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Sizing the geometrical parameters of semi-infinite delaminations using optically excited lock-in infrared thermography

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Abstract

The aim of this work is to characterize the geometrical parameters of a 2D delamination: length, depth and thickness. First, we calculate analytically and numerically the surface temperature oscillation of a sample, containing a semi-infinite delamination, as the material is homogeneously illuminated by a modulated light beam. Then, we perform an inverse parametric estimation of synthetic temperature amplitude and phase data to size the geometrical parameters of the delamination. Finally, we present lock-in infrared thermography experiments performed on AISI-304 stainless steel samples containing calibrated delaminations. We fit the numerical model to the experiments to retrieve the delamination parameters successfully.

1. Introduction

Delaminations are flat internal defects parallel to the sample surface. They reduce the material stiffness and the structure reliability. Optically excited infrared thermography (IRT) has been widely used to detect delaminations and to size their depths. However, less attention has been paid to the measurement of the delamination thickness (the width of the air layer). The aim of this work is to size the geometrical parameters of semi-infinite delaminations (length, depth and thickness) using lock-in IRT. After calculating the surface temperature oscillation, we have studied the sensitivity of both, amplitude and phase, to the three geometrical parameters. Then we have developed an inverse parametric estimation to retrieve the geometrical parameters of the delamination from the surface temperature field. Finally, we have performed lock-in IRT experiments on calibrated delaminations to verify the validity of the inverse procedure.

2. Theory

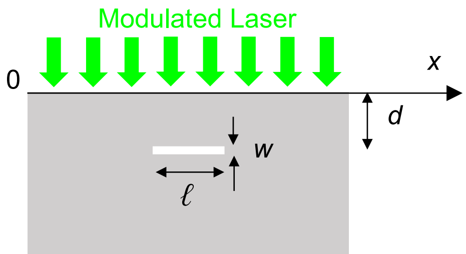

Fig. 1. Cross-section of an opaque sample containing a horizontal delamination, infinite in the perpendicular direction.

Let us consider an opaque and isotropic sample. It contains a delamination of length ℓ (in the x direction) and thickness w, buried at a depth d beneath the surface. This delamination is infinitely long in the perpendicular direction. The cross-section of the sample, whose front surface is illuminated uniformly by a (CW) laser modulated at a frequency f, is shown in Fig. 1.

We have solved the heat diffusion equation for this configuration, both analytically (using the thermal quadrupoles method) and numerically (FEM). We have verified that both methods give the same values of the surface temperature oscillation, τ. This complex quantity, which can be split into amplitude, $|\tau|$, and phase, Ψ, can be calculated for any value of the geometrical and thermal parameters and for any modulation frequency.

3. Sensitivity analysis

In order to be able to characterize the delamination, we need to verify that the geometrical parameters of the delamination are not correlated, i.e. a given temperature x-profile across the delamination is univocally ascribed to a single set (ℓ,d,w). We have settled this question by calculating the local sensitivity of the normalized values (with respect to a non-defective zone) of the amplitude, $|\tau_n|$, and phase, Ψ_n, to the three geometrical parameters of the delamination. Fig. 2 shows the calculations of the sensitivity of the x-profiles to the three parameters at f = 0.4 Hz, for an AISI-304 stainless steel sample containing the following buried delamination: ℓ = 10 mm, d = 1 mm and w = 10 μm. As can be observed, the sensitivity to ℓ is concentrated at the edges of the delamination, while the sensitivity to d and w is maximum at the centre of the delamination. Although the sensitivities of the phase to *d* and *w* are almost correlated, this correlation is broken in the amplitude. Accordingly, both amplitude and phase channels must be fitted simultaneously to retrieve the three geometrical parameters.

