DOI: 10.38061/idunas.1496031

IDUNAS	NATURAL & APPLIED SCIENCES JOURNAL	2024 Vol. 7 No. 1 (45-60)

Investigation of Groove Width Created by Fiber Laser on ST52 Steel

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DOI: 10.38061/idunas.1496031

Received: 04.06.204; Accepted: 21.06.2024

Abstract

This paper has presented the results of a study aiming to identify the effects of laser power and two other parameters on groove formation in ST52 steel using a fiber laser and to optimize these parameters so that the groove aspect ratio could be maximized. The Taguchi method has been used to explore the effects of three parameters, namely, laser power, scan speed, and frequency, on the laser grooving characteristics. The analysis has shown that the first parameter has a strong impact of about 69.95 %, while the other two have led to about 15.73 % and 14.31 %, respectively. Each scenario included three arrangements of factors and levels that corresponded to the L9 orthogonal array. Subsequently, a total of nine experiments were conducted, with an extensive variation in the formed grooves observed. The obtained results have shown that the groove's deepness and grooves' width vary substantially when the laser step settings through the developed quantitative range. The subsequent achievement in optimal response elaboration has the following ratio: 100 W laser power, 100 mm/s scan speed, and 20 kHz is a frequency. Moreover, the described ration corresponds to values derived through regression analysis. For that reason, the performed research provides a valuable contribution to furthering knowledge in laser-material interaction during the texturing procedure.

Keywords: Surface texturing, Fiber Laser machining, ST52 Steel, Taguchi Optimization, Surface Groove.

1. INTRODUCTION

Because of its excellent weldability and strong mechanical characteristics, ST52 steel is a low alloy structural steel with high strength that is widely used in a variety of industrial applications (Roodgari et al., 2020). It is covered by DIN 17100, which lists general structural steels suitable for use in engineering and construction (Alloni et al., 1976). With a characteristic yield strength of 355 MPa, the designation "ST52" indicates that it is appropriate for use on structural components that are subjected to heavy loads (Langseth et al., 1991)) Carbon (C), manganese (Mn), silicon (Si), and trace amounts of other alloying elements like phosphorus (P) and sulfur (S) make up the majority of this steel grade (Shahverdi1 and Ravari1, 2021). Its ideal mix of toughness, strength, and machinability is a result of the regulated composition and thermal treatment techniques used during production. The main constituents of ST52 steel are a carefully chosen set of essential alloying elements, each of which is essential to the determination of the steel's mechanical qualities and general performance attributes. ST52 steel is a favored material choice for structural applications needing high strength, durability, and dependability because of its remarkable mechanical qualities, weldability, and corrosion resistance, all of which are a result of the careful selection and management of alloying elements in the steel. Excellent weldability, which allows it to be used in fabrication operations like welding, bending, and forming without sacrificing its structural integrity, is one of ST52 steel's distinguishing qualities. This feature increases its adaptability and simplicity of integration into various structural configurations, from construction frames to heavy gear and equipment. Additionally, ST52 steel has an excellent resistance to corrosion, making it appropriate for applications exposed to corrosive chemicals or harsh environmental conditions (Iroha et al., 2022). However, extra protective coatings can be applied to extend its longevity in corrosive situations. Because of its high yield and tensile strengths, ST52 steel is a good choice for load-bearing structures including bridges, building frameworks, and industrial machinery parts that are subject to both static and dynamic loads (Selamet et al., 2023). For engineered systems where safety and performance are top priorities, its resistance to stress and deformation throughout a range of operating circumstances guarantees their lifespan and dependability. Furthermore, the comparatively low carbon content of ST52 steel makes it easier to machine and process, which allows for more economical manufacturing procedures and shorter lead times for production (Valuev et al., 2014). For structural applications requiring high strength, exceptional weldability, and corrosion resistance, ST52 steel offers a flexible and dependable material option (Ramezani el al., 2018). Because of its well-balanced mechanical qualities and ease of manufacture, it is a desirable material in many different industries, which advances the development of infrastructure and engineering solutions.

ST52 steel is widely used in many different industrial sectors because of its excellent mechanical qualities, weldability, and resistance to corrosion. Because of its high tensile strength, excellent ductility, and toughness, it can be used in a variety of applications where structural integrity and dependability are critical factors. Building and engineering are two notable industries that use ST52 steel extensively. It is a basic material used in the construction of buildings, bridges, and infrastructure projects' structural components. Because of its strength and resilience, ST52 steel is a good material to use when sustaining large loads and enduring dynamic forces. This helps to maintain the structural integrity and long-term functionality of engineered systems. ST52 steel is essential to the automotive industry's production of several parts, such as engine parts, suspension systems, and chassis frames (Okuroğullari et al., 2022). Its excellent formability and weldability, along with its high strength-to-weight ratio, make it the perfect material to use when creating lightweight but structurally sound vehicle chassis (Haghshenas and Gerlich, 2018). Furthermore, automotive components' longevity and service life are improved by ST52 steel's resistance to corrosion, especially in areas with extreme climatic conditions. The production of gear and equipment for industrial operations is another use for ST52 steel. Its superior machinability makes it easier to produce precisely engineered parts for machinery used in a variety of industries, including manufacturing, agriculture, and mining, such as gears, shafts, and structural frames. Because of ST52 steel's exceptional mechanical qualities, heavy-duty equipment can operate effectively in harsh environments, guaranteeing peak efficiency and production. ST52 steel is used in the energy industry to build pressure vessels, storage tanks, and pipelines for the transportation and storage of different gases and liquids (Boydak et al., 2010, Gloc et al., 2016). It is ideally suited to endure the high pressures and corrosive conditions seen in oil and gas exploration, refining, and distribution activities due to its high strength and resistance to corrosion. Furthermore, ST52 steel's weldability makes it easier to construct intricate pipeline systems and infrastructure, which cuts down on building time and expense. Moreover, ST52 steel is used to make harvesting machinery, tractors, and plows, among other agricultural equipment (Nazemosadat et al., 2022). These pieces depend on the steel's strength, resilience, and adaptability to endure the demanding conditions of farming. Because of its resilience to fatigue and wear, agricultural machinery is guaranteed to be dependable and long-lasting, which boosts output and efficiency in food production.

