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Theory and verification of a method for parameter-free laser-flash diffusivity measurement of a single-side object

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ABSTRACT

A new single-side flash method for thermal diffusivity determination is presented. The method is based on a laser-flash pulse excitation and infrared thermography non-contact temperature measurement of a thermal response of a studied object. Using this method, the both excitation and measurement at one side (front side) of the studied object are provided. An exact knowledge of the thickness, absorbed energy, emissivity or other material parameters of the object as well as temperature measurement on the opposite side (back side) of the object are not required. Thus, the method can be described as an object parameter-free single-side thermal diffusivity measurement method. The thermal diffusivity measurement procedure and data processing using an approximation algorithm are described in the paper. Simulation and experimental verification of the method is presented for several materials.

1. Introduction

Thermal diffusivity is one of the basic parameters for infrared non-destructive testing (IRNDT) using flash heating. It gives the possibility to detect defects as well as the depth of their occurrence [1]. Classical flash methods for determination of thermal diffusivity require knowledge of the exact thickness of the studied object or surface emissivity and absorptivity for correct determination of temperature distribution and light absorption [2–4]. This makes all of them too complicated and sometimes inapplicable, especially in cases when measurement should be done remotely and fast. Additional problems appear for inspection of objects with an inaccessible back side, like boxes, boarding, paneling or sheeting. Moreover, the problem of non-contact thermal diffusivity determination remains unresolved for very thick objects [5]. On the other hand, other object parameter-free single-side diffusivity measurement methods with analyses of temperature history have a limitation in minimal time for heating distribution analyses [6,7]. Presumably, the presented method, in combination with plane flash NDT methods, gives a possibility of fast determination of the thickness of a component. It also allows determination of subsurface structures or the location of defects in solid materials without previous knowledge of their thermal and optical properties. This can be done by thermal diffusivity determination using the presented method and subsequent NDT using the determined thermal diffusivity of the inspected material.

This paper presents a single-side laser-flash diffusivity measurement method, which is based on infrared thermography measurement [8] and a laser-flash pulse thermal excitation. In this method a flash-light source and infrared (IR) camera are installed in front of the studied object. A short flash irradiation of the object provides an instantaneous source of heat on the surface. The object́s heating temperature history measured by the IR camera allows to determine the thermal diffusivity of the material. The method is quick enough and fully non-contact.

Similar methods of thermal diffusivity measurement based on active infrared thermography principles are introduced for example by Vavilov et al. [9] or Cernuschi et al. [10]. The procedure published in [9] requires knowledge of the exact value of thickness of a tested sample. The method introduced in [10] assumes an accurate monitoring of surface temperature profile. Inputs for the method presented in this paper are laser spot size and relative changes of mean temperature. The novelty and main advantage of this method is that information of the exact thickness of a measured

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List of symbols

c	specific heat
c_l	light speed
C_1	first radiation constant
C_2	second radiation constant
$f_{T,t}$	modified temperature history function for central point
f_{rat}	rational fitting function of the modified time history
$f_{T(r,t)}$	modified temperature history function for whole area
g	substitution variable $g = R^2/4\alpha$
h	Planck's constant
I_0	modified Bessel function of the first order
I_b	radiation energy from blackbody
$I(\lambda)$	radiation energy from the "gray" surface recorded by IR camera
k	thermal conductivity
k_b	Boltzmann constant
L	thickness (of measured material)
m	calibration coefficient for extreme point position correction
n	dimensionless ratio parameter between previous and next time
p_1	coefficient of the rational function f_{rat}
p_2	coefficient of the rational function f_{rat}
Q	absorbed light energy
q_1	coefficient of the rational function f_{rat}
q_2	coefficient of the rational function f_{rat}
q	heat supply rate
R	radius of the spot
r	distance from the center of a light spot
t	time
t'	time in the next moment of the temperature history $t' = t \cdot n$
t_{max}	time value at maximum point in modified time
t_{ext}	theoretically derived position of the extreme point
T	temperature, temperature in the center of a light spot
T'	temperature in the next moment of the temperature history $T' = T \cdot V$
T_b	black body temperature
ΔT	temperature difference
V	dimensionless time parameter
w	substitution variable $w = e^{-r^2/12\alpha t}$
x	x-coordinate
y	substitution variable $y = g/t$
z	depth coordinate
α	thermal diffusivity
ε	emissivity
μ	diffusion length
λ	wavelength
ξ	geometric constant for diffusion length expression
ρ	density

