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Vertical cracks characterization using lock-in thermography: I infinite cracks

N W Pech-May¹,2, A Oleaga¹, A Mendioroz¹, A J Omella³, R Celorrio³ and A Salazar¹

¹ Departamento de Física Aplicada I, Escuela Técnica Superior de Ingeniería, Universidad del País Vasco
UPV/EHU, Alameda Urquijo s/n, 48013 Bilbao, Spain
² Department of Applied Physics, CINVESTAV Unidad Mérida, carretera Antigua a Progreso km6, A.P.
73 Corredor, Mérida Yucatán 97310, Mexico
³ Departamento de Matemática Aplicada, EINA/IUMA, Universidad de Zaragoza, Campus Río Ebro,
Edificio Torres Quevedo, 50018 Zaragoza, Spain

E-mail: agustin.salazar@ehu.es

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Abstract
Early detection of cracks is a challenging task to prevent failures in working structures. In the last decades the 'flying spot' method, based on heating the sample with a moving laser spot and detecting the surface temperature with an infrared detector, has been developed to detect cracks in a fast manner. The aim of this work is to measure the width of an infinite vertical crack using lock-in thermography. An analytical solution for the surface temperature of a sample containing such a crack when the surface is illuminated by a modulated laser beam focused at a fixed spot close to the crack is obtained. Measurements on samples containing calibrated cracks have been performed using an infrared camera. A least square fit of the amplitude and phase of the surface temperature is used to retrieve the thickness of the crack. A very good agreement between the nominal and retrieved thicknesses of fissure is found, even for widths down to 1 µm, confirming the validity of the model.

Keywords: infrared thermography, crack detection, quantification of crack width, thermal waves, analytical solution, nondestructive evaluation

(Some figures may appear in colour only in the online journal)
detecting the time evolution of the surface temperature with an infrared camera [10–16]. This technique has been implemented for different excitation regimes, mostly continuous wave [9–12] and pulsed illuminations [13–16] and less often, modulated [14] excitations. Using this method, cracks with openings as small as a few micrometers can be detected [13].

In the last years several approaches to characterize the geometrical parameters of the crack (depth, length, width, orientation…) have been published [17, 18]. They take advantage of the asymmetry of the temperature field at both sides of the crack arising from the thermal resistance produced by the crack, which partially blocks heat flux when the laser spot is focused close to the crack.

In Part I of this work, we deal with the characterization of infinite vertical cracks using lock-in thermography, which is able to provide surface temperature amplitude and phase images with a very low noise level. First, we have found an analytical expression for the surface temperature of a sample containing such a crack when the surface is illuminated by a modulated laser beam that is focused at a fixed spot close to the crack. In previous works, the surface temperature close to the edge of the sample [19, 20] or in samples containing open cracks [21–24] was calculated using the Green functions. In this work, we take advantage of the Hankel transform [25] to obtain simple analytical solutions for infinite vertical cracks. Two geometries of the laser spot are considered: a circular Gaussian spot and a line Gaussian one. The presence of the defect produces an abrupt jump in the amplitude and phase of the temperature profile at the crack position. The influence of the experimental parameters (laser beam radius, distance spot-crack, modulation frequency and width of the crack) on the jump height is analyzed. The goal is to measure the thermal contact resistance \( R_{th} \) of the crack, which quantifies the width of the crack.

In order to prepare calibrated infinite vertical cracks, very thin metallic tapes down to 1 \( \mu \)m thick are inserted between two identical blocks under pressure. A modulated laser beam that is focused at a fixed spot close to the crack. In previous works, the surface temperature close to the edge of the sample [19, 20] or in samples containing open cracks [21–24] was calculated using the Green functions. In this work, we take advantage of the Hankel transform [25] to obtain simple analytical solutions for infinite vertical cracks. Two geometries of the laser spot are considered: a circular Gaussian spot and a line Gaussian one. The presence of the defect produces an abrupt jump in the amplitude and phase of the temperature profile at the crack position. The influence of the experimental parameters (laser beam radius, distance spot-crack, modulation frequency and width of the crack) on the jump height is analyzed. The goal is to measure the thermal contact resistance \( R_{th} \) of the crack, which quantifies the width of the crack.