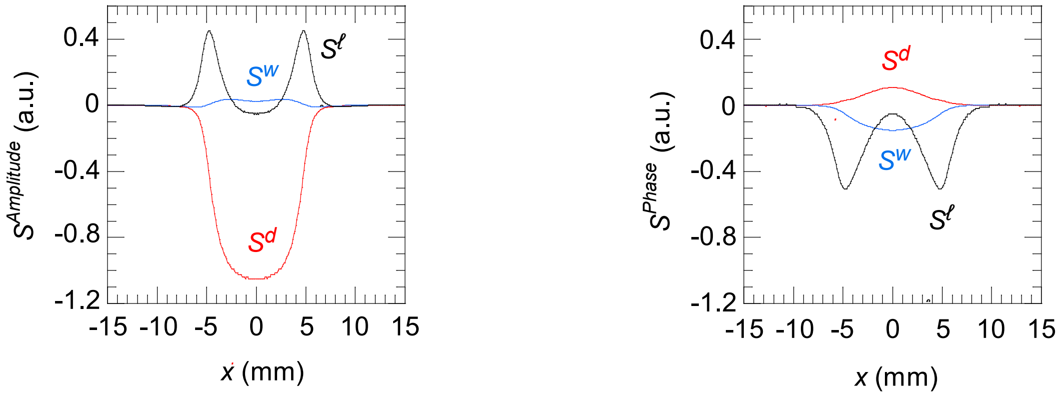

Fig. 2. *Calculation of the sensitivity of the x-profile of the amplitude and phase to the three geometrical parameters of the delamination. Calculations are performed for AISI-304, f = 0.4 Hz, ℓ = 10 mm, d = 1 mm and w = 10 μm.*

4. Experimental results

In order to obtain calibrated delaminations we have eroded parallelepiped blocks of AISI-304 stainless steel to generate U shaped through-thickness notches with *ℓ* = 10.0 mm and *d* = 1.01 mm. An independent parallelepiped block of the same material is tightly inserted in the notch. Two metallic tapes of thickness 20 μm are placed at the outer ends, between the two stainless steel pieces, which are pressed together to guarantee an air gap 20 μm thick. Fig. 3 shows the *x*-profiles of τ_n and Ψ_n at several frequencies. Dots are the experimental data and the continuous lines are the fits to the model, showing a very good agreement. Moreover, the retrieved values of the geometrical parameters of the air gap fit the real values very well: *ℓ* = 10.4 ± 0.2 mm, *d* = 1.02 ± 0.02 mm and *w* = 22 ± 3 μm. It is worth noting the ability of lock-in IRT to obtain the thickness of the buried air layer accurately.

Other delaminations with lengths in the range 2 - 10 mm, depths in the range 1 – 2 mm and thicknesses in the range 5 – 100 μm have been characterized successfully. Studies on 3D delaminations are now in progress.

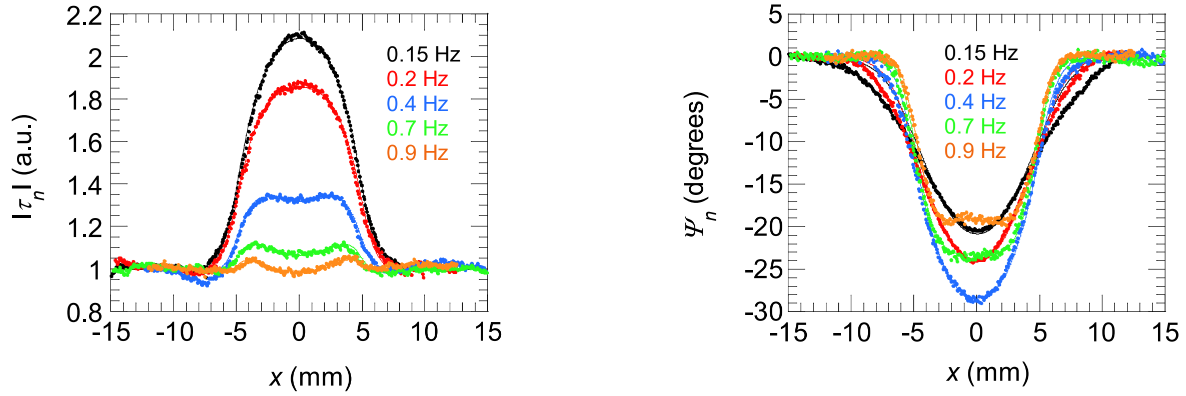

Fig. 3. *Experimental normalized temperature amplitude and phase x-profiles for an AISI-304 sample containing a delamination with the following geometrical parameters: ℓ = 10.0 mm, d = 1.01 mm and w = 20 μm. Dots are the experimental data and the continuous lines are the fits to the model. Results for five modulation frequencies are shown.*

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