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Optimization of laser marking with the help of simulation models

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Abstract: This article covers the results of several numerical experiments carried out with specific software working under MATLAB for marking of tool steel and electronic elements. CuBr and Nd:YAG lasers were used in this study. Simulations with 3 different durations of pulse of laser radiation were achieved. Numerical calculations were performed with values (for laser sources and technological parameters) based on real experiments.

Key words: Graphic images, laser, temperature field

1. Introduction

Laser marking is progressively enlarging its share in the output of electronics and machine-building products since it enables firms to respond to up-to-date requirements of quality control. The laying of serial numbers, matrix-codes, barcodes, technical parameters, tables, and other operative information is the main factor for correct optimization and monitoring of production processes [1]. Laser technology for marking equally satisfies requirements for marking of superfragile and miniature elements in electronics as well as of supersolid tools and articles of machine-building. The impetuous invasion of new technology in industrial output is due primarily to its special features, such as contactless process realization, possibility for variance in terms of diameter of working spot as parameters of the laser source, selectivity of impact to treatment of the material, and opportunity for heating, melting, or vaporization of material from the processing zone [2].

2. Presentation

The purpose of this report is to present the opportunity for obtaining prognostic working intervals of the basic technological parameters under laser marking for electronic and mechanical engineering products.

In our exploration, we applied the program TEMPERATURFELD 3D [3] for the simulation of different models and we obtained as a final result 3-dimensional temperature fields in the laser impact zone. Some of the particular cases of laser marking serial number experiments were accomplished to obtain temperature fields in the laser marking of a sample as some of the following parameters are changing [4,5]: λ – length of laser wave; q_S – laser power density; τ – length and ν – frequency of repetition of pulses; d – diameter of working spot; v – speed of marking.

In the simulation the optical and thermo-physical material properties' values are reading (R – reflection coefficient, δ – depth of penetration of laser beam, k – thermal conductivity, c – specific heat capacity, ρ – density of the material), as well as the way in which they vary when temperature in the zone of impact increases.

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The numerical experiments were completed with samples of Si; Ge; SiO_2; tool steels Y10, Y11, Y12, and Y13; and rapid tool steels P9 and P6M5. The sources of heat created as a result of the interaction of laser radiation with samples of the first 3 materials are considered as volumetric and for the steels as surface [6]. Laser sources with length of laser wave $\lambda = 1064$ nm and $\lambda = 511$ nm are used for the calculations; the basic parameters are indicated in the Table.

The following simulations are considered in the research:

- Marking through a surface modification for samples of steel with a CuBr laser;
- Marking through a surface modification under impact with Nd:YAG lasers with different duration of impulses for steel samples;
- Marking through a melt of Si samples with a CuBr laser.

Table. Basic parameters of laser courses.

Laser / Parameters	Laser IS 1064	JenLaser MOPA N45	JenLaser MOPA M45	Laser CuBr
Length of wave λ, nm	1064	1064	1064	511
Average power P, W	3	20	20	20
Frequency ν, kHz	10	100	100	19
Length of pulse τ, ns	10	100	1000	30
Diameter of working spot d, μm	2	30–80	30–100	30–80

3. Results and analysis from the research

The subject of research in the first simulation was the temperature profiles in samples of carbon steel under CuBr lasing with density of lasing power q_s (6.00×10^9–1.40×10^{10} W/m^2) providing maximum temperature on the surface below the melting point. This was due to the fact that marking through modification of the product's surface through oxidation or structural changes in a very small surface layer is a method often used in practice.

The following conclusions can be drawn from the progress of temperature profiles during the numerical experiments performed and shown in Figures 1 and 2:

- Temperature quickly decreases when moving away from the zone of impact in the radial direction for distances of 200 μm from the center of the working spot it reaches about 3 times and the temperature is close to the environmental temperature;
- When changing the density of power in the range examined, the temperature on the sample's surface varies within limits of 850–1780 K.

From the diagram of the temperature field (Figure 1, the power density $q_s = 6.82 \times 10^9$ W/m^2) it is seen that the surface temperature of the sample is below that of structural changes. In our other real experimental studies with the same power density a pale, low-contrast slightly visible line appears (Figure 3). The obtained marking is due to the oxidizing processes on the steel surface. The temperature field in Figure 2 indicates the maximum temperatures on the sample surface, exceeding 1003 K, where structural changes occur ($q_s = 9.98 \times 10^9$ W/m^2).

