TECHNICAL UNIVERSITY-GABROVO

Faculty of “Machine building and instrumentation”

eng. PETAR STOIANOV TSVYATKOV

OPTIMIZATION OF THE LASER COLOR MARKING PROCESS OF CARBON STEEL PRODUCTS

A U T O R E F E R A T

acquire an educational and scientific degree
Doctor

Field of higher education: **5. Technical Sciences**
Professional direction**: 5.1 Mechanical Engineering**
Doctoral program: **Precision Instrumentation**

Gabrovo, 2026 г.

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Gabrovo, 2026 г.

The dissertation was discussed and directed for official defense at a meeting of the Extended Department Council of the "Machine Building and Instrumentation" Department at the "Machine Building and Instrumentation" Faculty of the Technical University - Gabrovo, held on June 15, 2026.

The dissertation contains 184 pages. The scientific content is presented in an introduction, 5 chapters and one appendix and includes 107 figures and 20 tables. 150 literature sources are cited. The numbering of figures, tables and formulas in the abstract corresponds to that in the dissertation.

The development/research for the dissertation was carried out in the "Machine Building and Instrumentation" Department at the "Machine Building and Instrumentation" Faculty of the Technical University - Gabrovo, the laser center at RTU - Rezekne, Latvia and at "Technoles" JSC.

The official defense of the dissertation will take place on .... from .... in hall .... at the Technical University - Gabrovo.

Author: M.Sc. Eng. PETAR STOIANOV TSVYATKOV
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GENERAL CHARACTERISTICS OF THE DISSERTATION

Relevance of the problem

Laser marking is established as an effective method for surface modification of metal products, thanks to the high energy density, good directionality and coherence of laser radiation. In modern industry, there is a growing need for durable, high-contrast and environmentally friendly markings on metal products that provide traceability, protection against counterfeiting and long-term readability under extreme operating conditions.

Analysis of the scientific literature shows that research in the field of color laser marking is focused primarily on titanium and stainless steels, with over 60% of published works devoted to these materials. Carbon steel C75, despite its wide application in mechanical engineering and tool production, is significantly less studied. This creates a significant scientific gap that the present dissertation work aims to fill.

The practical significance of the research is determined by the need for the implementation of sustainable technologies in the production of local enterprises specializing in the production of circular saws and band saw blades. Traditional marking methods - electrochemical, mechanical and inkjet - are characterized by a number of disadvantages, including the use of harmful chemicals, low productivity, insufficient resolution and low durability of markings.

Scientific interest in laser marking marks a steady upward trend, as the analysis of publications in Scopus, Google Scholar and ScienceDirect shows an average annual growth of 10-12% in recent years, which confirms the relevance of the topic.

Aim and objectives of the dissertation

The aim of the dissertation work is to optimize the process of laser color marking of carbon steel products through the development and application of a theoretical-mathematical model, methodical approaches and technological regimes, allowing quantitative investigation of the influence of laser and technological parameters on the marking characteristics.

To fulfill the formulated aim, the following objectives have been solved:

1. Identification and systematization of factors affecting the contrast and readability of laser marking on carbon steel C75.
2. Development of a theoretical-mathematical model for determining suitable laser parameters for color marking of carbon steel.
3. Development of a methodology for conducting experimental studies of the laser color marking process.

4. Selection and configuration of a laser source and scanning system that meet the requirements of the research and the industrial applicability of the process.
5. Experimental investigation of the influence of laser and technological parameters on the main characteristics of the marking, including contrast, roughness, microhardness, color difference, color reproducibility, scratch resistance and corrosion resistance.

Research methods

Theoretical methods: analysis of scientific literature, mathematical modeling of thermophysical processes, numerical calculations of critical power densities, analysis of energy balance.

Experimental methods: laser marking with fiber laser systems Raycus RF-30 and Rofin PowerLine F-20 Varia, spectrophotometric measurements, profilometry with Olympus OLS5000 laser microscope, microhardness testing with DUH-211S dynamic ultra-microhardness tester, scratch resistance testing with CSM REVETEST Scratch Macrotester, corrosion testing in Q-FOG CCT1100 chamber.

Scientific novelty

The scientific novelty of the dissertation consists of:

1. The development of an integrated methodology for optimization of the laser color marking process, combining analytical models, numerical analysis and experimental dependencies, as the critical values of power density corresponding to the regimes of oxidation, melting and evaporation under action on C75 steel have been determined.
2. The definition of a technological window for color laser marking of carbon steel C75, based on experimentally validated boundaries of the main parameters.
3. The establishment of quantitative dependencies between contrast, color difference and surface morphology of laser-marked zones, experimentally confirmed for carbon steel C75.

Applicability

- Demonstrated practical applicability of the results for purposeful design of markings with predetermined functional properties.
- Created methodology for assessing color reproducibility, which can be used as a quality control tool in serial and mass production.
- Developed practical recommendations for industrial implementation of the color laser marking process on carbon steel C75.

Approbation of the dissertation

The main results of the dissertation have been reported and discussed at international scientific conferences and published in the following editions:

1. Pulov, D., Tsvyatkov, P. Optical Systems for Reducing the Divergence of Laser Beams 14th International Scientific and Practical Conference Environment. Technology. Resources. Rezekne, Latvia, Volume 3, pp 339–343, DOI: 10.17770/etr2023vol3.7217
2. Tsvyatkov, P., Teirumnieks, E., Yankov, E., Pīgožnis, K., Lazov, L. Investigation of the Influence of Technological Parameters of Laser Marking on the Degree of Contrast 14th International Scientific and Practical Conference Environment. Technology. Resources. Rezekne, Latvia, Volume 2, pp. 370–374, DOI: 10.17770/etr2023vol3.7319
3. Tsvyatkov, P., Teirumnieks, E., Yankov, E., Pīgožnis, K., Lazov, L., Investigation of Surface Roughness of Carbon Steel Machined Parts after Nanosecond Fiber Laser Marking 14th International Scientific and Practical Conference Environment. Technology. Resources. Rezekne, Latvia, Volume 2, pp. 358–362, DOI: 10.17770/etr2023vol3.7317
4. Tsvyatkov, P., E. Yankov, L. Lazov, L., E. Teirumnieks, E.Teirumnieks, Color marking of stainless steel and titanium with the laser oxidation method14th International Scientific and Practical Conference Environment. Technology. Resources. Rezekne, Latvia, Volume 2, pp. 363–369, https://doi.org/10.17770/etr2023vol3.7318
5. L Lazov , P Tsvyatkov , N Angelov. Analysis of the process of laser ablation of marble surfaces. XXI International Conference and School on Quantum Electronics. Resources. Journal of Physics: Conference Series. IOP Publishing, 2021. p. 012014. DOI: 10.1088/1742-6596/1859/1/012014
6. P. Tsvyatkov, Reproducibility of laser color marking on c75 steel obtained by a nanosecond pulsed laser , Mashinostroene i mashinoznanie, 2026

Structure and volume of the dissertation

The dissertation is structured in an introduction, five chapters, conclusion and appendices. The total volume is 184 pages, including 107 figures, 20 tables and 1 appendix. 150 literature sources are cited.

CONTENT OF THE DISSERTATION

Chapter 1: Analysis of the current state of color marking of metal products

1.1 Conventional methods for color marking of metals Traditional methods for coloring metal surfaces include electrolytic (anodizing), thermal and thermochemical oxidation, in which the change in optical properties is due to the controlled growth of oxide layers. These processes are often characterized by complex equipment maintenance, high energy consumption and generation of environmentally harmful waste. Inkjet and thermal transfer printing provide greater flexibility and productivity, but the resulting markings have low wear resistance and are easily erased.

1.2 Laser marking of metal products Laser marking is established as a high-tech alternative, offering **high precision** with the ability to create durable oxide layers, without mechanical contact with the material. The method allows complete automation and environmental compatibility, and does not use consumables and aggressive chemicals.

1.3 Methods for laser color marking

According to the literature analysis, there are four methods for color laser marking, which are shown in Figure 5.

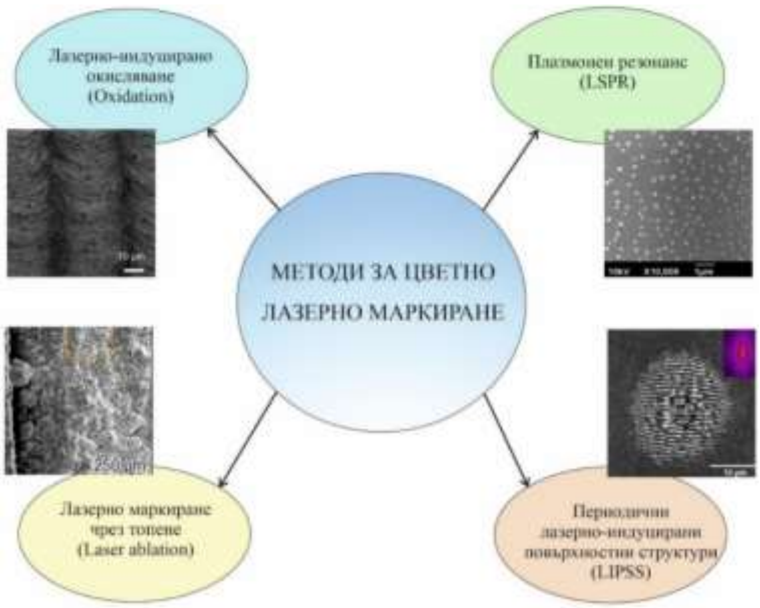


Figure 5. Methods for laser color marking

The laser oxidation method can be implemented in industry. The formed thin interference oxide films (10-500 nm) are resistant to external influences.

