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Investigation of the effect of Fiber Laser Parameter on Arithmetic Mean Height (S_a) and Friction coefficient of ST52 Steel Surface

Research Article

Timur Canel[1*], Çağla Pilavcı[2]

[1] Kocaeli University, Faculty of Art and Sciences, Department of Physics, Kocaeli University, Kocaeli, Türkiye.

[2] Kocaeli University, Institute of Educational Sciences. 41380 Umuttepe, Kocaeli, Türkiye.

Author E-mails:
tcanel@kocaeli.edu.tr
cagla.pilavci@gmail.com
T. Canel ORCID ID: 0000-0002-4282-1806
Ç. Pilavcı ORCID ID: 0009-0005-5237-9598

*Correspondence to: Timur Canel, Kocaeli University, Faculty of Art and Sciences, Department of Physics, Kocaeli University, Kocaeli, Türkiye.

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Abstract

In this study, the surfaces of ST52 steel plates were textured using a fiber laser. The topographies of the resulting surfaces were examined, and the relationship between the coefficient of friction and the Arithmetic Mean Height (Sa) of the surface was investigated, focusing on the Arithmetic Mean Height (Sa) of the surface roughness parameters. Different laser parameters were used to obtain different Sa values. To minimize the Sa value and reduce the coefficient of friction, three independent laser parameters, laser power, scan area ratio, and the type of pattern created on the surface were examined. The three parameters were examined at four levels using the Taguchi Optimization Method. As a result of the Taguchi optimization method, it was predicted that the Sa value would be 4.24 while using the necessary laser parameter levels for obtaining the lowest coefficient of friction, with a square pattern type, 20% scan area, and 40W laser power. The ANOVA analysis revealed that the parameters most influential in obtaining optimum values were, in order, azer power (48.61% contribution), followed by scanning area ratio (32.67%) and pattern type (18.72%). The results of the study show that the friction coefficients of surfaces can be altered by precisely controlling the Arithmetic Mean Height (Sa), a parameter of surface roughness.

Keywords: Fiber Laser Parameter, Arithmetic Mean Height of a Surface (S_a), Friction coefficient, ST52 Steel, Taguchi Method.

1. INTRODUCTION

ST52 steel, a low-alloy high-strength structural steel frequently preferred in many fields from the construction sector to the automotive sector, also possesses many superior mechanical properties such as impact resistance and high toughness [3]. To increase its weldability and formability, ST52 has a relatively low carbon content of approximately 0.22% compared to other steels [1]. In addition to its carbon content, it has a high tensile strength of 490–630 MPa and a high yield strength of approximately 355 MPa due to the appropriate proportions of manganese (Mn), silicon (Si), phosphorus (P), and sulfur (S) [2]. Its suitability for both hot and cold forming provides flexibility in production processes. One of the main reasons for its preference in many industrial fields is its low cost and long service life, as well as its good weldability and high strength-to-weight ratio [4]. ST52 steel is preferred in machine parts requiring high impact resistance such as crane arms, load-bearing beams and chassis components [5]. Thanks to its suitability for heat treatment, surface hardening and low post-weld cracking rate, it is preferred especially in areas where wear resistance is important [6].

ST 52 steel is preferred in industry, manufacturing, and consequently in research and development due to its very wide range of applications. It is particularly favored in sectors such as heavy machinery manufacturing, construction and crane equipment production, and high-rise building and bridge construction where structural strength is paramount. Similarly, it is preferred in components used in heavy-weight transportation such as trains and ships. It is also preferred in the manufacture of high-pressure pipes and vessels due to its strength and weldability properties. In all these areas, it is preferred because it provides optimum efficiency due to its machinability, superior mechanical properties, and especially its low cost.
In addition to improving the mechanical properties of materials, numerous engineering and academic studies have been conducted on surface texturing, which is preferred in many areas of industry to meet aesthetic needs [7]. The performance of a machine component used in industry is related not only to the components of the material from which it is manufactured, but also to the properties of the material's surface structure. Surface treatment can improve many properties of materials, including their mechanical properties such as friction coefficient, adhesion and bonding behavior, corrosion resistance, and wear resistance, as well as their biocompatibility and electrical conductivity [8]. In addition to all these outstanding contributions, it can increase the service life by contributing to the mechanical performance of the materials. For all these reasons, the surface quality of the material is considered a parameter in surface engineering.

