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Investigation of laser texturing on the surface of anodized aluminium

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Abstract. **This study examines the texturing of anodized aluminium using a Rofin PowerLine F 20 Varia nanosecond Yb doped fiber laser. It explores how varying laser parameters like scanning speed, hatching step, laser power, and frequency impact the surface's wetting properties, particularly the contact angle with a water droplet. The research aims to understand the influence of these parameters on the aluminium's surface, offering insights into the laser micromachining process and its industrial and material science applications. This study examines the texturing of anodized aluminium using a Rofin PowerLine F 20 Varia nanosecond Yb doped fiber laser. It explores how varying laser parameters like scanning speed, hatching step, laser power, and frequency impact the surface's wetting properties, particularly the contact angle with a water droplet. The research aims to understand the influence of these parameters on the aluminium's surface, offering insights into the laser micromachining process and its industrial and material science applications.**
This study investigates the texturing of anodized aluminium using a Rofin PowerLine F20 Varia nanosecond fiber laser. It investigates how different laser parameters such as scan speed, hatching step, laser power and frequency affect the surface wetting properties, especially the contact angle of a water droplet. The research aims to understand the influence of these parameters on the aluminium surface, offering insights into the laser micromachining process and its applications in industry and materials science.

Keywords: nanosecond laser, laser texturing, fiber laser, roughness, wettability.

I. INTRODUCTION

Aluminium stands out as the most abundant metal in the earth's crust, and he are one of the most widely used metal structural materials. Anodized aluminium exceptional chemical, electrical, thermal, and mechanical properties make it indispensable across numerous industries, ranging from aerospace to consumer electronics. Through anodising aluminium can develop a transparent coating with hardness akin to sapphire, contingent upon the coating thickness and anodising procedure employed. In recent years, the exploration of surface treatment techniques has garnered significant attention to further enhance aluminium performance characteristics. Additionally, it examines the role of laser marking as a complementary method for achieving precise surface modifications [1] - [4].

The strengths of various laser marking techniques, and their suitability for industrial use, have been amply analysed and reported by many researchers over the years. The vast expertise accumulated to-date makes it possible to understand the influence of various material properties and processing parameters on the quality [5].

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 [6].

Laser technology offers an efficient approach for creating micro/nano structures directly onto various materials while ensuring precise control over their size.

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Researchers are actively investigating hydrophobic metal structures crafted using nanosecond laser techniques. Laser machining at micro and nano scales enables the fabrication of surfaces with robust hydrophobic or hydrophilic features, presenting promising applications across environmental, medical, agricultural. Recent focus has been on surface wettability, particularly super-hydrophilic and super-hydrophobic characteristics. The terms hydrophilic and hydrophobic have been extensively used in literature to describe water behaviour on solid surfaces, typically measured through water droplet contact angles (CA). Surface roughness and energy significantly influence wettability, with roughness being a primary determinant. According to the Cassie-Baxter model, incomplete wetting on rough surfaces is attributed to entrapped air pockets, resulting in higher contact angles compared to smoother surfaces. Surfaces are categorized as hydrophilic, when the CA is less than 90 and hydrophobic, when the CA is greater than 90°. Superhydrophobic surface is when the CA is greater than 150° [7] - [12].

Numerous studies revealed that laser-textured surfaces are usually hydrophilic shortly after laser treatment, then turn superhydrophobic after storage in an ambient atmosphere [13].

Prior to implementing the laser method for various industrial products, it is crucial to optimize the technological procedures. This involves performing a combination of numerical simulations and practical experiments to pinpoint the optimal operational parameters for laser marking [14].

The main objective of this study is to investigate the laser marking techniques on the aluminium anode surface, in particular delving into the effects of various parameters on the surface structure and hydrophilicity. By fine-tuning the laser processing parameters, we can generate different micro/nano structures, thus influencing the hydrophilic properties of the surface.

II. MATERIALS AND METHODS

2.1 Material

Anodized aluminum is a material that has undergone an anodizing process in which the aluminum surface is covered with an oxide layer, increasing its resistance to corrosion and improving other physical and chemical characteristics. Anodized aluminum is widely used in various industries and elsewhere where high resistance to corrosion and mechanical wear is required.

In the experimental investigation used anodized aluminum plates measuring 50 mm x 50 mm x 1.1 mm. To ensure the integrity of our results, surface samples underwent a thorough cleaning process with $C_5H_{12}O$ to eliminate any contaminants that could impact the experimental outcomes.

