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DETERMINATION OF WORKING INTERVALS OF POWER DENSITY FOR LASER MARKING OF 50ChN STEEL

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Abstract: Studies relate to two basic methods of steel marking − by melting and by evaporation. Based on theoretical considerations, preliminary intervals of power density for laser marking of 50 ChN steel are determined. Experiments are carried out with fiber laser, operating in the near infrared area. Graphics on the dependence of contrast of marking from the power density of laser radiation for two methods of marking were developed. Working intervals of the power density for marking by melting and by evaporation for visual perception of marking and using the readers were defined.
Keywords: laser marking, structural alloy steel, fiber laser, contrast, melting, evaporation, power density, working intervals.

1. INTRODUCTION

Laser marking of products made of metals and alloys is a complex technological process [1,2]. Power density is one of the most important parameters influencing the process. To obtain good contrast for marking of the product, appropriate working intervals for this parameter must be determined. It is most quickly achieved by obtaining preliminary engineering-forecast results and conducting experimental studies to clarify the role of power density. The obtained intervals are used to fill the database [3] on basic process parameters, one of which is power density. They help the operator of the laser technological systems.

2. PRESENTATION

The purpose of the work was to study the influence of power density on the process of laser marking by melting and evaporization of structural alloy 50 ChN steel products with fiber laser and by receiving the working intervals of power density for two methods of marking.

The two most used method of laser marking are by melting and evaporation:

A. Marking by melting

In this method of marking in the zone of impact the material is heated to a temperature above that of the melting point to obtain a melt. Optical properties of the material in this area are changed, for example, most often it darkens. The obtained contrast between the area of influence and the adjacent zone is presented belowd (Figure 1).

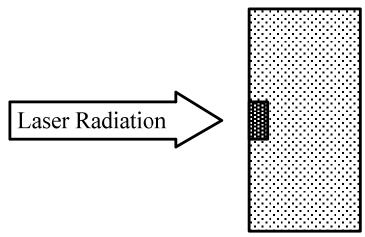

Figure 1. Marking by melting

B. Marking by evaporation

- Creating channels in the material

Under the action of laser radiation the surface evaporates in the zone of impact, leading to the formation of a channel with a certain depth (Figure 2). There is a possibility to fill the channels with an imaging agent.

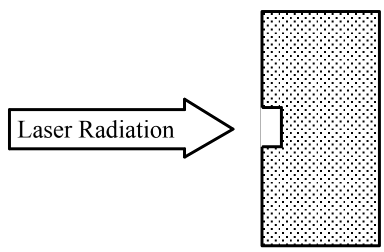

Figure 2. Marking by removing material

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- Withdrawal of the layer, affixed on the sample

The applied layer has a higher absorbance for the falling laser radiation compared to the base material (Figure 3). In the area of influence it evaporates to make a contrast marking as the color of the base material contrasts with the color of the layer.

50 ChN steel is widely used in industry. It is used for making the rolls for hot rolling, pinion shafts, gears, tires, crankshafts, connecting rods, bolts, exhaust valves, and other major structural parts. Its chemical composition is given in Table 1 and its basic thermo-physical characteristics are presented in Table 2 [7,8].

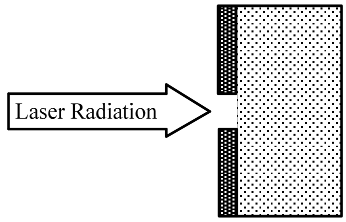

Figure 3. Marling by withdrawal of the layer, affixed on the sample

Table 1. Chemical composition of the structural alloy steel 50ChN

Chemical composition	C	Ni	Cr	S
Content, %	0,46 ÷ 0, 54	1,0 ÷ 1,4	0.45 ÷ 0.75	< 0.035
Chemical composition	Si	Mn	Cu	P
Content, %	0,17 ÷ 0,37	0,50 ÷ 0,80	< 0.3	< 0.035

Table 2. Thermo-physical characteristics of structural alloy steel 50G: thermal conductivity k, specific heat capacity c, density ρ and thermal diffusivity a