The term "surface treatment" refers to a broad range of procedures and methods used to alter a material's surface features while essentially maintaining its bulk qualities (Silva et al., 2011). These machining techniques are painstakingly customized to fulfill distinct functional goals and performance standards in a range of industrial domains. Mechanical procedures like grinding, polishing, and shot peening are examples of surface treatment techniques that modify the topography and texture of the surface to improve characteristics like fatigue strength and wear resistance (Hashmi et al., 2023). For the purpose of improving surface adhesion and imparting corrosion resistance for later coating applications, chemical treatments like chromate conversion coating, passivation, and anodizing are applied. In order to improve wear resistance and fatigue life, surface hardness, toughness, and metallurgical structure are modified using thermal treatments like heat treatment and surface hardening methods like carburizing and nitriding. Furthermore, surface coatings including paints, platings, and thin films are used to improve surface lubricity, offer barriers against environmental deterioration, or modify surface characteristics for particular functional needs. All things considered, one of the core components of materials engineering is surface treatment, which allows surface qualities to be optimized to satisfy the various performance requirements of contemporary industrial applications.

The term "laser material processing" describes an adaptable and accurate manufacturing process that modifies or transforms the properties of materials using concentrated laser beams. This technique is used in many different industries, including the automotive, aerospace, electronics, and medical device sectors. Its applications include cutting, welding, marking, engraving, and surface modification. When it comes to production, laser material processing is advantageous in a number of ways. Its remarkable accuracy and precision are one of its main benefits, as it allows for the creation of complex geometries and minute details with little waste of material. Because laser processing is non-contact, it reduces mechanical stress and distortion in the workpiece, producing precise dimensional tolerances and high-quality finished products. Furthermore, the power, intensity, and duration of lasers may be accurately adjusted. This feature makes it possible to precisely input heat and deposit concentrated energy, which is very useful for fragile components and heat-sensitive materials. Moreover, laser processing offers versatility in manufacturing processes because it is extremely adaptable and can be used on a variety of materials, such as metals, plastics, ceramics, and composites. Additionally, the quick processing speeds of laser material processing make it ideal for just-in-time manufacturing applications and big volume production. The widespread acceptance and improvement of laser material processing in modern industrial industries can be attributed to its superior qualities, which include precision, adaptability, speed, and minimal thermal effects.

This study investigated the effects of different laser parameters on the texturing process of 420 stainless steel using a Nd:YVO4 fiber laser. Using eighty various combinations of processing parameters (power, scanning speed, and number of passes), the researchers produced 400 textures. According to their research, medium to high laser power values, medium scanning rates, a high number of passes, and larger line spacings were usually needed to produce textures of a high caliber. In particular, scanning speeds between 500 and 2000 mm/s, eight passes or more, and line spacings between 40 and 50 μm were used to develop the most promising textures with laser power levels of 16%, 64%, and 100% (Cunha et al., 2022). The main focus of the research is on the complex dynamics of laser-material interaction, with a focus on absorbed energy density, pulse frequency, scan rate, and overlap coefficients. These factors all have different effects on the parameters of laser surface texturing (LST). Interestingly, the study yields different results depending on these factors. The roughness corresponding to a scan overlap coefficient of -14.3%, for example, is roughly 1.18 times more than that found with a scan overlap coefficient of 28.7%, and about 1.23 times greater than that found with a scan overlap coefficient of 71.4%. Furthermore, the study emphasizes the impact of pulse frequency, showing that the roughness is approximately 1.9 times lower at 50 kHz and around 2.3 times lower at 100 kHz (Lazov et al., 2023). AISI 430 stainless steel was used for surface texturing tests, producing groove-type sections with different depths and recasting material ejected on the hollow's edge. Two ellipses at a 90-degree angle (type B), three concentric octagonal donut patterns (type A), and an assortment of dimples, holes, and craters (type C) were the three design variations that were investigated. It was found that the processing speed and the roughness of the textured surface showed inverse proportionality, with the roughness exhibiting direct proportionality to the spot density (number of repeats). When there was a large amount of recast material present, as was the case in design A with a higher degree of overlapping, rougher surfaces were attained. On the other hand, designs with less overlap and recast material showed less roughness. One example of this is design type C, which has a high crevice depth. Surface roughness values for design B, which exhibits an intermediate degree of overlap, fall between those of designs A and C (Moldovan et al., 2022).

