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THE IMPACT OF LASER ENGRAVING PARAMETERS ON THE COLORIMETRIC PROPERTIES OF STEEL SURFACES

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Abstract: *Laser engraving technology is increasingly prevalent in the graphics engineering industry due to its speed, precision, and capacity for individualization. This method is widely used for decorative metalwork, metal packaging, and signage, providing high-quality aesthetic results on various surfaces. This study investigates the impact of different laser engraving parameters, such as speed, hatching, frequency, and power, on the colorimetric properties of steel surfaces. The experiments were conducted using a fiber laser with a power of 30 W and a wavelength of 1064 nm on polished steel plates measuring 20 x 20 cm with a thickness of 4 mm. Engraved samples, each measuring 5 x 5 mm, were produced, with laser parameters varied for each sample. After engraving, each sample was analyzed under a microscope and measured using a spectrometer to accurately determine colorimetric values, offering precise quantification and analysis.*

The results indicate that engraving speed significantly affects the depth and intensity of color, with lower speeds allowing deeper oxidation and more saturated colors. Increased laser power generates greater heat, resulting in more vibrant color tones. The frequency and pulse duration of the laser influence energy distribution and heating patterns, with shorter pulses producing precise changes in colorimetric properties and longer pulses causing deeper alterations. The hatching pattern also affects the colorimetric properties due to variations in heat distribution and energy absorption. High temperatures are critical for color formation as they facilitate the oxidation process, where the oxide layer's thickness and composition determine the final color.

These findings enable designers and technicians in the graphics engineering industry to control the aesthetic aspects of steel engraving with greater precision. Moreover, the results of this study could be utilized to develop software for the automatic adjustment of engraving parameters to achieve desired color images on steel surfaces. Such software would significantly enhance the efficiency and effectiveness of laser engraving processes, offering new possibilities for creative applications in the design of metal packaging and signage. By integrating these insights, the graphics industry can achieve more consistent and high-quality outcomes, driving innovation and expanding the potential uses of laser engraving technology.

Key words: laser engraving, colorimetric properties, hatching patterns, spectrometry analysis

1. INTRODUCTION

Lasers have been widely used in industry for welding and cutting operations, but with increased technology development and progress, lasers are now being used for marking, engraving and decorative designs on various materials. Nowadays, industry product identification is of high importance for many reasons such as improving security and efficiency or brand protection (Mehta & Thakkar, 2015). This type of technology has been increasingly prevalent in the graphics industry due to its speed, precision, non-contact technique and ability for individualization. Laser engraving can provide high-resolution and sometimes permanent marks and can be applied on metallic and non-metallic surfaces. This technology does not produce waste, nor does it require printing inks or additional solvents which can be very practical and environmentally friendly (Roozbahani et al., 2020). Light Amplification by Stimulated Emission of Radiation (LASER) is a powerful and focused energy that can modify surfaces of materials. Laser color marking is a complex process of removing the top layer surface of a material. With the optimization of certain parameters, laser can create high contrast marks on a metal surface that can result in color generation due to surface oxidation when the laser beam interacts with the specific material (Maltais et al., 2016; Tsvyatkov et al., 2023). Color generation can vary depending on the chemical structure of the metal and different parameters that are set for a specific laser. Similar colors can be achieved using a different set of parameters and this area of metal colorization needs to be further investigated (Veiko et al., 2016). Color variation also depends on a laser being used for color laser marking.

In a study of laser-induced color marking (Antończak et al., 2013) it was found that initial temperature of a sample, as well as its size, does not have an impact on color variation of similar samples, while parameters such as speed and power had dominant influence on color change. They also found that lower frequencies gave more saturated colors. Amara et al. (2015) concluded that the difference in the thickness of an oxidized layer was responsible for different color generation on steel surfaces. This can indicate that varying speed and line distance has an influence on forming different oxide layers. In a formation of color on stainless steel study (Linggamm et al., 2021) it was found that defocusing distance, hatch distance and pulse width have a great effect on obtaining color on stainless steel surface. The study shows that the same colors can be produced with different laser parameters, but the brightness and saturation of colors can differ. Linggamm et al. (2021) also investigated roughness of the surface of the color obtained. The study concluded that roughness of the surface is an important aspect of color making where smoother surface and large value of pulse width produces brighter and lighter colors because the heat is distributed more evenly. Respectively, the rougher the surface the color gets darker. The study also found that pulse width and defocusing distance had more influence on coloring stability than hatching distance. A review on parametric optimization of laser engraving on various materials (Mehta & Thakkar, 2015) concluded that almost all laser parameters and their effects on different surfaces have been studied and that it is possible to create a proper optimization of the laser parameters for high production with great quality which could be beneficial for graphics industry.