Surface treatment techniques can be classified into four main categories based on their applications in industry: thermal, chemical, laser, and mechanical methods [9,10]. In industrial applications, various methods are employed to mitigate or eliminate surface defects, such as residues or burrs, which emerge during or post-manufacturing [11]. Alternatively, chemical methods are utilized to eradicate minor manufacturing flaws as well as post-production contaminants, including oxidation or surface grease [12]. Furthermore, the hardness and mechanical resistance of fabricated materials can be enhanced both during and after manufacturing via thermochemical treatments, such as nitrogen diffusion (nitriding), or by projecting molten or semi-molten protective materials onto the surface at high velocities [13]. Beyond these conventional techniques, laser surface processing offers significant advantages as an alternative approach. Its primary benefits include high precision, reproducible results sustained at this precision, minimized environmental impact, and the elimination of tool wear due to the non-contact nature of the process. Laser material processing involves numerous operational parameters contingent upon the characteristics of the material, the laser system, and the processing environment. Factors influencing the process outcomes include laser specifications (e.g., wavelength, frequency, and spot size), material properties (e.g., metallic, polymeric, or alternative substrates), and environmental conditions (e.g., ambient temperature, humidity, and the stand-off distance between the laser and the material). By implementing optimal laser parameters, well-defined micro- or macro-scale patterns can be generated on the material surface through continuous processing.

The primary advantages of laser material processing reside in its high precision and reproducibility, which collectively yield significant time and material savings. Through the selection of an appropriate laser source and optimized processing parameters tailored to the specific application and substrate, highly reproducible micro-scale patterns can be successfully generated on material surfaces.

Laser surface texturing, which involves generating diverse surface patterns ranging from nano to macro scales on various materials through the selection of appropriate lasers and processing parameters, finds utilization across a wide range of applications [14]. By selecting optimal processing parameters, laser energy can be transferred to the material surface at a desired rate, thereby enabling controlled heating, melting, and vaporization. This mechanism can be precisely replicated through appropriate energy transfer protocols. The morphology and particularly the dimensions of the target patterns on the material surface can be governed by the laser frequency or wavelength, whereas the depth of these patterns is directly correlated with the laser energy delivered to the surface.

ST52 steel is extensively preferred across various industrial sectors due to its high ductility, which is defined as the capacity to undergo significant plastic deformation and elongation under tensile stress without fracturing, enabling drawing into fine wires or sheets, as well as its high strength denoting the ability to withstand applied loads and deformation without failure. In many instances, to enhance the adhesion durability of subsequent coatings or to optimize tribological characteristics, surface texture is implemented on ST52 and equivalent steel substrates.

Particularly in the energy and biomedical sectors, micro-scale surface roughness can mitigate friction by enhancing lubricant retention during component lubrication. Concurrently, these micro-scale roughness profiles contribute to the hydrophobicity or hydrophilicity of the surface thereby improving its self-cleaning or anti-fouling characteristics.

Different roughness parameters characterize disparate topographical features of the surface. Various indicators correspond to specific roughness characteristics such as the height, width, spatial density, and sharpness of the surface asperities. These parameters directly dictate surface properties including friction and adhesion. Consequently, a direct correlation exists between the target surface roughness parameters and the overall surface performance. Accordingly, one of the primary objectives of this study is to establish the relationship between the laser processing parameters and the arithmetic mean height (Sa), a key roughness parameter, thereby elucidating the correlation between the coefficient of friction, the roughness parameter (Sa), and the laser operational parameters.

If the surface is properly lubricated, the surface irregularities can help the lubricant film adhere to the surface, preventing the surfaces from coming into direct contact and reducing friction. However, roughness on unlubricated dry surfaces causes an increase in friction force. Additionally, the homogeneity of the type of surface roughness and its uniform distribution across the entire surface significantly affect the coefficient of friction. Since the effects of each surface roughness parameter on the surface's friction behavior differ, optimizing these parameters is essential in scientific research and engineering applications to improve surface friction properties in the desired direction and achieve both energy and material savings.

In this study, the relationship between friction and one of the surface roughness parameters, the Arithmetic Mean Height of a Surface (Sa), was investigated. For this purpose, roughening processes were applied on the surface of ST52 steel material using different laser parameters. Surface topographic images of each sample were obtained by an optical profilometer, and roughness coefficients were calculated using specialized computer software. To reduce the number of experiments and analyses in the experimental section, the Taguchi optimization method was employed. The results were interpreted using ANOVA analysis.

