Determination of preliminary operating intervals of the power density for laser technological processes on copper samples

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***Abstract*. The report investigates the role of power density of melting and evaporation and speed to realize several laser technological processes on copper samples for a fibre laser and a CuBr laser. A methodology has been developed to determine preliminary operating intervals of power density for different speeds for the laser marking, laser ablation and laser texturing processes. From theoretical calculations, graphics of the dependences of the critical power density of melting and evaporation on the speed were drawn. Areas where oxidation, melting or evaporation occur were defined. Comparing the theoretical results and the obtained experimental results shows a very good convergence between them for both laser sources.**

Keywords: Laser density, Laser power, Laser surface texturing, Laser manufacturing - modelling and simulation on technology processes.

I. Introduction

In the domain of laser material processing, laser surface treatment technologies show substantial potential for growth in the forthcoming years [1]. Therefore, there is a necessity for a comprehensive understanding of the physicochemical and phase changes that occur during the interaction between laser beam and various material types. Presently, laser surface treatment stands as a focal point of cutting-edge scientific research due to its application in diverse sectors such as aeronautics, mechanical engineering, medicine, and other pivotal domains shaping modern economic development worldwide [2] [3].

Laser surface treatment technologies offer a broad spectrum of opportunities to achieve innovative surface properties. The modification of the surface layer is dictated by laser processing parameters and the optical and thermal properties of materials [4] [5].These factors collectively influence the resulting temperature profile within the processing zone, thereby instigating alterations in the material's properties (including mechanical, corrosion resistance, tribological, antibacterial, etc.) in both depth and radial directions [6] [7] [8]. The achieved modifications of the surface properties of the layer are largely determined by the settings of the parameters of the laser source, such as: wavelength of the laser beam, continuous wave (CW) or pulsed mode of operation, pulse length, peak power, shape of the pulse, repetition rate, beam energy distribution in its cross section, including focal spot size and depth of focus [9] .

The application of different laser technologies also leads to different effects on the modified surface properties. Thus, for example, in addition to the power density and the energy density in the processing area, the scanning speed or the laser interaction time have a strong influence on the modification of a metal surface [10] [11] [12]. All these specific features determine the number of advantages of laser surface treatment over conventional treatment methods, such as local heating of the surface without changing the properties of the substrate material, precision, and high speed of work and low cost [13] [14].

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The use of copper in several industries, such as mechanical engineering, electronics, aircraft construction and aeronautics, is increasing as copper-based components are used in personal computers, cellular telephones, and the expansion of telecommunications [15] [3]. Modern laser processing of copper has its inherent problems due to its high reflectivity and very high thermal conductivity, and today it faces several challenges [2].

The surface critical density of laser power in the context of melting and vaporization of metals is a significant parameter in laser material processing. It represents the threshold at which the incident laser power density is sufficient to induce phase changes in the material [16] [17] [18] [19].

Determining this critical density is essential for several reasons. Knowing the threshold power density for melting or vaporization optimizes laser processing parameters. It enables precise control of the energy input required for specific material transformations, ensuring efficient and accurate processing. Understanding critical power density prevents excessive energy input, reducing the risk of unintended material damage or property alterations. It contributes to achieving consistent, high-quality results in laser material processing, ensuring reproducibility and uniformity in treated material properties like surface morphology, hardness, and microstructure. Accurate determination of critical power density aids in cost efficiency, minimizing energy and material wastage by precisely directing the energy needed for desired material changes. Moreover, it is a critical parameter in research and development efforts aimed at exploring new applications and improving laser-based manufacturing techniques, informing the development of novel processes and applications. In essence, determining the surface critical laser power density in metal melting and vaporization is fundamental for precision control, quality assurance, cost-effectiveness, and advancing laser material processing technologies [20] [21] [22] [23].

This work develops a numerical surface heat treatment method to analyse various phase changes on the surface of copper samples. The phase state of the melting and evaporation surface is analysed, and the surface morphology of Cu samples is investigated concerning key laser processing parameters, including power density, processing speed. Numerical calculations are compared with our experimental studies by varying the above process parameters.

II. THEORETICAL ASPECTS AND METHODOLOGY

A. Theoretical Aspects

The power density q_s and the speed 'v' are the main parameters determining the temperature T in the impact zone for laser technological processes such as laser marking, laser engraving, laser ablation, laser texturing, laser cutting, laser welding, laser sintering, etc. There is a relationship and interdependence between these three quantities. And such a theoretical relationship between the critical melting and evaporation power density and the processing rate has been obtained by several other authors.

