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Investigation of the effect of laser power, speed and frequency on surface roughness and color marking on AISI 304

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Abstract. **Austenitic steels are widely used in machine and tool making, and many of the products produced are marked with ink or impact marking systems. This study aims to investigate contrast color marking methods using advanced, environmentally friendly fiber laser systems.**

We developed marking matrices with 14 columns and 6 rows, each square measuring 5x5 mm. We investigated the effect of scanning speed, laser power and frequency on color marking and surface roughness. Our results showed that increasing the scanning speed leads to a decrease roughness, resulting in different colored markings. As the average power increased, the marking changed to different colors. At low frequencies of 50 kHz, the color marking was observed with a lower contrast saturation, while increasing the frequency to 300 kHz resulted in a more homogeneous and contrast with brighter and more saturated colors. These results provide valuable information for improving color marking techniques using laser systems in the manufacturing industry.

Keywords: AISI 304, Fiber laser, Laser color marking, LIPSS, Surface roughness.

I. INTRODUCTION

Today, laser technology is increasingly preferred in industrial production for marking products, due to its undeniable advantages over traditional methods [1], [2], [3]. Modern manufacturers strive to adopt laser technology as a reliable technique for marking their products [4].

In the field of surface modification of materials, the quest for precision and flexibility has led to the widespread adoption of fiber laser technology. With their compact design, high efficiency, and exceptional beam quality, 20 W optical lasers have become powerful tools for numerous industrial applications. Among the various materials subjected to laser processing, stainless steel AISI 304 stands out as a prime candidate, valued for its durability, corrosion resistance, and aesthetic appearance. Numerous studies have been conducted on laser color marking [5], [6], [7], [8], [9].

Some interesting research in this area is worth noting; for example, Veiko [10] proposed an original palette development method in the nanosecond pulse duration laser coloring process. The authors [11] in their study analyzed the laser color marking process of AISI 304 steel samples by examining 15 different colors. The influence of the gas environment on the composition and color of the nanosecond laser-modified surface was demonstrated by Luo et al. [12]. In [13], Lazov et al. studied laser marking on the fly of the product.

While the aforementioned studies investigated laser color marking with nanofiber lasers, the authors in [14] [15] [16] focused on investigating the process using a femtosecond laser. On stainless steel, they achieved

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iridescent metallic shades of different colors when viewed from different angles, demonstrating good reproducibility of results. Adams et al. [17] investigated the growth of interference oxide films on the surface of 304L stainless steel.

Despite the successes achieved, further research is needed to achieve high reproducibility of different colors in marking, thus expanding its widespread use in the industry.

This paper seeks to explore the potential of 20 W optical lasers for color marking on AISI 304 stainless steel, delving into the subtleties of laser parameters, surface interactions, and practical applications affecting contrast and roughness in the machining zone. From understanding the role of laser parameters such as power, speed, and frequency to exploring innovative techniques to achieve precise and durable color markings. By elucidating the basic principles and showing examples from real experiments, we aim to provide insights for the industry to use the full potential of fiber laser technology for color marking on AISI 304.

II. Material, Laser System and Methodology

A. Material.

The research was conducted on samples made of a commonly used type of stainless steel AISI 304 (chemical composition: *(LEAX measurements)* C = 0.017 %, Si = 0.37 %, Mn = 1.79 %, P = 0.028 %, S = 0.010 %, Cr = 18.1 %, Ni = 8.0 %, Mo = 0.40 %, Cu = 0.34 %, N = 0.06 %,) with dimensions of 43 mm × 93 mm and thicknesses of 3 mm. Samples were marked on fiber laser with different laser parameters. The samples were marked in the atmospheric air and room temperature.

B. Laser Marking System.

Experiments were made using a Rofin PowerLine F 20, shown in Figure 1, laser specification shown in (Table 1). A pulsed fiber laser is used. The laser system has good positioning accuracy and a high degree of repeatability.

