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EXPERIMENTAL ANALYSIS ON LASER CUTTING OF HASTELLOY C 276: EFFECTS OF PROCESS PARAMETERS ON KERF WIDTH, SURFACE ROUGHNESS, HAZ USING TAGUCHI TECHNIQUE

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Abstract

Hastelloy C276, a nickel-based alloy widely utilized in aerospace, defense, energy, and food processing, was the subject of an experimental investigation presented here in order to determine the optimal laser machining process parameters for this material. In laser cutting, a high-powered laser beam melts and vaporizes the material without ever touching it. The effects of laser machining process parameters (laser power, cutting speed, and gas pressure) on Kerf width, surface roughness (Ra), Heat-Affected Zone (HAZ) were studied using the Taguchi method experimental design with the analysis of variance (ANOVA) methodology. Which measurement is the most precise is determined using the signal to noise ratio. Using certain optimization techniques, a set of parameters that are close to the best ones was constructed to achieve the good results.

Keywords: Heat-Affected Zone (HAZ), surface roughness (Ra), Kerf Width, Hastelloy C-276, cutting speed, laser power, gas pressure, Taguchi Method,

1. INTRODUCTION

Hastelloy is a group of nickel-based alloys with excellent strength, corrosion resistance, and heat resistance due to the addition of molybdenum, chromium, and other metals in various proportions. Because of its durability and resistance to corrosion, Hastelloy is frequently used in industries like chemical processing, oil and gas production, defense, and aerospace. It has also been a very desirable material for use in maritime situations [1-3]. Since it can cut many different materials quickly and precisely, laser cutting has become increasingly popular in recent years. Due to its high melting point, limited thermal conductivity, and tendency to form a hard and brittle heat-affected zone (HAZ) during laser cutting, Hastelloy presents unique challenges [4-5]. In this investigation, the state of laser cutting technology for Hastelloy and discuss its possible uses across a range of sectors. When it comes to cutting Hastelloy, laser cutting has several advantages over more conventional methods like plasma or water jet cutting [6-7].

To begin, laser cutting is a type of cutting that does not involve any physical contact and does not call for the use of any sort of mechanical force, which lowers the possibility of the material being damaged. Second, laser cutting results in a thin kerf width as well as a smaller heat affected zone (HAZ). These characteristics contribute to the reduction of production waste and damage. Finally, laser cutting can reach high cutting speeds and maintaining high levels of accuracy, which makes it a perfect option for applications involving mass manufacturing and complex structures [8-11]. Yet, there are several restrictions when it comes to cutting Hastelloy using a laser. The tremendous amount of energy that is being input by the laser beam has the possibility of causing the material to melts, vaporize, and oxidized, which can result in surface roughness, cracking, and porosity [12-14]. In additional to this, the thermal stress that is generated by the laser beam may leave the material with a distorted appearance and an increased level of residual stress. When cutting Hastelloy with a laser, the accuracy of the cut is determined by several different process parameters, including the laser power, cutting speed, focal location, assist gas, and nozzle diameter. Cutting depths, kerf width, and edge roughness are all affected by the amount of energy given by the laser [15-16]. The cutting speed influences the amount of heat that is transferred into the material as well as the time at which it cools, which also influences the material's microstructure and HAZ thickness. The spot size and energy density at the cutting surface are both affected by the focal location because it is affecting the focus diameter and structure of a laser beam. The assist gas, frequently composed of nitrogen or oxygen, works to evacuate the molten material, and prevent oxidation in the cutting zone [17-19]. The gas flow rate and pressure are affected by the size of the nozzle, which changes the gas flow pattern and the shape of the molten pool. Laser surface treatment in an argon atmosphere was used to improve the wear resistance of Hastelloy C-276.

