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# Determination of the Optimum Laser Processing Parameters Required to Obtain a Stable Hydrophobic Surface on the Surface of AA1050 Aluminum Alloy

Research Article

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## Abstract

In this study, the surfaces of sheets made of AA1050 aluminum alloy, which has high aluminum purity and high strength, were roughened with a fiber laser. The aim of the study was to obtain a surface with a highly stable contact angle. For this purpose, it was necessary to minimize the change in the contact angle with time. Three different laser processing parameters were used. The effects of the laser parameters on the stability of the contact angle were investigated. According to the data obtained from the study, the type of texture created on the surface was calculated as the most effective parameter to obtain a stable surface. The rate of influence of the texture type parameter on the result is 61.61%. The parameter with the least effect on the result was calculated as laser-scanned factor with 15.31%. The parameter that moderately affected the result was calculated as laser power with 23.08%. In addition, ANOVA calculations suggested that a more stable surface pattern could be obtained by experimental parameters.

**Keywords:** Surface Texturing, Fiber Laser Machining, AA1050 Aluminum Alloy, Taguchi Optimization, Hydrophobic Surface.

## 1. INTRODUCTION

A metal alloy is a substance made of two or more metals, or a metal and non-metallic elements mixed to improve the metal's characteristics for a particular use. Beyond what is achievable with pure metals, alloys are utilized to increase mechanical strength, durability, corrosion resistance, conductivity, and heat tolerance. Typical examples are brass (copper and zinc), bronze (copper and tin), and steel, which is an alloy of iron and carbon. These alloys have qualities that make them invaluable in a variety of industrial fields. For example, steel is perfect for the construction, automotive, and shipbuilding industries because of its increased strength and resistance to wear, whereas stainless steel, which has chromium, is used for kitchenware and medical devices because it resists corrosion.

Aluminum alloys are frequently utilized in the aerospace sector due to their high strength-to-weight ratio and low density, which are essential for decreasing the weight of spacecraft and airplanes [1]. Due to its extreme strength and heat resistance, titanium alloys are indispensable in biomedical and aerospace applications, including implants and prosthetic limbs. Superalloys based on nickel are essential for high-temperature settings, such as gas turbines and jet engines, where oxidation and heat resistance are required. Because of their excellent electrical conductivity, copper alloys are frequently employed in electronics for electrical wiring and connectors [2]. Because of their adaptability, metal alloys are used extensively in a variety of industries, including the energy sector, where they are used in oil rigs, nuclear reactors, and pipelines because they can withstand high temperatures and pressures [3]. In the automotive industry, for example, advanced high-strength steels improve safety and fuel efficiency [4]. Because alloys may be customized to meet specific requirements, they are essential to contemporary industrial processes and technologies.

With an aluminum percentage of 99.5% or more, AA1050 aluminum alloy is a commercially pure aluminum alloy from the 1000 series [5]. Because of its high purity, AA1050 has several numbers of beneficial qualities, including as good electrical, thermal, and corrosion resistance as well as workability [6]. Since AA1050 is a pliable and soft substance, it can be easily stamped, drawn, or shaped, which makes it perfect for applications where formability is crucial [7]. Nevertheless, compared to other aluminum alloys, its mechanical strength is comparatively low, which prevents it from being used in structural applications that call for great strength.

The electrical industry is one of the main sectors that benefits from AA1050's characteristics [8]. This alloy is widely used for busbars, conductors, and electrical cables where efficiency in current transmission is crucial because of its high electrical conductivity. Because of the alloy's superior resistance to corrosion, it can be used in places like heat exchangers and chemical processing plants where other metals could corrode due to exposure to chemicals or moisture. With exceptional thermal conductivity, it is also a well-liked material for cooling components like heat sinks, which are crucial for HVAC and electrical systems [9]. Because AA1050 is non-toxic, resistant to contamination, and simple to mold into thin sheets, it is frequently used in the packaging sector to produce food containers and aluminum foil [10]. Another noteworthy characteristic of the alloy is its reflectivity, which qualifies it for use in the renewable energy industry for solar panel frames, reflectors, and lighting fixtures. Moreover, AA1050 is employed in architectural applications, including cladding, roofing, and decorative panels where aesthetics, durability, and weather resistance are required. Although AA1050's lower strength precludes its usage in load-bearing applications, its high conductivity, resilience to corrosion, and ease of manufacturing make it a flexible material suitable for a wide range of applications in industries, including environmental protection, food packaging, and electrical and building systems [11]. Because surface treatment improves a material's mechanical, chemical, and physical qualities without changing its bulk characteristics, it is an essential technique in many sectors [12]. To enhance a product's resistance to corrosion, wear and tear, adhesion, electrical conductivity, and aesthetic appearance—all of which contribute to its durability and effectiveness in particular environments—material surface modification is frequently the preferred approach [13]. Surface treatment is economically necessary to prevent degradation, as industry data estimates that corrosion costs alone account for 3-4% of GDP in many industrialized nations [14]. To overcome these difficulties, techniques such as anodizing, plating, coating, and surface hardening are frequently employed. Furthermore, surface treatments are necessary to increase the lubricity of machine parts, lower wear and friction, and prolong the life of vital components [15]. For example, research indicates that in extremely abrasive environments, surface-hardened steel can increase part life by up to three or five times.

