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ONE METHOD OF DETERMINATION OF THE EFFECTIVE ABSORPTION COEFFICIENT IN PULSED LASER IRRADIATION OF METALS

A. Evtushenko,[a,b] E. Ivanik,[a] and K. Rozniakowski[b]

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An experimental-theoretical method of determination of the absorption coefficients in laser treatment of metals has been proposed based on the solution of the boundary-value axisymmetric problem of heat conduction for a half-space and metallographic measurements of the dimensions of the thermal-hardening zone.

Introduction. In investigating numerous processes occurring in a deformed medium under the action of pulsed laser irradiation, one must know, where possible, the reflection coefficient R or the absorptivity $A = 1 - R$ of the irradiated material with the highest degree of exactness. The values of the indicated parameters depend, first of all, on the electromagnetic wavelength, grade of steel (mainly its chemical composition), temperature, finish of the working surface of a metal, and properties of the environment [1].

It is clear that the parameters R and A in laser irradiation of materials do not coincide with the corresponding Fresnel coefficients which are found experimentally or numerically for ideally smooth and clean surfaces at low specific powers of electromagnetic radiation not changing the properties of the metal in the irradiation zone. At the same time, a laser pulse even of a low specific power ($Q \cong 10^8$ W/m^2) substantially affects the structure and chemical composition of the irradiated material, initiating different thermochemical processes, such as nitriding and oxidation, with subsequent change in the optical properties of the surface layer. On the other hand, with such a power the quantity of the energy absorbed is sufficient to heat a thin near-surface layer about 1 μm thick to a temperature much higher than the environment temperature. Then a thin film "smearing" the boundary between the treated surface and the environment additionally appears on the path of the incident radiation. A diffusion component changed in the process of irradiation appears in the reflected radiation in addition to the mirror component, and the mechanism of reflection from such a layer itself depends on the physical properties of the material and the technology of the surface finish, the intensity of the incident radiation, and the space-time distribution of the pulses employed (monopulse, spike generation, etc.) [2].

Thus, determination of the coefficient of reflection (absorption) in the case of pulsed action of concentrated heat fluxes on metals is a difficult problem calling for simultaneous account for the influence of many factors. This problem still remains to be finally solved, although it has been the focus of an ample amount of literature [3–11].

The absorption coefficient A is most frequently determined experimentally with the use of the definitive equality $A = Q_2/(Q_1 + Q_2)$. Consequently, one must simultaneously determine the values of Q_1 and Q_2. This is usually done by calorimetric methods, which, unfortunately, possess a low accuracy of measurement. Furthermore, we should take into account that Q_2 additionally contains the diffusion radiation component directed deep into the treated specimen. Its recording calls for calorimeters of special design which simultaneously possess a large aspect angle and a high absorptivity.

For certain temperature levels not exceeding the melting temperature we have polymorphous transformations or characteristic changes in the internal structure (recrystallization, grain growth, etc.) of metals. These changes result in a new crystal structure which is not identical to the initial structure. For high cooling rates, in particular, a so-called martensite structure is formed, whose main component is martensite — a supersaturated solution of carbon in α iron.

[a]Ya. S. Podstrigach Institute of Applied Problems of Mechanics and Mathematics, National Academy of Sciences of Ukraine, L'vov, Ukraine; [b]Polytechnic Institute (Politechnika Lódzka), Lódz, Poland. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 76, No. 5, pp. 10–15, September–October, 2003. Original article submitted November 28, 2002.

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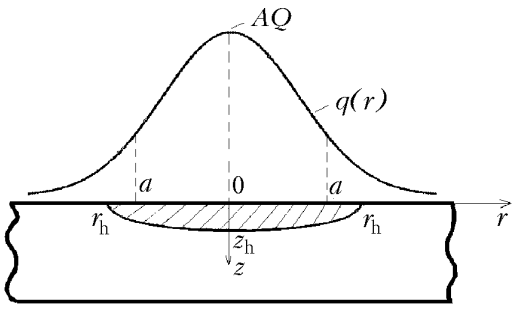


Fig. 1. Scheme of heating and formation of the martensite structure of metal.