1.4 Influence of technological and laser parameters on the properties and structure of materials processed with laser radiation.

The quality and characteristics of the marking are determined by the complex interaction of the following investigated parameters:

- **Power and energy density:** Optimal levels (e.g. 18–22 W for stainless steel) guarantee high contrast, while exceeding them leads to overheating and layer destruction.
- **Scanning speed (v):** Directly affects the thickness of the oxide layer; at high speeds (>400 mm/s) oxidation is insufficient for contrast marking.
- **Pulse frequency (f):** Determines heat accumulation; high frequencies can lead to lower contrast due to overheating.
- **Step between lines (x):** Small step (<6 μm) leads to large overlap and inhomogeneity.
- **Defocus:** Positive defocus (+0.5 to +1.5 mm) contributes to the formation of a more uniform protective layer and improves corrosion resistance.
- **Number of repetitions:** Usually 2-3 repetitions provide maximum durability and microhardness, while more passes can cause cracking.

Research shows that these parameters directly affect the contrast, microhardness (increase up to 30%), wear resistance and corrosion resistance of the surface layer.

1.5 Color marking on metals

Scientific research in the field of color laser marking focuses primarily on **titanium and stainless steel** (over 60% of publications), due to their ability to form stable oxide layers with high durability and a wide color gamut. At the same time, materials such as aluminum and copper alloys remain less studied, and for **carbon steel C75** systematic data in the literature is practically absent. This scientific deficit justifies the need for detailed investigation of technological parameters in marking less studied, but mass-used in industry materials.

1.6 Types of lasers for color marking

The choice of laser source is critical for the coloring mechanism. The main types include nanosecond fiber lasers (most common in industry), MOPA systems, picosecond and femtosecond lasers (for precise nanostructures with minimal thermal influence).

The summarized comparative characteristics of these sources are presented in Table 8 below:

Table 8. Summary information on the four lasers used for color marking.

Criterion	Nanosecond lasers (ns)	MOPA lasers	Picosecond lasers (ps)	Femtosecond lasers (fs)
Pulse duration	10–300 ns	10 ns – 1 μs (adjustable)	1–100 ps	10–500 fs
Suitable materials	Stainless steel, aluminum, some plastics	Stainless steel, titanium, some polymers	Metals (LIPSS effect), ceramics, transparent materials	All metals, steel, titanium with nanostructures, glass, polymers
Colors	★★☆ (limited range): black, golden, gray	★★★☆ (wider range): blue, green, red	★★★★ (LIPSS effects)	★★★★★ wide range
Marking speed	★★★★☆ (High)	★★★☆☆ (Medium)	★★☆☆☆ (Low)	★☆☆☆☆ (Very low)
Integration in production lines	★★★★☆ (Easy)	★★★☆☆ (Optimization)	★★☆☆☆ (Complex)	★☆☆☆☆ (Limited)
Thermal impact	★★★☆☆ (High)	★★☆☆☆ (Moderate)	★☆☆☆☆ (Minimal)	☆☆☆☆☆ (Absent)
Control complexity	★☆☆☆☆ (Easy)	★★☆☆☆ (Medieum)	★★★☆☆ (Complex)	★★★★☆ (Very complex)
Price	★☆☆☆☆ (Low)	★★☆☆☆ (Medium)	★★★☆☆ (High)	★★★★☆ (Very high)
Energy efficiency	★★★☆☆ (Medium)	★★★★☆ (Goof)	★★☆☆☆ (Low)	★☆☆☆☆ (Very low)
Manufacturers and types	Fiber lasers (IPG, SPI), Nd:YAG	MOPA-fiber (IPG, Raycus)	Solid-state (Trumpf, Coherent)	Titanium-sapphire, Yb-doped fiber

Based on the analysis performed in this part of the work, the following conclusions can be made:

1. **Significant scientific deficit for carbon steels:** While titanium and stainless steel are the subject of large-scale research, carbon steel (especially type C75) is significantly less studied with respect to laser color marking, and conventional methods such as anodizing are completely inapplicable for this material.
2. **Advantages of laser oxidation:** The laser oxidation method is defined as the most promising approach for color marking of carbon steels, as it allows the formation of stable and durable oxide layers with high precision and environmental compatibility.
3. **Choice of optimal technology:** Industrial application is most effectively realized through nanosecond fiber laser systems, due to their reliability and

easy integration, while innovative methods such as LIPSS and DLIP remain limited due to their high price and complex configuration.

4. **Need for systematic research:** A lack of quantitative dependencies between technological parameters (power, speed, frequency) and operational characteristics of marking (contrast, durability and color) on carbon steel has been established, which justifies the relevance of the dissertation.

CHAPTER 2. FACTORS AFFECTING THE CONTRAST OF MARKING

The aim of this part of the work is the formulation of theoretical foundations for analysis and optimization of the laser color marking process. Analytical models are introduced that will serve as a tool for planning experimental studies.

2.1 Factors related to the laser source. These factors determine the concentration of energy in the interaction zone. The main parameter is the average power P, which in pulsed mode is determined by the pulse energy Ep and the frequency ν:

$$P = E_p.\nu \qquad (2.1)$$

For the formation of contrast marking, the power density qs is crucial,

$$q_S = \frac{4P}{\pi d^2} \qquad (2.5)$$

characterizing the concentration of energy on the working spot with diameter d.

The degree of energy accumulation during movement of the laser beam in a straight line is determined by the pulse overlap coefficient

$$k_{\mathrm{Lx}} = (1 - \frac{v}{\nu . d}).100\% \qquad (2.8)$$

where v is the marking speed. Optical characteristics, such as wavelength λ and absorption coefficient α, additionally determine the depth of penetration and heating intensity.

2.2 Factors related to the technological process

Technological parameters control the interaction time and spatial distribution of energy. The marking speed v is inversely related to the interaction time tvz of the laser beam with the material:

$$t_{вз} = \frac{d}{v} \qquad (2.11)$$

In raster marking, quality is determined by the step between lines Δx, which sets the overlap coefficient of raster lines kLy:

$$k_{Ly} = (1 - \frac{\Delta x}{d}).100\% \qquad (2.14)$$

Additional factors such as defocusing and number of repetitions N allow fine tuning of the delivered energy to achieve deeper or more intense oxidation.

2.3 Factors of complex nature These quantities combine the influence of the main laser and technological parameters for a more complete description of the process. Linear energy density (LED) reflects the absorbed energy per unit length in the marking zone. Linear pulse density (LPD) corresponds to the number of pulses falling per unit length along the trajectory. To estimate the energy per unit area, the effective energy is used

$$E_{eff} = ЛПЕ\,.\,ЛПИ = \frac{P.\nu}{v^2} \qquad (2.18)$$

2.4 Factors related to material properties.

Optical and thermophysical characteristics, such as absorption and thermal conductivity coefficients, determine the heat balance and phase changes necessary for oxide layer formation.

Conclusions and findings

1. Analysis shows that laser and technological parameters are functionally interrelated and must be evaluated as a set determining the effective energy load.

2. The introduced generalized energy quantities of complex nature allow reducing the number of independent factors and serve as a basis for precise optimization of the marking process.

3. The identified key parameters (power, speed, frequency and step) form the analytical framework for conducting experimental studies on carbon steel C75

CHAPTER 3. NUMERICAL ANALYSIS AND DETERMINATION OF WORKING RANGES OF TECHNOLOGICAL PARAMETERS FOR LASER COLOR MARKING

3.1 Determination of working ranges of power density This chapter is devoted to the numerical determination of the working ranges of the main technological parameters necessary for planning experimental studies on carbon steel

C75. Through theoretical mathematical calculations, the boundaries between oxidation, melting and evaporation regimes are determined, which are critical for the quality and energy efficiency of the process. The obtained results serve for scientifically grounded choice of experimental regimes and interpretation of final results.

Minimum diameter of the laser working spot The size of the focal spot d0 is a critical parameter, as it directly affects the power density. Calculations are performed according to the following formula:

$$d_0 = M^2 \frac{4\lambda f}{\pi D} \qquad (3.1)$$

The quality of radiation, focal length, as well as wavelength are taken into account.