1.1. Relationship between Friction and Arithmetic Mean Height of a Surface (Arithmetic Mean Height)-S_a

In tribology, the study of friction, wear and lubrication, the relationship between friction and the arithmetic mean height (S_a) of a surface is important. The average height deviations of a surface from its mean plane are measured using a quantity called arithmetic mean height (S_a). This is a simple statistical measurement of surface roughness, which has a direct impact on the frictional behavior of the surface [15]. A smoother surface is indicated by lower S_a values, while a rougher surface is indicated by higher S_a values. When considering solely the arithmetic mean height (Sa) parameter, surfaces exhibit higher mechanical interlocking if the surface asperities are confined to micro-scale dimensions, thereby elevating the coefficient of friction. Conversely, a reduction in surface roughness—characterized by lower (Sa) values—attenuates mechanical interlocking, consequently resulting in a lower coefficient of friction. This means the surface has fewer irregularities—and thus fewer surface protrusions, which leads to a lower coefficient of friction [16]. Sa, one of the surface roughness parameters, does not linearly affect the coefficient of friction [17]. Surface properties, like other parameters, are factors that influence the coefficient of friction. The fact that adhesive forces become more dominant at the microscopic scale serves as evidence of how significantly surface roughness dimensions affect the coefficient of friction [18]. For these reasons, when examining the effect of each surface roughness parameter on the coefficient of friction between surfaces, certain parameters such as surface wettability, lubrication level, or temperature must also be taken into account.
The reason for aiming to obtain the smallest possible Sa value in this study is that among the surface roughness parameters required to reduce the coefficient of friction, the Sa value is intended to be the smallest.

1.2. The relationship between the arithmetic mean height (Sa) of a rough surface and the degree of surface adhesion

The relationship between the arithmetic mean height (Sa) of a surface and surface adhesion is referred to as surface bonding; the strength of the bond formed between surfaces and the duration of the bond serve as indicators of the quality of the bond between them [19].

One of the surface roughness parameters that affects the quality of mechanical or adhesive bonding between surfaces is the surface Sa value [20]. To achieve higher efficiency when using bonding agents—such as adhesives—to join surfaces, the surfaces must have higher Sa values. Higher Sa values allow adhesive materials to spread more extensively across the surface due to the increased surface area, thereby enabling a stronger bond to the surfaces [19].

In this study, achieving a lower coefficient of friction on the surfaces of ST52 steel substrates is targeted. L Sources in the literature have established that surfaces with a reduced coefficient of friction exhibit lower (Sa) values. Accordingly, this study investigates the specific laser processing parameters required to obtain surfaces with lower (Sa) values. Furthermore, the laser operational parameters that exert the most significant influence on achieving the desired surface topography have been identified. Consequently, the mechanisms by which laser processing parameters affect the coefficient of friction have been partially clarified from a scientific perspective.

2. EXPERIMENTAL

In this study, microscale surface patterns were fabricated on ST52 steel using a fiber laser operated under different processing conditions. The primary objective was to determine the laser processing parameters that yield the lowest Arithmetic Mean Height (Sa), thereby producing a surface with a reduced friction coefficient. Three laser processing parameters were investigated, each at four different levels, to optimize the surface texturing process.

To minimize the number of experimental trials, as well as the associated time and cost, the Taguchi optimization method was employed. This approach has been widely adopted and validated in engineering and scientific research as an efficient experimental design technique. Instead of performing all 64 experiments required by a full factorial design (4^3), the optimum processing parameters were successfully identified using an L16 orthogonal array consisting of only 16 experimental runs.

In addition, an analysis of variance (ANOVA) was conducted to quantify the statistical contribution of each processing parameter to the observed response. The surface topographies of the laser-textured steel specimens were characterized in detail using an optical profilometer. Based on the acquired three-dimensional surface data, the Arithmetic Mean Height (Sa), one of the most widely used roughness parameters in surface engineering, was determined for each specimen using the profilometer software.

Since surface roughness is closely related to the frictional behavior of engineering surfaces, the Sa values obtained from all laser-treated specimens were carefully evaluated. Accordingly, the Smaller-the-Better quality characteristic given in Equation (1) was adopted for the Taguchi optimization. The Arithmetic Mean Height (Sa) values obtained from the topographical characterization of all laser-textured surfaces, together with their corresponding Signal-to-Noise (S/N) ratios, are presented in Table 1.

3. RESULTS AND DISCUSSION

Table 1. Arithmetic average height (s_a) and s/n ratios for all experiments.