This is where consumers found the best laser parameter settings for making a wear-resistant surface without making a brittle phase [20-21]. Researchers looked at how certain laser cutting process parameters affect Ra and HAZ when Inconel 718, a nickel-based super alloy, is machined. Using an X-ray and a scanning electron microscope. aimed to utilize the preference selection index technique to identify the optimal values for the CO2 laser cutting process parameters that enhance the target qualities during machining of stainless steel (Ra, HAZ, kerf width, and MRR). laser process factors including laser power, cutting speed, and focal position were analyzed statistically using the RSM method to determine their effect on the characteristics "Ra and geometry" when cutting polycarbonate sheets. Using a compressed gas and a Nd:YAG laser, one can achieve a high-frequency cut, The kerf deviation, kerf breadth, and kerf taper were all represented in a multi-objective optimization [22–24]. Particle swarm optimization, a swarm-based optimization method, was used to maximize the objective function, i.e., the geometrical quality, of an experiment conducted on Inconel-718 using a pulsed Nd:YAG laser beam [25]. Analyze the effect of variables including laser intensity, cutting speed, focus point, and gas pressure, when cutting the profile of gears made of alloy stainless steel 304, surface roughness and operational studies are undertaken using a CO2 laser [26]. Investigation research using RSM to examine the effect of cutting variables such as cutting speed, gas pressure, laser beam power, and sheet thickness on the cutting quality of poly methyl methacrylate materials [27]. Experimental studies on the effects of speed, laser power, standoff distance, and sheet thickness on temperature and cutting-edge quality during CO2 laser cutting of Al 6061 T6 alloy. It was found that the evaluated output quality is significantly affected by the power of the laser [28].

The quality of the cut made on Hastelloy C 276 is the highest importance, hence the primary purpose of this study is to investigate the parameters that influence the cutting process on specific machines. Therefore, in order to construct the experimentation, a Taguchi L_9 and an orthogonal array was utilized to find the ideal settings for the laser cutter so that the Kerf width, average surface roughness, and HAZ of the cutting material can be kept to a minimum in the most efficient conditions for Hastelloy C 276. This will allow for the most accurate cutting possible. A study has investigated how the three major process parameters like laser power, cutting speed, and gas pressure have an impact on the kerf width, average surface roughness, and the HAZ during a process.

2. METHODS AND MATERIALS

2.1 Taguchi Method

Genichi Taguchi created a set of mathematical techniques sometimes referred to as "robust design methods" to enhance the quality of manufactured items; these techniques have since found applications in engineering, biology, advertising, and more [29-32]. Expert statisticians have praised Taguchi's efforts and the results they've produced, especially his work in developing designs for analyzing variance, but they've also pointed out the ineffectiveness of several of Taguchi's recommendations [33-34].

2.1.1 Loss functions in the statistical theory

In the past, treatment effects were estimated using mean-unbiased estimators in statistical models. Least squares estimators have the smallest variance of any mean-unbiased linear estimators under the assumptions of the Gauss-Markov theorem. The law of large numbers, which states that sample means converge to the true mean, also provides comfort for the prevalent use of mean comparisons. In his experimental design textbook, Fisher stressed the importance of comparing treatment means. however, loss functions were avoided by Ronald A. Fisher [35].

2.1.2 Taguchi's use of loss functions

Taguchi's knowledge of statistical theory came primarily from those who, like Ronald A. Fisher, shied away from loss functions. Taguchi, responding to Fisher's approach to experimental design, saw in it an opportunity to improve the average results of a process. Indeed, long-term programs to improve harvests were a major inspiration for Fisher's work, specifically programs to compare agricultural yields under different treatments and blocks.

However, Taguchi realized that in much industrial production, there is a need to produce an outcome on target, for example, to machine a hole to a specified diameter, or to manufacture a cell to produce a given voltage. He also realized, as had Walter A. Shewhart and others before him, that excessive variation lay at the root of poor manufactured quality and that reacting to individual items inside and outside specification was counterproductive.

Therefore, he argued, quality engineering must first consider the costs associated with poor quality in a variety of contexts. Quality costs are often calculated as the number of products that are out of specification times the price per unit for rework or scrap in traditional industrial engineering. Taguchi, on the other hand, pushed for manufacturers to widen their perspectives to include societal cost. Any manufactured item that deviates from nominal will incur some loss to the customer or the larger community, whether it be through premature wear and tear, difficulties in interfacing with other parts (which are also likely to deviate widely from nominal), or the need to build in safety margins. Manufacturers tend to disregard these costs because they have little bearing on their bottom line and are instead concerned with their own. Analyses of public economics show that these externalities hamper the effective functioning of markets.

