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Using CO_2 Laser, Optimization of Laser Power, Exposure Time and Frequency for Cavity Formation on Hardox Steel Plate

Research Article

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Abstract

The texture of the surfaces of materials causes changes in mechanical properties such as friction. Micro-scale cavities have been created on Hardox steel plate, which has recently been the focus of attention in demanding applications with its hardness, toughness, and wear resistance. A CO_2 laser was used in the cavitation process on the surface and the power, exposure, and frequency of the laser used were optimized to obtain a cavity with the desired geometry. Taguchi method was used in the optimization process. In addition to obtaining the optimum parameters, the effect ratios of the parameters were also calculated. Optimum laser parameters were obtained as 5 s for laser exposure duration, 60 W for laser power, and 50 kHz for laser frequency. According to the optimization calculations, the parameter with the highest effect on the result was laser exposure duration with a rate of 71,86 %. Laser power and laser frequency affected the result by 23.02 % and 5.12 % respectively.
Keywords: Laser machining, Optimization, Hardox Steel, Surface texturing.

1. INTRODUCTION

Developed by Swedish steelmaker SSAB, Hardox Steel is a brand covering a range of high-strength, wear-resistant steels that are widely used in a variety of industrial applications. These steels are renowned for their exceptional toughness, hardness, and wear resistance. This makes them an important material in environments subject to extreme wear and impact conditions [7]. This study aims to delve deeper into the properties, applications, and advantages of Hardox steel and shed light on its importance in modern engineering and manufacturing. Hardox steel derives its superior properties from its unique composition and manufacturing process. These steels are typically alloyed with elements such as carbon, manganese, chromium, and other trace elements to achieve a fine balance between hardness and toughness [9]. The microstructure of Hardox steel consists of martensite, a hard crystalline structure that contributes to its exceptional hardness and toughness. In addition, the controlled heat treatment process further enhances the properties of the steel, resulting in a material with high impact resistance, excellent formability, and weldability [6].

The versatility of Hardox steel has led to its widespread adoption in numerous industrial sectors [8]. Hardox steel is used in the mining industry to manufacture buckets, dump truck bodies and crushing equipment where it resists abrasion from the movement of rocks and minerals. In construction and infrastructure projects, it finds use in excavator buckets, bulldozer blades, and concrete mixers, where its strength extends the service life of critical components. In addition, Hardox steel is a preferred choice in the production of agricultural machinery, forestry equipment, and waste management systems due to its ability to withstand the rigors of harsh working conditions [5]. The use of Hardox steel offers several notable advantages that contribute to increased operational efficiency and reduced maintenance costs. The exceptional wear resistance extends the life of components, minimizing the need for frequent replacement and downtime. Hardox steel's high strength-to-weight ratio enables the design of lightweight yet durable structures, resulting in increased load-carrying capacity and fuel efficiency. In addition, the steel's weldability facilitates ease of fabrication and repair, enabling manufacturers to adapt to changing requirements without compromising on quality [4]. Hardox steel is a prime example of advanced materials engineering, offering a unique combination of properties that meet the demands of industries grappling with severe wear and impact conditions. Its exceptional hardness, toughness, and wear resistance, combined with its widespread applicability, position Hardox steel as a vital resource in modern engineering and manufacturing. As industries continue to push the boundaries of performance and durability, Hardox Steel remains a steadfast partner in the pursuit of innovation and excellence.

Surface texturing of materials has emerged as a very important area of research and application in the field of materials science and engineering. The deliberate modification of a material's surface topography at micro, nano and even atomic scales has proven to provide numerous advantageous effects that influence properties such as friction, wear, adhesion, wettability, and optical properties. This study also aims to explore the techniques used in surface texturing, explain the benefits they offer, and examine their various applications in industries.

Surface texturing encompasses a range of techniques that impart specific patterns or structures to the surface of a material [10]. These techniques can be broadly categorized as mechanical, chemical, and physical methods. Mechanical techniques include processes such as grinding, polishing, and shot peening where controlled material removal or deformation results in desired surface topographies. Chemical techniques include processes such as etching and electrochemical methods that selectively remove material and create complex surface patterns. Physical techniques, on the other hand, include laser ablation, plasma treatment, and ion beam milling, which provide precise control over surface properties at nanometer scales. These techniques can be combined or modified to achieve a variety of surface textures tailored to specific applications.