This study investigated the effects of fiber laser engraving parameters on the colorimetric properties of steel surfaces. The laser parameters examined for color generation included power, speed, frequency, hatching, and pulse width. Representative color samples were measured using an iProfile Pro spectrometer and surface structures were observed under a microscope to identify correlations with the resulting color parameters. Additionally, the study explored the color variation that occurred when altering the angle of the laser beam while engraving larger surface areas. The findings provide insights into the relationships between various factors influencing laser-induced coloration on steel surfaces.

2. MATERIALS AND METHODS

Laser parameters from previous studies were tested and it was concluded that repeatability of gaining the same colors for different laser machines is not possible. It was necessary to conduct new tests for this specific laser with different parameters. The study was performed on JPT Mopa C fiber laser with output power of 30 W with working area of 15 x 15 cm. Laser wavelength is 1064 nm, with frequency range from 1 to 400 kHz and speed up to 7000 mm/s. The experiments were conducted on polished steel plates each measuring 20 cm x 20 cm with thickness of 4 mm. The testing procedure involved arranging 5 x 5 mm fields into a table, with the values of two parameters varying along the x and y axes, as shown in Figure 1. In each test, two parameters and their potential correlation were evaluated. Initially, parameters that were not subject to change were set to their default values.

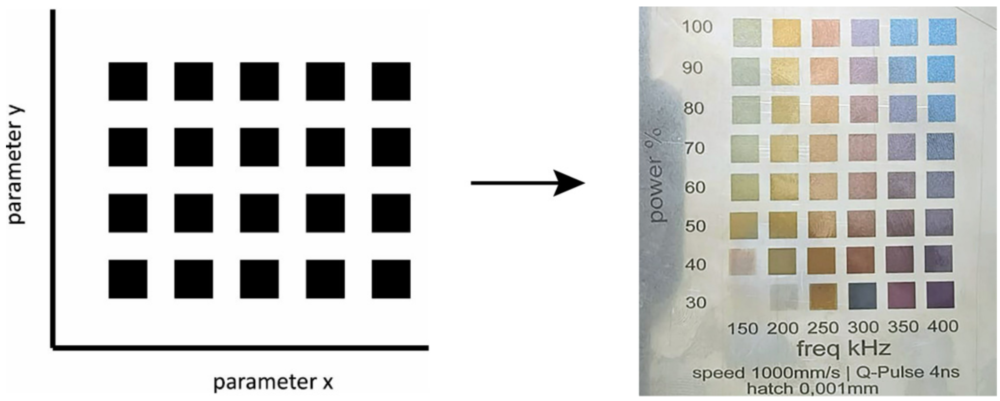

Figure 1: Laser parameter matrix for color testing

Initially, power and frequency were tested. Power values ranged from 10% to 100%, in 10% increments, while frequency was varied from 50 kHz to 400 kHz across eight steps. The hatch (line distance) was maintained at 0.001 mm, with a speed of 1000 mm/s and a pulse width of 200 ns. The initial test indicated the emergence of color within the 30% to 70% power range and between 150 kHz and 300 kHz in frequency. Subsequently, speed and hatch were examined. The speed ranged from 700 mm/s to 7000 mm/s, and hatch varied from 0.001 mm to 0.008 mm. Based on the results of the previous test, optimal values for frequency and power were determined to be 50% power and 200 kHz. The findings demonstrated that with

increasing speed and hatch, the colors faded rapidly. It was concluded that speeds above 3500 mm/s were unnecessary when power was set at 50%, and the optimal speed range was identified as 1000 mm/s to 2400 mm/s. Additionally, the most saturated colors were observed with a line distance of 0.001 mm.
The test has shown that frequency changed color, while power was toning the color from light saturated to vibrant or showing a change in similar colors such as from purple to blue. Lower pulse width gave more saturated colors with mat finish. The test has also shown a wide range of colors from yellow, orange, light red, purple and blue. 50% power row showed the most saturated colors, and that power was chosen as optimal. The next step was to test the impact of changing the Q-pulse and frequency on color formation. The results showed that low pulse widths and frequencies below 250 kHz do not produce an oxidized layer necessary for color formation. With power set to 50%, the next step was to investigate whether color could be achieved by increasing the pulse width in combination with power scaling. The results further confirmed that power alone does not influence color, and that high power combined with a larger pulse width leads to burnt areas. To generate color, power and Q-pulse values must have an inverse relationship; high pulse widths should be paired with lower power percentages, and vice versa, to achieve saturated colors on stainless steel.
With the optimal power, frequency, and pulse width determined, speed and hatch were varied. The same power-frequency test was conducted with a 0.002 mm line distance (hatch), and the resulting colors were similar to those achieved with a 0.001 mm line distance, though the order in which they appeared through frequency scaling was inverted. This test demonstrated that similar or identical colors can be obtained with different line distances, potentially accelerating the laser engraving process. However, if a larger line distance is selected, it is essential to adjust other parameters accordingly. A 0.001 mm hatch was chosen for most of the tests, as it produced a finer color structure. The drawback of using a smaller line distance is the slower engraving time. Accelerating the laser engraving process is crucial for broader commercial applications in graphic technology. Therefore, the next step was to test different speed values and assess their influence on oxidation and color appearance on steel surfaces.
The power-speed test further confirmed that power primarily modulates the intensity of colors achieved with specific parameters. Lower power values combined with higher speeds produced dull, low-saturation colors, as shown in Figure 4. The frequency-speed test (Figure 6) visually demonstrated a linear correlation between these two parameters. Similar colors can be obtained when both parameters are doubled. For example, the color in the lower-left corner at a frequency of 150 kHz and a speed of 600 mm/s can also be achieved by setting the frequency to 300 kHz and the speed to 1200 mm/s with a 0.001 mm line distance.
After testing all relevant parameters and generating the necessary color palettes, the next phase involved measuring the colorimetric values of the samples. The following section presents the obtained results along with their analysis.