Under some simplifying assumptions (independence of thermophysical and optical parameters from temperature) for the critical power density of melting q_{scm} the expression is obtained

$$q_{scm} = \frac{(1+s)k(T_m - T_0)}{2A}\sqrt{\frac{\pi v}{ad}}, \qquad (1)$$

where k is coefficient of thermal conductivity, T_m – melting point, T_0 – initial temperature (environmental temperature), A – absorbed laser energy, a – coefficient of thermal diffusivity, d - diameter of work spot, the parameter s is determined by the formula.

$$s = \frac{L_m}{c(T_m - T_0)}, \qquad (2)$$

L_m is latent heat of melting, c – specific heat capacity.

For the critical power density of vaporization q_{scv} under the same simplifying assumptions, it is used the expression:

$$q_{scv} = \frac{(1+s')k(T_v - T_0)}{2A}\sqrt{\frac{\pi v}{ad}} \qquad (3)$$

where T_v is vaporization temperature, The parameter s' is determined by the formula:

$$s' = \frac{L_m + L_v}{c(T_v - T_0)}, \qquad (4)$$

L_v is latent heat of evaporation.

It should be noted that each specific laser system used for a given technological process has a maximum power density q_{smax} of the laser radiation with which to affect the processed area. It is given with the expression:

$$q_{smax} = \frac{4P_{max}}{\pi d^2} \qquad (5)$$

where P_{max} is the maximum power of the laser.

To achieve the goals, work is being done in two directions:

B. Steps in Determining Preliminary Power Density Operating Intervals

The following sequence is used to determine the preliminary laser power density operating intervals for **oxidation, melting**, and **evaporation** laser texturing:

1) Determination of the maximum power density q_{smax} for the used laser system fibre laser (λ = 1,06 µm) and CuBr laser (λ = 511&578 µm).

Each laser has a certain maximum power of its radiation, which is associated with its manufacture and is of a constructive nature. When it is built into a specific technological system, its maximum power density can also be determined, which is of a constructive nature. It has a constant value and does not depend on the speed with which the laser beam moves, and other factors related to the technological process, i.e. it is the design maximum density of the power of the laser radiation. The maximum power density q_{smax} for the laser system is determined by formula (5), which is required for the preliminary operating intervals of the power density of evaporation q_{scv}.

2) Calculation of critical melting power density q_{scm} for different speeds v.

Calculations of the critical melting power density for different speeds for the two lasers (fibre laser and CuBr laser) are performed using expressions (1) and (2). The speed v varies from 10 mm/s to 100 mm/s in 10 mm/s increments. The selected laser impact speeds 'v' is suitable for the technological process laser texturing of metals (including Cu). Graphics of the dependence of the melting power density on the speed are drawn from the obtained results.

3) Calculation of critical power density of vaporization q_{scv} for different speeds v.

Calculations of the critical power density of vaporization q_{scv} for different speeds for the two lasers are performed using expressions (3) and (4). The speed v varies from 10 mm/s to 100 mm/s in 10 mm/s increments. They draw graphs of the dependence of the power density of evaporation q_{scv} *on* the speed 'v'.

These two power densities (q_{scm} and q_{scv}) are technological in nature and depend on the speed v of the laser beam.

4) Determination of power density q_s intervals during marking by **oxidation**, by **melting** and by **evaporation** of the selected laser and material.

When determining the preliminary operating intervals of the power density q_s for different speeds 'v', the following requirements are observed:

- For laser texturing by **oxidation** - the power density q_s is less than the critical melting power density q_{scm} for the respective speed 'v'.
- For laser texturing by **melting** - the power density q_s is between the critical melting q_{scm} power density and the critical evaporation power density q_{scv} for the respective speed 'v'.
- For laser texturing by **vaporization** – the power density is between the critical vapor power density q_{scv} for the respective speed 'v' and the maximum power density q_{smax} of the laser system.

Graphical dependences for each laser are being given on a separate coordinate system. Three areas of laser texturing are defined on the graphic field: area 1 – by oxidation; area 2 – by melting; area 3 – by evaporation.

B. Experimental studies on fibre laser and copper bromide laser copper wafers and comparison of experimental data with calculation results

Laser technological experiments of copper are performed with both lasers at different power densities q_s and speeds 'v'. The treated areas (squares) are photographed with a metallographic microscope, and it is determined whether there is surface oxidation, melting or evaporation in the affected area. A comparison is made with the location of the specific processed zone in the formed areas (it is marked with a black dot) and the actual obtained way of texturing. Design matrices for performing experimental studies on the influence of speed 'v' and power '*P*' (respectively power density 'q_s') are presented in Figure 1. They are suitable for the technological processes of laser marking, laser ablation and laser texturing. Experiments are conducted using a raster method. The treated fields are 10 mm squares, and the experiments are conducted according to the designed matrices (see Figure 1). To investigate the influence of speed at 3 constant powers, the test field consists of 6 rows of 8 squares for impact with both types of lasers.

