# Non-destructive evaluation of materials in motion using laser-spot thermography

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We present recent advances in monitoring materials in motion using laser-spot infrared thermography aimed at the non-destructive evaluation of industrial parts in production chains. First, we focus on anisotropic materials moving in an arbitrary direction with respect to the principal directions in the sample surface. We present analytical expressions for the surface temperature showing that any radial profile features a linear behaviour with the distance to the laser spot. The principal thermal directions and diffusivities in the sample surface are determined by fitting the slopes of the linear profiles as a function of their orientation. This finding has straightforward applications in monitoring thermal anisotropies in moving parts. Second, the technique is applied to the characterization of planar cracks in materials that move at constant speed. We show that the surface temperature of a material containing an ideal infinite vertical crack can be written semi-analytically and the effective crack width can be determined by fitting the theoretical expression to experimental data. For other crack configurations, numerical methods are necessary to calculate the surface temperature. We present a numerical approach to calculate the temperature field when the sample and the laser are in relative motion, together with some applications.

## I – Principal thermal directions and diffusivities of moving samples

Laser-spot infrared thermography (IRT) is a well-known technique to measure the in-plane thermal diffusivity of solids at rest. Recently, it has been applied to determine the thermal diffusivity of materials moving at constant speed [1] with some limitations, such as the use of scarce information of the thermogram, which limits the accuracy of the results, and the necessity of having anisotropic samples moving in one of the principal directions. Here we present a general approach to characterize the thermal diffusivity of isotropic and anisotropic materials that makes use of the whole thermogram and allows determining the orientation of the in-plane principal directions and the principal diffusivities of anisotropic samples moving in an arbitrary direction.

Let us consider an anisotropic sample whose principal directions $x$ and $y$, with diffusivities $D_x$ and $D_y$, respectively, are parallel to the sample surface. The sample moves at constant speed $v$ along a direction that makes an angle $\alpha$ with principal direction $x$. A tightly focused continuous wave (CW) laser spot is illuminating the sample at the origin of coordinates. The geometry is depicted in Fig.1a. After reaching the steady state, the temperature at the surface in polar coordinates writes:

$$T(r,\varphi) = \frac{A}{r} e^{m_{\varphi,\alpha} r} \qquad \text{Eqn. 1}$$

where $A$ is a constant. Eqn. 1 shows that the natural logarithm of any radial temperature profile multiplied by the distance to the laser spot $r$ is a straight line. The slope $m_{\varphi,\alpha}$, which is a function of the

in-plane principal diffusivities $D_x$ and $D_y$, and the (unknown) angles that the principal $x$ direction makes with the particular profile $\varphi$ and with the direction of motion $\alpha$, writes:

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

The fitting of these slopes as a function of the angle $\beta$ between each profile and the direction of motion (which is the angle that can be controlled) allows obtaining the principal diffusivities $D_x$ and $D_y$ and the orientation of the principal $x$-axis, $\alpha$.

In Fig. 1b we show a thermogram taken on a carbon fiber reinforced composite (CFRC) sample moving at $v$ = 5.55 mm/s, with unidirectional fibers making an angle of 60º with the direction of motion. The spatial resolution of the thermal image is 30 µm. Unlike the case of static samples, the orientation of the principal axes is not obvious from the thermogram. Several experimental ln ($Tr$) profiles are depicted in Fig. 1c for different values of $\beta$. In Fig 1d we show the slopes of the linear fits of the data in Fig. 1c as a function of $\beta$, together with the fitting to Eqn. 2.

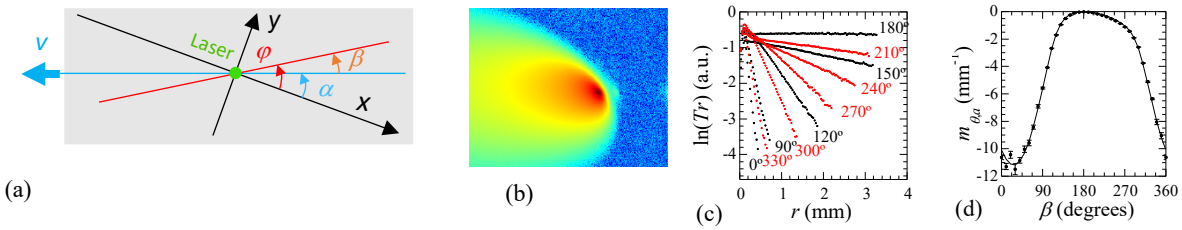


**Fig. 1. (a)** Geometry of the problem. **(b)** Experimental thermogram on a unidirectional CFRC sample moving at $v$ = 5.55 mm/s along a direction that makes an angle of 60º with the fibers. **(c)** Experimental radial ln ($T \cdot r$) profiles of the thermogram in Fig. 1b for several angles $\beta$. **(d)** Values of the slopes of the profiles in Fig.1c (symbols) and fitting to Eqn. 2 (solid line).

