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Analysing the Influence of Technological Parameters on the Process of Laser Marking of Surface of Anodised Aluminium Samples

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Abstract. **The requirements for marking in terms of contrast and durability are constantly increasing. In order to meet all these challenges, it is necessary to carry out research leading to the optimisation and increase in efficiency of the technological process of laser marking. In the case of aluminium, the contrast and durability of the marking depend on the values of the laser marking parameters. In order to determine the optimal laser marking method, experimental studies have been carried out, controlling the power, speed, frequency, pulse duration and line raster step for a specific anodised aluminium. The studies carried out were analysed and subsequently optimized to obtain a contrast marking. A Rofin PowerLine F 20 Varia fiber laser system and aluminium alloy 1050 with anodised surface were used for the research. The surface changes after the laser treatment were analysed using a laser scanning microscope and contrast determination method. The dependence of contrast and roughness on speed, power, frequency and raster step was analysed. Comparative plots of contrast and roughness variations versus laser marking technological parameters were constructed.**

Keywords: laser marking, fiber laser, laser surface texturing, aluminium, contrast, roughness.

I. INTRODUCTION

Aluminium's distinctive chemical, electrical, thermal, and mechanical properties make it suitable for a wide range of applications. By utilizing an electrochemical process known as anodising, aluminium can produce a transparent coating that can achieve a surface hardness like that of sapphire, depending on the thickness of the coating and the anodising procedure used. Anodising is an electrochemical technique that transforms the metal surface into a long-lasting, corrosion-resistant, decorative, anodic oxide finish that is completely fused with the aluminium base, preventing chipping or peeling. Aluminium is utilized as a raw material for a broad range of products, and these items typically require some characters or symbols to be printed directly on them. In this regard, laser marking is a widely used, dependable, and efficient process in the industry. Nonetheless, when it comes to marking aluminium, laser marking still produces unsatisfactory results since it cannot generate a dark mark, resulting in poor contrast [1] - [3].

In modern electronics and machine production, laser marking has become a crucial tool for meeting current quality control standards. Laser marking is frequently used in industrial manufacturing and trade to mark serial numbers, matrix codes, 1D and 2D barcodes, technical parameters, tables, and other operational information, as well as for monitoring production processes. This has made laser marking an integral part of the production process [4]. Laser marking is well-suited for marking intricate geometries at a rapid processing speed [5]. The three primary components of laser marking systems are the control unit, laser source, and scanner. The control

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unit processes the commands of the laser operator and manages both the laser source and scanner. The laser source produces a beam and is regulated by input parameters such as pulse repetition frequency, pulse energy, and pulse duration. The scanner guides the laser beam and is regulated by input parameters such as scanning speed, line step, and focal length. These input parameters of both the laser source and scanner are collectively known as laser parameters [6].

The use of laser processing enables an increase in the hardness and wear resistance of aluminium surfaces [7].

Laser marking has been increasingly utilized in recent years for automated reading of alphanumeric or coded information such as bar and matrix codes on individual components or products. The laser-marked parts and details containing coded information can be automatically read, allowing for monitoring during the manufacturing process and throughout the supply chain. This is beneficial for finding service parts and repairs, filing claims, and ensuring accountability and warranty compliance [8].

In general, laser marking involves the targeted removal or melting of material from a surface using a high-powered, focused laser beam, resulting in localized heating and various modifications to the material, such as melting, vaporization, decomposition, or chemical alteration. The resulting marks or engravings are influenced by the laser and material parameters and are typically generated through material removal via ablation or the induction of a phase change [9].

In order to enhance the laser marking of aluminium products, it is crucial to determine the most appropriate marking method, as well as the optimal parameters of the laser and technological process specific to each individual case [10].

Numerous publications have investigated the influence of marking speed and raster step on the process of laser marking. Through the optimization of certain parameters, it is possible to create high-contrast markings on the surface of aluminium [11] - [13]. For marking on an anodised aluminium sample, it is recommended to use a fiber laser as it produces the darkest colour [14]. The quality of the marking is crucial when handling products in warehouses, sales outlets, and other settings [15].

The quality of laser marking is significantly influenced by the level of contrast [16]. For the laser marking process to be optimized, it is necessary to conduct experiments and optimize parameters for each new product [17].

