Finite element modeling of laser aluminum marking

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Abstract. This work makes use of the finite element model, whose results are validated by experiments. The effect is discussed of the speed on the laser marking process. Numerical experiments are performed to determine the temperature fields produced by laser pulses on samples of aluminum, a material with wide industrial uses. The numerical calculations are performed for the cases of a fiber laser and a CuBr laser. Plots are drawn of the temperature dependence on the speed for two power densities for both lasers. Preliminary working speed intervals are determined for the power densities used.

1. Introduction

Laser marking is a complex technological process applied to products made from metals, alloys, semiconductors and many non-metals (plastic, organic glass, ceramics, rubber, wood, leather, textile materials, etc.) [1-4]. The laser marking technology satisfies equally the requirements to marking ultra-fragile and miniature elements in electronics, and those for very hard tools and mechanical engineering products. Laser marking has occupied a permanent position in the modern production of electronics and machine-building products, because it enables companies to meet the present requirements for quality control. Laser marking of serial numbers, matrix codes, 1D and 2D barcodes, technical parameters, tables and other operational information is often needed in the industrial production and trade and in monitoring production processes [5-7].

The rapid integration of this new technology in industrial processes is primarily due to its features: contactless process; high quality; high precision; marking of hard-to-reach places; possibility for installation in production lines; high efficiency; environmentally clean process, etc. [8-9]. When implementing it, the action of various factors must be taken under consideration, such as: marking speed, power density, pulse repetition rate and duration, pulse power, pulse energy, defocus, size of focal spot etc. [10-11]. A number of authors have studied these factors and analyzed the functional relationships between them [12-14].

In recent years, in order to reduce the number of primary experiments and determine more quickly the optimal operating ranges, preliminary numerical experiments have been conducted on the basis of process modeling. The use of numerical methods and modeling makes it possible to correctly determine
the boundary zones and modes of operation of various laser technological systems for marking materials. They also contribute to clarifying complex questions related to the optimization of the physical processes [15-20]. Preliminary numerical experiments save money and time, which is of great importance for companies that intend to introduce laser marking in their production process.

In the article by Otto, Koch et al. [15] a dynamic model of the laser impact on the substance is taken into account. Numerical calculations were performed with the COMSOL software to clarify the influence of the angle of incidence of the beam and the duration of the pulses on the technological processes of laser cutting, laser welding and laser drilling of holes. The results obtained from the calculations are compared with experimental results and a good correlation is found.

A physical model of the laser marking process of metals and alloys was developed in our publication [16]. The interaction is analyzed of the laser radiation with the samples in the laser impact zone. The process of absorption of laser radiation, as well as the heat transfer and distribution in the samples is additionally discussed. The weight of each of the heat transfer mechanisms for the laser marking of metals and alloys is evaluated.

In [17], on the basis of numerical experiments, the influence is discussed of the technological parameters in laser cutting of sheet steel on the quality of the process. The dimensions of the heat affected zones and the isotherms obtained are analyzed. The ABAQUS software is used to obtain three-dimensional temperature fields. The authors also compared the results with those of experiments.

A method for optimizing the process of laser strengthening of steel parts using the finite element method and the COMSOL Multiphysics software (module Heat Transfer in Solids) is developed in the article by Martinovs et al. [20]. The thickness of the strengthening layer is determined by a series of numerical experiments. Mathematical modeling and numerical experiments are also used to optimize the laser layering process.

The aim of this article is to analyze through numerical experiments the influence of the laser beam speed on the marking process of aluminum (Al) samples in the cases of a CuBr laser and a fiber laser and two power densities. We are thus able to compare the effects of laser radiation in the visible range ($\lambda = 511, 578$ nm) and the near-infrared range ($\lambda = 1064$ nm) on aluminum samples.

2. Methodology of the experiment

When metals are exposed to laser radiation, absorption occurs in a very thin layer, as the electromagnetic energy is almost instantly converted into thermal energy. Thus, a surface heat source is formed in the treated area. After the absorption of the electromagnetic energy by the metal, heat begins to be transferred to the material according to the laws governing thermal conductivity.

The heat transfer in the process of laser marking is described by the differential thermal conductivity equation:

$$c\rho \frac{\partial T}{\partial t} = \text{div}(k \text{ grad } T) + q_s(1 - R)\alpha$$

(1)

where $q_s$ is the surface power density; $R$, the reflection coefficient; $\alpha$, the absorption coefficient; $c$, the specific heat capacity; $\rho$, the density; and $T$, the temperature.

The differential equation of thermal conductivity is very complex and cannot be solved analytically in the general case. In practice, various software products are used to solve it, such as COMSOL MULTIPHYSICS, ANSYS, ABAQUS, MATLAB, TEMPERATURFELD3D and others [19].