Experimental results are drawn as black dots on the graphical images for both types of lasers. The experimental results are compared with the theoretical ones.

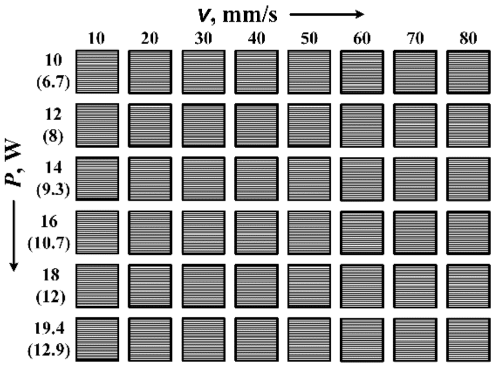

Fig. 1. Design matrix for experimental studies on the influence of speed and power in impact with fibre laser and CuBr laser on copper plates (data in brackets are for CuBr laser)

III. RESULTS AND DISCUSSION

According to the established methodology, research was carried out in two directions:

A. Determination of preliminary operating intervals of power density for laser marking and texturing by oxidation, laser marking and laser marking by melting, laser ablation and laser texturing by evaporation.

In order to study the dependence of the critical power density of melting q_{scm} and evaporation q_{scv} on the speed v of laser impact on copper samples, the following steps were taken. According to the methodology presented above, the values of the critical density power of melting q_{scm} (see formulas 1 and 2) and evaporation q_{scv} (see formulas 3 and 4) were calculated for copper samples for the different speeds v. Formulas (1) and (3) are derived for lasers operating in continuous mode. Due to the high frequency ν = 20 kHz of the lasers, it can be assumed that the lasers work in CW mode. In the experiments performed with both lasers, the pulse overlaps k_{ovr} coefficient varied from 86.7% to 98.5%.

The necessary data for copper characteristics are taken from Table 2. The calculations refer to a fibre laser and a CuBr laser. From the obtained values of the quantities, graphics of the dependence of the critical density power of melting q_{scm} and evaporation q_{scv} on the speed for copper samples were drawn.

The graphics that apply to a fibre laser are presented in Fig. 2. It follows from their analysis:

- A non-linear increase in both the critical power density of melting and the critical power density of evaporation is observed as the speed increases.

- In the speed v interval from 10 mm/s to 100 mm/s, the critical power density q_{scm} of melting changes from 0.24×10[10] W/m[2] to 0.76 ×10[10] W/m[2].
- In the speed v interval from 10 mm/s to 100 mm/s, the critical power density q_{scv} of evaporation changes from 2.32×10^{10} W/m^2 to 7.35×10^{10} W/m^2.

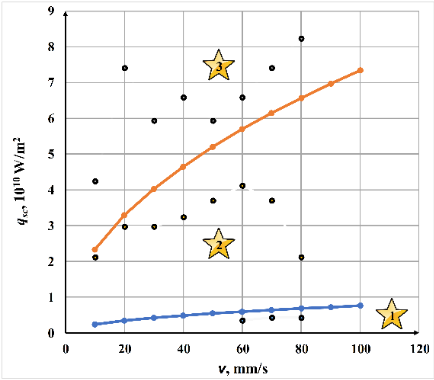

Fig. 2. Graphics of critical power density versus speed v for a fibre laser: blue colour - of melting q_{scm}, orange colour - of evaporation q_{scv}. Legend: area 1 – by oxidation; area 2 – by melting; area 3 – by evaporation.

The same graphical dependencies are given in Fig. 3, but for a CuBr laser. The blue coloured graphic is for the critical power density of melting and the orange-coloured graphic is for the critical power density of evaporation. The following conclusions can be done from them:

- With an increase in speed, a non-linear increase of the two critical power densities is again observed for the entire studied interval of speed.
- In the speed interval from 10 mm/s to 100 mm/s, the critical power density q_{scm} of melting changes from 0.16×10^{10} W/m^2 to 0.51×10^{10} W/m^2.
- In the speed interval from 10 mm/s to 100 mm/s, the critical power density q_{scv} of evaporation changes from 1.54×10^{10} W/m^2 to 4.90×10^{10} W/m^2.
- The critical power density of melting and evaporation of a CuBr laser is about 33% less than that of a fibre laser. It is explained by the greater absorption capacity of copper for the radiation of the CuBr laser compared to the fibre laser.

