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DETERMINATION OF THERMAL DIFFUSIVITY OF AUSTENITIC STEEL USING PULSED INFRARED THERMOGRAPHY

WYZNACZANIE DYFUZYJNOŚCI CIEPLNEJ STALI AUSTENITYCZNEJ PRZY WYKORZYSTANIU AKTYWNEJ TERMOGRAFII PODCZERWIENI

The simple method of determining thermal diffusivity of solid materials at room temperature using the pulsed infrared thermography (IRT) is proposed. The theoretical basis of the method and experimental results are presented. The study was conducted on austenitic steel 316L. The obtained results show that the thermal diffusivity value of the tested steel determined by means of pulsed infrared thermography is very approximate to the values given in the literature, obtained by using more complicated methods. The differences between these values are 0.5%.

Keywords: thermal diffusivity, pulsed infrared thermography, heat conduction, austenitic steel

W niniejszej pracy przedstawiono prostą metodę wyznaczania dyfuzyjności cieplnej ciał stałych w temperaturze pokojowej przy wykorzystaniu aktywnej termografii podczerwieni. Zaprezentowane zostały teoretyczne podstawy metody oraz wyniki badań doświadczalnych. Badanie przeprowadzono dla stali austenitycznej 316L. Otrzymane rezultaty pokazują, że wyznaczona wartość dyfuzyjności cieplnej badanej stali jest bardzo bliska wartościom podanym w literaturze, otrzymanym za pomocą bardziej skomplikowanych metod. Różnica między tymi wartościami sięga zaledwie 0,5%.

1. Introduction

Thermal diffusivity is a material parameter describing the movement of the isothermal surface during the heat flow through the material. Therefore, this parameter is sometimes called the temperature conductivity. Thermal diffusivity α characterizes a material in a complex way, because it includes the heat conductivity λ, specific heat c and the mass density ρ of the material:

$$\alpha = \frac{\lambda}{c\rho}. \tag{1}$$

The range of thermal diffusivity values of solids is quite wide. For example, the thermal diffusivity of silver is $1.597 \times 10^{-4}\ \frac{m^2}{s}$; whereas, polystyrene thermal diffusivity is $1.172 \times 10^{-7}\ \frac{m^2}{s}$. The value of this quantity depends on the chemical composition of the material and its internal structure. Investigations of measurement techniques for thermophysical properties of solid materials are of great importance in relation to the development of new and advanced engineering materials. It is still necessary to improve and simplify already existing methods of determining characteristics of materials and develop new ones including methods of determining their thermal diffusivity.

Reviewing the literature, we can distinguish some methods of determining thermal diffusivity, such as the Angström method [1,2], the laser pulse method [2], or a few types of Poensgen apparatus [3].

The heat conduction equation can be solved for a wide variety of boundary conditions, and these solutions include values of the thermophysical properties [4-5]. Thus, the values of these properties can be determined by measuring appropriate temperature field and comparing the results with the solution of the heat conduction equation. However, the inability to satisfy the assumed boundary conditions in the experiment has led to disadvantages in some of the classic techniques. One of the disadvantages is trouble with ensuring the temperature increase of the specimen in accordance with a formula assumed in the boundary conditions [6]. Other disadvantages are caused by a thermal resistance between the specimen and its associated heat source. To avoid this difficulty, a flash method of measuring thermal diffusivity has been elaborated. Such approach was described for the first time in the seventies of the last century [7-10]. Since then, the world's scientific centres have been trying to develop the foundation of this method taking into account the possibilities offered by other research fields, such as laser technology [11-14]. However, all these methods are rather complicated, because of the manner of specimen preparation, complicated apparatus and measuring system, and sometimes a relatively long time of the study. Some of them require the use of advanced mathematical transformations.

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It seems that at present there is a lack of a method of determining thermal diffusivity, which would allow a quicker and simpler way to determine this quantity for solid materials. This state of the art constitutes the genesis of the study on the use of the pulsed infrared thermography (ITR) to determine the thermal diffusivity of solids.

