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Research Article

Optimization of laser treatment parameters for contact angle of 1.2379 tool steel using Taguchi method and ANOVA

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ABSTRACT

Since the industry recognizes material surface properties as an important criterion, selecting appropriate laser settings with minimal trial and error, low cost, and high reliability to achieve the desired surface finish is important. Therefore, the Taguchi analysis is an effective method for evaluating the laser parameters affects. In this research, the influence of laser processing conditions on the wettability behavior of 1.2379 cold work tool steel induced by Ytterbium fiber laser treatment were investigated. The laser power, scan speed and repetition rate were varied to determine the optimal settings to maximize the contact angle. A Taguchi L9 experimental design was employed, and the signal-to-noise ratios were calculated. The ANOVA results revealed contributions of 50.31% for the scan speed, 38.86% for laser power, and 11.24% for the repetition rate. The regression analysis equation, with an R^2 of 0.98, predicted a maximum contact angle of 96.274°, indicating a hydrophobic surface. The results indicate that the Taguchi method effectively identifies the optimum laser parameters for the desired surface properties with high confidence and minimal experimentation. The originality of this study is associated with the systematic application of statistical experimental design and variance analysis laser surface modification of 1.2379 tool steel for controlling its surface wettability.

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INTRODUCTION

The Taguchi method has been effectively employed for multiparameter problems in experimental designs because of its practicality and robustness [1-7]. The proposed method provides a significant advantage in understanding how the effects of various laser parameters used at different stages in the manufacturing sector affect the properties of materials through its low-experimentation approach. The impact of laser settings on the characteristics of processed materials has been investigated in previous studies. Jakupi et al. [8] optimized the laser parameters of 316L stainless steel made by Direct Metal Laser Sintering (DMLS) using the Taguchi

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method. Laser power was found to be the most important parameter affecting the roughness of the material. Laser power also affects the melt pool development [9]. Xu et al. [10] applied a laser surface pre-treatment process by varying the laser speed, power and frequency to improve the surface wettability of aluminum 7075-T6 alloy and it was determined that the most dominant parameter was laser power. In another study [11], 316L stainless steel was subjected to laser melting and it was determined by Analysis of Variance (ANOVA) that the main process parameters affecting wettability were laser power and scanning speed. Kasman et al. [12] processed the surface of Co-Cr-Mo alloy with a 20 W pulsed fiber laser, while contact angle measurements were performed. The Taguchi technique and ANOVA were used to examine the data, and it was found that the scan speed with 37% was the most beneficial parameter for the contact angle. Kasman et al. [13] investigated the influence of fiber laser processing parameters on Ti-6Al-4V surface roughness by integrating an L18 orthogonal array with ANOVA and found that scanning speed and scanning direction significantly affected both surface roughness and milling depth at 95% confidence level. Ozbey et al. [14] determined that the parameters used in fiber laser surface treatments have a important effect on the surface roughness and hardness of 1.2379 steel. This study also shows that fiber lasers are an important processing method that can be used to enhance tool steel's surface characteristics.

A drop of liquid will create a spherical cap when it is put on a level solid surface. The static contact angle θ is the angle at which liquid, vapor, and solid come together [15]. The intermolecular forces in equilibrium between the three surfaces meeting at the triple line are represented by Young's equation [16-17].The contact angle formed by the placement of liquid drops on solid surfaces is an indicator of the molecular interaction between the liquid and the solid [18-20]. Contact-angle measurements play an important role in surface-quality control in industrial applications [21]. The surface characteristics of films, including their wettability, hydrophilicity and interaction energy, can be determined by measuring the contact angle [22, 23]. The contact angle is a measure of the wettability of a surface; a surface is considered hydrophilic when the contact angle is below 90°, whereas contact angles exceeding 90° indicate hydrophobicity [24, 25]. In other words, the contact angle is a direct quantitative indicator of surface wettability; lower contact angles indicate greater surface wettability and hydrophilic behavior, whereas higher contact angles are associated with lower wettability and hydrophobic characteristics. This significantly influences adhesion, lubrication and corrosion resistance characteristics of surfaces in practical applications [26-28]. The physical and chemical features of the substrate influence the wettability of nonideal surfaces. Therefore, the physical characteristics of the materials significantly affect the contact angle measurements. Four primary factors, heterogeneity, surface roughness, particle size and particle shape, affect the contact angle [29]. Controlling the micro/nanostructure and chemical composition of the surface is critical for wettability [30]. Furthermore, wettability exhibited a direct relationship with surface roughness [31, 32].Recent developments in image processing have also contributed to surface analysis techniques in related fields [33]. It is possible to provide superhydrophobic properties on steel surfaces. In ref. [34] 304 stainless steel surface was treated with nanosecond laser and the surface obtained was a durable superhydrophobic surface with a contact angle of 156.5 ° and the hydrophobicity of the surface was maintained after abrasion tests.