3. RESULTS

In this section, we present the analysis of the test samples created using various laser parameters. The samples were examined using both a spectrometer and a microscope to provide a comprehensive evaluation of the surface coloration. The spectrometer measurements offer quantitative data on the colorimetric properties, while the microscopic analysis allows us to observe the surface structure and texture in detail. By combining these methods, we aim to identify key correlations between the laser settings, surface morphology, and the resulting color stability and intensity.

3.1 Spectrometer measurements

In this section, we analyze the colorimetric values of the test fields created using various laser parameters, measured with a spectrometer. This approach allows us to quantify the color properties and identify correlations between specific laser settings and the consistency of surface coloration. By examining the spectrometer data, we aim to better understand how adjustments in production parameters influence the stability and intensity of the colors generated on the steel surface. Spectrometric curves are presented in the figures below. On the x-axis is wavelength in nanometers, values form 380 nm to 730 nm, and on the y-axis is the intensity of the reflected light.

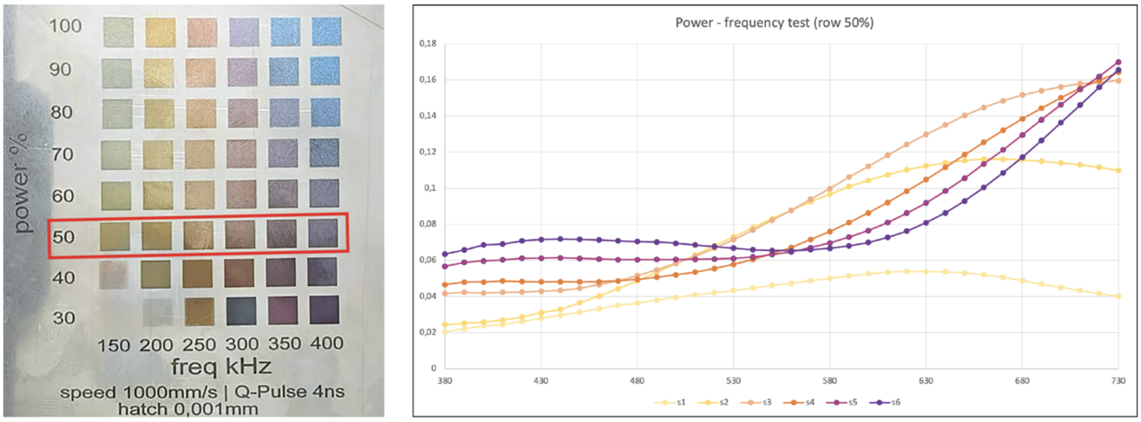

Figure 2: Power-frequency test results

The results on Figure 2 illustrate how laser power (%) and frequency (kHz) influence the color formation on a steel surface. Left side of the Image, power-frequency color grid shows the color variation on the surface at different combinations of power (vertical axis) and frequency (horizontal axis). At 50% power, which is highlighted in red, there is a clear progression of colors across different frequencies, ranging from light tones to deeper, more saturated hues.

The graph represents the relationship between power, frequency, and colorimetric values for different color categories. Different curves are plotted for color samples, showing how the colorimetric value changes with increasing frequency at 50% power. The test indicates that 50% power combined with a mid-range frequency (around 250-350 kHz) produces the most saturated and vibrant colors on the steel surface. Frequency appears to be the primary factor for controlling the hue, transitioning from warm to cool colors as the frequency increases. Power, on the other hand, seems to control the intensity of the colors, with mid-power settings generating more pronounced and diverse color variations. In summary, the combination of 50% power and frequency between 150-350 kHz seems to be optimal for achieving a range of vibrant colors.