Surface treatments like thermal spraying and chemical vapor deposition (CVD) are frequently used in the automotive and aerospace sectors to improve resistance to high temperatures and mechanical strains. In the electronics industry, surface treatments are also used to enhace adhesion properties since materials like circuit boards and semiconductors need changed surfaces to promote coating and adhesive bonding [16]. Industries can customize the surface qualities for particular applications, lowering total material costs while attaining improved performance, by concentrating on surface modification rather than changing the core material. Reducing material waste and extending product life are economic methods and help to improve manufacturing sustainability and energy efficiency.

The process of altering a material's surface qualities with a high-energy laser beam is called laser surface treatment. This process modifies the surface morphology, microstructure, and chemical composition of a material by directing a laser beam onto a particular region of its surface to cause localized heating, melting, or vaporization. The precision and controllability of this method are its main advantages. The depth of penetration and the intensity of the heat applied can be precisely controlled by adjusting the laser's power, wavelength, and pulse duration. This allows for targeted change without changing the material's bulk properties. Techniques such as laser surface melting (LSM), laser surface alloying (LSA), laser cladding, and laser hardening are frequently used in the laser surface treatment process. For instance, in laser hardening, the material's surface is heated by the laser beam to a temperature higher than its critical point, and then the treated region rapidly self-quenches, improving the treated area's hardness and wear resistance [17, 18]. When a material is melted by a laser and applied to a surface, it may take the form of wire or powder that is coated with a protective layer. These procedures are carried out in a regulated setting, frequently with inert gasses present, to avoid oxidation and other unwanted chemical reactions.

In industrial applications, laser surface treatment is particularly advantageous due to its various better advantages over traditional surface treatment technologies [19]. Lasers offer a number of advantages, one of which is localized treatment. Because the laser beam can be precisely targeted, there can be fewer heat-affected zones and nearby materials won't sustain thermal damage. This high degree of precision lowers the possibility of microstructural alterations or distortion to the bulk material, which is crucial for high-performance parts with precise mechanical requirements.

Furthermore, laser surface treatments are incredibly effective and adaptable. Processing durations can be shortened and manufacturing efficiency raised by conducting the procedure quickly and automatically. Additionally, a variety of materials, such as metals, ceramics, and composites, may be treated by lasers, which makes them useful in a variety of sectors. Another significant benefit is the ability to customize surface attributes. Manufacturers can customize surface properties like hardness, roughness, and corrosion resistance to match particular application needs by varying the laser's parameters. Furthermore, compared to conventional techniques like electroplating or chemical coatings, laser treatments frequently use fewer chemical agents, lowering hazardous waste. This makes them environmentally benign. Because laser surface treatment is precise, adaptable, and may improve surface qualities without sacrificing material integrity, it is favoured in many scientific study domains as well as many enterprises [20].

The automobile industry is one of the main applications for laser surface treatment, where it is used to harden crankshafts, gears, and engine components [21]. Critical automotive parts have a longer lifespan thanks to laser hardening, which lowers maintenance costs and improves vehicle performance by increasing wear resistance and fatigue life. Similar techniques are used in the aerospace sector to reinforce and repair parts subjected to harsh environments, like landing gear and turbine blades, which undergo high levels of stress and temperature cycling. These techniques include laser cladding and surface alloying. Surfaces treated with lasers function better at high temperatures and against oxidation and wear.

Laser surface treatment is a commonly employed technique in the tooling and manufacturing industry to improve the longevity of cutting tools, dies, and molds [22]. By increasing the surface hardness of tools through laser hardening, machining procedures can be performed with less wear and tear. Furthermore, laser texturing is employed to generate precise surface patterns on molds, an essential step in achieving superior surfaces in metal forming and plastic injection molding. In order to improve mold performance and product aesthetics, laser surface treatment is crucial since it allows for precise control over surface roughness and texture [23]. In the biomedical industry, laser surface treatment is also widely utilized to alter the surfaces of medical implants and equipment [24]. To improve osseointegration—the process by which bone grows into an implant—on the surface of orthopaedic implants, for example, laser texturing can produce microstructures. This increases the implants' long-term durability [25]. In the oil & gas and power generation industries, in particular, laser cladding is the material of choice for repairing and strengthening vital parts including drilling equipment, turbine blades, and pipelines. In abrasive settings, the treatment helps prevent erosion, corrosion, and wear. Laser surface treatment is utilized in science to create cutting-edge coatings and materials. Researchers examine how surface alteration affects material performance in harsh situations, including nuclear reactors or space exploration, using lasers. Additionally, laser treatments are used in research on nanotechnology and photonics, where the development of sensors, photonic devices, and functional surfaces with distinctive optical properties requires controlled surface alteration at the micro- and nanoscale. Overall, laser surface treatment is favoured across multiple industries and research fields for its ability to enhance surface properties, improve component performance, and contribute to innovation in material science and engineering [26].

