Simulation and approbation of the marking laser process on metal materials

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Abstract. The article is devoted to the technological process modeling of marking on the surface of metal products using a pulsed laser. The described mathematical model allows us to select the optimal technological parameters of the laser marking complex in order to form the desired marking symbols on the surface of steel and alloy products with various chemical compositions, taking into account the physical properties of the marked material. The developed technological regimes have been tested and recommended for industrial applications in various industries, such as engineering, automotive, aircraft manufacturing and railway transport, as well as for the widespread usage of marking serial products from metal materials.

1. Introduction
The laser marking is widely used in many industries to apply the information about products and their identification throughout the whole product life cycle. At the same time, this method of applying marking symbols is a modern technological process and its application for the metal products of mechanical engineering and automotive industry is especially relevant. The applied in this way marking has a high resolution and will be very long time existing. The ability to obtain multi-color images through the laser processing of metal materials is determined by the features of the processes, which are taking place on the surface of metals, the method manufacturability and as well with an extremely high flexibility of this method, since the laser beam can be controlled in time and space, and it is also possible to accurately dose and control the radiation energy [1, 2].

But it is far from always possible to reproduce the desired color and the required readability of the marking symbol on the surface of metal products, even exactly following the technical instructions and the proposed modes of the laser marking complex manufacturer. The quality of marking symbols will be influenced by many factors, the main of them are accepted for calculation in the being presented mathematical model, which takes into account the physical properties of the marked metallic material and the technological parameters of the laser complex [3].

2. Materials and Methods
When marking the metal products with a pulsed fiber laser, a partial fusion and an intense heating of the metal surface layer with the subsequent oxidation occurs in the exposure area of the focused laser beam on the surface [4]. This leads to the appearance of a special form trace (an imprint) in the area of the laser beam affection (Figure 1). The imprint diameters were measured for two variant materials and they appeared to have different sizes from effect of the laser beam with the same technological regimes.
Figure 1. The metal surface microstructure after the single laser pulse exposure, x500: a) steel 08X18H10T; b) titanium grade 2. Both imprints were done under the average output power of 15 W and pulse duration as 30 ns.

The dimensions of the imprints on the metal surface and their specific location relatively to each other will differ for the different alloy chemical composition and the technological parameters of the laser complex: for example, depending on the such parameter as a pump current of the diode array (I), which determines the average output power (Q<sub>av</sub>) and physical properties alloy, the diameter of the imprint will change (Figure 2). The speed of a laser beam movement (scanning speed) (V) and the pulse repetition rate (F) will determine how closely the prints overlap in a row, the proximity of each row is determined by the specified lineature [5]. An optimally specified lineature will be selected correct in that case when there are no gaps of the unworked metal between the rows, but the adjacent rows do not overlap each other so that the heating during the formation of the next row does not affect the color of the previous one.

Figure 2. Sorts of imprints at the various pump current of the diode array on the steel 08X18H10T, x100.

As a result of processing by pulsed laser radiation, an oxide film is being formed on the surface of metal products [6]. The temperature regime of the oxides structures formation is below the melting temperature of the material. The laser radiation exposure area is extremely smaller than the surface sample area, so the oxide structure forms only within the effect area of the laser beam.

A colored oxide film is being formed over the area from the previous imprint of the laser beam. The thickness of the film depends on the heating degree of the steel or alloy – films of different thicknesses reflect light rays differently, and this fact is the reason for one or another color of the film tint. To create a homogeneous oxide film of a given color tint, the laser beam imprints should be superimposed on each other with a certain shift so that the region of the visible color oxide film
overlaps the area affected by the subsequent pulse. The distance between two successive pulses depends on the scanning speed and pulse repetition rate:

$$dx = \frac{V}{F},$$  \hspace{1cm} (1)

where $dx$ is the distance between pulses, m; $V$ is the scanning speed of the laser beam, m/s; $F$ - pulse repetition rate, Hz. The imprints overlap each other if $dx$ is significantly smaller than the diameter of the imprint itself (Figure 3). The oxide film is being formed in the previously activated area (cleaned from the regular oxide film) by the preceding laser pulse [7, 8]. The mathematical model scheme for calculation the pulse consecution is shown in Figure 4: D – the diameter of the imprint of the laser beam on the surface of the material (m); $dx$ – next pulse imprint displacement (m); $t_a$ – laser beam heating temperature on metal surface (°C); $t_x$ – temperature of the oxide formation zone by the next pulse (°C), $S$ – heat affected zone of the laser pulse (m).

