Influence of the Overlap Coefficient on the Contrast in Laser Marking of C110W Steel

Nikolay Angelov
Technical University of Gabrovo
Gabrovo, Bulgaria
angelov_np@abv.bg

Lyubomir Lazov
Rezekne Academy of Technology
Rezekne, Latvia
lyubomir.lazov@rta.lv

Edmunds Teirumnieks
Rezekne Academy of Technology,
Rezekne, Latvia
edmunds.teirumnieks@rta.lv

Abstract **- The laser marking process by melting samples of C110W carbon tool steel was studied. The experiments were performed with a fiber laser and a CuBr laser. A field of squares is marked in a raster method for different values of the overlap coefficient and power density. The contrast of the marking is determined on each marked square. From the obtained experimental data, graphs of the dependence of the contrast on the overlap coefficient for three power densities were drawn. The obtained results for the two lasers are compared and the influence of the wavelength is indirectly analysed. The working intervals of the overlap coefficient for the studied power densities for the two lasers at which the optimal contrast in the processing zone is obtained are determined.**

Keywords **-** *laser marking, fiber laser, CuBr laser, C110W steel, overlap coefficient, power density, contrast.*

I. Introduction

Laser marking is a modern technology that is increasingly used in modern production in electronics, electrical engineering, mechanical engineering, medicine, and others. One of its main advantages is that it allows manufacturers to meet modern requirements for tracking and quality control of their products. Laser marking of serial numbers, matrix codes, barcodes, logos, tables, and other operational information is the main factor for proper optimization and monitoring of production processes [1 ÷ 3], [11 ÷ 17]. The wide penetration of laser marking technology in industrial production is primarily due to its special characteristics, such as non-contact during the process, which allows processing both ultra-hard materials for mechanical engineering and brittle and thin materials for microelectronics. The selectivity of the laser interaction with the material combined with the simultaneous ability to achieve heating, melting, and evaporation of the material in a very small area is another significant advantage of this innovative technology over other marking methods. The ability of modern laser scanners to control the movement of the laser beam in space at high speed and to position it with high accuracy is another important factor that has significantly contributed to the entry of this technology in the modern production of various types of products [4].

Laser marking is a complex technological process that depends on a number of factors that can be combined into three main groups [5, 6]. It can be noted that these factors in most cases are interrelated and have a complex effect on the specific technological process [7]. The article [8] with a nanosecond pulsed laser analyses the influence of the pulse tracking frequency and the distance between the processing lines when scanning titanium alloy substrates on the process of colour laser marking. The authors in [9] investigated the effect of a number of parameters of laser processing, such as power and fill factor of laser pulses on a certain working area when marking barcodes on the surfaces of aluminum alloys. The results show that the processing parameters significantly affect the surface roughness.

The study [10] demonstrated a processing technique related to the overlap of the laser pulses and the overlap between the scanning lines influencing the formation of specific microstructures on the surface of Ti6Al4V samples. The topology of processing in the process considered by the authors varies in a wide range between 40% and 90% and leads to a change in the density of the absorbed laser energy in the range from 0.49 J/cm^2 to

12.28 J/cm^2 and this in turn to optimization of the quality of the technological process.

The present study focuses on the analysis and the relationship between two technological factors, the overlap coefficient and the scan overlap coefficient, on the quality of the marking and in particular on the contrast in the processing area. Their influence has a direct impact on the linear density of the pulses entering at the processing area, as well as on the linear energy density and the effective energy for the realization of the specific technological process.

II. Topology of the experimental study

The overlap coefficients k_{ov} of the laser pulses and the overlap coefficient k_s in the scanning process are complex factors that give us a relationship between the marking speed (factor related to the technological process), on the one hand, and the pulse repetition rate and laser power density in diameter. at the workplace (factors related to the parameters of the laser) on the other hand.

Considering that, the physical interaction of the laser radiation with the substance in the treatment area leading to heating, melting and evaporation is strongly influenced by the absorbed energy (effective energy for the specific technological process E_{eff}).

Considering that the linear energy density at laser action is the quantity defined by the absorbed energy per unit length in the laser marking area

$$E_\ell = \frac{AP}{v} \,, \qquad (1)$$

where v is the marking speed, P is power and A is absorption capacity.

In the case of pulsed raster marking, as in our study, the overlap coefficient k_{ov} significantly affects the value of the linear pulse density of laser pulses entering the processing line

$$L_p = \frac{v}{v} \,, \qquad (2)$$

where v is the frequency of pulse repetition.

