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NUMERICAL EXPERIMENTS TO INVESTIGATE THE LASER MARKING PROCESS OF C35 STEEL SAMPLES

Nikolay Angelov[1], Miroslav Kokalarov[2]

[1]Technical University of Gabrovo, 4 Hadzhi Dimitar str., Gabrovo, Bulgaria;
[21]Technical University of Gabrovo, 4 Hadzhi Dimitar str., Gabrovo, Bulgaria;

** Miroslav Kokalarov: m.kokalarov@tugab.bg*

Abstract

The research concerns the process of laser marking by melting C35 structural steel samples. Numerical experiments are done for fiber laser and CuBr laser technological systems. Temperature fields are obtained for different values of power density, speed and two values of wavelength. The temperature dependence of the material parameters was reported. Graphs of temperature versus power density for three speeds and temperature vs. speed for three power densities are plotted. The results have been analyzed and preliminary operating intervals have been determined for these quantities for the laser marking process by melting.

Keywords: laser marking, fiber laser, CuBr laser, C35 steel, temperature fields, power density, speed, preliminary working intervals.

INTRODUCTION

Laser marking is a modern technological process and can be applied to almost all types of solid materials. One of these possibilities is laser marking of metals and alloys (including steels). Laser marking of steel products is becoming increasingly relevant due to effective marking solutions in various industries. The urgency of the problem stems from several key factors [7]:

- High quality;
- Traceability requirements for industrial products;
- Wear resistance;
- High precision [8];
- Environmentally clean process;
- Economic benefit [9, 10];
- Adaptability to different types of steel;
- Rapid technological progress in the capabilities of laser systems.

The quality of laser marking depends on a number of basic parameters such as power density, speed, frequency, pulse duration, pulse power, pulse energy, raster step, defocus, number of repetitions, etc. [7, 12]. Real and numerical experiments are used to study their influence on the laser marking process. Numerical experiments complement real experiments by allowing faster optimization by simulating different conditions. In addition, they are much more economical than real experiments.

The process of laser marking of metals and alloys has been studied by a number of authors:

In publication [1], the authors investigated the process of marking stainless steel using a pulsed fiber laser. They performed corrosion tests on samples of laser-marked materials. They analyzed the structure and corrosion properties of the surface of the marked areas.

In article [2], color laser marking of stainless steel is investigated in terms of repeatability and stability of color markings. The dependence of the obtained colors on various laser processing parameters was analyzed. In addition, the stability of the color markings was investigated in terms of environmental, mechanical and chemical resistance. The resulting colors have shown high resistance to most environmental conditions except very high temperatures, extreme humidity and high acidity.

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In the paper [3], the authors identify the parameters and guidelines that can be used to control the laser marking process in the production environment. The problem of the surface of the marked metal material is discussed in the conducted experiments. A visual and microscopic assessment was made of how changing the laser parameters can affect the final appearance of the tested metal materials.

The publication [4, 14] investigates the influence of the technological parameters speed, raster step and number of repetitions on the contrast and roughness of the marking for copper samples. A technological system with a fiber laser was used to perform the experiments. It was found that as the speed increased, the contrast and roughness decreased. The regularity was obtained that increasing the step of the raster leads to a decrease in contrast and an increase in roughness.

In the publication [5, 13], the main methods for laser marking are systematized. The advantages of the laser method over other marking methods are shown. Experimental studies have been conducted with the CuBr laser (copper bromide vapor laser) for specific machining details. Working technological parameters for their marking are given.

The authors of [6] applied the laser color marking method on stainless steel and investigated their surface morphology and optical properties by atomic force microscopy (AFM), laser scanning microscopy, reflection spectroscopy and ellipsometry. The reflectance spectra of the samples show that the reflectance maxima correlate with the visible colors of the samples and with the extrema in the non-monotonic spectral dependences of the derivative of the real part of the complex permittivity derived from the ellipsometric data.