In Part II of this work, we deal with vertical cracks of finite size and arbitrary shape. In this case there is no analytical solution for the temperature field. We have developed a discontinuous finite element method which allows us to calculate the surface temperature distribution in the presence of cracks of any size, shape and thickness. Discontinuous finite elements is a natural tool to tackle physical problems with discontinuous solutions where classical finite element methods fail [26].

2. Theory

Let us consider a semi-infinite and opaque material with an infinite vertical crack placed at plane \( y = 0 \). The sample surface is illuminated by a laser beam modulated at a frequency \( f (\omega = 2\pi f) \). The centre of the laser spot is located at a distance \( d \) from the crack. The geometry of the problem is shown in Figure 1. We assume adiabatic boundary conditions at the sample surface, i.e. heat losses to the surrounding air are neglected. Two kinds of laser profiles are used: (a) a circular Gaussian profile of radius \( a \) (at 1/e² of the intensity) and (b) a line Gaussian profile of width \( a \). The aim of this section is to calculate how the crack modifies the surface temperature distribution.

2.1. Circular Gaussian illumination

Let us start by considering an infinite material containing an infinite crack at plane \( y = 0 \), together with a point-like heat source located at \( (0, d, 0) \) of modulated power \( P(t) = \frac{1}{2} P_0 [1 + \cos(\omega t)] \), see Figure 1(a). The expressions for the spherical thermal wave \( T \) generated at the heat source
and the thermal waves scattered at the crack travelling through $y > 0$ and $y < 0$, $\tau_+$ and $\tau_-$, respectively, are given by [27]

$$T(x, y, z) = \frac{P_o}{4\pi K} \left[ \frac{e^{-|qR|}}{R} \right] = \frac{P_o}{4\pi K} \int_{0}^{\infty} \delta I_o(\delta r) \frac{e^{-\beta \delta}}{\beta} d\delta$$

$$\tau_+(x, y, z) = P_o \int_{0}^{\infty} \delta I_o(\delta r) A e^{-\beta \delta} d\delta$$

$$\tau_-(x, y, z) = P_o \int_{0}^{\infty} \delta I_o(\delta r) B e^{-\beta \delta} d\delta,$$

where $q = \sqrt{i\omega D}$ is the thermal wave vector, $K$ and $D$ the thermal conductivity and diffusivity of the material, respectively, $I_o$ is the Bessel function of order zero, $\beta = \sqrt{\delta^2 + q^2}$, $\delta$ is the Hankel variable, $R = \sqrt{x^2 + (y - d)^2 + z^2}$ and $r = \sqrt{x^2 + z^2}$. Note that the last expression in equation (1) represents a spherical thermal wave in the Hankel space. The temperature of the material at $y > 0$ is given by $T_+ = T + \tau_+$, and the temperature of the material at $y < 0$ by $T_- = T + \tau_-$. Finally, the values of $A$ and $B$ are determined from the boundary conditions at the crack: heat flux continuity and temperature discontinuity due to the lack of thermal contact:

$$-K \frac{dT_+}{dy} \bigg|_{y=0} = -K \frac{dT_-}{dy} \bigg|_{y=0} (4)$$

$$\left( T_+ - T_- \right)_{y=0} = R_{th} K \frac{dT_+}{dy} \bigg|_{y=0} \tau_+, \tau_-$$

where $R_{th}$ is the thermal contact resistance of the crack, which is related to the air gap width $L$ through the equation $R_{th} = L/K_{air}$ [28]. By solving equations (4) and (5), we obtain

$$A = -B = \frac{R_{th}}{4\pi} \frac{e^{-\beta d}}{2 + R_{th} K \beta} d.$$  

Accordingly, the temperature inside the material at both sides of the crack is given by

$$T_z(x, y, z) = \frac{P_o}{4\pi K} \frac{e^{-|qR|}}{R} \pm P_o \int_{0}^{\infty} \delta I_o(\delta r) A e^{-\beta \delta} d\delta.$$  