Since tissue morphology has a significant effect on surface wettability, various wettability modifications have been achieved in recent decades using Laser Surface Treatment (LST) techniques through the manipulation of different tissue morphologies. [35]. Laser material processing is a widely used technique for enhancing the surface properties of materials [36]. Surface modification plays a important role in adapting the functional behaviour of the material, such as improving corrosion resistance or thermal performance [37, 38]. In the theoretical framework of laser-material interaction, special mathematical functions such as generalized Chebyshev polynomials and Laguerre-type Bessel functions are particularly important in modelling complex light-matter interactions in Free Electron Lasers (FEL) and can be used for in-depth study of surface modification phenomena [39-41].

By processing the surface of the material with a laser, its wettability, i.e. the connection angle, can be improved [35]. The surface of the steel (with hydrophilic surface) was treated by Zhu et al. [42] using a femtosecond laser to render it a superhydrophobic surface. By improving hydrophobicity, the material surface exhibits better anti-corrosion and biofouling resistance behavior. Superhydrophobic surfaces on copper and brass were obtained by Ta et al. [43] using a fiber laser. Zemaitis et al. [44] increased the contact angle of stainless-steel parts from 4° to 150° by varying laser fluence from 4 J/cm^2 to 2.6 kJ/cm^2 with applying a femtosecond laser structuring process.

Laser processing is non-contact and precise; thus, it is a useful technique for controlling metal surface wetting, however, there are certain difficulties with this procedure [45, 46]. Due to this increase in surface energy, the contact angle cannot be further increased immediately after laser treatment [47]. The adsorption of organic molecules from the medium can be facilitated by low-temperature annealing or exposure to air, which can reduce the high surface energy [48-50].

In the literature, there is a research gap regarding nanosecond laser machining of 1.2379 cold work tool steel and measuring the contact angle of the treated surfaces. In the present study, the surface of 1.2379 steel was treated using a Ytterbium fiber laser with a wavelength of 1080 nm and the Taguchi method was used to invastigate the effect of laser parameters (laser power, scan speed and repetition rate) on the contact angle. The experimental design was carried out consisting of 3 levels and 3 factors using an L9 Orthogonal

Array (OA). The Taguchi signal-to-noise analysis was used to determine the optimal combination of laser parameters for maximizing the contact angle. In addition, ANOVA and multiple regression analyses were performed.

MATERIALS AND METHODS

The influence of laser processing parameters on the wettability of 1.2379 cold-work tool steel was examined using experimental and analytical methods. Before laser proceesing, 1.2379 cold work tool steel specimens (30 x 30 x 60 mm) underwent a series of treatments to prepare them for testing. First, the specimens were cleaned in an ultrasonic bath with acetone solution at 50°C for four minutes, gradually ground between 240 and 2000 grit using SiC abrasive sheets, and then polished with diamond paste. The chemical compositions, mechanical properties and physical properties of the steels used in the experiments are given with Table 1.