From the literature review, it can be seen that the process of laser marking of steel is up-to-date. There are many unexplored areas, because for each specific steel, type of laser and marking method research must be done to optimize the technological process.

The purpose of the present work is to investigate the laser marking process by melting C35 steel samples by means of numerical experiments and obtaining preliminary working intervals of the power density and speed.

EXPOSITION

A. LASER SYSTEMS

The numerical experiments refer to two laser technology systems with a fiber laser and a CuBr laser.

The main parameters of the fiber laser system are presented in Table 1. A fiber laser is a pulsed laser operating in the near infrared region. It has a high efficiency and extremely high beam quality. The laser system provides high speed of beam movement and high positioning accuracy.

Parameters of the CuBr laser system are given in Table 1. The CuBr laser is a pulsed laser operating in the visible region. What is unique about it is that its radiation is absorbed by metals and alloys much better than that of lasers operating in the near and far infrared region. It has good beam quality and relatively high efficiency. The laser system is characterized by high positioning accuracy.

Table 1. Main parameters of fiber laser and CuBr laser systems

Laser Parameter	Fiber	CuBr
Wavelength λ, nm	1064	511&578
Power P, W	30	10
Frequency ν, kHz	80	20
Pulse duration τ, ns	100	30
Pelse energy E_p, mJ	0.375	0,50
Pulse power P_p, kW	3,75	16,7
Beam quality M^2	< 1,1	< 1,7
Positioning accuracy, µm	2,5	2,5
Efficiency, %	40	20

B. MATERIAL

Numerical calculations refer to structural steel C35. It is a low-carbon steel widely used in industry. It is used to produce low-strength parts that experience low stress: axles, cylinders, crankshafts, connecting rods, spindles, gears, rods, rims, sleepers, shafts, connecting rods, discs and other parts. It has relatively high coefficients of thermal conductivity and thermal conductivity. When performing the numerical experiments, the temperature dependence of the steel parameters is taken into account, which is given in Table 2.

Table 2. Dependence of basic parameters of C35 steel on temperature

T, K	k, W/(m.K)	ρ, kg/m^3	c, J/(kg.K)
293	50	7826	446
373	49	7804	469
473	49	7771	490
573	47	7737	511
673	44	7700	532
773	41	7762	553
873	38	7623	578
973	35	7583	611
1073	29	7600	708
1173	28	7549	699

Legend: T is temperature, k – coefficient of thermal conductivity, ρ – density, c – specific heat capacity.

C. SOFTWARE

The numerical experiments were performed with the Temperaturfeld3D program [11]. It is a working environment for calculating temperature fields during laser impact on materials. What is specific about these processes is the very small area of impact.

At the beginning, a model of program operation is selected. Then the main window opens (Fig. 1) and from it previous calculations can be loaded and their results analyzed or some parameters can be changed and the numerical experiments can be continued. The input parameters are set: program parameters, geometric parameters, laser parameters and material parameters. Calculations are started and the resulting data can be saved. As output results, the program provides the following options: animation of the researched process; maximum temperature profile, temperature variation with depth.

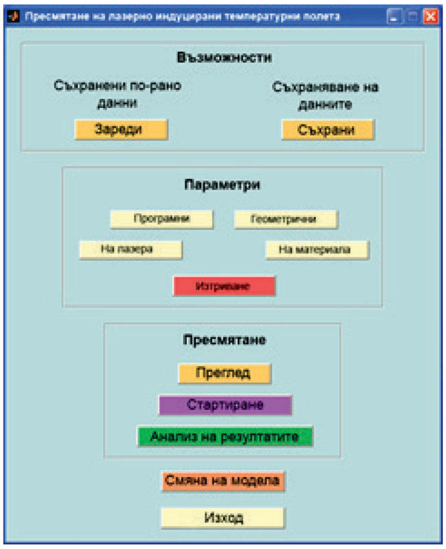


Figure 1. Main window of Temperaturfeld3D program

D. NUMERICAL EXPERIMENTS, RESULTS AND ANALYSIS

Numerical experiments are carried out with different values of power density and marking rate. The remaining parameters are kept constant for each laser.