The focus of this study is laser marking the aluminium surface of the anode, with a specific emphasis on investigating the impact of various parameters on surface roughness, including laser power, pulse frequency, scanning speed, and raster step. Furthermore, the study also examines the effect of these parameters on contrast.

II. MATERIALS AND METHODS

Material

For the experimental study, sulfuric acid anodised aluminium plates of 50 mm x 50 mm x 1,1 mm have been employed.

Surfaces samples were cleaned with $C_5H_{12}O$, to remove all dirt that would influence the results of the experiments.

Experimental set-up

Nanosecond pulse mode was employed in the research using the Rofin Sinar Laser GmbH PowerLine F 20 Varia machine, which is a Yb-doped fibre laser, see in Fig. 1.

Fig. 1. Rofin PowerLine F 20 fiber laser.

A f-theta lens with a focal distance of 184 mm was installed on this fibre laser, resulting in a spot size of 40 μm at the focus point. The general specifications of the employed laser system are summarized in Table 1.

TABLE 1. CHARACTERISTICS ROFIN POWERLINE F 20 FIBER LASER OF THE LASER SYSTEM

Parameter	**Value**
Wavelength λ, nm	1064
Power P, W	0-19.7
Pulse duration τ, ns	4-200
Frequency f, kHz	2-1000
Scan speed v, mm/s	1-2000

The laser processed anodised aluminium sample's structure change was examined with laser scanning microscope Lext 3D OLS5000, which is shown in Fig. 2.

Fig. 2. Lext 3D measuring G Laser microscope OLS5000.

The marked anodised aluminium samples contrast was measured with Adobe Photoshop by previously scanning samples with a HP Scanjet G3010 scanner.

Methodology

To carry out the experiments, the Visual Laser Marker software integrated into the PowerLine F 20 Varia laser was utilized to create a matrix with 6 columns and 6 rows. A specialized matrix consisting of squares with 5 mm sides was then prepared for the study. This matrix enabled the application of different technological parameters to each square based on the selected experimental methodology. Laser marking was conducted on two anodised aluminium samples, resulting in 2 unique and distinct laser-processed samples with varying technological parameters.

First matrix is processed with different scanning speeds (v, 25 – 150 mm/s) and raster step (Δx, 5 µm -30 µm). General view of an exemplary experimental first matrix given in Fig. 3. The parameters that are kept constant are given in Table 2.

TABLE 2. PARAMETERS THAT DO NOT CHANGE DURING EXPERIMENTS

Parameter	**Value**
Power P, W	3.2
Frequency f, kHz	20
Pulse duration τ, ns	14

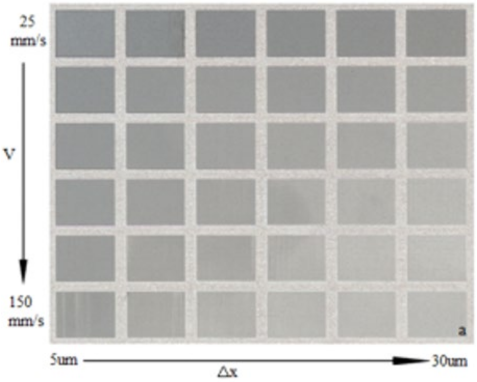


Fig. 3. General view of an exemplary experimental first matrix used in the researches.

Second matrix was marked with different average power (P, 0.1 - 2.5 W) and frequency (f, 2 – 25 kHz). General view of an exemplary experimental first matrix given in Fig. 4. The parameters that are kept constant are given in Table 3.

TABLE 3. PARAMETERS THAT DO NOT CHANGE DURING EXPERIMENTS

Parameter	**Value**
Raster step Δx, µm	10
Scanning speed v, mm/s	100
Pulse duration τ, ns	8

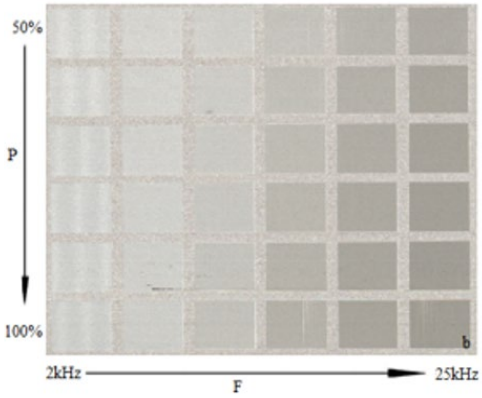


Fig. 4. General view of an exemplary experimental second matrix used in the researches.