Magnitude Temperature T, K	k, W/(m.K)	c, J/(kg.K)	ρ, kg/m^3	a, m^2/s
293	45	490	7860	$1{,}17.10^{-5}$
373	43	500	7830	$1{,}10.10^{-5}$
473	40	510	7800	$1{,}01.10^{-5}$
573	39	560	7770	$8{,}96.10^{-6}$
673	38	630	7740	$7{,}79.10^{-6}$
773	37	700	7710	$6{,}86.10^{-6}$
873	36	800	7680	$5{,}86.10^{-6}$
973	32	910	7650	$4{,}60.10^{-6}$
1073	23	650	7620	$4{,}64.10^{-6}$
1173	24	610	7590	$5{,}18.10^{-6}$
1273	25	700	7560	$4{,}72.10^{-6}$

Experiments were carried out with the laser technological system with fiber laser. It operates in the near infrared area and is suitable for laser marking of metals and alloys. A general view of laser technological systems for marking with fiber laser and its scheme are given in Figure. 4. Laser works in the pulsed mode, which is suitable for laser marking. The basic parameters of laser technological system for marking with this laser are given in Table 3 [5,6].

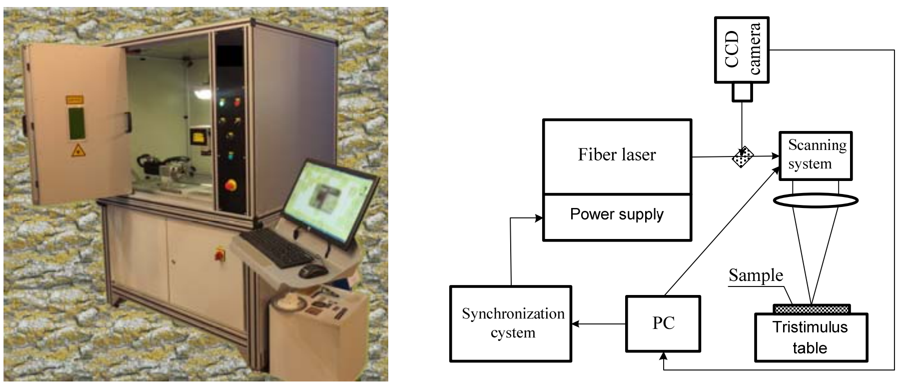

Figure 4. General view and block-scheme of laser system with fiber laser

Table 3. Some basic parameters of laser technological system for marking with fiber laser

Parameter	Value
Wavelength λ, nm	1064
Power P, W	40
Frequency v, kHz	250
Pulse duration τ, ns	250
Pulse energy E_p, mJ	0,16 ÷ 2,00
Beam quality M^2	1,05
Positioning accuracy, μm	2,5
Efficiency, %	40

Theoretical calculations:

1. Determination of preliminary intervals for power density for marking by melting

To obtain marking, the power density of the laser radiation should be sufficient to cause melting of the material in the treatment zone and / or its partial evaporation. During research it is necessary to take into account the fact that, with its increasing, the absorbance of steel increased.

Because the power density of laser radiation q_S is one of the fundamental parameters that determine the changes in the physical state of the material in the area of influence for marking, there is a connection between it and temperature T of heating of sample. It can be obtained from the following transformations. According to [4], the time t for reaching a certain temperature T in the area of influence is obtained

$$t = \frac{\pi^3 k^2 r^4 (T - T_0)^2}{4aA^2P^2}, \quad (1)$$

where P is the power of the falling laser radiation, k – thermal conductivity, A – absorbance, a – thermal diffusivity, T_0 – ambient temperature; r – radius of the working area.

It is recognized that

$$t = \frac{d}{\mathrm{v}}, \quad (2)$$

$$r = \frac{d}{2} \quad (3)$$

and

$$q_S = \frac{4P^2}{\pi d^2} \quad (4)$$

where v is the speed of marking, d – diameter of the working area.

After substitution of (2), (3) and (4) in (1) for temperatures less than the melting temperature of the tool steel, the following dependence is obtained:

$$q_S = \frac{k(T - T_0)}{2A}\sqrt{\frac{\pi \mathrm{v}}{ad}} \,. \quad (5)$$

The power density is one of the most important parameters determining the contrast of marking. Therefore, there is a connection between contrast marking and temperature. Furthermore, the heating temperature of the surface of the sample determines the method of detection – by melting or by evaporation. All this shows that the knowledge of the temperature fields is very important for optimization of the process of laser marking.

Critical values of power density for melting $q_{S\kappa pm}$ and evaporation $q_{S\kappa pv}$ include the magnitudes defining the intervals in which performs laser marking on products of structural steel for various methods - by melting and by evaporation.

The formula (5) may be transformed to determine the critical power density for melting and evaporization for metals and alloys (including structural steels).

