Calculation of intrinsic absorption coefficient in high power laser material processing

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Abstract. A method of analytical and numerical calculation of the absorption coefficient of laser radiation was proposed and tested based on the results of a simplified experimental cutting setup. The results are compared with available theoretical predictions and experimental data the literature forecasts in a wide range of angles of inclination. A significant difference between the absorption coefficients for mild steel used in the theory and reconstructed from experimental data. The obtained absorption coefficient can be used for further modeling of laser material processing technologies.

1. Introduction

Different types of industrial lasers offer different wavelength ranges for high-power material processing technologies. The wavelength of the radiation, its quality and polarization are the main parameters of any such type process. During laser cutting, welding, surfacing high power radiation interacts with a wide range of industrial materials surface, which is inclined at different angles and heated to different temperatures. The absorption coefficient can be found theoretically with known complex refractive indexes of Fresnel, but the theory works well only for several materials at low temperatures. However, for most materials, especially in the molten state, the refractive index is unknown. The obtained accuracy of theoretical predictions is unsatisfactory for understanding the processes, modeling and designing new technologies.

Usually, in the simulation of laser material interaction during industrial laser material processing, the absorption coefficient is calculated from the Fresnel formulas (1). These formulas are recommended for application in classical handbooks of laser technologies [1-2] and can be found in the theoretical part of the majority of works on this topic. Koji Hirano had the experimental work where he investigates if this formula can be applied to laser cutting of steel. [3].

\[
R_s = \left| \frac{\cos \gamma - (N_w^2 - \sin^2 \gamma)^{\frac{1}{2}}}{\cos \gamma + (N_w^2 - \sin^2 \gamma)^{\frac{1}{2}}} \right|^2, \quad R_p = \left| \frac{N_w^2 \cos \gamma - (N_w^2 - \sin^2 \gamma)^{\frac{1}{2}}}{N_w^2 \cos \gamma + (N_w^2 - \sin^2 \gamma)^{\frac{1}{2}}} \right|^2, \quad (1)
\]

where \( R_s \) and \( R_p \) are the reflection coefficients for the transverse and longitudinal polarizations, \( N_w = n + ik \) – complex refractive index for a metal.
For polarized radiation the coefficient of absorption depends on the angle between polarization and plane of incidence [4-5]. For unpolarized or circular polarized radiation absorption coefficient $A(\gamma)$ could be found with formula (2)

$$A(\gamma) = 1 - \frac{R_y(\gamma) + R_z(\gamma)}{2}$$

(2)

Coefficients $n$ and $k$ are required for calculation of coefficient of absorption with formulas (1). In many papers, the authors do not even give a source of value for these coefficients. Meanwhile, they are quite different in different sources. The $n$ and $k$ values used in laser cutting studies and found in general methodological studies are presented in Tables 1-2. In addition Brewster angle ($\gamma_B$), the maximum value of the absorption ($A_{max}$) and the absorption with zero incident angle ($A_0$) are given.

### Table 1. Refractive indexes for radiation wavelength 10 µm

|                | $n$  | $k$  | $\gamma_B$, deg | $A_{max}$ | $A_0$ |
|----------------|------|------|------------------|-----------|-------|
| Niziev, Nesterov, 1999 [5] | 4.2  | 12.0 | 85.55            | 0.25      | 0.10  |
| Mahrle, Bayer, 2009 [6]   | 15.0 | 14.6 | 87.31            | 0.42      | 0.13  |
| Zaitsev, Kovalev, 2004 [4] | 17.7 | 28.4 | 88.33            | 0.35      | 0.06  |
| Dausinger, 1993 [7]       | 14.8 | 15.5 | 87.37            | 0.41      | 0.12  |
| Querry, 1985 [8]          | 5.36 | 29.2 | 88.60            | 0.12      | 0.01  |

### Table 2. Refractive indexes for radiation wavelength 1 µm

|                | $n$  | $k$  | $\gamma_B$, deg | $A_{max}$ | $A_0$ |
|----------------|------|------|------------------|-----------|-------|
| Mahrle, Bayer, 2009[6] | 5.3  | 3.82 | 81.34            | 0.49      | 0.39  |
| Zaitsev, Ermolaev, 2014 [9] | 5.46 | 3.96 | 81.61            | 0.48      | 0.38  |
| Dausinger, 1993 [7]     | 3.6  | 5.0  | 80.82            | 0.40      | 0.31  |
| Werner, 2009 [10]       | 9.2  | 12.8 | 86.40            | 0.38      | 0.14  |

Objectively, such a difference must affect the results of the prediction. For example, the maximum cutting speed and the stability of the shape of the cutting surface depend significantly on the Brewster angle [9, 11]. Moreover, the absorption coefficient for orthogonal incidence of radiation differs for three times for fiber lasers and for more than 10 times for CO2-laser radiation.