**Figure 3.** A series of the superimposing each other imprints of a laser beam on a metal surface, x500.

**Figure 4.** The pulse consecution scheme for calculation of the oxide film formation.

The surface temperature from an instantaneous concentrated heat source acting on a semi-infinite plate can be described by the expression:

$$t_a = \frac{2\eta Q_i}{K \pi r^2} \sqrt{\frac{K \tau_i}{g c \pi^2}},$$  \hspace{1cm} (2)

where $t_a$ – surface activation temperature, (°C), $Q_i$ – impulse power (W), $\eta$ – absorption factor, $r$ – laser beam imprint radius (m), $\tau$ – pulse duration (s), $K$ – thermal conductivity of the material (W/(m-deg)), $g$ – material density (kg/m³), $c$ – heat capacity of the material (J/(kg-deg)).

The impulse power can be determined from the expression (2) as follows:

$$Q_i = \frac{t_a \pi r^2}{2\eta} \sqrt{\frac{K g c \pi}{\tau_i}}.$$  \hspace{1cm} (3)
The pulse repetition rate can be expressed in terms of the pulse duration, the average output power and the impulse power:

\[ F = \frac{1}{t_i} \frac{Q_{av}}{Q_i}, \text{ or } F = Q_{av} \cdot \frac{2\eta}{t_a \pi r^2} \cdot \sqrt{\frac{1}{\tau_i K g c \pi}} \]  

(4)

where \( F \) – pulse repetition rate (Hz), \( Q_{av} \) – average output power (W).

Since the time between pulses is significantly longer than the heating-cooling cycle, the cooling of the area after heating with a laser pulse will end and that surface area gets cool before the next pulse effect begins. Therefore, heating of the surface area for the oxide film formation is possible only due to the thermal influence of the heat affected zone from the subsequent pulse (S in Figure 4).

The extension of the heat affected zone from a point source is determined from the following expression:

\[ S = \sqrt{\frac{2\pi K t_i}{g c}}. \]  

(5)

It can be seen from (5) that the extension of the heat affected zone is determined only by the physical properties of the processed material and does not depend on the technological parameters of the laser facility. The displacement magnitude of the subsequent pulse can be determined as follows: the average temperature in the \( dx \) area (Figure 4) should correspond to the temperature of the oxide film formation, i.e. \( t'_m = (t_a + t_f)/2 \), whence;

\[ t_x = 2t'_m - t_a. \]  

(6)

where \( t'_m = t_f + \Delta t \) and \( t_f \) – temperature of the oxide film formation with a given colorimetric characteristic (color tint), and \( t'_m \) – melting temperature (°C).

On the other hand, in accordance with the scheme in Figure 4:

\[ \frac{t_x}{S-dx} = \frac{t_a}{S}. \]  

(7)

Substituting (6) into (7) after simple transformations we obtain:

\[ dx = 2S \left( 1 - \frac{t'_m}{t_a} \right). \]  

(8)

The scanning speed of the laser beam is determined from the expressions:

\[ V = 2SF \left( 1 - \frac{t'_m}{t_a} \right) \text{ or } V = 2F \left( 1 - \frac{t'_m}{t_a} \right) \sqrt{\frac{2\pi K t_i}{c g}}. \]  

(9)

Expressions (4) and (9) determine the relationship between the technological parameters of the laser marking process, the thermophysical properties of the processed material and the formation of an oxide film with the desired color characteristics.

The oxide film formation with a certain thickness is determined by the temperature-time characteristics of the effect on a metal surface. As can be seen from formulas (2) - (4) and (9) in the case of surface treatment with laser radiation for metal surfaces these characteristics depend on the laser beam imprints spreading density and power of the laser radiation. An indirect characteristic of the change in the output radiation power can be the size of the imprint in the area of the laser beam effect. The surface treatment with a laser marking complex should be performed line by line to obtain the color oxide structures. So that the temperature conditions for the formation of the second line do not affect the formed previous line, it is necessary, as mentioned above, that the lines do not overlap each other.
3. Results and Discussion

Using expressions (4) and (9), the technological parameters of the regime for the oxide films formation of various color tints were calculated and tested for three metallic materials. Laser treatment of the metal surface was carried out in an oxygen medium (in air) at room temperature. In order to reduce the power of laser radiation, defocusing was used, i.e. increase or decrease in focal length relative to the focal plane. When the image sector of a given color is being formed on the metal surface by means of laser radiation, this part of an image is divided by the controlling laser complex program into parallel segments for the laser beam following. Before turning on the laser, the laser beam is positioned at the initial coordinates of the segment being formed. Then there is a continuous exposure to pulses with a given repetition rate and scanning speed movement of the beam until the end of the segment. Before changing the position to the beginning of the next segment (while the beam is moving from segment to segment), the laser is turned off. Thus, a gradual filling of the cultivated area occurs. So, one portion of the image in overall dimensions may contain several segments on which an oxide film is formed with predetermined color characteristics (Figure 5).