Surface texturing provides a range of benefits to materials, making it a crucial tool in optimizing performance and functionality [1]. Enhanced oil retention and reduced coefficients of friction are achieved by retaining lubricants in textured surface structures, leading to improved wear resistance and energy efficiency in tribological applications. Enhanced hydrophobic or hydrophilic behavior can be achieved through controlled texturing, impact applications on self-cleaning surfaces, antifouling paints, and microfluidics. Surface texture also plays a crucial role in controlling light interaction, finding applications in optical devices, solar panels, and sensors [13]. Furthermore, tailored surface textures can influence cell adhesion and proliferation, making it a promising avenue in biomedical implants and tissue engineering.

The range of surface texturing applications is wide and covers various industrial sectors. In automotive engineering, textured engine components reduce friction and improve fuel efficiency. Aerospace applications benefit from improved aerodynamics and reduced ice accumulation on textured surfaces. In electronics, micro- and nano-textured materials contribute to improved heat dissipation and miniaturization. Furthermore, the renewable energy field uses surface texture to optimize light absorption and energy conversion in photovoltaic cells and light-emitting diodes. Biomedical applications include implants with improved osseointegration, drug delivery systems with controlled release profiles and diagnostic devices with enhanced precision.

Surface texturing of materials has evolved into a versatile discipline with far-reaching implications across industries. The techniques used, along with the numerous benefits offered, enable the tailoring of material surfaces to achieve specific performance improvements. As the field of research and innovation continues to move forward, surface texturing will undoubtedly remain a crucial strategy for enhancing material properties, optimizing functionality, and promoting advances in a wide range of technological fields.

Laser processing has emerged as a transformative process in modern manufacturing, enabling precision material removal and surface modification with unparalleled accuracy and versatility. This academic discourse aims to provide an in-depth investigation covering the fundamental principles of laser processing, its various techniques, and its wide-ranging applications across industries. This technology has revolutionized materials processing by leveraging the unique properties of laser light, offering a new paradigm for complex and efficient manufacturing processes. Laser processing is based on the principles of focused, high-intensity laser beams interacting with materials to trigger controlled material removal or replacement. The process begins with the generation of coherent, monochromatic laser light, usually by methods such as optical amplification or stimulated emission. The laser beam is then precisely focused onto the surface of the material, leading to localized heating and vaporization, cutting, or melting. The choice of laser wavelength, pulse duration, power density, and beam characteristics determine the extent and nature of material removal, providing fine-tuned control over the processing results. Laser processing encompasses several different techniques, each tailored to specific material types, geometries, and desired results. Laser cutting involves the use of focused laser beams to cut or melt materials along predefined paths resulting in precise and burr-free cuts. Laser cutting removes material by vaporization, leaving minimal heat-affected zones, making it suitable for delicate materials or high-precision applications. Laser engraving and marking uses controlled laser pulses to engrave patterns, text, or images onto surfaces, often used for product marking, labeling or aesthetic embellishments. Laser welding and cladding use localized heating and melting to fuse or coat materials, respectively, offering advantages in joining dissimilar materials or creating wear-resistant coatings. Laser processing applications span a wide range of industries, demonstrating its adaptability and transformative impact. In the automotive sector, laser cutting enables the production of complex and lightweight components, contributing to improved fuel efficiency and vehicle performance. The electronics industry utilizes precision laser ablation in microfabrication processes that produce miniaturized circuits, sensors, and semiconductor devices. Aerospace applications include laser drilling of cooling holes in turbine blades and the creation of complex aerospace structures. In addition, the medical field utilizes laser processing for precision ablation in surgeries to improve biocompatibility, in the manufacture of medical devices, and in the surface modification of implants. Laser processing is the cornerstone of modern manufacturing, offering an exceptional blend of precision, versatility, and efficiency. Leveraging the unique properties of laser light, this technology has revolutionized material processing across a range of industries. The ability to remove, surface modify and join complex materials with micron-level precision has paved the way for innovative advances in engineering, electronics, aerospace, and healthcare. As the field of laser processing continues to evolve through research and technological innovation, the potential to shape the future of materials processing remains limitless.