Pulsed IRT is one of the active thermography methods based on stimulation of the material surface by a heat pulse (pulse duration is equal to few milliseconds) and recording the material response, as a time evolution of the surface temperature distribution, by means of an infrared (IR) camera. Such evolution contains information about thermal diffusivity of the tested material. The objective of the presented work is to extract this information.

2. Theoretical foundations of determining thermal diffusivity

The theoretical basis of determining thermal diffusivity of materials based on solutions of heat conduction equation formulated for a plate of a finite thickness when one of its surfaces is uniformly heated by a short heat pulse. If the surface of the plate is sufficiently large in comparison with the region of interest, it may be considered as infinite and then the one-dimensional model of heat conduction can be presumed (Fig. 1).

The heat conduction equation for the plate was solved on the basis of the following assumptions:

- The specimen of the measured material is infinite, homogenous and isotropic plate of constant thickness.
- The surface of the specimen is heated uniformly.
- The initial condition (before the heat stimulation): both surfaces of the plate are isothermal.
- It is assumed that the transport of heat by convection and radiation compared with the heat conduction mechanism are negligible.

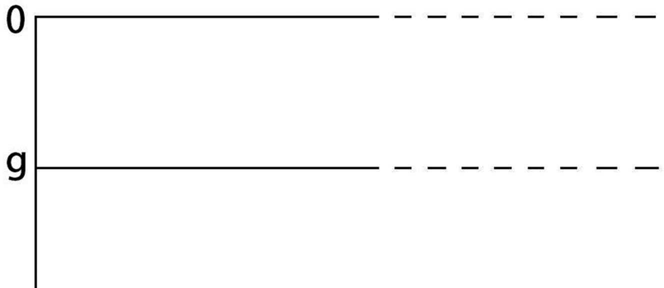

Fig. 1. Schematic representation of the infinite homogeneous layer of material

The solution of such problem determines the temperature as a function of time at any point of the specimen (Fig. 1.). The time evolution of temperature of the opposite surface with respect to the stimulated one is described by the solution for $z = g$. This solution includes the thermal diffusivity of the material of the plate. Therefore, if the temperature of this surface is measured in time, it is possible to determine the thermal diffusivity of the tested material.

The differential equation of heat conduction for the one-dimensional model has the following form:

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial z^2} + \frac{1}{\rho c} q, \tag{2}$$

where: α is the thermal diffusivity of the tested material, ρ is the mass density, c is the specific heat of the material and q is the function of heat sources associated with the surface density of energy Q_s delivered to the specimen during its heat pulse stimulation:

$$Q_s = \int_0^{\infty} \int_{-0}^{g} q\,(t, z)\, dt\, dz. \tag{3}$$

Eq. (2) has been solved for relatively simple, homogeneous initial and boundary conditions:

$$T\,(t = 0) = T_o, \tag{4}$$

$$\frac{\partial T}{\partial z}\,(z = 0) = 0 \text{ and } \frac{\partial T}{\partial z}\,(z = g) = 0. \tag{5}$$

To obtain the dimensionless form of Eq. (2) we introduce the following quantities:

$$\bar{t} = \frac{t}{t_c},\ \bar{z} = \frac{z}{g},\ \vartheta = \frac{T - T_o}{T_c},\ \bar{q} = \frac{q}{q_c}, \tag{6}$$

where: t_c is the characteristic time, g is the thickness of the specimen, t is time,

T is the current temperature, T_o is the initial temperature, T_c and q_c, are characteristic values of temperature rise and a function of heat sources.

$$t_c = \frac{g^2}{\alpha}\,[s] \tag{7}$$

$$q_c = \frac{\alpha}{g^3} Q_s \left[\frac{W}{m^3}\right], \tag{8}$$

$$T_c = \frac{1}{g\rho c} Q_s = \frac{g^2}{\rho c \alpha} q_c [K]. \tag{9}$$

Neglecting convection phenomenon it can be assumed that, after a relatively long time the temperature of the opposite surface with respect to the stimulated one will reach the maximum and constant value $T_\infty = T\,(t \to \infty)$.