When a material surface repels water, it is said to be hydrophobic. This is indicated by a high contact angle, usually more than 90 degrees, between the surface and the water droplet [27]. This characteristic stems from the surface's poor affinity for water molecules, which is frequently brought about by particular chemical compositions or surface microstructures that lessen the surface-water interaction. Originating from the Greek words "hydro" (water) and "phobos" (fear), the phrase "hydrophobic" means "water-fearing." Water tends to form droplets rather than spreading out when it comes into contact with a hydrophobic surface, which reduces the amount of surface area that the water and the material have in contact. Natural examples of this behaviour include the lotus plant's leaves, which maintain their cleanliness and dryness because to their inherent. Artificial methods for achieving hydrophobicity include surface treatments, chemical coatings, and the fabrication of certain micro- and nanostructures that improve water repellency. Additionally, these surfaces may have the ability to self-clean, with dirt and pollutants being removed by water droplets that roll off the surface. Not only do hydrophobic surfaces repel water, but they are also very desirable in industrial applications because they can show resistance to fouling, corrosion, and biological contamination. This idea is furthered by superhydrophobic surfaces, which have nearly zero water adhesion and even more extreme water-repellent qualities (contact angles above 150 degrees) [28]. Artificial methods for achieving hydrophobicity include surface treatments, chemical coatings, and the fabrication of certain micro- and nanostructures that improve water repellence. Additionally, these surfaces may exhibit self-cleaning properties, where dirt and pollutants are removed by water droplets that roll off the surface. Not only do hydrophobic surfaces repel water, but they are also very desirable in industrial applications because they can show resistance to fouling, corrosion, and biological contamination. This idea is furthered by superhydrophobic surfaces, which have nearly zero water adhesion and even more extreme water-repellent qualities (contact angles above 150 degrees) [29].

Hydrophobic coatings are used in the automotive and aviation sectors to improve aerodynamic performance by lowering drag brought on by water buildup on vehicle surfaces [30]. Hydrophobic coatings are especially useful for windows and windshields because they increase visibility by keeping water from sticking to them and producing droplets that might obscure eyesight. Hydrophobic coatings can also stop ice, frost, or hydrate deposits from forming on pipelines and equipment, which could otherwise interrupt operations in the oil and gas sector. In biotechnological and medical applications, hydrophobic surfaces are also very important because they help stop biological materials like bacteria, proteins, and cells from adhering to them [31]. This anti-fouling characteristic is especially crucial for devices like implants, surgical equipment, and catheters where reducing the danger of contamination is essential.

Furthermore, hydrophobic surfaces are favoured in uses where water-resistant packaging is necessary, including in the food and pharmaceutical sectors, where it's critical to maintain dry and moisture-free items. Hydrophobic surfaces are used in many different industrial domains because of their exceptional capacity to reject water, withstand fouling, and preserve hygienic conditions. Hydrophobic coatings are frequently used on side mirrors, paint, and windshields in the car industry to increase visibility during rainy weather and lessen cleaning requirements. These coatings improve driver safety by keeping water from sticking to the surface and lessen wiper wear. Hydrophobic coatings can also be applied to vehicle's exterior, creating self-cleaning surfaces that prevent dirt buildup and extending the life of the paint job.

Hydrophobic coatings are applied to aircraft wings, fuselages, and windows in the aviation and aerospace sectors to lessen drag brought on by water accumulation [32]. This can increase fuel economy and lessen the weight load of ice building. These coatings are also necessary for de-icing applications, which stop ice from forming on important surfaces while the aircraft is in flight. This is essential for averting mishaps and guaranteeing the aircraft's performance and safety in a range of environmental circumstances.

Hydrophobic surfaces are also highly beneficial to the construction sector, especially for building materials like concrete, glass, and ceramics [33]. Building facades are shielded from water penetration by hydrophobic coatings, which over time prevent efflorescence (salt deposits), water damage, and cracking. These coatings increase the longevity of infrastructure and buildings by making surfaces water-repellent, especially in areas with high humidity or frequent rains.

In the electronics sector, hydrophobic coatings are applied to wearables, tablets, and smartphones to enhance water resistance [34]. Maintaining the performance of consumer devices that are frequently exposed to moisture—like those used outside or accidentally spilled—requires doing this. Hydrophobic films are also applied to some electronic parts, such printed circuit boards (PCBs), to stop water-induced corrosion and extend their lifespan.

In the marine industry, where exposure to seawater can cause quick corrosion and biofouling, hydrophobic surfaces are especially crucial [35]. Ship hulls, offshore platforms, and subsea equipment are coated with hydrophobic materials to stop water seepage, corrosion, and the growth of organisms like algae and barnacles, which can have a detrimental effect on operating effectiveness. These coatings help lessen drag on the hulls of vessels, increasing fuel economy and requiring less maintenance.

Hydrophobic surfaces are used in the medical and healthcare sectors to stop bacterial development and contamination on implants, surgical tools, and other medical equipment. Catheters, stents, and other invasive devices with hydrophobic coatings minimize the adhesion of biological materials, therefore lowering the risk of infection. Hydrophobic coatings in pharmaceutical packaging shield medications from moisture, maintaining their stability and potency for longer.

All things considered, hydrophobic surfaces are essential to many different industries, offering advantages including improved performance, longevity, and safety by guarding against water-related damage and contamination. Hydrophobic treatments are vital in scientific and industrial applications because they can provide surfaces that are self-cleaning, water-repellent, and anti-fouling. By modifying the surface chemistry and topography, different surface modification techniques can convert the surfaces of aluminum alloys AA1050 into hydrophobic surfaces that promote water repellency.

Combining surface texturing with chemical treatments is one of the most successful strategies. In order to achieve hydrophobicity, texturing techniques are designed to provide micro- or nanoscale roughness on the surface. This limits the surface's area of contact with water droplets. For this, laser surface texturing—which involves using a laser to create a patterned microstructure on the aluminum surface—is frequently utilized. The resultant hierarchical patterns resemble the surfaces found naturally in hydrophobic phenomena, such the leaf of a lotus plant.