As a further step, we consider now a semi-infinite sample whose free surface is located at plane $z = 0$. If we consider adiabatic boundary conditions at the sample surface ($z = 0$), the effect of this surface is accounted for by introducing a reflected image of the laser spot with respect to the surface (image method). As in our problem the laser spot is located at the sample surface, applying the image method means having a laser spot of double power. Accordingly, the temperature in the material is twice the value given by equation (7) for the infinite material

$$T_z(x, y, z) = \frac{P_o}{4\pi K} \frac{e^{-|qR|}}{2\pi R} \pm 2 P_o \int_{0}^{\infty} \delta I_o(\delta r) A e^{-\beta \delta} d\delta.$$  

Finally, if we consider not an ideal point-like heat source but a real circular Gaussian spot of total maximum power $P_o$ and radius $a$ (at $1/e^2$ of the intensity), the temperature inside the material is obtained by adding the contribution of each point of the Gaussian spot weighted by its intensity

$$T_z(x, y, z) = \frac{P_o}{\pi K} \int_{0}^{\infty} \int_{0}^{\infty} \int_{0}^{\infty} \delta I_o(\delta r) A e^{-\beta \delta} d\delta$$

$$\times \left[ e^{-qR_{th}} R_{th} \pm K R_{th} y \right] \int_{0}^{\infty} \int_{0}^{\infty} \delta I_o(\delta r) A e^{-\beta \delta} d\delta$$

where $R_{th} = \sqrt{(x - a)^2 + (y - d)^2 + z^2}$ and $r_o = \sqrt{(x - a)^2 + z^2}$.

(9)

Finally, if we consider not an ideal point-like heat source but a real circular Gaussian spot of total maximum power $P_o$ and radius $a$ (at $1/e^2$ of the intensity), the temperature inside the material is obtained by adding the contribution of each point of the Gaussian spot weighted by its intensity

$$T_z(x, y, z) = \frac{P_o}{\pi K} \int_{0}^{\infty} \int_{0}^{\infty} \int_{0}^{\infty} \delta I_o(\delta r) A e^{-\beta \delta} d\delta$$

$$\times \left[ e^{-qR_{th}} R_{th} \pm K R_{th} y \right] \int_{0}^{\infty} \int_{0}^{\infty} \delta I_o(\delta r) A e^{-\beta \delta} d\delta$$

where $R_{th} = \sqrt{(x - a)^2 + (y - d)^2 + z^2}$ and $r_o = \sqrt{(x - a)^2 + z^2}$.

(9)

Here $R_{th} = \sqrt{(x - a)^2 + (y - d)^2}$, $I_o$ is the modified Bessel function of order zero, erf is the error function and erfc is the complementary error function [29].

2.2. Line Gaussian illumination

The geometry we are dealing with is shown in figure 1(b). As in the previous subsection, let us start considering an infinite material containing an infinite crack at plane $y = 0$. It is heated by an infinitely thin modulated line heat source located at $x = d$, of modulated power per unit length $P'(t) = \frac{P_o}{\pi}[1 + \cos(\omega t)]$. The expressions for the cylindrical thermal wave $T$ generated at the heat source, and the thermal waves scattered at the crack travelling through $y > 0$ and $y < 0$, $\tau_+$ and $\tau_-$, respectively, are

$$T(y, z) = \frac{P_o}{4\pi K} K_o(qR_2) \int_{0}^{\infty} \cos(\delta z) e^{-qR_{th} \delta} d\delta,$$