The diffusivities in the directions parallel and perpendicular to the fibers are retrieved with an accuracy of about 10%. The estimated angle values are remarkably precise, featuring an accuracy of about 1º. This reliability in the evaluation of angles opens the possibility of using laser-spot thermography for monitoring thermal anisotropies in moving parts such as the non-destructive assessment of fiber orientation in the production of CFRC.

## II – Crack characterization in isotropic materials in motion

Laser spot thermography can also be applied to characterize cracks in samples in motion. In these experiments, a crack of width $w$ behaves as a thermal barrier whose thermal resistance per unit area is $R_{th}=w/K_{air}$, ($K$, thermal conductivity). In the ideal case of "infinitely deep" vertical cracks, the surface temperature of the moving cracked sample illuminated with a CW laser spot can be modelled semi-analytically. A fast characterization of the effective width of the crack can be carried out by fitting the model to experimental temperature data at different positions of the sample [2]. However, out of these ideal conditions, the surface temperature of the cracked material has to be calculated numerically.

In this work we present recent advances based on finite elements methods (FEM) that allow calculating numerically the temperature of an isotropic sample illuminated by a CW laser spot when relative velocity is $\vec{v}$. The problem consists in solving the heat diffusion equation:

$$\frac{\partial T(\vec{r},t)}{\partial t} = D\nabla^2 T(\vec{r},t) \qquad \text{Eqn.3}$$

with boundary condition:

$$K\nabla T(\vec{r},t)\cdot\vec{n} = \frac{2P_0}{\pi a^2} e^{\frac{-2(\vec{r}-\vec{r}_{vt})^2}{a^2}}\Big|_I - \gamma\left(T(\vec{r},t) - T_{amb}\right)\Big|_{n-I} \qquad \text{Eqn. 4}$$

where $\vec{n}$ is the unit vector normal to the surface, $|_I$ and $|_{n-I}$ stand for the illuminated and non-illuminated surfaces, $P_0$ and $a$ are the laser power and radius, γ is the coefficient of heat losses and $T_{amb}$ is room temperature. A planar crack is introduced in the numerical domain as a thermal resistance $R_{th}$, described by boundary conditions of heat flux continuity and temperature jump over the crack:

$$\left[\left[K\nabla T(\vec{r},t)\right]\right]_{crack} = 0 \qquad \Delta T(\vec{r},t)\Big|_{crack} = R_{th} K\nabla T(\vec{r},t)\Big|_{crack} \qquad \text{Eqn. 5}$$

In order to calculate the temperature field with accuracy but keeping a reasonable computational cost, a dynamic FEM spatial discretization refinement has been applied. Fig. 2 shows a simulation for a stainless steel sample ($D = 3.8 \cdot 10^{-6}$ m$^2$/s, $K = 15$ Wm$^{-1}$K$^{-1}$) moving at 5 cm/s, containing a planar vertical crack 20 μm wide that penetrates 1 mm into the material. We present the validation of the numerical method in different cases.

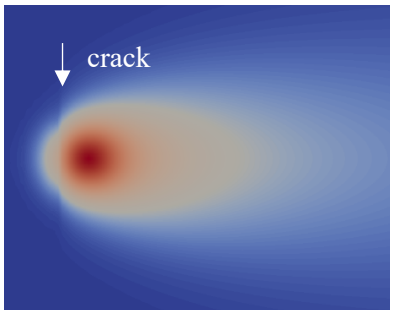


**Fig. 2.** FEM simulation of a stainless steel cracked sample moving at 5 cm/s. Crack width 20 μm and depth 1 mm.

These methods open the possibility of modelling a wide variety of practical situations and promise a high potential of laser-spot IRT for the quantitative assessment of materials condition in production chains and for the development of flying-spot thermography.

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