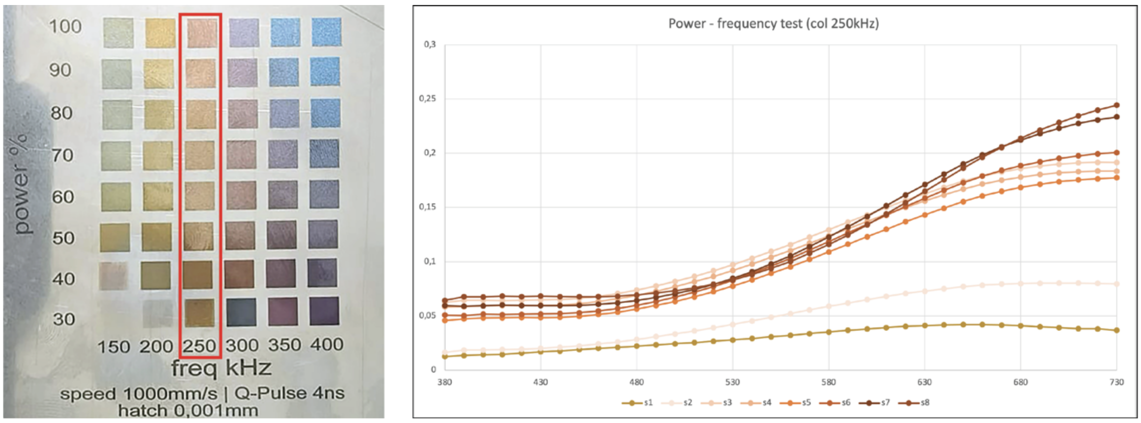

Figure 3: The influence of laser power on surface coloration

The graph on Figure 3 displays how different power levels affect color intensity and appearance at a fixed frequency of 250 kHz. As power increases beyond a certain threshold, particularly in the range power levels (50%-80%), the colorimetric values show a steady rise, indicating more pronounced color saturation. In summary, the data indicate that 250 kHz frequency is effective for producing a range of colors, but power settings need to be carefully adjusted to avoid overburning. The power ranges from 50%-80% appears to be the sweet spot for achieving the most vibrant and desirable colorations.

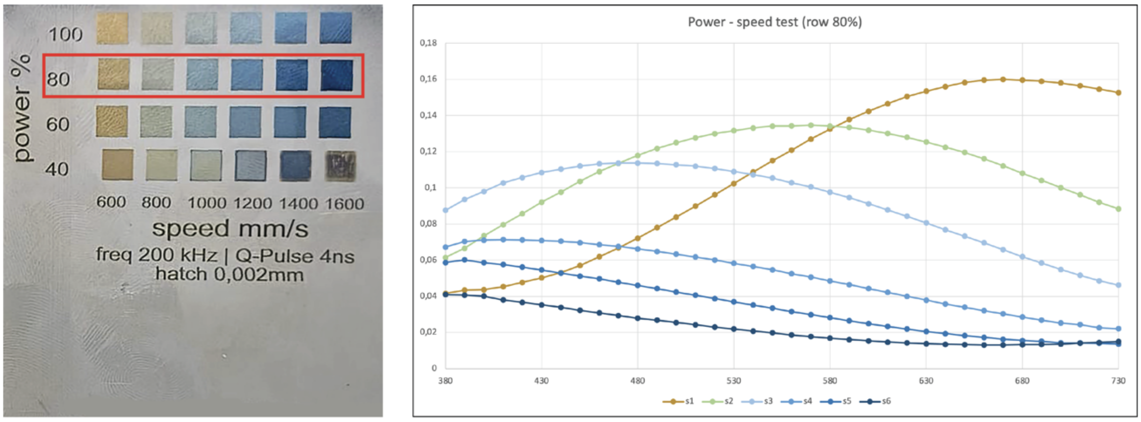

Figure 4: The influence of laser speed on surface coloration

The row corresponding to 80% power is highlighted, showing the colors obtained as the speed varies from 600 mm/s to 1600 mm/s. At 80% power, there is a progression from lighter to darker hues as speed increases. Lower speeds (600-800 mm/s) produce lighter colors, such as light blues and pale golds, and as speed increases (1000-1200 mm/s), the colors become more saturated and pronounced, with deeper blues and purples emerging. At higher speeds (1400-1600 mm/s), the colors appear darker and may show signs of overburning, with less color variation. The faster the laser moves, the less time it interacts with the material. This generally leads to less heat accumulation, which explains why colors become more intense and saturated at moderate speeds (1000-1200 mm/s).