Maximum power density q_{smax} is determined by the maximum average power *Pmax* and spot diameter.

$$q_{smax} = \frac{4P_{max}}{\pi d_0^{\,2}} \qquad (3.2)$$

For the system used with power 30 W and focal length 290 mm, the following values were obtained:

Table 10. Parameters of the marking system

Laser	P_{max}	f	d_0	q_{smax}
Fibre	30 W	290 mm	43,24 µm	$20{,}4 \times 10^9$,W/m^2

Critical power density for melting (q_{scm}**) and evaporation (**q_{scv}**)** To determine the threshold conditions for C75 steel, the following expressions are used:

Melting $$q_{scm} = \frac{(1+s)k(T_m - T_0)}{2A}\sqrt{\frac{\pi.v}{a.d}} \qquad (3.3)$$

Evaporation $$q_{scv} = \frac{(1+s")k(T_v - T_0)}{2A}\sqrt{\frac{\pi.v}{a.d}} \qquad (3.5)$$

Figure 12 shows the dependence of critical power density on speed.

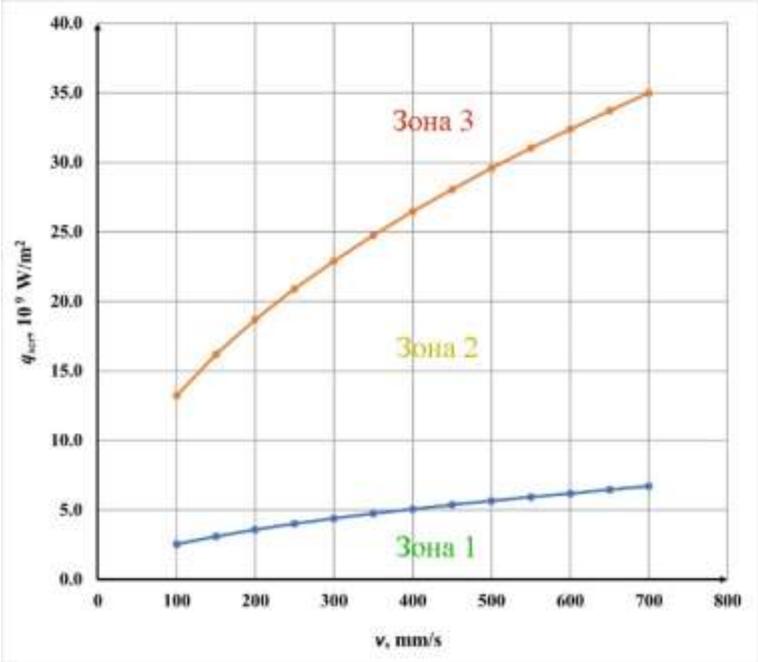


Figure 12. Graphs of the dependence $q_{scr} = q_{scr}$ (v)for marking with fiber laser FP-30: blue – melting; red – evaporation.

Based on the calculations, three working zones are defined:

1. **Oxidation zone (Zone 1):** Located below the melting curve (qs<qscm); here color marking is realized through controlled heating and oxidation.
2. **Melting zone (Zone 2):** Located between the melting and evaporation curves; in it the material passes into liquid phase.
3. **Evaporation zone (Zone 3):** Located above the qscv curve; here engraving and channel creation is carried out through material removal.

Conclusions and findings

1. Determination of critical power densities allows precise differentiation of oxidation, melting and evaporation regimes, which defines technological thresholds.
2. It has been established that with increasing speed from 100 to 700 mm/s, the required power density for transition to melting or evaporation increases non-linearly by about 2.65 times.
3. For high-quality color marking, frequencies in the range of 80–160 kHz and raster step 0.02–0.035 mm are recommended, ensuring maximum homogeneity of the oxide layer at industrial processing speeds

CHAPTER 4. APPARATUS AND METHODOLOGY OF CONDUCTED STUDIES

4.1 Experimental setup and material For the needs of the experiment, two laser systems based on fiber lasers were used - Raycus RF-30 and ROFIN PowerLine

F-20 Varia. The systems are equipped with high-precision galvanometric scanners Galvoscan RS1001 and Rofin BLG-P12, providing marking speeds up to 20,000 mm/s. Process control is performed through specialized software EZcad and Visual Laser Marker, allowing precise adjustment of energy parameters.

The material subject to investigation consists of cold-rolled sheets of high-carbon steel C75 with thickness 1 mm. The surface of the material is characterized by initial roughness Ra=0.112 μm. For the needs of the study, series of samples were prepared, in which the main energy characteristics of laser radiation such as power, frequency and pulse duration were systematically varied. The influence of technological parameters was traced through change of scanning speed and step between raster lines, set precisely through the specialized control software. Through these variations in marking regimes, the aim is to establish optimal conditions for formation of durable oxide layers with different color and contrast on the surface of C75 steel. For conducting comprehensive tests, series of samples were prepared, shown in Table 16

Table 16. Number of investigated samples by type of conducted studies

Type of study	Size	Number
Contrast investigation	80 × 100 × 1 mm	5 pcs.
Roughness investigation	80 × 100 × 1 mm	5 pcs.
Color difference	80 × 100 × 1 mm	10 pcs.
Scratch resistance test	13 × 100 × 1 mm	16 pcs.
Corrosion resistance test	80 × 100 × 1 mm	6 pcs.
Color reproducibility	80 × 100 × 1 mm	8 pcs.
Marking readability	80 × 100 × 1 mm	4 pcs.
Microhardness	10 × 10 × 1 mm	8 pcs.

4.2 Apparatus used

- **Olympus OLS5000:** 3D measuring laser microscope, used for visual surface analysis and precise roughness measurement.
- **Shimadzu DUH-211S:** Dynamic ultra-microhardness tester for determining the hardness of thin oxide layers.
- **CSM REVETEST Scratch Macrotester:** Apparatus for investigating friction coefficient, adhesion and marking
- **Q-FOG CCT1100:** Chamber for accelerated corrosion tests in salt spray and variable humidity.
- **Ocean Optics USB4000:** Spectrophotometer for measuring spectral characteristics and color coordinates in the CIE Lab system.

4.3 Methodologies of conducted studies

Methodology for determining marking contrast Contrast determination is performed through software processing of digital images, according to standard BDS 16383:1986. Color images are converted to grayscale (values 0–255) using Adobe Photoshop, to identify differences in intensity. The values of the marked zone (Nx) relative to the unprocessed material (Nf) are measured. The final contrast is calculated through linear interpolation, with the arithmetic mean value from five measurements taken for higher accuracy.

Methodology for determining surface roughness Measurement is conducted with OLYMPUS laser microscope by optical method according to standard ISO 4287. The methodology uses laser scanning and interference registration, which allows high resolution up to 10 nm vertically. Key parameters such as Ra are analyzed. The obtained data allow assessment of changes in microrelief depending on the laser energy density.

Methodology for determining microhardness Microhardness is investigated by the Vickers method according to ISO 14577-1 through loading with a diamond pyramid with apex angle 136°. A force of 50g is applied to the surface with holding under load for 22 seconds. The size of the obtained trace is measured with a camera, after which the hardness (HV) is calculated analytically. To ensure reliability, ten indentations are made per zone, with acceptable uncertainty below ±3%.

Methodology for testing corrosion resistance Testing is conducted in a neutral salt spray environment (5% NaCl) at temperature 35.0°C according to standard EN ISO 9227. Samples are subjected to exposure for 48 hours, with the pH level of the solution monitored within 6.5–7.0. Corrosion assessment is performed by measuring pitting depth through the double focusing method with a microscope. Additionally, the percentage ratio of corroded area to total marking surface is determined.

Methodology for measuring color difference For investigating color characteristics, standard ISO 11664-6 and the CIE Lab system ($L*,a*,b*$) are used. The spectrophotometer is calibrated with a reference white plate, and measurements are performed with source D65 and geometry 45°/0. The total color difference ΔEab is calculated as Euclidean distance between the coordinates of the marked and unmarked zone. For the criterion of color similarity in industrial conditions, a value of $\Delta Eab \leq 7$ is accepted.

Methodology for measuring scratch resistance Wear resistance and adhesion are determined through "scratch test" according to standard ISO 20502 using a Rockwell C diamond indenter. Progressive loading from 0 to 30 N is applied at speed 10 N/mm, while the friction coefficient and penetration depth are registered. Through an optical microscope (over 200x), the critical force Lc is identified, at which the first cracks or spalling of the oxide layer appear. This method allows comparative analysis of mechanical strength of marking under different laser regimes.

4.4 Conclusions and findings

1. The selected Raycus and Rofin laser systems possess the necessary stability and pulse accuracy to achieve reproducible results on C75 steel.
2. The comprehensive experimental apparatus and application of internationally recognized standards (ISO, BDS, EN) guarantee the scientific reliability and accuracy of measurements.
3. The combination of optical, mechanical and corrosion methods allows comprehensive quantitative assessment of operational characteristics of laser marking.