We will apply the equation of heat balance for melting of material

$$Q = Q_h + Q_m, \quad (6)$$

where Q is the amount of heat received by the material; Q_h – the amount of heat for heating the material;
Q_m – amount of heat for melting the material.

$$Q_h = cm(T_m - T_0), \quad (7)$$

where m is the mass, T_m – temperature of melting.

$$Q_м = L_m m, \quad (8)$$

where L_m is the latent heat of melting.

In consideration of (7) and (8) to (6), the following was obtained

$$Q = cm(T_m - T_0) + L_m m,$$

$$Q = cm(T_m - T_0)[1 + \frac{L_m}{c(T_m - T_0)}] \,.$$

The parameter

$$s = \frac{L_m}{c(T_m - T_0)}, \quad (9)$$

is introduced, taking into account the proportion of the amount of heat necessary to melt the material.

$$Q = (1 + s)Q_h. \quad (10)$$

The amount of heat Q is proportional to the critical power density melting $q_{S\kappa pm}$. Formula (5) can be written for critical power density of melting

$$q_{Skrm} = \frac{(1+s)k(T_m - T_0)}{2A}\sqrt{\frac{\pi \mathrm{v}}{ad}} \,. \quad (11)$$

With analogous considerations for critical power, $q_{S\kappa pv}$ the density of evaporation was obtained,

$$q_{Skrv} = \frac{(1+s')k(T_v - T_0)}{2A}\sqrt{\frac{\pi \mathrm{v}}{ad}}, \quad (12)$$

where parameter s′ is given by the expression

$$s' = \frac{L_m + L_v}{c(T_m - T_0)}, \qquad (13)$$

L_v – latent heat of vaporization.

If the sample must be heated to a temperature in the interval $T \in (T_m; T_v)$, the necessary power density is given by the expression

$$q_S = \frac{k[T - T_0 + s(T_m - T_0)]}{2A}\sqrt{\frac{\pi v}{ad}}. \qquad (14)$$

2. Determination of preliminary intervals for power density for marking by evaporation

The upper limit of power (and therefore power density) of each laser source is predefined and it is necessary to determine the optimum interval of modification of power density to achieve good quality of marking.

The maximum power density $q_{S\max}$ is determined by the expression

$$q_{S\max} = \frac{4P_{\max}}{\pi d_0^2}, \qquad (15)$$

where d_0 is the minimum diameter of the spot.

For used fiber laser the following was obtained

$q_{S\max} = 4{,}16.10^{10}$ W/m^2.

Computations for critical power density of melting $q_{S\kappa pm}$ and evaporation $q_{S\kappa pv}$ for different speeds of marking were performed. The following preliminary intervals for power density in marking by melting and evaporation constructional alloyed steel 50ChN were obtained (Table 4).

Table 4. Preliminary intervals on power density for steel 50ChN

Method of marking	By melting	By evaporation
v, mm/s	q_S, W/m^2	
20	$4{,}28.10^9 \div 9{,}08.10^9$	$9{,}08.10^9 \div 4{,}16.10^{10}$
30	$5{,}98.10^9 \div 1{,}11.10^{10}$	$1{,}11.10^{10} \div 4{,}16.10^{10}$
40	$6{,}05.10^9 \div 1{,}28.10^{10}$	$1{,}28.10^{10} \div 4{,}16.10^{10}$
50	$6{,}77.10^9 \div 1{,}44.10^{10}$	$1{,}44.10^{10} \div 4{,}16.10^{10}$
60	$7{,}41.10^9 \div 1{,}57.10^{10}$	$1{,}57.10^9 \div 4{,}16.10^{10}$
70	$8{,}01.10^9 \div 1{,}70.10^{10}$	$1{,}70.10^9 \div 4{,}16.10^{10}$
80	$8{,}56.10^9 \div 1{,}82.10^{10}$	$1{,}82.10^9 \div 4{,}16.10^{10}$
90	$9{,}08.10^9 \div 1{,}93.10^{10}$	$1{,}93.10^9 \div 4{,}16.10^{10}$
100	$9{,}57.10^9 \div 2{,}03.10^{10}$	$2{,}03.10^9 \div 4{,}16.10^{10}$

These intervals are very useful in conducting experimental research on laser marking of this steel.