Then

$$\frac{Q_c}{g} = \rho c\,(T_\infty - T_0)\,. \tag{10}$$

Therefore

$$(T_\infty - T_0) = \frac{Q_s}{g\rho c}, \tag{11}$$

taking into account Eq. (9):

$$(T_\infty - T_0) = T_c. \tag{12}$$

Thus, the characteristic temperature rise T_c is equal to the difference between the maximum temperature T_∞ of the opposite surface related to stimulated one and the initial temperature T_0 of the specimen.

By substituting the dimensionless parameters to the Eqs.: (2), (4) and (5), we obtain the dimensionless form of the heat conduction equation and initial and boundary conditions in dimensionless coordinates:

$$\frac{\partial \vartheta}{\partial \bar{t}} = \frac{\partial^2 \vartheta}{\partial \bar{z}^2} + \bar{q}, \tag{13}$$

$$\vartheta(\bar{t} = 0) = 0, \tag{14}$$

$$\frac{\partial \vartheta}{\partial \bar{z}}(\bar{z} = 0) = 0, \quad \frac{\partial \vartheta}{\partial \bar{z}}(\bar{z} = 1) = 0. \tag{15}$$

The dimensionless quantities are denoted by the bar. The formula for temperature of the tested surface as a dependence of time will be the function:

$$\vartheta(\bar{t}, \bar{z} = 1). \tag{16}$$

To find this function, we use "cosine" Fourier transform:

$$[\vartheta(\bar{t}, \bar{z})]_k = \int_0^1 \vartheta(\bar{t}, \bar{z}) \cos k' \pi \bar{z} d\bar{z}, \tag{17}$$

where $k = 0, 1, 2, 3\ldots\ldots$

Fourier transform of Eq. (13) has the form:

$$\begin{gathered} \int_0^1 d \frac{\partial \vartheta(\bar{t}, \bar{z})}{\partial \bar{t}} \cos k\pi\bar{z} d\bar{z} = \\ \int_0^1 \frac{\partial^2 \vartheta(\bar{t}, \bar{z})}{\partial \bar{z}^2} \cos k\pi\bar{z} d\bar{z} + \int_0^1 \bar{q} \cos k\pi\bar{z} d\bar{z} \end{gathered} \tag{18}$$

After calculating the appropriate integrals and using the adopted boundary conditions, we obtain:

$$\begin{gathered} \frac{d\,[\vartheta(\bar{t}, \bar{z})]_k}{d\bar{t}} = \\ -(k\pi)^2 [\vartheta(\bar{t}, \bar{z})]_k + [\bar{q}]_k \end{gathered} \tag{19}$$

After considering the initial condition and assuming a character of the heat source in the form: $\bar{q} = \delta(\bar{t})\,\delta(\bar{z})$, the solution of the Eq. (18) is the Fourier transform $[\vartheta(\bar{t}, \bar{z})]_k$ which has the following form:

$$[\vartheta(\bar{t}, \bar{z})]_k = \exp\left[(-k\pi)^2 \bar{t}\right]. \tag{20}$$

Inverse transform of the function Eq. (20) takes the form of the following Fourier series:

$$\begin{gathered} \vartheta(\bar{t}, \bar{z}) = [\vartheta(\bar{t}, \bar{z})]_{k=0} + \\ 2 \sum_{k'=1}^{\infty} [\vartheta(\bar{t}, \bar{z})]_{k'} \cos k\pi\bar{z}, \end{gathered} \tag{21}$$

where $k' = 1, 2, 3, 4\ldots\ldots$

Substituting Eq. (20) to Eq. (21), we obtain:

$$\begin{gathered} \vartheta(\bar{t}, \bar{z}) = 1 + \\ 2 \sum_{k'=1}^{\infty} \exp\left[-\left(k'\pi\right)^2 \bar{t}\right] \cos k'\pi\bar{z}. \end{gathered} \tag{22}$$