![Sample photograph](image)

The scanning speed of the laser beam mainly determines the distance between pulses and directly affects the thickness of the formed layer with metal oxide structures. The pulse repetition rate affects

| Simulation parameter                           | Material Grade |
|-----------------------------------------------|----------------|
| Melting temperature, \( t_m \), °C            | 12Cr17 08Cr18Ni10Ti Ti Gr 2 |
| Density, g, kg/m³                             | 1360 1360 1668 |
| Thermal conductivity, K, W/(m·deg)           | 7850 7850 4320 |
| Heat capacity, c, J/(kg·deg)                 | 25 26 22 |
| Surface activation temperature, \( t_a \), °C | 462 504 523 |
| Absorption factor, \( \eta \)                | 0.03 0.03 0.04 |
| Diode array pump current, I, A               | 13.0 13.0 16.0 |
| Impulse power, Q, W                          | 8469 10767 7530 |
| Average output power, Q_{av}, W              | 6.72 6.72 9.86 |
| Pulse repetition rate, F, Hz                 | 15510 15600 32740 |
| Scanning speed, V, m/s                       | 0.010 0.012 0.010 0.012 0.036 |
| Sample photograph (without magnification)    | ![Image 1](image) ![Image 2](image) ![Image 3](image) ![Image 4](image) ![Image 5](image) |

The results of the simulation and laser processing are presented in Table 1.
the intensity of the resulting tints, limiting the time between pulses and at the same time is in
correlation with the scanning speed of the laser beam, which determines the distance between the
imprints as well. Similarly calculated parameters (scanning speed and repetition rate), as well as such
a technological parameter as an average output power, can be calculated not only for marking
technology, but also for other types of laser processing, such as engraving [9, 10], significantly
reducing the number of test modes (regimes) and test samples in practice.

4. Conclusion
The dependences, obtained as a result of a theoretical analysis, describe the thermal conditions for the
formation of the film oxide microstructures on a metal surface under the influence of pulsed laser
radiation and have been developed on the basis of the thermodynamics theory general principles. The
thermophysical characteristics of materials, used for calculations, are well known and their values can
be found in the wide range of books of reference.

As a result of the carried out studies, we established a relationship between the technological
parameters of the laser marking process, the thermophysical properties of the processed material, the
parameters of the oxide film (thickness and, accordingly, color) and the characteristics of the output
color image on metal surfaces, which allows one to determine the temperature-time regime for the
marking symbols formation in the form of oxide films on metallic materials with specified color
characteristics, significantly reducing the number of practical marking tests.

References
[1] Svantner M, Kucera M and Houdkova S 2012 Possibilities of stainless steel laser marking
Proc. of 21th Int. Conference on Metallurgy and Materials METAL 2012 23, Brno, Czech Republic
[2] Gorny S, Veiko V, Odintsova G, Gorbunova E, Loginov A, Karlagina Yu, Skuratova A and
Ageev E 2013 Laser color marking of metal surfaces Journal of Photonics Russia 6.
[3] Sivenkov A V, Konchus D A, Chirkova O S and Pryakhin E I 2018 Assessment of laser
marking contrast with profilometer IOP Conference Series: Earth and Environmental Science 194
DOI: 10.1088/1755-1315/194/4/042022
[4] Zavestovskaya I 2010 Laser nanostructuring of the surface of materials Quantum Electronics
40 (11) 942-954
[5] Ganzulenko I Yu, Zakharenko A A, Larionova A V, Petkova A P and Priakhin A I 2013
Development and approbation of the technological process of application of information fields on
products from various materials for their protection against fakes, identification and registration
Innovatika and expert examination SRI FRCEC 2 (11) 142-154
[6] Kanygina E D, Denisova O V, Rastvorova I V 2019 Optical and electrical control in printed
circuit board manufacturing (Оптическое и электрическое управление в производстве
печатных плат) Proceedings of the 2019 IEEE Conference of Russian Young Researchers in
Electrical and Electronic Engineering, ElConRus pp. 536-538 DOI: 10.1109/EIConRus.2019.8656918
[7] Fedortsov A B, Ivanov A S 2018 Noncontact laser control of electric-physical parameters of
semiconductor layers Journal of Mining Institute 231 pp. 299-306 DOI: 10.25515/pmi.2018.3.299.
[8] Pryakhin E I 2015 Nanobar code as multi-purpose two-dimensional notations with new
features Journal of Mining Institute [in Russian – Zapiski Gornogo Instituta] 215 97-109
http://pmi.spmi.ru/index.php/pmi/article/view/5189
[9] Nikolidakis E, Choreftakis I and Antoniadis A 2018 Experimental investigation of stainless
steel SAE304 laser engraving cutting conditions Machines 6, 40 DOI:10.3390
[10] Lazov L, Deneva H and Narica P 2015 Laser marking methods Proceedings of the 10th
International Scientific and Practical Conference Environment. Technology. Resources I 108-115
Rezekne, Latvia