta T = A_\omega \sin(\omega t + P_\omega) + A_{2\omega}\sin(2\omega t + P_{2\omega}) = -T_o\left(K_0 - K_1\sigma_m\right)\Delta\sigma\sin(\omega t) - T_o K_2\left(\Delta\sigma\right)^2\cos(2\omega t) \quad (1)$$

where: $$K_0 = \frac{\alpha}{\rho C_\varepsilon};\quad K_1 = \frac{1}{\rho C_\varepsilon}\frac{1}{E^2}\frac{\partial E}{\partial T};\quad K_2 = \frac{1}{\rho C_\varepsilon}\frac{1}{4E^2}\frac{\partial E}{\partial T} \quad (2)$$

Most common metals have $K_2>0$ and, from eq. (1), this implies that the second harmonic has its peaks occurring at $\sigma=\sigma_m$, i.e. when the load assumes its average value, $\sigma=\sigma_m$.
Some studies have also demonstrated that a second harmonic arises due to heat dissipation [3,5,6]. In this case, the second harmonic peaks are synchronised with the peaks and troughs of the loading wave, so that:

$$\left(\Delta T\right)_{2\omega} = -\left|A_{2\omega}\right|\cos(2\omega t) = \left|A_{2\omega}\right|\sin(2\omega t - 90°) \quad (3)$$

From the previous equations, it is then found that a 180° phase shift is expected between a pure thermoelastic response and the response under a prevailing dissipation scenario. Figure 1a summarises the relative phase relationships between the applied load, the first thermelastic harmonic and the Second Harmonic predictions. It is here foreseen that the trend of $P2\omega$ with growing load amplitude should reveal such a significant 180° shift, as the material evolves from a pure thermoelastic to a dissipating thermomechanical behaviour.

Experimental setup

The phase of the Second Harmonic has been measured from C45 steel tensile samples (yield strength 450 MPa), subject to a sinusoidal cyclic load with ratio R=-1. The signal is collected from a ROI centred within the sample gauge area (see Fig1b). The temperature is sampled by a cooled sensor IR camera, over a time

interval of 10 sec, at 204.8 Hz. A stepwise approach is followed with minimum and maximum stress amplitudes of 260 and 360 MPa.
The acquired thermograms have been post-processed offline, with both Discrete Fourier Transform and Least Square Fitting algorithms [8], providing consistent values of harmonics amplitude and phase at both ω and 2ω.

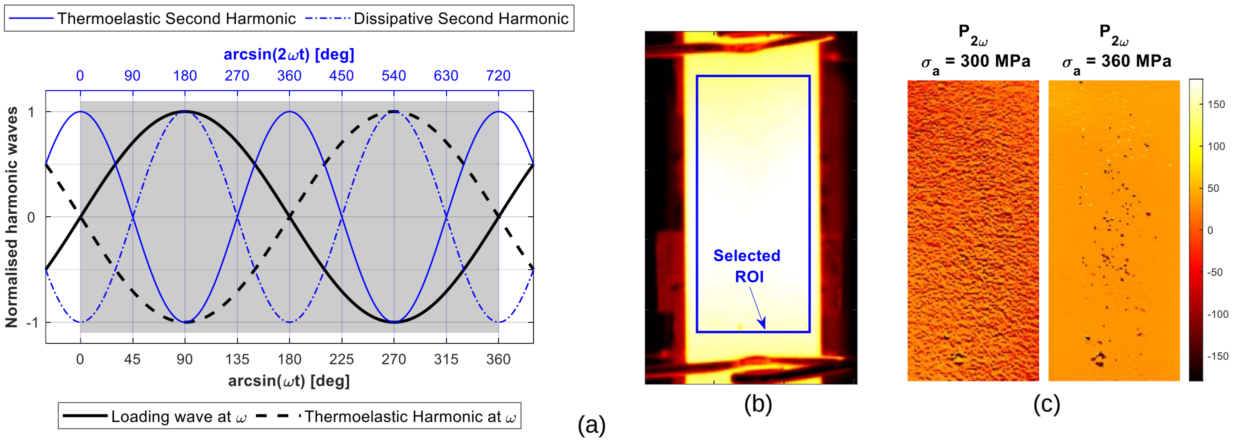

Fig. 1: a) phase comparison between the loading wave and predicted first and second harmonic waves (normalised amplitude); b) example of thermogram and ROI position between the extensometer anchors; c) maps of Second Harmonic phase at two values of applied stress amplitude σ_a.