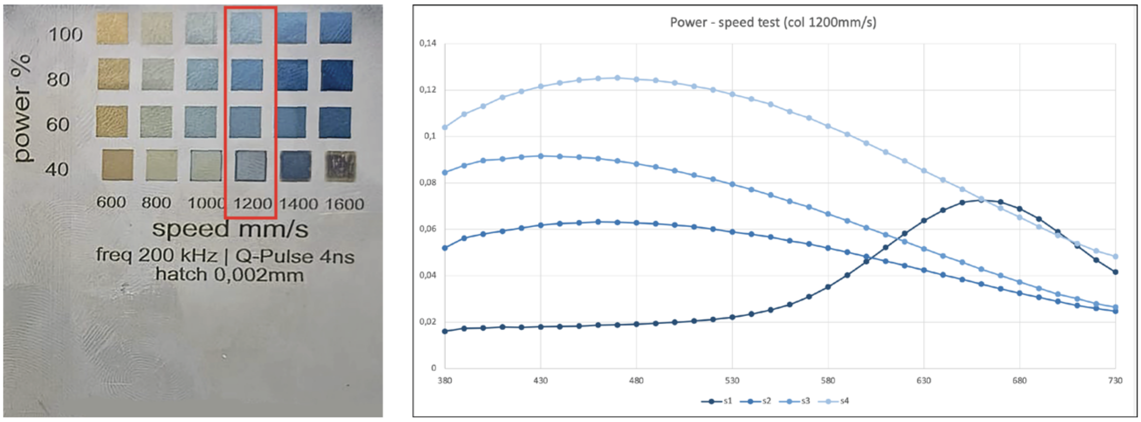

Figure 5: Power-speed test results

The highlighted column corresponds to a constant speed of 1200 mm/s with power levels ranging from 40% to 100%. The curves show a general rise in color intensity with increasing power, reaching a peak at approximately 80% power. This corresponds to the most saturated color response seen in the color grid. Beyond 80% power, the curves begin to decline, indicating that higher power levels may lead to overburning, which reduces the color intensity. The blue and purple curves (darker shades in the graph) show strong peaks, confirming that these hues are most prominent at mid-to-high power levels. Power plays a critical role in determining color saturation, with 80% power being the optimal setting for this speed. Lower power levels yield pale or weak colors, while higher power may lead to overburning.

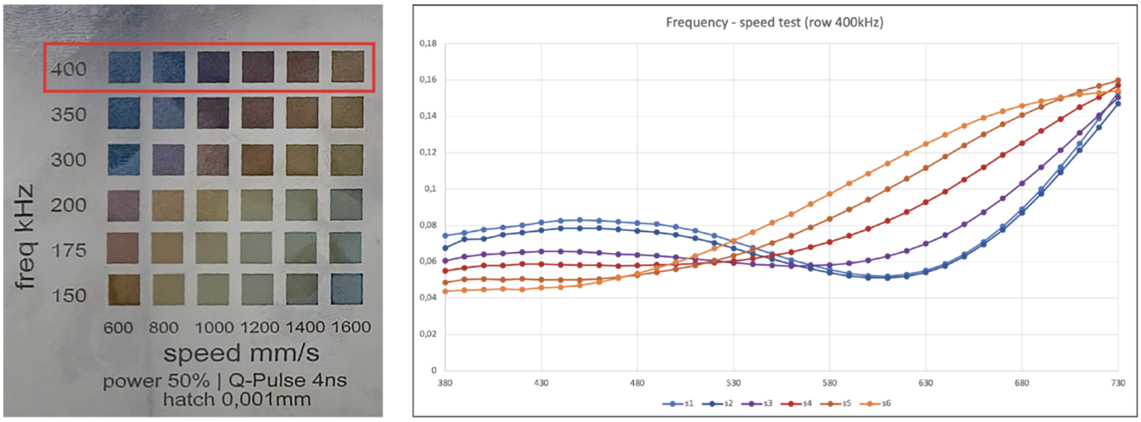

Figure 6: Frequency-speed test results at 400 kHz

The frequency-speed test at 400 kHz, illustrated by the spectral curves, reveals the relationship between color intensity and different laser parameters. At 400 kHz, higher speeds seem to amplify the intensity in both warm and cool color ranges, but the peaks for warmer colors suggest that these settings particularly enhance red-to-orange spectral regions. This implies that the combination of 400 kHz frequency and mid-range speeds (around 1000-1200 mm/s) results in the most intense and well-defined color output, particularly in the orange-to-red spectral range. These findings demonstrate the impact of laser parameters on the spectral characteristics of the surface, where controlling speed and frequency can be used to fine-tune the production of specific color hues through selective wavelength enhancement.