In traditional experimental methodology, each variable is examined separately. During this examination, the variable to be examined is changed while other variables are kept constant. This increases the number of experiments and the time spent on the experiments. Optimization methods, on the other hand, aim to obtain optimum parameters with fewer experiments. In this study, the optimum parameters were obtained by the Taguchi method, which has given successful results in many engineering and research fields [3].

The Taguchi method is a design and analysis method used to optimize industrial and statistical quality control processes and improve product or service quality. It was developed by Genichi Taguchi.

In product and process design, the Taguchi method aims to improve quality by making the product's performance sensitive to environmental variables (e.g. temperature, humidity, pressure) and minimizing variance. This method assesses the sensitivity of product quality to certain factors and factor levels and attempts to determine the optimal parameter settings.

One of the key concepts is "quality loss". According to Taguchi, the further a product or service deviates from the design specifications of its characteristics, the greater the loss of quality perceived by the customer. His goal is to minimize quality loss by keeping product or process performance as close as possible to the specifications. The Taguchi method differs from traditional experimental design methods. For example, the Taguchi method uses a "multifactor" experimental design that evaluates the interaction of variables, not the effect of individual variables. The Taguchi method is used especially in engineering, manufacturing and quality control and contributes to continuous quality improvement processes. This method helps to design products and processes more effectively and efficiently by providing a quality-oriented approach. The Taguchi method is a design and analysis method used to optimize industrial and statistics.

2. MATERIALS & METHODS

In this study, the CO_2 laser parameters used to create dimples of various sizes and shapes on Hardox steel plates were investigated. These dimples were produced using three different laser parameters, with the goal of obtaining varied geometries on the Hardox plates. The specific parameters used, along with their levels, are detailed in Table 1.

The ratios of the smallest value of the cavity diameter to the largest value are given in Table 4. The ratios of the smallest value of the cavity diameter to the largest value are given in Table 3.

Table 1. Laser parameters and levels used in experiments.

	Laser Exposure duration (s)	Laser Power (Watt)	Laser Frequency (kHz)
1st level	5	60	5
2nd level	10	90	25
3rd level	15	120	50

Laser power was studied between 60 and 120 watts. Since no cavity formation was observed on the Hardox material at laser power values lower than 60 W in the preliminary studies, the lowest value of the power was determined as 60 W. For similar reasons, the upper limit of the exposure time was set to 5 s, since no cavity formation was observed at laser exposure duration was less than 5 s. When the laser power exceeded 120 W and the laser exposure duration was higher than 15 s, more heat deformation was observed on the Hardox material due to excessive heat transfer.

2.1. Experimental Method

In an experimental design with three parameters and three levels for each parameter, the number of experiments required is 27. Optimization methods aim to obtain optimum results with the minimum number of trials possible instead of trying every combination [2]. With the Taguchi optimization method, the closest results to the optimum result can be obtained with 9 experiments instead of 27 experiments. In addition, the Taguchi method also calculates which parameter affects the result and to what extent. To achieve this, appropriate experimental sets are prepared by designing experiments by the Taguchi method [11, 12]. Thus, both experiment time and experiment cost are saved. The experiment sets are given in Table 2.

Table 2. Experiment sets according to the Taguchi optimization Method.

	Laser exposure duration (s)	Laser Power (Watt)	Laser Frequency (kHz)
1	5	60	5
2	5	90	25
3	5	120	50
4	10	60	25
5	10	90	50
6	10	120	5
7	15	60	50
8	15	90	5
9	15	120	25

The signal-to-noise ratio (S/N) used in the Taguchi method also represents the effects of noise from uncontrollable factors. Therefore, the highest signal-to-noise ratio is a desirable outcome. According to the Taguchi method, optimization can target one of three different states. The (S/N) is calculated for these different states ([14]) as given below.