In our numerical experiments, the program ABAQUS applying the finite element method is used to determine the temperature fields. Figure 1 shows the mesh of elements used with sizes from 10 $\mu$m to 300 $\mu$m and layer thicknesses from 20 $\mu$m to 300 $\mu$m. Specific to laser processes (including marking) is the very small impact area, which is from tens of micrometers to hundreds of micrometers. In our case, the diameter of the working spot is 30 – 35 $\mu$m.
The calculations are performed and the data obtained can be stored in a certain time step and as final calculations. The time step is selected bearing in mind the physics of the technological process, namely that the heating and cooling rates of the order of $10^6$ K/s.

As illustrated in figure 2, the technological process depends on the optical and thermo-physical properties of the material. Our numerical experiments were performed on aluminum samples, which were compared with real experimental data obtained from the MAXLASER Co, Sofia. The main physical characteristics used in the numerical calculations are listed in table 1.

![Figure 1. General view of the mesh of elements created and used for numerical calculations.](image1)

![Figure 2. Factors influencing the laser marking process.](image2)

**Table 1.** Physical characteristics of the samples of aluminum.

| Quantity                           | Value  |
|-----------------------------------|--------|
| Melting point $T_m$, K            | 933.47 |
| Evaporation point $T_e$, K        | 2743   |
| Density $\rho$, kg/m$^3$          | 2700   |
| Latent heat of melting $q_m$, kJ/mol | 10.71  |
| Latent heat of evaporation $q_v$, kJ/mol | 284    |
| Coefficient of thermal conductivity $k$, W/(m K) | 237    |
| Specific heat capacity $c$, J/(kg K) | 900    |

In our numerical experiments, we considered the interaction of a single-mode laser beam, i.e., a Gaussian intensity distribution. Thus, we assume that the laser energy is concentrated in a single-point cross section and shows a point symmetry. We chose this approach, because single-mode beams allow
for finer marking of higher quality than multi-mode beams, which have an inhomogeneous power distribution.

Figure 3. (a) Areas marked by a single-mode laser beam.

Figure 3. (b) Areas marked by a multi-mode laser beam.

2.1. Numerical experiments and discussion
According to the experimental plan, the numerical experiments were conducted in two series – A) and B):

A) Investigation of the dependence of the marking depth and width on the speed for a CuBr laser
In the first series, the speed varied in the interval \( v \in [20; 300] \text{ mm/s} \), and the laser radiation power was kept constant: \( P_1 = 7.00 \text{ W} \) and \( P_2 = 10.0 \text{ W} \). The experiments were performed sequentially with power \( P_1 \) and then with power \( P_2 \). The parameters used in the numerical experiments are given in table 2. The results of the numerical calculations in the impact zone outlined the geometry of the processed area and the isotherms around it (see figure 4). The evaporated zone is given in gray and there are no isotherms due to the absence of substance. The small heat-affected zone (HAZ) is impressive, and is in accordance with the real experimental data.

Table 2. Parameters that are kept constant during numerical experiments with a CuBr laser.

| Parameter                           | Value       |
|-------------------------------------|-------------|
| Wavelength \( \lambda \), nm        | 511 & 578   |
| Average power \( P_1 \), W          | 7.00        |
| \( P_2 \), W                        | 10.0        |
| Diameter of working spot \( d \), \( \mu \text{m} \) | 30          |
| Power density \( q_{\lambda 1} \), W/m\(^2\) | 0.99×10\(^{10}\) |
| Power density \( q_{\lambda 2} \), W/m\(^2\) | 1.42×10\(^{10}\) |
| Coefficient of reflection \( R \), % | 20.0        |
| Number of repetitions \( N \)       | 1           |
Based on the numerical calculations, the graphical dependences of the depth $h$ and width $b$ of the marking on the speed $v$ for power densities $q_{S1} = 0.99 \times 10^{10}$ W/m$^2$ and $q_{S2} = 1.42 \times 10^{10}$ W/m$^2$ are drawn (figures 5 and 6). The graphs describe the evaporation zone giving the shape of the channel marked in the sample. The following conclusions can be drawn from the analysis of the graphs:

- As the marking speed increases, a nonlinear decrease in the marking depth $h$ and the marking width $b$ is observed for both power densities studied;
- For power density $q_{S1} = 0.99 \times 10^{10}$ W/m$^2$, the depth $h$ and the width $b$ of the marking are about 20% less than for power density $q_{S2} = 1.42 \times 10^{10}$ W/m$^2$. This can be explained by the lower energy absorbed in the processing area.
- The recommended operating intervals of the speed of marking by evaporation for aluminum samples are:
  $v \in [20; 85]$ mm/s for $q_{S1} = 0.99 \times 10^{10}$ W/m$^2$;
  $v \in [20; 170]$ mm/s for $q_{S2} = 1.42 \times 10^{10}$ W/m$^2$.