The experiment was done in an open room. After samples were marked, they were stored in airtight bags to avoid stains.

The average power of Rofin Powerline Varia f20 laser depends on the frequency and impulse length used within the treatment process, as it is mentioned in laser system manual and confirmed using power measurement sensor OPHIR F150A-BB-26.

By observing Fig. 5 it could be seen how laser average power changes with different frequency and impulse width at different power factors (%) entered in the laser system software within 8 ns pulse duration.

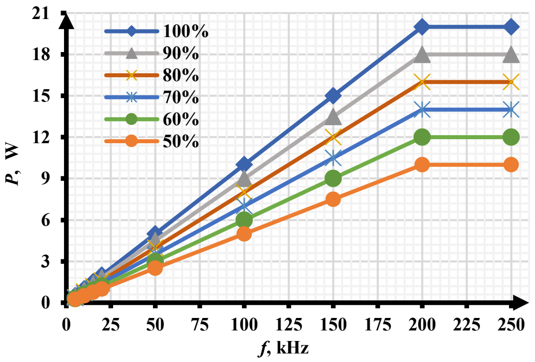


Fig. 5. Average power dependence of impulse width and frequency at different laser system software power factors.

The formula (1) was used to calculate marking contrast. The contrast is defined in percentages (%).

$$k * = \frac{N_n - N_f}{N_f} x\ 100\ \% \quad (1)$$

where: N_n – is the intensity of the light reflected from the affected zone on the sample; N_f - is the intensity of the light reflected from the untreated surface of the sample (from the background).

The overlap coefficient influences the roughness and contrast of the marking. There are two overlap coefficients: pulse overlap coefficient (K_{ov}) and coefficient of overlap between lines (K_{soc}). This coefficient determines the pulse or line overlap in percent within a single laser scanning path. They can be calculated by using formula (2) and formula (3):

$$K_{soc} = \left(1 - \frac{\Delta x}{d}\right) \times 100\ \% \quad (2)$$

$$K_{ov} = \left(1 - \frac{v}{f \times d}\right) \times 100\ \% \quad (3)$$

where: Δx – distance between scanning lines (mm); d – laser point diameter (mm), (for aluminium 0,04 mm); v – scanning speed (mm/s); f – laser frequency (kHz).

III. RESULTS AND DISCUSSION

A laser-marked sample is created with a grid of 5×5 mm squares, showing how the laser-marked surface changes for each square in the matrix.

The marking contrast for each of the marked surfaces was calculated according to equation (1). A prerequisite for good readability is a permanent high contrast between the applied marking and the surrounding material. To ensure that the Q-code is scanned accurately, the contrast between the Q-code and the surface on which it is applied should be greater than 15 %.

How different parameters affect the contrast of market anodised aluminium is shown in Fig. 6 to Fig. 9.

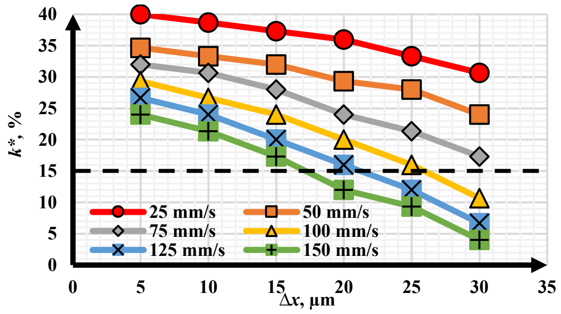


Fig. 6. Contrast dependence on the raster step and constant scanning speed.

Analysing the graph in Fig. 6, we can see that the highest contrast of 40 % is formed with a low scanning speed and raster step. Contrast marking is possible at all scanning speeds, but with a scanning speed of 100 mm/s, the contrast marking is formed with a raster step of 25 µm, with 125 mm/s up to 20 µm, and with 150 mm/s – 17 µm. The lowest contrast is formed with a large scanning speed (150 mm/s) and raster step (30 µm).

