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Method for Preliminary Estimation of the Critical Power Density in Laser Technological Processes

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***Abstract*—For a number of new laser technology processes, it is essential to plan an experimental plan for primary experimental engineering activities in terms of quality. The assessment of the critical power density to reach the melting or evaporation temperature of the surface with a suitable theoretical model is an important stage in the development of a particular manufacturing technology. With the help of numerical experiments, this report provides a method for pre-examining the influence of wavelength on the laser technological process. The calculations are performed with a specialized program, running MATLAB. A series of temperature fields were obtained at a change in power density and wavelength at laser impact for concrete types of structural steel. The temperature dependence of the optical and thermo-physical characteristics of the material is also reporded. The analysis is made for laser technology complexes working with lasers emitting in the ultraviolet, visible, near and distant infrared areas. For these wavelengths the critical power density of melting and evaporation is determined.**

Keywords—laser processing of materials, numerical experiments, temperature fields, structural steel, wavelength, power density.

I. Introduction

The specific properties of laser radiation, such as high monochromaticity, low distortion, coherence, as well as the possibility of achieving high energy density (respectively power density) in the processing area are the main arguments for the successful industrial application of laser sources over the last 58 years. Laser sources generate radiations with wavelength in a wide spectral range, from ultraviolet, visible and infrared, working in continuous and pulsed mode. Today, lasers are widely used in a number of areas of industrial production such as automotive, aircraft, shipbuilding, machine building and more. For marking, engraving, cutting, welding, drilling of holes, thermal annealing, measurements of linear and angular quantities. Other areas of life in which lasers have entered in recent years include communications, medicine, research, agriculture, the food industry, advertising, military, and so on.

Laser technological processes are complex to realising and depend on a number of factors. Some of them are power density, speed, frequency, pulse duration, impact time, pulse power, pulse energy, defocus, number of repetitions, absorption capacity of the material, depth of penetration, etc. For each technological process, material, and laser, preliminary studies must be performed to clarify the role of all factors and to optimize the process [1 - 4] - fig. 1.

The influence of some factors (fill factor, power, velocity and frequency) is investigated for optimizing the marking of barcodes on aluminum surfaces using the Nd: YAG laser [5].

The role of frequency on the process of marking stainless steel products with the Nd: YAG laser has been investigated, and the working interval for quality marking, has been determined [6].

In [7] analyzes the effect of power, velocity, defocustion, pressure and flow of the auxiliary gas on cutting process with CO_2 laser.

In [8] is considered the receiving of seamless laser welds of low carbon and stainless steel sheets. The influence of speed and power on the process is investigated. Technological tables have been compiled with optimal parameters for the studied steels.

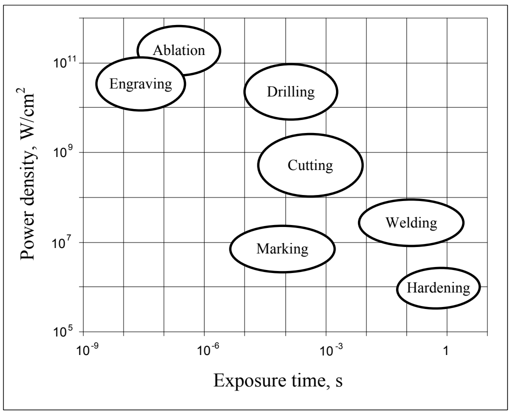

Fig. 1. Diapasons of the power density and time of impact for basic laser technological processes

Research on the determination of optimal technological parameters is mandatory when introducing laser technologies into practice, as the processes are complex and involve a number of processes of the interaction

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of the radiation with the substance (the materials being processed). They can generally be divided into two stages. First stage theoretical studies are related to modeling and simulations of process. The second stage is experimental for determining and achieving the qualitative criteria, pledged in the technology.

The purpose of the publication is to investigate the influence of the laser radiation density and the rate of processing to reach of critical power densities of melting and evaporation for concrete materials (samples) from the industry.