Chapter 5 EXPERIMENTAL RESULTS

In the present chapter, the results of conducted experimental studies aimed at establishing quantitative dependencies between laser parameters and main operational characteristics of color marking are presented and analyzed in detail

A large number of experimental studies were conducted, with the more important results being:

Contrast investigation *k,%**

Influence of average power P of the laser source

When marking a carbon C75 sample with fiber laser FP-30 with the following parameters: v = 300 mm/s; Δx = 0.03 mm; ν = 40 kHz for power in P Є [12, 30] W

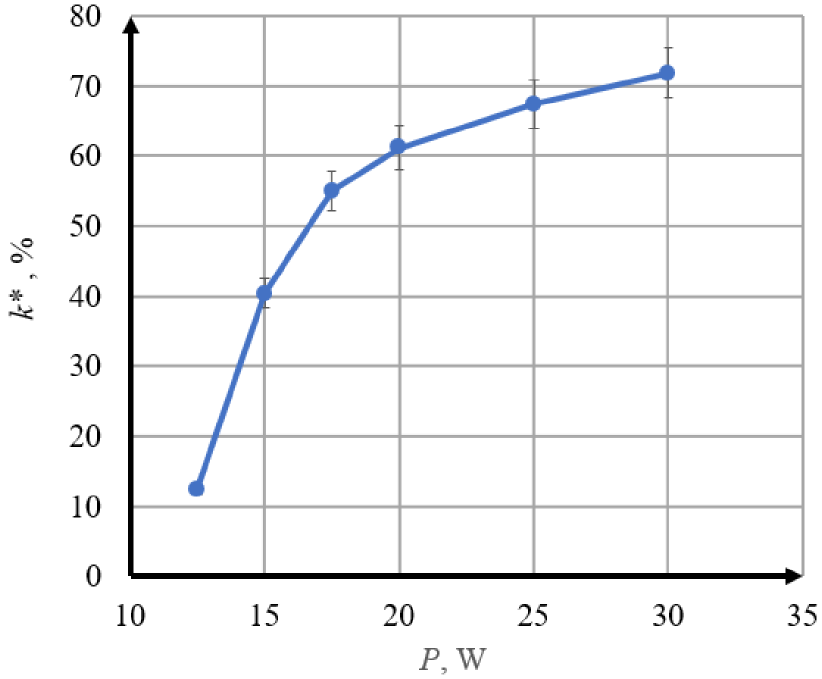


Figure 27. Graph presenting the experimental dependence k=k*(P)*

From the graph, the following conclusions can be made:

For powers in the range P Є [12, 17] W the rate of contrast increase as a function of power $\Delta k^*/\Delta P$ is 8,6 % / W

In this interval, marking is obtained through melting.

For powers in the range P Є [17, 30] W , the rate of contrast increase as a function of power $\Delta k^*/\Delta P$ e 1,36 % / W; With the higher power density in this marking range, marking is obtained through melting and evaporation.

The rate of contrast change in the interval P Є [12,17] W increases 6 times faster than that in the interval P Є [17,30] W. It can be said that the contrast of marking obtained through evaporation increases more slowly.

The optimal interval for surface power density of laser radiation at marking speed v = 300 mm/s is q_S Є [6,37.10^9; 7,64.10^9] W/m^2.

Influence of marking speed v

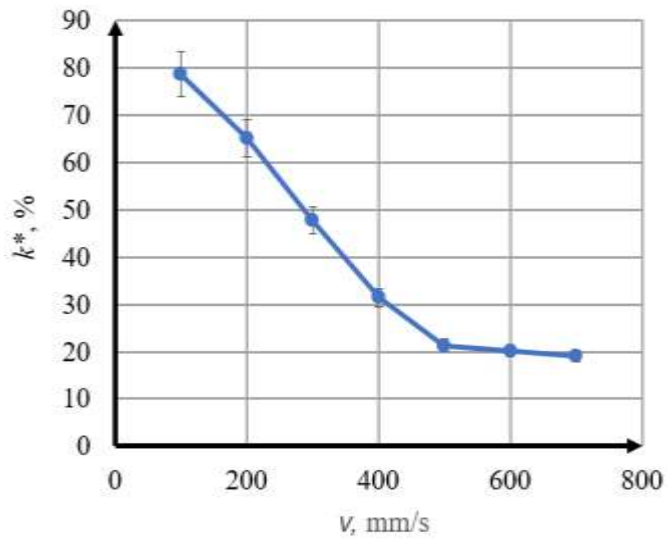


Figure 28. Graph presenting the experimental dependence k= k*(v)*

From the graph, the following conclusions can be made:

With decreasing interaction time, contrast also decreases;

When speed increases in the range v Є [100, 500] mm/s , non-linear contrast decrease is observed, with the rate of decrease as a function of speed $\Delta k^*/\Delta v$ being 0,147 % / mm/s;

For speeds in the range v Є [500, 700] mm/s no change in contrast is observed. An almost linear dependence is observed.

For speeds in the interval v Є [400, 700] mm/s it is not recommended to use, as the marking contrast is close to the minimum value of 15% for marking readability.

Roughness investigation Rq, µm

Roughness investigation in the range P Є [4, 15] W and v *= 400 mm/s and 600 mm/s;* $\nu = 100$ *kHz;* $\Delta x = 0,01$ *mm*

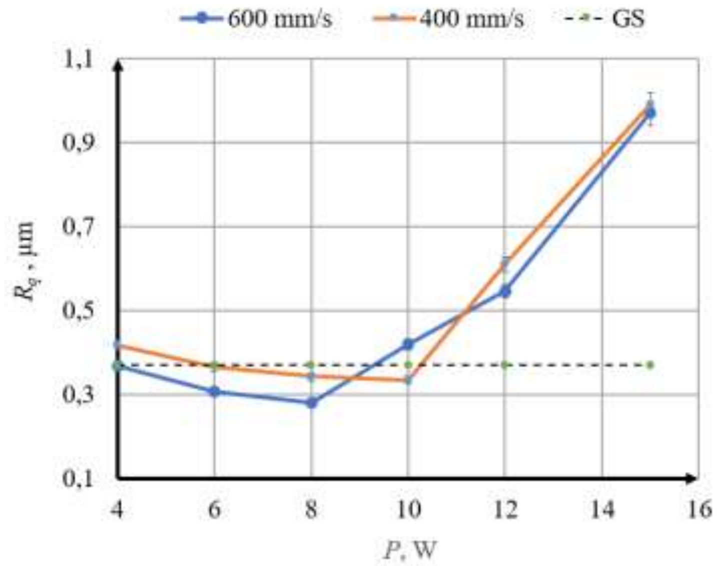


Figure 34. Graph presenting the experimental dependence $R_q = R_q (P)$

From the graph analysis, the following conclusions can be made:

With power increase in the range *P* Є [4, 15] W processing roughness increases non-linearly for both investigated speeds;

For powers in the range *P* Є [4, 8] W the roughness of the marked surface is below that of the as-delivered material.

For powers in the range *P* Є [10, 15] W he rate of roughness increase as a function of power $\Delta R_q / \Delta P$ e 0.131 µm / W. After 10W, a sharp increase in roughness is observed.

At 600 mm/s and 8 W, the lowest roughness of 0.281 µm is achieved, after which roughness begins to increase significantly with power increase, reaching 0.971 µm at 15 W.

Influence of pulse duration τ in the range *τ* Є [4, 200] ns

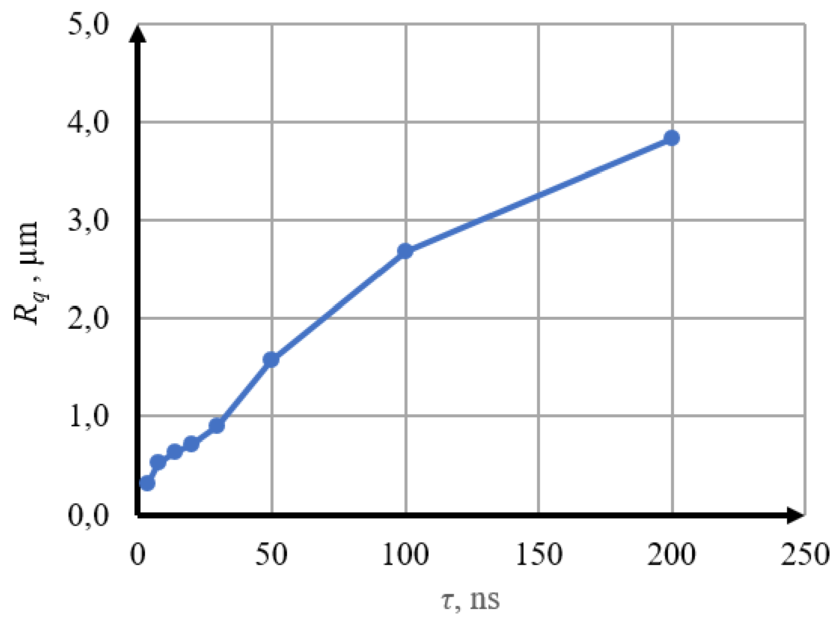


Figure 38. Graph presenting the experimental dependence $R_q=R_q(\tau)$

From the graph analysis, the following conclusions can be made:

In the interval τ Є [20, 200] ns, roughness increase becomes more pronounced, reaching a value of R_q = 3,836 μm at 200 ns.

