# Numerical experiments for determining laser-induced temperature fields

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**Abstract:** Based on the equation of energy balance and the equation of heat conductivity with the help of specialized software, tentative engineering calculations were performed for the process of laser marking by melting and structural changes. The functional capabilities of the software product were examined. Distribution of temperature by layers for samples of tool steel was obtained.

**Key words:** Graphic images, laser, temperature field

## 1. Introduction

Theoretical model investigations of the interaction of laser radiation with substances are of key importance in the analysis of experimental results obtained during various technology processes [1]. This appears to be a principal factor determining the trend in conducting a number of novel experimental investigations. In summary, their role in the specific practical applications of lasers in treating materials can be described as follows:

- Determining of destruction threshold in treating certain types of material by laser source;

- Optimizing the course of various laser technology processes such as marking, etching, cutting, welding, boring of holes, and hardening.

## 2. Presentation

With laser impact on tool steel a portion of the radiation is absorbed while the remaining part is reflected by the surface and another third part passes through it, thus satisfying the condition

$$E = E_A + E_R,$$

where $E$ is the falling energy, $E_A$ the absorbed energy, and $E_R$ the reflected energy.

Figure 1 is a general diagram of energy distribution of the process of laser impact upon alloys and metals (including tool steel).

Apart from the energy gained through absorbed radiation $E_A$, it is possible to obtain in the impact zone some energy that is produced by way of chemical reactions $E_{ch}$ while its temperature changes. The energy balance equation is then

$$E_A + E_{ch} = E_{proc} + E_c + E_r + E_{con} \tag{1}$$

where $E_{proc}$ is the energy of the process, $E_c$ the energy that has entered the thermally impacted zone around the work space, $E_r$ the energy of radiation, and $E_{con}$ the energy loss due to convection.

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## 2.1. Physical model

In the theoretical model under observation, the laser-induced temperature fields are calculated by taking into account these restrictions:

- Ignoring thermal losses resulting from convection and radiation;

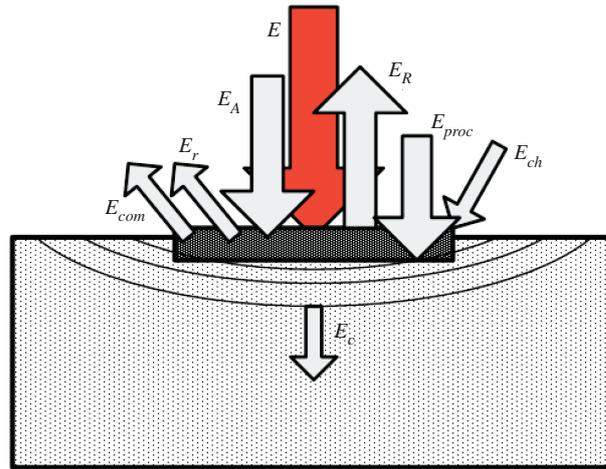- Ignoring nonuniformities and nonhomogeneities in the impact zone.



**Figure 1.** A general diagram of energy distribution of the process of laser impact upon alloys and metals.

Likewise, the thermal impact of laser radiation in the treatment zone in the model is assigned by the heat conduction equation

$$c\rho\frac{\partial T}{\partial t} \;=\; div(k\,grad\,T)\;+\;q_S(1\;-\;R)\alpha, \tag{2}$$

where $T$ is the temperature, $t$ the time, $c$ the specific thermal capacity, $\rho$ the density, $k$ the coefficient of thermal conductivity, $q_s$ the laser radiation power density, $R$ the coefficient of reflection, and $\alpha$ the coefficient of absorption.

Since the absorption of the falling laser radiation takes place in a thin layer close to the surface [2], in the theoretical model it is possible to regard thermal impact as a surface heat source. In laser marking of metal surfaces with pulse durations in the range $\tau = 10\text{--}1000$ ns, this requirement exists because the thickness of the sample under marking is much greater than the depth of penetration $\delta$ of laser radiation ($\delta = 1/\alpha$).

By means of the theoretical model, it is possible to estimate the required power density at which the surface material is being melted. This is of great importance for the method of laser marking affected by means of structural changes of second order or by oxidation.

Laser marking by means of taking off a pre-marked layer from the sample enjoys a considerable amount of practical application [2]. The theoretical model allows one to perform calculations in various solutions such as:

- Laser radiation is possible through the layer and absorption takes place at the layer/pad boundary;

- Laser radiation is absorbed by the layer and then evaporates it, thus uncovering the base material.

An important aspect in laser marking is the calculation of laser-induced temperature fields in treatments utilizing phase changes in the material. The proposed theoretical model allows the solution of this task as well. Heat conduction equations in this case are to be solved for both the solid phase and the molten metal.