Fig. 1. Rofin powerline f 20 marking fibre laser system

TABLE 1. CHARACTERISTICS OF THE LASER SYSTEM

Characteristic	Value
Wavelength	1064 nm
Output power (pulsed)	19 W
Max. Pulse Energy	1 mJ
Pulse Width	4 – 200 ns
Repetition Rate	20 to 1000 kHz
Efficiency	30 %

C. Microscope setup.

The marked stainless steel AISI 304 samples structure change was examined under microscope LEXT 3D MEASURING LASER MICROSCOPE OLS5000 shown in Figure 2. With set parameters at objective at 20X, measure pitch was 0.40 µm, measure field 645 µm x 645 µm. Witch was used to measure the laser marking samples of AISI 304 plates.

Fig. 1. Lext 3D measuring laser microscope OLS5000

D. Methodology.

In order to fulfill the objective of the scientific report, it was necessary to perform at least 2 marking processes with different laser parameters. The samples were treated from grease and contaminants of the sample surface with technical spirt.

By performing such an operation, we understand what changes occur when the parameters of the lasers are changed, and we can evaluate the results.

During the experiments, two stainless steel samples were used. The following constant parameters were set on sample 1: raster step *Δx* was set as 10 µm, pulse duration was 4 ns, frequency – 400 kHz. Also, there was set of variable parameters, these parameters are shown in Fig. 3.

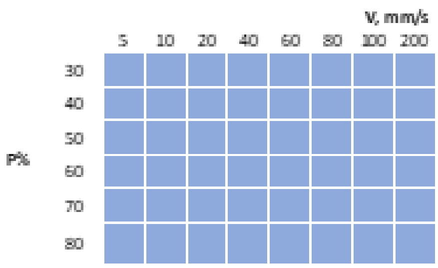


Fig.3. Scheme for laser marking of stainless steel sample 1.

On sample 2, raster step *Δx* was set same as on the sample 1, 10 µm, pulse duration was 4ns, and laser power *P* was 12,8 W. And during changes on constant parameters we also change variable parameters, these parameters is shown in Fig. 4.

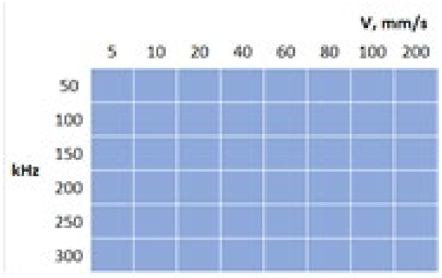


Fig.4. Scheme for laser marking of stainless steel sample 2.

The experiment began with the scheme test method. Through the combination of parameters, a square area of 5 mm × 5 mm was created on the surface of the sample, with an interval of 1.5 mm between the rows and columns. The entire stainless-steel plate contained 48 areas (squares), as shown in Fig. 5.

Roughness Measurement Methods. Roughness measurements and the resulting microstructure were examined with an Olympus model "OLS5100-EAF" laser microscope (Fig. 2). The obtained microstructural images were carried out using a 10× objective, magnification 227×, as the examined area for each measurement 1280 µm ×1280 µm with a measurement accuracy of ± 2.0 µm. From the obtained 3D images with the laser system of the microscope, the roughness Ra for the entire examined area 1280 µm ×1280 µm were measured. The obtained values are plotted in tables and graphical dependences of changes in roughness depending on speed and step during surface laser processing are shown. The built dependencies are presented in the results.

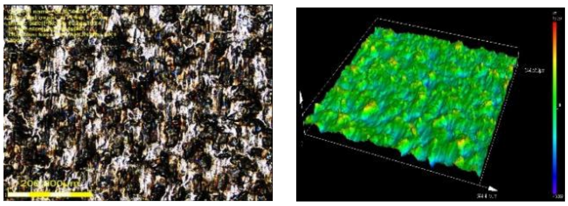
III. Results and Discussion

A. Results of surface roughness measurement.

After raster marking was carried out on the first sample according to the above methodology, a textured surface was obtained on the squares. A general view of the obtained picture on the sample is presented in Fig. 5. Average line roughness (R_a) measurements were taken. Average surface roughness on untreated surface was R_a = 0.695 µm.

In Fig. 6 shows the marked square with the largest roughness (2.33 µm) with technological parameters power P = 9.6 W and speed v = 5 mm/s. In fig. 6a shows the 2D image of the marked square, and in fig. 6b – the 3D image.