In the interval τ Є [4, 20]ns the rate of roughness increase as a function of pulse duration $\Delta R_q/\Delta\tau$ is 0,0254 μm/ns;

Roughness R_q increases 1,47 times faster in the interval τ Є [4, 20] ns compared to the second interval τ Є [20, 200] ns.

The conducted studies show that longer pulses lead to rougher surface processing, which can be explained by the larger amount of energy

Microhardness investigation $HV_{0,05}$

Influence of average power P of the laser source when marking a carbon C75 sample with fiber laser FP-30 with the following parameters: *v = 450 mm/s; Δx = 0,01 mm; ν = 100 kHz* for power in *P Є [6, 10] W*

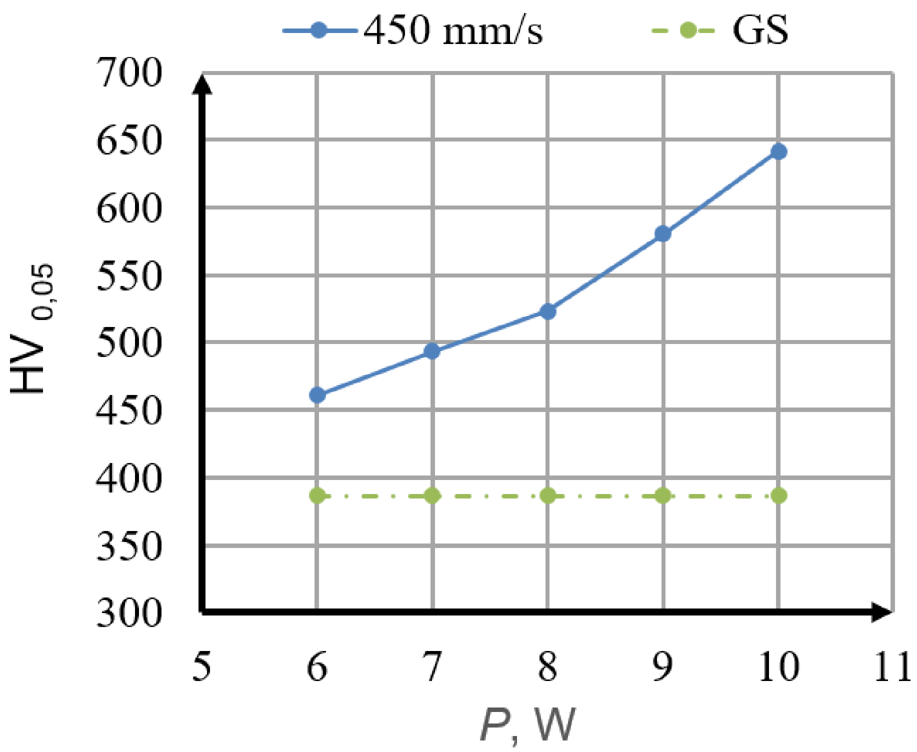


Figure 41. Graph presenting the experimental dependence $HV_{0,05} = HV_{0,05}(P)$.

From the graph, the following conclusions can be made:

The increase in microhardness of the marked surface relative to the unprocessed surface (GS) is:

- At power *P* = 6 W **there is an** 18,49% increase
- At power *P* = 10 W **there is a** 64,91% increase

Microhardness increases linearly with power change in the range *P* Є [6, 10] W. In the investigated interval, the rate of microhardness increase as a function of power $\Delta HV_{0,05}/\Delta P$ is 45 $HV_{0,05}$/W;

In the interval *P* Є [9, 10] W the rate of microhardness increase as a function of power $\Delta HV_{0,05}/\Delta P$ is 61 $HV_{0,05}$/W. Microhardness in this interval has increased 1.57 times relative to the unprocessed (base) material;

This study shows that increasing laser power leads to significant improvement in C75 steel microhardness, with this increase being more pronounced at higher powers. Loading and penetration curves confirm microhardness increase with power increase.

Color difference investigation

Influence of marking speed v when marking a carbon C75 sample with fiber laser FP-30 with the following parameters: *P = 15 W; Δx = 0,03 mm; ν = 40 kHz* for speed in *v Є [100, 700] mm/s*

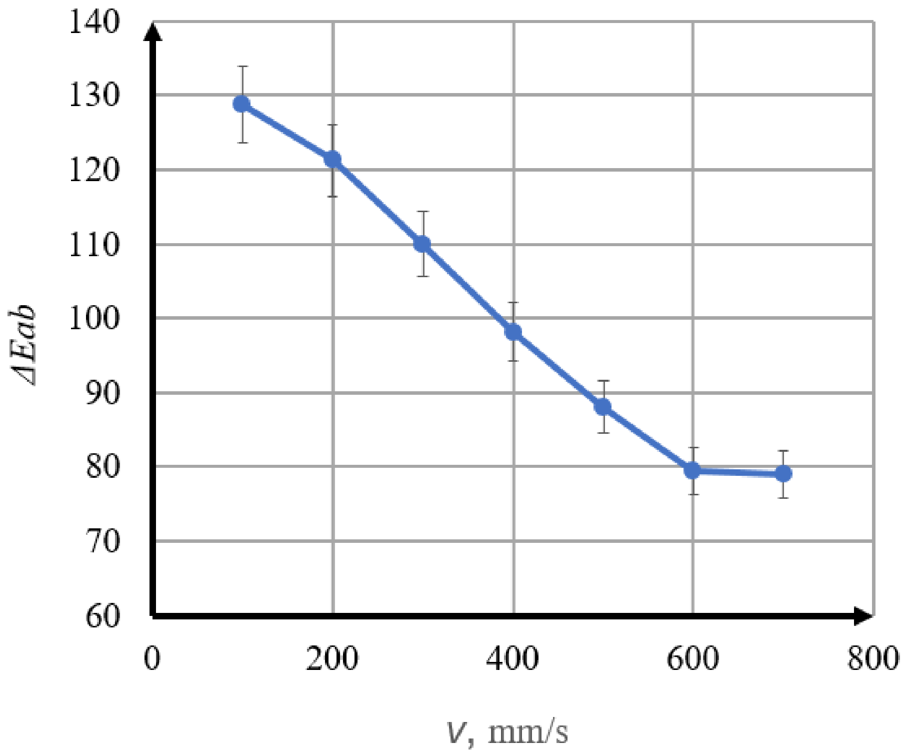


Figure 49. Graph presenting the experimental dependence ΔEab = ΔEab (v)

From the graph analysis, the following conclusions can be made:

At low speeds *v* = 100 mm/s, the laser has longer time to interact with the material, which leads to more intense and deeper structural changes and this leads to greater color difference *ΔEab*.

With speed increase, at values in the interval *v* Є [600, 700] mm/s changes in color difference are not noticeable. Power density per unit area is very small. q_s =

$6{,}7.10^9$ W/m^2 this energy weakly affects the chemical and physical properties of the oxide layer.

When speed increases in the range v € [100, 600] mm/s , non-linear decrease in color difference is observed, with the rate of color difference decrease as a function of speed $\Delta Eab/\Delta v$ being 0,01 ΔEab / mm/s;

For speeds in the interval v € [600, 700] mm/s it is not recommended to use, as the color difference of marking is close to the minimum value distinguishable by electronic devices ΔEab <3.

Influence of effective energy E_{eff}

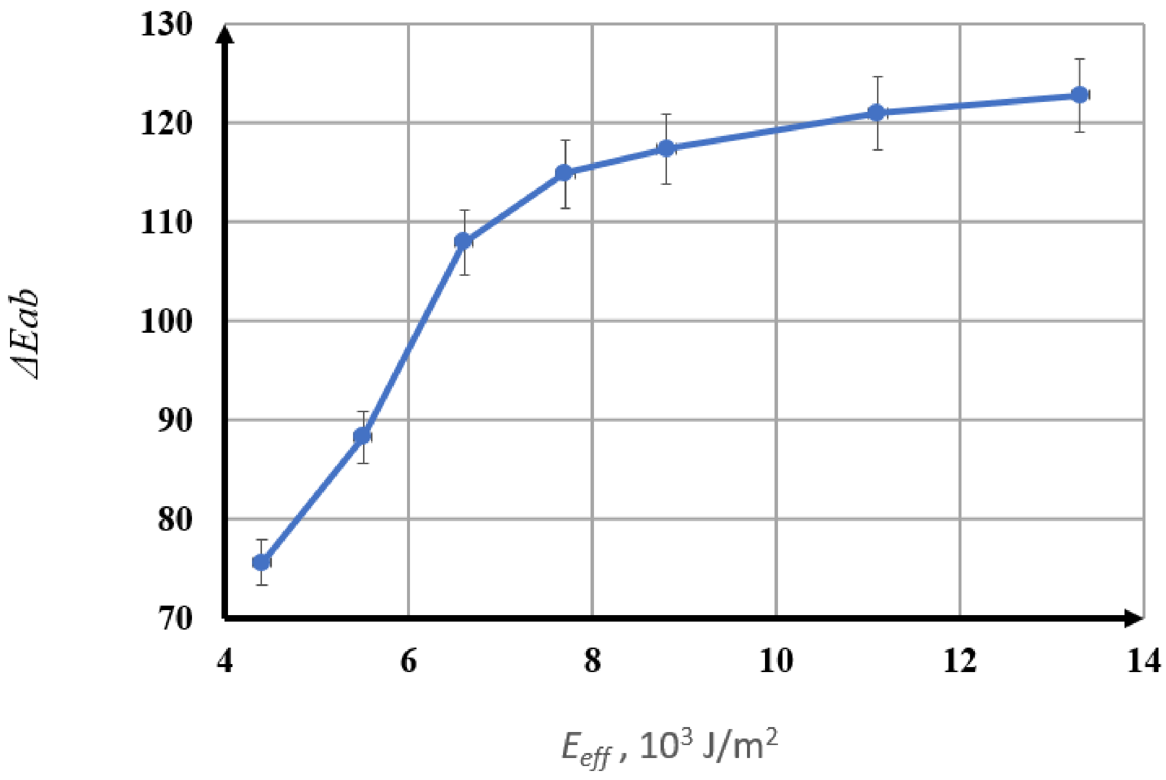


Figure 53. Graph presenting the experimental dependence $\Delta Eab = \Delta Eab\ (E_{eff})$.