The most important factor determining the surface properties of materials processed with lasers is the applied laser parameter value. In this study, the most effective laser parameters, namely the scanning speed and repetition rate, were determined as input parameters. The parameter range was determined based on pre-experimental studies. In the experimental design, an L9 (3^3) OA, which is an efficient design requiring relatively fewer experiments, was used. In this study, 9 experimental runs were performed across 3 factors and at 3 levels. The laser input parameters used in the experiments are listed in Table 2 and the design matrix for the L9 OA is shown in Table 3.

Table 1. Chemical composition (wt.%) [51], physical [52], and mechanical properties [14], [53] of 1.2379 tool steel

Chemical composition (wt.%)				
Fe	Cr	C	V	Mo
~ 84.1	11.86	1.56	0.84	0.83
Mechanical properties				
Hardness (HV 0.5)	Roughness (Ra)	Izod impact unnotched	Poisson's ratio	Elastic modulus
307	0.485 µm	77.0 J	0.27-0.30	190-210 GPa
Physical properties				
Density	Electrical resistivity	Specific heat capacity	Linear expansion coefficient	Melting temperature
7.60g/cm^3	3.15 µΩ*m	460 J/kg*K	10.00 (10^6)/°C	1560°C

Table 2. Design levels and process parameters

Variables	**Levels**		
	1	**2**	**3**
Laser power, P (W)	10	15	20
Repetition rate, R (kHz)	20	60	100
Scan speed, v (mm/s)	10	50	90

Table 3. Design matrix for L9 (3^3) orthogonal array

Exp. No.	**Laser power (W)**	**Repetition rate (kHz)**	**Scan speed (mm/s)**
1	10	20	10
2	10	60	50
3	10	100	90
4	15	20	50
5	15	60	90
6	15	100	10
7	20	20	90
8	20	60	10
9	20	100	50

The LST procedure was carried out using a Ytterbium fiber laser operating at 1080 nm, capable of delivering a maximum pulse peak power of 20 kW at 20 kHz, with pulse durations below 50 ns and repetition rates adjustable between 20 and 100 kHz [54]. The fiber laser surface treatment is schematized in Figure 1. A Galvo scanner was employed to control the laser beam's movement, with a maximum scanning speed of 3000 mm/s. Each test was performed at the focal position.

After the LST process, the contact angle of the material was measured according to ASTM standards [55]. In the contact angle measurement system, using a spring-screw mechanism attached to the needle, droplets not exceeding 20 µL were deposited on the surface of the material in the vertical direction. The droplets were photographed under a uniform light source with the camera in monochrome mode. ImageJ software was used to analyze the drop. Figure 2 displays a graph that depicts the measurement system.

Several technological improvements have been made. It is critical to identify the ideal criteria before using these technologies to create a product. Optimization methods have been employed in manufacturing processes to identify the process parameters that provide the most favorable production conditions [56]. One of the best experimental techniques for determining the fewest tests that must be conducted within the permitted factor and level limit is the Taguchi method [57]. The Taguchi approach can be implemented through three main steps, namely experimental design using DOE, evaluation of the signal-to-noise (S/N) ratio, and determination of the optimal process conditions.[58].

The Taguchi method is a unique process optimization technique that uses the S/N ratio. In the S/N ratio expressions, the signal component (S) denotes the square of the mean value or the desired target, and the noise component (N) represents the variance in the response variable [58]. In the first phase, the S/N ratio is used to find control elements that minimize variability [59] and to determine control factors that move the mean toward the target while having a low impact on the S/N ratio. When unpredictable noise variables do not significantly affect a process or product's performance, the process or product is considered robust. The control factors, once their values are selected, remain constant once their values are selected and are controllable by the manufacturer. The S/N ratio is a statistical indicator used to evaluate both the average response and the variation in the observed data. Reducing the susceptibility of a control