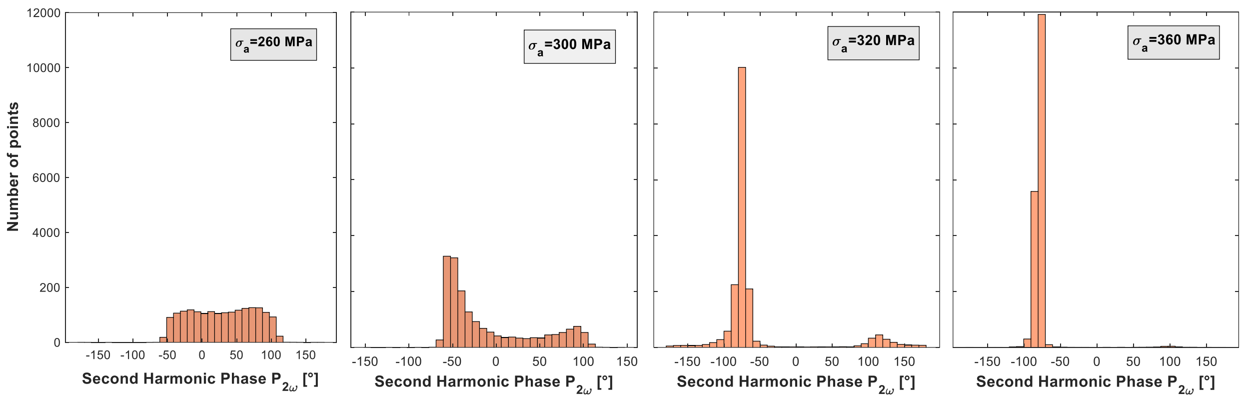

Fig. 2: Histograms reporting the distribution of the second harmonic phase over the pixels in the analysed ROI.

Results and conclusions

Figure 1c shows an example of two maps of $P_{2\omega}$ at two stress amplitude values. Figure 2 also reports histograms of the distribution of phase angle from all points falling inside the ROI. It is seen that the phase dispersion is uniformly distributed and no localised damage is detected yet. Also, the distribution is bimodal, with a tendency to become unimodal towards higher stress amplitudes. The phase shift between the two bimodal peaks is about 180°. Moreover, the unimodal peak at higher stress amplitudes tend to align with the positions of the peaks and troughs of the load wave, confirming the tendency to evolve from a thermoelastic to a dissipative behaviour.
The results are in good agreement with the theoretical assumptions, thus proposing the phase of the second harmonic of temperature as a potential good metric for detecting and monitoring the rise of heat dissipation in the material as the fatigue stress amplitude increases.

References

[1] M. Ricotta, G. Meneghetti, B. Atzori, G. Risitano, and A. Risitano, *Comparison of experimental thermal methods for the fatigue limit evaluation of a stainless steel*, Metals, 9(6) (2019).
[2] J. Krapez, D. Pacou, and G. Gardette, *Lock-in thermography and fatigue limit of metals*, Quant Infrared Thermogr, 5 (2000) 277-282.
[3] R. De Finis, D. Palumbo, and U. Galietti, *A multi-analysis thermography based approach for fatigue and damage investigations of ASTM A182 F6NM steel at two stress ratios*, Fatigue Fract. Eng. Mater. Struct. 42 (2019) 267–283.
[4] D. Shiozawa, T. Inagawa, T. Washio, and T. Sakagami, *Accuracy improvement in dissipated energy measurement by using phase information*, Meas. Sci. Technol. 28 (2017) 044004.
[5] N. F. Enke, *An enhanced theory for thermographic stress analysis of isotropic materials*, SPIE 1084 (1989) 84-102.
[6] G. Meneghetti and M. Ricotta, *Estimating the intrinsic dissipation using the second harmonic of the temperature signal in tension-compression fatigue: Part I. theory*, Fatigue Fract Eng Mater Struct. 44 (2021) 2168– 2185.
[7] A. Wong, J. Sparrow, and S. Dunn, *On the revised theory of the thermoelastic effect*, J. Phys. Chem. Solids, 49 (1988) 395–400.
[8] S. Di Leonardo, R. Cappello, G. Burriesci, G. Pitarresi, *Investigation of the Thermomechanical Response of Cyclically Loaded NiTi Alloys by Means of Temperature Frequency Domain Analyses*. Materials, 14(24) (2021) 7866.