From the graph analysis, the following conclusions can be made:

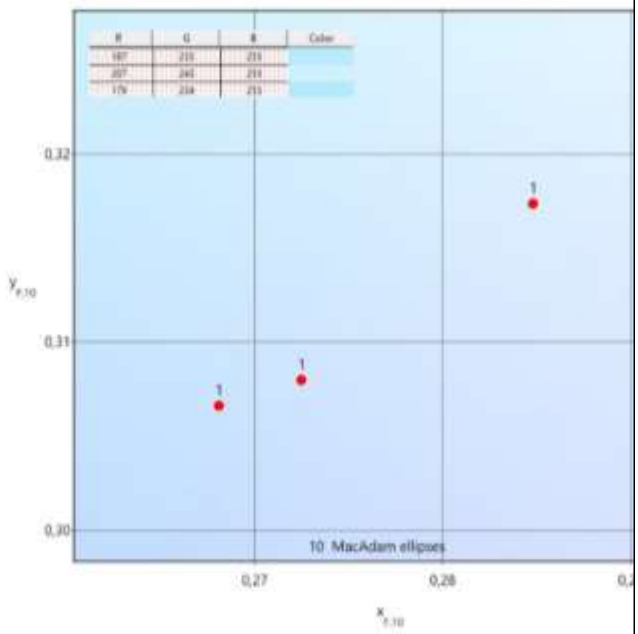
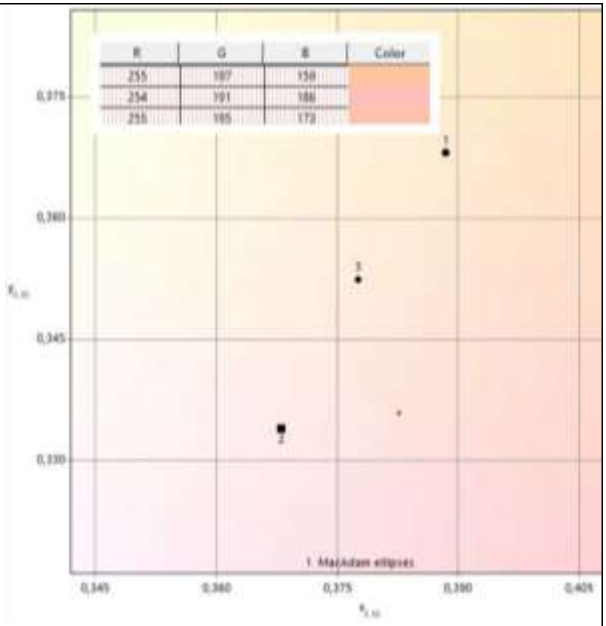
Percentage change of color difference ΔEab is greatest in the interval between E_{eff} € [5,5; 6,6] $.10^3$ J/ m^2, being 23%

For effective energy in the range E_{eff} € [4,4; 7,7] the rate of color difference increase as a function of effective energy $\Delta Eab / \Delta E_{eff}$ is 11,89; In this range there is a high rate of color difference increase.

The optimal value for effective energy is to be around 7.7 J/m², because from the graph it is seen that after this point the change in color difference is minimal with energy increase.

Color reproducibility investigation

For performing the assessment, the CIE 1931 color space is used, with the values of x,y coordinates of each marked sample measured with a spectrometer plotted on CIE 1931, and color change is assessed through Euclidean distance Δd.

<table>
<tr>
<td>
</td>
<td>
</td>
</tr>
<tr>
<td>Figure 56. Color change in zone 1 – 400 mm/s</td>
<td>Figure 59. Color change in zone 4 – 550 mm/s</td>
</tr>
<tr>
<td>Color change is Δd_{400} = 0,0197</td>
<td>Color change is Δd_{550} = 0,0389</td>
</tr>
</table>

Low repeatability with greater color change of marking is recorded at speed v = 550 mm/s. At this speed, color reproduction is most unstable and marked zones have large visual deviation. This speed with these marking parameters should be avoided.

Best repeatability with smallest change in color coordinates is recorded at speed v = 400 mm/s, which is light blue color. This speed shows best reproducibility and color stability, which is suitable for precise marking.

Other optimal values for marking are at the following values:

$P = 15\ W;\ v = 300\ mm/s;\ \Delta x = 0,03;\ \nu = 40\ kHz;\ \underline{\Delta d = 0,0081}$

Scratch resistance investigation

Investigation of the influence of loading force Fn on friction coefficient μ of samples marked with different laser source power *P* Є [10, 30] W

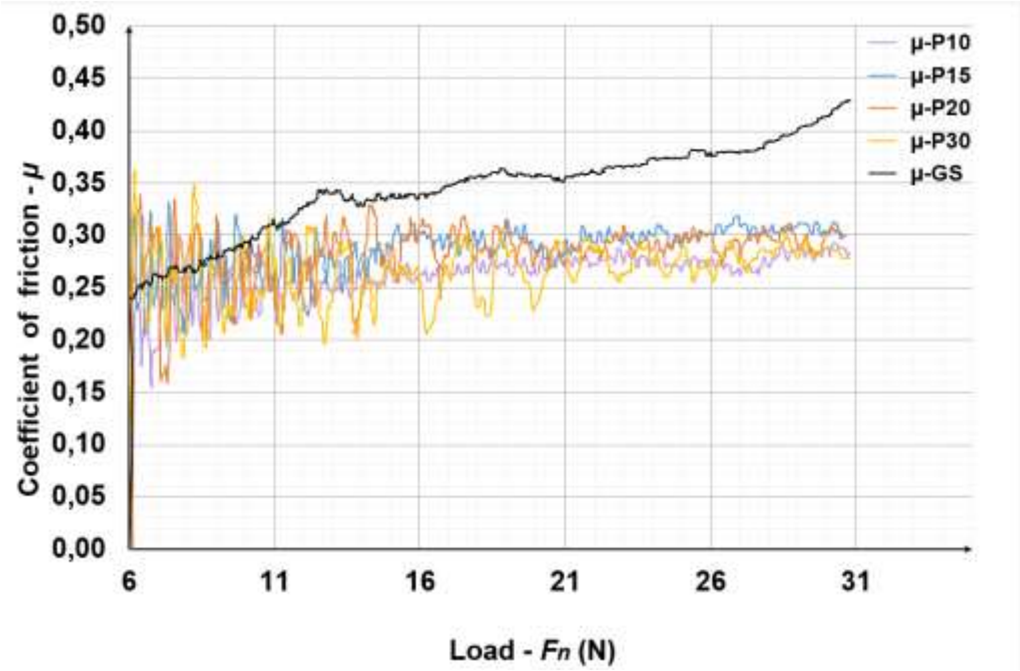


Figure 63. Graph presenting the experimental dependence μ=μ (Fn).

From the graph, the following conclusions can be made:

As a result of melting and evaporation processes occurring during marking with power *P* Є [20, 30] W, large fluctuations in friction coefficient μ are observed at loading *Fn* Є [6, 20] N. On the sample surface, marking with deep channels and craters is obtained, as a result of action with power density q_s Є [12; 15,3] .10^9 W/m^2, which have large roughness, and hence large friction coefficient.

Laser marking with power P Є [10, 15]W has improved the physical properties of the steel, resulting in scratch-resistant marking.

Investigation of the influence of loading force *Fn* on friction coefficient μ of samples at different interaction time of the laser source.