2.2 Experimental set-up

For the marking of the anodized aluminium samples are used the nanosecond Fiber laser Rofin PowerLine F 20 Varia, see in Fig. 1.

A fiber laser was equipped with an f-theta lens having a focal length of 184 mm, which yielded a spot size of 40 µm at the focal point. The technical specifications of the Rofin PowerLine F20 laser system are presented in Table 1.

Fig. 1. Fiber laser Rofin PowerLine F20 [15].

A fiber laser was equipped with an f-theta lens having a focal length of 184 mm, which yielded a spot size of 40 µm at the focal point. The technical specifications of the Rofin PowerLine F20 laser system are presented in Table 1.

TABLE 1. LASER SYSTEM ROFIN POWERLINE F 20 TEHNICAL SPECIFICATIONS

Laser type	Fiber laser
Wavelength	1064 nm
Power	0…19.7 W
Pulse duration	4, 8, 14, 20, 30, 50, 100, 200 ns
Pulse repetition frequency	2…1000 kHz
Scan speed	1…20000 mm/s
Line step	0,001…120 mm
Focus shift	-10…10 mm
Beam quality	<1,5 M^2

With the assistance of a digital microscope, the layer of deionized water applied by a dispenser onto the processed square of anodized aluminium sample was measured. The digital microscope is shown in Fig 2.

Fig. 2. Microscope Dino-Lite AM7115MZT EDGE [16].

The technical parameters of the digital microscope are presented in Table 2.

TABLE 2. TEHNICAL SPECIFICATION OF DINO-LITE EDGE AM7115MZT

Light/ LED type	White
Number of LEDs	8
Resolution	5 mega pixels (2592x1944)
Magnification	10-220x
Dimensions	10.5cm (height) x 3.2cm (diameters)
Operating system	Windows

Before measuring the contact angle, the samples of anodized aluminium were cleaned with C5H7OH, to remove all dirt.

Using a microscope Dino Capture 2.0 software and pulling down a tangent line between the sides of the drop, similar to what was indicated above in Fig. 4 was measured wettability angle. The controlled dose of the drop is 10 µl, which is administered manually, according to standard D7334-08.

Schematic view of experimental set-up could be observed in Fig.3.

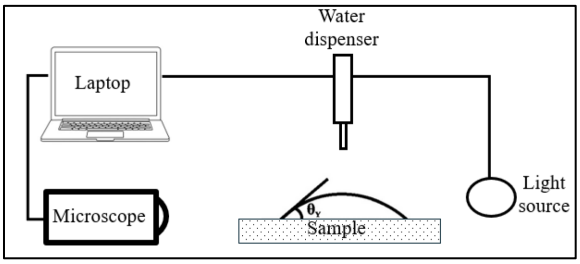

Fig. 3. Schematic view of experimental set-up of wettability measurement.

Example of made wettability measurements could be observed in Fig. 4.

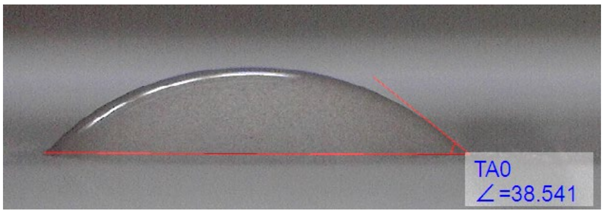

Fig. 4. Anodized aluminium with laser measurement of market surface wetting, where the contact angle of the water drop is 38,5°.

2.3 Methodology

The experiment was done in laser technologies research center.

The experiment began with the use of the Visual Laser Marker software to generate a matrix with 6 columns and 6 rows. Subsequently, the software was configured to set laser parameters accordingly. Following this setup, the matrix was then marked onto an anodized aluminium plate. As a result, two matrices were created, each featuring different laser processing parameters.

In the first matrix, the constant parameters were the average power (*P*), frequency (*ν*), pulse duration (*τ)* and different - scanning speed (*v*) and raster step (*Δx)*. In the second matrix, the constant parameters were the raster step (*Δx*), scanning speed (*v*), pulse duration (*τ)* and different - average power (*P*) and frequency (*ν*).

The matrix parameters are presented in Table 3.