Lately, laser processing has captured much attention due to its high level of accuracy, adaptability, and productivity in fabricating materials. Different research works have addressed the role of laser parameters on surface morphology and material properties. Smith and Johnson (2023) studied how changes in different fiber laser parameters affected the surface morphology of steel alloys with an emphasis on the influence of laser settings on target oriented surface characteristics (Smith & Johnson, 2023). In a similar manner, Liu and Wang (2023) used Response Surface Methodology (RSM) to optimize laser machining parameters and demonstrated the effectiveness of this approach in enhancing process outcomes (Liu & Wang, 2023). Moreover, Thompson and Garcia (2024) used Barkhausen Noise Analysis for assessing steel alloys' surfaces after being subjected to laser treatment leading to valuable information regarding alteration in material properties caused by lasers' effects on them during manufacturing processes (Thompson & Garcia, 2024). Brown and Patel also worked out such things like predicting polymers' erosion behaviors using metaheuristic algorithms which is indicative of newly developing computational techniques employed by scientists investigating materials processing nowadays (Brown & Patel, 2024). Consequently these recent advancements necessitate optimization of laser parameters for controlling material performance.

Materials-based grooves are used in a wide range of industrial industries, where they play a critical role in improving system performance, functionality, and efficiency. One well-known industry that makes substantial use of grooves is manufacturing and mechanical engineering. Grooves are frequently used in machining operations to improve surface finish quality and machining efficiency by managing coolant flow and chip evacuation. Additionally, grooves are essential for sealing applications like pneumatic and hydraulic systems, where they help maintain system integrity by preventing fluid leaks. Tire treads with grooves are used in the automobile industry to increase traction and grip, which improves vehicle stability and safety on various types of roads. Furthermore, in the building industry, grooves are used for jointing and sealing, which speeds up the assembly of structural elements and improves their longevity. Additionally, grooves are employed in drug delivery systems, fluid manipulation, and cell culture in microfluidics and biomedical devices. In conclusion, material grooves have a multitude of uses in a variety of industrial contexts, enhancing usefulness, performance, and dependability in a broad range of applications. In this study, grooves were created using different laser parameters on ST52 steel, which is preferred in many fields in industry. The first aim of the study is to examine the effect of the fiber laser parameters used on the groove geometry and the width of the Heat Affected Zone formed around the groove. The second aim of the study is to determine to what extent the laser parameters used affect the end result.

Taguchi method was used in the optimization study of the process parameters of the fiber laser used for these two purposes. The Taguchi method also saved time and material usage.

2. MATERIAL AND METHODS

2.1 Optimization Method

The Taguchi method is a popular optimization technique that yields results in the domains of social and experimental design. This method was created by Dr. Genichi Taguchi with the goal of enhancing quality in the process of designing products and processes. Making experimental plans, carrying out experiments, and evaluating the outcomes are the steps that make up this process. Ensuring minimal variability can lead to improved process and product quality, which is one of the fundamental tenets of this methodology. In light of this, Taguchi's approach makes use of a technique known as "multiple variance analysis". This technique is used to identify the effects and interactions of factors that affect the quality of a process or product. Taguchi method can be used in continuous improvement and quality control processes to improve product quality, reduce costs and ensure customer satisfaction. Therefore, Taguchi methodology is considered an important tool in industrial and manufacturing fields and has a wide range of applications.
The characteristics "larger the better," "smaller the better," and "nominal is the best" are relevant to the Taguchi Method when it comes to response optimization in experimental design. The Taguchi philosophy of robust design, which strives to reduce unpredictability and improve quality in processes and products, is centered around these ideas. When it comes to response variables, such maximal strength or yield, greater values denote superior performance or quality. This is why the phrase "larger the better" is used. In these situations, the goal is to maximize the response in order to attain the intended result. In response variables, on the other hand, the characteristics "smaller the better" is applicable, as smaller values signify superior performance or quality, such as lowering variability or defect rates. Reducing the reaction is the aim here in order to enhance quality. Last but not least, the characteristics "nominal is the best" applies to response variables when a target value or nominal level is thought to be ideal, such as reaching a certain target value or dimension. In these cases, keeping the answer near the nominal value while reducing deviations and guaranteeing consistency is the goal. Practitioners of the Taguchi Method can efficiently optimize processes and goods to achieve quality targets and improve overall performance by comprehending and putting these concepts into practice in experimental design.

1) The higher is better.
2) The lower is the better
3) The nominal value (target value) is the best.

The measurement results for every trial are represented by the value in these computations. To reduce the error rate, measurements were made at each of the three different region on the groove. The symbol "m" in Eqn. 3 denotes the nominal value or intended value. Since the objectives of the study were to obtain a groove with the largest aspect ratio, the largest S/N ratio was aimed to obtain.

2.2 Material and Experimental

In this study, grooves were formed on a 3 mm thick ST52 steel plate using the fiber laser parameters given in Table 1. According to Taguchi method, L_9 orthogonal array was used for 3 parameters and three different levels of these three parameters. The fiber laser settings that were used to create the proper shaped dimples on ST52 Steel plates are examined. Using the Taguchi approach, the effects of different fiber laser parameters on the width of the generated dimples were investigated. This study looked into three parameters that are listed in Table 1 and the three levels that correspond to them.

Table 1. Fiber laser parameters and their levels.

	Laser Power (Watt)	Scan Speed (mm/s)	Laser Frequency (kHz)
1st level	20	1	20
2nd level	60	50	100
3th level	100	100	200

The laser device used in the study is a fiber laser with a wavelength of 1064 nm operating in pulse mode. The maximum power of the fiber laser is 100 W and the average power value is obtained by changing the duty cycle of the PWM signal between 10% and 100%. In addition, the frequency of the fiber laser can be changed between 20-200 kHz and can reach a speed of 9000 mm/s. The laser processing process was carried out in an air environment.

