Optica Applicata, Vol. XVI, No. 3, 1986

Letter to the Editor

On a possible application of liquid crystals to visualization of temperature maps evoked by laser radiation

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1. Introduction

The detection of small temperature differences and production of temperature maps is an important measurement technique in the non-destructive investigations [1], [2]. However, the devices used in this method are both complex and expensive. For this reason many replacement techniques are being developed. The evaporography and the technique of temperature map determination based on properties of the so-called liquid crystals may be mentioned, among others [3], [4].

The most popular applications of cholesterol liquid crystals are based on the selective reflection of light from the planary oriented layers made of these substances. The colour of the selectively reflected light depends on many external factors. Among the latter the colour dependence on the substance temperature is very important for these applications. Due to this property a thin layer of cholesterol liquid crystal covering the surface of a solid body maps very exactly the temperature distribution across this surface in the form of a colour map.

The first step in temperature distribution examination (thermography) on the surface of a definite body is to select a suitable cholesterol mixture so that the colour corresponding to the lowest temperature on the examined body be red changing over to the blue-violett colour at the place of highest temperature [4].

Thermooptical properties of liquid crystals may be exploited also for visualization of the transverse field of laser light beam ([5] for He-Ne laser, or [6] for neodymium glass laser working in the system with the q-factor modulation).

One of the authors of the present work (K. Rożniakowski [7]) applied also cholesterol liquid crystal indicators of temperature (LIT) to estimate the average distribution of power density in the cross-section of the light beam emitted by neodymium glass laser working in the free generation regime.

The purpose of our work was the measurement of small temperature differences and the recording of surface temperature fields (STF) changing in time and evoked by the laser radiation. Examinations of this kind may be applied in laser processing of materials, for instance.

2. Experiment

The scheme of the measurement setup used in the examinations is shown in Fig. 1. The neodymium glass laser radiation of power density distribution either similar to that of Gaussian type or of high spatial disorder was directed onto a plate made of St3SX steel [8]. The laser worked in the free generation regime ($\lambda = 1.06$ μm, $\tau_i \approx 2$ ms, $E = 6$ J). The laser light pulse parameters were recorded by

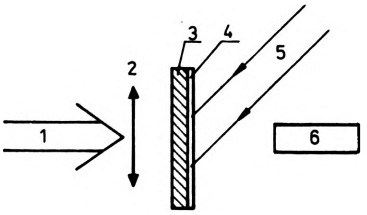

Fig. 1. Block scheme of the measuring setup: 1 – light beam of the Nd^{+3} laser, 2 – lens, 3 – sample, 4 – LIT, 5 – white light beam, 6 – photocamera

using the method described in [7]. The power density of radiation incident on the surface of the sample was changed by changing the geometry of irradiation. The applied power densities $q = (0.32\text{–}1.38) \times 10^5$ W cm^{-2}, were such that the absorbed energy caused neither evaporation nor melting of the irradiated region of the sample but only some heating of this region up to the temperature higher than the hardening temperature (for the St3SX steel the hardening temperature is ~ 850°C).

The sample of sizes $60 \times 50 \times 3.7$ mm was chemically blackened in order to increase the absorption coefficient of the incident radiation and to improve the conditions of visualization of the colour map of temperature observed in the white light.

A thin LIT layer was composed of a mixture of propionate chloride and olein cholesteride produced at the Institute of Physics, Technical University of Łódź (Poland). LIT changed colour when changing the surface temperature in the following way: $T_r = 30.7$°C, $T_o = 31.3$°C, $T_{yg} = 31.7$°C, $T_g = 32.4$°C, $T_b = 33.2$°C, $T_v = 33.5$°C.

Change of colour indicator in time, and thus the equivalent (STF) was recorded on a negative colour ORWO CHROM film of 15 Din sensitivity by using the Arriflex film camera. The rate of taking pictures was 24 frames per second.

