REVIEW

by Assoc. Prof. Tsanko Vladimirov Karadzhov
of the dissertation by Petar Stoyanov Tsvyatkov, M.Eng., on the topic:

Optimization of the Laser Color Marking Process for Carbon Steel Products

for the award of the academic and scientific degree of "Doctor"
Field of Higher Education: 5. Technical Sciences
Professional field: 5.1 Mechanical Engineering
Doctoral Program: "Precision Engineering"

1. Relevance of the Dissertation

This dissertation addresses a current and practically significant problem related to the optimization of the laser color marking process for carbon steel products. In modern mechanical engineering production, there are increasing demands for the durability, legibility, stability, and environmental friendliness of markings used for the identification, traceability, and protection of products. This is particularly important for components and tools operating under conditions of mechanical stress, friction, corrosion, and elevated operational demands.

Traditional marking methods, such as inkjet printing, thermal transfer printing, electrochemical marking, and thermal oxidation, have a number of limitations related to insufficient durability, lower precision, the need for additional materials, and, in some cases, adverse environmental impacts. In this context, color laser marking represents a modern, non-contact, high-precision, and more environmentally friendly technology that enables the formation of durable oxide layers and the production of markings with high information density.

The topic is particularly relevant because C75 carbon steel has been relatively less studied in terms of color laser marking compared to materials such as titanium and stainless steel. This necessitates systematic research into the influence of laser and process parameters on the contrast, color stability, roughness, microhardness, wear resistance, and corrosion resistance of the resulting markings.

2. Understanding the State of the Art

Based on the literature review presented, it can be concluded that the author has a sufficiently in-depth understanding of the state of the research problem. The dissertation examines both conventional methods for color marking of metal products and modern approaches to laser color marking. The basic principles of operation, technological characteristics, capabilities, and limitations of the various methods are presented.

Particular attention is paid to the influence of laser and process parameters on the structure, properties, and quality of the treated surfaces. Materials suitable for color laser marking are analyzed, as well as the laser sources and process systems used. The author also examines the application of laser marking in the creation of one-dimensional and two-dimensional barcodes, arguing for its advantages in terms of durability, readability, precision, and stability compared to other marking methods.

The review shows that the author has identified a significant lack of systematic research focused on the influence of laser and technological parameters on the characteristics of color

marking on carbon steels. This demonstrates a good understanding of the state of the art and a correct identification of the scientific niche in which the dissertation is positioned.

3. Alignment of the Methods for Solving the Problem with the Stated Objective

The main objective of the dissertation is to optimize the process of laser color marking of carbon steel products by developing and applying a theoretical-mathematical model, methodological approaches, and technological regimes that allow for a quantitative investigation of the influence of laser and technological parameters on the characteristics of the marking.

To achieve this objective, the following tasks have been set: identifying and systematizing the factors affecting the contrast and legibility of the laser marking; developing a theoretical-mathematical model; developing a methodology for experimental studies; selecting and configuring a laser source and scanning system; and experimentally investigating the influence of the main parameters on contrast, roughness, microhardness, color difference, color reproducibility, wear resistance, and corrosion resistance.

The methods for determining contrast, roughness, microhardness, color difference, wear resistance, and corrosion resistance have been appropriately selected and allow for a comprehensive assessment of the quality of the resulting markings.

Therefore, I believe that the selected methods fully correspond to the stated objective and the formulated tasks. They provide the necessary scientific and engineering basis for optimizing the process of laser color marking of C75 carbon steel.

4. Analytical Characterization of the Content and Reliability of the Obtained Results

The dissertation is structured in a logically coherent manner and consists of five main chapters covering the theoretical foundations, analytical studies, experimental methodology, and analysis of the results obtained.

The first chapter presents an in-depth literature review and analysis of existing conventional methods for color marking of metal products. Their operating principles, technological characteristics, capabilities, and limitations are presented. A detailed comparative evaluation is made between traditional methods and modern laser color marking technologies, highlighting the main advantages and disadvantages of each, as well as their areas of practical application.

Particular attention is paid to the various methods of laser marking on metallic materials and alloys. Results from a number of scientific publications related to the influence of laser and process parameters on the structure, properties, and quality of the treated surfaces are systematized. Various materials suitable for color laser marking are analyzed, as well as the laser sources and technological systems used.

The author also examines the application of laser marking in the creation of one-dimensional and two-dimensional barcodes, convincingly arguing its advantages in terms of durability, precision, and stability compared to other marking methods.

The second chapter is devoted to the study of the factors determining the quality of color laser marking on C75 carbon steel products. The main parameters affecting the contrast, legibility, and visual perception of the marking are analyzed. These factors are categorized into four main groups: laser source parameters, process parameters, properties of the material being processed, and complex factors arising from the interaction between the other groups. The interrelationships between these factors and their impact on the final outcome of the process are examined.

In Chapter 3, a numerical analysis of the laser color marking process was conducted to determine optimal ranges for varying the main process parameters. The minimum spot diameters

were calculated for optical systems with different focal lengths, as well as the critical values of power density corresponding to the melting and vaporization processes of the material.

