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LASER COLOR MARKING ON STAINLESS STEEL: AN OVERVIEW

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Abstract

Laser color marking on stainless steel is an advanced technique for producing durable, high-contrast colors on metal surfaces. This article explores recent advancements in laser technology, focusing on optimizing laser parameters and refining oxidation techniques to enhance color formation and stability. By using diverse laser sources such as nanosecond and femtosecond lasers, the process achieves various surface modifications that support repeatable and stable color markings. Widely applied in industrial, artistic, and jewelry contexts, laser color marking's ability to generate corrosion-resistant colors makes it a preferred choice for both practical and decorative applications.

Keywords: laser color marking, laser marking parameters, laser oxidation, stainless steel.

INTRODUCTION

Since Theodore Maiman introduced the first laser in 1960, lasers have greatly evolved. They are now extensively used in many fields, including industry, science, telecommunications, medicine, and the military. In industry, the main applications of lasers include cutting, welding, drilling, hardening, and laser marking. Among these, laser marking is particularly significant. An important application of laser marking is for marking goods to ensure traceability and prevent counterfeiting. Laser marking can be performed on a wide range of materials, and lasers are extensively used for metal marking, especially for creating color markings on stainless steel. Laser coloring has found applications in various industries, including consumer electronics, decorative art, and medical devices [1].

Laser marking can be achieved through various physical processes involving the interaction of the laser beam with the substrate, as shown in figure 1. In laser marking systems, different types of lasers and optical delivery systems are used to transmit, focus, and direct the beams for marking metals, ceramics, glass, plastic, leather, wood, and other materials. Laser marking typically involves applying alphanumeric and 2D data matrix codes to the surface of the product, which contain information such as the date of manufacture, serial number, and more. [2]

Fig. 1. *Physical processes in laser marking on metals [2]*

Laser color marking on stainless steel has become a preferred method for producing

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durable, high-contrast markings that withstand mechanical, chemical, and environmental conditions. The ability to create stable colorations via laser-induced oxidation on stainless steel surfaces provides an eco-friendly alternative to traditional coloring techniques. This article explores the mechanisms, challenges, and applications of this process, referencing key studies in the field.

Numerous research studies have been conducted worldwide on laser color marking on metal, with many authors contributing their knowledge and experience to the field. The first PhD thesis in Latvia on laser color marking on stainless steel was written by Dr. Pavel Narica under the guidance of Professor Lyubomir Lazov in 2017.

EXPOSITION

1. Mechanisms of Color Formation in Laser Marking

Laser color marking primarily involves the controlled oxidation of the stainless steel surface, where laser-induced heat creates oxide layers of varying thickness, refracting light to produce distinct colors. Unlike engraving or etching, laser color marking does not remove material but rather alters the surface's physical and chemical properties, creating vibrant, lasting colors without the need for additional chemicals or coatings. When stainless steel is exposed to a focused laser beam, thermal and photonic energy create a localized oxide layer, which refracts light and produces a visible color [3]. Research by Swayne et al. [4] and Linggamm et al. [5] shows that the thickness and uniformity of these oxide layers are closely controlled by laser parameters such as wavelength, fluence (energy density), and scanning speed. Studies also indicate that higher fluence accelerates oxidation, enhancing color intensity and stability.

Figure 2 shows a sample of laser color markings on stainless steel 316L.

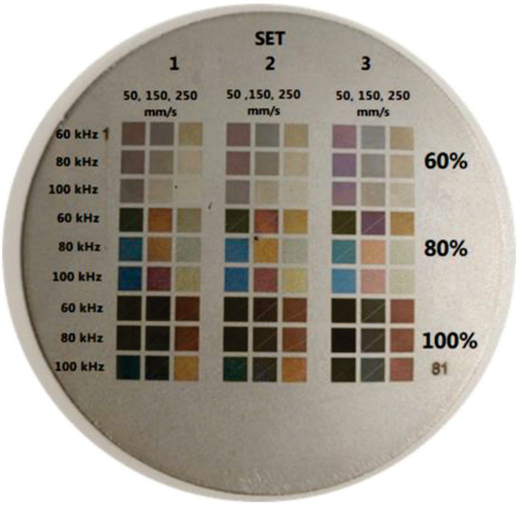


Fig. 2. *Photograph of 81 laser-processed areas of 5 by 5 mm produced on a stainless steel 316L disk [4]*

Figure 3 below illustrates how fluence and wavelength adjustments impact color depth and contrast, showing a positive correlation between fluence and marking quality.