The sample was kept at the temperature T_r while the light pulse power density was selected so that the temperature of the back side of the sample covered with LIT did not exceed the T_v temperature due to the laser heating. The maximal diameters d of the irradiation regions were much smaller than the sizes of the sample.

3. Results

On the basis of an exact analysis and measurements of the spatial distribution of colours of STF recorded on N first successive frames of the film the basic results of examinations may be formulated as follows.

1. Irradiation of sample with a laser light beam of high spatial disorder leads to creation (on the back side of the sample) of an initially disordered STF which is mapped by LIT in the form of a colour map (Fig. 2). After a period of time depending on q value this distribution becomes radially symmetric. It is characteri-

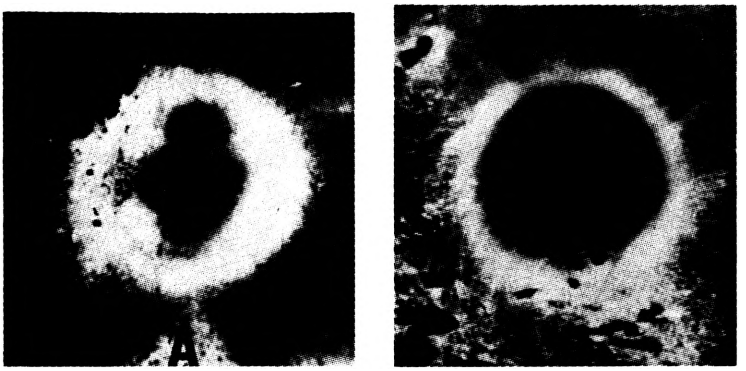

Fig. 2. Photography of the temperature map. Dark region in the middle of the photo corresponds to the violet and blue colours. Power density distribution spatially disordered (A) and similar to Gaussian (B)

stic that in its central part there occurs a region (of diameter D_v) limited by the isotherm T_0. Inside this region there exists a radially distributed area in which the temperature is maximal and equal to T_v.

When the sample was irradiated by a laser beam of the spatial power distribution close to that of Gaussian type the spatial distribution of temperature recorded by LIT was, as it should be expected, radially symetric from the very beginning (Fig. 2). This means also that the thermal properties of the sample in the irradiated regions were isotropic.

2. When analysing the spatial distribution of colours recorded on successive frames of the film the temperature distribution $T=f(R)$ may be determined for each frame N, i.e., at the time intervals $t_1 \approx 1/24$ s, where R is the distance

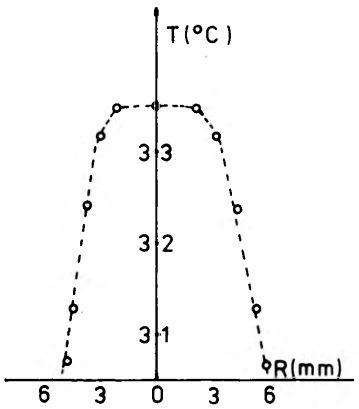

Fig. 3. Spatial distribution of temperature $T=f(R)$, ($N = 3$ from the initial point exposure, $q = 0.50 \times 10^5$ Wcm^{-2})

measured from the centre of the violet region to successive colours taken by the indicator. As an example the distribution $T=f(R)$ recorded on a frame $N = 3$ and produced by a laser pulse of power density $q = 1.38 \times 10^5$ Wcm^{-2} is shown in Fig. 3. From this distribution it follows that $D_v = 5$ mm and $D_o = 11$ mm. By taking account of this distribution the temperature gradient k defined as

$$k = \frac{\Delta T}{\Delta R} = \frac{2(T_v - T_o)}{D_o - D_v}$$

may be determined.