TABLE 3. LASER MARKING PARAMETERS FOR ANODIZED ALUMINIUM SAMPLE

Matrix	**1**	**2**
Power	3.2 W	0.1 - 2.5 W
Frequency	20 kHz	2 – 25 kHz
Pulse duration	14 ns	8 ns
Scanning speed	25–150 mm/s	100 mm/s
Raster step	5 -30 µm	10 µm

General view of an exemplary experimental first matrix given in Fig. 5.

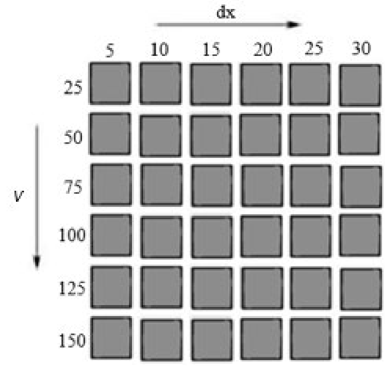

Fig. 5. General view of an exemplary experimental first matrix used in the researches.

General view of an exemplary experimental second matrix given in Fig. 6.

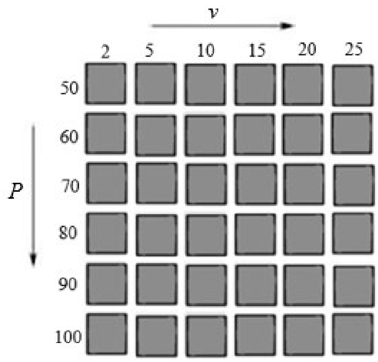

Fig. 6. General view of an exemplary experimental second matrix used in the researches.

The average power of the Rofin Powerline Varia F20 laser varies depending on the frequency and pulse length used in the treatment process. This is confirmed by both the laser system manual and measurements made with the OPHIR F150A-BB-26 power measurement sensor.

Fig. 7 show how the average laser power changes with different frequencies and pulse widths at different power factors (%) entered in the laser system software with an 8 ns pulse duration [17].

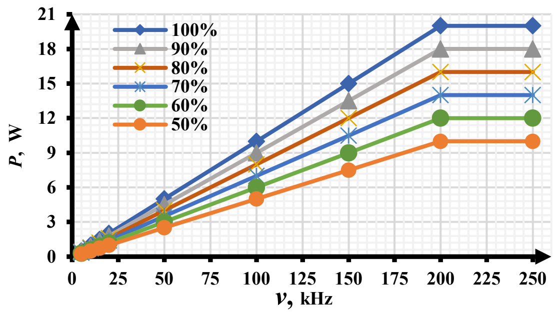

Fig. 7. Average power dependence of impulse width and frequency at different laser system software power factors [17].

Pulse overlap (k_{ov}) is parameter in laser processing, which determines the pulse overlap in percent within single laser scanning path. It can be calculated by using formula (1).

$$k_{ov} = \left(1 - \frac{v}{\nu \times d}\right) \times 100\ \% \qquad (1)$$

where: v – scanning speed (mm/s),

ν – laser frequency (kHz),

d – laser point diameter (mm).

Line overlap (k_{soc}) is parameter in laser processing, which determines the line overlap in percent within a single laser scanning path. It can be calculated by using formula (2).

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

where: Δx – distance between scanning lines (mm),

d – laser point diameter (mm).

Laser point diameter for aluminium is 0,04 mm.

III. RESULTS AND DISCUSSION

How different parameters affect the hydrophobicity and hydrophilicity of marked anodised aluminium is shown in Fig. 8 to Fig. 15.

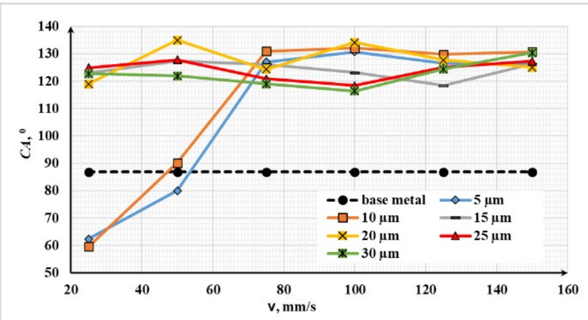

Fig. 8. Contact angle dependence on the scanning speed.

Analysing the graph in Fig. 8, can see that a hydrophilic surface can be obtained with a scanning speed of 25 mm/s and raster step of 5 µm,10 µm, as well as with a scanning speed of 50 mm/s and a raster step of 5 µm, because the contact angle is less than 90 degrees.