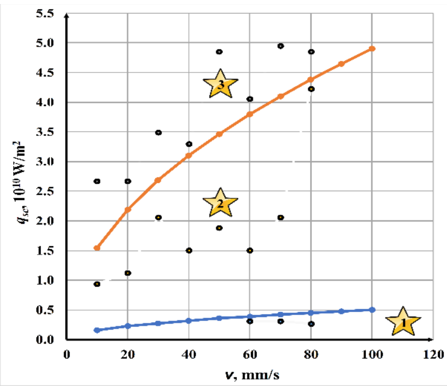

Fig. 3. Graphics of critical power density versus speed for a CuBr laser: blue colour - of melting q_{scm}, orange colour - of evaporation q_{scv}. Legend: area 1 – by oxidation; area 2 – by melting; area 3 – by evaporation.

To determine the preliminary operating intervals of the power density, it is necessary to determine the maximum power density of the two lasers. According to formula (5), the following values are obtained: $q_{smax} = 10.1\times10^{10}$ W/m^2 for the fibre laser and $q_{smax} = 6.37\times10^{10}$ W/m^2 for the CuBr laser. The preliminary operating intervals of the power density for oxidation, melting and vaporization at different rates for fibre laser and CuBr laser, respectively, are given in Tables 1 and 2. The selected speeds are used in the industry for the relevant laser technological processes.

TABLE 1: PRELIMINARY OPERATING INTERVALS OF THE POWER DENSITY FOR COPPER SAMPLES AND FIBRE LASER.

Marking Method	Oxidation	Melting	Evaporation
v, mm/s	*q_s, 10^{10} W/m^2*		
10	< 0.240	0.240 - 2.32	2.32 - 9.90
20	< 0.339	0.339 - 3.28	3.28 - 9.90
30	< 0.416	0.416 - 4.03	4.03 - 9.90
40	< 0.480	0.480 - 4.65	4.65 - 9.90
50	< 0.537	0.537 - 5.20	5.20 - 9.90
60	< 0.558	0.558 - 5.69	5.69 - 9.90
70	< 0.635	0.635 - 6.15	6.15 - 9.90
80	< 0.679	0.679 - 6.57	6.57 - 9.90
90	< 0.720	0.720 - 6.97	6.97 - 9.90
100	< 0.759	0.759 - 7.35	7.35 - 9.90

TABLE 2. PRELIMINARY OPERATING INTERVALS OF THE POWER DENSITY FOR COPPER SAMPLES AND CUBR LASER.

Marking Method	Oxidation	Melting	Evaporation
v, mm/s	q_s, 10^{10} W/m^2		
10	< 0.160	0.160 - 1.55	1.55 - 6.37
20	< 0.226	0.226 - 2.19	2.19 - 6.37
30	< 0.277	0.277 - 2.88	2.68 - 6.37
40	< 0.320	0.320 - 3.10	3.10 - 6.37
50	< 0.358	0.358 - 3.46	3.46 - 6.37
60	< 0.392	0.392 - 3.79	3.79 - 6.37
70	< 0.423	0.423 - 4.10	4.10 - 6.37
80	< 0.453	0.453 - 4.38	4.38 - 6.37
90	< 0.480	0.480 - 4.65	4.65 - 6.37
100	< 0.506	0.506 - 4.90	4.90 - 6.37

A. Comparison of experimental results for laser marking and laser ablation of copper plates with theoretically obtained results

According to the plan in the methodology, experimental studies were carried out with a fibre laser and a CuBr laser on copper samples. The experiments are for the technological processes of laser marking, laser ablation and laser texturing. A raster way for marking and ablation was applied to 3 copper plates (two plates with fibre laser and one plate with CuBr laser). Obtained experimental results are placed in Figures 2 and 3 with black dots with certain power densities and speeds.

- **Results for fibre laser**

Photographs of the impact zones taken with a laser microscope are given in Fig. 4. Fig. 4a is for laser impact with a fibre laser at power density $q_s = 0.42\times10^{10}$ W/m^2 and velocity v = 80 mm/s. Oxidation can be observed on the treated area. The experimental result is plotted in the first zone, which shows agreement between theory and experiment. Figures 4b is at the power density q_s = 2.12×10^{10} W/m^2 and velocity v = 80 mm/s, and Figure 4c is at the power density $q_s = 3.24\times10^{10}$ W/m^2 and velocity v = 40 mm/s. The two results are in area 2 of Fig. 2, which corresponds to melting. From the photographs, melting from laser processing can be observed, which shows a good agreement between the theoretical and experimental results. Laser marking by evaporation, laser ablation and laser texturing was obtained in Fig. 4d. The channels obtained because of the laser processing are clearly outlined. The values $q_s = 8.24\times10^{10}$ W/m^2 and v = 80 mm/s locate the treated area in zone 3, corresponding to evaporation. For all the pictures shown in Figure 4, good agreement between theory and experiment is obtained.

