Measuring the depth and width of delaminations by photothermal radiometry

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Photothermal methods have been widely used for sizing the depth of delaminations. However, less attention has been paid to size their width. In this work, we use modulated photothermal radiometry (PTR) to measure the depth and width of narrow delaminations by fitting the theoretical temperature expression to the experimental frequency spectrum of the PTR signal. We have established a general detectability limit that includes the material's properties: in good thermal conductors, submicronic delaminations can be sized down to 10 mm, whereas in thermal insulators it is difficult to go below 0.5 mm. Experiments on calibrated delaminations confirm these predictions.

Theory – Let us consider a semi-infinite an opaque sample containing a delamination of infinite area parallel to the sample surface, buried at a depth d and having a width w. The front surface of the sample is uniformly illuminated by a CW laser modulated at a frequency f (ω=2πf). The surface temperature of the delaminated sample normalized to a sound one is given by

$$T_n = \frac{2K_{air} + \sqrt{i\omega}\varepsilon w\left(1 + e^{-2\sqrt{i\omega}d/\sqrt{D}}\right)}{2K_{air} + \sqrt{i\omega}\varepsilon w\left(1 - e^{-2\sqrt{i\omega}d/\sqrt{D}}\right)}, \qquad \text{Eqn. 1}$$

where K, D and ε are the thermal conductivity, diffusivity and effusivity of the sample respectively. Note that the delamination depth and width are correlated to the thermal diffusivity and effusivity of the sample respectively.

With the aim of stablishing the sizing limits of ideal delaminations, we show in Fig. 1 the minimum quantifiable width for a given depth. We have selected an arbitrary but reasonable criterion for a delamination to be measurable: when it produces a normalized phase contrast higher than 5º. This corresponds to the green area in Fig. 1. The slope of the diagonal border indicating the transition from non-measurable to measurable regions is 200/3 mKW^{-1}. We have added another practical criterion to avoid using too low frequencies: the delamination is sizable if the normalized phase minimum appears at frequencies higher than 0.2 Hz. This corresponds to the red line in Fig. 1. In this way, the crossing point between the diagonal and the red lines indicates the highest retrievable depth, limited by the modulation frequency. Note that Fig. 1 is general in the sense that it is applicable to any material of known thermal properties.

Experimental results and discussion – In order to obtain calibrated delaminations we have prepared a sample by combining a glassy carbon plate of known thickness (0.52, 0.97 and 2.01 mm) and a thick sample of the same material. These samples are put in contact using some pressure. In order to calibrate the air gap between the plates, metallic tapes 0, 25, 75 and 125 μm thick are sandwiched between the carbon plates, at two opposite edges, producing an air gap between the glassy carbon pieces. For normalization purposes, we divide the PTR signal of the sandwiched sample by the PTR signal of a thick homogeneous sample of the same material.

Experiments have been performed using a conventional modulated PTR setup. In Fig. 2 we show by dots the experimental PTR frequency spectrum of the normalized phase for one of the delamination depths studied in this work: $d = 0.52$ mm and several delamination widths. The continuous lines are the best fits to Eq. (1), using two free parameters: $d/\mathrm{sqrt}(D)$ and εw. Since the thermal properties of the glassy carbon and air are known, the depth and width of the delamination are obtained simultaneously and are given in the inset of Fig. 2. As can be observed, the data feature low noise and the quality of the fittings is very good.

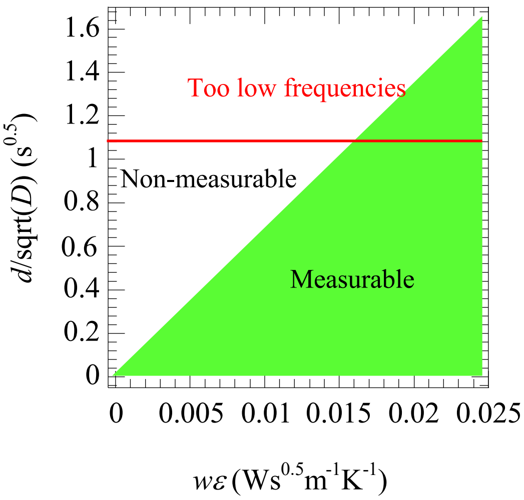

Fig. 1. This graphic indicates, for a given material (known thermal properties D and ε), whether a particular delamination (d,w) is measurable or not.

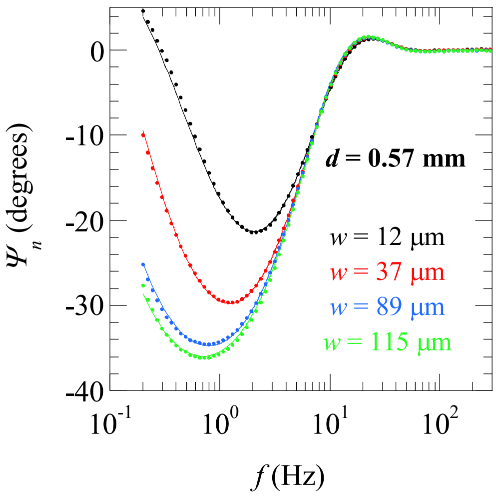

Fig. 2. Experimental frequency dependence of the normalized PTR phase (symbols) for a nominal depth $d = 0.52$ mm. Four nominal delamination widths are studied: 0, 25, 75 and 125 µm. The continuous lines are the fits to Eq. (1), leading to the d and w values given in the inset.

The depth of the delamination is slightly overestimated (10%), probably due to radiation between the glassy carbon surfaces in contact. Regarding the delamination width, if we look at the case of nominal width $w = 0$ (black dots and lines in Fig. 2), the retrieved width is not zero but a value of 12 µm, indicating that the contact between the two plates is not perfect. Even though the surfaces in contact are polished and some pressure is applied to the combined pieces in contact, it is difficult to obtain a perfect thermal match between them. Accordingly, when putting the metallic plates the retrieved delamination widths are affected by this offset. Anyway, the results confirm the validity of the model, and show that it is possible to size the width and depth of ideal delaminations within the established detectability limits.

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