The portions of material with such a structure have a higher-than-average strength and wear resistance, which is widely used in creating a protective surface layer in many structural elements of modern machines. A martensite layer whose depth can very accurately be measured by metallographic methods with the use of a scanning microscope is formed in local heating of steels [12–16].

The present investigation seeks to develop an experimental-theoretical procedure of determination of the effective absorption coefficient based on the analytical solution of the corresponding boundary-value problem of heat conduction for a semi-infinite body and on a sufficiently accurate measurement, by metallographic methods, of the dimensions of the zone of structural changes occurring in metals under the action of laser irradiation.

Temperature Field. The action of a laser beam on metal under certain conditions is equivalent to heating it by a distributed surface source of prescribed specific power (by a heat flux with a known intensity). Therefore, the boundary-value problem of heat conduction for a semi-infinite body which is heated by a pulsed laser operating in the quasistationary regime of radiation will be formulated in the form [17]

$$\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}+\frac{\partial^2 T}{\partial z^2}=\frac{1}{k}\frac{\partial T}{\partial t},\quad r\ge 0,\quad z>0,\quad t>0; \tag{1}$$

$$T(r, z, 0)=0,\quad r\ge 0,\quad z\ge 0; \tag{2}$$

$$K\frac{\partial T}{\partial z}=-q(r)\,H(t_s-t),\quad r\ge 0,\quad z=0,\quad t>0; \tag{3}$$

$$\frac{\partial T}{\partial r}=0,\quad r=0,\quad z\ge 0,\quad t>0; \tag{4}$$

$$T(\infty, z, t)=T(r, \infty, t)=0,\quad t>0. \tag{5}$$

We take the normal (Gauss) distribution of the heat-flux intensity (Fig. 1)

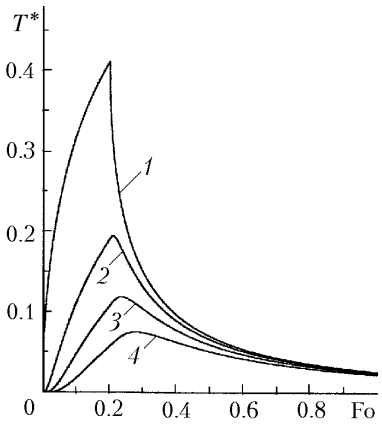
$$q(r)=AQ\exp(-K_c r^2),\quad r\ge 0. \tag{6}$$

The concentration coefficient K_c in formula (6) is related to the radius a of the heat flux by the relation [1]

$$K_c=a^{-2}, \tag{7}$$

while the total specific power Q of the luminous flux incident on the metal surface over the period t_s is equal to

$$Q=\frac{E}{\pi a^2 t_s}. \tag{8}$$



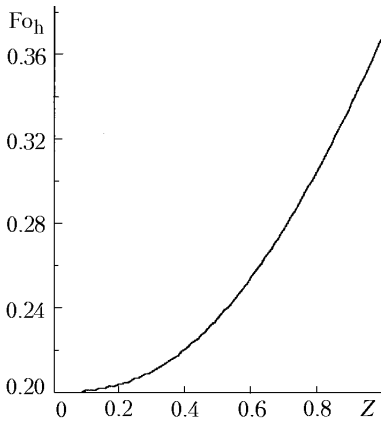


Fig. 2. Evolution of the dimensionless temperature T^* with time: 1) Z = 0, 2) 0.3, 3) 0.5, and 4) 0.7. ρ = 0 and $\mathrm{Fo_s}$ = 0.2.

Fig. 3. Change in the dimensionless time $\mathrm{Fo_h}$ of attainment of the maximum value by the temperature T_h with distance from the irradiation surface. ρ = 0 and $\mathrm{Fo_s}$ = 0.2.