Chemical etching is another technique for making micro-rough surfaces. Using acidic or alkaline solutions, material is removed selectively to produce a rough surface with micro- and nanostructures [36]. The next stage is to alter the surface chemistry to improve the water-repelling qualities of the surface once the suitable texture has been obtained. Low-surface-energy coatings are usually applied to achieve this, as they reduce the interaction between water molecules and the surface. For this reason, fluoropolymer coatings and silane-based coatings are frequently employed since they impart hydrophobic functional groups, including methyl groups ($-Si(CH_3)_3$) or fluoro groups ($-CF_3$), into the aluminum surface. Because of the considerable surface energy reduction provided by these coatings, water droplets are able to roll down the surface in beads rather than spreading out.

Apart from chemical treatments and laser texturing, anodization is a further technique that can be utilized to improve the hydrophobicity of aluminum alloys AA1050 [37]. The aluminum surface develops a thick, porous oxide layer during anodization, which can be further functionalized with hydrophobic substances. When paired with chemical treatments, the anodized surface can display superhydrophobic qualities, which are defined by water contact angles greater than 150 degrees.

Whether applied individually or in combination, these methods enable the surfaces of AA1050 aluminum alloys to become extremely water-repellent. This property makes the alloys suitable for use in outdoor construction materials, automotive components, and marine environments where resistance to corrosion and moisture is crucial.

In this study, an attempt was made to optimize the laser process parameters required to obtain a stable hydrophobic surface. The process parameters used to obtain more stable hydrophobic surface. For this purpose, pure water was applied to the surfaces obtained with different process parameters. The contact angle was measured for the first 10 seconds after the water was dripped. Contact angles were measured every second in the first 10 seconds.

The value with the least deviation from the average of the contact angles in the first 10 seconds was accepted as the most stable value. Accordingly, the value with the smallest standard deviation was accepted as the most stable hydrophobic surface and the smallest standard deviation was characterized as the best value. A statistical tool used to quantify the degree of variation or dispersion in a set of data values is the standard deviation. It sheds light on how widely distributed a dataset's values are around the mean (average). Whereas a large standard deviation suggests that the values are dispersed over a larger range, a small standard deviation suggests that the values tend to be close to the mean. The square root of the variance, or the average of the squared deviations from the mean, is what is known as the standard deviation in mathematics. Equation 1 provides the formula for the standard deviation (σ) of a population:

$$\sigma = \sqrt{\frac{\sum(x_i - \mu)}{N}} \tag{1}$$

Where:

$\sigma$ = population standard deviation

$x_i$= each data point

$\mu$ = population mean
$N$ = number of data points

Since the standard deviation gives a numerical depiction of data variability, it is a crucial statistical tool. It is essential for comprehending the consistency and dependability of datasets in domains like finance, economics, quality control, and research.

Standard deviation comes in two primary varieties, each with a distinct function:
*Population Standard Deviation (σ):* This kind of standard deviation is applied when the study takes into account every member of a group or population. It is a representation of the dataset's overall variability. In domains such as biology or engineering, where the complete collection of measurements is accessible, comprehending the general variance within the population is crucial. The population standard deviation proves especially useful in these scenarios.

*Sample Standard Deviation (s)*: When there is only a sample of the population available, the sample standard deviation (s) is utilized. The sample standard deviation aids in estimating the variability of the population from which the sample is obtained, as a sample is merely a subset of the entire population. When utilizing a sample, the formula divides by $N-1$, where N is the total number of observations in the sample, to account for any bias. This is known as Bessel's correction, ensures that the sample provides an unbiased estimate of the population variance.
The precision and dependability of standard deviation computations are impacted using both types, which vary based on whether the dataset represents the full population or merely a sample. Standard deviation is a crucial tool in engineering for dependability analysis, risk management, and quality control. It aids engineers in comprehending measurement, process, or system variability, which is essential for creating reliable and consistent products. There are various applications of standard deviation in engineering.

*Quality Control:* Standard deviation is essential for keeping an eye on product consistency in manufacturing and production. For example, engineers monitor the standard deviation of important measurements when making components that need to meet certain tolerances to make sure the process stays within allowable bounds. In a production process, a low standard deviation means that the majority of the products fall within the intended parameters; on the other hand, a high standard deviation could suggest flaws or differences in the procedure.

*Reliability Engineering:* Standard deviation is used in the field of reliability engineering to evaluate the lifespan and robustness of systems or goods. Through the assessment of performance indicators including fatigue life, failure rates, and time-to-failure variability, engineers are able to forecast the degree of system reliability under various scenarios. A lower standard deviation suggests more predictable performance, which is essential in systems where reliability is critical, such as aerospace or automotive industries.

*Risk and Safety Analysis:* Standard deviation is another tool used by engineers in risk and safety analyses. For example, in structural engineering, the standard deviation can be used to assess the variability in material strengths or load-bearing capacities in order to forecast possible dangers or failure modes. Standard deviation aids engineers in creating safe structures that can resist changing loads or environmental circumstances.

*Process Control and Optimization:* Standard deviation is a tool used in process engineering to find variations in processes. It is used by engineers to assess a process's consistency over time. Process engineers can create a more stable and optimized process that is more cost-effective and efficient by lowering the standard deviation.