Realized tasks:

1. Study of the dependence of the contrast of marking from the power density for marking by melting

Samples of structural alloy steel 50G were prepared. Two test fields on 10 squares with 5 mm-side were marked. The parameters, which were kept constant throughout the experiments, are given in Table 5. Power density of laser radiation are budged for in the interval $q_S \in [0{,}832.10^{10}; 1{,}30.10^{10}]$ W/m^2 with step $5{,}20.10^8$ W/m^2. Laser marking by melting was realized.

Table 5. Technological parameters, which were kept constant throughout the experiments

Parameter	Value
Speed v_1, mm/s Speed v_2, mm/s	50 70
Frequency v, kHz	30,0
Pulse duration τ, ns	100
Step Δx, µm	50
Number of repetition, N	1

Figure 5 shows the obtained experimental dependence $k^* = k^*(q_S)$ for marking by melting on the samples of studied steel with fiber laser. From their analysis it follows that:

−By increasing the power density nonlinear increase in the contrast and for the two speeds of the marking was observed;

−By using Lagrange polynomials dependence $k^* = k^*(q_S)$ was obtained in an analytical type for the studied interval

$k^* = -161{,}3.10^{-20}q_S^2 + 443{,}55.10^{-10}q_S - 237$ for speed $v_1 = 50$ mm/s;

$k^* = -169{,}3.10^{-20}q_S^2 + 471{,}27.10^{-10}q_S - 269{,}52$ for speed $v_2 = 70$ mm/s,

where k^* is in %, q_S is in W/m^2.

−Working intervals for the power density are:

for visual perception of the marking

$q_S \in [1{,}04.10^{10}; 1{,}30.10^{10}]$ W/m^2 for speed $v_1 = 50$ mm/s;

$q_S \in [1{,}04.10^{10}; 1{,}30.10^{10}]$ W/m^2 for speed $v_2 = 70$ mm/s.

by using readers

$q_S \in [[0{,}832.10^{10}; 1{,}30.10^{10}]$ W/m^2 for speed $v_1 = 50$ mm/s;

$q_S \in [0{,}920.10^{10}; 1{,}30.10^{10}]$ W/m^2 for speed $v_2 = 70$ mm/s.

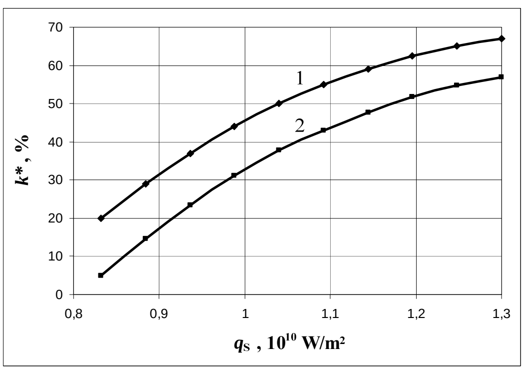

Figure 5. Graphs of dependence $k^* = k^*(q_S)$ for marking by melting for speeds: 1 – v_1 = 50 mm/s; 2 – v_2 = 70 mm/s

2. Study on the dependence of the contrast of marking from the power density for marking by evaporation

In the second series of experiments we applied laser marking by evaporation. For the two speeds were marked were two test fields from 10 squares with a 5 mm-side. The parameters, which were kept constant throughout the experiments, are given in Table 5. Power density of laser radiation are budged for in the interval q_S Є [1,87.10^{10}; 2,81.10^{10}] W/m^2 with step 1,04.10^9 W/m^2.

Figure 6 shows the obtained experimental dependence $k^* = k^*(q_S)$ for marking by evaporation on the samples of studied steel with fiber laser. From their analysis we can draw the following conclusions:

By increasing the power density nonlinear increase in the contrast and for the two speeds of the marking was observed;

The rate of increase of the contrast is
for interval q_S Є [1,87.10^{10}; 2,39.10^{10}] W/m^2
7,69.10^{-10} %/(W/m^2) for speed v_1 = 50 mm/s;
11,5.10^{-10} %/(W/m^2) for speed v_2 = 70 mm/s;
for interval q_S Є [2,39.10^{10}; 2,81.10^{10}] W/m^2
4,76.10^{-10} %/(W/m^2) for speed v_1 = 50 mm/s;
7,14.10^{-10} %/(W/m^2) for speed v_2 = 70 mm/s.

By using Lagrange polynomials, the dependence $k^* = k^*(q_S)$ in an analytical type for the studied interval was obtained.
$k^* = -\ 2,739.10^{-20}q_S^2 + 19,243.10^{-10}q_S + 42,594$ for speed v_1 = 50 mm/s;
$k^* = -\ 4,108.10^{-20}q_S^2 + 28,85.10^{-10}q_S + 20,4$ for speed v_2 = 70 mm/s,
where k^* is in %, q_S is in W/m^2.

