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Letter to the Editor

Determination of thermal diffusivity on the base of imaged temperature field induced by laser radiation*

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1. Introduction

An application of laser in examinations of thermophysical properties, including the determination of thermal diffusivity α is based on specific properties of laser heating of the sample surface, which are: i) possibility of a relatively simple regulation of both the power density and duration of the energy stream, ii) a possibility of quick (up to 10^{10} K/s) heating up the small objects while the quasi-adiabatic conditions are realized, iii) a possibility of heating up to the higher temperature without object contact with the other materials [1].

The experimental methods of determination of the thermal diffusivity α are based on analysis of the heat pulse passage via a plane-parallel plate, one surface of which is irradiated with a short pulse light [2], [3].

When the sizes of the sample heated at its centre are much greater than the diameter $2R$ of the irradiating beam then according to [4] (radial-heat flow method)

$$\alpha = R^2 \tau / t \tag{1}$$

where t denoted the time, and τ — the Fourier number.

In this method, the determination of α requires that both the temperature history T_r on the other side of the sample at the fixed distance $r > R$ and the temperature history T_0 for $r = 0$, i.e., on the axis of the heating beam (Fig. 1) be recorded. For given relations $\psi = r/R$ and $x = \Delta T_r / \Delta T_0$ the Fourier number may be calculated [4] (ΔT_r and ΔT_0 are the temperature increments at the points $r > R$ and $r = 0$, respectively).

The histories of temperatures T_r and T_0 are recorded usually with the help of thermocouples [4]. In this work the history of temperatures on the surface of sample (and its surface distribution) are recorded with the help of liquid-crystal temperature indicator LTI [5].

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The purpose of this work is to show that the time-varying surface temperature distributions may be applied while determining the thermal diffusivity α (for St3SX steel, as an example) with the help of the radial-heat flow method.

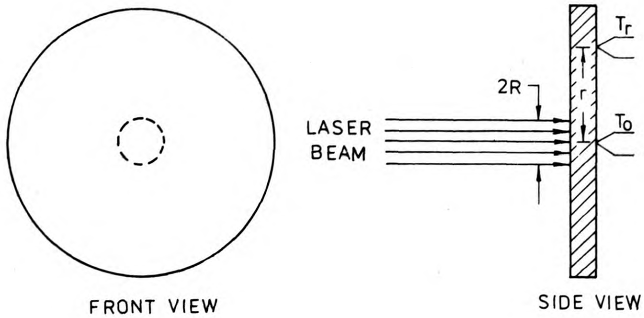

Fig. 1. Scheme of the radial-heat flow method [4]

2. Experiment

The scheme of the measuring setup used in the examinations is shown in Fig. 2. The neodymium glass laser radiation ($\lambda = 1.06$ μm, $\tau_i = 2$ ms, $E = 6.0$ J), the power density distribution of which being close to that of Gaussian type (the laser

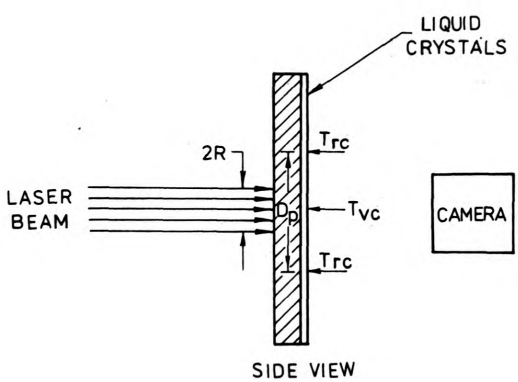

Fig. 2. Scheme of measurement setup

working in the free-generation regime) is directed to the central part of the plate made of St3SX steel. The applied power densities were such that the absorbed energy caused only the heating of the irradiated region up to the temperature higher than the hardening temperature (for the St3SX steel the hardening temperature being 850°C). The sample of dimensions $90 \times 80 \times 3.7$ mm was chemically blackened in order to increase the coefficient of absorption of the incident radiation as well as to improve the visualizing conditions of the coloured temperature map observed in the white light.

A thin LTI layer was a mixture of chloride propionate and cholesterol oleate changing its colour with the temperature as follows: red colour – $T_{rc} = 30.7$°C, orange colour – $T_{oc} = 31.3$°C, yellow-green colour – $T_{ygc} = 31.7$°C, green colour – $T_{gc} = 32.4$°C, blue colour – $T_{bc} = 33.2$°C and violet colour – $T_{vc} = 33.5$°C.

