Lasers in Manufacturing Conference 2023

Generation and characterisation of different colors on 304 stainless steel using femtosecond laser pulses in GHz burst mode

Arnas Vyšniauskas [a,c,*], Evaldas Kažukauskas [a,b], Valdemar Stankevič [a,c]

[a]*Akoneer, Mokslininkų st. 6B, LT-08412 Vilnius, Lithuania*
[b]*Laser Research Center, Faculty of Physics, Vilnius University, Saulėtekio Ave. 10, LT-10223 Vilnius, Lithuania*
[c]*Center for Physical Sciences and Technology, Savanorių Ave. 231, LT-02300 Vilnius, Lithuania*

Abstract

Our study presents an approach for color generation on 304 Stainless Steel surfaces using femtosecond laser pulses in GHz burst mode and the analysis of processing parameters influence to the generated colors. The colors on a metal surface are usually generated by few mechanisms: 1) color generation due to the surface heating and oxide layer growth and 2) color generation due to femtosecond laser-induced nano-structures. We demonstrate the processing window sensitivity to obtain a constant color using a spectrometer color characterization method. The CIE color difference parameter $\Delta E_{ab}*$ was used and allowed to compare the obtained colors. The wide range of colors on stainless steel surface was demonstrated. The problems with color homogeneity occur when processing larger surfaces and this was analyzed using a hyperspectral camera. This approach has potential applications for decorative coatings and surface engineering and provide valuable insights into the mechanisms of color generation on stainless steel.

Keywords: Stainless steel; Femtosecond; Burst pulses; Color difference

1. Introduction

Laser based color generation on material surface can be widely applied technology to improve its visual properties. In this process, various metals can be utilized. However, for our experiments, stainless steel was chosen due to its widespread usage in the industry. This is relatively cheap and abundant material, also strong, ductile, and resistant to corrosion. It can be used in many fields, such as automotive industry, energy

* Corresponding author. Tel.: +370-602-94855
E-mail address: arnas@akoneer.com.

[1] or medical solutions [2]. The femtosecond pulsed laser is an ideal choice for the color generation process, offering precise marking possibilities. By manipulating the surface properties of stainless steel at a microscopic level, we can unlock new opportunities in fields such as development of new aesthetic surface for sanitary ware parts to introduce a whole range of products in the market. Adding vibrant and durable colors through color marking on stainless steel surface can elevate the visual impact, enrich the aesthetic appeal and can be used for authentication or traceability of a product [3]. To achieve these goals, we need to have as many available colors for marking as possible. Main problem of femtosecond laser color generation is lack of stable colors. Usually, it consists of black and white shades with few other colors [3]. The generation of bigger color palette on stainless steel can be done by incorporating GHz burst mode in the process. Understanding the underlying mechanisms and techniques for producing vibrant and durable colors on stainless steel can revolutionize the way we perceive and utilize this versatile material.

The primary cause of the coloration seen in femtosecond laser marking on stainless steel is the structural color effect [4]. It is accomplished by creating laser-induced formation of periodic surface structures (LIPSS) on material surface with ultrashort pulsed lasers [5]. Second approach employs a laser as a source of heat, enabling the creation of a transparent or semi-transparent oxide film on the surface of the metal [6,7]. Here color effect is achieved due to the effect of interference between oxide and metal surfaces. By employing laser structuring it becomes possible to induce alterations in the optical properties of the material surface within the visible range [8, 9].

2. Experiment details

The study was conducted by employing the femtosecond diode-pumped solid state laser FemtoLux 30 (Ekspla, Ltd). It has a wavelength of 1030 nm, an output power of 30 W, a pulse duration of 340 fs, a pulse repetition rate ranging from 0.2 to 4 MHz, and a beam quality factor of M2 < 1.2. The laser beam was focused using an F-Theta lens with a focal distance of f = 118 mm. The diameter of the focused beam was approximately 35 µm.

