10.21611/qirt.2016.112

Sizing the thermal resistance of vertical cracks using pulsed infrared thermography with laser spot excitation

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Abstract

We propose a method to measure the width of infinite vertical cracks using pulsed laser spot infrared thermography. We obtain the theoretical time evolution of the surface temperature of a sample containing such a crack when the surface is illuminated by a pulsed circular Gaussian laser spot. The surface temperature on a sample with calibrated cracks is measured using an infrared camera. By fitting the surface temperature to the model, the thickness of the crack is obtained. A good agreement between the nominal and retrieved thickness of the fissure is found confirming the validity of the model.

1. Introduction

The growing necessity of in-service non-destructive testing and evaluation of surface breaking cracks in a wide variety of devices has been a challenging task for modern industries and laboratories. Several well established methodologies like dye penetrants, magnetic particles, eddy currents, and x-rays have been proposed and used to detect fissures as well as defects in materials. In the last decades infrared thermography, both ultrasonically and optically excited, has been applied to detect this kind of flaws.

In a recent work, the authors sized the thermal resistance of infinite vertical cracks using lock-in infrared thermography, by illuminating the sample surface with a modulated and focused laser spot close to the crack [1]. This method is very accurate, because of the low noise that can be achieved in the temperature amplitude and phase images, but it is also very time consuming (tens of minutes). That is the reason why we propose working in the time domain, using pulsed laser spot thermography to size the width of vertical cracks in a fast manner.

2. Theory

Fig. 1 shows the diagram of a semi-infinite and opaque material containing an infinite vertical crack placed at plane $y = 0$. The sample surface is illuminated by an infinitely brief (Dirac-like) laser pulse of Gaussian profile and energy per pulse Q_o. The center of the laser spot is located at a distance d from the crack and its radius is a (at 1/e^2 of the intensity). Adiabatic boundary conditions at the sample surface have been assumed.

Under these conditions, the temperature at any point of the material has been already solved in the frequency domain (see Eq. (9) in Ref. [1]), i.e., when the sample surface is heated up by a modulated laser beam of power P_o and frequency f ($\omega = 2\pi f$). The inverse Laplace transform of this modulated solution gives the surface temperature evolution, which contains a very time consuming triple integral. However, the temperature profile along the y-axis reduces to a semi-analytical expression containing a single integral:

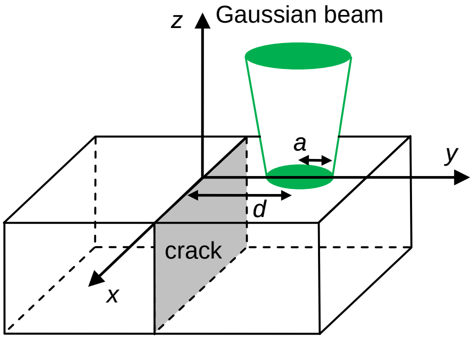

Fig. 1. *Scheme of a semi-infinite sample which contains an infinite vertical crack (in gray) and that is illuminated by a Gaussian beam.*

$$T(0,y,0,t) = \frac{2Q_o}{e\sqrt{\pi^3 t}} \frac{e^{-\frac{2(y-d)^2}{a^2+2\mu^2}}}{a^2+2\mu^2} + \mathrm{sign}(y) \frac{Q_o}{e\pi^2 a\sqrt{t}\,\mu\sqrt{a^2+2\mu^2}} \int_{-\infty}^{\infty} \mathrm{d}y_o \,\mathrm{sign}(y_o)\, e^{-\frac{2(y_o-d)^2}{a^2}-\frac{u^2}{\mu^2}} \cdot$$

$$\cdot \left[1 - \frac{\sqrt{\pi}\mu}{KR_{th}} e^{\left(\frac{\mu}{KR_{th}}+\frac{u}{\mu}\right)^2} \mathrm{erfc}\left(\frac{\mu}{KR_{th}}+\frac{u}{\mu}\right)\right], \qquad (1)$$

where $\mu = \sqrt{4Dt}$ is the so called thermal diffusion length, D is the thermal diffusivity, K is thermal conductivity, $e = K/\sqrt{D}$ is the thermal effusivity and $u = |y| + |y_o|$. $R_{th} = L_{crack}/K_{air}$ is the thermal contact resistance, related to the crack width (L_{crack}). According to Eq. (1), the thermal resistance is correlated to the thermal conductivity through the factor KR_{th}. This means that narrow cracks are better detected in high thermal conducting materials (metals, alloys, ceramics…) than in thermal insulators (polymers, composites…).