Fig. 5. Raster marked sample of stainless steel at different speeds and powers

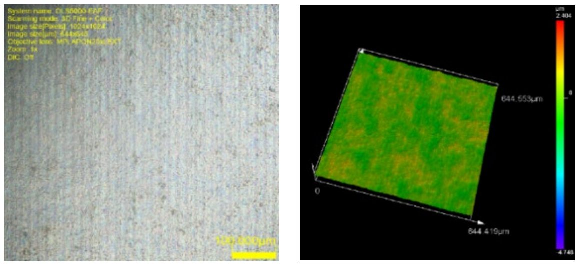


a) b)

Fig 6. Marked square with biggest roughness R_a for the first sample

Smallest roughness (0.70 µm) on marked surface was with parameters P = 4.8 W and v = 200 mm/s as shown in Fig. 7. As we can see that surfaces also visually looks different, and colours also has been different. In Fig. 6a we observe brown colour and in Fig. 7a its grey.

At a speed of 200 mm/s, the roughness of the machined surface approaches that of the untreated surface (0.695 µm) for all studied powers.



a) b)

Fig 7. Marked square with smallest roughness R_a for the first sample

The experimental dependence of the roughness on the velocity for three powers for the studied sample is presented in Fig. 8. The following dependencies are observed:

- As speed increases, roughness decreases for all three powers. In the interval from 5 mm/s to 100 mm/s, the curves are significantly steeper than those in the interval from 100 mm/s to 200 mm/s;
- For power 4.8 W, the roughness changes from 2.33 µm to 0.64 µm, and in the interval from 100 mm/s to 200 mm/s it is almost constant and is close to that of the untreated surface;
- For power 6.4 W, the roughness changes from 1.82 µm to 0.80 µm;
- For a power of 9.6 W, the roughness changes from 0.97 µm to 0.70 µm;
- In the interval of 5 mm/s to 100 mm/s, the roughness change rate at 9.6 W is 15% greater than that at 6.4 W and 85% greater than that at 4.8 W.

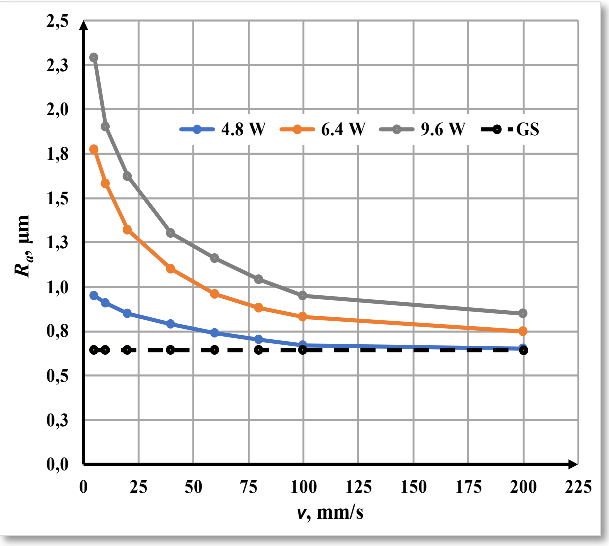


Fig 8. Dependence of the roughness R_a on the speed v during laser marking of a sample of stainless steel for powers *P*: blue color - 4.8 W, orange color - 6.4 W, gray color - 9.6 W and GS – ground (untreated) surface.

On the second sample (see Fig. 9) raster marking of squares with different speeds and frequencies was performed. The speed was varied in the interval from 10 mm/s to 200 mm/s.