II. EXPOSITION

A number of laser technology processes such as hardening, alloying, welding, cladding, marking, engraving, etc. are carried out in the intervals between the temperatures of: quenching $T_{н}$, melting T_{m} and evaporation T_{v} of the treated materials – fig. 2.

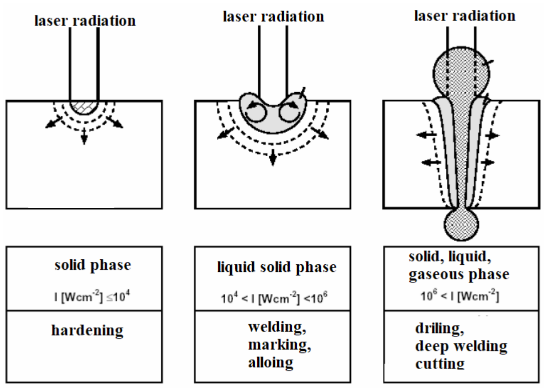

Fig. 2. Mechanism of interaction of the laser radiation with the substance for the different processes

Preliminary numerical experiments and model simulations and analyzes were performed for three types of laser systems and two types of materials.

Laser technological systems

The researches are for laser technological systems with a CuBr laser (operating in the visible area), a fiber laser (operating in the near infrared area), a CO_2 laser (operating in the far infrared area). In the Table I are showed some parameters of these systems. The fiber laser has higher radiation quality and higher efficiency compared to the other two lasers. All three laser systems have high positioning accuracy and good repeatability.

TABLE I. BASIC PARAMETERS OF TECHNOLOGICAL SYSTEMS WITH CUBR LASER, FIBER LASER AND CO_2 LASER

Laser parameter	CuBr laser	Fiber laser	CO_2 laser
Wavelength λ, µm	0,511	1, 062	10,6
Power P, W	20,0	40,0	100
Frequency v, kHz	20,0	20	50
Pulse duration τ, ns	30	250	250
Pulse energy E_p, mJ	1,00	2,00	2,00
Pulse power P_p, kW	33,3	8,00	8,00
Beam quality M^2	< 1,7	< 1,1	10,0
Positioning accuracy, µm	2,5	2,5	2,5
Efficiency, %	10	40	20

Materials

Numerical experiments refer to samples of structural steels C45 and 18ChGT. They are widely used in the industry [9]. C45 is used for making gears, crankshafts and camshafts, sprockets, spindles, sealants, cylinders, cams and other parts that are normalized, improved and subjected to surface heat treatment requiring increased strength. From steel 18ChGT are produced improved or cemented important details, which require increased strength, as well as high surface hardness, which require increased strength, as well as high surface hardness, operating under impact loads. n the Table II and Table III are showed the temperature dependence of some parameters of the studied steels. They are characterized by high coefficients of thermal conductivity and thermal diffusivity.

TABLE II. TEMPERATURE DEPENDENCE OF CERTAIN PARAMETERS OF CONSTRUCTION STEEL C45.

Legend: k – coefficient of thermal conductivity, ρ – density, c – specific heat capacity, a – coefficient of thermal diffusivity.

T, K	k, W/(m.K)	ρ, kg/m³	c, J/(kg.K)	a, m²/s
293	49	7826	457	$1{,}37.10^{-5}$
373	48	7799	473	$1{,}35.10^{-5}$
473	47	7769	494	$1{,}22.10^{-5}$
573	44	7735	515	$1{,}10.10^{-5}$
673	41	7698	536	$9{,}94.10^{-6}$
773	39	7662	583	$8{,}73.10^{-6}$
873	36	7625	578	$8{,}17.10^{-6}$
973	31	7587	611	$6{,}69.10^{-6}$
1073	27	7595	720	$4{,}94.10^{-6}$
1173	26	7565	708	$4{,}85.10^{-6}$

TABLE III. TEMPERATURE DEPENDENCE OF CERTAIN PARAMETERS OF CONSTRUCTION STEEL 18CHGT.