RESULTS AND DISCUSSION

A 20–100 watts laser power range was examined. The lowest power value was found to be 20 W as, in the first investigations, no groove growth was seen on the steel material at laser power values lower than 20 W. Similar to the previous point, no groove creation was seen at speeds higher than 100 mm/s, so that was the maximum laser scan speed limit set. More heat deformation was seen on the steel material as a result of excessive heat transfer when the laser power was more than 100 W and the laser scan speed was 1 mm/s.

When three parameters with three levels are investigated, 3^3 (=27) experiments are needed according to traditional experimental design. Fewer experiments are needed to produce efficient findings when optimization techniques are used [5]. The Taguchi method, which yields good results in many scientific and engineering domains, was applied in this investigation. The Taguchi approach states that choosing the right orthogonal array should come first in order to minimize the number of experiments [6]. The Taguchi approach states that choosing the right orthogonal array should come first in order to minimize the number of experiments. L_9 orthogonal array was utilized in this investigation because 3 parameters and 3 levels were employed [7]. Experiment sets were constructed, and the laser settings listed in Table 1 were arranged in accordance with the L_9 orthogonal array. Table 2 included the experiment setups.

Table 2. Experiment sets generated using the Taguchi method and grouped in accordance with the L_9 orthogonal array.

	Scan Speed (mm/s)	Laser Power (Watt)	Laser Frequency (kHz)
1	20	1	20
2	20	50	100
3	20	100	200
4	60	1	100
5	60	50	200
6	60	100	20

7	100	1	200
8	100	50	20
9	100	100	100

Table 2 provides experimental sets created using the Taguchi approach. Fig. 1 displays 3D topographic views of the surfaces that were produced by the experiments with the settings in the experimental sets. A laser non-contact optical profilometer was used to obtain all of the images that depict the material surface's detailed topography (Nanovea PS50, USA). Three distinct sections on the groove were selected for measurement in order to lower the experiment's error rate and errors resulting from potential surface inhomogeneity. The utilized laser beam has a diameter of 50 µm.

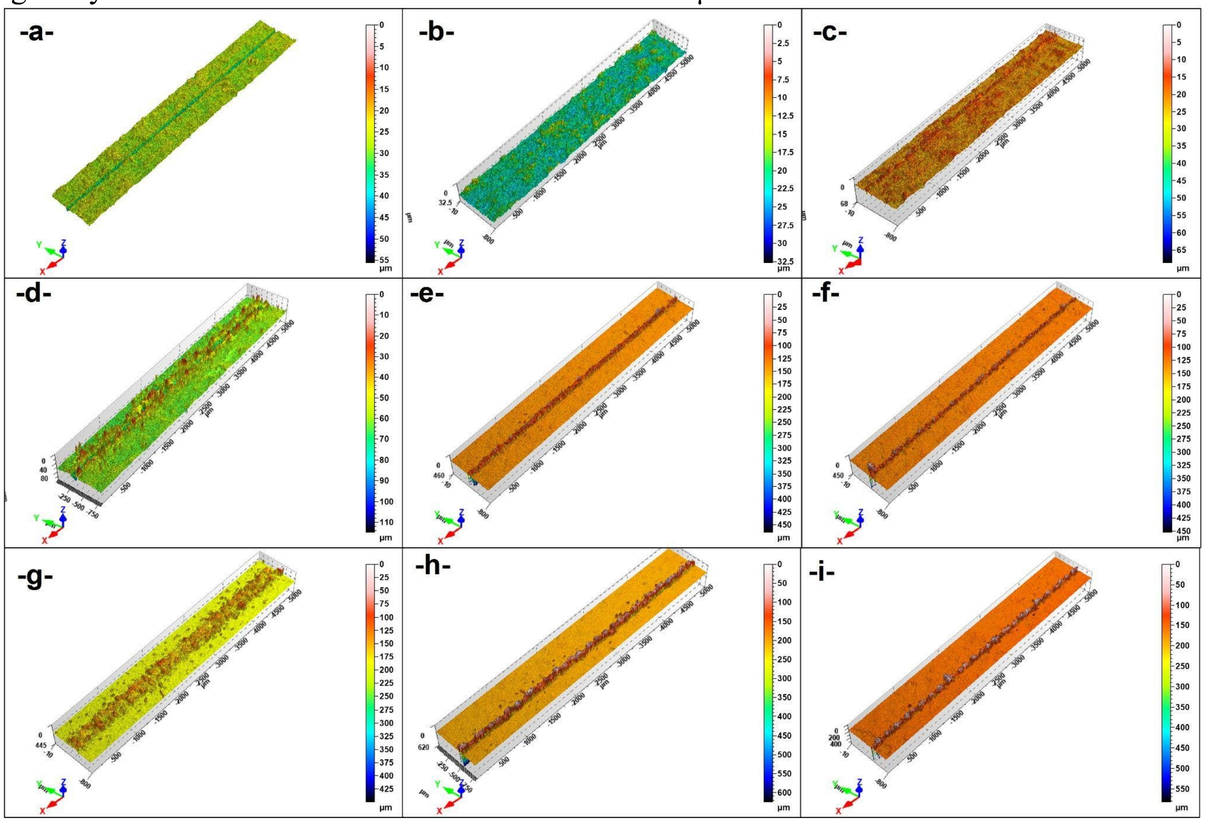

Fig. 1. The grooves that were created using the Taguchi Method from the experiment sets. The experiment sets are: (a) the first set; (b) the second; (c) the third; (d) the fourth; (e) the fifth; (f) the sixth; (g) the seventh; (h) the eighth; and (i) the ninth.