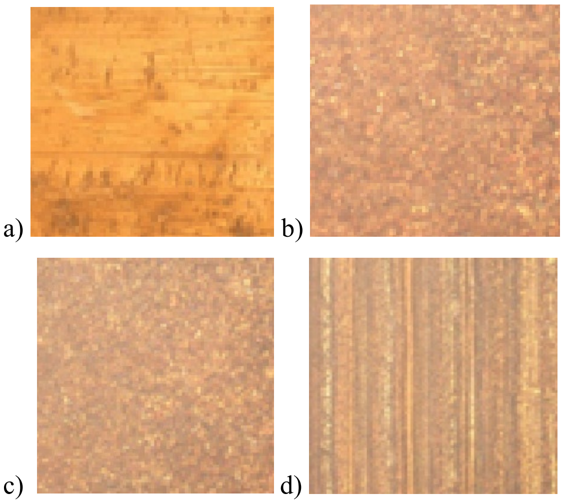

Fig. 4. Areas of impact with a fibre laser: a) oxidation; b) & c) melting; d) evaporation.

- **Results for CuBr laser**

Photographs of the impact zones, also taken with a laser microscope, are presented in Fig. 5. In Fig. 5a laser marking by oxidation is obtained, in Figures 5b and 5c we have laser marking by melting, and in Fig. 5d is obtained laser marking by evaporation, laser ablation and laser texturing. When considering the power densities and velocities, these experimental results are in the correct areas of Fig. 3. Good agreement is again obtained between the theoretical and experimental results. It should be noted that the placement of the black dot in Fig. 5c is close to the plot of the dependence of the critical density of the melting power on the speed. This explains the obtaining of poorly formed channels, which are observed in the photograph.

In the experiments performed with both lasers, the pulse overlap coefficient varied from 86.7% to 98.5%. The pulse energy of the CuBr laser (350 µJ) is much higher than that of the fibre laser (20 µJ), which helps to enable the processes with CuBr laser at lower power densities.

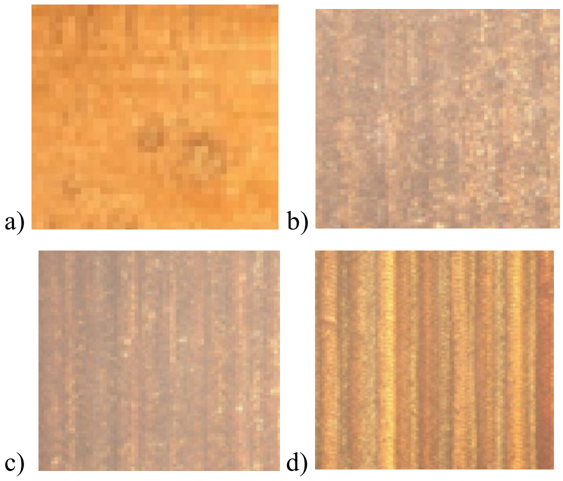

Fig. 5. Areas of impact with a CuBr laser: a) oxidation; b) & c) melting; d) evaporation.

IV. Conclusion

In the present work, the following results were achieved when investigating the role of power density for the processes of laser marking, laser ablation and laser texturing of copper samples:

- Preliminary operating intervals of oxidation, melting and vaporization power density for copper samples using a fibre laser have been determined.
- Preliminary operating intervals of oxidation, melting and vaporization power densities for copper samples using a CuBr laser have been determined.
- A good correlation was obtained when comparing experimental results for laser marking, laser ablation and laser texturing of copper wafers with theoretically obtained results.

The preliminary working intervals contribute to increasing the efficiency when conducting the real experiments, because indicate to the researcher in which power density interval they should conduct research for the certain laser process, in the case of laser marking, laser texturing or laser ablation. The resulting operating intervals serve as a basis for optimizing laser processing parameters, ultimately improving the capabilities and applications of laser technology in the production of copper products. Research can also continue for the role of other fundamental quantities such as speed, frequency, pulse duration, pulse energy together with power density on these technological processes with both types of lasers.

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