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# Letters to the Editor

## An application of the hardening effect to the estimation of the reflection coefficient of laser radiation*

Kazimierz Rożniakowski, Stanisław Włodarczyk

Institute of Physics, Technical University of Łódź, ul. Wólczańska 219, 93–005 Łódź, Poland.

### 1. Introduction

One of the most promising ways of material processing is that with the use of laser. Theoretical bases of the laser technology of material processing and, especially, of both the metals and their alloys are presented in papers [1–4]. In accordance with the tendency of the specialized application of lasers in technology, observed during the last years, the optimization of the operation of the respective devices used in the concrete situations becomes of great significance. The choice of optimal operating conditions allows such devices to be exploited with the maximum efficiency, their weight and sizes be diminished and the costs of processing under industrial condition reduced [5].

There exist many effects influencing the energy losses in the process of laser heating of the material (steel, for instance). One of them is the reflection effect, which may be characterized by the total coefficient of reflection $R$ of the irradiated surface ($R = Q_1/Q_2$, where $Q_1$, $Q_2$ – power densities of the reflected and incident radiations, respectively, directed onto the sample [6]). Obviously, $R$ should not be indentified with the Fresnel coefficient of reflection determined experimentally for small power densities, because the laser radiation pulse ($Q_2 \geqslant 10^4$ W/cm$^2$) changes significantly the structure of the surface in the region of irradiation. For such power densities the quantity of the absorbed light energy is sufficient to heating up the near-surface layer $l \simeq (10^{-4}–10^{-5})$ cm ($l_\lambda$ – being the distance passes by the laser photon of the wavelength $\lambda$) to the critical temperature [7].

Then, there appears a layer of plasma on the way of the incident radiation, which washes away the sharp limit ($\sim 10^{-8}$ cm) between the surface of a solid body and its surrounding. The reflection of the strong light pulse from such a transition layer depends on the density distribution which, in turn, depends obviously upon the properties of the matter (among others also upon the way of preparing the surface, for instance, on its roughness [8], [9], incident radiation

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power density and also on the space-time character of the applied light pulses [7]). Thus, the problem of light absorption by different metals or their alloys is very complex because of many factors that can influence the interaction mechanism.

Hence, many experimental and theoretical works have been devoted to determination of the reflection coefficient $R$ (for instance [10–14]), but as yet this problem has not been completely examined and clarified. It is obvious that this problem is of cognitive significance and that the examinations carried out in this field may also be used to optimize the working parameters of the laser devices in real technological operations.

To the authors' knowledge, no attempts have been made yet to determine the reflection coefficient $R$ by exploiting the phase transition temperatures occurring in the material due to the heating by laser light. Hence, in this work it is suggested that the reflection coefficient $R$ for the neodymium glass light from the surface of steel 45 be determined from hardening effect in near-surface layer of the steel sample.

## 2. Theoretical principles

### 2.1. Heating

It is well known [1–4], [15] that the heat source appearing in the metal (alloy) due to laser light absorption may be considered to be a surface source. This is justified by the fact that for such materials the depth of light penetration is much less than that of the layer heated due to thermal conduction.

If the energy of laser pulse of the duration $\tau$ is suitably high then, after the steel surface is irradiated by such a pulse, a layer of maximal depth $z_h$ may be hardened (a phase transition may occur).

If the following assumptions are made:

– laser pulse is of rectangular shape and the time development of the power density is of the form

$$Q_2(t) = \begin{cases} Q_2 & \text{for } \tau \geqslant t > 0 \\ 0 & \text{for } \qquad t > \tau \end{cases}; \tag{1}$$

– power density has such a value that neither evaporation nor melting of the surface occurs in a distinct way;

– energy losses at the sample surface due to irradiation and convection are negligible;

– physical constants of the irradiated material do not depend on the temperature;