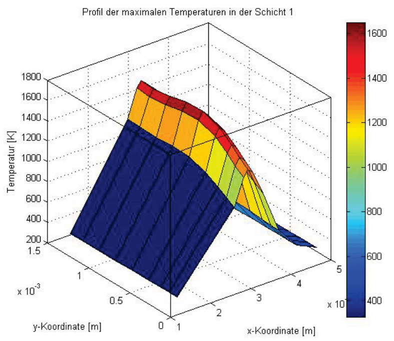
The numerical experiments were carried out in two directions:

1) Investigation of temperature dependence of power density for three speeds

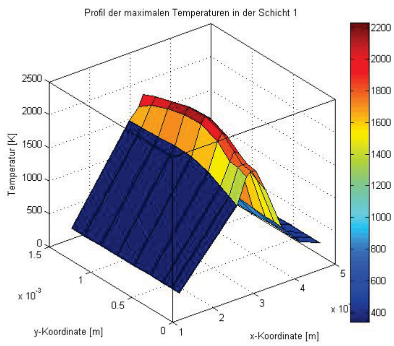
a) For fiber laser

The power density varied in the interval q_s € [0.70, 1.60] 10^{10} W/m^2 with step 1,00.10^9 W/m^2. Calculations were performed for three speeds v: 40 mm/s, 50 mm/s, 60 mm/s. For each specific experiment, temperature fields in and around the impact zone were obtained. In Fig. 2a a 3D temperature field is given with the following parameters: $q_s = 0.80\times10^{10}$ W/m^2 and v = 50 mm/s. The maximum temperature in the impact zone is 1620 K and it is below the melting temperature.

Fig. 2b shows a 3D temperature field with the following parameters: q_s = 1.30×10^{10} W/m^2 and v = 50 mm/s. The maximum temperature in the impact zone is 2240 K and it is between the melting temperature and the vaporization temperature of the steel. In this case, the process of laser marking by melting can be realized.



a)



b)

Figure 2. Temperature fields from the numerical experiments with the following parameters: a) q_s = 0.80×10^{10} W/m^2 and v = 50 mm/s; b) q_s = 1.30×10^{10} W/m^2 and v = 50 mm/s

Graphs of the dependence of temperature on power density were constructed from the obtained results (Fig. 3). The following can be concluded from their analysis:

- As the power density increases, there is a linear increase in temperature for all three speeds;
- For a speed of 40 mm/s, the temperature increases from 1620 K to 2893 K for the power density interval from 0.70×10^{10} W/m^2 to 1.60×10^{10} W/m^2;
- For a speed of 50 mm/s, the temperature increases from 1473 K to 2630 K for the entire investigated power density interval;
- For a speed of 60 mm/s, the temperature increases from 1350 K to 2411 K for the entire studied power density interval;
- The following preliminary power density operating intervals are defined

q_s € [0.83, 1.60] 10^{10} W/m^2 for v=40 mm/s;
q_s € [0.95, 1.60] 10^{10} W/m^2 for v=50 mm/s;
q_s € [1.08, 1.60] 10^{10} W/m^2 for v=60 mm/s.