After the comparison of the results from the conducted numeral experiments, the intervals for the power density q_s were defined, for which the temperature is in between the allowable for occurrence of structural changes in the surface layer, determined as follows: q_s $(8.30 \times 10^9 – 1.15 \times 10^{10}$ W/m$^2)$. The critical power density for reaching the melting point in the processing area was determined as $q_{Scr} = 1.47 \times 10^{10}$ W/m^2 (Figure 4).

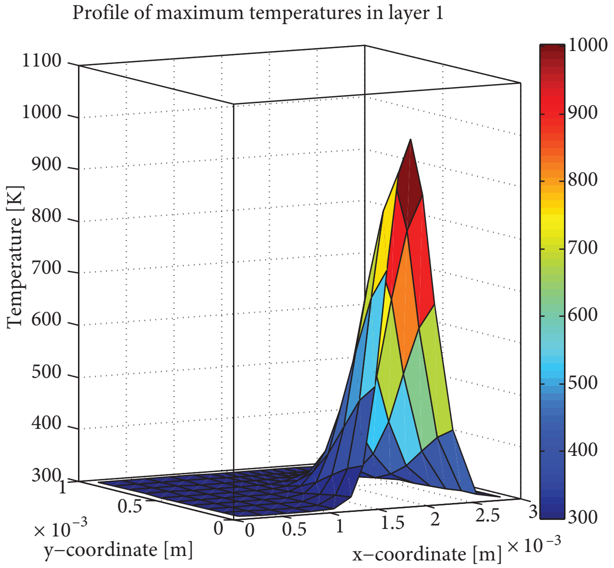

Figure 1. Temperature field of tool steel Y11 for power density $q_S = 6.82 \times 10^9$ W/m^2 with a CuBr laser.

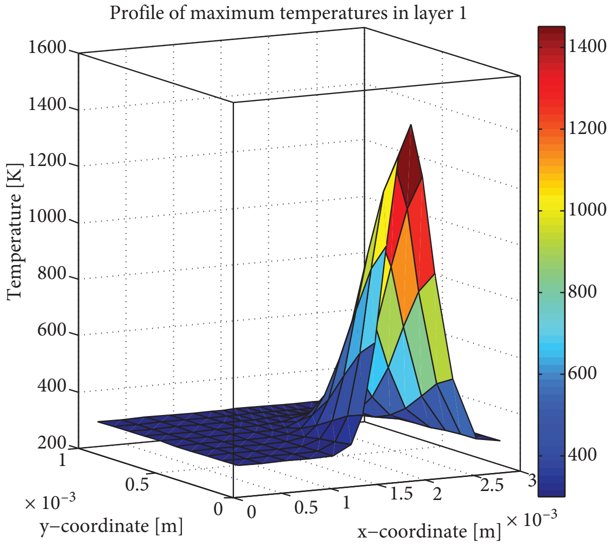

Figure 2. Temperature field of tool steel Y11 for power density $q_S = 9.98 \times 10^9$ W/m^2 with a CuBr laser.

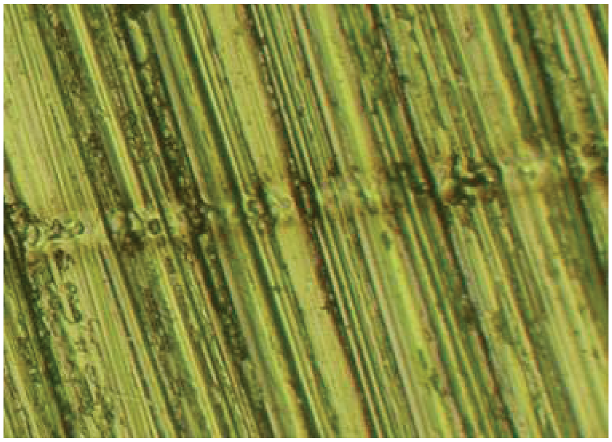

Figure 3. Laser marking of tool steel Y11 for power density $q_S = 6.82 \times 10^9$ W/m^2 with a CuBr laser.

