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Refraction by gas inhomogeneities during laser heating of a metal

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Received December 27, 2021
Revised December 27, 2021
Accepted December 10, 2022

An analysis is made of the distribution of the refractive index near the boundary of a metal heated by laser radiation. The gradient of the refractive index of the gas, caused by the heat flux, and the distribution of the refractive index in the inhomogeneously heated gas are found. The drift of the laser beam due to the refraction of radiation in a gas is estimated, which shows an increase in the drift for narrow laser beams.

Keywords: refraction in gas, gas heating, metal laser heating.

DOI: 10.21883/EOS.2022.04.53739.55-21

Currently, 3D-printing methods based on the effect of laser radiation on metals, plastics and other substances are being intensively developed. The processes of heating the substance (hereinafter, we consider metal) largely determine the quality of the samples produced. In the theoretical analysis of the heating process, as a rule, it is assumed that the optical radiation in the sample plane has a given (Gaussian) profile and is not affected by the temperature distribution processes in the gas that cools the metal surface [1–7]. A certain justification is the extreme smallness of the gas absorption coefficient and the closeness of its refractive index to unity. However, the accuracy of printing achieved in precision devices reaches values of the micron range [8], which requires taking into account the effect of the presence of gas in the installation (chamber) on the propagation of radiation. This problem is the subject of this article.

Obtaining estimates of the effect is facilitated by the weakness of the heterogeneity of the gas. This makes it possible, first of all, to estimate the heterogeneity of the gas itself caused by laser heating, which we will assume to be non-ionized. In this case, it is permissible to completely neglect the absorption of radiation in the gas itself, so that its heating is due to the heat flux from the metal surface. The central part of a wide laser beam can be simulated by a plane wave. Then stationary gas heating is described by the heat conduction equation

$$\frac{d}{dz}\left[\Lambda\frac{dT}{dz}\right]+w_g=0,\quad w_g=u\rho c_v(T_g-T),\quad z<0. \tag{1}$$

The coordinate z is directed orthogonally to the metal surface located at $z=0$. The component w_g describes the gas cooling rate, i.e., the rate of replacement of heated gas by cold gas with temperature T_g (decrease in the amount of heat in the gas). It is proportional to the temperature difference of cold and heated gas T_g-T, its density ρ, heat capacity at constant volume c_v. The parameter u with dimensionality s^{-1} is proportional to the velocity of the cooling gas v; for a sample of size w, we get $u=v/w$.

Neglecting the temperature dependence of thermophysical parameters, the solution of equation (1) is written in the form

$$T=T_g+A\exp(\gamma z),\quad T(z=-\infty)=T_g,\quad \gamma^2=u\rho c_v/\Lambda. \tag{2}$$

To take into account the smooth (slow) temperature dependence of these parameters in the semiclassical approximation (SCA), one can make the substitution

$$\exp(\gamma z)\to\exp\left(\int^{z}\gamma\big(T(z)\big)dz\right). \tag{3}$$

We will not use this approximation, since the form (2) turns out to be sufficient for estimates.

The constant A in (2) is determined, generally speaking, by crosslinking at the gas-metal interface, so that the heat equations for gas and metal should be solved jointly. However, for estimates we will assume that at $z=0$ the gas temperature is equal to the boundary temperature of the metal T_m. The latter is calculated separately, but it is also known from experiments, so we will assume that it is given.

Thus, we have obtained an estimate for the temperature profile in the gas. The refractive index profile of the cooling gas can now be evaluated. For Ar under normal conditions, the temperature dependence of the refractive index n and permittivity ε is as follows [9]:

$$n(T)=1.000284-\alpha_n(T-T_0),\quad \alpha_n=10^{-6}\ (K^{-1}),$$

$$\varepsilon(T)=n^2(T)\approx 1-2\alpha_n[(T_g-T_0)+(T_m-T_g)\exp(\gamma z)]. \tag{4}$$

These formulas are sufficient to estimate the shift (refraction) of laser radiation during its oblique incidence and the passage of a gas layer with a nonuniform refractive index; estimates show that another factor (change in the reflection coefficient) practically does not manifest itself under the conditions of metal cooling with argon.

In the approximation of geometrical optics from the Snell refraction law in a plane-layered medium with permittivity $\varepsilon(z)$, the transverse coordinate of the beam is generally described [10] by the expression

$$x(z) = x_0 + \sin\theta_0 \int_{z_0}^{z} \frac{dz}{\sqrt{\varepsilon(z)/\varepsilon_0 - \sin^2\theta_0}}. \tag{5}$$

Here θ_0 is the angle of incidence at the inhomogeneous layer input $z = z_0$ and $\varepsilon_0 = \varepsilon(0)$ (at normal incidence $\theta_0 = 0$). In our case

$$\varepsilon(z) \approx a + b\exp(\gamma z), \tag{6}$$

where

$$a = 1 - 2a_n(T_g - T_0), \quad b = -2a_n(T_m - T_g), \quad b^2 \ll a^2 \sim 1. \tag{7}$$

Then

$$x(z) \approx x_0 + \sin\theta_0 \Big\{ A(z - z_0) + (B/\gamma)\big[\exp\big(\gamma(z - z_0)\big) - 1\big] \Big\}. \tag{8}$$

The beam shift due to refraction can be considered a value proportional only to the heating coefficient of the metal, $B = -b/2 = a_n(T_m - T_g)$:

$$\delta x = \sin\theta_0 (B/\gamma)\big[\exp(\gamma L) - 1\big] \approx BL\left(1 + \frac{1}{2}\gamma L\right)\sin\theta_0. \tag{9}$$

The last expression in (9) is valid for a sufficiently small thickness of the inhomogeneous gas layer L ($\gamma L \ll 1$).

Let us give numerical estimates for the characteristic parameters: $\Lambda = 17.72 \times 10^{-3}\,\mathrm{W/(m\cdot K)}$, $\rho = 1.78\,\mathrm{kg/m^3}$, $c_v = 17.7 \times 10^{-3}\,\mathrm{W\cdot s(kg\cdot K)}$ [11], $v = 10\,\mathrm{cm/s}$, temperature differences $T_m - T_g = 1200\,\mathrm{K}$. Let us assume the thickness of the cooling gas layer $L = 2\,\mathrm{cm}$ and the width of the beam $w = 4\,\mathrm{cm}$. Under these conditions, the temperature gradient-induced beam deflection for a wide beam is $\delta x \approx 24 \cdot \sin\theta_0\,\mu\mathrm{m}$. This is comparable to the precision printing accuracy mentioned above, highlighting the importance of accounting for gas heterogeneity to improve this accuracy. For narrower beams, for example, with the width of $w = 20\,\mu\mathrm{m}$, the deflection value is so large that relation (9) formally leads to the deflection value exceeding the width of the beam itself. This variant goes beyond the accepted plane-wave approximation and thus this case requires a separate analysis. But it certainly indicates the importance and necessity of taking into account the refraction of thin beams of laser radiation near the surface of the heated metal.

Funding

The study was supported by the Russian Foundation for Basic Research -21-52-53009 NSFC.

Conflict of interest

The authors declare that they have no conflict of interest.

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