In the mathematical model (1)–(8), it is assumed that the specific power of radiation is such that no melting and evaporation of the near-surface layer are observed; the loss of thermal energy from the surface of the irradiated specimen modeled by the half-space due to radiation and convection is insignificant; the thermophysical properties of the material are independent of temperature.

The solution of the boundary-value problem of heat conduction (1)–(5), constructed by taking successively the integral Hankel transform of zero order with respect to the radial variable r and the Laplace transform with respect to the time t, has the form

$$T(r, z, t) = A\Lambda \int_0^\infty \varphi(\xi)\, \Phi(\xi, Z, \mathrm{Fo})\, J_0(\xi\rho)\, d\xi\,, \quad r \ge 0\,, \quad z \ge 0\,, \quad t \ge 0\,; \tag{9}$$

$$\varphi(\xi) = \int_0^\infty \rho \exp(-\rho^2)\, J_0(\xi\rho)\, d\rho = 0.5 \exp(-\xi^2/4)\,, \tag{10}$$

$$\Phi(\xi, Z, \mathrm{Fo}) = \Phi_0(\xi, Z, \mathrm{Fo})\, H(\mathrm{Fo}) - \Phi_0(\xi, Z, \mathrm{Fo} - \mathrm{Fo_s})\, H(\mathrm{Fo} - \mathrm{Fo_s})\,, \tag{11}$$

$$\Phi_0(\xi, Z, \mathrm{Fo}) = \frac{1}{2}\left[\exp(-\xi Z)\, \mathrm{erfc}\left(\frac{Z}{2\sqrt{\mathrm{Fo}}} - \xi\sqrt{\mathrm{Fo}}\right) - \exp(\xi Z)\, \mathrm{erfc}\left(\frac{Z}{2\sqrt{\mathrm{Fo}}} + \xi\sqrt{\mathrm{Fo}}\right)\right]. \tag{12}$$

When $t_\mathrm{s} \to \infty$ ($\mathrm{Fo_s} \to \infty$), relation (11) yields $\Phi(\xi, Z, \mathrm{Fo}) = \Phi_0(\xi, Z, \mathrm{Fo}) H(\mathrm{Fo})$ and the known solution for the quasistationary regime of heating [17].

A numerical analysis according to formulas (9)–(12) has been made for the dimensionless temperature T^*. On the surface of the body, the maximum temperature is attained at the instant $t = t_\mathrm{s}$ of switching-off of the laser, while in the near-surface layer it is attained at $t = t_\mathrm{h} = t_\mathrm{s} + \Delta t$ (Fig. 2). The delay time Δt rapidly increases with distance from the working surface of the body (Fig. 3). This effect was noted earlier in [18].

Absorption Coefficient. To determine the parameter Δt we employ the condition of attainment of the maximum value inside the body at a point with coordinates (r, z) by the temperature T:

$$\left.\frac{\partial T(r, z, t)}{\partial t}\right|_{t=t_\mathrm{h}} = 0\,, \quad 0 \le r < \infty\,, \quad 0 < z < \infty\,. \tag{13}$$

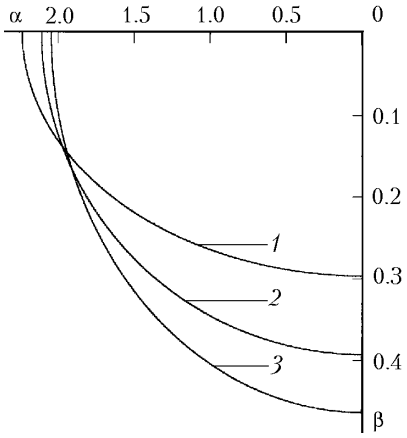


Fig. 4. Isotherms of the maximum dimensionless temperature T_h^0: 1) ΔFo = 0.01, 2) 0.02, and 3) 0.03. Fo_s = 0.2.