Taguchi claimed that if manufacturers took steps to reduce such losses, it would improve their brand's reputation, help them gain market share, and ultimately increase revenues. This would be comparable to the tragedy of the commons.

When an item is extremely minute, any losses are minimal. Within the bounds of the specifications, we can ignore the possibility of losses, as Donald J. Wheeler put it. Losses increase when we deviate from nominal, and we reach the specification limit when the losses are no longer ignorable. Taguchi sought a statistically meaningful way to reflect these losses, which W. Edwards Deming would characterize as “unknown and unknowable”. Taguchi outlined three cases in which [36]

- Larger the better (for example, agricultural yield),
- Smaller the better (for example, carbon dioxide emissions),
- On-target, minimum-variation (for example, a mating part in an assembly).

In this context, the Taguchi method was used to establish the optimal values for the processing variables that would result in the lowest kerf width, Surface roughness and HAZ during the CO2 Laser cutting. Taguchi suggested adopting orthogonal arrays to collect unique information and analyzing the information to discover the optimal approach variables. The Taguchi quality concept design suggests that there are three possible output features to consider when evaluating the signal-to-noise ratio: the lower-the-better, the higher-the-better, and the nominal-the-better. Using orthogonal arrays, this approach requires only a small sample size to evaluate a wide variety of parameters. There is a correlation between a higher signal-to-noise ratio and improved output characteristics. In this case, the best S/N ratio performance can be achieved at the stage of the process parameters. The lower kerf width, Surface roughness and HAZ have been chosen for the characteristics that will maximize machining productivity. The measurements of output period were used in the following equation to determine the values for the lower is better criterion for the corresponding S/N ratios.

$$\text{S/N ratio } (\eta) = -10\log_{10}\frac{1}{n}\sum_{i=1}^{n} y_i^{2}$$

2.2 Material

Hastelloy C-276 with 3.7 mm sheet was selected as the material for this investigation. Hastelloy C-276 is split into its essential chemicals and presented in Table 1. The preparation of the material, a sheet made of Hastelloy that has the required thickness and dimensions. It is important to clean the surface of the material so that any dirt, grease, or debris can be removed. Put the materials down on a work area that is stable and level. Hastelloy C 276 has 15.5% chromium, 0.6% magnesium, 0.088% carbon, 0.034% silicon, 0.001% Sulphur, and 0.004% phosphorus. Carbon level, which has a mixed value, is kept at a level that is good for most service uses. After Spectro analysis, Table 1 shows the chemical composition of the sample, and Table 2 shows how the materials used in the research worked.

Table 1. Chemical composition of Hastelloy C-276

Element	C	Mn	Si	S	P	Cr	Ni	Mo	Co	W	Fe	V
W%	0.005	0.41	0.02	0.002	0.005	15.83	Bal	16.36	0.05	3.45	6.06	0.17

Table 2. Carbon steel's mechanical characteristics

Material	Tensile strength (MPa)	Yield strength (MPa)	Elongation	Density
Hastelloy C-276	790	355	40%	8.89/cm3

2.2.1 Experimental setup

The laser cutting machine is set up as shown in Fig 1 which is continuous 4 kW CO2 laser cutting machine. This machine set up was utilized for the said investigations, where it is kept in a well-ventilated area. The cutting operations were performed with safety glasses, gloves, and a face mask. Before the experiment, the laser beam was checked to make sure it was aligned and focused correctly by performing the trail experimentations in a Nitrogen assist gas.

Fig. 1. Experimental set up of laser cutting process

3. PROCESS PARAMETERS AND DESIGN OF TESTS (DOE)

Research can carry out more methodically by using the Design of Experiments. The process factors and their respective levels are presented in Table 3. When analyzing a wide variety of parameter options, the Taguchi technique employs a straightforward layout of orthogonal arrays and a limited number of test cycles. The research utilized a Taguchi-based experimental setup with a typical L_9 orthogonal array and three levels of three essential process parameters, such as laser power, cutting speed, and gas pressure.

