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Determining the thermal diffusivity and principal directions of anisotropic materials in motion by laser-spot thermography

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Abstract

We present a methodology to determine the in-plane principal thermal diffusivities and principal directions of anisotropic materials moving at constant speed using laser-spot thermography. From analytical expressions of the surface temperature, we show that the radial profiles through the center of the spot are straight lines whose slopes depend on the profile orientation and on the principal diffusivities and directions. The methodology involves fitting these slopes as a function of the angle with the direction of motion. Experimental data on calibrated samples validate the method. This approach can be useful for on-line assessment of fibre orientation in CFRP.

1. Introduction

Laser-spot thermography has been applied in different configurations (lock-in, pulsed, step-heating) for the evaluation of the thermal diffusivity of samples at rest. Recently [1,2], it has been shown that it can also be used to evaluate the thermal diffusivity of samples moving at constant speed. When dealing with anisotropic materials, these methodologies require knowledge of the principal directions in the surface, as well as having the sample velocity parallel to one of the principal directions. This is a serious drawback in order to apply the technique for product monitoring in production chains. Here, we propose a methodology aimed at identifying the principal directions in the sample surface and measuring the principal diffusivities. Starting from the analytical expression of the surface temperature, we show that the natural logarithm of any radial temperature profile multiplied by the distance to the excitation point features a linear dependence with the distance. By fitting the slope values as a function of the angle of the profile with the direction of motion, we are able to determine the orientation of the principal axes and to measure the principal diffusivities. The experimental results obtained in calibrated materials confirm the validity of the method.

2. Theory

Let us consider an anisotropic sample that moves at speed v in a direction that makes an angle β with the principal axis x. The sample is illuminated by a CW laser spot of negligible size, which remains at rest (see figure 1).

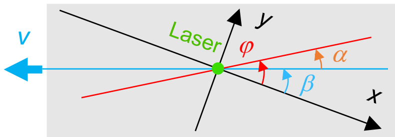

Fig. 1. *Geometry of the problem. The sample moves to the left at speed v and the laser remains at rest.*

The principal diffusivities along the x and y directions are D_x and D_y, respectively. When the steady-state has been reached, the surface temperature can be written in a closed form:

$$T(r,\varphi) = \frac{\eta P_o}{2\pi\varepsilon_z}\frac{1}{r}\frac{1}{\sqrt{D_x\sin^2\varphi + D_y\cos^2\varphi}}e^{m_{\varphi,\beta}r}, \quad (1)$$

where P_o is laser power and ε_z the thermal effusivity along the z-axis.

Accordingly, the radial ln ($T \cdot r$) profiles have a linear dependence with r, whose slopes are:

$$m_{\varphi,\beta} = -\frac{v}{2}\left[\frac{\cos\varphi\cos\beta}{D_x} + \frac{\sin\varphi\sin\beta}{D_y} + \sqrt{\left(\frac{\sin^2\beta}{D_y}+\frac{\cos^2\beta}{D_x}\right)\left(\frac{\sin^2\beta}{D_y}+\frac{\cos^2\beta}{D_x}\right)}\right] \quad (2)$$

If the principal directions are unknown, the parameter that can be controlled is the angle α between the temperature profile and the direction of motion. Introducing in Eq. (2) $\varphi = \alpha + \beta$ and fitting Eq. (2) to the experimental slopes as a function of the angle α, the principal diffusivities D_x and D_y, and the angle β of the sample velocity with the principal direction x can be obtained. As will be shown in the next section, the finite size of the laser spot affects the temperature distribution in the vicinity of the excitation but, the linearity of the radial ln ($T \cdot r$) profiles and the slopes values given by Eq. 2 stay the same at a distance from the laser spot.

3. Experimental results and discussion

We have conducted laser-spot thermography experiments using a CW laser (532 nm, up to 6 W) of Gaussian profile focused on the sample surface down to a radius of about 50 μm, and an IR video camera (3-5 μm, 320x256 px, 30 μm pitch) equipped with a 1:1 macro lens, which provides a spatial resolution of 30 μm. The samples move on a cart driven by an engine that makes it slide on a track at a constant speeds ranging between 1 and 150 mm/s.

As an example, figure 2a displays the steady state thermogram obtained in a CFRP sample moving to the left at v = 5.55 mm/s in a direction that makes and angle β = 30º with respect to the fibres. Note that, unlike the case of static samples, the directions of the principal axes are not evident from the thermographic image. Figure 2b displays radial ln($T \cdot r$) profiles making different angles α with the direction of motion, and the corresponding linear fits. The values of the slopes of these fits as a function of α together with the fitting to Eq. 2 are depicted in figure 2c.

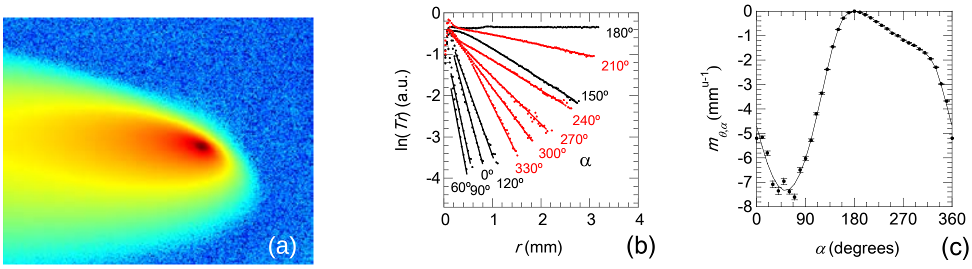

Fig. 2. *(a) Steady-state thermogram of a CFRP sample moving to the left at speed v = 5.5 mm in a direction that makes an angle α = 30º with the fibres. (b) Radial* ln ($T \cdot r$) *profiles and (c) slopes as a function of* α *and fitting to Eq. 2.*

The results are summarized in table 1. The principal diffusivities ($D_{||}$ and $D_{\perp}$, in the directions parallel and perpendicular to the fibres, respectively) are determined with high accuracy and uncertainties of about 10%. The method features a remarkable reliability in identifying the principal directions, with accuracy of about 1º. This ability opens the possibility of using this methodology for fibre orientation monitoring of CFRP.

Table 1. Principal thermal diffusivities and orientation of the principal directions in CFRP moving at 5.55 mm/s for different values of β. Literature values: $D_{||}$ = 2.9 ± 0.1 mm²/s and $D_{\perp}$ = 0.40 ± 0.02 mm²/s.

β (actual)	β (estimated)	$D_{\|\|}$ (mm²/s)	$D_{\perp}$ (mm²/s)
0º	-0.45 ± 0.2º	2.8 ± 0.2	0.41 ± 0.04
30º	28.6 ± 1.4º	2.7 ± 0.2	0.40 ± 0.04
60º	61.0 ± 1.1º	2.9 ± 0.4	0.42 ± 0.03
90º	89.4 ± 1.1º	2.7 ± 0.6	0.42 ± 0.03

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