THERMOGRAPHIC APPLICATION OF BLACK COATINGS ON METALS.

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Keywords: Lock-in thermography, Heat conduction, Black coating, Thermal diffusivity, Hankel transform.

Abstract:

Thermographic studies on metals need the application of an emissive layer, usually labelled as "a thin black paint layer", in order to enhance and homogenize the sample absorptivity and emissivity. The aim of the present work is to characterize the thermophysical properties of such layers, actually their thermal diffusivity, as a preliminary study before the measurement of the substrate diffusivity. Since we intend to measure the metal properties by means of lock-in photothermal thermography under modulated laser irradiation, the same technique is applied here to the characterization of the layers.

For the lock-in procedure, a photodiode gives the reference signal by recording a part of the laser beam, allowing amplitude and absolute phase measurements. An infrared camera, CEDIP IRC 320-4LW, records series of images of the thermal response. Both laser modulation and IR maps recording are controlled by the same computer, then a program under Labview™ allows the numerical lock-in detection of real and imaginary parts of the complex temperature.

The geometry of the thermal direct model is considered as 2D axis-symmetrical and the heat diffusion equation is solved for a bi-layer medium in harmonic regime:

$$\frac{\partial^2 T(r,z)}{\partial r^2}+\frac{1}{r}\frac{\partial T(r,z)}{\partial r}+\frac{\partial^2 T(r,z)}{\partial z^2}-\frac{jw}{a}T(r,z)=-\frac{q(\vec{r})}{k}$$

After application of a zero-order Hankel transform to the complete set of equations, the thermal response is searched using harmonic Green's functions [1], which are solutions of:

$$\frac{d^2 H(\lambda,z|z')}{dz^2}-\sigma_i^{\,2} H(\lambda,z|z')=-\frac{\delta(z-z')}{k}$$

The Hankel transform of the temperature in the layer 1 (black coating) is finally expressed as:

$$\overline{T_1}(\lambda,z)=\int_0^l H_{11}(\lambda,z|z').\overline{q_1}(\lambda,z').dz'+\int_l^d H_{21}(\lambda,z|z').\overline{q_2}(\lambda,z').dz'$$

A simple identification technique in such photothermal localized measurements consists in using one radial profile of the complex temperature to determine the parameters by an inverse method [2]. However, experimentally, the beam distribution is not perfectly axis-symmetrical. So, the experimental profiles can be different enough, leading to parameter variations depending on the profile choice.

The method proposed in this study consists in using the complete maps, as supplied by the matrix detector. At first, a Gaussian fit approach is used on the experimental amplitude map together with a Levenberg-Marquardt algorithm, in order to determine the coordinates of the map centre. Then, the complete experimental cartesian maps are used to rebuild a single radial distribution. Next, the experimental data are used to calculate a normalized discrete Hankel transform of the temperature:

$$T^{*}(\lambda, z) = \frac{2}{r_0^2} \sum_i T(r_i, z) J_0(\lambda r_i) r_i \Delta r_i$$

Finally, the analytical model of the Hankel transform is fitted on this Hankel experimental distribution, a Gauss-Newton algorithm yielding an estimation of the thermal properties, directly in the Hankel space [3]. The relevant spatial frequency band is determined from the classical Fourier variables and from the experimental parameters. The main advantage of this method is that the spatial high-frequency noise of the measurement is completely deleted. Indeed, the inversion in the spatial frequency domain (Hankel or Fourier) is confirmed as an efficient tool for infrared thermography [4].

Many works have been published on "black" coatings such as matt black paints, graphite-black coatings or carbon aerogels and their deposition process [5]. In the present work, the investigation of a common "black" coating is first presented : the Krylon™ ultra flat black paint. Widely used by thermography experimenters, this type of layer is simply sprayed on the metal substrate, until the minimum thickness required for visual opacity is obtained. The diffusivity of the Krylon™ black paint layer is found to be: $a_1 = 0.15/2 \cdot 10^6 = 7.5 \cdot 10^{-8}$ $m^2.s^{-1}$. However, to ensure the quality of estimations it is essential to measure with a good accuracy the thickness of the layer and to check its uniformity. More particularly, dedicated sensitivity studies have shown that, for a thickness near 20 µm, the model is not sensitive enough to the thermal conductivity of the substrate.

Consequently, an amorphous carbon deposit, with a thickness near 1 µm, was investigated, with a vue to more precise determinations of the thermophysical properties of steel samples. These thin films are realized by magnetron sputtering [6], a process presenting great advantages: the deposit can be applied at the plasma temperature (100°C in our case) and the layer thickness is particularly uniform with a good reproducibility.

For thermographic applications, the low value of the paint layer thermal diffusivity could become inappropriate for the study of quick transient phenomena. For a diffusivity of $7.5\ 10^{-8}$ $m^2.s^{-1}$, the characteristic time of a 20 µm-thick paint layer is $l^2/a \approx 5$ ms. For the 1µm-thick amorphous carbon layer, the characteristic time falls to 1 µs. For non-destructive characterization of metals by photothermal radiometry, the black paint brings favourable higher and more uniform absorptivity and emissivity. However, the enhancement of the thermal signal due to the insulating property of the layer could be a harmful drawback, since it brings strong sensitivity to the layer parameters instead of the substrate ones.

References

[1] Gillet Y., Bissieux C., "Diffusion harmonique de la chaleur appliquée au contrôle non destructif par méthodes photothermiques", International Journal of Thermal Sciences, vol.38, pp. 530-540, 1999.

[2] Pron H. and Bissieux C., "3D thermal modelling applied to stress-induced anisotropy of thermal conductivity", Int. J. Therm. Sci. Vol. 43/12, pp. 1161-1169, 2004.

[3] D. Legaie, H. Pron, C. Bissieux, "Characterization of a black paint layer by photothermal lock-in thermography. Parameter identification in the Hankel space" QIRT Journal, vol 4, pp. 201-218, 2007.

[4] Maillet D., Batsale J.-C., Bendada A., Degiovanni A., "Integral methods and nondestructive testing through stimulated infrared thermography", Int. J. Therm. Sci., vol.35, pp. 14-27, 1996.

[5] Persky M. J., "Review of black surfaces for space-borne infrared systems", Review of Scientific Instruments, vol.70, pp. 2193-2217, 1999.

[6] Rubin M., Hopper C.B., Cho N-H., Bhushan B., "Optical and mechanical properties of dc sputtered carbon films", Journal of Materials Research, vol.5, pp 2538-2542, 1990.