3. Experimental results and discussion

We have prepared calibrated vertical cracks using two blocks of AISI-304 stainless steel 2 cm thick. As this metallic alloy has a shiny surface, a thin graphite layer about 3 μm thick has been deposited onto the surface to increase both the absorption of the heating laser and the emissivity at infrared wavelengths. In order to calibrate the air gap thickness between the two AISI-304 blocks, we placed nickel tapes 25, 10, 5, 2.5 and 1 μm thick between them.

In Fig. 2a we show the thermogram corresponding to a 1 μm thick crack, obtained 70 ms after the heating pulse. As can be seen, even such a small air gap is clearly visible in the thermal image. Figure 2b shows the temperature profiles along the *y*-axis for the vertical cracks at t = 70 ms after the laser pulse. The temperature values are shifted in order to better show the temperature jump at the crack position. Dots represent the experimental data and the continuous lines the fit to Eq. (1). A non-linear least square fit based on the Levenberg-Marquardt algorithm was implemented with two free parameters (KR_{th} and Q_o/e). The other two experimental parameters (a and d) were determined independently. We fitted data collected at five times, from 70 to 110 ms, to obtain the standard deviation of the estimated values. The obtained crack widths are: 28 ± 4, 12 ± 3, 5.4 ± 0.3, 1.9 ± 0.1 and 0.74 ± 0.05 μm. Notice the good agreement between the estimated width values and the tapes thicknesses.

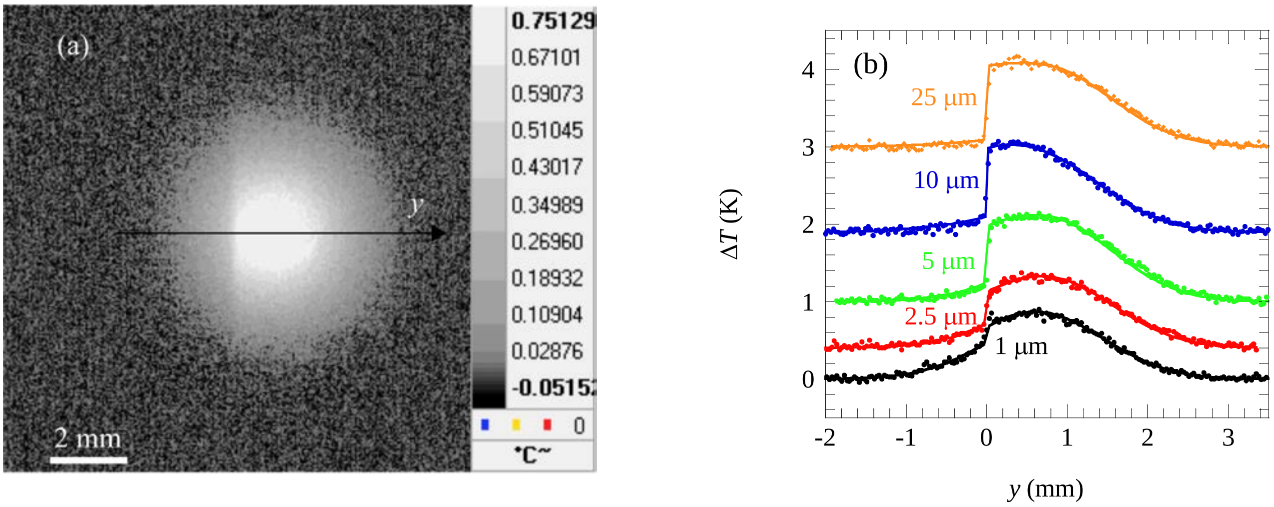

Fig. 2. *(a) Thermogram for two AISI-304 blocks put in contact to simulate an infinite vertical crack 1 μm thick at t = 70 ms. (b) Temperature profiles along the y-axis for several crack widths at t = 70 ms. Dots correspond to experimental data and continuous lines to the fit to Eq. (1).*

In order to assess the thinnest thermal resistance to be detected, we put the two AISI-304 blocks in direct contact, i.e. without nickel tapes between them. As the surfaces in contact are polished, they simulate an extremely thin crack. Although the result depends slightly on the position in which the sample is excited, probably due to the different edge surface conditions, we estimate a lower limit $L_{crack} \geq 0.4$ μm. Similarly, on polymeric plates (polyether-ether-ketone), we could establish $L_{crack} \geq 8$ μm, which is in agreement with the fact that the thermal conductivity of AISI-304 is around 30 times the thermal conductivity of this polymer.

This work has been supported by the Ministerio de Ciencia e Innovación (MAT2011-23811), by Gobierno Vasco (IT619-13), by UPV/EHU (UFI 11/55), by CINVESTAV Unidad Mérida and by CONACYT.

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