For $\bar{z} = 1$:

$$\partial(\bar{t}, \bar{z})_{\bar{z}=1} = 1 + 2(-1)^{k'} \exp\left[\left(-k'\pi^2\right)\right] \bar{t} \tag{23}$$

The elements of the series Eq. (23) are getting smaller with t, with an increase of the number k(long-time regime). So, it can be seen that for a sufficiently large value of t, error omission of elements $k > 1$ does not exceed the error of temperature measurement. Accordance with this approximation:

$$\vartheta(\bar{t}, \bar{z})_{\bar{z}=1} = 1 - 2\exp\left[(-\pi)^2 \bar{t}\right] \tag{24}$$

Substituting to Eq. (24):

$$\bar{t} = \frac{t}{t_c}, \ \bar{z} = \frac{z}{g}, \ \vartheta = \frac{T - T_o}{T_c}, \ T_c = T_\infty - T_0, \tag{25}$$

we obtain the dimensional form of the expression for the temperature of the specimen surface (opposite to the stimulated one).

$$T(t) = T_\infty - 2(T_\infty - T_0)\, exp\left(-\frac{\pi^2 \alpha}{g^2} t\right), \tag{26}$$

The logarithm of this equation has a linear character:

$$\ln(T_\infty - T) = (-\frac{\pi^2}{g^2}\alpha)t + \ln 2(T_\infty - T_0), \tag{27}$$

where

$$\frac{\pi^2 \alpha}{g^2} = A \tag{28}$$

is the tangent of the slope straight line to the timeline.

So, if one of the specimen surfaces will be heated by a short impulse of heat and the temperature of the opposite surface will be measured as a function of time, we can determine the thermal diffusivity α:

$$\alpha = \frac{g^2 A}{\pi^2}. \tag{29}$$

3. Experimental procedure and results

The specimen was cut out from 316L austenitic steel sheet of 1.5 mm thickness. Other dimensions of the specimen were chosen in such a way, so that the influence of its edges on the surface temperature distribution was negligible. In order to ensure high and homogeneous emissivity the specimen surface was coated by graphite paint. The emissivity of graphite is 0.86. The surface of the specimen was uniformly heated using the halogen lamp of the pulse energy of 6 kJ. Pulse duration was 3 ms and the lamp to specimen distance was equal to 0.5m. Temperature distribution on the opposite surface vs. time was measured by the Titanium 560M infrared thermographic system (Cedip Company) with InSb detector. The spectral range of the detector was (3.6-5.1) μm. The thermal sensitivity of the system at 25°C is 20 mK. The thermal images (640×512 pixels) were recorded with the frequency 100 Hz. The IR camera and stimulating lamp were located at the rear side of the specimen (Fig. 2).

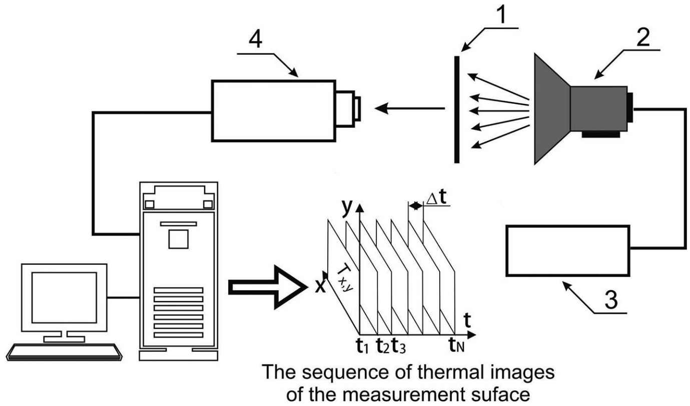

Fig. 2. The scheme of the measuring systems for determining the diffusivity of solids.
1 is specimen, 2 is flash lamp, 3 is power supply, 4 is IR camera, 5 is computer with appropriate software to enable recording thermal images of the specimen surface as functions of time