In turn, the above two relations (1) and (2) have a significant influence on the effective absorbed energy of the laser radiation per unit area of the laser impact zone

$$E_{eff} = \frac{APv}{v^2} \qquad (3)$$

and on the volume absorbed energy of the laser radiation

$$E_\rho = \frac{AP}{dv\delta} \,, \qquad (4)$$

where δ is the penetration of laser radiation into the substance.

Taking into account all these interrelated relations between the physical quantities and the technological parameters of the processing of formulas (1) - (4) it is seen that the topology of the experiment is essential for the expected result of the processing.

The overlap coefficient k_{ov} of the laser radiation pulses is a complex factor that gives a relationship between the marking speed (factor related to the technological process) on the one hand and the frequency of pulse repetition and laser power density through the diameter of the working spot (factors related to the laser parameters) on the other hand. It is defined by the expression

$$k_{ov} = \frac{x}{d} . 100\% = (1 - \frac{\ell}{d}) . 100\% \,, \qquad (5)$$

where d is the diameter of the working spot, x is the width of the overlapped part of two consecutive pulses of laser radiation, ℓ is the distance between two consecutive pulses (Fig. 1).
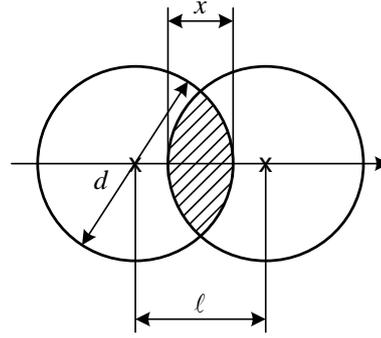

Fig. 1. Position of two consecutive pulses in the presence of overlap
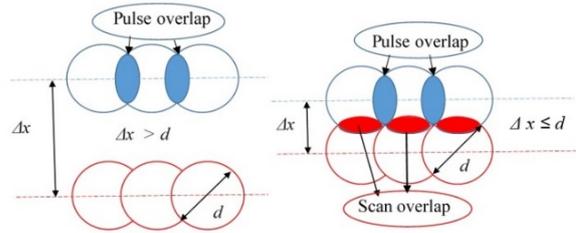

Fig. 2. Intervals of change of the scan overlap coefficient k_s

Taking into account that

$$\ell = \frac{v}{v} \qquad (6)$$

where v is the marking speed and v is the frequency of pulse repetition, and replacing (2) in (1) is obtained

$$k_{ov} = (1 - \frac{v}{vd}) . 100\% \qquad (7)$$

The laser marking process also is affected on the scan overlap coefficient k_s. It depends on the diameter d of the working spot and the raster step Δx. The scan overlap coefficient is given by the formula

$$k_s = \left(1 - \frac{\Delta x}{d}\right).100\% \quad (8)$$

When the condition $\Delta x \leq d$ is fulfilled, it has positive values and is in the interval $k_s \in [0, 100]$ %. When the condition $\Delta x > d$ is fulfilled, it takes negative values. The limitation for raster marking is that the consecutive lines are at a smaller distance from the limiting ability of the human eye, i.e. $\Delta x \leq 70$ μm. In this case, the homogeneity of the marking is not disturbed.

It should be noted that there is a relationship between some of the considered physical quantities and technological parameters. For example, the overlap coefficient k_{ov} can be related to the linear pulse density L_p and the effective energy E_{eff} with the expressions

$$k_{ov} = \left(1 - \frac{1}{L_p d}\right).100\% \quad (9)$$

and $$k_{ov} = \left(1 - \frac{AP}{E_{eff} v d}\right).100\% \quad (10)$$

III. EXPERIMENTS AND DISKUSIONS

The experiments refer to C110W carbon tool steel. It is widely used in industry. C110W steel is used for making hand taps, rasps, needle files, saws for woodworking, matrices for cold stamping. It is high carbon steel and has relatively high coefficients of thermal conductivity and diffusivity (see Table 1).

TABLE 1. BASIC CHARACTERISTICS OF THE C110W CARBON TOOL STEEL

Characteristic	Value
Coefficient of thermal conductivity k, W/(m.K)	45
Specific heat capacity c, J/(kg.K)	460
Density ρ, kg/m^3	7850
Coefficient of diffusivity a, m^2/s	1.25×10^{-5}

The experimental studies were performed with laser technological systems for marking with fiber laser and CuBr laser. Their main parameters are presented in Table 2.