$$\tau_+(y, z) = P_o \int_{0}^{\infty} \cos(\delta z) A e^{-\beta \delta} d\delta,$$

$$\tau_-(y, z) = P_o \int_{0}^{\infty} \cos(\delta z) B e^{-\beta \delta} d\delta,$$

where $R_2 = \sqrt{(y - d)^2 + z^2}$ and $K_o$ is the modified Bessel function of the second kind order zero. The last expression in equation (11) represents a cylindrical thermal wave in the Fourier space. The temperature of the material at $y > 0$ is given by $T_+ = T + \tau_+$, and the temperature of the material at $y < 0$ by $T_- = T + \tau_-$. Using the boundary conditions at the crack given by equations (4) and (5), we obtain the same values of $A$ and $B$ given in equation (6).
Accordingly, the temperature inside the material at both sides of the crack is given by

\[ T_\pm (y, z) = \frac{P_o}{4\pi K} K_o (qR_c) \pm P_o \int_0^\infty \cos (\delta z) \, A e^{i\theta} d\delta \]  

(14)

For a semi-infinite material whose free surface is located at plane \( z = 0 \), the temperature is twice the value given by equation (14) for the infinite material

\[ T_\pm (y, z) = \frac{P_o}{2\pi K} K_o (qR_c) \pm 2P_o \int_0^\infty \cos (\delta z) \, A e^{i\theta} d\delta . \]  

(15)

Finally, if we do not consider an ideally thin line hot source but a real line Gaussian spot of total power per unit length \( P_o \) and radius \( a \) (at 1/e^2 of the intensity), the temperature inside the material is obtained by adding the contribution of each line of the Gaussian spot weighted by its intensity

\[ T_\pm (y, z) = \frac{2}{\pi} \frac{P_o}{Ka} \int_{-\infty}^\infty dy e^{\frac{-2(y-y_0)^2}{a^2}} \frac{1}{2\pi} \frac{R_{th}}{2 + 2KR_d\beta} \]  

(16)

where \( R_1 = \sqrt{(y-y_0)^2 + z^2} \). If we confine the temperature calculations to the surface of the sample \( (z = 0) \), the order of the integrals is reduced

\[ T_\pm (y, 0) = \frac{P_o}{\sqrt{2\pi} Ka} \int_{-\infty}^\infty dy e^{\frac{-2(y-y_0)^2}{a^2}} K_o (qR_c) \pm \frac{P_o}{4\pi K} R_{th} \int_0^\infty \frac{e^{\frac{2(y-y_0)^2}{a^2}}}{2 + 2KR_d\beta} \]  

(17)

where \( R_1 = \sqrt{(y-y_0)^2} \).

3. Numerical simulations

In this section, we analyze how the presence of a vertical crack modifies the surface temperature of a semi-infinite sample. The influence of parameters \( d, a \) and \( f \) in the visibility of the crack is studied. All of the simulations are performed for AISI-304 stainless steel \((D = 4.0 \text{ mm}^2 \text{s}^{-1} \text{ and } K = 15 \text{ Wm}^{-1} \text{K}^{-1})\). Figure 2 shows the calculation of the natural logarithm of the temperature amplitude \( \ln |T| \) and phase \( \Psi \) along the y-axis for a semi-infinite AISI-304 sample containing an infinite vertical crack \( (y = 0) \) and illuminated by a circular Gaussian spot. Calculations are performed using equation (10) with \( d = 1 \text{ mm}, a = 0.75 \text{ mm} \) and \( f = 1 \text{ Hz} \). Four thermal resistances ranging from \( 10^{-2} \text{ m}^2\text{KW}^{-1} \) to \( 10^{-2} \text{ m}^2\text{KW}^{-1} \) are analyzed. As can be observed, there is an abrupt discontinuity at the crack position in both \( \ln |T| \) and \( \Psi \). Note that the same scale level is used in \( \ln |T| \) and \( \Psi \) in order to clearly show that the jump at the crack is much higher for the former. Regarding \( \ln |T| \), the height of the leap increases with \( R_{th} \). However, the behaviour of \( \Psi \) is more complicated. Whenever the laser spot is very close to the crack and especially when it overlaps the crack \( (a > d) \), the phase jump is reversed, i.e. the jump is upwards. Besides, the higher the value of \( R_{th} \), the more pronounced the reversal.