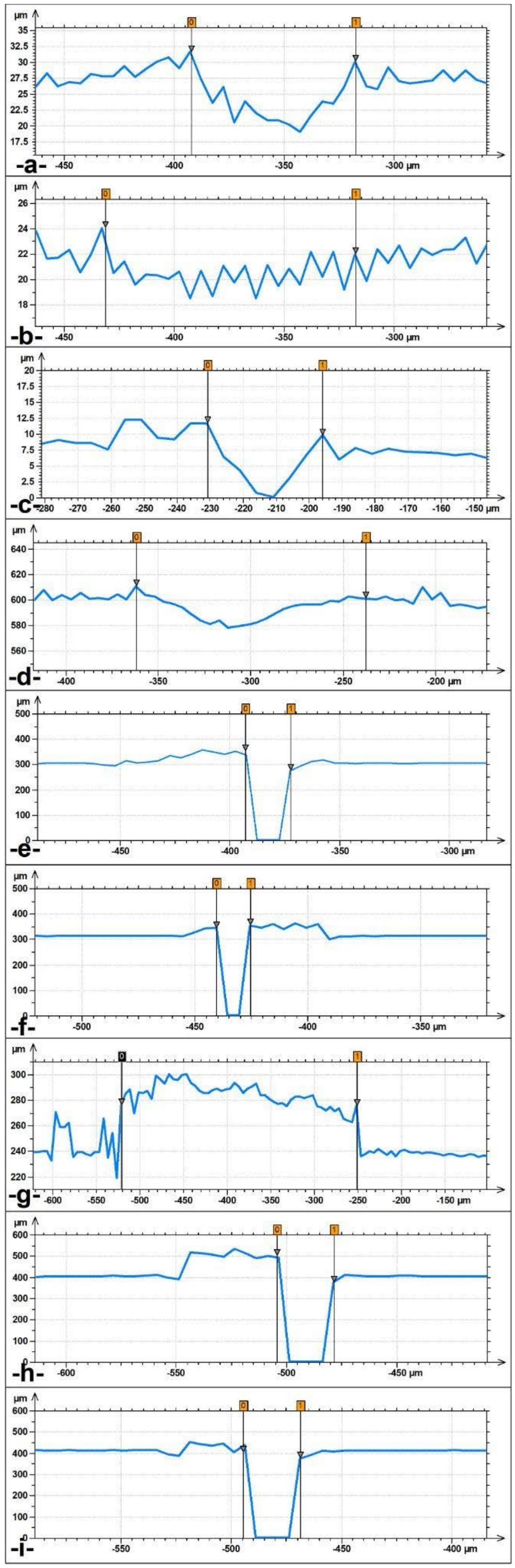

Fig. 2_a. The grooves cross-section width and depth geometry from the experiment sets. The experiment sets are: (a) the first set; (b) the second; (c) the third; (d) the fourth; (e) the fifth; (f) the sixth; (g) the seventh; (h) the eighth; and (i) the ninth.

There are nine sets of experiments, where different grooves were obtained by using various laser machining parameters. Each graph depicts one individual set of experiments, with the depth of the grooves on the Y-axis and their placements on the X-axis. The first set with an average groove depth of 10.65 µm and a width of 74.77 µm has slight variations of the depth. In the second set, the average depth amounted to 4.75 µm, which is relatively low, with the width of 113.86 µm, which is wider compared to others. It means that scan speeds should be higher, or power settings should decrease in this case. The third set with an average depth of 9.83 µm and a width of 34.80 µm has been produced using scan speeds that were lower and power settings that were higher. The fourth set has a groove that is the deepest and the widest, where the average depth is 24.67 µm, and the width is 124.30 µm. Sets 5 and 6 have the deepest grooves, of 309.49 m and 315.23 m, respectively. However, both grooves have very narrow widths, probably because of high power and very slow scan speed. The seventh set reports an average width of 270.27 µm and a height of 60.00 µm. The geometry that emerged with these parameters emerged as an elevation instead of a groove. Lastly, the last two sets, i.e., Set 8 and Set 9, have the deepest grooves, 508.01 µm, and 424.00 µm in-depth, respectively. Such grooves have a width of about 25 µm and demonstrate a highly concentrated energy application. The above findings have shown the drastic impact of varying laser parameters on both the material removal rate and groove dimensions. Therefore, minimizing human factors ensures greater control in micro-machining.

All of the rendered images represent optical microscope views of surfaces undergoing laser treatment at 50x magnification. Three series of images, namely -a-, -d-, and -g-, correspond to the lowest laser power used at different scan speeds and frequencies. Low-energy interactions with the surface result in small, almost unnoticeable surface modifications, and these images depict such processes. When images -b-, -e-, and -h-, captured using the same scan speed and varied frequency settings, are considered, the complexity of the surface structure increases. These two series of images are characterized by more complex and transformed surfaces, which suggest enhanced energy absorption and elaborated interaction with the material. We used the highest power settings under varying scan speeds, and images -c-, -f-, and -i- represent the generated results. These images are associated with the surfaces' extensive morphological and textural changes. The images -f- and -i- exhibit significant melting and re-solidification of the material, which are typical for high-energy laser processing. The -c- image is the least transformed among high-power samples and is most similar to the lowest-energy images. The scan speed of the high-energy laser was the shortest, which means that the duration for energy deposition was insufficient for significant texture alteration. As a result, this variety of images indicates that laser power is the determining factor in surface modification extent and type, and speed and frequency further define the nature of these changes.

