QIRT'2022

10.21611/qirt.2022.3032
16th Quantitative InfraRed Thermography Conference

Numerical modeling of static and flying spot thermography for narrow crack characterization

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Abstract

In this work different numerical models have been developed to detect and characterize narrow cracks in high performance materials such as alloys or composites used in aeronatic or automotive industries. Two diferent methodologies have been theoretically addressed, static lock-in laser-spot thermography and the so-called flying spot thermography, which involves a relative movement between the sample and a continuous heating laser source. Both numerical models have been experimentally validated and used to feed specific inverse models able to accurately retrieve the main geometric features of cracks even in the sub-micron scale.

1. Introduction

The search of cracks in highly performing materials is a critical issue for extensively material demanding sectors like aeronautics or automotive. The presence of cracks, even if narrow, could lead to catastrophic material failures. As a consequence, different crack detection methods are usually implemented, which do not always guarantee the complete preservation of the pristine material. In this frame, infrared thermography has been revealed as a true non-destructive method, able not only to detect but also to characterize the geometrical features of cracks, even in the sub-micron scale [1].

Two are the thermographic methods revisited in this paper. First, static methods, which involve a fixed laser excitation source over the surface of the inspected material. In these regards, lock-in excitation offers an optimized noise/signal ratio with improved accuracy for, potentially, any planar crack morphology. Second, the so-called flying spot thermography [2], which involves a relative motion between a continuous laser heating source and the material, adding important advantages in order to explore large sample surfaces in a continuous examination process.

In this work, for both mentioned methods, first the direct heat diffusion problem is solved by means of numerical finite element methods (FEM). After succesfully validating the direct model by experimentation, the FEM model is fed to specific inverse models, retrieving the crack morphological parameters.

2. Numerical models

Both investigated thermographic methods, static lock-in laser-spot and flying spot, require solving the conventional heat diffusion equation:

$$\frac{\partial T(\vec{r},t)}{\partial t} = \alpha \nabla^2 T(\vec{r},t) \tag{1}$$

being α the thermal diffusivity of the material

The crack is introduced in the numerical domain as a two-dimensional interface thermal resistance, $R_{th} = \frac{w}{\kappa_{air}}$, where w is the crack width filled by air with κ_{air} thermal conductivity, leading to the boundary conditions:

$$\begin{cases} [\![\kappa \nabla T(\vec{r},t)]\!]\big|_{Crack} = 0 & \textit{(Heat flux continuity over the crack)} \\ \Delta T(\vec{r},t)\big|_{Crack} = R_{th}\kappa \nabla T(\vec{r},t)\big|_{Crack} & \textit{(Temperature difference over the crack)} \end{cases} \tag{2}$$

being κ the thermal conductivity of the investigated material and $[\![\,]\!]$ the 'jump' operator, accounting for the heat flux difference in both crack sides.

These equations, together with the additional boundary conditions introduced by each particular thermographic method, explained below, are solved in a continuous spatial FEM discretization.

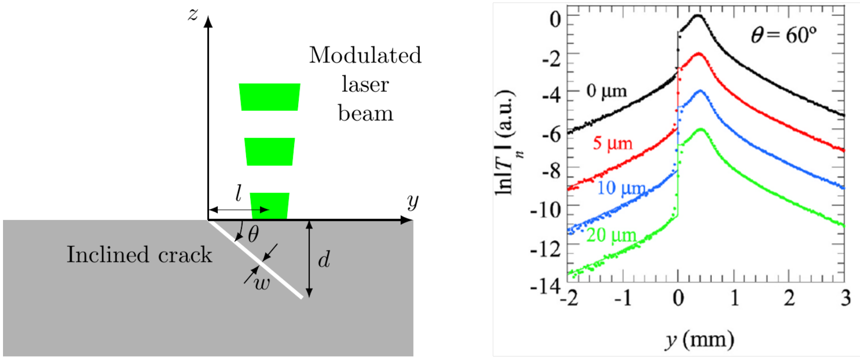
2.1 Lock-in laser-spot thermography

In this thermographic method, depicted in figure 1a, the Gaussian profile laser source is harmonically modulated. As a consequence, a quasi-stationary state is obtaied where thermal waves travel through the material changing their amplitude and phase. Consequently, to the Eq. 1 and Eq. 2, the heat source boundary needs to be added:

$$\kappa \nabla T(\vec{r},t) \cdot \hat{n} = \frac{2P}{\pi a^2} e^{\frac{-2\vec{r}^2}{a^2}} \cos(2\pi f t)\big|_{Illum} - \gamma (T(\vec{r},t) - T_{amb})\big|_S \tag{3}$$

where $\hat{n}$ is the normal direction to the illuminated sample surface, P is the laser source power, a is the Gaussian laser radius, f is the laser lock-in modulation frequency, $\left.\right|_{Illum}$ stands for the illuminated sample surface, γ is the heat losses coefficient, $\left.\right|_S$ corresponds to the complete sample surface.

The validated direct model has been used to feed an inverse model with the objective of retrieving the morphological features of the investigated cracks such as their widht, depth or orientation. The implemented inverse model is the so-called nl2sol model [3] which can be seen as a generalized Levenberg-Marquardt, non linear, constrained and gradient-based least squares optimization method. Figure 1b shows the accuracy of both, the direct and inverse models applied on a variety of laboratory calibrated infinite depth cracked samples with nominal width values ranging from 0 to 20 μm and an orientation angle of $\theta = 60°$



$w_{ret}\,(\mu m)$	$\theta_{ret}(°)$
3.1 $\pm$ 0.2	66 $\pm$ 5
9.5$\pm$ 0.4	66 $\pm$ 3
12.2$\pm$ 0.6	60 $\pm$ 3
18.6$\pm$ 0.8	62 $\pm$ 3

(a) **(b)**

Fig. 1. *(a) Schematic view of a lock-in thermographic experiment with a cracked sample. (b) Inverse model fittings vs. experimental results. AISI 304 sample ($\alpha = 4\,mm^2/s$, $\kappa = 15\,Wm^{-1}K^{-1}$), $f = 0.8$ Hz, $a = 0.2$ mm, full domain depth (infinite) and $l = 0.4$ mm*

2.2 Continuous heating flying spot

The second developed numerical model deals with continuous heating and a constant laser spot velocity movement respect to the sample. As a result, together with Eq. 1 and Eq. 2, the added boundary condition is:

$$\kappa\nabla T(\vec{r},t)\cdot\hat{n} = \frac{2P}{\pi a^2}e^{\frac{-2(\vec{r}-\vec{v}t)^2}{a^2}}\left.\right|_{Illum} - \gamma(T(\vec{r},t) - T_{amb})\left.\right|_S \quad (4)$$

where $\vec{v}$ is the velocity of the laser source with respect to the sample. In order to successfully calculate the resulting temperature field, a dynamic FEM spatial discretization refinement method has been used, providing the neccessary accuracy maintaining an appropriate computational economy, as seen in figure 2.

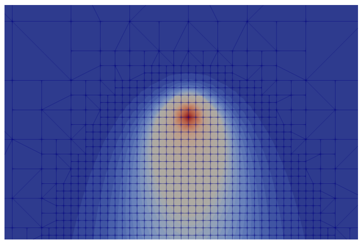


Fig. 2. *Calculated flying-spot surface temperature field*

Acknowledgments

This work has been supported by Ministerio de Ciencia e Innovación (Grant PID2019-104347RB-I00 funded by MCIN/AEI/10.13039/501100011033) and by Universidad del País Vasco UPV/EHU (GIU19/058).

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