1) highest is the best

$$\left(\frac{S}{N}\right) = -10log_{10}\left[\frac{1}{n}\sum_{i=1}^{n} y_i^2\right] \tag{1}$$

2) lowest is the best

$$\left(\frac{S}{N}\right) = -10log_{10}\left[\frac{1}{n}\sum_{i=1}^{n} \frac{1}{y_i^2}\right] \tag{2}$$

3) the nominal value (defined value) is the best

$$\left(\frac{S}{N}\right) = -10log_{10}\left[\frac{1}{n}\sum_{i=1}^{n} (y_i - m)^2\right] \tag{3}$$

The y_i value in these equations represents the measurement results for each trial. Measurements were taken at any 5 locations on the dimple to reduce possible errors. In equation (3), “m” denotes the nominal value, which means the desired value.

3. RESULTS & DISCUSSION

Figure 1 shows examples of optical microscope images of cavities obtained on Hardox plates using the laser parameters listed in Table 3. Since the laser beam is circular and the material is assumed to be theoretically homogeneous, the geometry of the dimple should be close to a perfect circle. To verify this, the maximum and minimum values of the diameters of the dimples formed on Hardox plates were measured. The ideal circularity is achieved when the minimum diameter value is as close as possible to the maximum, ideally a ratio of '1', which was considered the best value. In order to minimize the rate of experimental systematic errors, each set of experiments was repeated five times. The ratios of the smallest value of the cavity diameter to the largest value are given in Table 3.