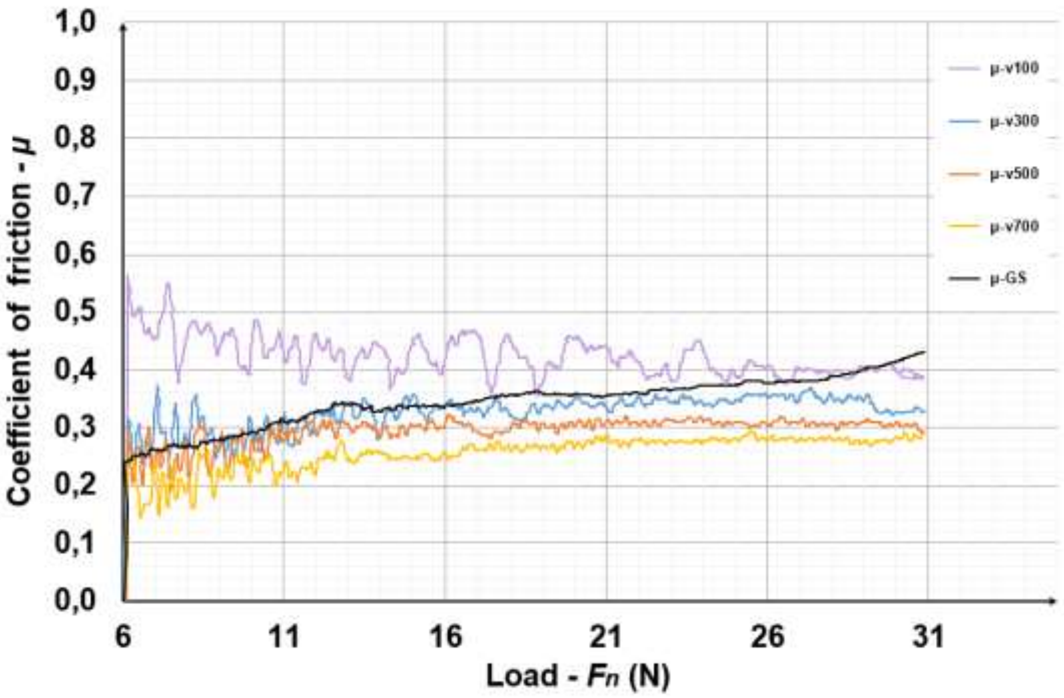


Figure 71. Graph presenting the experimental dependence μ=μ (Fn).

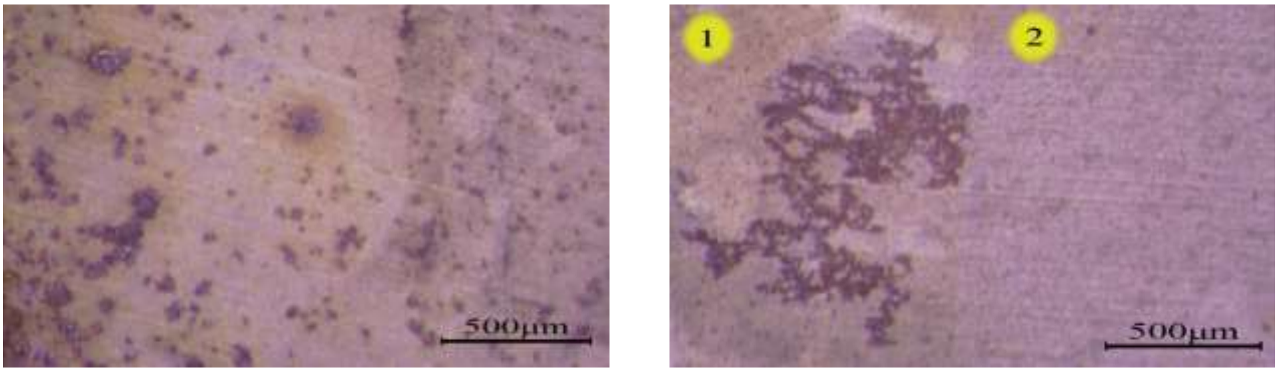
From the graph, the following conclusions can be made:

As a result of prolonged interaction time during marking with speed *v*=100 mm/s, deep channels are formed on the steel surface as a result of melting and evaporation processes. Surface roughness is large and hence there are large fluctuations in friction coefficient μ at loading Fn Є [6, 25] N. For this investigated zone, the friction coefficient has become larger compared to the base unprocessed material GS. At this speed *v*=100 mm/s, the wear resistance of the steel is reduced and this regime should not be used for marking.

For samples marked with speed v Є [300, 700] mm/s, friction coefficient μ has lower value than the as-delivered material and is within Fn Є [0,27; 0,31], which means that surface hardening has occurred as a result of laser marking.

5.7 Corrosion resistance investigation

The as-delivered steel (unmarked) after exposure to salt spray conditions has 100% affected area. Corrosion has local character (pitting), due to the presence of surface defects (from mechanical processing). There is a change in surface color, as well as separate colored corrosion products. Figure 84 shows images of marked and unmarked surfaces after exposure to salt spray conditions.



B D

Figure 84. Images of marked and unmarked surfaces before and after exposure to salt spray conditions.

B – steel in as-delivered condition, on the surface corrosion products in color characteristic of iron are observed. Pitting is observed, which in some places has developed into intergranular corrosion.

D – zone1 – surface in as-delivered condition. In zone 1, the presence of colored corrosion products and multiple pitting, which are colored brown and dark brown, is clearly visible, showing that they are deep. In some areas, pitting corrosion has developed into intergranular. In zone 2 – laser-marked surface, no development of intergranular corrosion is observed. In some places there is some pitting, but they are isolated and shallow. In places, the gray metallic surface is preserved.

The graphical dependence of the change in coating protection ability assessment coefficient R_p as a function of average power P is shown in Figure 88.

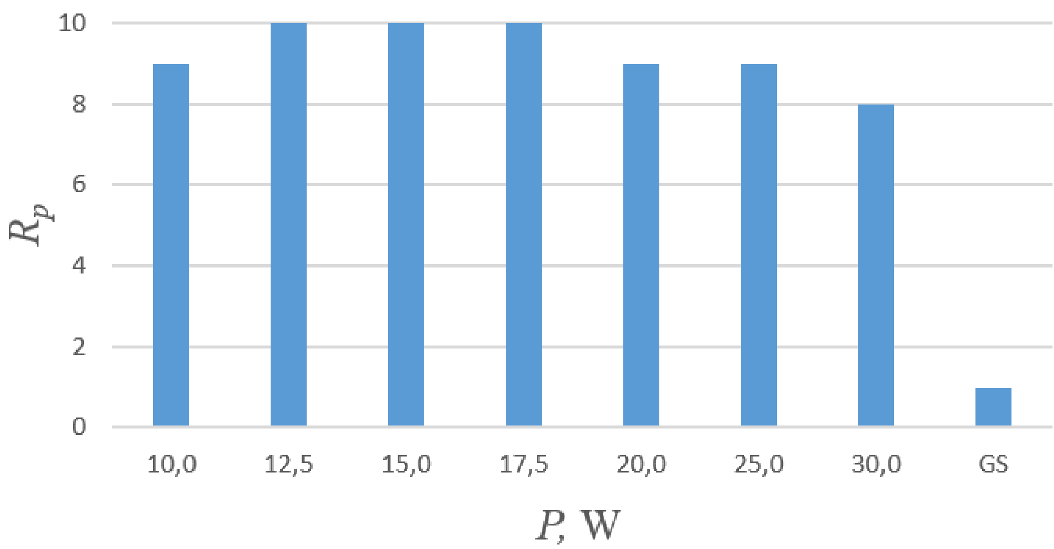


Figure 88. Graph presenting the dependence $R_p = R_p (P)$.

With power increase, appearance corrosion damage increases, with markings with power density above $q_s > 14.10^9$ W/m^2 not recommended because they are not corrosion-resistant.

Markings with power density below $q_s < 5.10^9$ W/m^2 have reduced corrosion resistance. Below this power density value, the energy is insufficient to obtain corrosion-resistant coating.

Optimal power density value is in the range q_s Є [5 , 9].10^9 W/m^2 at which corrosion-resistant marking is obtained.

SUMMARIZED CONCLUSIONS

1. Laser color marking of carbon steel C75 is a highly dependent process on the combination of laser and technological parameters, such as power, speed, frequency, step between raster lines and pulse overlap. Optimization of these parameters is key to achieving high contrast, stable colors and good mechanical and corrosion resistance.
2. Theoretical models for critical power density allow clear differentiation of oxidation, melting and evaporation regimes, with optimal intervals for color marking located in the zone of controlled oxidation and partial melting. Evaporation regimes lead to structural damage and worsened corrosion resistance.
3. Marking contrast is directly related to energy density and interaction time, with highest values achieved at densities $q_s \in [6.37\times10^9;10.2\times10^9]$ W/m². Contrast is in positive correlation with color difference ΔEab under regimes leading to thick and uniform oxide layers.
4. Color difference ΔEab is highly sensitive to power, speed and frequency, with low speeds and medium powers leading to saturated and stable colors. High speeds reduce ΔEab below the threshold of distinguishability, making marking difficult to read.
5. Color reproducibility depends on thermal regime stability, with best results achieved at speeds 400–600 mm/s and frequencies 70–100 kHz. Regimes with unstable heat accumulation (e.g. 550 mm/s) lead to significant color deviations.
6. Marked surface roughness is in non-linear dependence on power, speed and step between raster lines.
   - Low powers and high speeds respectively make the surface smooth.
   - High powers respectively increase roughness and risk of microcracks. Roughness directly affects corrosion resistance and tribological properties.
7. Microhardness of the marked zone increases significantly with power increase and speed decrease, with 64.91% increase relative to as-delivered material achieved at 10 W. Increased microhardness improves wear resistance and reduces friction coefficient.
8. Wear resistance is substantially improved as a result of laser marking, with friction force Ft decreasing 1.5–1.7 times depending on regime. Lowest μ values

are achieved at 10 W and frequencies 20–60 kHz, where surface hardening is observed.