In the field of engineering, a distribution with a small standard deviation signifies limited variability within the dataset, as the data points are tightly packed around the mean. This implies that the system or process under analysis has a high degree of precision and that the observed values or results are consistent. In the manufacturing industry, for example, a minimal standard deviation in a produced part's dimensions indicates that the production process is well-controlled, and the parts are almost similar, which results in improved quality and reliability. This consistency is frequently desired in engineering design since it increases system performance predictability and lowers the possibility of failures or outliers. Furthermore, a low standard deviation lessens the requirement for significant safety factors or contingencies in design and analysis by giving engineers more confidence that the measured values accurately reflect the system's performance or behaviour. In general, decreasing variability is essential to ensuring efficiency, safety, and precision in many engineering applications.

In light of this, standard deviation is an effective statistical instrument that helps engineers comprehend, manage, and maximize variability in systems, procedures, and measurements—thereby enhancing the dependability, security, and caliber of engineering endeavors and output.

## 2. MATERIALS AND METHODS

### 2.1 Optimization Method

In scientific and engineering research, optimization techniques are crucial because they facilitate the methodical and effective search for the best answers to challenging issues. In engineering, many design procedures, such as lowering energy consumption in systems, optimizing material utilization, or enhancing the performance of machines, require judgments among several factors. Finding the best balance between conflicting goals would take a lot of time and resources if optimization techniques weren't used. In scientific research, optimization algorithms are essential for data analysis, simulation, and model fitting. They enable scientists to fine-tune parameters and produce results that are dependable and accurate. This is particularly beneficial in domains like computational biology, physics, and chemistry, where optimization aids in the design of experiments and in solving difficult equations. Furthermore, sophisticated optimization techniques like gradient-based methods, heuristic approaches, and genetic algorithms offer significant computational advantages, making it possible to solve problems that would otherwise be insurmountable as they become more complex with larger datasets or more variables. Therefore, optimization plays a crucial role in enhancing the efficacy and efficiency of scientific and engineering undertakings, which in turn spurs innovation and discovery.

Genichi Taguchi created the Taguchi method, a statistical technique for enhancing process efficiency and product design with an emphasis on lowering variability and raising quality. The Taguchi technique is centered on resilient design, which tries to improve consistency and reliability by lessening the sensitivity of processes or products to fluctuations brought about by outside influences (noise). Multiple factors can be evaluated simultaneously with fewer experiments thanks to a technique that uses orthogonal arrays to systematically design experiments. This efficiency in experimental design is one of its key advantages, since it cuts time and costs while still generating valuable insights into the impact of many factors. The Taguchi approach also incorporates a loss function, which measures the financial deviation from the target performance and promotes not only satisfying the requirements but also minimizing the impact of any deviation.

The Taguchi technique has several benefits, such as being easy to use, affordable, and capable of handling several variables without requiring a lot of processing power. Moreover, it works especially effectively in scenarios where standard optimization techniques would be hard to use, including complicated variable interactions in processes or costly or impracticable real-world testing. The Taguchi method has a wide range of applications. It is widely used in industrial industries, especially in the electronics, automotive, and aerospace sectors, to improve process efficiency and product quality. It has been used, for instance, to create high-performance materials, enhance production procedures, and optimize machining parameters. The Taguchi technique has been applied outside of manufacturing, in areas including chemical processing, environmental engineering, and biotechnology, where it is crucial to optimize experimental conditions and reduce variability. All things considered, the Taguchi technique offers an organized, effective method of optimization, which makes it useful in many different fields of science and industry.

In the Taguchi method, three different characteristics are used according to the purpose of the experiments. If the largest value is to be obtained in the experiments, ‘larger the better’ characteristic is used, if the smallest value is to be obtained, ‘smaller the better’ characteristic is used. If the experiments are intended to approach a predetermined numerical target, the ‘nominal the best’ characteristic is used. According to these three different characteristics, three different calculation formulae are used. These are

For Larger the better characteristic;

$$ {}^{S}/_{N_i} = -10log_{10}\left[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_{ij}^{2}}\right] \tag{2} $$

For Smaller the better characteristic;

$$ {}^{S}/_{N_i} = -10log_{10}\left[\frac{1}{n}\sum_{i=1}^{n}y_{ij}^{2}\right] \tag{3} $$

For Nominal the best characteristic;

$$ {}^{S}/_{N_{NB}} = -10log_{10}\left[\frac{1}{n}\sum_{i=1}^{n}(y_i - m)^2\right] \tag{4} $$

This study aims to obtain the most Stable Hydrophobic Surface. For this purpose, the “smaller the better” characteristic was used.

## 2.2 Material and Experimental

In this study, the surfaces of 2 mm thick AA1050 aluminum sheets were machined with different machining parameters given in Table 1. A high precision fiber laser was used to process the surfaces.

In this study, fiber laser technology was used to engrave various geometric patterns onto the surface of an aluminum alloy from the AA1050 series. Four distinct laser power levels (40 W, 60 W, 80 W, and 100 W) and four distinct "Theoretical laser scanned area factors (%)" (80%, 60%, 40%, and 20%) were applied to each of the four geometric designs (Square, Diamond, Hexagon, and Circle) that were examined. These studies were carried out to investigate the response of laser-processed surfaces to different laser parameters and surface geometries in terms of surface energy, microstructure characteristics, and surface roughness.

The shapes of the laser-applied patterns were used to categorize the textures, and for every geometric design, a number of experimental situations were investigated. The aim of this research is to examine how laser processing parameters affect aluminum surfaces and identify the prerequisites for achieving ideal surface characteristics.

High-intensity laser beams can be produced using dependable, effective fiber laser systems. They find extensive application in micromechanical applications, materials processing, and marking procedures. Fiber lasers are notable for their long lifespan, high beam quality, little maintenance, and energy efficiency. For medium-to-high power applications, a fiber laser with a 100W power output is perfect. It works well for metal cutting, marking, and surface modification.