	Pattern Type	Scanned Area Rate (%)	Power (W)	S_a	S/N
1	Square	80	40	9.86	-19.88
2	Square	60	60	72.20	-37.17
3	Square	40	80	7.65	-17.67
4	Square	20	100	47.50	-33.53
5	Diamond	80	60	176.00	-44.91
6	Diamond	60	40	9.18	-19.26
7	Diamond	40	100	35.10	-30.91
8	Diamond	20	80	124.00	-41.87
9	Hexagon	80	80	223.00	-46.97
10	Hexagon	60	100	147.00	-43.35
11	Hexagon	40	40	93.60	-39.43
12	Hexagon	20	60	6.67	-16.48
13	Circle	80	100	177.00	-44.96
14	Circle	60	80	109.00	-40.75
15	Circle	40	60	6.88	-16.75
16	Circle	20	40	4.11	-12.28

Statistical reliability was tested by calculating the total sum of squares. The ANOVA results are presented in Table 2. The highest levels were obtained as follows: "Level 1 (Square)" for the pattern type, "Level 4 (20%)" for the scanning area ratio, and "Level 1 (40 W)" for laser power. The expected S/N ratio and S_a value for the optimum combination were calculated as -12.54 and 4.24, respectively.

Table 2. ANOVA Table for Achieving a Smaller Coefficient of Friction (Smaller S_a) Based on the Taguchi Method.

	Average S/N						
Factors	1. Level	2. Level	3. Level	4. Level	Factors	Optimum Level	Optimum Parameter
Pattern	-27.06	-34.24	-36.56	-28.68	18,72	1	Square
Scanned Area	-39.18	-35.13	-29.33	-26.04	32,67	4	20 %
Power	-22.71	-28.83	-36.81	-38.19	48,61	1	40 W
Average		-31.63					
Total					100.00		
Optimum S/N							-12.54
Optimum S_a							4.24

The most effective parameter for achieving a more hydrophobic surface was found to be laser power with a contribution rate of 48.61%. The second most influential parameter was the scanning area, contributing 32.67%. Among the parameters examined, the least effective was the pattern type formed on the surface with a contribution rate of 18.72%. The main effect plots for the coefficient of friction are presented in Figure1.

In this part of the study, as shown in Figure 1, the effects of the processing parameters on the Arithmetic Average Height (S_a) of a surface were examined.

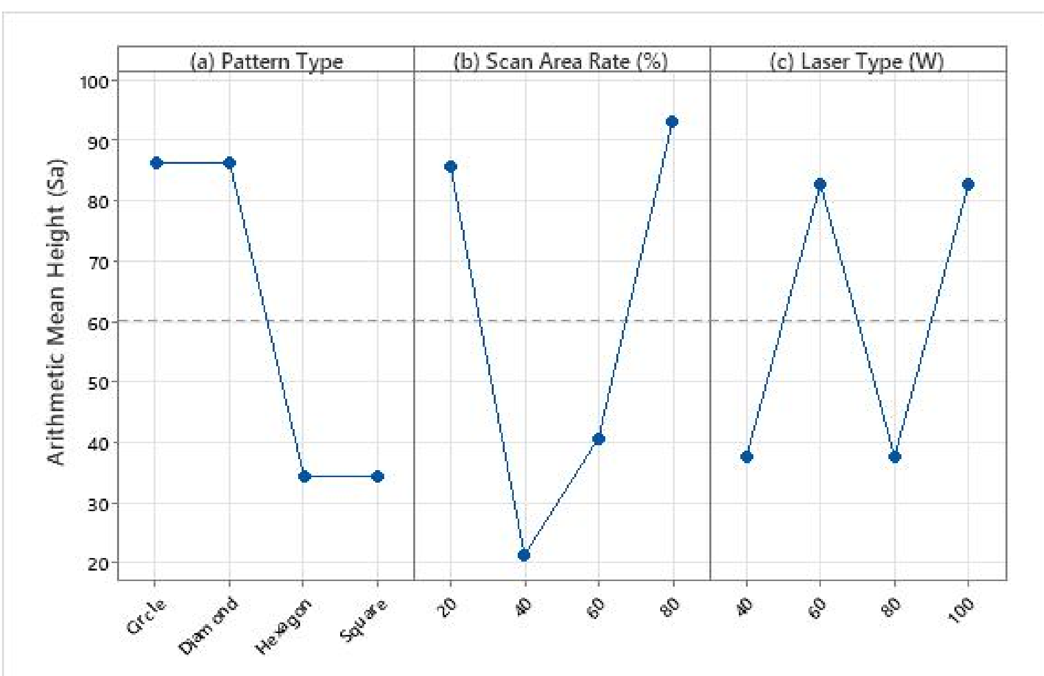

Figure 1. Main Effect Plots for the Effects of Laser Processing Parameters on the Arithmetic Average Height (S_a) of a Surface