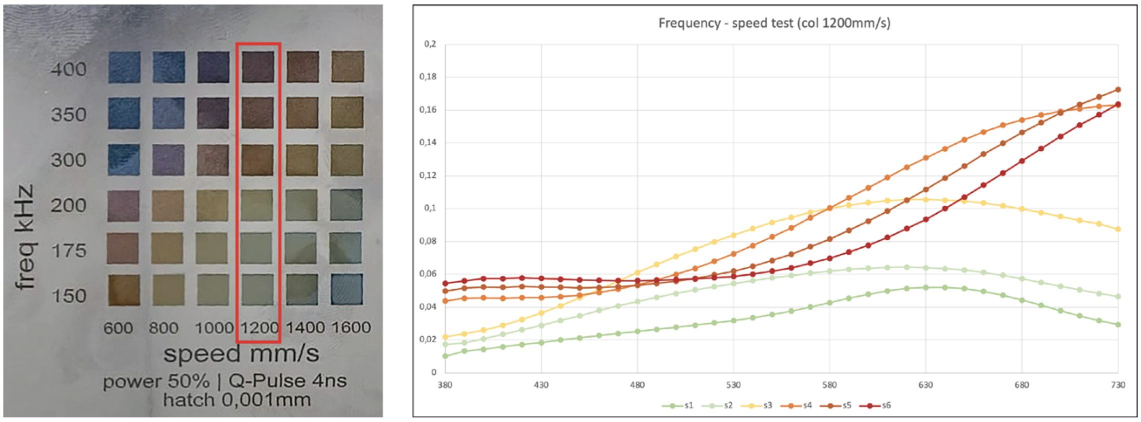

Figure 7: Frequency-speed test results at 1200mm/s

The results shown in the Figure 7 illustrate the relationship between laser frequency and speed. The color grid on the left shows how frequency impacts the color formation on the surface, while the spectral curves on the right reflect how different frequencies influence the color intensity across various wavelengths. At lower frequencies (150-200 kHz), the colors generated are lighter and less saturated, suggesting that lower frequencies do not produce the desired surface oxidation needed for strong color formation. As the frequency increases, particularly from 300 kHz to 400 kHz, the colors become more vibrant. The spectral curves support this observation, as intensity increases significantly with higher frequencies, indicating that at 400 kHz, the laser produces stronger color responses at longer wavelengths (600-700 nm). The overall relationship suggests that higher frequencies combined with a mid-range speed of 1200 mm/s enhance color saturation. Lower frequencies, on the other hand, result in muted or less saturated colors. Therefore, the findings indicate that to achieve optimal color formation, particularly for deeper and cooler tones, a combination of higher frequencies (300-400 kHz) and a speed of 1200 mm/s provides the most effective results.

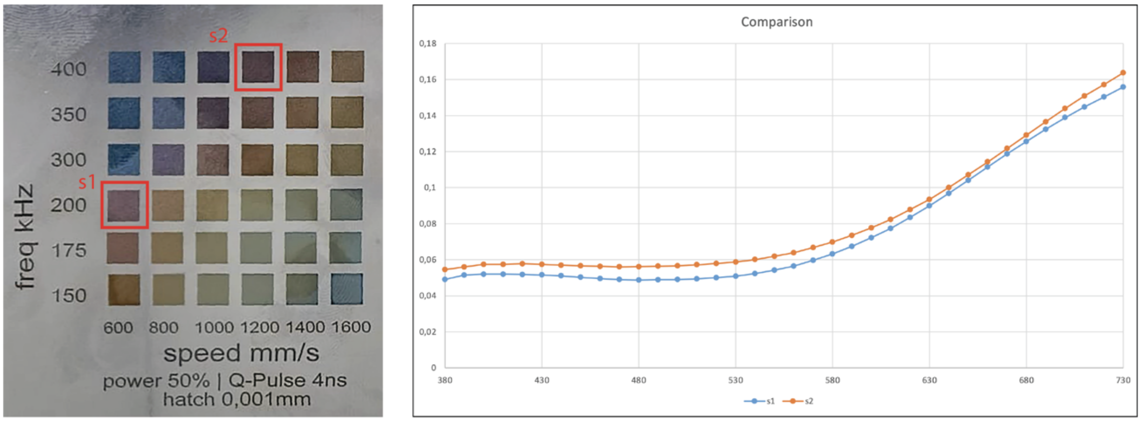

Figure 8: Comparison of two fields with the same coloration achieved using different laser parameters

The Figure 8 highlights two specific fields, S1 and S2, which exhibit similar colorimetric values but are generated under different laser frequency and speed conditions. The selected fields demonstrate how different combinations of parameters can produce nearly identical visual results. S1 is achieved with a frequency of 200 kHz and a speed of 600 mm/s, while S2 is achieved with a frequency of 400 kHz and a speed of 1200 mm/s. Despite the difference in frequency and speed settings, the spectral curves on the right show that the intensity values across the visible spectrum (represented by wavelengths on the x-axis) are almost identical for both samples. The two curves, S1 (blue) and S2 (orange), are closely aligned throughout the spectrum, particularly at longer wavelengths (600-700 nm), indicating that the colors produced in both cases are visually and spectrally similar. This result demonstrates that similar color effects can be achieved using different frequency-speed combinations. In this case, a higher frequency and speed (S2) can replicate the same color results as a lower frequency and speed (S1). This implies that there is flexibility in the laser parameters, allowing for adjustments in frequency and speed while still maintaining consistent colorimetric outcomes. This flexibility can be beneficial for optimizing engraving efficiency without sacrificing the desired color quality.