In the experiments, the 3 parameters given in Table 1 were analysed at 4 different levels. Two of these parameters are numerical parameters and the other one is the classification of the patterns formed on the surface.

**Table 1.** Three machining parameters and their fours of levels.

| Pattern Type | Scanned Area factor (%) | Laser Power (Watt) |
|---|---|---|
| Square | 80 | 40 |
| Diamond | 60 | 60 |
| Hexagonal | 40 | 80 |
| Circle | 20 | 100 |

## 3. RESULTS AND DISCUSSION

Traditional experimental design requires $3^4$ (=81) experiments when three factors with four levels are studied. When optimization techniques are applied, fewer experiments are required to yield effective results. This inquiry used the Taguchi method, which produces good findings in many scientific and technical disciplines. To reduce the number of experiments, the Taguchi technique suggests that selecting the appropriate orthogonal array should be done first. According to the Taguchi approach, in order to reduce the number of tests, selecting the appropriate orthogonal array should be done first. Because three parameters and four levels were used in this experiment, the $L_{16}$ orthogonal array was used. The laser machining sets specified in Table 1 were arranged in accordance with the $L_{16}$ orthogonal array, and experiment sets were built. Table 2 lists the experimental configurations and the means of the standard deviations of the contact angle values of the surfaces obtained using these configurations.

**Table 2**. Sets of experiments produced by the Taguchi method, arranged according to the $L_{16}$ orthogonal array.

| | **Texture** | **Scanned area factor (%)** | **Power (W)** | **Standard deviation of contact angles** | **S/N values of contact angle** |
|---|---|---|---|---|---|
| 1 | Square | 80 | 40 | 2.16 | -6.68 |
| 2 | Square | 60 | 60 | 2.03 | -6.16 |

| | | | | | |
|---|---|---|---|---|---|
| 3 | Square | 40 | 80 | 3.55 | -11.00 |
| 4 | Square | 20 | 100 | 4.58 | -13.22 |
| 5 | Diamond | 80 | 60 | 12.22 | -21.74 |
| 6 | Diamond | 60 | 40 | 6.17 | -15.81 |
| 7 | Diamond | 40 | 100 | 7.24 | -17.19 |
| 8 | Diamond | 20 | 80 | 4.20 | -12.46 |
| 9 | Hexagon | 80 | 80 | NA | NA |
| 10 | Hexagon | 60 | 100 | NA | NA |
| 11 | Hexagon | 40 | 40 | 9.03 | -19.12 |
| 12 | Hexagon | 20 | 60 | 5.54 | -14.87 |
| 13 | Circle | 80 | 100 | 10.36 | -20.30 |
| 14 | Circle | 60 | 80 | 8.25 | -18.33 |
| 15 | Circle | 40 | 60 | 40.14 | -32.07 |
| 16 | Circle | 20 | 40 | 2.75 | -8.79 |

Table 2 reveals that reliable data could not be obtained with the 9th and 10th test sets. This may be due to the inhomogeneity of the material surface. The contact angles of the textured surfaces obtained using the test sets were made every second for the first 10 seconds after the droplet was dropped on the surface. The contact angles of the surfaces generally show a decreasing trend. This indicates that the liquid dripped over time is dispersed on the surface. In this study, it is aimed to obtain the machining parameters required to obtain the surface with the least change in the contact angle or the least change in the contact angle. For this purpose, the standard deviations of the contact angles measured in the first 10 seconds were calculated and the results are presented in Table 2. Signal to noise ratios of these standard deviation values were calculated according to Taguchi method. The obtained signal to noise ratio values were given in Table 2. As seen in Table 2, the lowest standard deviation was obtained with the experiment set number 2. The largest standard deviation value was obtained with the experiment set numbered 16. Figure 1 shows the image of the droplet on the surface where (a) the smallest and (b) the largest standard deviation values are obtained. The largest value of the contact angle of the droplet in Figure 1a is 165.22° and the largest value of the contact angle of the droplet in Figure 1b is 107.16°.

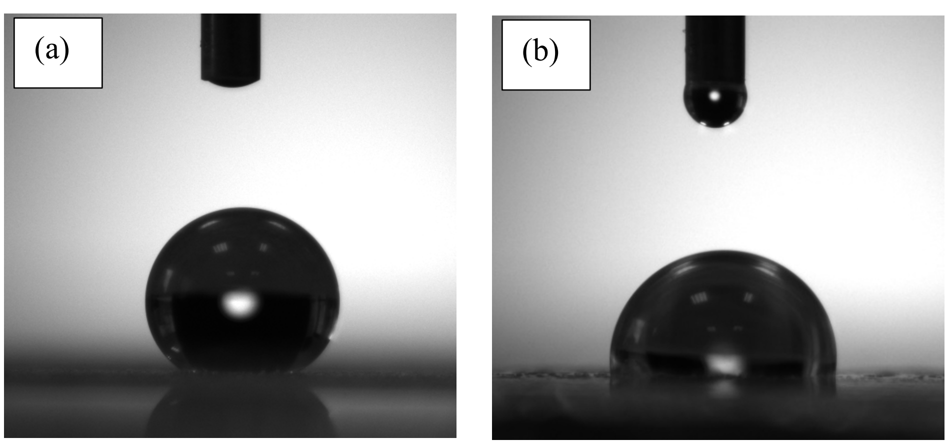


**Figure 1**. Images obtained during the measurement of contact angles of the surfaces giving the (a) largest and (b) smallest standard deviation values.