Table 3. Process Factors and Levels

Input process	Unit	Notation	Min Limit	Max
Laser Power	watt	LP	2100	3500
Cutting Speed	mm/min	CS	1200	2500
Gas Pressure	bar	GP	12	16

L_9 orthogonal arrays are used to estimate a high number of critical effects in a perpendicular way with a small sample size. These arrays are also used to set up experiments that use a L_9 orthogonal matrix. Table 4, shows DOE with the obtained surface roughness, kerf width, HAZ and S/N ratio for each experimental condition

Table 4. DOE with the obtained surface roughness, kerf width, HAZ and S/N ratio

Exp. No.	LP	CS	GP	Ratio of kerf width	SNRA1	Surface Roughness	SNRA2	HAZ	SNRA3
1	2100	1200	12	1.17	2.64	0.84	1.51	0.16	15.91
2	2100	1850	14	1.91	-1.48	0.74	2.61	0.14	17.07
3	2100	2500	16	0.85	4.84	0.70	3.09	0.12	18.41
4	2800	1200	14	1.49	-0.45	0.95	0.44	0.19	14.42
5	2800	1850	16	1.12	2.42	0.90	0.91	0.16	15.91
6	2800	2500	12	1.29	1.66	0.90	0.91	0.16	15.91
7	3500	1200	16	1.56	0.32	1.12	-0.98	0.22	13.15
8	3500	1850	12	1.09	0.81	1.06	-0.50	0.24	12.39
9	3500	2500	14	1.31	1.39	1.03	-0.25	0.21	13.55

4. RESULTS AND DISCUSSION

The Taguchi method was successfully applied to conduct the nine different experiments. The results of the tests conducted on kerf width, surface roughness and HAZ are displayed in Tables 4, along with the relevant S/N ratios. When carrying out machining operations, it is usual practice to make achieving low kerf width, surface roughness and HAZ values to make ensuring a high level of quality and accuracy. So, for kerf width, surface roughness and HAZ, it's best if the data given is as low as possible.

The ratio of kerf width, should also be evaluated after the principal effects plots have been drawn (Fig 2). The monitoring features are organized with the use of an orthogonal matrix. The ratio of kerf width measurements, as represented in terms of the signal-to-noise ratio (S/N), are shown in Table 5.

Table 5. Response Chart for Ratio of kerf width Signal-to-Noise Ratios

Level	LP (Watt)	CS (mm/min)	GP (bar)
1	1.310	1.407	1.183
2	1.300	1.373	1.570
3	1.320	1.150	1.177
Delta	0.020	0.257	0.393
Rank	3	2	1