The experiments were conducted on AISI 304 grade stainless steel plates with dimension 80 mm × 50 mm and thickness of 1 mm. The chemical composition of this type of steel was as follows: Chromium (Cr) accounts for 18%, Nickel (Ni) accounts for 8%, Manganese (Mn) accounts for 2%, Carbon (C) accounts for 0.06%, and the remaining balance was Iron (Fe) [10]. Before conducting any experiments, the plates were cleaned with acetone since they had been coated with oil during the manufacturing process.

During the characterization stage, a color measuring setup was assembled, which included an optical spectrometer (FLAMES, Ocean insight) with a Tungsten halogen light source. Additionally, a hyperspectral camera (Ximea Snapshot, Imec) was utilized to measure color homogeneity. The visual representation of the optical setup scheme is shown in Fig. 1. With the help of a spectrometer we are able to measure visible spectra range of wavelengths and provide high-resolution spectral data.

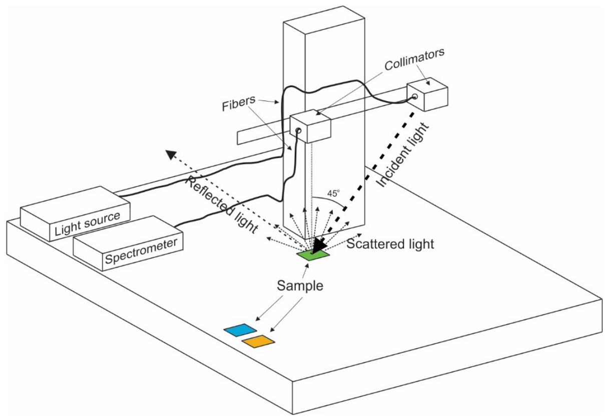

Fig. 1. The schematic representation of the assembled optical setup for color measurement using a spectrometer.

3. Optimization of the marking parameters

At the beginning of experiments, a primary pulse repetition rate of 203 kHz was set. Other parameters such as scanning speed, average power, hatch, GHz burst count, and pulse duration were varied. Initially, some colors were generated but they lacked homogeneity. Through parameter exploration, It was discovered that reducing the repetition rate to below 50 kHz was necessary to achieve uniform colors. After optimizing the scanning speed, average power, hatch and GHz burst count, a color palette was successfully generated depicted in Fig. 2. By increasing the scanning speed, separate scanning lines became apparent, displaying light blue colors. However to achieve a brighter blue color on a smooth surface, a higher average laser power and increased overlap between pulses are required. These conditions contribute to a larger percentage of oxygen in the generated color, indicating the growth of a thicker oxygen layer.

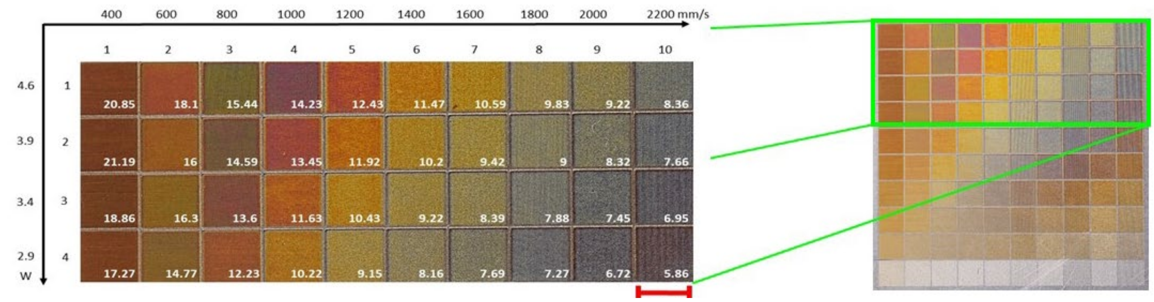

Fig. 2 Color palette generated on stainless steel surface using femtosecond laser in GHz burst mode. The white numbers on the picture indicate the percentage of the oxygen.