Figure 3 shows the same type of simulations as in figure 2, but for a line Gaussian laser. Calculations are performed using equation (17) with the same parameters as in the previous figure. As can be seen, the general trend is similar for both kinds of illumination. The only remarkable difference between both illuminations is that \( \ln |T| \) is steeper for circular illumination than for line illumination. This result is related to the fact that for the former, a spherical thermal wave is generated while for the latter the thermal wave is cylindrical. Nevertheless, as the crack jumps are almost the same for both kinds of spots, in the remainder of the section only simulations with circular Gaussian illumination are shown.

In order to quantify the strength of the temperature jump at the crack position, we introduce two parameters: (a) the temperature amplitude contrast at the crack \( \Delta T \), which is defined as

\[ \Delta T = \frac{|T_+ (0, 0, 0)| - |T_- (0, 0, 0)|}{|T_+ (0, 0, 0)|} . \]  

(18)

and (b) the phase contrast \( \Delta \Psi \), defined as

\[ \Delta \Psi = \Psi_+ (0, 0, 0) - \Psi_- (0, 0, 0) . \]  

(19)
Equations (10) and (17) show that both $T$ and $A$ depend on 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…). Moreover, $T$ and $A$ do not depend on the laser power $P_{o}$.

First, we analyze the dependence of $T$ and $A$ on the thermal contact resistance $R_{th}$. The results are shown in figure 4 for $d = \mu$ and $a = \mu/2$, where $d = \mu$ is the thermal diffusion length. Three modulation frequencies are tested: 0.01, 1 and 100 Hz. Continuous lines correspond to $T$ and dashed lines to $A$. As can be seen, both $T$ and $A$ exhibit a sigmoid shape. For low $R_{th}$ (very narrow cracks), there is no temperature contrast and the crack remains undetected. For large $R_{th}$ (thick cracks), the temperature contrast saturates, indicating that these cracks are easy to detect, but $R_{th}$ is difficult to quantify. The highest sensitivity to the thermal resistance appears for intermediate $R_{th}$ values. Note that as the modulation frequency is increased by two orders of magnitude, the sensitivity to $R_{th}$ is displaced to lower values by one order of magnitude. This result means that the high frequencies are better suited to detect and characterize extremely narrow cracks.

Anyway, the results shown in figure 4 have no general validity. In figure 5, we show the same kind of calculations as in figure 4 for $f = 1$ Hz and three combinations of $d$ and $a$: (1) $d = \mu$ and $a = \mu/2$, (2) $d = \mu$ and $a = \mu$, and (3) $d = \mu/2$ and $a = \mu/4$. As can be seen, the amplitude contrast $A$ is always a sigmoid function, but as $a$ approaches $d$ the shape of the phase contrast $A$ is no longer a sigmoid. In fact, the phase contrast can be even negative, as it has been shown in figure 2(b). It is worth noting that for a fixed frequency the region of the highest sensitivity of $T$ to $R_{th}$ (the region with the steepest slope) is independent of the couple $(d, a)$. In fact, it only depends on $f$.

The dependence of $T$ and $A$ on the laser spot radius is analyzed in figure 6. Calculations are performed with $d = \mu$. Three thermal resistances are studied: $10^{-5}$, $10^{-4}$ and $10^{-3}$ m²K/W. As can be observed, the highest amplitude contrast corresponds to $a \approx 1.2\mu$, i.e. when the laser spot
slightly overlaps the crack. This result is independent of $R_{th}$. On the other hand, the highest phase contrast appears for a tightly focused laser beam. Note the negative phase contrast for some combinations of $R_{th}$ and $a$. A negative contrast means that the phase increases at the other side of the crack with respect to the heating spot. This result has already been shown in figure 2(b) for $R_{th} = 10^{-5}$ m$^2$K W$^{-1}$.