– irradiated sample is a half-infinite body restricted by the plane through which the heat power density described by (1) is provided;

then the temperature distribution for times $t > \tau$ along the axis $z$ perpendicular to the plane of the radiation incidence is given by the formula [16]

$$T(z,t) = \frac{2Q\sqrt{a}}{K}\left[\sqrt{t}\, i\, \mathrm{erfc}\left(\frac{z}{2\sqrt{at}}\right) - \sqrt{t-\tau}\, i\, \mathrm{erfc}\left(\frac{z}{2\sqrt{a(t-\tau)}}\right)\right] \tag{2}$$

where: $a$ – temperature conduction coefficient, $K$ – thermal conduction coefficient, $z$ – distance from the surface of heat supply plane, measured along the axis perpendicular to this plane, $Q$ – power density absorbed by the sample. The $i\,\mathrm{erfc}(x)$ function is defined as follows:

$$i^n \mathrm{erfc}(x) = \int_x^{\infty} i^{n-1} \mathrm{erfc}(\xi)\, d\xi, \qquad n = 1, 2, \ldots,$$

$$\mathrm{erfc}(x) = 1 - \mathrm{erf}(x), \ \mathrm{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-\xi^2} d\xi.$$

At the definite depth $z_h$ the temperature reaches the maximal value after the time $t_h = \tau + \Delta t$. The time $\Delta t$ may be determined from the condition [17]

$$\left.\frac{\partial T(z,t)}{\partial t}\right|_{z=z_h} = 0, \tag{3}$$

which leads to the equation

$$\frac{\sqrt{\Delta t}}{\sqrt{\tau + \Delta t}} = \exp\left[-\frac{z_h^2 \tau}{4a\Delta t(\tau + \Delta t)}\right]. \tag{4}$$

The value of $\Delta t$ may be estimated numerically from Eq. (4).

### 2.2. Reflection coefficient

There exists a relationship between the incident power density $Q_2$ and absorbed power density $Q$ [6]

$$Q = (1-R)Q_2 \tag{5}$$

where $R$ is the reflection coefficient of radiation reflected from the surface.

By taking account of Eq. (5) in formula (2) the reflection coefficient $R$ may be presented in the form

$$R = 1 - \frac{T_h K}{2Q_2\sqrt{a}}\left[\sqrt{t}\, i\,\mathrm{erfc}\left(\frac{z_h}{2\sqrt{at}}\right) - \sqrt{t-\tau}\, i\,\mathrm{erfc}\left(\frac{z_h}{2\sqrt{a(t-\tau)}}\right)\right]^{-1}. \tag{6}$$

Equation (6) may be used to determine $R$ since: for the given material (type of steel) the hardening temperature $T_h$ is known, $z_h$ may be measured on the basis of metalographic cross-section, while $t = t_h = \tau + \Delta t$ being equal to the sum of time $\tau$ (duration of laser pulse) and the time $\Delta t$ may be determined numerically from Eq. (4).

It should be emphasized that the hardening effect has been here expolited only for determining the maximal temperature (in this case the hardening temperature at the depth $z_h$). This is, however, only one of many possibilities. The same temperature may be determined also on the basis of other phase transitions known for given a material.

## 3. Method of examinations

The object of examinations was a sample of 20 cm diameter and 6 mm thickness performed of steel 45 ($T_h = 850°\,C$, $K = 0.335$ W/cm K, $a = 0.15$ cm$^2$/s) of roughness $\bar{h} = 0.7$ μm measured by using an optical method [8]. The sample was irradiated at 10 different places by light pulses from neodymium glass laser working in the regime of free generation in one transversal mode $TEM_{00}$ ($\lambda = 1.06$ μm, $Q_2 \simeq 1.5$ J, $\tau = 0.002$ s).

The pulse power density has been changed by altering the geometry of the focusing system. The pulse parameters ($\tau$, $Q_2$) have been measured according to the methods reported in paper [18]. After irradiation the metallographic cross-sections of the irradiated sample regions have been made and the depths $z_h$ of the hardened regions measured with the help of Epityp 2 metallographic microscope and BS 300 electronic microscope. The diameters of the observed regions were much greater than the maximal hardening depths $z_h$. Next, the corresponding coefficients of reflection $R$ have been calculated from the formula (6).

## 4. Results and conclusions

In Figure 1 the photos of metallographic cross-sections of two regions of the samples irradiated by neodymium laser pulse light have been presented. The photo **a** was made with the help of Epityp 2 microscope while the photo **b** with the help of BS 300 microscope. Maximal thicknesses of the hardened layer amounted to 80 μm and 100 μm, respectively.