Another approach for color generation involved laser beam defocusing. By defocusing the beam from the stainless steel surface, the beam diameter changes, thus altering the pulse overlap. The marking parameters were chosen for green color at focus position (see Fig. 3.) and by beginning to defocus by 0.5 mm, a bright blue color was achieved when the defocusing distance reached 3 mm. At each step, a new color emerged, but beyond 3 mm, the color became uneven. It is important to note that the surface structure of the colored area remained unchanged and could be compared to the original stainless steel surface.

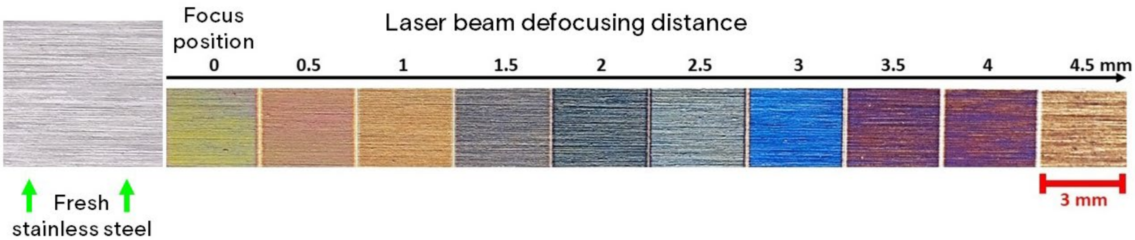

Fig. 3. Color palette generated on stainless steel surface using femtosecond laser in GHz burst mode.

Black and white marking was also performed on the stainless-steel surface. When complete surface remelting occurs and surface is rough enough, the stainless-steel turns black (see Fig. 4.). This black coloration is attributed to the trapping of light within the micro-roughness of the sample. Achieving black marking does not require any specific laser parameters, simply employing the maximum average laser power is sufficient. Conversely, in order to achieve bright coloring, a GHz burst regime needs to be employed. Without it, the white shade does not appear as vibrant.

4. Color characterization

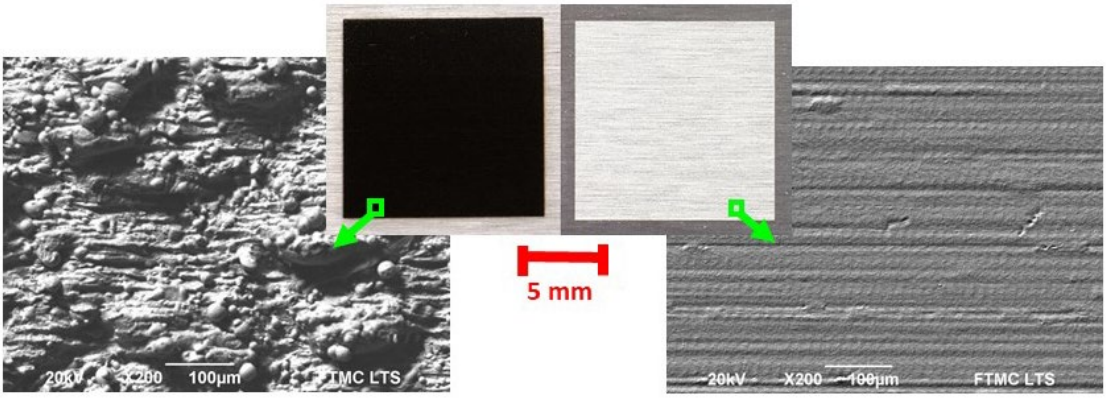

Fig. 4. SEM and regular camera photos of black and white color marking on stainless steel surface.

During the sample characterization, our focus was on measuring color homogeneity (see Fig. 5) and spectral data. This is crucial for industrial manufacturing processes, where achieving even color distribution across large surface areas is essential. A specific area was selected and photographed with the hyperspectral camera device for later data analysis. During the data analysis, pixel classification was performed using the Spectral Angle Mapping (SAM) method. By appropriately selecting the SAM angle to ensure that only pixels within our desired zone of interest were marked, the uniformity of desired marked area could be calculated as a percentage. During the color characterization we found that the sample color changes depending on applied parameters.