TABLE 2 SOME BASIC PARAMETERS OF A LASER TECHNOLOGICAL SYSTEM FOR MARKING WITH FIBER LASER TYPE STYLES

Parameter	Fiber laser	CuBr laser
Wavelength λ, nm	1 064	511 & 578
Power P, W	20.0	10.0
Frequency v, kHz	80	20
Pulse duration τ, ns	100	30
Pulse energy E_p, mJ	0.25	0.50
Pulse power P_p, kW	2.50	16.7
Quality of beam M2	< 1.1	< 1.7
Positioning accuracy, μm	2.5	2.5
Efficiency, %	40	10

The fiber laser is a modern laser emitting in the near infrared range. It works in pulse mode. It has extremely high beam quality, high efficiency. and cheap

maintenance. The laser system has high precision and very good repeatability.

The CuBr laser emits in the visible range. It works in pulse mode. It is characterized by good beam quality and relatively good efficiency. The laser system has high precision and maintains stable parameters during operation.

During the experiments, the scan overlap coefficient k_s remained constant. Squares with a side of 5 mm were marked in a raster method way. The contrast was determined several times for each marked square. The contrast was measured according to the procedure described in [7]. The mean contrast value for each square was then obtained.

The experiments were conducted in two directions:

1. Investigation of the dependence of the contrast of the marking $k*$ on the overlap coefficient k_{ov} for fiber laser

A series of experiments was carried out in order to study the influence of the overlap coefficient kov on the contrast $k*$ of the marking. The overlap coefficient changes in the interval $k_{ov} \in [72.5 \div 95]$ % through 2.50 %. Experiments refer for three values of the power density: $q_{s1} = 1.24\times10^{10}$ W/m^2; $q_{s2} = 1.50\times10^{10}$ W/m^2 and $q_{s3} = 1.77\times10^{10}$ W/m^2. The parameters that are kept constant are given in Table 3. During the experiments, the scan overlap coefficient had value $k_s = -25$ %.

TABLE 3. PARAMETERS THAT DO NOT CHANGE DURING EXPERIMENTS

Parameter \ Laser	Fiber	CuBr
Pulse duration τ, ns	100	40
Diameter of working spot d, μm	40	30
Raster step Δx, μm	50	50
Number of repetition	1	1
Defocusing Δf, mm	0	0

The obtained experimental dependencies of the contrast $k*$ of the marking from the overlap coefficient kov are presented in graphical form in Fig. 3.

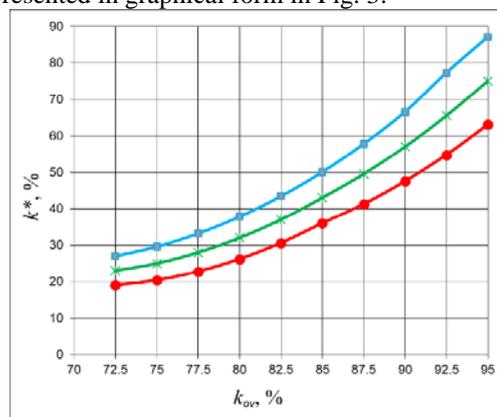

Figure 3. Dependence of the contrast on the overlap coefficient for marking with a fiber laser for power densities: red colour – $q_{s1} = 1.24\times10^{10}$ W/m^2; green colour – $q_{s2} = 1.50\times10^{10}$ W/m^2; blue colour – $q_{s3} = 1.77\times10^{10}$ W/m^2.

From the analysis of experimental results it sees that:

- With increasing the overlap coefficient results in a non-linear increase in contrast for all three power density. In the interval $k_{ov} \in [80 \div 95]$ % the contrast k^* increases significantly faster versus the interval $k_{ov} \in [72.5 \div 80]$ %;

- The rate of increase of the contrast k^* is given in the table below.

The rate of increase of the contrast k^*					
interval k_{ov} [**72.5** ÷ **80**] %			interval k_{ov} [**80** ÷ **95**] %		
q_{s1}	q_{s2}	q_{s3}	q_{s1}	q_{s2}	q_{s3}
0.96	**1.20**	**1.44**	**2.45**	**2.87**	**3.28**

The faster increase of the contrast in the interval $k_{ov} \in [80 \div 95]$ % compared to the interval $k_{ov} \in [72.5 \div 80]$ %kov is explained by the fact that with increasing the overlap coefficient the absorbency of the material in the impact zone also increases.