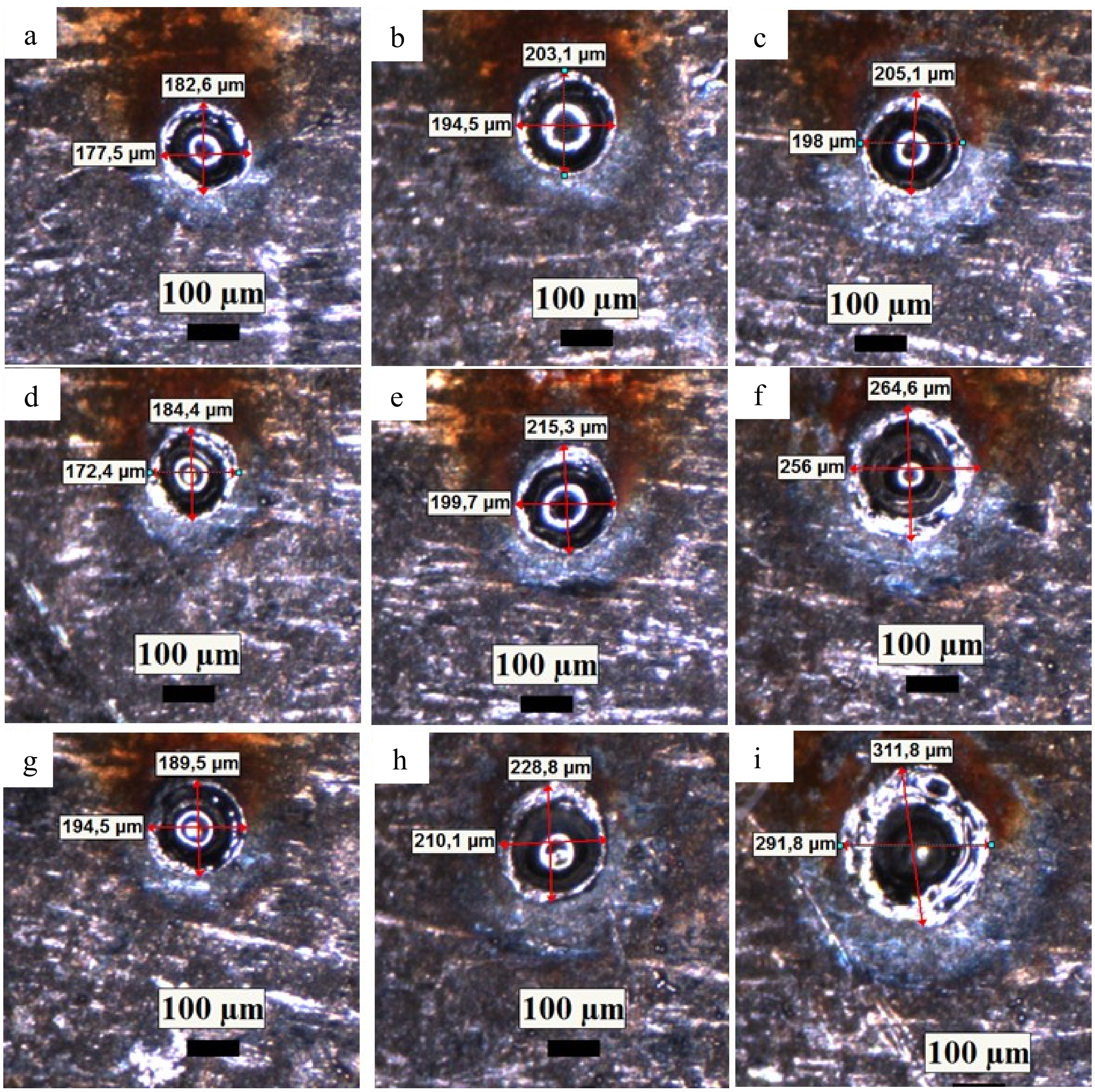

Figure 1. Optical microscope images of dimples obtained with the experimental sets in Table 2. (a) Experimental set number 1, (b) Experimental set number 2, (c) Experimental set number 3, (d) Experimental set number 4, (e) Experimental set number 5, (f) Experimental set number 6, (g) Experimental set number 7, (h) Experimental set number 8, (i) Experimental set number 9.

Since the result with the largest ratio of the minimum value of the measured cavity diameter to the maximum value is considered the best result, equation (1) was used to calculate the S/N ratio. S/N ratios calculated according to equation (1) are also given in Table 3.

Table 3. Ratios of the smallest value to the largest value of the cavity diameter and S/N values.

	1st	2nd	3rd	4th	5th	S/N
1	0.98	0.94	0.94	0.98	0.97	-0.32
2	0.96	0.99	0.97	0.93	0.94	-0.38
3	0.99	0.96	0.98	0.97	0.90	-0.37
4	0.96	0.93	0.92	0.92	0.89	-0.67
5	0.88	0.94	0.93	0.92	0.96	-0.68
6	0.91	0.90	0.97	0.99	0.97	-0.47
7	0.95	0.98	0.97	0.98	0.93	-0.32
8	0.92	0.94	0.96	0.90	0.94	-0.64
9	0.97	0.93	0.94	0.92	0.97	-0.50

To identify the optimum parameters, an ANOVA table was prepared as shown in Table 4. This table, particularly its last column, details the optimum experimental parameters. Beyond simply identifying the optimum parameters, the Taguchi method is also capable of quantifying the impact of each parameter on the results. The sum of squares (SST) within the table represents the variance of the signal-to-noise ratio (S/N), as described by Yang and Tarng ([14]).

$$SS_T = \sum_{i=1}^{n} \left(\eta_i - \eta_m\right)^2 \tag{4}$$

The SS_T value is the sum of the squares of each factor ($SS_T=SS_A+SS_B+SS_C$) and it can also be obtained by equation (4).

$$SS_A = \sum_{i=1}^{k_A} n_{Ai} \left(\eta_{Ai} - \eta_m\right)^2 \tag{5}$$

Table 4 was obtained by using the data in equation (4) and the data in equation (5).

Table 4. ANOVA table for Optimum Ratio of Dimple diameter to HAZ diameter.