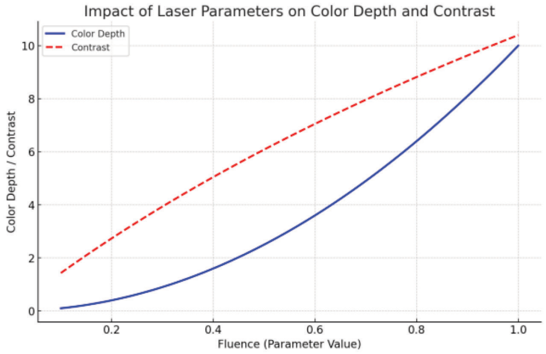


Fig. 3. *Caption impact of laser parameters on color depth and contrast*

In laser color marking, color depth refers to the perceived richness and saturation of a color produced on a metal surface, particularly stainless steel. This characteristic is influenced by the thickness and composition of the oxide layer formed during the laser marking process.

The laser's fluence (energy density), wavelength, pulse duration, and environmental factors control how deeply the laser modifies the metal surface, which in turn affects the oxide layer's thickness. Thicker oxide layers typically result in darker and more intense colors due to enhanced light absorption and interference effects, as observed in studies by Antonczak et al. [6] and Veiko et al. [7]. Conversely, thinner oxide layers reflect lighter and more subtle hues. Schkutow and Frick demonstrated that varying fluence—energy per unit area—affects the oxide thickness, which directly influences color depth and saturation [8]. The fluence threshold is a critical factor for stable color reproduction. High fluence not only enhances color depth but also allows for color consistency across large surface areas. Lower fluence results in lighter hues, while higher fluence creates deeper colors due to a thicker oxide layer.

In practical terms, achieving optimal color depth is essential for creating high-contrast, durable markings that are visually striking and resistant to wear. This makes color depth a key factor in applications where clarity and longevity of color markings are essential, such as in industrial labels and decorative products.

2. Effects of Laser Types on Color Marking

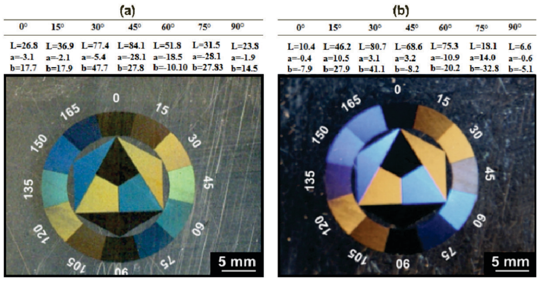
The choice of laser type significantly impacts the quality and color of markings. Femtosecond lasers, for instance, allow for high-precision, high-contrast markings due to minimal thermal diffusion. As highlighted by Butkus et al. [9] and Ma et al. [10], femtosecond lasers are ideal for intricate applications such as jewelry marking. Nanosecond lasers offer a balance of power and control, producing moderately detailed and stable color markings [11, 12].

Table 1 below summarizes the effects of various laser types on marking quality, showing the relative advantages of femtosecond, nanosecond, and continuous-wave (CW) lasers. A sample of nanosecond laser color marking on stainless steel AISI 304 is shown in figure 4.

Table 1. *Effects of various laser types (femtosecond, nanosecond, and CW) on marking quality*

Laser Type	Contrast	Precision	Applications	Sources
Femtosecond	High	High	Jewelry, intricate designs	[9], [10].
Nanosecond	Moderate	Moderate	Industrial, hybrid marking	[11], [12].
Continuous Wave (CW)	Low	Low	Basic marking	[5].

Nd:YAG lasers and fiber lasers are commonly used for laser color marking, each offering distinct benefits. Nd:YAG lasers, as discussed by Dywel et al. [14], are effective in marking stainless steel, providing strong, well-defined colors and stable oxide layers due to precise wavelength control. These lasers are particularly beneficial for materials such as AISI 304 and AISI 316 stainless steel, where uniform color depth is required.