9. Corrosion resistance is highly dependent on surface morphology and pulse overlap.
   - Optimal regimes: K_{Lx}=93%, frequency 70–90 kHz, step Δx=0.035–0.045 mm.
   - Regimes with evaporation and high power density values worsen resistance, with cracks and NaCl deposits on the surface.
10. The dissertation work is devoted to optimizing the process of laser color marking of carbon steel C75 through combination of theoretical models and experimental studies. The set goal is achieved through sequential clarification of physical mechanisms, determination of critical energy regimes and analysis of the influence of main laser and technological parameters on optical, mechanical and corrosion characteristics of marking.
11. In the first chapter, a comprehensive review of existing color marking methods was made and the lack of systematic research on carbon steels was established. The second chapter defines the factors determining marking contrast and quality.
12. In the third chapter, theoretical dependencies for power density, overlap and critical processing regimes were developed. In the fourth chapter, a methodology for experimental studies is presented, and in the fifth chapter, results for contrast, roughness, microhardness, color difference, reproducibility, wear resistance and corrosion resistance are analyzed.
13. The obtained results show that optimal color marking is achieved under balanced regimes of power, speed, frequency and overlap, which ensure stable oxide layers, high readability, good mechanical durability and increased corrosion protection. Interrelationships between morphology, microhardness, wear and corrosion, as well as between color difference, contrast and color reproducibility have been established.
14. The relevance of the research is determined by the increasing requirements for durable, environmentally friendly and high-precision markings. The achieved results contribute to expanding scientific knowledge in the field of laser processing of carbon steels and provide practically applicable regimes for industrial implementation of durable color markings, including for products with high requirements for wear resistance, readability and protection against counterfeiting.
   - Smoother surface has better corrosion resistance.
   - Higher microhardness has lower friction and higher wear resistance.
   - Uniform oxide layers have higher contrast and greater color difference ΔEab.
15. Optimal regimes for color marking of C75 steel are those that ensure balanced thermal impact, without transition to evaporation:
   - power 10–15 W
   - speed 300–600 mm/s
   - frequency 70–100 kHz
   - step 0.02–0.04 mm
   - overlap 85–93%

16. The dissertation fills a significant gap in scientific research, being the first to systematically analyze the influence of laser and technological parameters on color difference, color reproducibility, mechanical properties and corrosion resistance of carbon steel C75.

CONCLUSION

The dissertation work is devoted to optimizing the process of laser color marking of carbon steel C75 through combination of theoretical models and experimental studies. The set goal is achieved through sequential clarification of physical mechanisms, determination of critical energy regimes and analysis of the influence of main laser and technological parameters on optical, mechanical and corrosion characteristics of marking.

In the first chapter, a comprehensive review of existing color marking methods was made and the lack of systematic research on carbon steels was established. The second chapter defines the factors determining marking contrast and quality.

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The obtained results show that optimal color marking is achieved under balanced regimes of power, speed, frequency and overlap, which ensure stable oxide layers, high readability, good mechanical durability and increased corrosion protection. Interrelationships between morphology, microhardness, wear and corrosion, as well as between color difference, contrast and color reproducibility have been established.

The relevance of the research is determined by the increasing requirements for durable, environmentally friendly and high-precision markings. The achieved results contribute to expanding scientific knowledge in the field of laser processing of carbon steels and provide practically applicable regimes for industrial implementation of durable color markings, including for products with high requirements for wear resistance, readability and protection against counterfeiting.

SCIENTIFIC-APPLIED CONTRIBUTIONS

1. An integrated methodology for optimization of the laser color marking process has been developed and tested, which combines analytical models, numerical analysis and experimental dependencies, while simultaneously determining the critical values of power density corresponding to the regimes of oxidation, melting and evaporation under action on C75 steel.

2. A technological window for color laser marking of carbon steel C75 has been defined, based on experimentally validated boundaries of main parameters, with optimal technological regimes identified for formation of stable oxide layers, ensuring high corrosion resistance and long-term color stability.

3. Quantitative dependencies between contrast, color difference and surface morphology of laser-marked zones have been established, with these dependencies experimentally confirmed for carbon steel C75 and supplementing previously missing systematic data in scientific literature.

4. Correlation between microhardness, wear resistance and friction coefficient for laser-marked surfaces has been proven, with mechanisms of color marking instability related to thermal fluctuations, insufficient energy accumulation and incomplete overlap of laser lines revealed and analyzed.

APPLIED CONTRIBUTIONS

1. Practical recommendations for industrial implementation of the color laser marking process on carbon steel C75 have been developed, aligned with requirements for reproducibility, productivity and operational durability.

2. A methodology for assessing color reproducibility has been created, which can be used as a quality control tool in serial and mass production and specific color solutions with potential for anti-counterfeiting applications.

3. The practical applicability of results for purposeful design of markings with predetermined functional properties (contrast, durability, color stability) has been demonstrated, allowing process adaptation to specific industrial requirements.

LIST OF PUBLICATIONS ON THE DISSERTATION

1. Pulov, D., Tsvyatkov, P. Optical Systems for Reducing the Divergence of Laser Beams 14th International Scientific and Practical Conference Environment. Technology. Resources. Rezekne, Latvia, Volume 3, pp 339–343, DOI: 10.17770/etr2023vol3.7217
2. Tsvyatkov, P., Teirumnieks, E., Yankov, E., Pīgožnis, K., Lazov, L. Investigation of the Influence of Technological Parameters of Laser Marking on the Degree of Contrast 14th International Scientific and Practical Conference Environment. Technology. Resources. Rezekne, Latvia, Volume 2, pp. 370–374, DOI: 10.17770/etr2023vol3.7319
3. Tsvyatkov, P., Teirumnieks, E., Yankov, E., Pīgožnis, K., Lazov, L., Investigation of Surface Roughness of Carbon Steel Machined Parts after Nanosecond Fiber Laser Marking 14th International Scientific and Practical Conference Environment. Technology. Resources. Rezekne, Latvia, Volume 2, pp. 358–362, DOI: 10.17770/etr2023vol3.7317
4. Tsvyatkov, P., E. Yankov, L. Lazov, L., E. Teirumnieks, E.Teirumnieks, Color marking of stainless steel and titanium with the laser oxidation method14th International Scientific and Practical Conference Environment.

Technology. Resources. Rezekne, Latvia, Volume 2, pp. 363–369, https://doi.org/10.17770/etr2023vol3.7318
5. L Lazov, P Tsvyatkov , N Angelov. Analysis of the process of laser ablation of marble surfaces. XXI International Conference and School on Quantum Electronics. Resources. Journal of Physics: Conference Series. IOP Publishing, 2021. p. 012014. DOI: 10.1088/1742-6596/1859/1/012014
6. P. Tsvyatkov, Reproducibility of laser color marking on c75 steel obtained by a nanosecond pulsed laser , Mashinostroene i mashinoznanie, 2026

TITLE: OPTIMIZATION OF THE LASER COLOR MARKING PROCESS OF CARBON STEEL PRODUCTS

Author: mag. eng. Petar Stoianov Tsvyatkov

ABSTRACT: *Laser color marking has emerged as a crucial technology for high-precision, eco-friendly industrial identification, yet its application on specific high-carbon steel materials remains insufficiently explored.*

This dissertation addresses the significant scientific deficit regarding C75 carbon steel, which, despite its industrial importance, has been largely overlooked in laser processing literature.

The research underscores the necessity of a scientific investigation to establish quantitative dependencies between technological parameters and the resulting operational characteristics of the markings

Optimization was conducted using an integrated methodology that combines a theoretical-mathematical model for determining critical power densities with comprehensive experimental validation.

The investigation utilized two high-precision fiber laser systems to carry out extensive testing across a wide range of optical and mechanical properties

Systematic evaluations covered critical performance indicators, including contrast, color difference, surface roughness, microhardness, and wear resistance

The study identified optimal technological regimes that significantly enhance the durability of the markings, specifically achieving superior scratch and corrosion resistance compared to untreated surfaces

Ultimately, the results provide a scientifically grounded framework for the industrial implementation of stable, high-quality color markings on carbon steel products.

Keywords: *Laser color marking, C75 carbon steel, Fiber laser, Theoretical-mathematical model, Contrast, Color difference, Wear resistance, Corrosion resistance.*

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