3.2 Microscope measurements

For further measurements specific colors that are representative for each main color of the spectra were chosen. Those colors were red, green, blue, white, cyan, magenta, yellow, and black. Their parameters are presented in Figure 9. The selected colors were captured under a microscope, and their surfaces were digitally analyzed to investigate the relationship between surface complexity and coloration.

Figure 9: Produced selected color samples

The selected colors are commonly used in the graphic industry and represent the primary colors, which is why they were chosen for further analysis. In this section, the reproducibility of previous results was also tested. By understanding how laser parameters affect color formation, a selected palette was created. The Table 1 presents the laser parameters (speed, power, frequency, Q-pulse, and hatch) that were used to create the selected colors based on previously collected results.

Table 1: Laser parameters of chosen colors

	red	green	blue	white	cyan	magenta	yellow	black
Speed [mm/s]	1000	1000	1000	1000	1000	1000	1000	100
Power [%]	70	20	100	60	50	40	50	60
Frequency [kHz]	300	350	150	400	350	350	150	80
Q-Pulse [ns]	4	12	4	4	7	4	6	16
Hatch [mm]	0,001	0,001	0,002	0,004	0,001	0,001	0,001	0,005

The Figure 10 presents the microscopic views of the surface textures for selected colors: Red, Green, Blue, White, Cyan, Magenta, Yellow, and Black. Each color's surface is split into two sections: the left side shows the laser-engraved colored surface, while the right side displays the corresponding thresholded binary image, highlighting the surface's complexity. The binary (black and white) side provides a detailed look at the surface structure. The white regions represent the raised or oxidized areas, while the black regions represent lower or untouched areas. The patterns differ across colors, indicating that surface complexity varies with the color produced by the laser. These observations suggest that the degree of surface complexity plays a key role in determining the final color, with the warmer and darker colors generally requiring more intricate surface structures to achieve their visual properties.

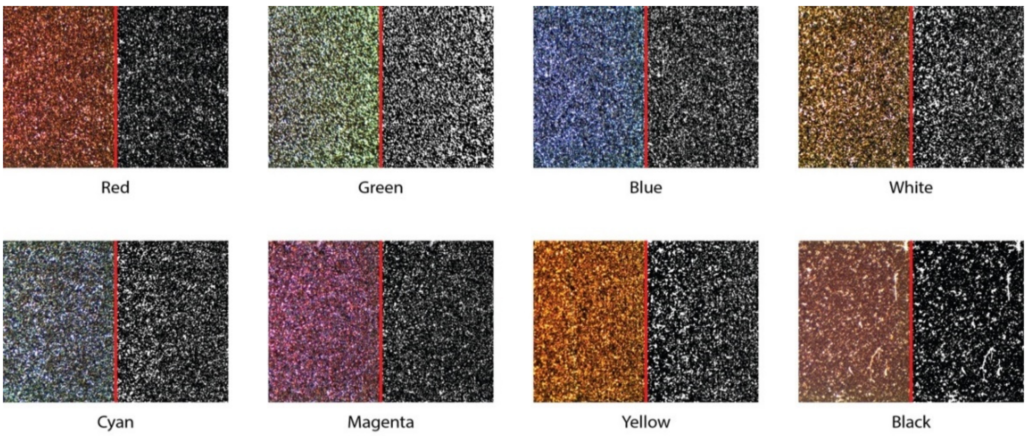

Figure 10: Surface structure complexity– left: microscopic image of the surface (35x magnification), right: thresholded sample

The analysis of surface complexity based on the binary images provides valuable insights into the role of laser parameters in color generation. However, to gain a more comprehensive understanding of surface modifications, future studies should also investigate surface roughness as a complementary parameter. By correlating roughness measurements with the observed surface complexity, a more complete picture can be obtained regarding how laser-induced texture impacts color formation. This additional data would allow for a deeper exploration of the interplay between surface morphology and colorimetric outcomes, further refining the optimization of laser engraving processes.

3.3 Working area

The Figure 11 shows the results of a test examining how changes in the working area of laser engraving affect the color output on steel surfaces. The concentric circles on the left represent different engraved areas, with diameters ranging from 60 mm to 150 mm, simulating the effects of engraving over increasingly larger surface areas. The graph on the right plots the colorimetric values for these tests, with the x-axis representing the wavelength and the y-axis the intensity of the color response. The variation in color across different working areas can likely be attributed to changes in the incident angle of the laser beam. As the engraving area expands, the laser beam needs to cover a wider surface, causing a significant change in the beam's angle of incidence. This alters the energy distribution across the surface, impacting how much oxidation and color formation occurs.