Finally, in figure 7 the dependence of $\Delta \phi_1$ and $\Delta \phi$ on the distance of the laser spot to the crack is analyzed. Calculations are performed for a fixed laser beam radius $a = 0.75 \mu$. The same three thermal resistances as in the previous figure are studied. As expected from figure 6, the highest amplitude contrast is produced when the laser spot overlaps the crack $d \approx 0.5 \mu \approx 0.7 a$. Note that this result is independent of $R_{th}$. It is worth mentioning that as the laser spot moves away from the crack the contrast in amplitude decreases, but surprisingly the phase contrast increases until it reaches an asymptotic value.

According to the simulations shown in this section, we arrive at the following conclusions:

(a) For a given thermal resistance the largest amplitude and phase contrast are not obtained with the same set of experimental parameters ($d, a$). The highest amplitude contrast appears when the spot slightly overlaps the crack $a \approx 1.25 d$. On the other hand, tightly focused spots ($a < d$) produce the highest phase contrast. We propose $d \approx a \approx 1.25 d$ as a rule of thumb to obtain good enough amplitude and phase contrast simultaneously.

(b) In order to detect very narrow cracks the appropriate experimental conditions are a high frequency with $d \approx a \approx \mu$. These conditions mean a tightly focused laser spot. For instance, using $a = d = 0.1$ mm on metallic samples together with a frequency $f \approx 100–1000$ Hz allows detection of thermal resistances as low as $10^{-6}–10^{-7}$ m$^2$K W$^{-1}$. It is worth noting that under these experimental conditions thicker cracks are also clearly detected.

(c) In order to retrieve $R_{th}$, frequencies producing the highest temperature amplitude/phase contrast must be avoided, since they are insensitive to $R_{th}$. Instead, lower frequencies showing an amplitude contrast half of the maximum one are the most sensitive to $R_{th}$ variations.

4. Experimental results

The scheme of the experimental setup is shown in figure 8. A continuous wave laser (512 nm), whose intensity is modulated by an acousto-optic modulator, is directed to the sample surface by means of a mirror and a silicon window, which is transparent to IR wavelengths. By means of a 10 cm focal length lens, the laser beam is focused onto the sample surface. The laser power is changed at each frequency (50–200 mW) in order to obtain a similar temperature rise at the centre of the laser spot of about 5 K. An IR video camera (FLIR, model...
NETD, than for a 1 mm thick crack obtained with the following experimental parameters: $f = 0.6 \text{ Hz}$, $d \approx 0.65 \text{ mm}$ and $a = 0.35 \text{ mm}$. It is remarkable that such a thin crack is clearly detected using lock-in thermography. In figures 10(a) and (b), we show the amplitude and phase thermograms corresponding to a 1 mm thick crack obtained with the following experimental parameters: $f = 0.6 \text{ Hz}$, $d \approx 0.65 \text{ mm}$ and $a = 0.35 \text{ mm}$. It is remarkable that such a thin crack is clearly detected using lock-in thermography. In figures 10(c) and (d), we show by dots the temperature profiles along the y-axis for the five cracks we are studying. The continuous lines are the least squares fits to equation (10) using four free parameters: $P_{oo}$, $a$, $d$, and $R_{th}$, where $P_{oo}$ and $a$ are coefficients used to fit the temperature profiles, and $d$ and $R_{th}$ are the thickness and thermal resistance of the nickel tape, respectively. The main advantage of using the nickel tape is that this material is at the same time highly absorbing at visible wavelengths and highly emissive at infrared wavelengths. This means that its surface does not need to be prepared (painted or coated) in order to obtain a high enough signal to noise ratio, as it happens with metals and alloys.