The thermal image is a surface distribution of infrared radiation power, emitted by the tested surface. This distribution depends on emissivity of the surface and temperature distribution on this surface. Thus, knowing the emissivity of graphite (ε =0.86), the surface temperature distribution was determined and the average value of temperature of the specimen's back surface as a function of time was obtained. This function is presented in the Fig. 3.

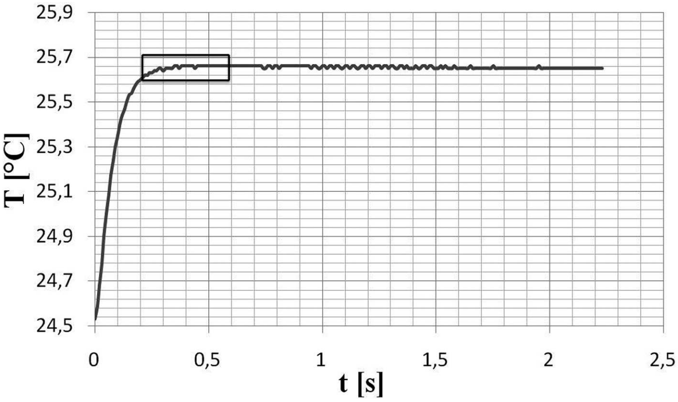

Fig. 3. Experimentally determined the surface temperature vs. time. The marked plato shows that the convection development requires a certain time interval

In the Fig. 3, there is a fragment of a graph, in which the average temperature value of the tested surface is constant. Hence, it may be concluded that the process of convection does not develop until $t = 0.72\,s$, and it may be not taken into consideration. The maximum temperature $T_{\max}$ is equal to the surface temperature T_∞, which would be reached after a long time if heat convection did not take place, $T_{\max} = T_\infty$.

On the basis of experimental data presented in Fig. 3 the difference between the maximum value of temperature $T_{\max}$ and current values (T) as a function of time has been calculated (Fig. 4).

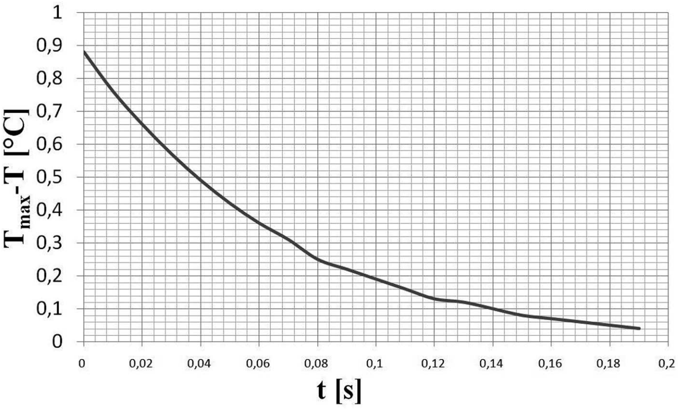

Fig. 4. The difference between the maximum value of temperature ($T_{\max}$) and current values (T) as a function of time

The dependence of $\ln(T_{\max} - T)$ on t is presented in Fig. 5.