Preliminary operating ranges of power density for different processing speeds were determined. The influence of speed, pulse frequency, and working spot diameter on the overlap coefficient of the laser pulses was analyzed. The results obtained provide the necessary engineering basis for planning and conducting experimental studies under optimal conditions.

Chapter 4 presents the material used, the experimental apparatus, and the methodologies developed for conducting the studies. The physical, mechanical, and technological characteristics of the material under study—C75 carbon steel—are described in detail. A schematic representation is provided of the laser processing system used, as well as the measuring equipment, which includes a laser microscope, a microhardness tester, a device for determining the coefficient of friction, a corrosion resistance test chamber, and a spectrometer for analyzing color characteristics.

A particularly valuable contribution is the development of original methods for determining marking contrast, assessing the roughness of laser-treated surfaces, measuring microhardness, investigating corrosion resistance, determining color difference and the degree of color similarity, as well as a method for evaluating the tribological characteristics of the resulting markings. These methods provide a reliable basis for an objective assessment of the quality of the process and the results obtained.

Chapter 5 presents the results of the experimental studies and their in-depth analysis. The influence of the main technological parameters—laser power, marking speed, pulse frequency, and raster step—on the quality indicators of the marking, including contrast, roughness, and microhardness, was investigated.

The experimental results confirm the validity of the scientific approach adopted and demonstrate that the objective and the tasks formulated in the dissertation have been successfully accomplished. The reliability of the results is based on the use of modern equipment, clearly defined methodologies, consistent numerical and experimental analysis, as well as a comparison of the results with the relationships established in the literature. Further confirmation of the significance of the results is their presentation in publications on the topic of the dissertation.

5. Scientific-applied and applied contributions of the dissertation

I believe that the contributions outlined in this dissertation are primarily of a scientific-applied and applied nature. They relate to the development, experimental investigation, and practical validation of technological parameters and methods for laser color marking of C75 carbon steel products.

Scientific-Applied Contributions

The scientific-applied contributions relate to the development and validation of a methodological approach for investigating and optimizing the process of laser color marking of C75 carbon steel. The dissertation identifies the main factors affecting marking quality, such as laser power, marking speed, pulse frequency, raster step, power density, and overlap ratio. Correlations were established between the process parameters and the resulting marking characteristics, including contrast, color difference, roughness, microhardness, wear resistance, and corrosion resistance.

The development of an experimental methodology for the comprehensive evaluation of the quality of laser-marked surfaces can also be included in this group of contributions. This

methodology enables an objective comparison of different processing modes and the selection of optimal parameters for obtaining durable color markings.

Applied Contributions

The applied contributions consist of determining practically applicable process parameters for laser color marking of C75 carbon steel products. The results obtained can be used when implementing laser marking in real production conditions, particularly when marking cutting tools, circular saws, band saw blades, and other carbon steel products.

The proposed methodology for evaluating the reproducibility of colors, contrast, and the durability of markings also has practical value and can be used as a quality control tool in production settings. The developed technological recommendations make it possible to produce durable, legible, and stable markings, including QR codes, without the use of chemical reagents and without the need for additional materials.

I consider these contributions to be substantial and consistent with the content and results presented in the dissertation.

6. Publications Related to the Dissertation

The results of the dissertation are presented in 6 publications related to the research topic. The publications cover topics related to optical systems for laser beams, the influence of process parameters on the contrast of laser marking, surface roughness after nanosecond fiber laser marking, color marking of stainless steel and titanium, laser ablation, as well as the reproducibility of laser color marking on C75 steel.

Five of the publications have been presented at international scientific conferences and published in peer-reviewed and indexed journals, indicating that the results have undergone scientific scrutiny and are accessible to the academic community. In a significant number of the publications, the doctoral candidate is the first author, which demonstrates his active participation and leading contribution to the development of the researched topic.

I consider this publication record to be in accordance with the requirements for the award of the educational and scientific degree of “Doctor.”

7. Comments and Recommendations on the Dissertation

I have no comments or recommendations regarding the dissertation.

8. Conclusion

In conclusion, it can be said that the presented dissertation is a comprehensive scientific and applied study dedicated to a current and practically significant problem. The work contains an in-depth literature review, a theoretical and mathematical analysis, numerical studies, an experimental methodology, and a thorough analysis of the results obtained. The stated objective has been achieved, and the formulated tasks have been fulfilled.

I consider that the dissertation meets the requirements of the Law on the Development of Academic Staff in the Republic of Bulgaria and the Regulations for its Implementation for the award of the educational and scientific degree of “Doctor.”

In light of the foregoing, I give a positive evaluation of the dissertation and propose that the esteemed Scientific Jury award Eng. Petar Stoyanov Tsvyatkov the educational and scientific

degree **of "Doctor"** in professional field **5.1 Mechanical Engineering**, doctoral program **"Precision Instrumentation"**.

03.09.2026

Reviewer: …….
/Assoc. Prof. Tsanko Karadzhov/