Moreover, increasing the scanning speed and the raster step decreases the colour reflection.

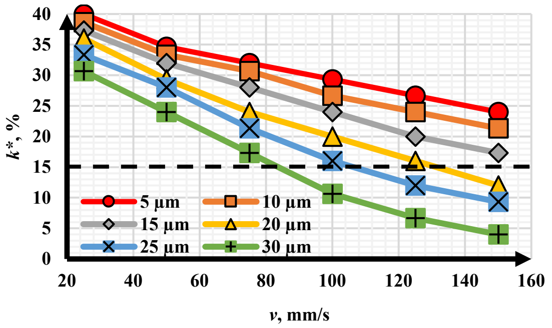


Fig. 7. Contrast dependence on the scanning speed and constant raster step.

Analysing the graph in Fig. 7, it is found that the contrast decreases with the increasing scanning speed and raster step, but the contrast is higher when the scanning speed and the raster step are the smallest.

The highest contrast is observed at a scanning speed of 25 mm/s and a raster step of 5 µm.

Changing the power and frequency of the laser, it turned out that a marking that is lighter than the material itself can be achieved.

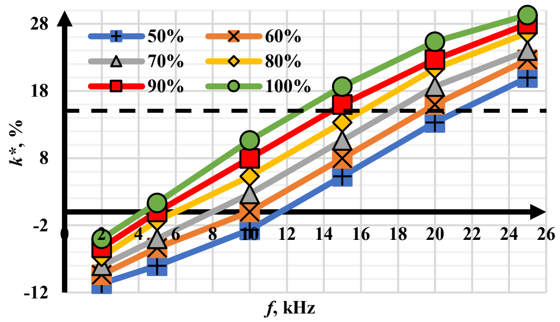


Fig. 8. Contrast dependence on the frequency and constant power.

Analysing the graph in Fig. 8, it can be observed that the contrast is higher with a high frequency and power. A contrast marking is possible if any laser power is used, but a frequency of 13 kHz and above must be used. In the graph, we can see a negative contrast because the marking appears white, which is lighter than the material itself.

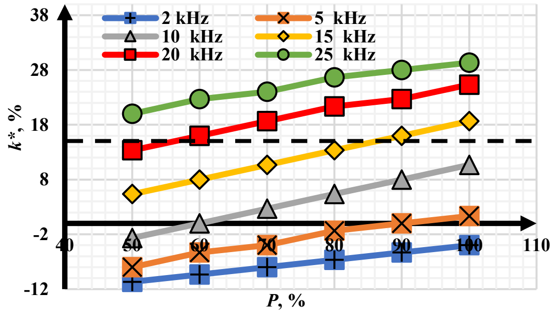


Fig. 9. Contrast dependence on the power and constant frequency.

From the analysis of the graphs in Fig. 9, increasing the laser power and frequency results in an increase in marking contrast. With a small frequency range of 2 to 10 kHz, a contrast marking is not formed. The highest contrast of 29 % is observed with a frequency of 25 kHz and power of 100%.

The effect of pulse overlap on the contrast of the marked anodised aluminium is illustrated in Fig. 10 to Fig.13.

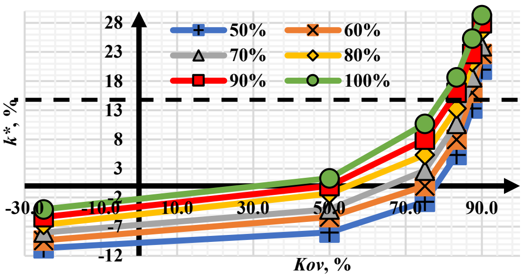


Fig. 10. Contrast dependence on the pulse overlap and constant power.

From the graph in Fig. 10, it can be observed that to achieve a contrast marking with a laser power of 10 to 100 %, a pulse overlap of 85 % of the laser pulses incident on the surface of the material is required.