In order to obtain calibrated vertical cracks we have used two glassy carbon plates ($D = 6.0 \text{ mm}^2 \text{s}^{-1}$ and $K = 6.3 \text{ Wm}^{-1} \text{K}^{-1}$) 6 mm thick, which are put together under some pressure. The two large surfaces in contact are mirror-like polished. In order to calibrate the air gap between the plates, nickel tapes 25, 10, 5, 2.5 and 1 mm thick are placed between the carbon layers (see figure 9). They represent thermal resistances of $10^{-3}$, $4 \times 10^{-4}$, $2 \times 10^{-4}$, $10^{-4}$ and $4 \times 10^{-5} \text{ m}^2\text{KW}^{-1}$ respectively. The main advantage of using glassy carbon is that this material is at the same time highly absorbing at visible wavelengths and highly emitting at infrared wavelengths. This means that its surface does not need to be prepared (painted or coated) in order to obtain a high enough signal to noise ratio, as it happens with metals and alloys.

Figure 8. Diagram of the experimental setup. AOM is the acousto-optic modulator and M is the microscope objective.

Figure 9. Diagram of the infinite vertical crack simulated for the experiment. Two thin Ni tapes of the same thickness are sandwiched between two blocks. Blocks are made of glassy carbon or AISI-304 stainless steel.

We have performed the same kind of measurements in two blocks of AISI-304 2 cm thick. As this metallic alloy has a shiny surface, a thin graphite layer about 3 mm thick has been deposited onto the surface in order to increase both the absorption to the heating laser and the emissivity to infrared wavelengths. The amplitude and phase thermograms corresponding to a 1 mm thick crack are shown in figures 12(a) and (b). The same experimental parameters as in figure 10 have been used. The temperature profiles along the y-axis together with the fits to equation (10) are shown in figures 12(c) and (d). We have obtained the following thermal resistance values: $7 \times 10^{-4}$, $4.7 \times 10^{-4}$, $2.4 \times 10^{-4}$, $5 \times 10^{-4}$, $1.1 \times 10^{-4}$, $3.5 \times 10^{-5} \text{ m}^2\text{K}^{-1}$, which correspond to air gaps of 27, 12, 5.2, 2.8 and 0.9 mm respectively. They are very close to the thicknesses of the nickel
tapes. As in the case of the glassy carbon, we have performed complementary measurements changing the experimental parameters $a$, $d$, $f$. We studied the temperature profiles along the $y$-axis for a $5\mu$m thick vertical crack keeping $d = 0.65$ mm but changing $a$ and $f$: (1) $a = 0.27$ mm, $f = 0.3$ Hz, (2) $a = 0.38$ mm, $f = 0.3$ Hz, (3) $a = 0.27$ mm, $f = 0.6$ Hz and (4) $a = 0.39$ mm, $f = 0.6$ Hz. The retrieved thermal resistances are $2.2 \times 10^{-4}$, $2.1 \times 10^{-4}$, $2.1 \times 10^{-4}$ and $2.0 \times 10^{-4}$ m$^2$K W$^{-1}$ respectively, corresponding to an air gap of $L = 5.5 \pm 0.5$ µm. This result confirms the robustness of the procedure.

Then, we put the two glassy carbon plates in direct contact, i.e. without inserting nickel plates. As the surfaces in contact...
are polished, they simulate an extremely thin crack. The result depends slightly on the position in which the sample is excited. At some positions, we observe neither temperature amplitude contrast nor phase contrast. Moving the positions of the excitation spot on the same sample, we have obtained amplitude and phase contrasts corresponding to air gaps below 300 nm, probably due to different surface conditions. At the locations where we do not detect the crack, it remains undetectable even when the modulation is increased up to 10 Hz and the laser beam is focused down to 100 µm. This result allows us to conclude that the upper limit for this thermal resistance is \( R_{\text{th}} \leq 10^{-6} \text{m}^2\text{K W}^{-1} \).