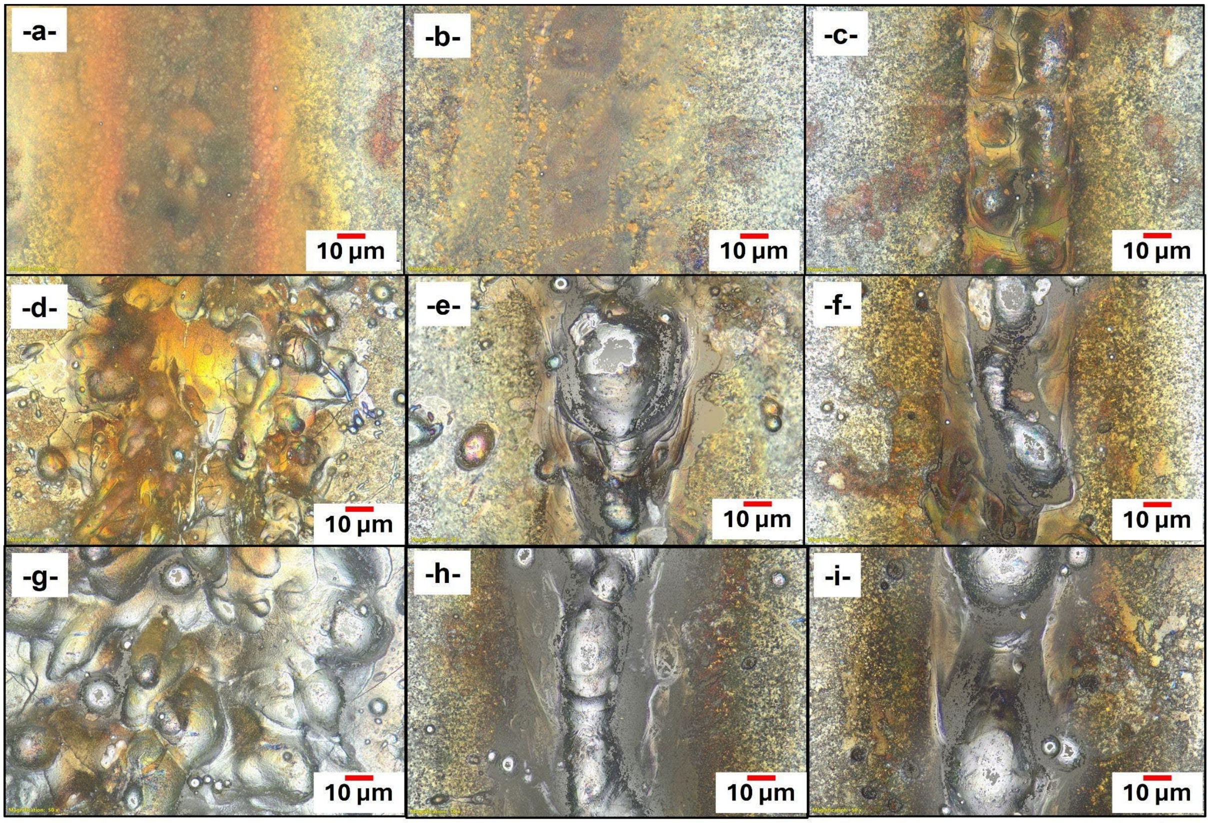

Fig. 3. The optic microscope pictures of laser grooves (a) the first set; (b) the second; (c) the third; (d) the fourth; (e) the fifth; (f) the sixth; (g) the seventh; (h) the eighth; and (i) the ninth.

In Taguchi optimization calculations, the "larger the better" feature was employed to generate a groove with the highest depth/width ratio. A groove with a big aspect ratio will work best for this purpose. Equation 1's "larger the better" characteristic was used to determine S/N for this reason. Table 3 presents the measurement outcomes and computed S/N values.

Table 3. Average values of groove depth, width and aspect ratios measured using the results obtained with the experimental sets. S/N values calculated according to the Taguchi method.

Exp. Set No	Average Depth of groove (µm)	Average Width of groove (µm)	Aspect Ratio (D/W)	Signal to Noise Ratio (S/N)
1	10.65	74.77	0.142	-16,93
2	4.75	113.86	0.042	-27,59
3	9.83	34.80	0.283	-10,98
4	24.67	124.30	0.198	-14,05
5	309.49	20.74	14.924	23,48
6	315.23	14.96.	21.070	26,47
7	270.27	-60.00	-4.505	13,07
8	508.01	25.82	19.672	25,88
9	424.00	26.14	16.220	24,20

In order to optimize the laser parameters that should be used to obtain the largest aspect ratio and to calculate which parameter affects the result and to what extent, the ANOVA table given in Table 4 was prepared. The calculated S/N values of the measurement results given in Table 2 were used to obtain the ANOVA table.