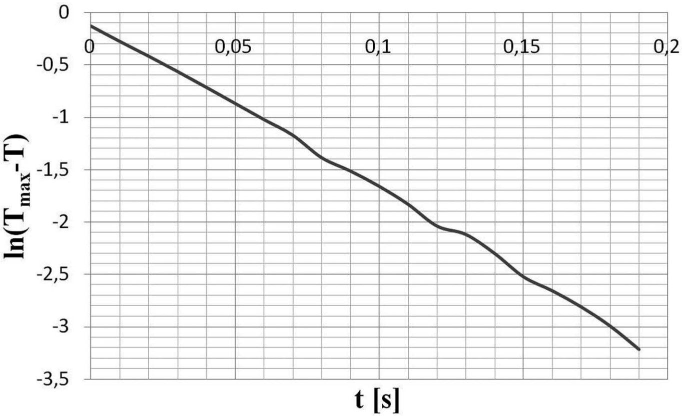

Fig. 5. The dependence of $\ln(T_{\max} - T)$ on time

The graph of this dependence has been approximated by the straight line:

$$\ln(T_\infty - T) = -16.13t + 0.078 \tag{30}$$

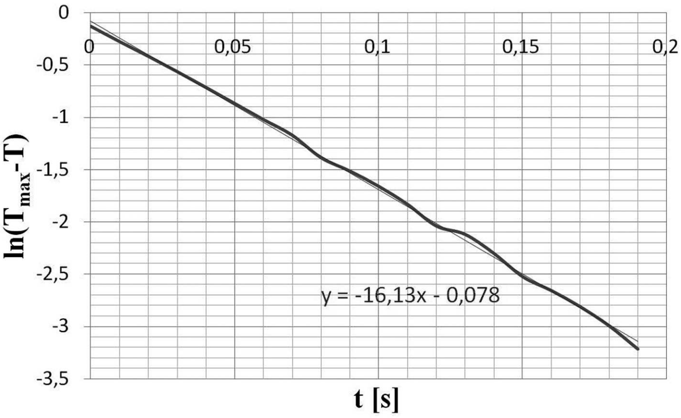

Fig. 6. The dependence $\ln(T_{\max} - T)$ vs. time approximated by the straight line:
($y = -16.13x - 0.078$).

The comparison of the equation of this line with Eq. (27) (Fig. 6) shows that

$$\frac{\pi^2\alpha}{g^2} = 16.13\ s^{-1}. \tag{31}$$

Thus, after transformation of Eq. (31) and substituting the value of the specimen's thickness g =1,5 mm, the value of thermal diffusivity of 316L steel was determined,

$$\alpha = 16.13\frac{0.0015^2}{\pi^2} = 3.67 \times 10^{-6}\frac{m^2}{s}. \tag{32}$$

In the TABLE 1, values of thermal diffusivity determined in a triple repetition of the experiment are presented.

TABLE 1

The results of measurements

Number of measurement	Determined value of thermal diffusivity of steel 316L $\left[\frac{m^2}{s}\right]$
1	3.67×10^{-6}
2	3.67×10^{-6}
3	3.61×10^{-6}
Average value	3.65×10^{-6}

The obtained results indicate the correctness of the presented approach.

The TABLE 2 presents the comparison of the value of tested steel determined by means of active thermography with the steel diffusivity given in the literature [15].

TABLE 2

Comparison of the thermal diffusivity of steel 316L obtained in the presented work the values for this steel given in [15]

The thermal diffusivity of steel 316L given in [15]	The thermal diffusivity of the same steel determined in the presented work
$3.71 \times 10^{-6}\ \frac{m^2}{s}$	$3.65 \times 10^{-6}\ \frac{m^2}{s}$

4. Concluding remarks

The value of the thermal diffusivity of austenitic steel determined using pulsed IRT is very approximate to literature ones obtained by using more complicated methods. The difference between these values is 0.5%.

The advantages of the proposed method are as follows:

- a contactless method,
- a really simple measurement methodology,
- a simple arrangement of a measurement system,
- short time of measuring,
- simple way of specimen preparation,
- making use of the solution of the equation of heat conduction for simple boundary conditions,
- easy interpretation of results.

The presented method has also some limitations as a relatively high cost of thermographic system, and the necessity to cover the surface of the specimen with substance of high emissivity. The presented method allows to determine the thermal diffusivity of materials only at room temperature

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