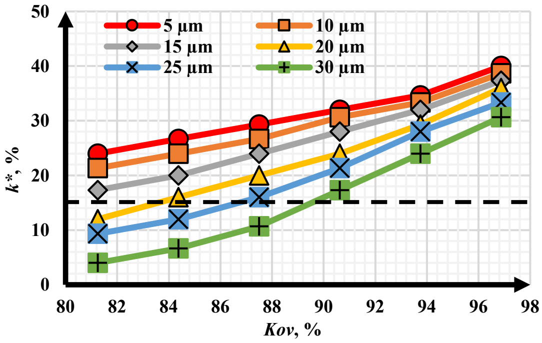


Fig. 11. Contrast dependence on the pulse overlap and constant raster step.

From the analysis of the graphs in Fig. 11, it can be concluded that contrast increases with an increase in raster step and pulse overlap. A contrast marking is possible at a raster step of 5, 10, and 15 µm, but to obtain a contrast marking at a higher raster step, a 90 % pulse overlap of one laser scan path is required.

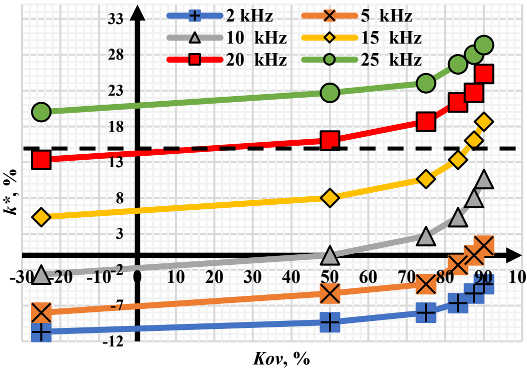


Fig. 12. Graph of the contrast of the marking from pulse overlap and frequency.

From the analysis of the graphs in Fig. 12, it can be concluded that a contrast marking is possible at a frequency of 25 kHz. With a frequency of 20 kHz, a contrast marking can be formed at a pulse overlap of 20 %.

Analysing the graph in Fig. 13, it is found that the contrast increases with an increase in pulse overlap. A contrast marking is possible with a scanning speed of 25, 50, and 75 mm/s, but a pulse overlap of 90 % is required when using a scanning speed of 100mm/s.

The most important result of the contrast analysis after marking is that the highest contrast is formed at low scanning speed and raster step.

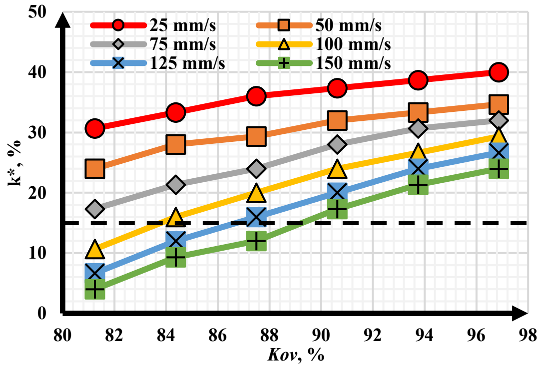


Fig. 13. Graph of the contrast of the marking from pulse overlap and scanning speed.

Analysing the roughness of a labelled sample is crucial for evaluating the durability of a part. If a part is rougher than it needs to be, there can be irregularities in the surface that will cause quicker wear and tear, breaks, and corrosion. The effect of different parameters on the roughness of the marked anodised aluminium is illustrated in Fig. 14 to Fig. 19.

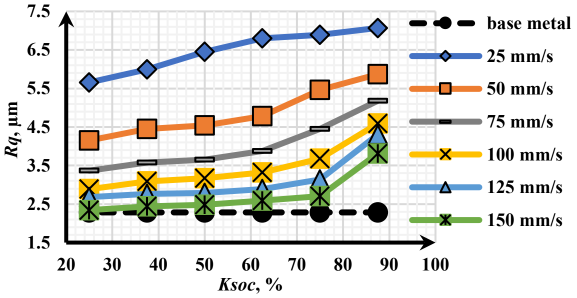


Fig. 14. Roughness dependence on the overlap between line and constant scanning speed.

From the analysis of the experimental roughness results, it can be observed that:

- The smallest roughness is formed with a scanning speed of 150 mm/s and an overlap between lines of 25 %.
- The highest roughness, on the other hand, is formed at a scanning speed of 25 mm/s.