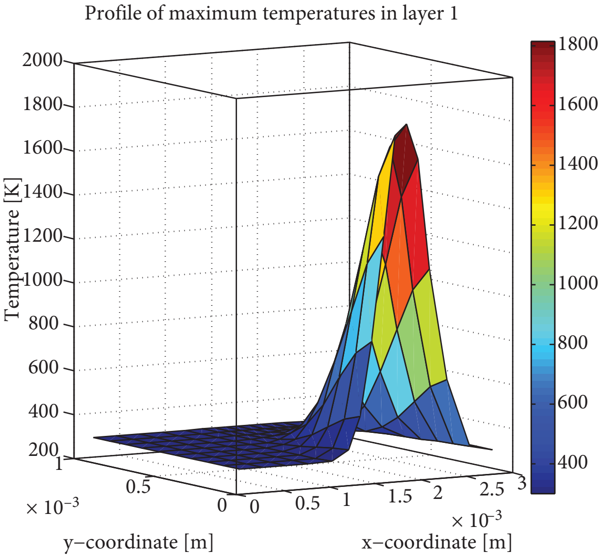

Figure 4. Temperature field upon reaching the melting point of tool steel Y11 ($q_{Scr} = 1.47 \times 10^{10}$ W/m^2) with a CuBr laser.

The influence of the pulse length t on the process of laser-marking was investigated under the conditions of the other simulations, by using Nd:YAG laser systems in 3 different operating modes (t = 10 ns, 100 ns, 1000 ns) (see Table).

Figures 5, 6, and 7 show the temperature fields during laser marking through structural changes in instrument steel Y12, with a velocity v = 100 mm/s using 3 Nd:YAG lasers.

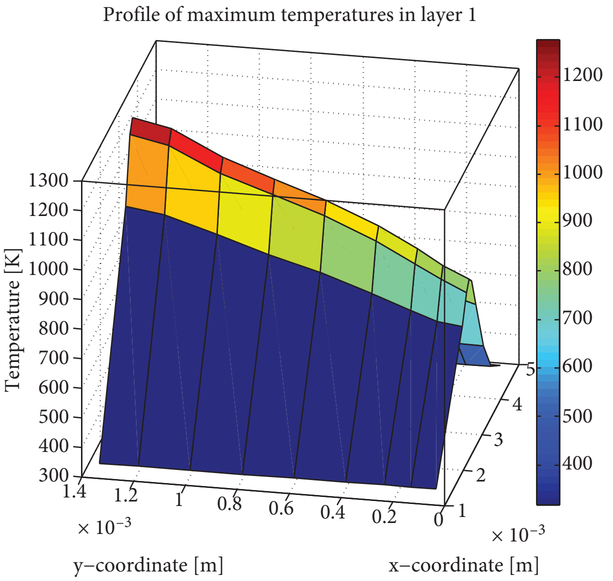

Figure 5. The temperature field during laser marking through structural changes in tool steel Y12, with a Nd:YAG laser, pulse length τ = 10 ns.

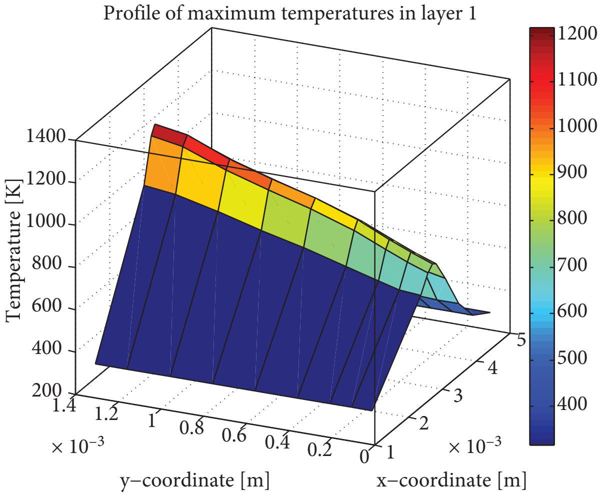

Figure 6. The temperature field during laser marking through structural changes in instrument steel Y12, with a Nd:YAG laser, pulse length τ = 100 ns.

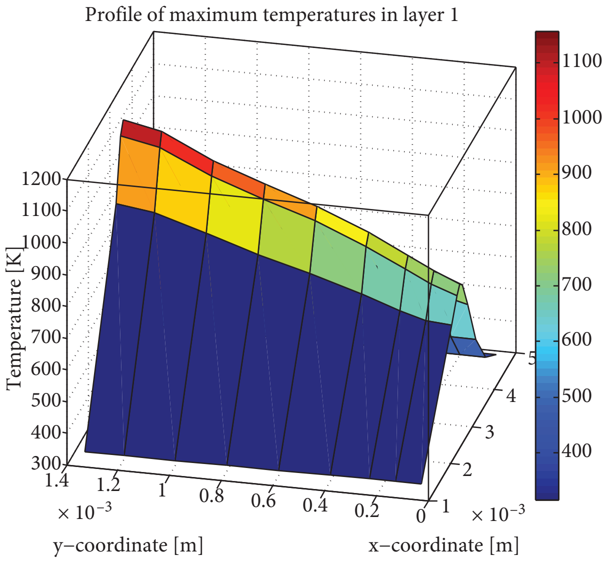

Figure 7. The temperature field during laser marking through structural changes in tool steel Y12, with a Nd:YAG laser, pulse length τ = 1000 ns.