The working interval for the power density coincides with the whole studied interval, i.e.
q_S Є [1,87.10^{10}; 2,81.10^{10}] W/m^2.

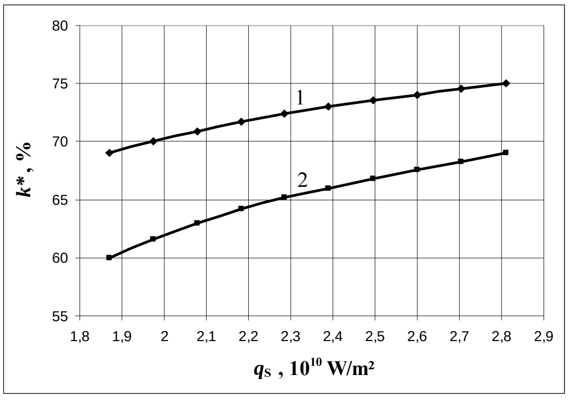

Figure 6. Graphs on dependence $k^* = k^*(q_S)$ for marking by evaporation for speeds: 1 – v_1 = 50 mm/s; 2 – v_2 = 70 mm/s

3. CONCLUSION

The results obtained from experimental studies allow the formulation of the following statements:

− Upon marking by melting the contrast of marking highly depends on the power density of the laser radiation;

− Upon marking by evaporation the contrast of marking was hardly influenced by the power density of the laser radiation;

− The relationship between the contrast of marking and the power density can be expressed analytically by Lagrange polynomial of the second degree.

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3. REFERENCES

[1] Л. Лазов, Н. Ангелов, *Basic Factors Determining the Quality for Marking the Metals and Alloys* [In Bulgarian: Основни фактори, определящи качеството на маркировката на метали и сплави], International Conference AMTEH'07, Gabrovo 2007, Vol. I, 102–107.

[2] T. Hoult, *Laser Marking with Fiber Lasers*, Industrial Laser Solutions for Manifacturing: Technical Digest, pp. 3−10, http://www.ipgphotonics.com/Collateral/Documents/English-US/IPG_ILSTechnicalDigest.pdf.

[3] Н. Ангелов, *Optimization of the Process of Marking with Laser Radiation the Samples of Tool Steel* [In Bulgarian: Оптимизация на процеса маркиране с лазерно лъчение на образци от инструментална стомана], doctoral thesis, TU Gabrovo, 2011, 9−15. http://www.tugab.bg/images/stories/2011/petrov/avtoreferat_01b.pdf.

[4] С. Динев, *Lasers in Modern Technology* [In Bulgarian: Лазерите в модерните технологии], Alfa, Sofia 1993, 26.

[5] 30W/40W G3.1 Pulsed Fiber Laser, SPI Lasers, Ltd. 2010, Document No: SM-S00177_B 100907, p. 66.

[6] С. Вудс, М. Дака, Г.Флин, *Fiber Lasers of Medium Power and Their Application* [In Bulgarian: Волоконные лазеры средней мощности и их применение], Fotonika, Vol. 4 (2008), 6−10, http://www.photonics.su/journal/article/2627

[7] http://www.splav-kharkov.com/choose_type_class.php?type_id=3

[8] www.metallicheckiy-portal.ru/marki_metallov/search/?gvid=

ОДРЕЂИВАЊЕ РАДНИХ ИНТЕРВАЛА ГУСТИНЕ ЕНЕРГИЈЕ ЛАСЕРА ПРИ ОЗНАЧАВАЊУ ЧЕЛИКА 50 ChN

Сажетак: Испитивања се односе на два главна метода за обиљежавање челика − топљењем и испаравањем. На основу теоријских разматрања одређени су прелиминарни интервали густине снаге за ласерско обиљежавање челика 50 ChN. Експерименти су рађени са оптичким ласером који ради у блиском инфрацрвеном подручју. Урађен је графички приказ зависности контраста обиљежавања од густине снаге ласерског зрачења за двије методе означавања. Дефинисани су радни интервали густине енергије за обиљежавање топљењем и испаравањем ради визуелне перцепције означавања и коришћење читача.

Кључне ријечи: ласерско обиљежавање, структурна легура челика, оптички ласер, контраст, топљење, испаравање, густина енергије, радни интервали.