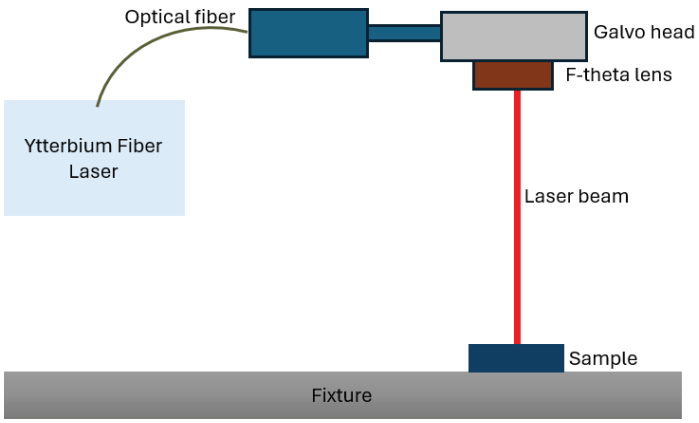


Figure 1. Experimental setup for the laser processing of 1.2379 tool steel surfaces.

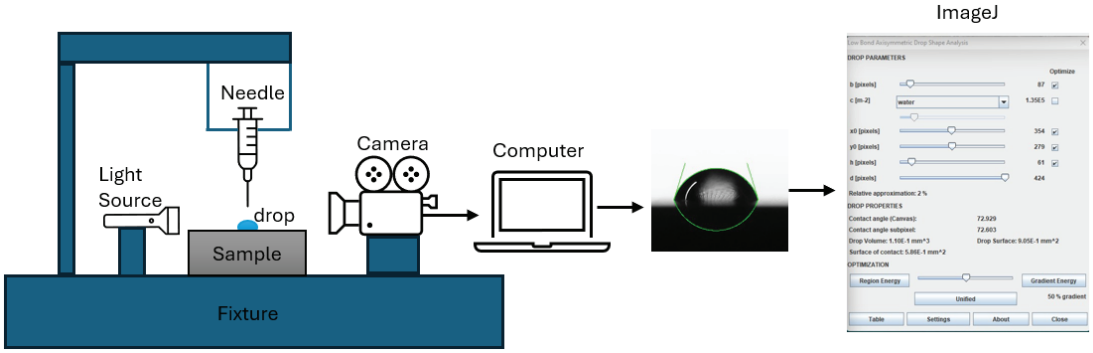


Figure 2. Contact angle measurement of 1.2379 cold-work tool steel for wettability test.

Table 4. Experimental findings and S/N ratio values

Exp. No	Laser power (W)	Repetition rate (kHz)	Scan speed (mm/s)	Contact Angle (⁰)	S/N
1	10	20	10	41.354	32.3303
2	10	60	50	60.561	35.6439
3	10	100	90	65.486	36.3230
4	15	20	50	77.951	37.8364
5	15	60	90	70.291	36.9380
6	15	100	10	64.198	36.1505
7	20	20	90	70.543	36.9691
8	20	60	10	57.294	35.1622
9	20	100	50	84.204	38.5066

characteristic susceptibility to noise effects is the objective of robust design [60]. In optimization problems, three fundamental categories of S/N ratios are recognized: the nominal the best, larger the better, and smaller the better models [61]. A detailed explanation of the S/N ratio is given in Ref. [62].

A larger is better characteristic approach was used for the Taguchi setting in the present study because a maximum contact angle value is expected in order to achieve a hydrophobic surface. Equation 1 [62, 63], where Y denotes the measured response for a given factor-level combination, while n represents the number of observations obtained for that combination, expresses the S/N ratio for a larger is better characteristic [62, 63]. Table 4 presents the experimental findings together with the corresponding S/N ratio values.

$$\frac{S}{N} = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} {}^{1}/_{y_i{}^2}\right) \quad (1)$$

RESULTS AND DISCUSSION

This study primarily aimed to identify the optimum contact angle for laser-machined 1.2379 tool steel using experimental and statistical methods. It aims to render the surface of the material hydrophobic, so it is desirable to obtain the maximum contact angle. Thus, for the S/N ratio in the MINITAB program, the "larger the better" criterion has been used. In the first part of this study, the response (contact angle) values were controlled using a normality test. Probability charts are vital for examining whether a dataset matches a particular theoretical distribution. These plots compare actual datasets with theoretical distributions to test the hypothesis that a statistical sample is derived from a specified distribution [64]. Figure 3 illustrates the probability plot corresponding to the measured contact angle values. The mean contact angle was 65.76°, the standard deviation was 12.39 and the p-value of the graph was 0.214. The p-value is greater than 0.05; therefore, the response values are normally distributed and follow almost a straight line. Thus, surface roughness data can be used in statistical analysis.