Table 4. 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	Unit	1st level	2nd level	3rd level	A	B	C	D	E	F
Power	mm/s	-18.50	11.97	21.05	2	3433.45	858.36	69.95	3	100 W
Speed	W	-5.97	7.25	13.23	2	772.28	193.07	15.73	3	100 mm/s
Frequency	Hz	11.81	-5.81	8.52	2	702.38	175.60	14.31	1	20 kHz
	Average		4.84							
	Total					4908.11		100.00		
	Optimum S/N									36.41
	Aspect Ratio of Expected Groove									66.15

As can be seen in the ANOVA table given in Table 4, Sum of squares of S/N values (SSi) and variance of these values were calculated by using the averages of S/N values of each level. As can be seen from the table, according to the Taguchi method, the Aspect ratio value of the groove to be obtained in the experiment to be carried out using laser power 100W, scan speed 100 mm/s and laser frequency 20 kHz parameter values is calculated as 66.15. Again, as can be seen from the ANOVA table, the parameter that affects the Aspect ratio the most is calculated as laser power by 69.95%. Secondly, laser scan speed affects the result by 15.73%. The parameter that affected the result the least with a very small difference was laser frequency with 14.31%.

Main Effect Plots

A vital tool in statistical analysis, main effect plots are especially useful when discussing experimental design and analysis of variance (ANOVA). When all other factors are held constant, these plots offer a visual depiction of the average response of a dependent variable across various values of a single independent variable. Main effect plots are primarily used to investigate and depict the link between the independent and dependent variables, which facilitates the interpretation of experimental data. The capacity of main effect plots to identify the existence and strength of main effects—that is, the influences of distinct independent variables on the dependent variable—is one of their fundamental advantages. Main effect plots let researchers evaluate the overall effect of an independent variable on a dependent variable, independent of the levels of other variables, by charting the mean response for each level of the independent variable. This makes it easier to spot trends, patterns, and variations in the dependent variable at various levels of the independent variable. A useful diagnostic tool for identifying possible interactions between independent variables is the main effect plot. When the amount of one independent variable affects the dependent variable in a different way, this is known as an interaction. Researchers can get insight into the intricate dynamics of the system they are studying by analyzing main effect plots in conjunction with interaction plots to determine whether the connection between the independent and dependent variables varies across levels of other independent variables. Main effect plots are essential for model validation and selection in addition to helping to evaluate experimental results. Researchers can determine whether the linearity and homoscedasticity assumptions that underpin the statistical model are met by visually examining the main effect plots. Additionally, major effect plots can help choose the right model modifications or transformations to better represent the underlying data structure, enhancing the precision and dependability of the statistical analysis.