	Average S/N					
	1st level	2nd level	3rd level	Degree of Freedom	Effect Rate	Optimum Parameters
Scan Speed (mm/s)	-0.36	-0.61	-0.49	4	71.86	50 mm/s
Power (W))	-0.44	-0.57	-0.45	4	23.02	120 W
Frequency (kHz)	-0.48	-0.52	-0.46	4	5.12	50 kHz
Total		-0.48			100	
Optimum S/N						-0.28
Optimum Ratio of Minimum Dimple diameter to HAZ diameter						0.97

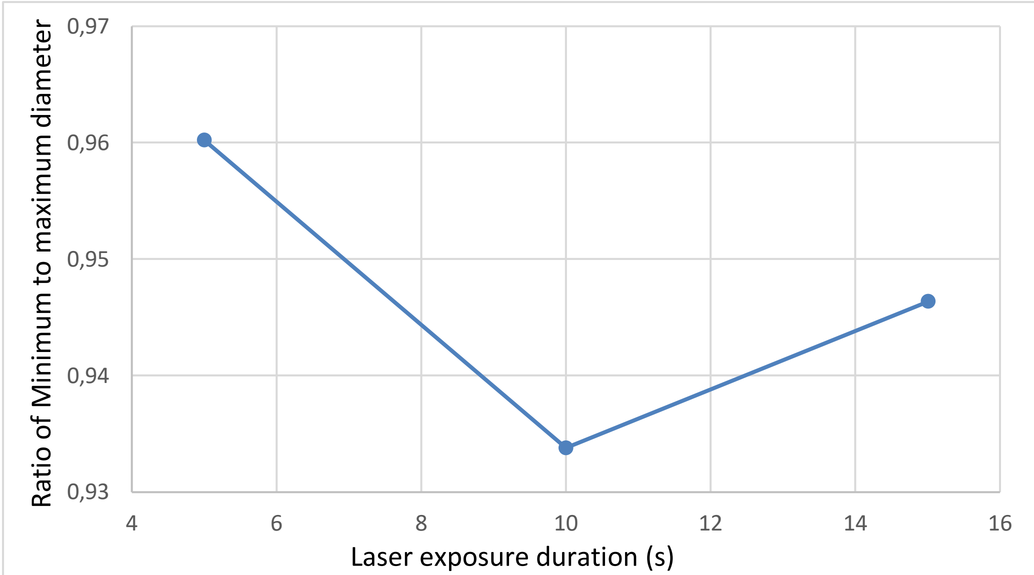

Figure 2. Main effect plot for laser power on the ratio of cavity diameter to HAZ diameter.

As shown in Figure 2, increasing the laser exposure duration from 5 seconds to 10 seconds results in a decrease in the diameter ratio. However, further increasing the duration from 10 seconds to 15 seconds leads to an increase in the width ratio, but at a slower rate than previously observed. The highest width-to-diameter ratio was recorded when the laser exposure duration was set at 5 seconds.

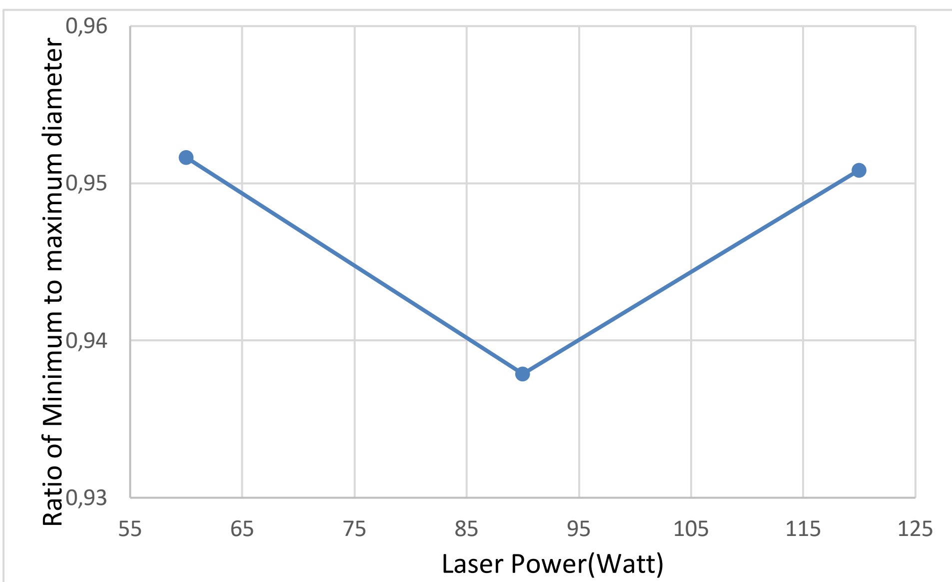

Figure 3. Main effect plot for laser power on the ratio of cavity diameter to HAZ diameter.