T, K	k, W/(m.K)	ρ, kg/m³	c, J/(kg.K)	a, m²/s
293	37	7800	485	$9{,}78.10^{-6}$
373	38	7773	495	$9{,}88.10^{-6}$
473	38	7743	508	$9{,}66.10^{-6}$
573	37	7709	525	$9{,}14.10^{-6}$
673	35	7672	537	$8{,}50.10^{-6}$
773	34	7636	567	$7{,}85.10^{-6}$
873	31	7599	588	$6{,}94.10^{-6}$
973	30	7561	626	$6{,}34.10^{-6}$
1073	29	7569	705	$5{,}43.10^{-6}$

Numerical experiments

To determine the critical values of the power density of melting q_{Scrm} and evaporation q_{Scrv}, numerical experiments with the program TEMPERATURFELD3D [10] were carried out. It is a specialized program for obtaining temperature fields in the area of laser impact. The calculations refer to the examined technological systems with CuBr laser, fiber optic laser, CO_2 laser [11-13] and structural steels C45 and 18ChGT. The temperature dependence of some parameters of steels (according to Table II and Table III) is recorded.

- **for CuBr laser**

In Fig. 3 and Fig. 4 are presented graphics of the dependencies of the critical power densities of melting $q_{Sкрm}$ and evaporation $q_{Sкрv}$ from the speed for steels C45 and 18ChGT. From the obtained results, the following conclusions can be drawn:

- The critical power densities of melting and evaporation increment non-linearly with increasing of speed for structural steels C45 and 18ChGT with speed in the interval v Є [20; 100] mm/s;
- The rate of increase in critical power density of melting is

for interval v Є [20; 60] mm/s
$7{,}55.10^{8}$ (W/m^2)/(mm/s) for steel C45;
$8{,}82.10^{8}$ (W/m^2)/(mm/s) for steel 18ChGT;
for interval v Є [60; 100] mm/s
$5{,}18.10^{8}$ (W/m^2)/(mm/s) for steel C45;
$6{,}12.10^{8}$ (W/m^2)/(mm/s) for steel 18ChGT;

- The rate of increase in critical power density of evaporation is

for interval v Є [20; 60] mm/s
$12{,}0.10^{8}$ (W/m^2)/(mm/s) for steel C45;
$14{,}2.10^{8}$ (W/m^2)/(mm/s) for steel 18ChGT;
for interval v Є [60; 100] mm/s
$8{,}25.10^{8}$ (W/m^2)/(mm/s) for steel C45;
$9{,}75.10^{8}$ (W/m^2)/(mm/s) for steel 18ChGT;

- For structural alloy steel 18ChGT, the critical values of power densities of melting and evaporation density are about 17% greater than for structural carbon steel C45. The reasons for this are the higher melting and evaporation temperatures of steel 18ChGT.

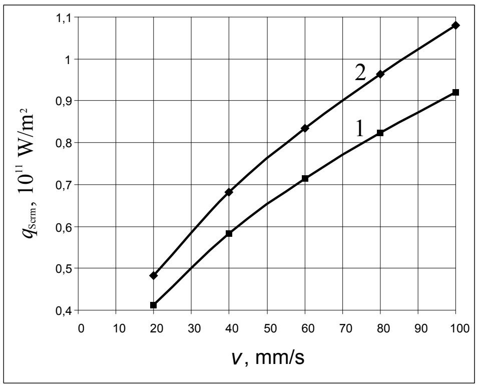

Fig. 3. Graphics of dependence of critical power density of melting from speed for CuBr laser for: 1 – steel C45; 2 – steel 18ChGT

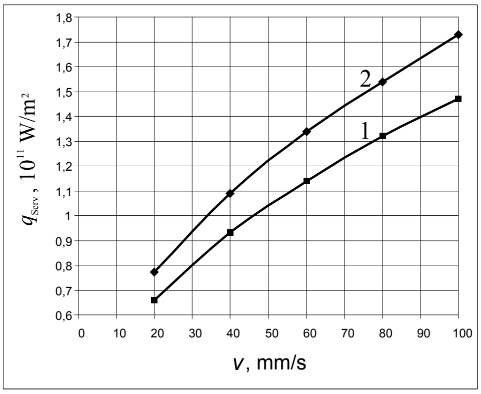

Fig. 4. Graphics of dependence of critical power density of evaporation from speed for CuBr laser for: 1 – steel C45; 2 – steel 18ChGT