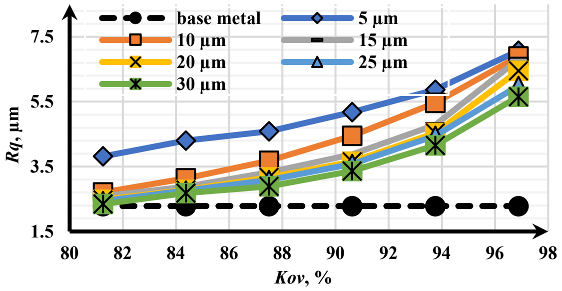


Fig. 15. Roughness dependence on the pulse overlap and constant raster step.

Analysing the structural change in anodised aluminium, a smallest roughness can be obtained with a raster step of 30 µm and an overlap of pulses of 81%.

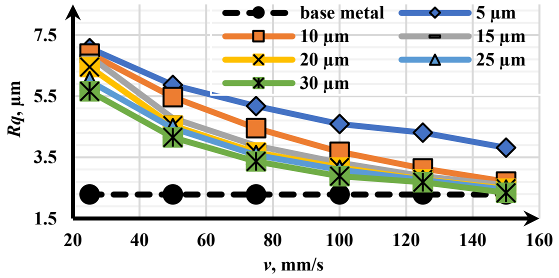


Fig. 16. Roughness dependence on the scanning speed and constant raster step.

Analysing the graph in Fig. 16, it can be observed that the roughness of the marked samples decreases as the scanning speed increases. The smallest roughness is formed at a scanning speed of 150 mm/s and a raster step of 30 µm compared to the average unmarked sample.

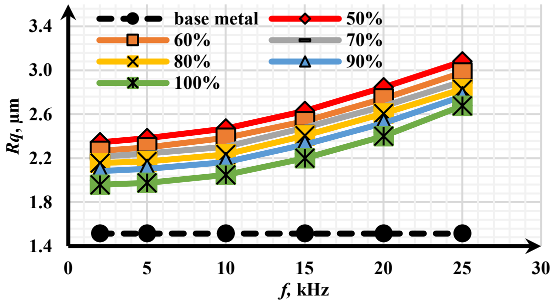


Fig. 17. Roughness dependence on the frequency and constant power.

From the analysis of the graphs in Fig. 17, it can be seen that the roughness is high with 50% power and 25 kHz frequency, while small roughness is obtained with 100 % power and 2 kHz frequency.

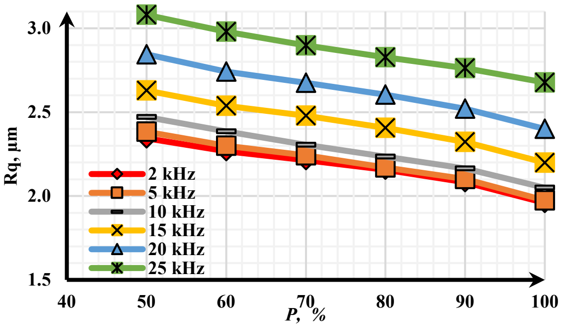


Fig. 18. Roughness dependence on the power and constant frequency.

From the analysis of the graphs in Fig. 18, it can be seen that the smallest roughness is obtained with 2kHz frequency and 100 % laser power.

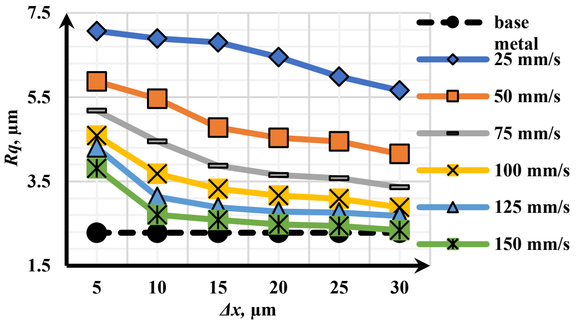
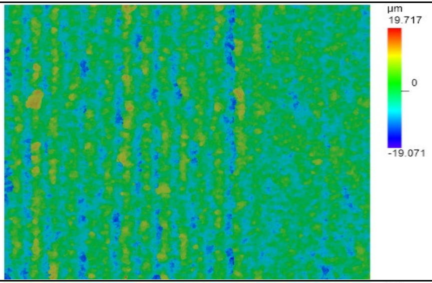
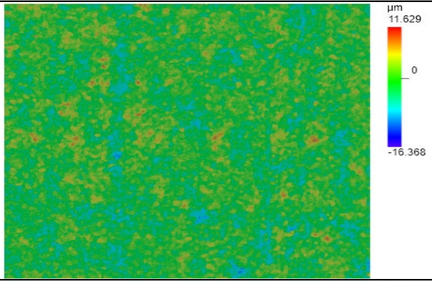
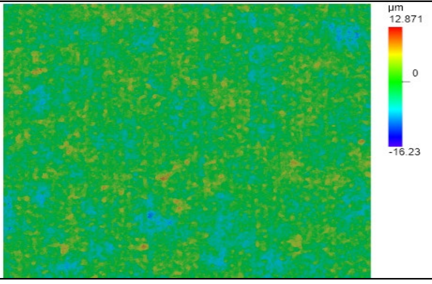