The ANOVA table presented in Table 3 shows the sum of the squares (SSi) of the means of the S/N values for each level and the variance of these values. The table shows that according to the Taguchi method, the standard deviation of the contact angles measured in the first 10 seconds of the textured surface to be obtained in the experiment with the experimental set with texture type square, scanned factor 20 % and laser power 40 W is 1.43. The ANOVA table also shows that the factor with the greatest influence on the standard deviation is the texture type with 61.61%. The second most influential factor was laser power with 23.08% and the least influential factor was scanned factor with 15.31%.

**Table 3.** ANOVA table prepared using the Taguchi technique. A- Degree of freedom, B- Sum of squares (SSi), C- Average of sum of squares (variance), D- Effect of factors (%), E- Optimum Levels, F- Optimum Values (calculated).

| | Average S/N | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Factors | 1st level | 2nd level | 3rd level | 4th level | A | B | C | D | E | F |
| Texture | -9.26 | -16.80 | -16.99 | -19.87 | 4 | 247.46 | 61.87 | 61.61 | 1 | 1 |
| Scanned Factor (%) | -16.24 | -13.43 | -15.77 | -12.33 | 4 | 61.50 | 15.38 | 15.31 | 4 | 20% |
| Power (W) | -12.60 | -18.71 | -13.93 | -16.90 | 4 | 92.68 | 23.17 | 23.08 | 1 | 40 W |
| | | -15.55 | | | | | | | | |
| Total | | | | | | 401.65 | | 100.00 | | |
| Optimum S/N | | | | | | | | | | -3.09 |
| Minimum standard deviation | | | | | | | | | | 1.43 |

### *Main Effect Plots*

Main effect plots are an essential tool in statistical analysis, particularly when talking about experimental design and analysis of variance (ANOVA). These plots provide a visual representation of the average response of a dependent variable across different values of a single independent variable while all other parameters are maintained constantly. To make it easier to analyse experimental data, main effect plots are mainly used to examine and illustrate the relationship between independent and dependent variables. One of the key benefits of main effect plots is their ability to show the presence and magnitude of main effects, or the influences of various independent factors on the dependent variable.

By plotting the mean answer for each level of the independent variable, main effect plots allow researchers to assess the overall effect of an independent variable on a dependent variable, regardless of the levels of other variables. This facilitates the identification of trends, patterns, and variances in the dependent variable across different independent variable levels. The main effect plot is a helpful diagnostic tool for determining potential interactions between independent variables. An interaction occurs when the amount of one independent variable has a varied effect on the dependent variable. By examining main effect plots in conjunction with interaction plots, researchers can get insight into the complex dynamics of the system they are studying. Specifically, they can ascertain whether the relationship between the independent and dependent variables varies across levels of other independent variables. Main effect plots are helpful in assessing experimental results and are necessary for model validation and selection. By visually analysing the main effect plots, researchers can ascertain whether the linearity and homoscedasticity assumptions that form the basis of the statistical model are satisfied.

As can be seen from the main effect plots given in Figure 2, although "texture type" does not express a numerical value, all three plots show similar characteristics. Since the aim of the study was to obtain a stable surface considering the contact angle, the smallest standard deviation values were obtained when the texture type was square. The largest standard deviation values were obtained when the texture type was circle. Considering the scanned factor, the smallest standard deviation value is obtained at the smallest value of the scanned factor. An increase in the standard deviation is observed until the scanned factor reaches 40 %. After this value, a relatively slow decrease is observed until the scanned factor reaches 60 %. However, when the scanned factor increased from 60% to 80%, the standard deviation increased rapidly again. Considering the laser power, the smallest standard deviation values were obtained at 40 % and 80 %. As can be seen in this graph, when the laser power increased from 40 W to 60 W, a rapid increase in the standard deviation was observed, but when the power was increased from 60 W to 80 W, the standard deviation decreased at the same rate. When the power was increased from 80 W to 100 W, a very small increase in the standard deviation was observed.