In terms of practical application, it is interesting to examine the case in which the material underneath the surface in the absorption zone starts boiling and bursts out due to the high pressure generated; part of that material is deposited aside of the marking zone in the form of splashes. During work with pulses of $\tau = 10$ ns, sublimation (direct evaporation from the impact zone) is observed. This process is of great importance in the case of precision etching of metal surfaces.

Theoretical model estimations could be subjected to the following principal tasks that are of substantial importance to the specific processes and methods of laser marking and etching:

- Clarifying the effect of the wavelength $\lambda$ of laser radiation for the concrete material. This facilitates the selection of an appropriate laser source (fiber laser with $\lambda = 1064$ nm, Nd:YAG laser with $\lambda = 1064$ nm, laser of CuBr with $\lambda = 511$ nm; 578 nm, excimer lasers (in the ultra-violet range), etc.);

- Clarifying the role of the duration of pulses $\tau$ in spatial distribution of temperature field and the physical process of radiation interaction with the metal $\tau = 10$–1000 ns;

- Determining the effect of diameter $d$ at the work spot upon temperature distribution $d = 10$–200 $\mu$m;

- Clarifying the role of pulse frequency upon the temperature field;

- Clarifying the role of the laser beam's relative speed of displacement, with regard to the treated surface, upon the profile of the temperature field.

## 2.2. Basic elements of related software

Temperaturfeld3D software is used for calculating temperature fields with a wide set of input parameters and possibilities for analysis of estimated results [3].

Two models of estimation are used: dynamic and static. With the dynamic model the laser beam moves within the $xy$-coordinate system and affects the material. Temperature fields are determined both at the surface of the material and at depth. In this case there are 3 dimensions, $x$, $y$, and $z$, that determine the complexity and time for calculations. With the static model the laser beam remains static and the material has radial symmetry. Thus dimensions are reduced to $2 - r$ and $z$ and calculation is accelerated considerably.

After selecting the model the main window opens. From there the user has access to the 3 principal sections of the software: input/output, model parameters, and calculation. To calculate one of the models it is necessary to enter a lot of parameters:

### 2.2.1. Program/Software parameters

- File name; - Initial time step/interval;

- Minimum time step/interval; - Maximum time step/interval;

- End up of calculations; - Ambient temperature;

- Radiation capacity; - Calculations accuracy;

- Initial time for storing results; - Coefficient of storing;

- Liquid phase transition; - Method for model calculation.

There are 2 methods available: Gear and Adams with a variety of sub-versions.

### 2.2.2. Geometry parameters

Here are defined the geometry dimensions of a treated sample as well as the number of composite materials it is made of.

- Geometry model (3 geometry models are available: rectangular prism, layer, and semi-space);

- Computerized generation of elements;

- Geometry dimensions.

### 2.2.3. Laser parameters

Here we set the parameters of laser radiation and movement of the laser beam.

- Type of laser; - Time distribution of power density;

- Gaussian radius of beam; - Time for following of pulses;

- Initial coordinates and laser beam speed.

### 2.2.4. Material parameters

Here are given various types of materials and their physical characteristics.

- List of available materials;

- Booting database;

- Defining a new material (in a series of windows wherein the 4 groups of parameters are defined: reflection coefficient, heat conduction coefficient, specific heat capacity, and absorption capacity);

- Change of parameters of the materials.

### 2.2.5. Calculation

The stages of calculation are described in the items that follow:

- Preparation (prior to starting calculations all necessary parameters are checked for availability);

- Calculation and results (following the writing of data in the respective file, the calculation kernel is activated to perform calculation of temperature fields);

- Calculations analysis.

Upon opening the analysis window all data from the file with calculated results are booted automatically:

- Approximation of results; - Animation of the entire process;

- Temperature profile of material at certain moment; - Maximum temperature profile;

- Temperature time dependence; - Material in-depth change of temperature.

## 2.3. Examples of numeric experiments

By means of this software numeric calculations are performed aiming to find out the appropriate operation mode for marking samples made of tool steel type Y11 with a Nd:YAG laser by means of the surface structural changes method. The aim is to determine the distribution of laser radiation absorbed energy inside the sample according to the developed physical model [4] and to compare the results with those of the experimental investigations. Marking done by this method is carried out below the surface destruction threshold for steel type Y11, that is, the temperature in the treatment zone in numeric experiments should not exceed the melting temperature. In numeric experiments the zone under laser impact is divided into 3 layers with thickness of $\Delta h_1 = 12.5$ $\mu$m, $\Delta h_2 = 30.0$ $\mu$m, and $\Delta h_3 = 300$ $\mu$m. The time for laser impact is kept constant, i.e. the speed of movement, duration, and frequency of pulses in numerical experiments remain unchanged.