- The following working intervals were determined for the overlap coefficient k_{ov} .

for power density q_s, W/m²	the overlap coefficient k_{ov}
1.24×10¹⁰	91 % ÷ 95 %
1.50×10¹⁰	87.5 % ÷ 95 %
1.77×10¹⁰	85 % ÷ 95 %

These intervals refer to the visual perception of the marking, for which the contrast must be at least 50%.

2. *Investigation of the dependence of the contrast k^* of the marking on the overlap coefficient k_{ov} for CuBr laser*

A number of experiments was carried out in order to study the influence of the overlap coefficient k_{ov} on the contrast k^* of the marking. The overlap coefficient changes in the interval $k_{ov} \in [63.33 \div 93.33]$ % with step 3.33 %. The experiments were performed at three constant values of power density $q_{s1} = 0.99 \times 10^{10}$ W/m²; $q_{s2} = 1.20 \times 10^{10}$ W/m² and $q_{s3} = 1.42 \times 10^{10}$ W/m². The parameters that are kept constant are given in Table 3. During the experiments, the scan overlap coefficient had value $k_s = -66.7$ %

The obtained experimental dependencies of the contrast k^* of the marking from the overlap coefficient k_{ov} are presented in graphical form in Fig. 4. From the analysis of experimental results, it sees that:

- With increasing the overlap coefficient results in a non-linear increase in contrast for all three power density. In the interval $k_{ov} \in [73.3 \div 93.3]$ % the contrast k^* increases significantly faster versus the interval $k_{ov} \in [63.3 \div 73.3]$ %;

- When working with a CuBr laser, the optimal contrast of the marking is achieved with lower values of power

density q_s and overlap coefficient than when marking with a fiber laser. It is explained that CuBr laser radiation ($\lambda = 511$ nm & 578 nm) is better absorbed by the studied material than fiber laser radiation ($\lambda = 1064$ nm).
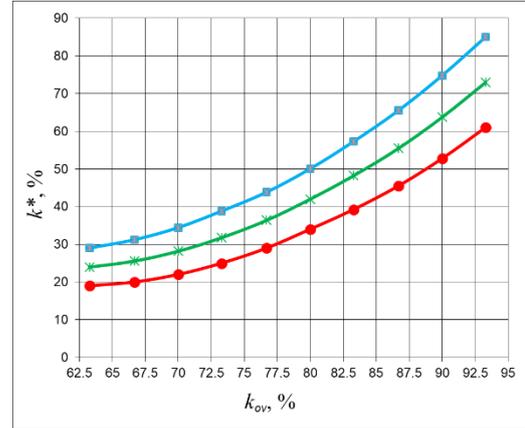

Figure 4. Dependence of the contrast on the overlap coefficient for marking with a CuBr laser for power densities: red colour – q_{s1} = 0.99×10^{10} W/m²; green colour – q_{s2} = 1.20×10^{10} W/m²; blue colour – q_{s3} = 1.42×10^{10} W/m².

- The rate of increase of the contrast k^* is given in the table below.

The rate of increase of the contrast k^*					
interval k_{ov} [**63.3** ÷ **73.3**] %			interval k_{ov} [**73.3** ÷ **93.3**] %		
q_{s1}	q_{s2}	q_{s3}	q_{s1}	q_{s2}	q_{s3}
0.60	**0.78**	**0.98**	**1.80**	**2.06**	**2.31**

Here again, the different rate of contrast increase is due to the dependence of the absorbency of the material on the overlap coefficient.

- The following working intervals were determined for the overlap coefficient k_{ov} for visual perception of the marking.

for power density q_s, W/m²	the overlap coefficient k_{ov}
0.99 ×10¹⁰	88.5 % ÷ 93.3 %
1.20 ×10¹⁰	84 % ÷ 93.3 %
1.42 ×10¹⁰	80 % ÷ 93.3 %

CONCLUSIONS

This study examines the effect of laser parameters on contrast in the area of marking. The processing field (squares) is marked using the raster method at different values of the overlap coefficient between the individual laser pulses and the overlap coefficient between the scanning lines. The research is related to optimizing the influence of the overlap coefficient on the marking process and more precisely on the contrast. The results and analyses of this study have a direct impact on the optimization and

quality of application of two-dimensional QR codes on C110W carbon tool steel surfaces with two types of lasers - fiber and CuBr.

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