**B) Investigation of the dependence of the marking depth and width on the speed for a Nd:YAG fiber laser**

In the second series of numerical experiments, the speed varied in the interval $v \in [20; 300]$ mm/s. The calculations were performed for two powers that were kept constant: $P_1 = 15.0$ W and $P_2 = 20.0$ W. The parameters used in the numerical experiments are given in Table 3. The results of the numerical
calculations are the isotherms obtained in the studied samples around the evaporation zone. The analysis is made based on the graphical dependences for the depth $h$ and the width $b$ of the evaporation zone.

**Table 3.** Parameters that do not change during numerical experiments with Nd:YAG fiber laser.

| Parameter                        | Value        |
|----------------------------------|--------------|
| Wavelength $\lambda$, nm         | 1064         |
| Average power $P_1$, W           | 15.0         |
| $P_2$, W                         | 20.0         |
| Diameter of working spot $d$, $\mu$m | 35           |
| Power density $q_{s1}$, W/m$^2$  | $1.56 \times 10^{10}$ |
| Power density $q_{s2}$, W/m$^2$  | $2.08 \times 10^{10}$ |
| Coefficient of reflection $R$, % | 30.0         |
| Number of repetitions $N$        | 1            |

Figures 7 and 8 present the graphical dependences of the depth $h$ and the width $b$ of the marking on the speed $v$ for power densities $q_{s1} = 1.56 \times 10^{10}$ W/m$^2$ and $q_{s2} = 2.08 \times 10^{10}$ W/m$^2$ obtained by the numerical experiments. The following conclusions can be drawn from the analysis of the graphs:

- As the marking speed increases, a nonlinear decrease in the marking depth $h$ and the marking width $b$ is observed for both power densities studied;

- For the power density $q_{s2} = 2.08 \times 10^{10}$ W/m$^2$, the depth $h$ and width $b$ of the marking is about 30% greater than for the power density $q_{s1} = 1.56 \times 10^{10}$ W/m$^2$. This is explained by the higher energy absorbed by the material in the impact zone.

- A comparison of the results for a CuBr laser and a fiber laser shows that a lower power density $q_S$ is required to achieve the same depth $h$ of the evaporated zone with a CuBr laser, i.e. the energy efficiency of the CuBr laser is better than that of the fiber laser (by about 25%). This is due to the fact that the absorption is a function of the laser radiation wavelength;

- The recommended operating intervals of the marking speed by evaporation of aluminum samples are:
  - $v \in [20; 120]$ mm/s for $q_{s1} = 1.56 \times 10^{10}$ W/m$^2$;
  - $v \in [20; 290]$ mm/s for $q_{s2} = 2.08 \times 10^{10}$ W/m$^2$.

![Figure 7](image1.png)  
**Figure 7.** Dependences of the depth $h$ and the width $b$ on the speed $v$ for $q_{s1} = 1.56 \times 10^{10}$ W/m$^2$.

![Figure 8](image2.png)  
**Figure 8.** Dependences of the depth $h$ and the width $b$ on the speed $v$ for $q_{s2} = 2.08 \times 10^{10}$ W/m$^2$. 
3. Conclusion
The methodology developed for studying the process of laser marking by evaporation of aluminum products by a fiber laser and a CuBr laser allows one to reduce the number of real experiments in order to optimize the technological process by replacing them with numerical experiments. It helps technologists and operators of laser technology systems for marking. It further allows one to determine the depth and the width of the marking obtained for different technological parameters.

The results of the studies presented on the influence of the laser beam speed on the process of laser marking by evaporation of aluminum products using a fiber laser and a CuBr laser can be summarized as follows:

- A graphical dependence was obtained for the depth and width of the marking on the speed for two power densities of a fiber laser;
- A graphical dependence was obtained for the depth and width of the marking on the speed for two power densities of a CuBr laser;
- Recommended operating intervals of the speed for two power densities of a fiber laser were determined;
- Recommended operating intervals of the speed for two power densities of a CuBr laser were determined;
- The results for the technological process for laser radiation in the visible and infrared regions were compared and analyzed.

Acknowledgements
The authors gratefully acknowledge the financial support of the European Regional Development Fund, Postdoctoral research aid Nr. 1.1.1.2/16/I/001 research application "Analysis of the parameters of the process of laser marking of new industrial materials for high-tech applications, Nr. 1.1.1.2/VIAA/3/19/474".

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