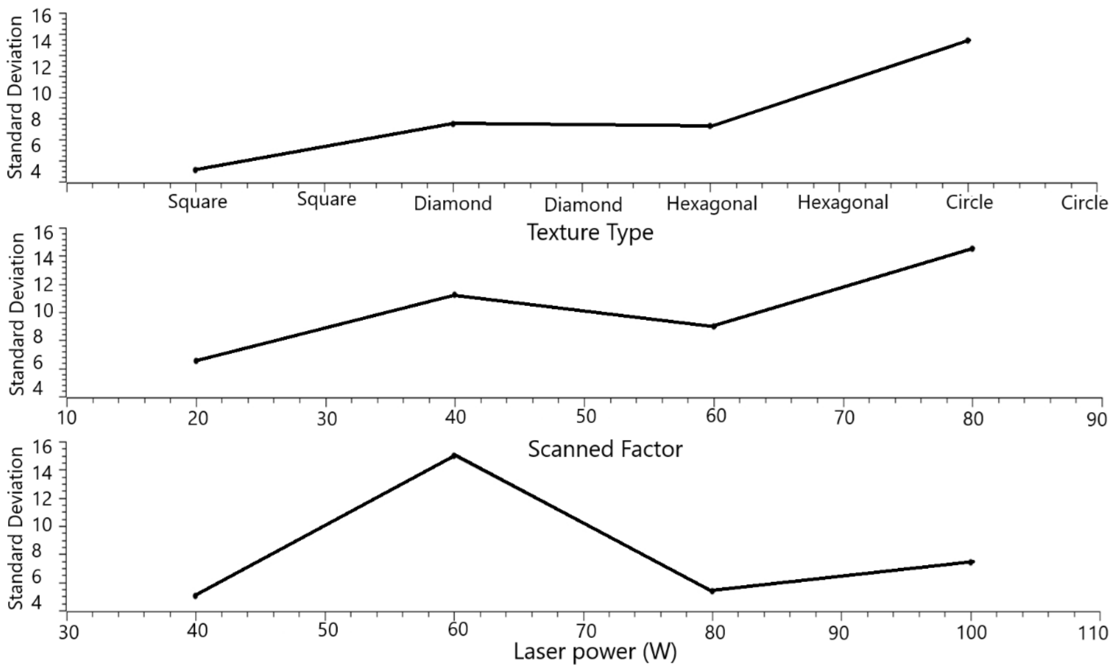


**Figure 2.** Main effect plots for; (a) Texture Type, (b) Scanned Factor and (c) Laser Power.

## *Regression Equation*

A regression equation represents the relationship between one or more independent variables and one or more dependent variables mathematically. Based on the known values of the independent variables, it is used to forecast or estimate the value of the dependent variable. The dependent variable is expressed as a linear combination of the independent variables plus an error term in the most basic form, known as linear regression. Nonlinear regression models can be used in more complicated situations to capture more complex interactions. Numerous scientific and engineering domains make extensive use of regression equations. They are used in structural modelling, material performance study, and load prediction in mechanical and civil engineering. They are employed in electrical engineering to represent system behaviour in signal processing and control systems. Regression models are used in environmental research to evaluate the effects of climate change and predict the dispersion of pollutants. In the biological sciences, regression analysis is also essential for simulating population dynamics or the spread of disease. Regression equations provide the advantages of being able to forecast outcomes, model real-world occurrences, and infer correlations between variables. The use of error terms allows scientists and engineers to account for uncertainties when analysing massive data sets, gaining actionable insights, and optimizing systems. Equations 5-8 present the regression equation obtained using Minitab 21.1.1 for regression analysis.

$$For\ Circle \qquad Std.Dev. = 15.6 + (0{,}011 \times SF) - (0{,}011 \times P) \tag{5}$$

$$For\ Diamond \qquad Std.Dev. = 7.7 + (0{,}011 \times SF) - (0{,}011 \times P) \tag{6}$$

$$For\ Hexagonal \qquad Std.Dev. = 7.5 + (0{,}011 \times SF) - (0{,}011 \times P) \tag{7}$$

$$For\ Square \qquad Std.Dev. = 3.3 + (0{,}011 \times SF) - (0{,}011 \times P) \tag{8}$$

Table 4 provides the minimal standard deviation values determined by the regression equation, as well as the standard deviation values and error rates derived from the data. Table 5 shows that the estimated values of the standard deviation agree rather well with the findings of the measurements.

**Table 4.** Calculated standard deviations.

| Exp No | Texture Type | Scan Factor (%) | P (W) | Calculated Std. Dev. With regression Equations |
|---|---|---|---|---|
| 1 | Square | 80 | 40 | 3,74 |
| 2 | Square | 60 | 60 | 3,3 |
| 3 | Square | 40 | 80 | 2,86 |
| 4 | Square | 20 | 100 | 2,42 |
| 5 | Diamond | 80 | 60 | 7,92 |
| 6 | Diamond | 60 | 40 | 7,92 |
| 7 | Diamond | 40 | 100 | 7,04 |
| 8 | Diamond | 20 | 80 | 7,04 |
| 9 | Hexagonal | 80 | 80 | * |
| 10 | Hexagonal | 60 | 100 | * |
| 11 | Hexagonal | 40 | 40 | 7,5 |
| 12 | Hexagonal | 20 | 60 | 7,06 |
| 13 | Circle | 80 | 100 | 15,38 |
| 14 | Circle | 60 | 80 | 15,38 |
| 15 | Circle | 40 | 60 | 15,38 |
| 16 | Circle | 20 | 40 | 15,38 |

## 4. CONCLUSION

The paper provides a systematic analysis of how to optimize the parameters of a fiber laser to produce patterns on AA1050 aluminum alloy plates that have various geometric properties. The ideal parameters for three important variables were found using the Taguchi technique. These three parameters are laser power, scanned factor, and texture type. The surface patterns' geometries are directly impacted by these characteristics. The study yielded data that indicated that the most beneficial parameter for achieving a stable surface was the texture type that was formed on the surface. The percentage of the outcome that is impacted by the texture type parameter is 61.61%. Laser scanned factor was shown to have the least impact on the outcome, accounting for 15.31% of the total. Laser power was found to have a moderate impact on the outcome, accounting for 23.08% of the parameter.

Experimental systems were constructed with the L16 orthogonal array. As a result, it was able to effectively explore the parameter space and produce precise results while avoiding resource waste. ANOVA calculations also revealed that a more stable surface pattern might be produced in an experiment with different parameters than those used in the actual studies.

Strong correlations between the experimental data and the anticipated model were also revealed by the regression analysis. This demonstrated the validity of the Taguchi technique for enhancing laser processing parameters. By presenting solid proof that these ideas are well-established and outlining the benefits that can already be obtained by figuring out the ideal conditions, this study adds to the ongoing discussion in this area.

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