- **for fiber laser**

In Fig. 3 and Fig. 4 are showed graphics of the dependencies of the critical power densities of melting $q_{S\kappa pm}$ and evaporation $q_{S\kappa pv}$ from the speed for steels C45 and 18ChGT From the obtained graphics, it follows:

- The critical power densities of melting and evaporation increment non-linearly with increasing of speed for both steels;
- The rate of increase in critical power density of melting is

for interval v Є [20; 60] mm/s
$0{,}94.10^{9}$ (W/m^2)/(mm/s) for steel C45;
$1{,}09.10^{9}$ (W/m^2)/(mm/s) for steel 18ChGT;
for intrval v Є [60; 100] mm/s
$0{,}64.10^{9}$ (W/m^2)/(mm/s) for steel C45;
$0{,}75.10^{9}$ (W/m^2)/(mm/s) for steel 18ChGT;

- The rate of increase in critical power density of evaporation is

for interval v Є [20; 60] mm/s
$1{,}52.10^{9}$ (W/m^2)/(mm/s) for steel C45;
$1{,}74.10^{9}$ (W/m^2)/(mm/s) for steel 18ChGT;
for interval v Є [60; 100] mm/s
$1{,}02.10^{9}$ (W/m^2)/(mm/s) for steel C45;
$1{,}25.10^{9}$ (W/m^2)/(mm/s) for steel 18ChGT;

- For structural alloy steel 18ChGT, the critical values of power densities of melting and evaporation density are about 17% greater than for structural carbon steel C45. The explanation is the same as with the CuBr laser;
- Higher values of critical power densities of melting and evaporation for the fiber laser compared to the CuBr laser are because the radiation in visible area is better absorbed from the steels from that in the near-infrared area.

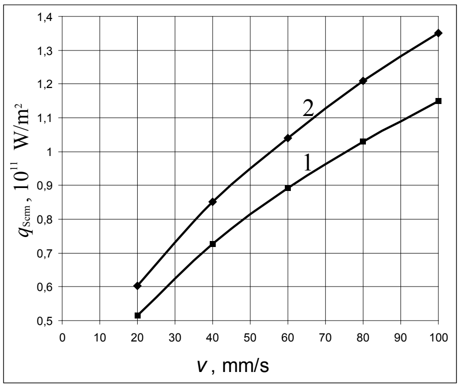

Fig. 5. Graphics of dependence of critical power density of melting from speed for fiber laser for: 1 – steel C45; 2 – steel 18ChGT

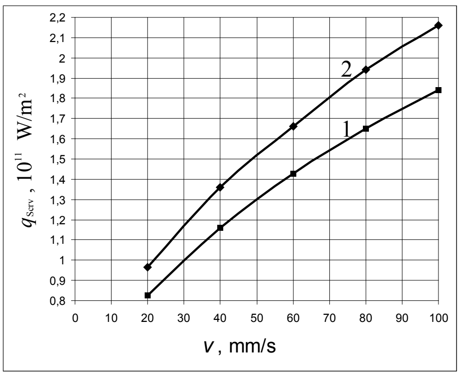

Fig. 6. Graphics of dependence of critical power density of evaporation from speed for fiber laser for: 1 – steel C45; 2 – steel 18ChGT

- **for CO_2 laser**

From the numerical experiments obtained, the dependencies of the critical power densities of melting q_{Scrm} and evaporation q_{Scrv} from the speed for steels C45 and 18ChGT (Fig. 7 and Fig. 8) were presented. The following conclusions can be drawn:

- The critical power densities of melting and evaporation increment non-linearly with increasing of speed for both studied steels;
- The rate of increase in critical power density of melting is

for interval v ∈ [20; 60] mm/s
1,32.10^9 (W/m^2)/(mm/s) for steel C45;
1,54.10^9 (W/m^2)/(mm/s) for steel 18ChGT;
for interval v ∈ [60; 100] mm/s
0,90.10^9 (W/m^2)/(mm/s) for steel C45;
1,08.10^9 (W/m^2)/(mm/s) for steel 18ChGT;

- The rate of increase in critical power density of evaporation is

for interval v ∈ [20; 60] mm/s
2,10.10^9 (W/m^2)/(mm/s) for steel C45;
2,48.10^9 (W/m^2)/(mm/s) for steel 18ChGT;
for interval v ∈ [60; 100] mm/s
1,45.10^9 (W/m^2)/(mm/s) for steel C45;
1,70.10^9 (W/m^2)/(mm/s) for steel 18ChGT;

- For structural alloy steel 18ChGT, the critical values of power densities of melting and evaporation density are greater than for structural carbon steel C45.;
- Critical power densities upon impact to CO_2 laser Критичните плътности на мощността при въздействие с CO_2 лазер are considerably larger than the other two lasers – with about 40% greater than fiber laser and about 75% greater than those for a CuBr laser.

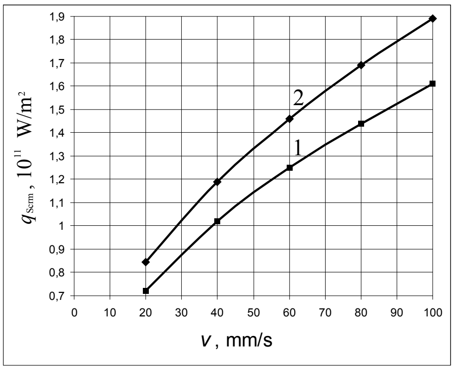

Fig. 7. Graphics of dependence of critical power density of melting from speed for CO2-laser for: 1 – steel C45; 2 – steel 18ChGT

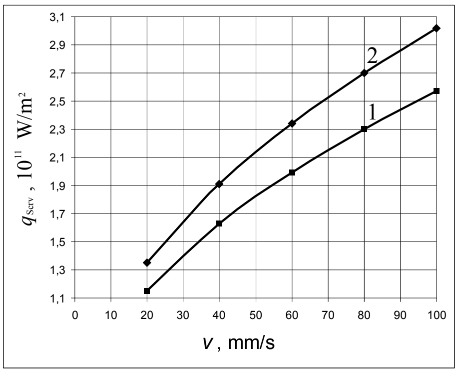

Fig. 8. Graphics of dependence of critical power density of evaporation from speed for CO_2- laser for: 1 – steel C45;

Fig. 9. 2 – steel 18ChGT

Summary

The pre-operating intervals of the power density for the laser technological processes hardening, marking and welding by melting for the three lasers and the two structural steels are given in Table IV.

THE PRE-OPERATING INTERVALS OF THE POWER DENSITY FOR THE LASER TECHNOLOGICAL PROCESSES HARDENING, MARKING AND WELDING BY MELTING

	Steel	C45	18ChGT
Laser	Speed		
CuBr laser	20	4,12.10^{10} ÷ 6,59.10^{10}	4,82.10^{10} ÷ 7,72.10^{10}
	40	5,83.10^{10} ÷ 9,32.10^{10}	6,82.10^{10} ÷ 1,09.10^{11}
	60	7,14.10^{10} ÷ 1,14.10^{11}	8,35.10^{10} ÷ 1,34.10^{11}
	80	8,24.10^{10} ÷ 1,32.10^{11}	9,64.10^{10} ÷ 1,54.10^{11}
	100	9,21.10^{10} ÷ 1,47.10^{11}	1,08.10^{11} ÷ 1,73.10^{11}
Fiber laser	20	5,15.10^{10} ÷ 8,24.10^{10}	6,03.10^{10} ÷ 9,62.10^{10}
	40	7,28.10^{10} ÷ 1,16.10^{11}	8,52.10^{10} ÷ 1,36.10^{11}
	60	8,92.10^{10} ÷ 1,43.10^{11}	1,04.10^{11} ÷ 1,66.10^{11}
	80	1,03.10^{11} ÷ 1,65.10^{11}	1,21.10^{11} ÷ 1,94.10^{11}
	100	1,15.10^{11} ÷ 1,84.10^{11}	1,35.10^{11} ÷ 2,16.10^{11}
CO_2 laser	20	7,21.10^{10} ÷ 1,15.10^{11}	8,44.10^{10} ÷ 1,35.10^{11}
	40	1,02.10^{11} ÷ 1,63.10^{11}	1,19.10^{11} ÷ 1,91.10^{11}
	60	1,25.10^{11} ÷ 1,99.10^{11}	1,46.10^{11} ÷ 2,34.10^{11}
	80	1,44.10^{11} ÷ 2,30.10^{11}	1,69.10^{11} ÷ 2,70.10^{11}
	100	1,61.10^{11} ÷ 2,57.10^{11}	1,89.10^{11} ÷ 3,02.10^{11}