Having differentiated the solution (9)–(12) with respect to time, we obtain

$$\frac{\partial T(r, z, t)}{\partial t} = A\Lambda \frac{k}{a^2} \int_0^\infty \varphi(\xi) \frac{\partial \Phi(\xi, Z, \mathrm{Fo})}{\partial \mathrm{Fo}} J_0(\xi\rho)\, d\xi\,, \tag{14}$$

$$\frac{\partial \Phi(\xi, Z, \mathrm{Fo})}{\partial \mathrm{Fo}} = \frac{\partial \Phi_0(\xi, Z, \mathrm{Fo})}{\partial \mathrm{Fo}} H(\mathrm{Fo}) - \frac{\partial \Phi_0(\xi, Z, \mathrm{Fo} - \mathrm{Fo}_s)}{\partial \mathrm{Fo}} H(\mathrm{Fo} - \mathrm{Fo}_s)\,, \tag{15}$$

$$\frac{\partial \Phi_0(\xi, Z, \mathrm{Fo})}{\partial \mathrm{Fo}} = \frac{\xi}{\sqrt{\pi \mathrm{Fo}}} \exp\left[-\left(\frac{Z^2}{4\mathrm{Fo}} + \xi^2\, \mathrm{Fo}\right)\right]. \tag{16}$$

Taking into account the form of the function φ(ξ) (10) and the value of the integral [19]

$$\int_0^\infty \xi \exp\left[-\xi^2\left(\frac{1}{4} + \mathrm{Fo}\right)\right] J_0(\xi\rho)\, d\xi = \frac{2}{1 + 4\mathrm{Fo}} \exp\left(-\frac{\rho^2}{1 + 4\mathrm{Fo}}\right),$$

upon substitution of relations (14)–(16) onto the left-hand side of condition (13) we arrive at the functional equation for the dimensionless delay time ΔFo:

$$C_1 C_2 = \exp\left[-(C_3\rho^2 + C_4 Z^2)\right], \tag{17}$$

where

$$C_1 = 1 - \frac{4\mathrm{Fo}_s}{1 + 4(\mathrm{Fo}_s + \Delta\mathrm{Fo})};\quad C_2 = \sqrt{1 - \frac{\mathrm{Fo}_s}{\mathrm{Fo}_s + \Delta\mathrm{Fo}}};$$

$$C_3 = \frac{4\mathrm{Fo}_s}{(1 + 4\Delta\mathrm{Fo})[1 + 4(\mathrm{Fo}_s + \Delta\mathrm{Fo})]};\quad C_4 = \frac{\mathrm{Fo}}{4\Delta\mathrm{Fo}(\mathrm{Fo}_s + \Delta\mathrm{Fo})}. \tag{18}$$

Having taken the logarithm of relations (17) and (18), we represent them in the form

$$\frac{\rho^2}{\alpha^2} + \frac{Z^2}{\beta^2} = 1\,,\quad |\rho| \le \alpha\,,\quad 0 < Z \le \beta\,, \tag{19}$$