With for the others scanning speed and raster step, hydrophobic surfaces can be obtained, because the contact angle of water is greater than 90 degrees.

In the first matrix an untreated anodized aluminium surface is hydrophilic. When marking anodized aluminium with scanning speed 50 mm/s and raster step 10 µm, the surface structure changes from hydrophilic to hydrophobic.

By changing the laser scanning speed and raster step, a superhydrophobic surface cannot be obtained.

The largest contact angle 135 degrees, formed with scanning speed 150 mm/s and raster step 20 µm.

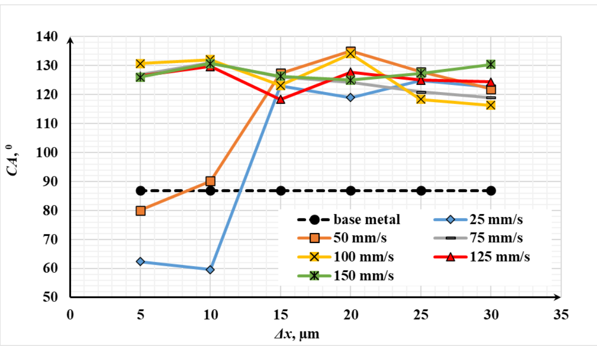

Fig. 9. Contact angle dependence on the raster step.

From Fig. 9 can see, the contact angle decreases with increasing scanning speed for all raster step values. This suggests that higher scanning speeds lead to a more wetted surface. The effect of scanning speed is more pronounced at smaller raster steps. This means that the difference in contact angle between different scanning speeds is larger at smaller raster steps.

There is a general trend of decreasing contact angle with increasing raster step for all scanning speeds. This suggests that larger raster steps lead to a more wetted surface.

Increasing the raster step, the contact angle is increased, and the line overlap (k_{soc}) is reduced, because the distance between the scanning points affects the laser deflection and the line arrangement on the surface of the material.

The smallest contact angle 60 degrees, formed with raster step 10 µm scanning speed 25 mm/s.

In the first matrix, the line overlap increases as the raster step increases, which means the lines are projected wider, and as a result, the overlap between them is reduced.

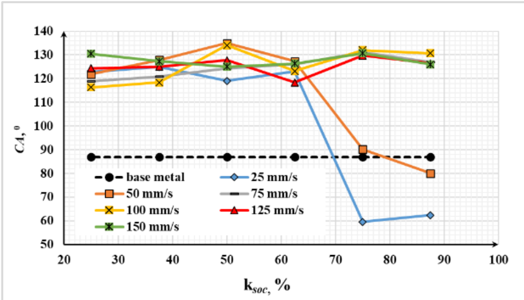

Fig. 10. Contact angle dependence on line overlap and scanning speed.

Fig. 10 show, the increasing the line overlap coefficient, the surface changes from hydrophobic to hydrophilic. At high scanning speed from 75 mm/s to 125 mm/s, the line overlap ratio indicates little change in hydrophobicity.

The smallest contact angle is 62 degrees, formed with a scanning speed of 25 mm/s and a line overlap coefficient of 75 percent.

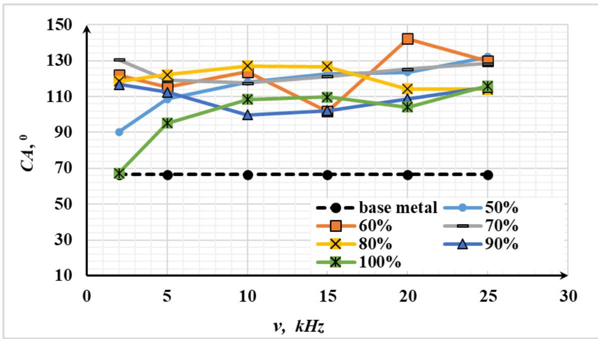

Fig. 11. Contact angle dependence on the frequency.

Based on the graph data in Fig. 11, it is evident that the formation of a hydrophobic surface on the second matrix occurs at all laser power setting and frequency, but only with laser power 100% and 2 kHz frequency are hydrophilic surface.

At the frequency from 2 to 25 kHz and laser power 50%, the water contact angle increases, but using others laser powers the contact angle both increases and decreases as the frequency changes.

The largest contact angle 142 degrees, formed with frequency 20 kHz and laser power 60%.