Figures 2, 3, and 4 show the temperature profiles for different layers of the sample for time moment $t = 3$ ms following the start up of the process. The movement of the laser beam is along the OY axis and the process starts from a point with coordinates (2, 0) mm. Laser radiation parameters and those of the technology process are as follows: wavelength $\lambda = 1064$ nm; power density $q_s = 5.70 \times 10^9$ W/m$^2$; duration of pulses $\tau = 100$ ns; frequency $\nu = 10$ kHz; speed of marking $\nu = 20$ m/s.

The graph in Figure 2 concerns the first layer of the tested sample, Figure 3 the second layer, and Figure 4 the third layer. Temperature drop in depth is in accordance with the physical model, which describes laser radiation absorption by the free electrons in metals and alloys.
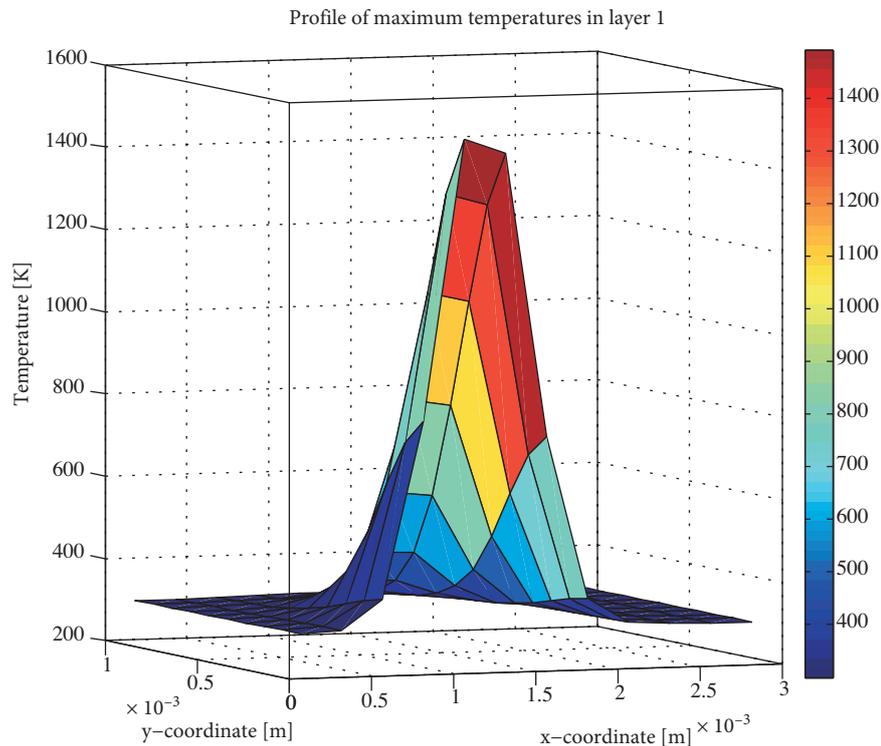


**Figure 2.** Temperature field of the upper layer with thickness of $\Delta h_1 = 12.5$ $\mu$m for sample made of steel type Y11 impacted by a Nd:YAG laser.
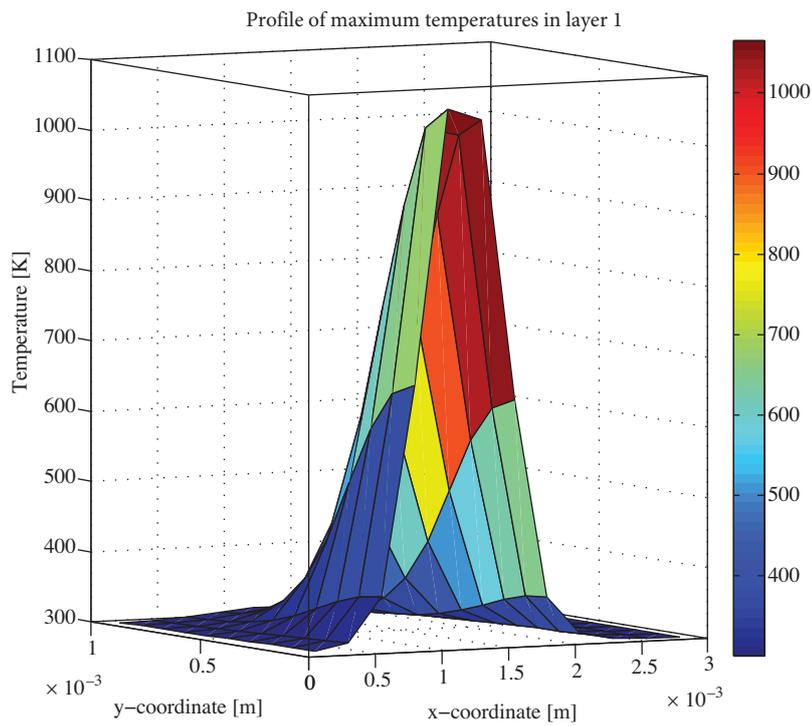
Profile of maximum temperatures in layer 1



