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Sizing vertical cracks using burst vibrothermography

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ABSTRACT

We apply burst vibrothermography to characterize (area and depth) vertical cracks in a fast way. We present the calculation of the evolution of the surface temperature distribution produced by a vertical crack excited by an ultrasound burst. We develop a stabilized inversion algorithm that is able to retrieve the area and depth of the crack from one thermogram and one timing-graph. We check its performance by inverting both, synthetic data and experimental data taken on samples containing calibrated heat sources. Depth limits are established for accurate reconstructions of the defects as a function of the noise in the data.

1. Introduction

Thermographic techniques have become a very useful tool to detect and characterize defects in a non-destructive manner, in particular planar defects parallel to the sample surface like delaminations, inserts and disbonds in layered composite structures [1–3]. Many efforts have been devoted to retrieve the size and depth of the defect using mainly homogeneous optical excitation and one dimensional (1D) modeling of heat propagation [4–6]. Different processing techniques like thermographic signal reconstruction (TSR) [3,5] or pulsed phase thermography (PPT) [4,6], have been applied to improve the characterization of planar defects parallel to the sample surface in aerospace materials. Vertical cracks, on the contrary, are elusive to techniques in which the sample surface is illuminated homogeneously because they barely modify the heat diffusion perpendicular to the sample surface. When dealing with these defects, focused illumination is more appropriate because it helps visualizing the thermal resistance produced by the crack which induces a temperature asymmetry across the crack [7,8]. Actually, the surface temperature profile across the crack through the center of the laser spot has been used to evaluate the thermal resistance characterizing the crack [7]. It has been shown that thermal resistances equivalent to air gap thicknesses down to 1 μm can be retrieved for infinite cracks from experiments performed with modulated focused spots [7]. Kissing cracks are more difficult to detect and characterize by means of focused optically excited thermography because of the low thermal resistance they produce. For these defects, ultrasound excited thermography (or vibrothermography) is a more adequate technique which has demonstrated ability to detect defects in a wide variety of materials [9–14]. In this technique, ultrasounds launched in the sample produce rubbing between the contacting defect surfaces. The thermal energy produced at the defect diffuses inside the sample and the defect is visualized by means of an infrared camera, as a temperature increase at the surface on a cold environment. This technique has been applied very successfully to the characterization of vertical cracks in the lock-in regime, i.e. by modulating the amplitude of the ultrasounds and measuring the surface temperature amplitude and phase [15,16]. In a previous work, using a 3D semi-analytical model, authors showed that it is possible to characterize buried vertical cracks (heat sources) in AISI 304 stainless steel, by combining amplitude and phase data obtained at several modulation frequencies, with the only prior knowledge of the plane containing the crack [17]. The frequency range, between 0.05 and 12.8 Hz (corresponding to thermal diffusion lengths ranging from 0.3 to 5 mm), was selected seeking to ensure detection of deep heat sources (low frequencies) as well as to provide details on the particular shape of the crack (high frequencies). The retrieval of the heat source distribution is an ill-posed inverse problem, which means that the solution is extremely sensitive to errors or noise in the data. In such

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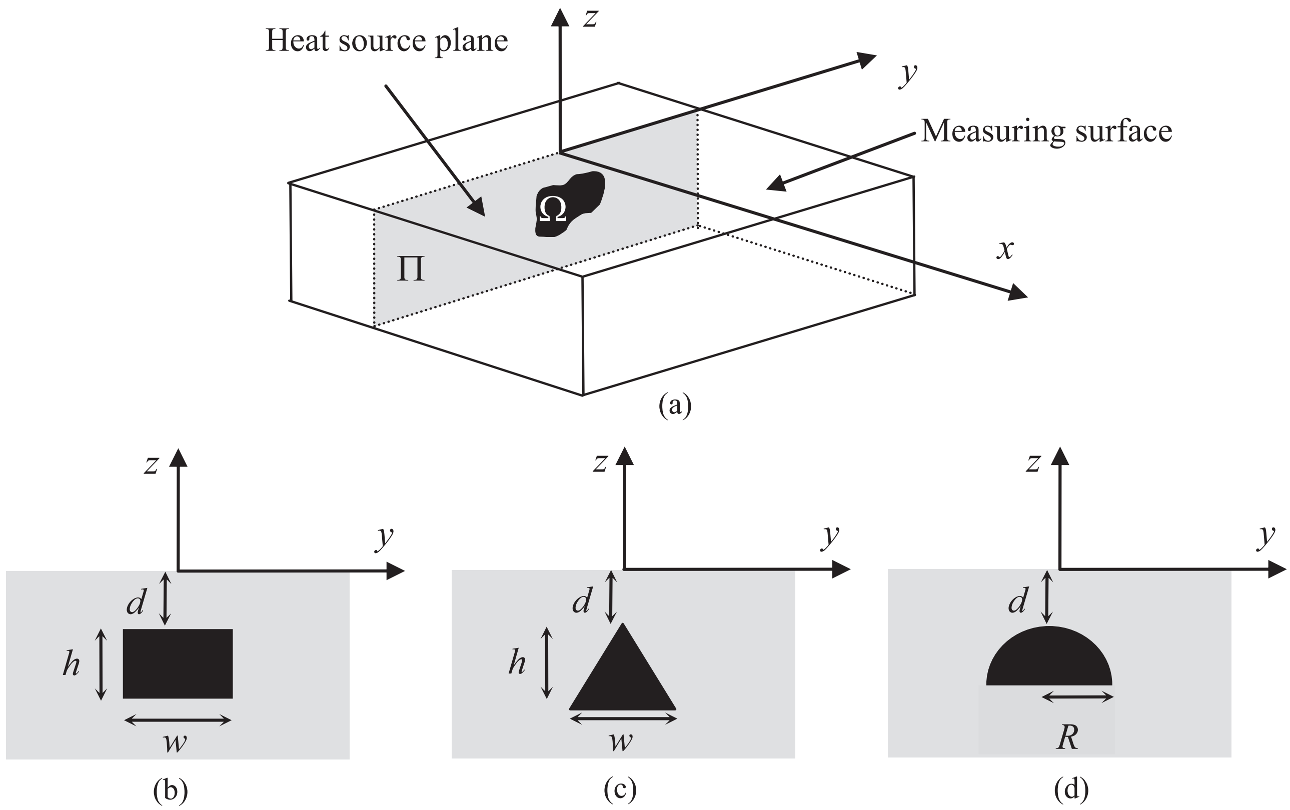