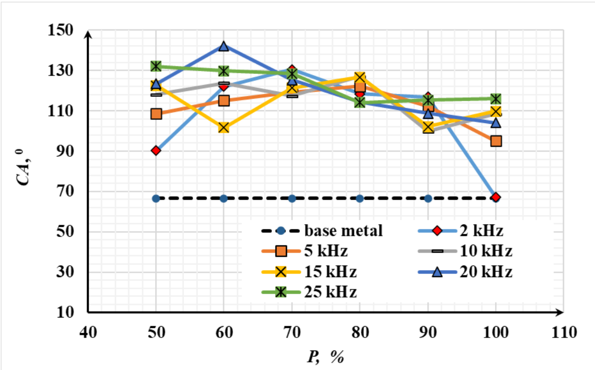

Fig. 12. Contact angle dependence on the average power.

From the analysis of the experimental wettability in Fig. 12, it can be observed that:

- The smallest contact angle 67 degree is formed with a power 100% and frequency 2 kHz.
- The untreated anode aluminium sample used in the experiment in the second matrix also forms a hydrophilic surface.
- Increasing the laser power from 50% to 80% and using frequency 5 kHz, the contact angle increases because each laser pulse has a longer duration on the surface, which leads to a deeper treatment of the material. This in turn can lead to deeper changes in surface structure and properties that can affect the contact angle.

Increasing the laser power and using hight frequency 25 kHz, the contact angle decreases, because a higher frequency means more laser pulses are being applied per unit time. This can result in more frequent interactions between the laser beam and the material's surface.

In the second matrix, the overlap of pulses (k_{ov}) increases as the frequency increases, which means that several pulses are sent to the surface close to each other.

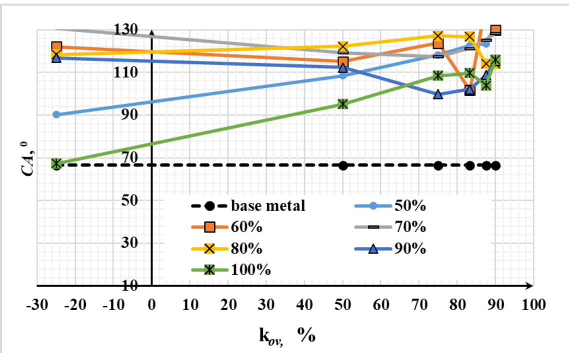

Fig. 13. Contact angle dependence on pulse overlap and power.

The increasing pulse overlap coefficient increases the contact angle, as can be seen in Fig. 13.

Hydrophobicity and hydrophilicity also can be influenced by roughness marking. Roughness can be different parameter:

- R_a - average roughness indicating the surface's average irregularity.
- R_q - root mean square providing information about the overall surface roughness, including all variations in the surface profile.
- R_z - maximum surface texture indicating the largest difference between the highest and lowest points in the surface profile.

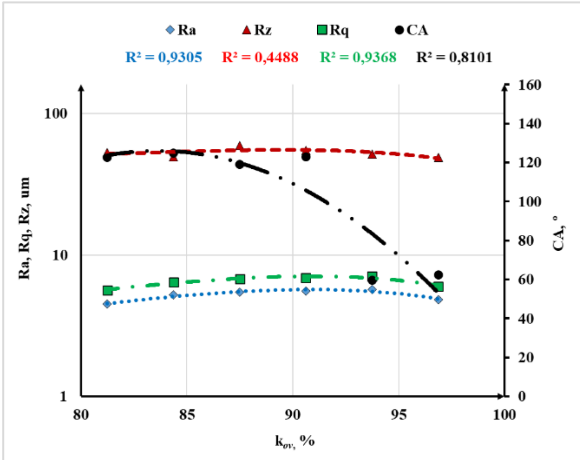

Fig. 14. Contact angle dependence on roughness for the first matrix on scanning speed 25 mm/s.

Wettability analyses trendline show that the contact angle generally increases with increasing roughness. Analyzing the Fig. 14 can see that hydrophobic surfaces repel water and cause larger contact angles, while hydrophilic surfaces attract water and cause smaller contact angles. Less roughness creates a hydrophobic character because they repel water better than a rough surface.