As seen in the Figure 3, increasing the laser power from 60 W to 90 W results in a decrease in the width ratio. Conversely, when the laser power is increased from 90 W to 120 W, the width ratio increases. The highest width ratio was observed at 60 W, but a nearly identical ratio was also reached at 120 W.

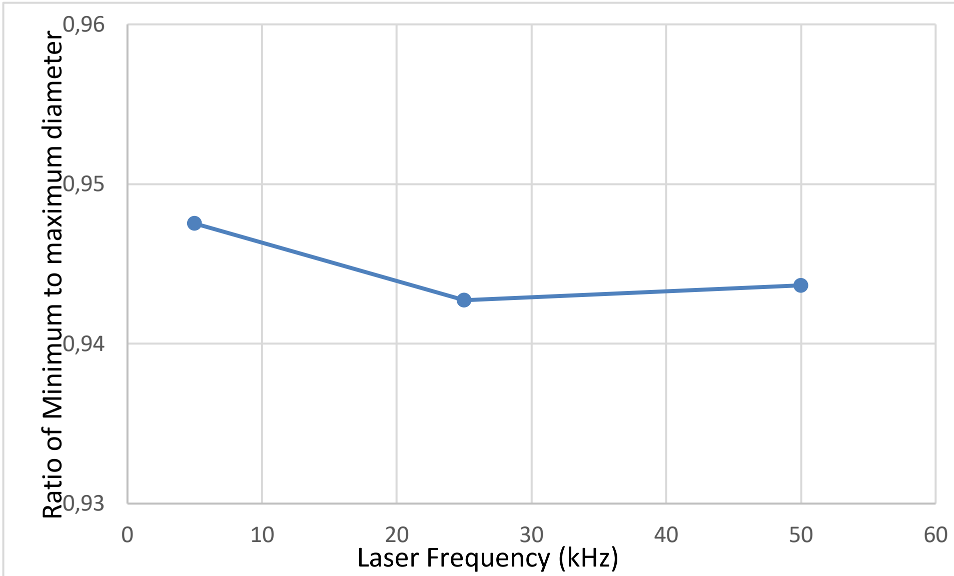

Figure 4. Main effect plot for laser frequency on the ratio of cavity diameter to HAZ diameter.

As seen in Figure 4, when the laser frequency is increased from 5 kHz to 25 kHz, the ratio of the widths decreases. However, when the frequency is increased from 25 kHz to 50 kHz, the width ratio increases. The highest ratio was observed when the frequency was 5 kHz.

4. CONCLUSION

The Taguchi method was used to optimize the largest cavity and the smallest heat-affected zone width in relation to this cavity. The optimum laser parameters were obtained as 5 s for laser exposure duration, 60 W for laser power, and 50 kHz for laser frequency.

As can be seen from the main effect plots, the ideal circularity has deviated from its optimal state at the middle values of all three parameters. Better results were observed at lower and high low and high values of the parameters compared to the middle values of the parameters. The best results can be obtained at low parameter values. However, cavity formation is not observed and becomes difficult at low values. In order to obtain deeper and circular dimples with better dimples, the laser should be applied for a longer time and the power of the applied laser beam should be high with equal quality. In addition, among the parameters analyzed in order to reach the desired result, the parameter that affected the result the most was calculated as laser exposure duration with a rate of 71,86 %. The influences of laser power and frequency on the results were comparatively lower, at 23.02% and 5.12% respectively.

5. CONFLICTS OF INTEREST

The authors declare no conflict of interest.

6. ACKNOWLEDGMENTS

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