The Dausinger work [7] is the most interesting in this series, where attention is paid precisely to the absorption coefficient for laser technologies. The data on the absorption coefficient dependence on temperature, for the melt and for the solid phase are collected, and the data for iron and for several types of steel are given. However, the comparison of experiments and theory is given for one of the sources only; the diversity of data for other sources is not discussed.

Koji Hirano and Remi Fabbro presented work [3], where the absorption coefficient is measured by direct methods under conditions closest to laser cutting processing.

### 2. Experimental data

The experimental data, we treated, are conducted by Koji Hirano and Remi Fabbro [11]. The feature of this work is laser cutting with collimated wide laser beam ($d_0\geq0.5\text{mm}$) with a near top-hat radiation distribution. Under these radiation conditions and at a sufficiently high speed, a cut is formed with wide and uniform inclined front.
Low carbon mild steel was used for cutting. The sheet thickness was 3 mm. The sheets were surface grinded in order to remove even minor oxide layers and to avoid unfavorable perturbations. Nitrogen was used as the assist gas.

The conditions of experiments are listed in Table 3, where $P$ is laser power, $V_c$ is speed of cutting, $d_0$ is laser beam diameter, $\alpha$ is the angle of front inclination, $Pe = \frac{V_c d_0}{2 \chi}$ is Peclet number, $\chi$ is a thermal diffusivity of the solid metal. The last column contains a description of the flow of the melt film. The humps are small bunches of molten material sliding down the kerf front. Hypothetically, they are responsible for the appearance of roughness [11].

| $P$ (W) | $d_0$ (mm) | $V_c$ (m/min) | $\alpha$ (deg) | $Pe$ | Melt flow       |
|--------|-----------|---------------|----------------|-----|----------------|
| 8000   | 1.7       | 0.6-1.5       | 5-10           | 0.7-1.7 | humps         |
| 8000   | 1.7       | 2-3           | 15-21          | 2.3-3.4 | stable flow   |
| 8000   | 1.7       | 4-6           | 45-60          | 4.5-6.8 | stable flow, not cut through |
| 8000   | 1.1       | 0.6-3         | 2-10           | 0.4-2.2 | humps         |
| 8000   | 1.1       | 4-5           | 13-17          | 2.9-3.6 | stable flow   |
| 8000   | 0.56      | 0.6-5         | 1-12           | 0.4-3.7 | no info       |
| 6000   | 1.7       | 0.6-5         | 1-12           | 0.4-3.7 | no info       |
| 4000   | 1.7       | 0.6-5         | 6-30           | 0.7-7   | no info       |
| 2000   | 1.7       | 0.6-5         | 6-30           | 0.7-7   | no info       |

The correct thermophysical properties of treated materials are another problem in the processing of experimental data. In this paper, we used the parameters presented in Table 4 [12].

| $c_s$ (average from 300 to 1700K) | 690 |
| $c_f$ Heat capacity of melt (J/kg K) | 748 |
| $H_m$ Heat of melting (J/kg) | 27600 |
| $\rho_s$ Density of solid metal(kg/m3) | 7860 |
| $\rho_f$ Density of solid metal(kg/m3) | 6980 |
| $T_m$ Melting temperature (K) | 1723 |
| $\lambda_s$ Heat conductivity of solid metal (W/(m K)) | 68.6 |
| $\lambda_f$ Heat conductivity of melt (W/(m K)) | 36.5 |

3. Calculation method

For the conditions described above, most of the radiation at the cutting front is absorbed on a flat area with a known inclination angle. In this case, the absorption problem, in the moving coordinate system associated with the points of melt surface, can be reduced to a one-dimensional heat transfer problem (3) with Stefan's problem at the boundary (4). Here we neglect thin melt film influence, but later we will discuss this.
where $\gamma$ is incident angle, $T(x)$ is temperature distribution in the metal, $V_n$ is normal velocity of cut front in the laboratory system, $x'$ is coordinate associated with normal to the front of cut, with $\theta$ on the melting surface, $I$ is intensity of laser radiation, $A$ is absorption coefficient.

The solution of this differential equation will be (5):

$$T = T_0 + (T_m - T_0) \exp(-x' V_c \sin \gamma \cdot \rho_s c_s / \lambda_s)$$

Substituting the solution into the boundary condition, we obtain a formula relating the cutting parameters, the absorption coefficient and the slope of the front (6).

$$V_c = V_c \sin \gamma$$

$$V_c \rho(H_a + \lambda_a \frac{\partial T}{\partial x'}(0)) = V_c \rho_s (H_a + c_s (T_m - T_0)) = A(\gamma) I \cos \gamma$$

$$V_c = A(\gamma) \frac{I}{\rho_s (H_m + c_s (T_m - T_0)) \cdot \text{ctg} \gamma}$$

$$A = \frac{V_c}{\text{ctg} \alpha}$$

where $V_s = \frac{I}{\rho (H + c(T_m - T_0))}$ is the velocity of metal melting if a melt ideally removed from the surface.