object and surface temperature profile measurement are not required for the thermal diffusivity evaluation.

The proposed measurement set-up, procedure and data processing algorithm are described in this paper. Additionally, analysis of possible errors induced by the uncertainty of an inspected materials emissivity, some additional algorithms of the presented method and MATLAB simulations of irradiations of different materials with spot radius 1–4 mm are included. A validation of the method was carried out by thermal diffusivity measurements of tin, brass, steel and textolite samples, where a high-speed cooled infrared camera and a submillisecond laser-flash excitation source were used. The results are compared with Hot Disk [11] thermal diffusivity measurement results.

2. Theory of the method

Thermal diffusivity α (m^2/s) is one of the most important parameters of materials in thermal properties characterization. It is defined as:

$$\alpha = k/\rho c, \tag{1}$$

where k is thermal conductivity, and ρ and c are density and specific heat, respectively.

Thermal diffusivity determines the change of temperature which would be produced in unit volume by a quantity of heat flowing in unit time through a unit area of a substance layer of unit thickness with a unit difference of temperature between its faces [12]. In other words, thermal diffusivity defines the speed and distance at which changes of temperature propagate in a material. The distance μ is called diffusion length and it depends on the time of heat distribution t according to the equation:

$$\mu = \xi\sqrt{\alpha t}, \tag{2}$$

where ξ is a geometric constant, which depends on a particular geometry of the problem [13].

The basic idea of the presented single-side flash method is based on finding a characteristic point in the temperature history of temperature changes in the center of the irradiated spot. The important assumptions in this method are a short irradiation time and a homogeneous light spot with a circular form and adjusted radius. The temperature history in the center of a circle spot for infinite material is given by Carslaw and Jaeger as [12]:

$$\Delta T(z,t) = \frac{q}{2\sqrt{\alpha t}}\left[1 - e^{-\frac{R^2}{4\alpha t}}\right]e^{\frac{-z^2}{4\alpha t}}, \tag{3}$$

where q – is heat supply rate, t is time of temperature distribution from the heating pulse, R is the radius of the spot, and z is the depth coordinate in the sample body. The heat supply defines heat instantaneously liberated over the disc [12]. The solution is identical to the solution of an instantaneous surface heating source with double strength $2q$ in the case of a semi-infinite medium ($z \geqslant 0$) [14]. This solution is valid for the presumption of no heat losses to the exterior, which can be accepted for short-time processes. Therefore, on the plane surface $z = 0$ for a semi-infinite sample the temperature history of temperature becomes:

$$\Delta T(t) = \frac{q}{\sqrt{\alpha t}}\left[1 - e^{-\frac{R^2}{4\alpha t}}\right] \tag{4}$$

The temperature history defined by Eq. (4) does not have an extreme point, as can be seen in Fig. 1, calculated for tin irradiated by a light spot with 2 mm radius. Absence of the extreme point in Eq. (4) makes it difficult further mathematical data processing, which would lead to an evaluation of the thermal diffusivity from the temperature history. Vavilov et al. [9] suggested an artificial function (modified temperature history), which was obtained by multiplying a front-surface temperature evolution by the cubic root of time or by the n-th power of time with n varying from 0.01 to 1.0. This approach formed a temporal extreme point of the modified temperature history function.

The approach used in this work suggests modification of the temperature history function (4) based on its multiplication by