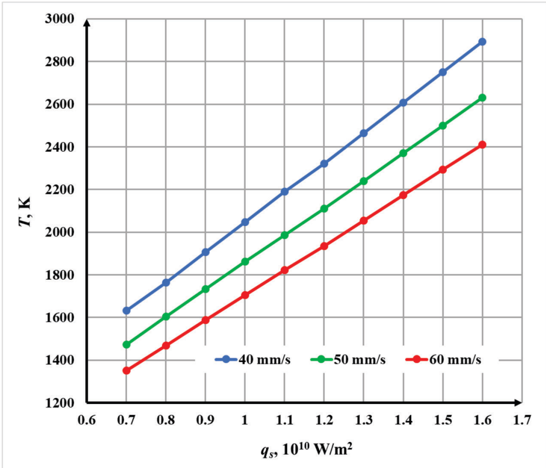


Figure 3. Graphics of temperature versus power density for three speeds.

b) For a CuBr laser

Numerical calculations were performed for three speeds v: 40 mm/s, 50 mm/s, 60 mm/s and power density from 0.4×10^{10} W/m^2 to 1.3×10^{10} W/m^2 with step 1.0×10^9 W/m^2. From the obtained results, graphics of the dependence of temperature on power density for three speeds are drawn (Fig. 4). Their analysis shows the following:

- As the power density increases, there is a linear increase in temperature for all three speeds;
- For a speed of 40 mm/s, the temperature increases from 1550 K to 2783 K for the power density interval from 0.40×10^{10} W/m^2 to 1.30.10^{10} W/m^2;
- - For a velocity of 50 mm/s, the temperature increases from 1409 K to 2512 K for the entire studied power density interval;

- For a velocity of 60 mm/s, the temperature increases from 1292 K to 2319 K for the entire studied power density interval;
- It is noticeable that with the CuBr laser, to obtain a given temperature, a much smaller power density is needed than with the fiber laser. It is explained by the fact that the absorptivity of steel in the CuBr laser (45%) is greater than that in the fiber laser (30%);
- The following preliminary operating intervals of the power density are defined

q_s € [0.58, 1.30] 10^{10} W/m^2 for v=40 mm/s;
q_s € [0.72, 1.30] 10^{10} W/m^2 for v=50mm/s;
q_s € [0.85, 1.30] 10^{10} W/m^2 for v=60 mm/s.

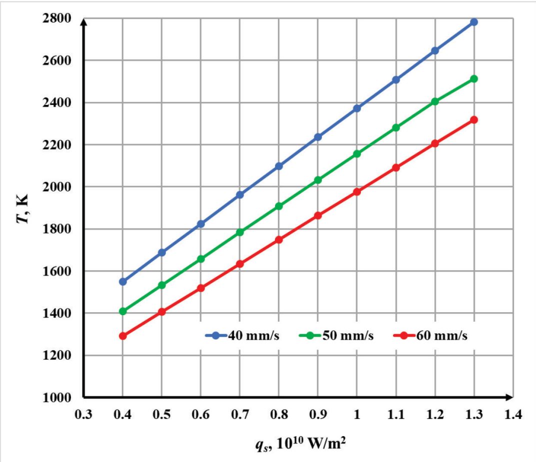


Figure 4. Graphics of temperature versus power density for three speeds.

2) Investigation of temperature dependence of speed for three power densities

a) For fiber laser

Calculations were performed for three power densities q_s: 0.60×10^{10} W/m^2, 1.10×10^{10} W/m^2 , 1.30×10^{10} W/m^2 and the velocity varied in the interval v € [20, 100] mm/s with step 10 mm/s. From the results of the numerical experiments, graphs of the dependence of the temperature on the speed were drawn for three power densities (Fig. 5). From their analysis it follows:

- As speed increases, a non-linear increase in temperature occurs for all three power densities;
- For the investigated interval of speeds, the temperature changes

from 2297 K to 1340 K for q_s = 0.90×10^{10} W/m^2
from 2500 K to 1500 K for q_s = 1.10×10^{10} W/m^2
from 2883 K to 1860 K for q_s = 1.30×10^{10} W/m^2;

- The following preliminary operating interval of the speed for laser marking by melting are defined

v € [20, 47] mm/s за q_s = 0.90×10^{10} W/m^2;
v € [20, 62] mm/s за q_s = 1.10×10^{10} W/m^2;
v € [20, 83] mm/s за q_s = 1.30×10^{10} W/m^2.