The spectral measurements revealed distinct color properties associated with laser-induced coloration on the metal samples. The reflectance spectra exhibited characteristic peaks and valleys across the visible spectrum, indicating selective absorption and reflection of different wavelengths. The observed colors ranged from violet to red and their combinations. Measured L*a*b* coordinates let us to convert spectral data to RGB values.

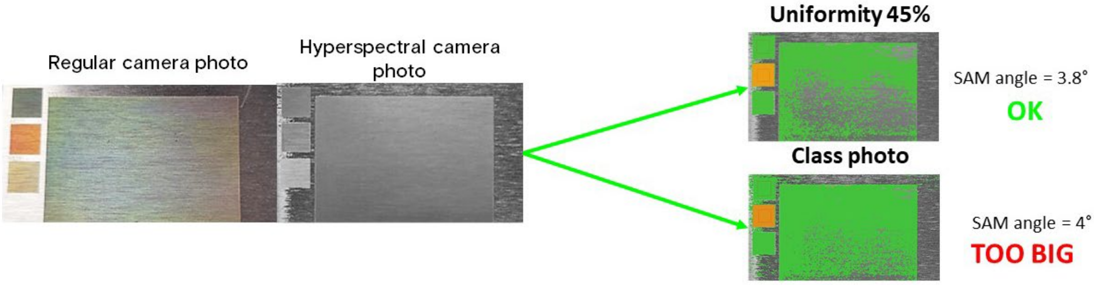

Fig. 5 Color classification path using hyperspectral camera and calculation program.

5. Conclusion

Overall, by utilizing the GHz burst mode, we are able to generate stable colors representing the entire visible spectrum, which do not change with variations in the viewing angle. Chemical analysis revealed that an oxide layer grows during the laser process, with the most significant changes observed in the composition of iron and oxygen. Following the experiments, further studies will be conducted, including the stitching of colored sectors and color measurement in CIELAB color space.

References

[1] A. Di Schino. "Manufacturing and applications of stainless steels," *Metals*, vol. 10, no. 3. MDPI AG, 2020.

[2] K. Yang and Y. Ren. "Nickel-free austenitic stainless steels for medical applications," *Sci Technol Adv Mater*, vol. 11, no. 1, 2010.

[3] G. Juhász, M. Berczeli, and Z. Weltsch. "Formation of Oxide Layers with Femtosecond Laser on Steel Surfaces for Color Marking," *International Journal of Engineering and Management Sciences (IJEMS)*, vol. 5, no. 2, 2020.

[4] Y. Lu *et al.* "Nanosecond laser coloration on stainless steel surface," *Sci Rep*, vol. 7, no. 1, Dec. 2017.

[5] Arkadiusz J. Antończak, Dariusz Kocoń, Maciej Nowak, Paweł Kozioł, Krzysztof M. Abramski. "Laser-induced color marking—Sensitivity scaling for a stainless steel," *Appl. Surf. Sci*, vol. 264, 2013.

[6] Z.L. Li, H.Y. Zheng, K.M. Teh, Y.C. Liu, G.C. Lim, H.L. Seng, N.L. Yakovlev. "Analysis of oxide formation induced by UV laser coloration of stainless steel", *Appl. Surf. Sci*. vol 256, 2009.

[7] A. Lehmuskero, V. Kontturi, J. Hiltunen, M. Kuittinen. "Modeling of laser colored stainless steel surfaces by color pixels," *Appl. Phys*. B **98**, 2009.

[8] A. Y. Vorobyev and C. Guo. "Direct femtosecond laser surface nano/microstructuring and its applications," *Laser and Photonics Reviews*, vol. 7, no. 3, 2013.

[9] B. Dusser, Z. Sagan, H. Soder, N. Faure, J.P. Colombier, M. Jourlin, and E. Audouard. "Controlled nanostructrures formation by ultra fast laser pulses for color marking," *Opt. Express* 18, 2010.

[10] M. Milad, N. Zreiba, F. Elhalouani, C. Baradai. "The effect of cold work on structure and properties of AISI 304 stainless steel," *Journal of Materials Processing Technology*, volume 203, Issues 1–3, 2008.