From the analysis of the 3-dimensional graphical images, the following results were determined:

- The surface temperature of the samples decreases by 100 K (from 1250 K at 10 ns to 1150 K at 1000 ns) when the pulse length is increased by 2 orders of magnitude;
- The heat-impacted area increases nonlinearly with the pulse length increase.

The obtained result can be explained by the physical model of interaction of the laser radiation with the substance [7], namely the duration of the short pulses is commensurate with the time for absorbance of a part from the incident photons from the free electrons and the redistribution of the energy of the electronic gas to the crystal grating. Rapid heating of the impact area takes place and accordingly rapid cooling occurs. The heat transfer through heat conductivity is epsilon squared and practically the whole absorbed energy remains in this area and a significant temperature increase takes place. In the case of greater pulse length, the heating of the sample surface is slower, and, accordingly, slower cooling occurs, compared with the shorter pulses. The energy transfer through heat conductivity in this case cannot be neglected; the heat impacted area expands as part of the absorbed energy is accumulated in it.

This results in lower temperatures in the impact area, compared to the case with shorter pulses used.

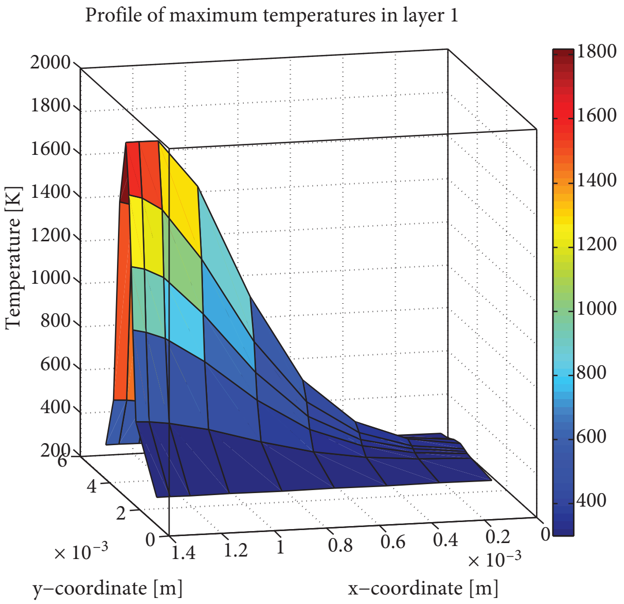

Figure 8. The temperature field during laser marking of Si with a Nd:YAG laser, power density $q_S = 2.90 \times 10^9$ W/m^2.

In the third simulation the goal was to study the heating of samples made of silicon in the process of marking through melting in the impact area, i.e. above the melting temperature. The studies were conducted using a Nd:YAG laser at the following initial conditions: $v = 50$ mm/s; $t = 100$ ns; $d = 80$ μm.

The changes in the optical and thermal and physical properties with temperature were also taken into consideration in the time of impact and latent heat of melting of the material. The heat source in the material was considered volumetric. During the investigation the power density was changed in the interval 2.6×10^9–4.3×10^9 W/m^2. The temperature field for one of these numerical experiments is presented in Figure 8. The power density of the laser radiation for this case was $q_s = 2.90 \times 10^9$ W/m^2.

From the analysis of the results from the numeric experiments in this simulation the following conclusions can be drawn:

- The heat impacted area is comparable with the diameter of the working spot. The temperature gradient in this area is ≈ 10 K/μm;
- The interval for the power density of the laser radiation where it produces marking through melting on samples made of silicon should be maintained in the interval 2.7×10^9–3.6×10^9 W/m^2.

4. Conclusion

The use of numeric methods and simulations helps in the proper determination of the border zones and operation modes for different laser technological methods for processing of materials. They contribute also to the clarification of complicated issues associated with the thermo-chemical reactions, phase transitions, and outbreak of substance in a liquid and evaporated from the zone of the laser impact.

These preliminary experiments result in sparing of funds and time, which is of great importance for companies intending to introduce different laser methods in their industrial production process.

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