The reflection coefficient $R$ determined from the formula (6) depending on the power density $Q_2$ of the incident beam is shown in Fig. 2.

The character of the dependence obtained in the examined range of power density indicates that the coefficient $R$ depends only slightly on $Q_2$. The value of the coefficient $R$ ranges within 50–70$^0/_0$ interval which is in good agreement with the results of investigations presented, e.g., in papers [5], [7], [10], although the way of preparation of the surface to irradiation has not been reported.

In the graph the errors $\Delta R$ calculated from the formula

$$R = \sum_n (\partial R/\partial x_n)\,\Delta x_n \tag{7}$$

are also marked, where $x_n$ — successive quantities appearing in (6), $\Delta x_n$ — measurement errors of these quantities. In the determination of $\Delta R$ no error caused by the approximate description of the heating up process of the real sample by the model of half-infinite body has been taken into account.

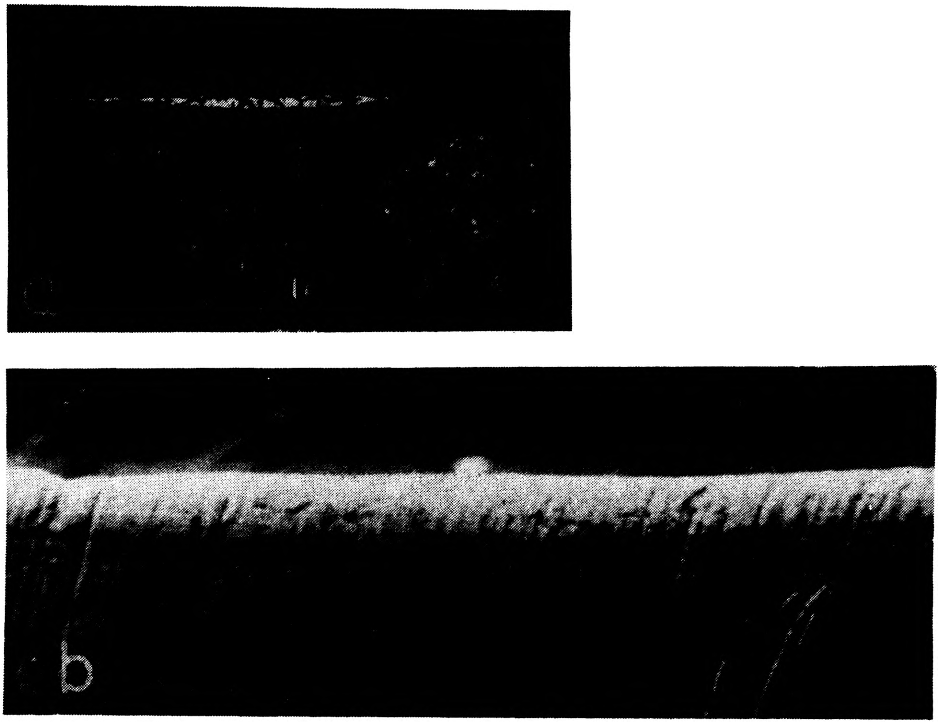


Fig. 1. Photos of the metallographic cross-sections of two irradiated regions of the sample. The photo **a** was made with the aid of the Epityp 2 microscope, and **b** – by using the BS 300 microscope. Maximal thickness of the hardened layer amounts to 80 and 100 μm, respectively

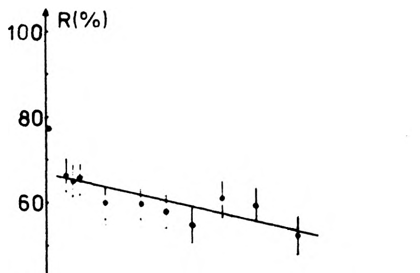


Fig. 2. Dependence of the reflection coefficient $R$ upon the power density $Q_2$ of the incident beam

The method of $R$ determination proposed by us may find its application mainly to such metals and their alloys, for which the phase transition temperature is well determined and the border of this transition can be obtained in the metallographic cross-section.

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