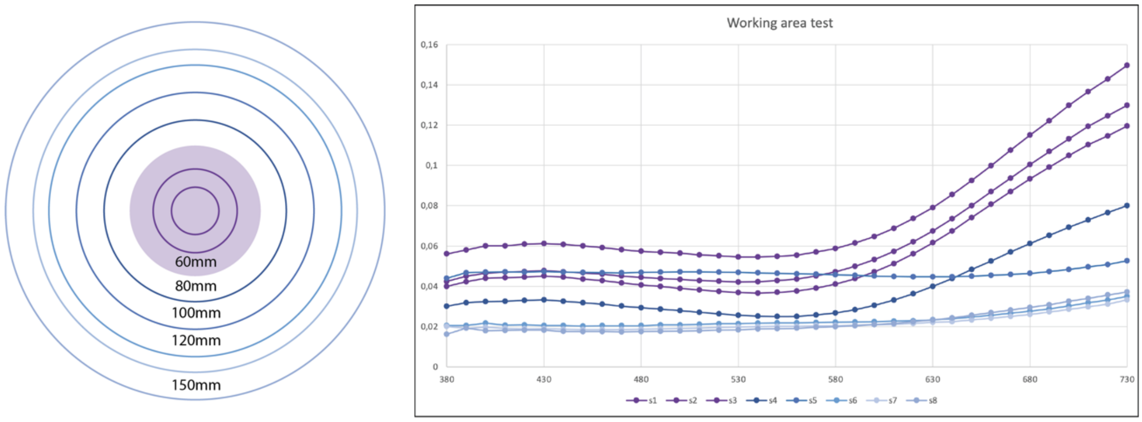

Figure 11: The influence of the laser beam angle on surface coloration

The purple curves, corresponding to smaller engraving areas, show higher intensity values, suggesting more saturated and vibrant colors when the working area is smaller, and the incident angle of the laser beam is more consistent. In contrast, the blue curves (representing larger engraving areas) show lower color intensity. This indicates that as the working area increases, the colors tend to fade or become less vibrant, likely due to the inconsistent angle of the laser beam across the surface. The results suggest that when engraving larger areas, there is a noticeable drop in color saturation and intensity, which can be directly linked to the changes in the laser's incident angle as it covers a broader surface. Smaller engraving areas produce more consistent and vibrant colors, while larger areas result in muted tones due to the variability in how the laser interacts with the surface. This highlights the importance of accounting for the working area size when aiming for consistent color results in laser engraving processes.

4. DISCUSSION

The results of this study demonstrate a clear correlation between laser parameters, such as power, frequency, speed, pulse width, and hatching, with the color and saturation achieved on steel surfaces. Variations in laser power indicate that lower power levels (below 40%) generally do not produce saturated colors, while mid-range power levels (50%-80%) yield the most vibrant hues. As the frequency increases, particularly in the range between 250 kHz and 400 kHz, the colors shift from warmer tones to cooler tones. This highlights the critical role of frequency in color control, while power modulates the intensity and saturation of the colors.

Furthermore, the tests investigating the combination of speed and frequency revealed that optimal speeds between 1000 mm/s and 1200 mm/s result in the best color saturation. Higher speeds, although reducing engraving time, lead to less saturated colors due to the reduced interaction time between the laser and the surface. Interestingly, certain colors can be achieved using different laser parameter combinations. For example, the same color can be produced with a combination of 200 kHz frequency and 600 mm/s speed, as well as with 400 kHz frequency and 1200 mm/s speed. This indicates that multiple parameter settings can lead to the same visual outcome, allowing flexibility in optimizing laser settings for different production requirements.

Experiments exploring the impact of the engraved area size showed that color changes as the surface area increases. On smaller areas (60 mm), the colors were more saturated and uniform, while on larger areas (>100 mm), color saturation decreased due to changes in the incident angle of the laser beam, which affected oxidation intensity.

5. CONCLUSIONS

Based on the results, it can be concluded that achieving optimal coloration on steel surfaces requires careful tuning of laser parameters. The optimal power range lies between 50% and 80%, while frequencies between 250 kHz and 400 kHz are most suitable for producing saturated colors. Engraving speeds of 1000 mm/s to 1200 mm/s yield the best results, and further adjustments to pulse width can enhance color precision. Additionally, it has been observed that the same color can be achieved through different combinations of laser frequency and speed, offering greater flexibility in process optimization. Finally, when engraving larger areas, it is important to account for changes in the incident angle of the laser beam, which may affect color quality. Future research should focus on the quantitative analysis of surface roughness to further confirm the relationship between surface morphology and the resulting colorimetric values.

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