The pre-operating intervals of the power density for the laser technological processes ablation, marking by evaporation, engraving, drilling and cutting of thin sheets for the three lasers and the two structural steels are given in Table V.

TABLE IV. THE PRE-OPERATING INTERVALS OF THE POWER DENSITY FOR THE LASER TECHNOLOGICAL PROCESSES ABLATION, MARKING BY EVAPORATION, ENGRAVING, DRILLING AND CUTTING OF THIN SHEETS

	Steel	C45	18ChGT
Laser	Speed		
CuBr laser	20	6,59.10^{10} ÷ 2,08.10^{11}	7,72.10^{10} ÷ 2,08.10^{11}
	40	9,32.10^{10} ÷ 2,08.10^{11}	1,09.10^{11} ÷ 2,08.10^{11}
	60	1,14.10^{11} ÷ 2,08.10^{11}	1,34.10^{11} ÷ 2,08.10^{11}
	80	1,32.10^{11} ÷ 2,08.10^{11}	1,54.10^{11} ÷ 2,08.10^{11}
	100	1,47.10^{11} ÷ 2,08.10^{11}	1,73.10^{11} ÷ 2,08.10^{11}
Fiber laser	20	8,24.10^{10} ÷ 3,18.10^{11}	9,62.10^{10} ÷ 3,18.10^{11}
	40	1,16.10^{11} ÷ 3,18.10^{11}	1,36.10^{11} ÷ 3,18.10^{11}
	60	1,43.10^{11} ÷ 3,18.10^{11}	1,66.10^{11} ÷ 3,18.10^{11}
	80	1,65.10^{11} ÷ 3,18.10^{11}	1,94.10^{11} ÷ 3,18.10^{11}
	100	1,84.10^{11} ÷ 3,18.10^{11}	2,16.10^{11} ÷ 3,18.10^{11}
CO_2 laser	20	1,15.10^{11} ÷ 3,60.10^{11}	1,35.10^{11} ÷ 3,60.10^{11}
	40	1,63.10^{11} ÷ 3,60.10^{11}	1,91.10^{11} ÷ 3,60.10^{11}
	60	1,99.10^{11} ÷ 3,60.10^{11}	2,34.10^{11} ÷ 3,60.10^{11}
	80	2,30.10^{11} ÷ 3,60.10^{11}	2,60.10^{11} ÷ 3,60.10^{11}
	100	2,57.10^{11} ÷ 3,60.10^{11}	3,02.10^{11} ÷ 3,60.10^{11}

III. CONCLUSION

The obtained critical power densities of melting and evaporation and pre-operating intervals of power density for the investigated technological processes help to plan real experiments in the study of concrete laser technological processes. The results will be in help of:

- operators of laser industrial processes in the industry who will use the pre-operating intervals of power

density in their work;
- engineers-technologists to optimize specific technological processes and to be able to quickly implement new products on which to implement laser technologies.

Similar studies can be made to investigate the impact of other basic technological factors (pulse energy, impulse power, impulse response, pulse duration, defocusing, etc.) onto processes of laser processing.

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