(a)

0°	15°	30°	45°	60°	75°	90°
L=26.8 a=-3.1 b=17.7	L=36.9 a=-2.1 b=17.9	L=77.4 a=-5.4 b=47.7	L=84.1 a=-28.1 b=27.8	L=51.8 a=-18.5 b=-10.10	L=31.5 a=-28.1 b=27.83	L=23.8 a=-1.9 b=14.5

(b)

0°	15°	30°	45°	60°	75°	90°
L=10.4 a=-0.4 b=-7.9	L=46.2 a=10.5 b=27.9	L=80.7 a=3.1 b=41.1	L=68.6 a=3.2 b=-8.2	L=75.3 a=-10.9 b=-20.2	L=18.1 a=14.0 b=-32.8	L=6.6 a=-0.6 b=-5.1

Fig. 4. *Scanned image of authentification templates for scanning exposure (a) and single point exposure (b). Each section corresponds to various LIPSS orientation angles (from 0° to 180°), chromaticity coordinates are given for every section. Recording parameters: $I = 1.7 \cdot 10^7$ W/cm^2; scanning exposure: $M_x = 1.8$ µm and $M_y = 9$ µm; single point exposure: $N = 40$ pulses, recording resolution 800 dpi [13]*

In recent studies, multifunctional laser systems have emerged as tools for artistic color marking applications. Zhao et al. [15] explored multifunctional laser systems that act like "paintbrushes," achieving complex color patterns and gradients on metal surfaces, expanding the potential applications of laser color marking in art and consumer products.

3. Advanced Applications in Laser Marking Techniques

Recent advancements in laser color marking have enabled specialized applications requiring high color fidelity and durability. Veiko et al. [7] demonstrated how spectrophotometric measurements can be applied to generate a full color palette on stainless steel, an essential technique for luxury goods and jewelry that require precise color consistency. Similarly, Odintsova et al. [16] explored plasmonic laser color printing for creating high-resolution patterns, showing the potential of laser color marking for decorative art and jewelry applications.

Laser color marking not only enhances aesthetics but also contributes to the mechanical and structural properties of stainless steel. According to Dywel et al. [14], the laser marking process can improve the material’s surface hardness and resistance to wear, making it suitable for functional applications in addition to decorative uses. Laser-induced color marking can also offer microstructural benefits, such as improved resistance to abrasion, which is essential for applications requiring durability, such as in medical and aerospace industries.

One of the most significant advantages of laser color marking is its environmental sustainability. As Sobotova and Badida [1] point out, laser marking does not require chemicals or secondary treatments, reducing waste and pollution. This makes it an attractive option for industries focused on eco-friendly production methods. The laser marking process is digitally controlled, enabling precise, repeatable marking patterns without the need for consumables, thereby minimizing environmental impact.

Multifunctional laser systems enable creative applications like complex visual art on metal surfaces, as demonstrated by Zhao et al. [15], who applied laser color marking techniques to produce unique aesthetic patterns. This artistic use of laser marking is especially popular in jewelry, fashion, and home decor, where vibrant, corrosion-resistant colors are desirable.

4. Stability and Environmental Resistance of Color Marks

Several studies have focused on the durability and stability of laser color markings on stainless steel. Roozbahani et al. [17] investigate the resistance of laser-marked colors against mechanical and environmental stressors. They report that the color markings maintain high stability under abrasion and exposure to various environmental conditions, including chemicals, making them suitable for demanding industrial applications.

Ma et al. [10] evaluate the long-term stability of color markings made with nanosecond pulsed lasers, noting that changes in parameters such as pulse frequency and energy can enhance the durability of the oxide layer, which is essential for maintaining color integrity over time.

5. Optimization of Color Marking Parameters

Optimizing laser parameters is key to achieving consistent, vibrant colors with enhanced durability. Research by Hristov et al. [18] and Lazov et al. [2] identified pulse repetition rate, fluence, and scanning speed as critical factors influencing marking quality. Adjusting these settings helps fine-tune color brightness and saturation, enabling improved efficiency and repeatability. Antonczak et al. [6] observed that controlling laser intensity can yield precise hues, contributing to a more reliable and reproducible marking process. Table 2 highlights key laser parameters and their effects on color marking results.