The S/N ratios for the laser parameters (laser power, scan speed and repetition rate) are given in Table 5 and Figure 4. In the Taguchi method, the level with the highest S/N ratio expresses the optimal setting [65]. Based on this criterion, the best S/N ratios for laser power, repetition rate

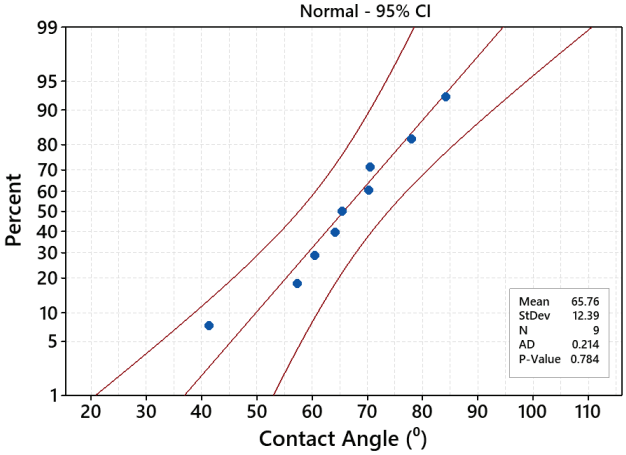


Figure 3. Probability plot of contact angle.

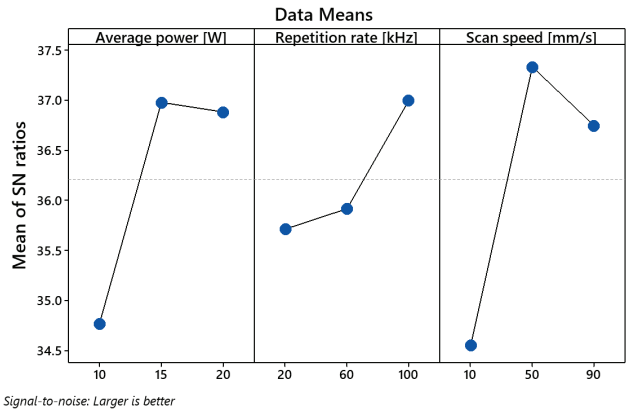


Figure 4. S/N graph of the contact angle of 1.2379 steel.

Table 5. Signal-to-noise ratios of the experimental laser parameters

Level	Laser power (W)	Repetition rate (kHz)	Scan speed (mm/s)
1	34.77	35.71	34.55
2	36.97	35.91	37.33
3	36.88	36.99	36.74
Delta	2.21	1.28	2.78
Rank	2	3	1

and scan speed were 36.97 (level 2), 36.99 (level 3) and 37.33 (level 2), respectively. As a result, as Figure 4 illustrates, the ideal laser treatment settings for the highest contact angle were 15 W of laser power, 100 kHz of repetition rate, and 50 mm/s of scan speed.