It is worth noting that detecting very narrow cracks requires using a high frequency together with a laser beam tightly focused close to the crack. However, in our infrared thermography setup the spatial resolution is 30 µm so measurements with a thermal diffusion length \( \mu < 100 \mu \text{m} \) are not allowed. Under these experimental conditions, thermal resistances verifying \( KR_{\text{th}} \leq 1 \mu \text{m} \) will remain undetectable.

Finally, we verify the unexpected reversal (upwards) jump of the phase at the crack position predicted by the model when the laser spot is very close and especially when it overlaps the crack. In figure 13, we show temperature phase profiles along

**Figure 12.** The same as in figure 10 for AISI-304 stainless steel.

**Figure 13.** Experimental phase profiles of the surface temperature along the y-axis for a 25 µm thick vertical crack in AISI-304. (1) \( d \approx 1.5 \text{ mm}, a \approx 2.0 \text{ mm}, f = 0.4 \text{ Hz} \). (2) \( d \approx 0.8 \text{ mm}, a \approx 1.0 \text{ mm}, f = 0.2 \text{ Hz} \). (3) \( d \approx 0.8 \text{ mm}, a \approx 1.0 \text{ mm}, f = 0.8 \text{ Hz} \). The upwards jump of the phase at the crack position (y = 0) can be clearly observed.
the y-axis for a 25 µm thick vertical crack in AISI-304. Three experimental configurations satisfying \( a > d \) are shown. The predicted reversal of the phase jump at the crack position is confirmed experimentally.

Note that the experimental results shown in figures 10–12 do not exhibit a sharp discontinuity at the crack but a smooth transition involving around four pixels. This result is due to the imperfect imaging system of the IR camera (diffraction, multiple reflections, flare…). The so-called point spread function (PSF) of the optical system quantifies its effect, which depends on the lens quality. As in our system the effect is only noticeable at the crack position, it has not been taken into account in the fittings of the whole profiles. Nonetheless, it is worth noting that the microscope lens (with a resolution of 30 µm) produces an abrupt jump in the amplitude and phase of the surface temperature containing such a crack when a modulated and focused laser beam impinges close to the crack. Both circular and line Gaussian spots are studied. The presence of the crack produces an abrupt jump in the amplitude and phase of the surface temperature at the crack position. Numerical simulations indicate that the highest amplitude temperature contrast is produced when \( a, d \) and \( \mu \) satisfy the following condition: \( d \approx \mu \approx 1.25a \). The validity of the model has been tested by performing lock-in thermography measurements on stainless steel and vitreous carbon samples containing cracks of calibrated width. By fitting simultaneously the amplitude and phase of the surface temperature to the analytical model, the width of the crack is obtained. The agreement between the optically calibrated width and the retrieved one is very good even for widths as narrow as 1 µm. In Part II of this work, the characterization of vertical cracks of finite size will be addressed.

5. Conclusions

In this work, we have dealt with the width characterization of infinite vertical cracks using lock-in thermography with optical excitation. First, we have found an analytical expression for the surface temperature of a material containing such a crack when a modulated and focused laser beam impinges close to the crack. Both circular and line Gaussian spots are studied. The presence of the crack produces an abrupt jump in the amplitude and phase of the surface temperature at the crack position. Numerical simulations indicate that the highest amplitude temperature contrast is produced when \( a, d \) and \( \mu \) satisfy the following condition: \( d \approx \mu \approx 1.25a \). The validity of the model has been tested by performing lock-in thermography measurements on stainless steel and vitreous carbon samples containing cracks of calibrated width. By fitting simultaneously the amplitude and phase of the surface temperature to the analytical model, the width of the crack is obtained. The agreement between the optically calibrated width and the retrieved one is very good even for widths as narrow as 1 µm. In Part II of this work, the characterization of vertical cracks of finite size will be addressed.

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