The magnitude of diameters D_o and D_v is evidently a function of time. The course of these dependences as function of N is shown in Fig. 4 for $q = 0.50$

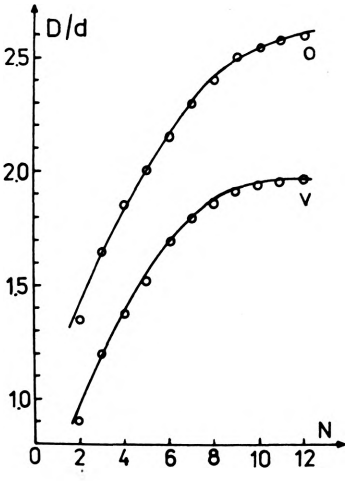

Fig. 4. Course of D/d as a function of time (number of frame N) for an isotherm corresponding to orange (o) colour ($T_o = 31.3$°C) and (v) violet ($T_v = 33.5$°C)

$\times 10^5$ Wcm^{-2}. Thus, the value k depends also on time which elapses from the exposure of the sample to the moment of temperature recording. The spatial distribution of temperature is characterized, among others, by the fact that at the time $t = t_m$, D_v reaches its maximal value equal to D_{vM}. The magnitude D_{vM} in our examinations depends on q (Fig. 5) and is an increasing linear function of q.

3. The applied power densities were such that they caused no significant damage of the front side of the sample. However, the absorbed energy was so large

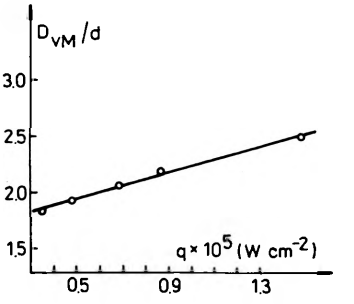

Fig. 5. Course of (D_{vM}/d) *for violet colour vs* q

that the surface layer of the steel was heated up to temperature higher than the hardening temperature.

By taking advantage of the methodics presented in [9] the average thicknesses of the hardened steel layer were measured and the average temperature $T(0, \tau_i)$ on its surface after a time $t = \tau_i$ (τ_i – laser pulse duration) was calculated. This temperature is a function of power density q of the radiation incident on the sample, similarly as was the case in [9]. The dependence $T(0, \tau_i)$ as a function of q is shown in Fig. 6. At the moment $t = t_m$ (Fig. 4) the quantity D (for any colour)

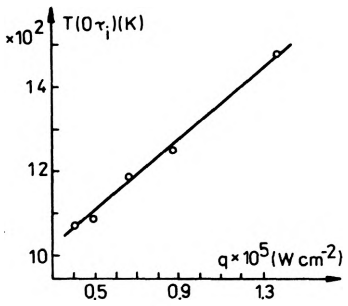

Fig. 6. Temperature $T(0, \tau_i)$ as a function of the power density q of the incident radiation

reaches its maximal value which means that at the moment t_m the temperature on the other side of the sample has also reached a maximal value. For the power density $q = 1.48 \times 10^5$ Wcm^{-2}, $t_m = 0.375$ s. The time t_m may be understood also as a sum of pulse duration τ_i and the time of retardation Δt, i.e., $t_m = \tau_i + \Delta t$. In other words the retardation Δt is the time needed for the isotherm T_v to reach the other side of the sample (covered with LIT). Taking account of the formulae (3) in [9] this retardation may be calculated also by using numerical methods. The value of t_m obtained in this way is $t'_m = 0.36$ s, i.e., it is reasonably consistent with the time t_m measured by means of LIT.

4. Conclusions

From the examinations carried out by us it follows that the liquid crystal indicators of temperature may be applied to estimation of the spatial distribution of laser radiation power density, which remains in good agreement with the results of similar examinations presented, among others, also in [2], [5], [6].

The selection of suitable parameters of the laser beam and the thermal properties of the sample gives also a possibility of exploiting the LIT to record the space-time changes of temperature generated by laser radiation in metals.

Thus, the LIT may, in our opinion, find application also in non-destructive laser examinations of both cognitive and practical character.

Acknowledgements – One of the authors (K. R.) wishes to express his thanks to Mr J. Bławut and A. Janicki, M. Sc., for filling the map of temperature, and to Mr W. Wypych for making the photographs.

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Received April 29, 1986