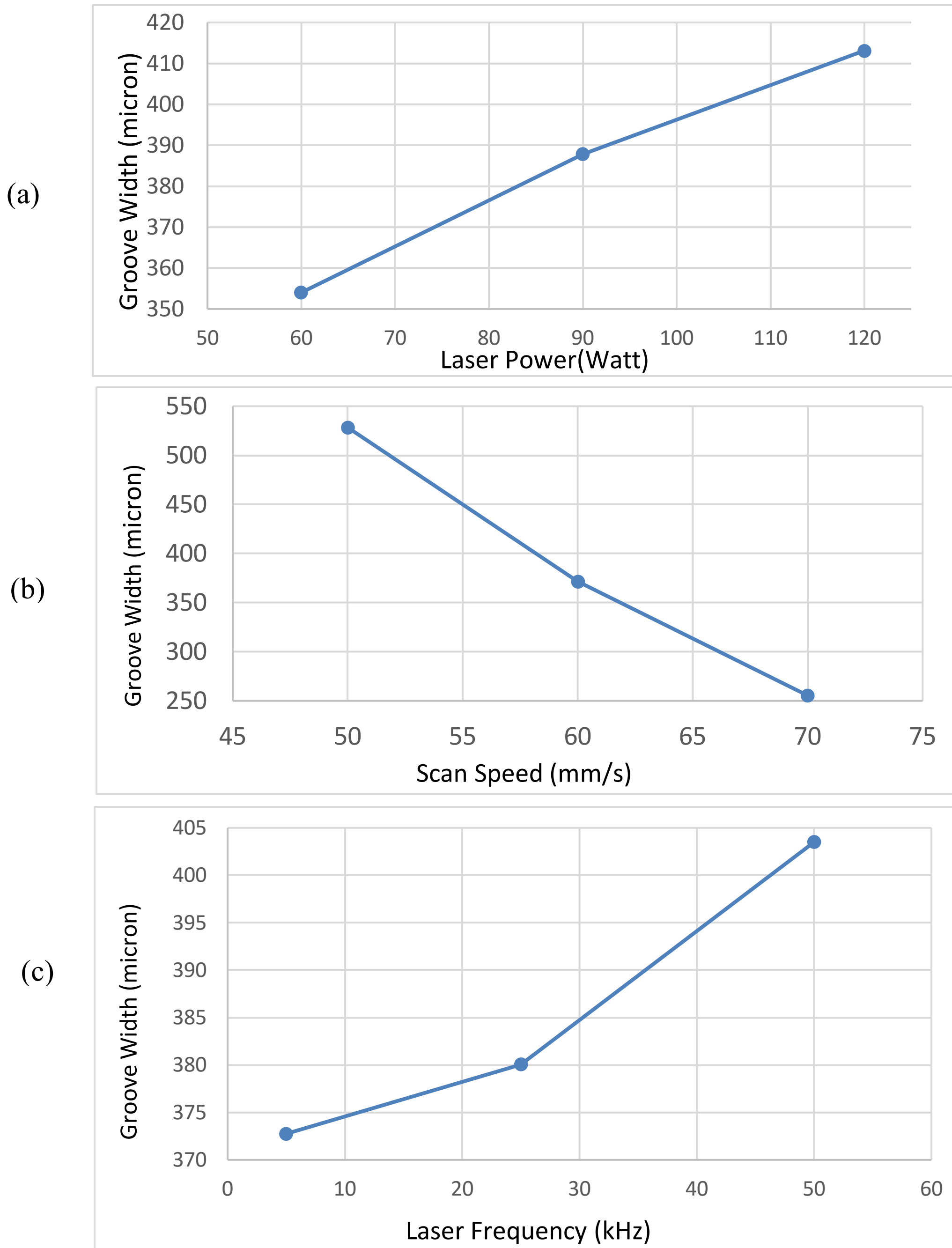

Fig. 4. Main effect plots for; (a) Laser Power, (b) Laser Scan Speed and (c) Laser Frequency.

As can be seen from the main effect plots in Fig. 4, laser power and laser scan speed showed similar behavior. When the laser power was increased from the lowest value of 20 W to the middle value of 60 W, the aspect ratio increased rapidly and reached its maximum value. When the laser power was increased from 60 W to 100 W, a "very slight decrease" was observed in the aspect ratio value, which can be interpreted as "no change". Similarly, when the laser scan speed was increased from its smallest value of 1 mm/s to 50 mm/s, the aspect ratio increased rapidly. When the laser scan speed was increased from 50 mm/s to 100 mm/s, a "very slight increase" in the aspect ratio value was observed, which can be interpreted as "no change". As can be seen from the graph explaining the interaction of aspect ratio with laser frequency, unlike the other two parameters, the aspect ratio decreased rapidly when the laser frequency was increased from its smallest value of 20 kHz to 100 kHz. When the frequency was increased from 100 kHz to 200 kHz, the rate of decrease of the Aspect ratio decreased.

Regression Equation

Mathematical models known as regression equations explain the connection between one or more independent variables and a dependent variable. Depending on the type of relationship that exists between the variables, regression equations can be either linear or nonlinear. Regression equations are primarily used to model and forecast dependent variable values based on independent variable values. Researchers can estimate the regression coefficients that most accurately reflect the relationship between the variables by fitting the regression model to the observed data. Upon estimating the model, predictions for the dependent variable can be made for novel or unknown values of the independent variables. In domains like economics, finance, marketing, and social sciences, where forecasting and comprehending the correlations between variables is crucial for making decisions, this predictive skill is very useful. Regression equations also measure the strength and direction of the associations between variables, which sheds light on the underlying structure and dynamics of the data. Researchers can evaluate the effect of individual independent variables on the dependent variable, find significant predictors, and find patterns and trends in the data by looking at the regression coefficients' magnitude and significance. As a result, theories can be tested, conclusions about the population from which the data were sampled can be drawn, and new insights that guide theory development and empirical study are produced. Regression equations are frequently used for hypothesis testing, model comparison, and causal inference in addition to prediction and inference. Through the statistical significance assessment of the regression coefficients and diagnostic tests, researchers are able to determine the model's goodness-of-fit, find significant observations, and detect model assumption violations. Regression analysis also helps establish causal inference and guide policy decisions by evaluating the causal relationship between variables while accounting for potential biases and confounding variables.

Regression equation obtained as a result of Regression analysis with Minitab®21.1.1 was given in Eqn. 4.

The aspect ratio values calculated with the regression equation and the aspect ratio values and error rates obtained as a result of the measurements are given in Table 5. As can be seen from Table 5, the calculated aspect ratio values are largely compatible with the measurement results.

Table 5. Measured and calculated aspect ratio values and their error rates.

Exp No	P (W)	SS (mm/s)	Frq (kHz)	Measured D/W	Calculated D/W	Error (%)
1	20	1	20	0.142	0.131	8.30
2	20	50	100	0.042	0.032	22.33
3	20	100	200	0.283	0.278	1.48
4	60	1	100	0.198	0.160	19.38
5	60	50	200	14.924	14.894	0.20
6	60	100	20	21.070	21.020	0.24
7	100	1	200	-4.505	-4.563	1.30
8	100	50	20	19.672	19.594	0.40
9	100	100	100	16.220	16.146	0.45

5. CONCLUSION

This research provides a methodical analysis of optimizing fiber laser parameters to create grooves on ST52 steel. Through the utilization of the Taguchi approach, we have identified the most optimal parameters for three key variables using the Taguchi approach: laser power, scan speed, and frequency. These parameters directly affect the aspect ratio of the grooves. Our findings indicate that laser power had the most significant impact on the aspect ratio, accounting for 69.95% of the variation. In comparison, scan speed and frequency contributed 15.73% and 14.31% to the aspect ratio, respectively.

We employed the L_9 orthogonal array to establish our experimental systems. By doing so, we were able to efficiently explore the parameter space and obtain accurate results without wasting resources.

Our regression study has also demonstrated a strong correlation between experimental data and the anticipated model. This proved that the Taguchi method for improving laser processing parameters was correct.

This work adds to the ongoing discourse in the field by presenting convincing evidence that these concepts are well-established, as well as demonstrating current advantages that may be achieved by defining optimal settings.

6. ACKNOWLEDGMENTS

1. The authors like to thank Sezgin Sac Ltd. Sti. for their help in providing the materials used.
2. This study was supported by the KOU-BAP project with code FBA-2024-3704.

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