ANOVA is a method of analysis used to evaluate the statistical relationship between a dependent variable and one or more independent variables. ANOVA evaluates whether statistically significant differences exist among group means, if the observations within each group follow a normal distribution and have equal variances. This is the basic principle of ANOVA, which is considered an effective tool for determining statistical differences [66]. ANOVA was performed to evaluate the effects of laser parameters on the contact angle. The statistical significance of the analysis was assessed using a significance level of α = 0.05 of the laser parameters. In other words, the analysis was performed using 95% confidence intervals (CIs). The r-squared value of the ANOVA test was 0.99; therefore, the model was statistically significant (Table 6). According to the results, the scan speed parameter was determined to be the most affecting parameter on the contact angle (50.31%), followed by laser power (38.86%). However, the effect of the repetition rate parameter was very low (11.24%). When the p-values were examined, it was found that laser power, repetition rate and scan speed were statistically significant because the p-value of these three parameters was lower than 0.05. Scan speed significantly affects contact angle, as also reported in Ti-40Al-9V-0.5Y alloys treated by SLM, where higher scan speeds increased the contact angle due to molten pool dynamics [67].

Experiments and mathematical methods are required to assess the influence of parameters [68]. Multiple linear regression analysis was conducted using Wolfram Mathematica 11.3 software to characterize the interaction between independent and dependent variables. The objective of regression analysis is to determine how independent factors affect the dependent variable [69-71]. In this regard, multiple linear regression equation (R2= 0.98) for the contact angle was determined using Equation 2. By using the given regression equation and the laser input parameters suggested by Taguchi, the maximum contact angle was determined as 96.274 °. The optimum contact angle was greater than 90°, resulting in a hydrophobic surface. Additionally, a contact angle of 45° was measured for the untreated base metal. As a result of the experimental work and analyses, we conclude that this value can be increased by 113%.

$$\begin{aligned} Contact\ Angle\ (^0) = {} & 37.5464 + 1.488\ Laser\ power\ (W) \\ & + 0.0889949\ Repetition\ rate\ (kHz) \\ & + 0.0111717\ Scan\ speed\ \left(\frac{mm}{s}\right) \end{aligned} \quad (2)$$

Figure 5 shows the contour plots generated using MINITAB 19. The graphs created by considering the binary combinations of the parameters show that the contact angle is directly related to these parameters. As can be seen from the graph, an increase in all three parameters results in a higher contact angle. Especially when high scanning speed and average power were used together, the contact angle reached >80°. This shows that the selected laser parameters significantly influence surface wettability by promoting a more hydrophobic surface characteristic.

The average response was estimated for every combination of control factor values in the Taguchi design, as shown in Figure 6. The figure demonstrates a strong correlation

Table 6. ANOVA results obtained for the contact angle

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Laser power (W)	2	446.82	36.35%	446.822	223.411	75.02	0.013
Repetition rate (kHz)	2	138.16	11.24%	138.163	69.081	23.20	0.041
Scan speed (mm/s)	2	638.14	51.92%	638.137	319.069	107.14	0.009
Error	2	5.96	0.48%	5.956	2.978		
Total	8	1229.08	100.00%				

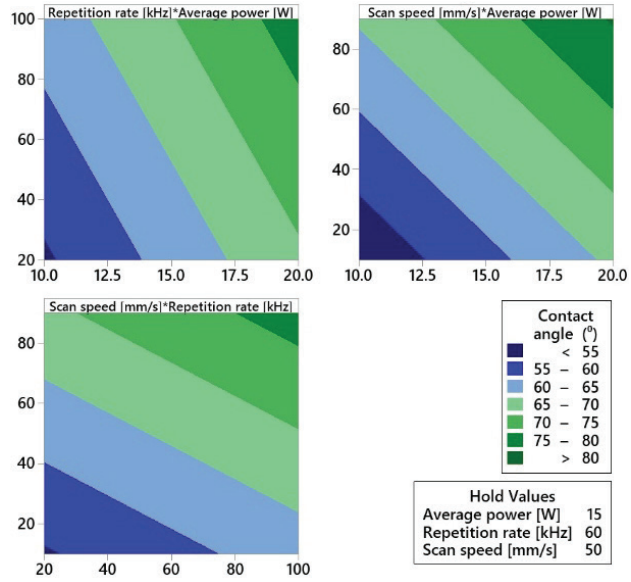


Figure 5. Contour plots of contact angle.