Table 2. *Key laser parameters and their effects on color marking results*

Parameter	Effect on Color Marking	Key Studies
Fluence	Higher fluence produces intense colors	[6], [7].
Wavelength	UV lasers provide finer control over color tones	[5], [19].
Pulse Duration	Short pulses result in high-contrast, detailed marks	[9], [10].
Scanning Speed	Higher speeds produce lighter colors	[17], [18].
Environmental Conditions	Ambient gases affect oxidation and color stability	[16], [2].

The bar chart below (figure 5.) illustrates the relationship between different laser types (Femtosecond, Nanosecond, and CW) and their marking quality, measured in terms of contrast and precision.

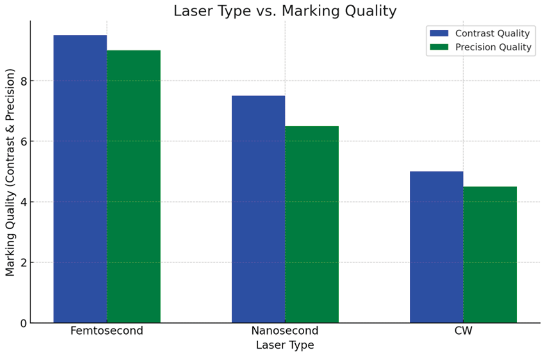


Fig. 5. *Laser type vs. marking quality*

Femtosecond lasers achieve the highest contrast and precision, due to their minimal thermal diffusion and ability to create finely detailed markings, as highlighted by Butkus et al. [9] and Ma et al. [10]. Nanosecond lasers provide a moderate level of contrast and precision, suitable for many applications but with slightly less refinement than femtosecond lasers. CW lasers yield the lowest marking quality, with reduced contrast and precision, as their continuous energy output causes more thermal diffusion and less detail.

Figure 6 visualizes the influence of scanning speed on color intensity. Higher speeds reduce color intensity due to limited laser-material interaction time, consistent with findings by Roozbahani et al. [17] and Hristov et al. [18].

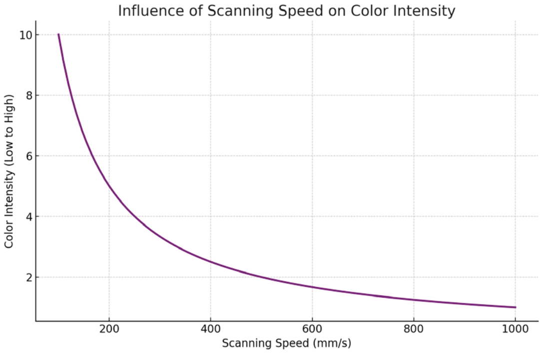


Fig. 6. *Influence of scanning speed on color intensity*

At scan speeds above 500 mm/s, color intensity decreases due to reduced laser–material interaction time, resulting in lighter traces, a finding consistent with studies by Roozbahani et al. [17] and Hristov et al. [18]. The stability and repeatability of laser color markings are crucial. Long-term stability is essential for practical applications of laser color marking. Factors such as chemical stability and environmental resistance are critical, as color markings must withstand wear, UV exposure and mechanical stress. Techniques that enhance stability, such as precise control over the thickness of the oxide layer, have been explored to achieve repeatable and durable markings [17, 20]. Laser color marking on stainless steel relies on nuanced control of laser parameters to create a variety of colors through selective oxidation. This process enables the production of durable, high-contrast markings for industrial, decorative and functional purposes.

CONCLUSION

Laser color marking on stainless steel offers a versatile, sustainable solution for applications requiring durable, high-contrast markings. Through advancements in laser technologies and an enhanced understanding of oxidation processes, the field has developed optimized techniques for consistent, vibrant, and long-lasting color applications. The research highlights ongoing efforts to refine laser parameters, enhancing repeatability and stability across various applications. From artistic applications to industrial markings, laser color marking offers an efficient, customizable solution that reduces environmental impact and enhances material properties, highlighting its potential as a transformative technology. Future studies will continue to explore innovative configurations and laser types, broadening the scope of laser color marking as a key technology in materials processing.

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