Fig. 19. Roughness dependence on the raster step and constant scanning speed.

Analysing the graph in Fig. 19, it can be observed that the highest roughness of the marked samples is 7.07 µm and the smallest roughness is 2.34 µm. Further analysis of the roughness data reveals the following:

- The marked samples exhibit the highest roughness at a scanning speed of 25 mm/s compared to the unmarked sample.
- The smallest roughness is obtained with a scanning speed of 150 mm/s compared to the average unmarked sample.

	V=150 mm/s
5 µm	
10 µm	
15 µm	

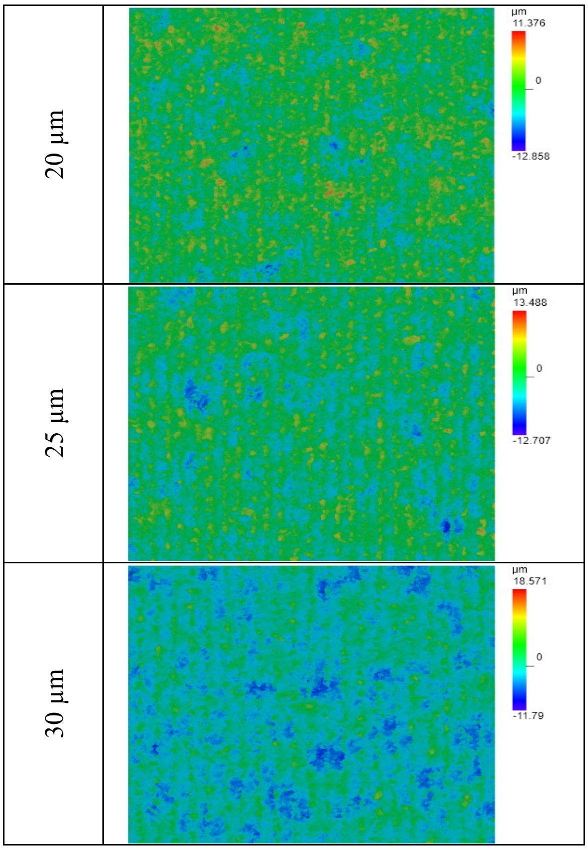


Fig. 20. Roughness changes in scanning speed 150 mm/s.

The most important result of the roughness analysis after marking is that the lowest roughness is obtained at the highest scanning speed and raster step, as shown in Fig. 20.

IV. CONCLUSIONS

This study used a Rofin PowerLine F 20 fiber laser to determine laser parameters impact for marking on anodised aluminium. The laser parameters were optimized to achieve high contrast marking. Based on the results of the experiment, it is possible to understand which parameters are suitable for contrast marking and which are not. From the experimental results, the main conclusions are:

- It is possible to understand which parameters are suitable for contrast marking and which are not based on the results of the experiment.
- Changing the power and frequency of the laser resulted in a lighter marking than the material itself. However, since the PowerLine F20 Varia system was used, it was impossible to make the frequency less than 2 kHz, so a contrasting white marking was not possible.
- The highest contrast was achieved at a speed of 25 mm/s and a raster step of 25 µm.
- Increasing the laser power and frequency increased the contrast of the marked surface.
- Laser marking with a frequency of 2 kHz and a laser power of 100 % produced the smallest surface roughness of anodised aluminium.
- A gradual increase in surface roughness values was observed at higher pulse and line overlap.

V. ACKNOWLEDGMENT

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