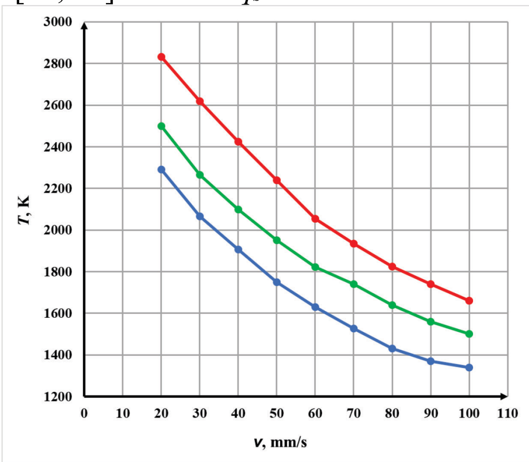


Figure 5. Graphics of temperature versus speed for power densities: blue – 0,90×10^{10} W/m^2; green – 1.10×10^{10} W/m^2; red – 1.30×10^{10} W/m^2.

b) For a CuBr laser

The numerical experiments were performed at the same speeds as those of the fiber laser and power densities: 0.60×10^{10} W/m^2, 0.80×10^{10} W/m^2 and 1.00×10^{10} W/m^2. The following conclusions can be done from the drawn graphs (Fig. 6):

- As speed increases, a non-linear increase in temperature occurs for all three power densities;
- For the investigated interval of speeds, the temperature changes

from 2195 K to 1295 K for q_s = 0.60×10^{10} W/m^2
from 2465 K to 1475 K for q_s = 0.80×10^{10} W/m^2
from 2833 K to 1660 K for q_s = 1.00×10^{10} W/m^2;

- When comparing the results for the fiber laser and the CuBr laser, it can be seen that concrete temperatures at a given speed are reached at significantly lower power densities of the CuBr laser;
- The following preliminary operating intervals of the speed for laser marking by melting are defined

v Є [20, 42] mm/s for $q_s = 0.60\times10^{10}$ W/m^2;
v Є [20, 57] mm/s for $q_s = 0.80\times10^{10}$ W/m^2;
v Є [20, 80] mm/s for $q_s = 1.00\times10^{10}$ W/m^2.

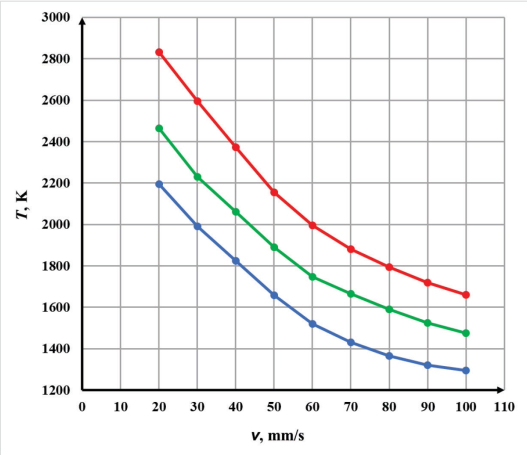


Figure 6. Graphics of temperature versus speed for power densities: blue – 0,60.10^{10} W/m^2; green – 0,80.10^{10} W/m^2; red – 1,00.10^{10} W/m^2.

CONCLUSION

In the research by means of numerical experiments on the influence of power density and speed for the laser marking process by melting C35 steel samples, the following results were achieved:

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- Preliminary power density operating ranges for three speeds for the fiber laser and the CuBr laser are determined;
- Preliminary operating speed ranges for three power densities for the fiber laser and the CuBr laser were determined.

The obtained results are necessary for subsequent experimental research of the laser marking process by melting C35 structural steel samples. Numerical experiments for this steel need to be continued with pulse duration, defocus, pulse power, pulse energy, etc., to complement the research on the influence of the main technological parameters on the research process.