As seen in Figure 1.a, the highest S_a values were obtained in the Circular and Diamond pattern types while the lowest S_a values were found in the hexagonal and square patterns. In Figure 1.b, which shows the effect of scanning area on S_a, a rapid decrease in S_a was observed when the scanning area increased from 20% to 40%. Subsequently, as the scanning area increased from 40% to 60%, and then to 80%, the S_a value quickly reached its maximum value. The highest S_a value was obtained at 80% scanning area while the lowest S_a value was obtained at 40%. In Figure 1.c, which examines the effect of laser power on S_a, as the laser power was increased from 40 W to 60 W, the Sa value increased rapidly. However, when the laser power was further increased from 60 W to 80 W, the Sa value decreased almost at the same rate. Then, as the laser power increased from 80 W to 100 W, the Sa value increased again at a similar rate.

For a more hydrophobic surface, a larger Sa value needs to be obtained. The main effect plot shows that larger S_a values, which means greater hydrophobicity, were achieved with Circular and Diamond patterns. A more hydrophobic surface can be obtained when the scanning area is 80%. Laser powers of 60 W and 100 W also resulted in larger S_a values. Therefore, for a more hydrophobic surface, the pattern type should be Circular or Diamond, the scanning area should be 80%, and the laser power should be 60 W or 80 W.
To obtain a surface with a smaller friction coefficient, a smaller Sa value needs to be achieved. The main effect plot shows that smaller Sa values, meaning surfaces with lower friction coefficients, were obtained with hexagonal and square patterns. A surface with a smaller friction coefficient can be obtained when the scanning area is 40%. Laser powers of 40 W and 80 W resulted in smaller Sa values.

5. CONCLUSION

The primary objective of this study was to create surface patterns on ST52 steel materials which are widely used in industry as machine components requiring a low coefficient of friction by employing various laser processing parameters to reduce the coefficient of friction. The Taguchi optimization method was employed in the analyses to save experimental costs and time. The "Smaller is better" criterion was used to achieve the lowest coefficient of friction and the smallest Sa value. Consequently, optimal parameters were determined based on the analysis results derived from measurement data from detailed surface topographies and Signal-to-Noise ratio calculations in the ANOVA analysis. Based on the measurements and calculations, the most effective parameters required to achieve the desired surface morphology such as laser power, scan area ratio, and pattern type were examined.

Two of the most important outcomes of the ANOVA analysis are the determination of optimal parameters and the identification of the extent to which the parameters used influence the results. The ANOVA analysis revealed that laser power, one of the laser processing parameters, was the most influential one accounting for 48.61% of the variation in the results of studies aimed at achieving the lowest Sa value. The scanning area was determined to be the second most effective laser processing parameter contributing 32.67% to the result. The parameter with the least effect on the result was determined to be the pattern type with a contribution of 18.72%. Based on these results, laser power was identified as the laser processing parameter that requires the most attention in future studies. According to the ANOVA results of the Taguchi optimization method, when the recommended laser processing parameters (a Square pattern for pattern type, a scan area ratio of 20%, and a laser power of 40 W) are used, the expected S/N ratio is calculated as -12.54 while the expected Sa value is 4.24.

According to these results, the closer the Sa value, which is one of the surface roughness parameters, approaches the target value, the lower the coefficient of friction of the laser-textured surface becomes. In this way, the tribological properties of the surface can also be achieved at the desired level. Since the objective of this study was to obtain the lowest coefficient of friction, efforts were made to produce a surface with the lowest Sa value. In some cases, it may be desirable to maintain the coefficient of friction at a specific value or within a specific range. In such cases, using the "nominal best" characteristic is more appropriate. It is evident from the fact that laser power is the most significant parameter affecting the result that the energy density delivered to the material surface is the most critical parameter in achieving the desired surface parameters. According to the results of the calculations, the type of patterns formed on the material surface was the parameter that had the least effect on the result. Considering the effect ratios calculated in this study, it is anticipated that in subsequent optimization studies, they will lead to a reduction in the number of experiments required.

This study focuses on the coefficient of friction among the tribological properties of laser material processing. Based on the results obtained from this study, designing experimental methods for future research will make achieving the desired surface properties easier. Following this study, it will be possible to determine whether the process parameters used influence one another and, if so, to what extent they do. This will allow a prioritization of the numerous process parameters used in laser material processing, where less influential parameters can be given less consideration while more influential parameters receive greater attention.

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