The change of colour of indicator in time, i.e., its equivalent temperature field on the sample surface was recorded on a negative ORWO CHROM colour film of 15 DIN sensitivity with the help of Arriflex camera. The filming speed was 24 frames per second. The sample was kept at the T_{rc} temperature, while the selected

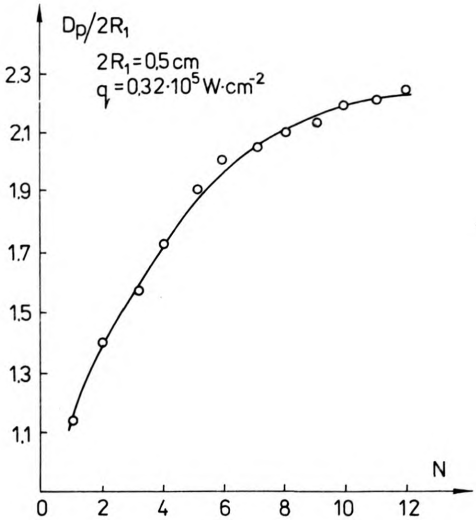

Fig. 3. Ratio of the diameter D_p of the region limited by the T_{rc} isotherme to the diameter of the "flair" diameter $2R$ vs time (number of frame N)

power density of the laser light pulse was such that, due to heating, the temperature at the back surface of the sample did not execeed T_{vc}. The maximal diameters $2R$ of the irradiated regions were much smaller than the sample dimensions.

3. Results

Irradiation of the sample with the laser light beam of power distribution similar to that of Gaussian type leads to the appearence of a colour, changing in time map generated by a definite temperature field [5]. This field is characterized among others by the fact that after some time there appears in its central part a region of violet colour (which corresponds to the T_{vc} temperature), surrounded by the T_{bc} isotherm. In another, radially distributed region surrounding the first one, the temperature decreases from T_{bc} to T_{rc} with the increasing distance from the centrum.

When analysing the colour maps of the temperature recorded on the sequential film frames the diameters of D_p of the regions limited by the isotherm T_{rc} may be measured among others. From the measurements it follows that the magnitude of diameters D_p is a function of time t which elapsed from the moment of sample irradiation to the moment of colour map recording. The diameter of the "trace" on the sample surface, i.e., the region of changed colour due to oxidation, has been assumed as a beam diameter $2R$. Next, the magnitude of $\psi = r/R = D_p/(2R)$ has been determined as a function of time t (frame number N, Fig. 2, Table).

Moreover, as already mentioned in the Introduction, in order to determine the

Results of the measurements (t, R – average time and average radius of the "trace" determined from several measurements for the power density q from the range $(0.32\text{–}0.50) \times 10^5$ W cm^{-2})

$\psi = D_p/(2R)$	τ	t [s]	τ/t [s^{-1}]
1.7	0.28	0.144	1.94
1.8	0.36	0.171	2.11
1.9	0.44	0.198	2.22
2.0	0.50	0.235	2.13
2.1	0.57	0.283	2.01
2.2	0.65	0.338 .	1.92

Fourier number τ the ratio of the temperature increments ΔT_r at the distance r from the beam axis to the temperature increments ΔT_0 at the beam axis, i.e., $x = \Delta T_r/\Delta T_0 = (T_{oc} - T_{rc})/(T_{vc} - T_{rc}) \simeq 21.4\%$ must be known. Thus, if the value of ψ at different moments of time and also the time-constant value of x are known, it is possible to estimate τ (Table) by taking advantage of the relation shown in Fig. 2 in [4] and to calculate α from formula (1)

$$\alpha = R^2 (r/t)_s = (0.225 \text{ cm}^2 \times 2.055 \text{ s}^{-1} = 0.104 \text{ cm}^2/\text{s}$$

where $(r/t)_s$ is an average value of this quantity taken from Table.

4. Conclusions

1. The time-dependent distributions of temperature recorded with the help of LTI [5] may be used to determine the coefficient α.

2. The values of α determined in this way remain in reasonable consistence with the values of α determined by other method [6].

3. Application of surface temperature distributions generated by laser irradiation and recorded with the help of LTI in order to determine α (due to radial heat-flow method [4]) is a new way of measuring this quality.

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