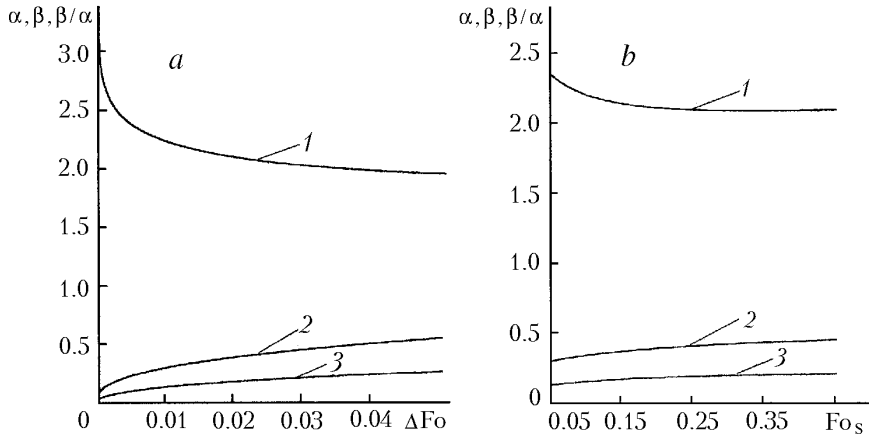


Fig. 5. Dimensionless axes α and β of the semiellipse of the region of thermal hardening of steel vs. dimensionless delay time ΔFo (a) (Fo_s = 0.2) and dimensionless irradiation time Fo_s (b) (ΔFo = 0.02): 1) α; 2) β; 3) β/α.

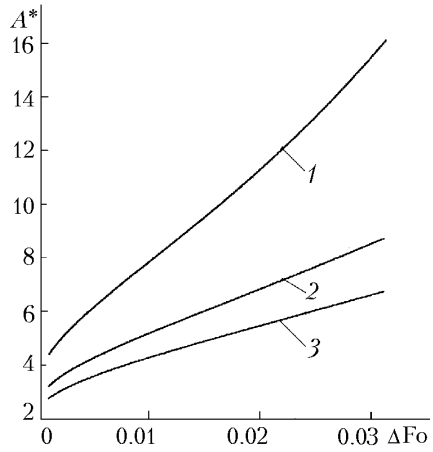


Fig. 6. Parameter A^* (22) vs. dimensionless delay time ΔFo for three values of the dimensionless irradiation time: 1) Fo_s = 0.1, 2) 0.2, and 3) 0.3.

where

$$\alpha^2 = -\frac{\ln (C_1 C_2)}{C_3}, \quad \beta^2 = -\frac{\ln (C_1 C_2)}{C_4}. \tag{20}$$

The semiellipse (19) with axes 2α and 2β (20) is the isotherm of a temperature maximum for prescribed dimensionless time parameters ΔFo_s and ΔFo (Fig. 4). The dependences of the dimensionless semiaxes α and β of the semiellipse (19) and of their ratio β/α on the delay time ΔFo are presented in Fig. 5a, while the dependences on the dimensionless heating time Fo_s are presented in Fig. 5b. We note that the dimensional values of the axes r_h and z_h of the ellipse bounding the region of hardening of steel (see Fig. 1) are equal to $r_h = \alpha a$ and $z_h = \beta a$, where a is the radius of the heat source (7).

As the characteristic maximum temperature for carbon steels we can take the temperature T_h of thermal hardening. Then from the condition $T(r, z, t_h) = T_h$, where the temperature T is given by relations (9)–(12), we obtain the calculation formula for the absorption coefficient:

$$A = \frac{T_h A^*}{\Lambda}; \tag{21}$$

here

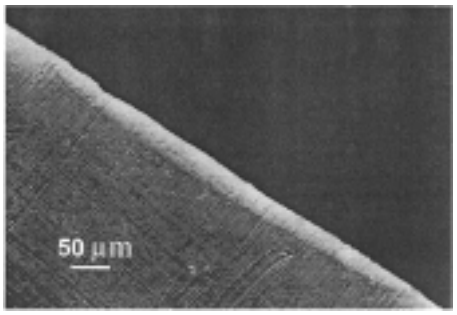


Fig. 7. Region of hardening of St 45 steel in laser irradiation.

$$A^* = \left\{ \int_0^\infty \varphi(\xi) \left[\Phi_0(\xi, Z, \mathrm{Fo}_s) - \Phi_0(\xi, Z, \Delta\mathrm{Fo}) \right] J_0(\xi\rho)\, d\xi \right\}^{-1}, \tag{22}$$

and the coordinates (ρ, Z) satisfy Eqs. (19) and (20).