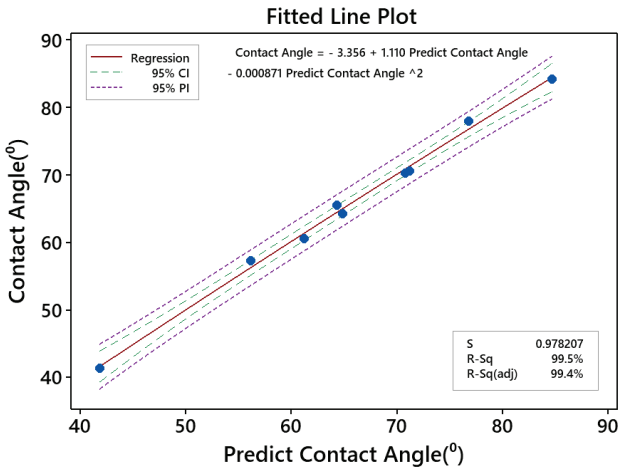


Figure 6. Comparison of experimental and predicted contact angle.

between experimental test results and predicted results for Taguchi. The calculated coefficient of determination (R^2) values, reaching 99.4%, for the equations used to determine the contact angle indicate a high degree of accuracy. Consequently, the Taguchi design was effective in estimating the contact angle within the 95% CI.

Overall, the results demonstrate that the wettability of 1.2379 cold work tool steel can be effectively controlled through nanosecond fiber laser surface treatment, offering an environmentally sustainable and technologically valuable manufacturing approach. Taguchi analysis is an ideal method for determining the impact of laser settings on the angle of contact.

CONCLUSION

In this study, the influence of laser surface treatment parameters on the contact angle of 1.2379 tool steel was evaluated through the Taguchi method, ANOVA, and regression analysis. This work contributes original findings by identifying the key laser parameters influencing the wettability of 1.2379 tool steel, a topic previously underexplored in literature. The analysis results led to the following conclusions:

1. Laser power, repetition rate, and scanning speed were found to have a significant influence on the contact angle.
2. The optimal contact angle was obtained at a laser power of 15 W, a repetition rate of 100 kHz, and a scanning speed of 50 mm/s.
3. According to ANOVA, the contributions of scanning speed, laser power and repetition rate were 50.31%, 38.86% and 11.24%, respectively.
4. Scan speed was identified as the most effective laser parameter in the laser surface treatment process, whereas repetition rate had a minor effect.
5. Using the Taguchi approach, it is possible to determine the laser parameters to be applied to the material surface for the optimum contact angle of 1.2379 steel with minimum experimentation and at a high confidence level.
6. The normal probability distribution confirmed the validity of the model within the 95% confidence interval.

Obtaining a hydrophobic surface on 1.2379 tool steel, which is commonly employed in the moulding industry, has important industrial effects such as improving the corrosion resistance of the material, reducing wear and friction, preventing fouling and extending tool life. This study is limited to 1.2379 tool steel and three laser parameters; surface analysis was based solely on wettability measurements. In future research, the effects of alternative laser types such as CO2, Nd-YAG, and femtosecond lasers instead of ytterbium fiber lasers on 1.2379 cold work tool steel can be investigated comparatively. Structural changes occurring at the microscopic level after laser treatment can be investigated in more detail. In addition, the integration of machine learning and artificial intelligence techniques to predict laser surface treatment results represent a potential research area. Future studies can also investigate the long-term stability and durability of laser-treated hydrophobic surfaces under various operational conditions such as high humidity, abrasion and chemical exposure.

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AUTHORSHIP CONTRIBUTIONS

S.O.: Conceptualization, Methodology, Investigation, Resources, Data curation, Formal analysis, Validation,

Visualization, Writing – original draft, Writing – review & editing. **H.S.A.:** Conceptualization, Formal analysis, Validation, Writing – review & editing, Supervision.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declared no competing financial or personal interests that could have influenced the work reported in this study.

ETHICS

Ethical approval was not required for this study.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

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