**Figure 3.** Temperature field of the upper layer with thickness of $\Delta h_2 = 30.0$ $\mu$m for sample made of steel type Y11 and impacted by a Nd:YAG laser.
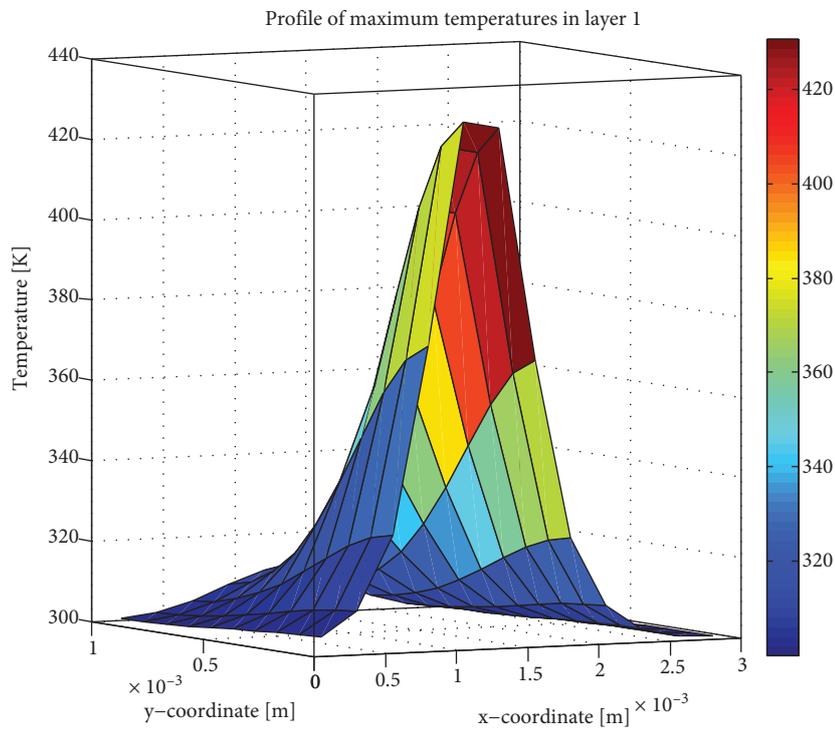
Profile of maximum temperatures in layer 1



**Figure 4.** Temperature field of the upper layer with thickness of $\Delta h_3 = 300$ $\mu$m for sample made of steel Y11 impacted by a Nd:YAG laser.

The depth of penetration of the laser radiation is $\sim 10^{-7}$ m, which suggests the consideration of surface heat source. Heat is distributed across the material by way of conduction (1). For the short time interval of laser impact (in ms), depending on the rate of marking and cooling of the impact zone, $\sim 10^{-6}$ K/s heat cannot reach a substantial depth. From the graph in Figure 4 it is evident that at depth the maximum temperature is equal to 450 K.

Numerical experiments led to the conclusion that the depth of marking achieved by the method of structural changes in the surface layer of the sample is approximately equal to 40 $\mu$m. It is known that structural changes in steel take place within the temperature interval of 1020–1050 K. Results obtained from numerical experiments correlate well with those obtained by real experiments [5].

## 3. Conclusion

Numerical experiments for determining temperature fields by means of this product are appropriate not only for optimizing the process of laser marking but also for other laser technology processes such as cutting, welding, boring, and hardening. Compared with the real experiment results they contribute to the rise in quality and effectiveness of laser treatment processes. The software features options for laser treatment numeric experimentation concerning various materials from mechanical engineering, electronics instrument engineering etc.

## References

[1] R. Poprawe, Lasertechnik für die Fertigung, (Springer, Berlin Heidelberg, 2005), p.521.

[2] N. Dinev, Laser in the modern technologies, (Alfa Publishers, Sofia, 1993), p.320.

[3] I. Belev, Bachelor degree thesis, Department of Computer Science, Technical University of Gabrovo, Bulgaria, 2009.

[4] N. Angelov, *Proceedings of International Scientific Conference, Gabrovo, Bulgaria*, **3**, (2004), 496.

[5] L. Lazov, N. Angelov, A. Atanasov, *Proceedings of International Scientific Conference, Gabrovo, Bulgaria*, **1**, (2006), 530.