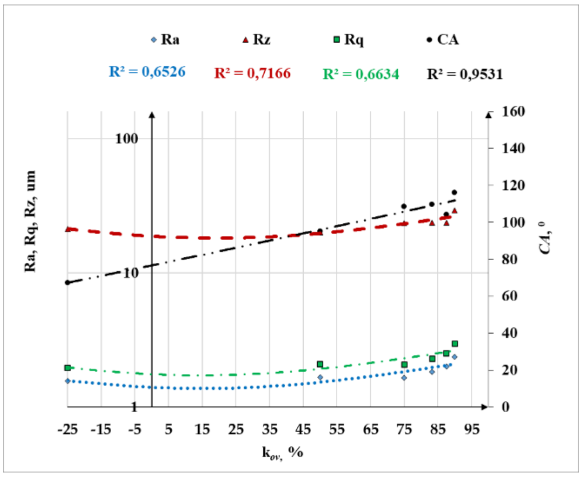

Fig. 15. Contact angle dependence on roughness for the second matrix on laser power 100 %.

Analysing the second matrix for the change in wettability from pulse overlap shows that there is a "-" sign at the beginning of the pulse overlap because the laser pulses are sent to the material with a long enough delay between them that they do not occur in an overlapping state. This situation arises because a low laser frequency of 2 kHz has been chosen.

When the pulse overlap is with the "-" sign, which means the laser pulses are not overlapped, it creates smooth surface with minimal roughness of 1.56 nm, which can be seen on the Fig. 15, and its formation a hydrophilic surface which promoting the spread of liquids across the surface. This results in a surface forms a small contact angle - 67 degrees.

Anodized aluminium samples surface wettability is changes over time, which can be seen on the Fig. 16.

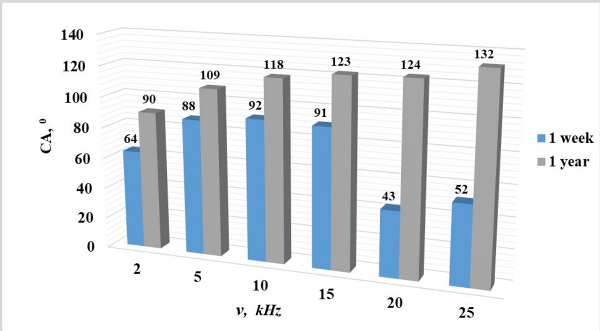

Fig. 16. Contact angle dependence on over time at laser power 50 %.

Studying the graph show it can be observed that the wettability of the anodized aluminium surface increases over time. Due to oxidation, carbon, oxygen content absorption from ambient environment [13].

The surfaces with higher average surface roughness exhibit significantly lower contact angles immediately after laser treatment compared to those with smoother surfaces. Furthermore, over time, the contact angles on surfaces with higher roughness increase at a faster rate than those with lower roughness.

IV. CONCLUSIONS

The analysis of various parameters' effects on the hydrophobicity and hydrophilicity of marked anodized aluminium reveals several significant trends.

- Specific combinations of scanning speed and raster step yield hydrophilic surfaces, characterized by contact angles less than 90 degrees. Conversely, other combinations produce hydrophobic surfaces, exhibiting contact angles greater than 90 degrees. Notably, altering these parameters can induce a transition from hydrophilic to hydrophobic surface characteristics.
- The water contact angle increases with increasing frequency, using laser power 50%, suggesting possible material-specific interactions. Change laser power and frequency the formation of a hydrophilic surface occurs exclusively at specific laser power and frequency setting.
- Higher pulse overlap leads to decreased contact angles, indicating a more uniform energy distribution and greater cumulative heating effects. In addition, the lack of pulse overlap, and high laser power create a hydrophilic surface due to minimal surface roughness.
- Roughness parameters Ra, Rq, and Rz significantly impact wetting behaviour, with lower roughness generally associated with hydrophilic and small contact angles.
- The wettability of the anodized aluminium surface gradually increases over time, transitioning from initially hydrophilic to eventually hydrophobic behaviour.

In conclusion, the manipulation of laser processing parameters allows for precise control over surface characteristics, impacting the wetting behaviour of marked aluminium surfaces. The formation of hydrophobic or hydrophilic surfaces is dependent on a combination of factors, including scanning speed, raster step, laser power, frequency, pulse overlap, and surface roughness. Understanding these relationships enables tailored surface engineering for desired wetting properties.

Hydrophobic and hydrophilic surfaces are essential to many industries, where they are used to improve product performance, durability, and safety, and to promote innovation and technology development.

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