Fig. 1. (a) Geometry of a sample containing a vertical buried crack of irregular shape. Cross-section of vertical cracks with different shapes: (b) rectangle, (c) triangle and (d) semicircle.

circumstances, regular algorithms aimed at finding the heat source distribution that minimizes the square differences between the data and the calculated temperatures do not converge. We used regularization techniques based on Total Variation functional [18,19] to stabilize the inversion algorithm and we showed that it is possible to use lock-in vibrothermography to characterize vertical cracks. The drawback of such an approach is that data taking is time consuming since only one frequency is proved at a time.

To overcome this difficulty, in a previous work [20] we explored the ability of burst vibrothermography, which is much faster than the lock-in technique, to characterize the height, length and depth of rectangular vertical kissing cracks. In the burst regime the sample is excited by a brief ultrasound burst of constant intensity and the evolution of the surface temperature distribution is recorded by an infrared camera. We proposed using the temperature evolution (timing-graph) right on top of the heat source and natural logarithms of two normalized temperature profiles obtained at the end of the burst (one along the direction of the plane containing the heat source, right on top of it, and another one along the direction perpendicular to the heat source plane, through the center) to characterize the crack. We showed that, by using similar number of data in space (thermogram profiles) and time (timing-graph), it was possible to characterize the three parameters describing the rectangular heat source for two decades of the burst durations, from 0.1 to 20 s. In this simplified approach, where the shape of the heat source is assumed to be known and there are only three parameters to be determined, the inverse problem is well-posed and the inversion is stable.

In this work, we tackle a more general problem in which the shape of the heat source is unknown and only the plane containing the heat source is assumed as prior knowledge. Our goal is to retrieve the shape, the area and the depth of the heat source. To this purpose, first we calculate the evolution of the surface temperature distribution produced by a vertical heat source emitting a constant flux over a certain time interval. In order to reduce the computational cost of the inversion procedure, we only use the thermogram at the end of the burst and the timing-graph on top of the heat source to characterize the crack. Without assumption of the shape of the heat source, the inverse problem consisting of determining the heat source distribution that produces the observed surface temperature is, as in the lock-in case, an ill-posed inverse problem. Given that the amount of information we want to use is now much more limited than in the lock-in case, we develop an improved inversion algorithm based on three regularization functionals, namely, Tikhonov [21], Total Variation [18,19] and Lasso [22,23]. We check the performance of the inversion algorithm by inverting synthetic data with different noise levels corresponding to different geometries of the heat source: rectangles, triangles and semicircles. We set the maximum depths of the crack for which we can get accurate reconstructions as a function of the noise in the data. We finally test the inversion procedure by inverting experimental data obtained with samples containing calibrated heat sources. The results confirm that it is possible to characterize vertical cracks down to depths of 6 mm in AISI stainless steel from burst vibrothermography experimental data in a fast manner: about 2 min, including data taking and inversion of the data.

2. Direct problem

We calculate in this section the evolution of the surface temperature distribution corresponding to a vertical heat source contained in plane Π perpendicular to the sample surface that occupies an area Ω and emits a constant and homogeneous flux during a time interval τ in a semi-infinite medium. It represents a