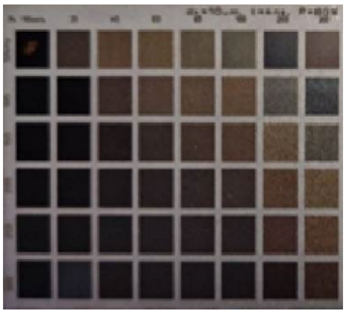
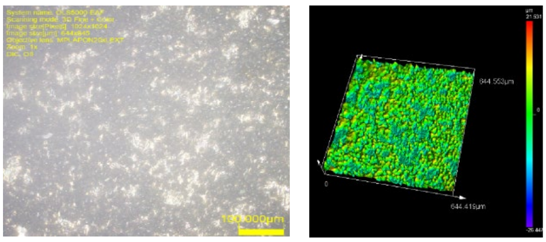


Fig. 9. Raster marked sample of stainless steel at different speeds and frequencies

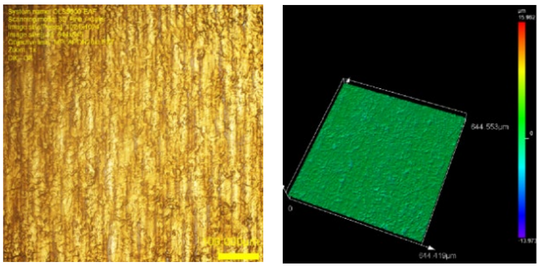
Biggest roughenss R_a on the sample was on laser parameters frequency ν = 50 kHz and speed v = 10 mm/s (see Fig. 10, Fig. 10a – 2D image, Fig. 10b – 3D image).



a) b)

Fig 10. Marked square with biggest roughness R_a

Smallest roughness on marked surface was with parameters frequency ν = 250 kHz and speed v = 200 mm/s as shown in Fig. 11.



a) b)

Fig 11. Marked square with smallest roughness R_a for the second sample

The dependence of the roughness on the speed for three frequencies for the second sample is presented in Fig. 12. From the obtained graphs it follows:

- As the speed increases, a nonlinear decrease in roughness is observed for the entire speed interval for all three frequencies;
- For a frequency of 50 kHz, the roughness is about 25 % greater than that for a frequency of 150 kHz and about 63 % greater than that for a frequency of 250 kHz;
- Again as with the graphs in Figs. 7, the curves in the interval from 10 mm/s to 100 mm/s are significantly steeper than those in the range from 100 mm/s to 200 mm/s.

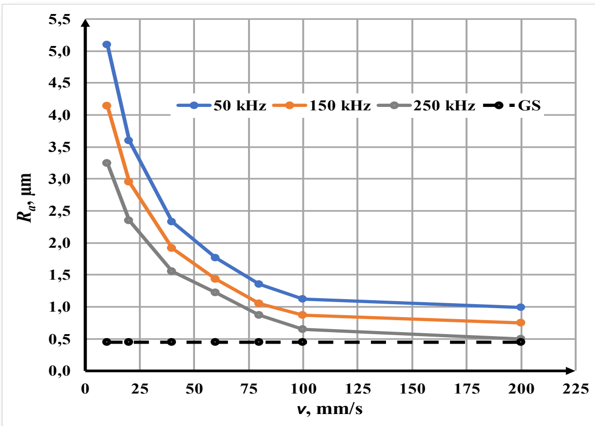


Fig 12. Dependence of the roughness R_a on the speed v during laser marking of a sample of stainless steel for frequencies ν: blue color – 50 kHz, orange color – 150 kHz, gray color – 250 kHz and GS – ground (untreated) surface.

IV. Conclusions

The quality of the marking is determined by a number of criteria, the most important of which are contrast, clarity, necessary roughness, wear resistance, etc. The influence of speed, power and frequency on the roughness of the marking was analyzed and the following regularities were established:

- It was found that with increasing speed, a non-linear decrease in roughness was observed for the three powers studied;
- With increasing power, an increase in roughness is observed as the roughness at 9.6 W is 15% greater than that at 6.4 W and 85% greater than that at 4.8 W;
- A decrease in roughness with increasing speed is observed for the three investigated frequencies;
- As the frequency increases, the roughness decreases as for a frequency of 50 kHz it is 25 % greater than that for 150 kHz and about 63 % greater than for 250 kHz;
- Two ways of laser marking (by melting and oxidation) were analyzed, in which color marking is obtained.

Research can also continue with the influence of step, number of repetitions and duration of pulses on the roughness of the marked areas. This will help to obtain the complex influence of more important parameters on the roughness of the marking.

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