The formula (6) gives the same estimates as the formula (9) in [11] without influence of the radiation losses in the side walls. Despite the fact that the Peclet number varies in the range from 0.5 to 5 and the thickness of the heated layer in the same order with beam radius, the heat loss does not significantly affect the slope of the cutting front. That will be shown by numerical simulation.
4. The calculation results

We used two complex coefficient of refraction for the computations: \( n=3.6, k=5 \), which Hirano used (originally taken from Dausinger work [7]) and \( n=10.66, k=11.61 \) (Werner [10] for \( \lambda=1.05\mu m \)) and the combination of absorption coefficients obtained with these refraction indexes \((0.4A_1+0.6A_2)\).

The cut front and temperature distribution inside metal were obtained with methods and software described in [9]. The cut surface in two projections with temperature distribution are presented in figure 2 \((P=8000 W, V_c=3 m/s, d_0=1.7 mm)\). We can see straight front profile with inclination angle \(\sim 20^\circ\) almost the same as in the experiment (axes not in one scale). The narrowing of the cut is due to a decrease in the cross-sectional area of the cylindrical beam in the lower part. In the computations, we had the same threshold of cutting speed \((3 m/s)\) where beam still pass through the metal sheet.

![Figure 2](image_url) Simulated cut surface with temperature distribution. \(P=8000 W, V_c=3 m/s, d_0=1.7 mm\)

Using the formulas (6) and experimental data, the relation between cutting speed \((V, m/min)\) and front of cut inclination \((\alpha)\) are obtained.

The results of front inclination for simulated cutting front and estimations by formula (6) are presented for \( d_0=1.7 mm \) in Figures 3 and for \( d_0=1.1 mm, d_0=0.56 mm \) in Figures 4.

We can see that calculation with Werner coefficient is in a good agreement with experimental curve for \( d_0=1.7 mm \). In the same time line for Hirano coefficient lies under experimental line. The calculations with combination of coefficients (marked as new absorption) is in an agreement with experiment for \( d_0=1.1 mm \). And we have not good theoretical line for \( d_0=0.56 mm \) experiments.

We reconstruct absorption coefficient dependence on incident angle with formula (6) and experimental data and add theoretical dependencies for two refractive angle in Figure 5.
Figure 3. Front inclination angle dependence on cutting speed. Experiments and computations. 
\[ d_0 = 1.7 \text{mm} \]

Figure 4. Front inclination angle dependence on cutting speed. Experiments and computations. 
\[ d_0 = 1.1 \text{mm}, d_0 = 0.56 \text{mm} \]
Figure 5. Absorption coefficient dependence on incident angle, reconstructed from experiments and theoretical.

5. Discussion

In figure 5 we can see, that reconstructed absorption coefficient is closer to the theoretical curve with Werner coefficients for smaller incident angles, but for large angles, it is closer to the Hirano (Dausinger) refractive index curve.

The coefficients obtained with a beam diameter of 0.56 mm are very different. In addition, there are problems with coinciding with cutting front numerical simulations with such diameter. It is possible that assumption of weak influence of melt flow does not work for these cases.

For modern laser cutting, it is more interesting to know the values $A(\gamma)$ at angles greater than 80 degrees, since the ratio of the beam diameter and the thickness of the cut material can exceed 30. We obtained a maximum absorption coefficient of about 40%, close to the theoretical one. The angle of Brewster seems to be closer to 80°. But the data for large angles should be treated cautiously. The surface of the cut was no longer smooth and even inclined and humps were periodically sliding along the front of the cut in the experiments. Due to this, the average angle of incidence at which the absorption occurred and the average angle of the slope of the front could differ significantly. In addition, the effect of the melt flow in this case will be uneven.

Nevertheless, it is important to know the value of the absorption coefficient at smaller angles. In this case, the value of the refractive index by Werner turned out to be closer.

We should remember that we do not consider melt flow in our estimations. The presence of a melt film can significantly affect the absorption coefficient. In the one-dimensional approximation, the temperature distribution changes to an exponential distribution in the melt. On the one hand, then the temperature on the surface will be higher and absorption should increase. On the other hand, in the
estimation of the absorption coefficient (6), the denominator will change, because now it is necessary not only to melt the metal, but also to heat the melt.

6. Conclusions
The formula for estimating the effective coefficient of metal absorption from the slope angle of the cutting front is presented.

A numerical 3D simulation of the cutting front taking into account the thermal conductivity in the cut walls were carried out for the parameters of experiments on cutting with a collimated laser beam. Different refraction coefficients were tested. For some cases, the slope angle of the cutting front remained almost constant as in experiment.

Based on the results of 3D modeling and using estimation formulas, it was shown that the refractive index for mild steel found by Werner (n=10.66, k=11.61) is more suitable for small angles of incidence, and the coefficient found by the Dausinger (n=3.6, k=5) is more suitable for large angles of incidence.

The absorption coefficient, found by the estimation and checked in the 3D simulations, is not real, but an effective coefficient, so in future works on this topic it is important to take into account the influence of the melt film.

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