The dependence of the parameter A^* (22) on the dimensionless delay time ΔFo for different values of the dimensionless period of irradiation Fo_s is shown in Fig. 6.

Comparison to Experimental Data. Experimental results of investigations of the laser hardening of St 45 steel have been presented in [20]. A specimen in the form of a circular cylinder of diameter 20 mm and thickness 6 mm, made of St 45 steel (T_h = 850°C, K = 33.5 W/(m·K), and $k = 15 \cdot 10^{-6}$ m^2/sec), was irradiated at different sites by pulses of an Nd:YAG glass laser in the standard regime of lasing (E = 1.5 J and r_s = 2 msec). After obtaining microsections of the formed hardened layer and etching them in an alcohol solution of nitric acid we measured the maximum length r_h and depth z_h of the hardening region with an EPITYP-2 metallographic microscope (Fig. 7). It was established that the depth of the hardened layer z_h most strongly depends on the specific radiation power, which was changed by focusing. Melting of the irradiated portions began when $Q > 85 \cdot 10^7$ W/m^2. For $Q = 58 \cdot 10^7$ W/m^2 we have found that z_h = 40 μm. From formula (8) we determined the radius of the surface heat source a = 0.64 mm and consequently the dimensionless period of irradiation Fo_s = 0.073. From Eq. (17) for ρ = 0 and $Z \equiv z_h/a$ = 0.062 we found the dimensionless time of delay $\Delta\mathrm{Fo} = 0.329 \cdot 10^{-3}$. For such values of the dimensionless geometric and time parameters we obtained A^* = 4.5 from (22) and determined the value of the absorption coefficient A = 41.8% (which is in good agreement with experimental data [2, 3]) from (21).

CONCLUSIONS

1. Based on the solution of the boundary-value problem of heat conduction for a half-space and corresponding experimental data on measuring the dimensions of the hardening zone, one can determine the effective absorption coefficient of carbon steel.

2. For St 45 steel the absorption coefficient substantially depends on the radiation intensity and is equal to 41.8% for $Q = 58 \cdot 10^7$ W/m^2.

3. In the approach to determination of the absorption coefficient proposed, we employ the isotherm bounding the hardening region of St 45 steel. It has been noted in [18] that there can be errors introduced into the evaluation of the temperature due to the inertia of hardening of steel. This imposes restrictions on the class of materials to which the procedure proposed is applicable.

NOTATION

A, absorption coefficient; a, radius of the heat source; E, energy of a radiation pulse; erf (·), error function; erfc (·) = 1 – erf (·); H(·), Heaviside unit function; J_0(·), Bessel function of the first kind and of zero order; K and k, thermal conductivity and thermal diffusivity; K_c, concentration coefficient; Q_1 and Q_2, mean-integral (over the heating spot) intensities of the reflected and absorbed radiations respectively; $Q = Q_1 + Q_2$; $q(r)$, intensity of the heat flux; R,

reflection coefficient; r and z, radial and axial components of the cylindrical coordinate system with origin at the center of the heat source; r_h and z_h, semiaxes of the semiellipse bounding the region of phase transformations; ξ, integration constant in the Hankel transform; T, temperature; $T^* = T/(A \cdot \Lambda)$, dimensionless temperature; $\Lambda = Qa/K$; T_h, temperature of thermal hardening of steel; t, time; t_h, time of formation of the region of thermal hardening of steel; t_s, period of hardening; Δt, delay time; $\rho = r/a$ and $Z = z/a$, dimensionless coordinates; $\mathrm{Fo} = kt/a^2$, $\mathrm{Fo}_s = kt_s/a^2$, $\Delta\mathrm{Fo} = k\Delta t/a^2$, and $\mathrm{Fo}_h = \mathrm{Fo}_s + \Delta\mathrm{Fo}$, Fourier numbers. Subscripts: h, hardening; s, time of switching-off of the laser; c, concentration.

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