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REFERENCES

[1] Kučera, M., Švantnera M., Smazalová E., Influence of laser marking on stainless steel surface and corrosion resistance, Lasers in Manufacturing Conference 2015, https://www.wlt.de/lim/Proceedings2015/Stick/PDF/Contribution231_final.pdf;
[2] Roozbahani, D., Alizadeh M., Alizadeh, HandroosHeikki, Salminen A., Color Laser Marking: Repeatability, Stability and Resistance Against Mechanical, Chemical and Environmental Effects, IEEE, Access 8:1, Vol. XX, 2020, DOI: 10.1109/ACCESS.2020.3040744;
[3] Sobotova, L., Demec P., Laser Marking of Metal Materials, MM Science Journal, 2015, pp. 808-812, DOI: 10.17973/MMSJ.2015_12_201410;
[4] Jurčs, V., Yankov E., Angelov N., Pacejs A., Adijāns I., Influence of Technological Parameters on Laser Marking Process of Copper Surfaces, Environment. Technology. Resources. Rezekne, LatviaProceedings of the 15th International Scientific and Practical Conference. Volume III, 2024, pp. 393-398, https://journals.rta.lv/index.php/ETR/article/view/8179/6489;
[5] Atanasov, A.; Lengerov A., Analysis of the methods for laser marking in mechanical Engineering, AIP Conf. Proc. 2980, 060003, pp. 1-8, 2024, DOI: 10.1063/5.0186439;
[6] Narica, P., Pankova S., Solovyev V., Vanin A., Yanikov M., Optical Properties of Laser-Colouring Marked Stainless Steel, Environment. Technology. Resources. Rezekne, Latvia, Proceedings of the 13th

International Scientific and Practical Conference. Volume 3, 2021, pp. 242-244;
[7] Angelov N., Optimization of the process of marking with laser radiation of samples of tool steel, Dissertation work for obtaining the degree of DOCTOR, Technical University - Gabrovo, 2011, 168 ps;
[8] Dichev, D., Zhelezarov I., System for Measuring the Attitude of Moving Objects using a Kalman Filter and MEMS Sensors, Proceedings of the Bulgarian Academy of Sciences, 72(11):1527-1536, 2019, DOI: 10.7546/CRABS.2019.11.10;
[9] Zlateva-Petkova, Ts., Human Resources Quality as a Factor for Competitive Power of Organizations, Marketing and innovation in management, № 3, T. 2, 2011, pp. 207-212, http://mmi.fem.sumdu.edu.ua/;
[10] Zlateva-Petkova, Ts., The necessity of organizational learning and its relation to knowledge management, International Conference Economics and management – based on new technologies, EMoNT 2014, Vranechka Banya, R. Srapska, 12-15 June 2014, ISBN 978-86-6075-037-4.11;
[11] Belev, I., Environment for calculating laser-induced temperature fields, Diploma thesis, Technical University of Gabrovo, 2009;
[12] Yankov, E., Minev, R., Tonchev, N., & Lazov, L., Determination of the optimal mode of laser surface marking of aluminium composite panels with CO2 laser. Tribol. Mater, 1, 114-119, ISSN 2812-9717, 2022, DOI: 10.46793/tribomat.2022.011;
[13] Georgiev, Borislav; Karadzhov, Tsanko. Comparative Analysis of Geometric Deviations In Contact Measuring Instruments For Control And Laser Contactless Scanning. Environment. Technologies. Resources. Proceedings of the International Scientific and Practical Conference, Rezekne, Latvia, v. 3, p. 306–310,2024. DOI: 10.17770/etr2023vol3.7182;
[14] Georgiev, Borislav; Karadzhov, Tsanko. Investigating The Repeatability Of 3D Printers Using A Multi-Sensor Measurement System. Environment. Technologies. Resources. Proceedings of the International Scientific and Practical Conference, Rezekne, Latvia, v. 3, p. 65–69, 2024. DOI: 10.17770/etr2024vol3.8114.