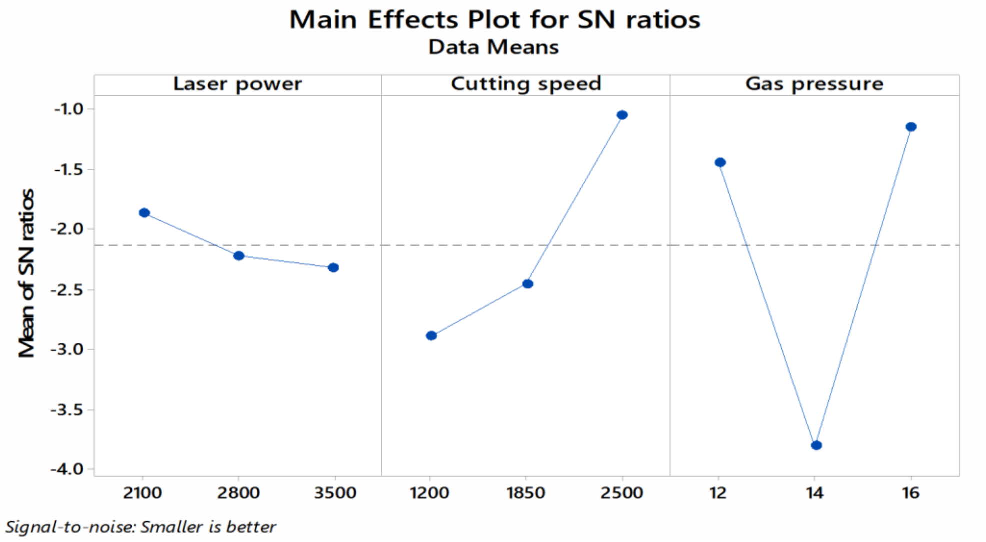

Fig. 2. Plots of the main effects for Ratio of kerf width

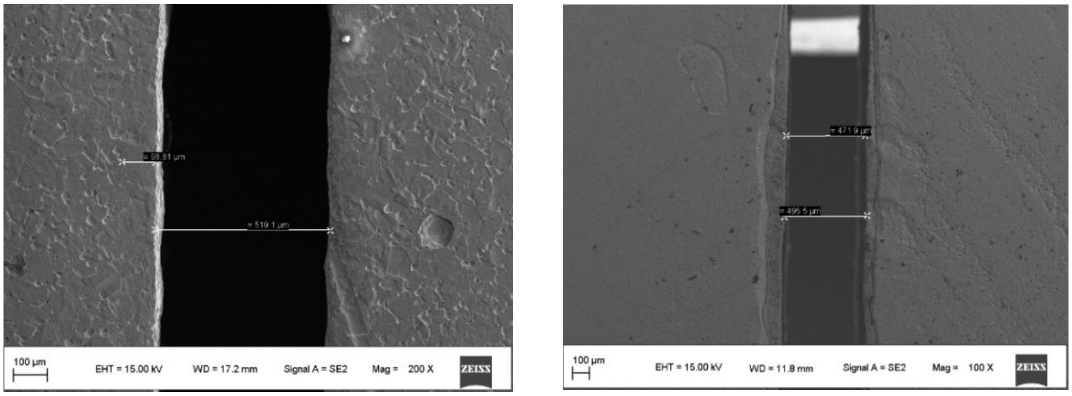

Fig. 3. Effect of laser process parameter on kerf width

In a similar manner, one should plot the primary impacts plots and evaluate the surface roughness. An orthogonal matrix is utilized to facilitate the organization of the monitoring characteristics. Table 6 presents the results of surface roughness measurements, which are also expressed in terms of the S/N ratio (Fig 4).

Table 6. Response chart for surface roughness signal-to-noise ratios

Level	LP (Watt)	CS (mm/min)	GP (bar)
1	0.7600	0.9700	0.9333
2	0.9167	0.9000	0.9067
3	1.0700	0.8767	0.9067
Delta	0.3100	0.0933	0.0267
Rank	1	2	3

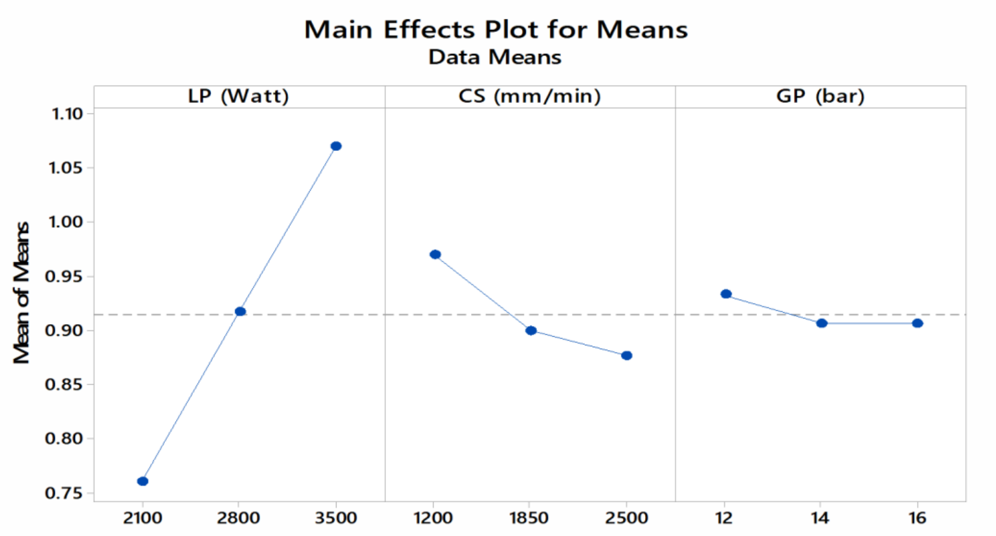

Fig. 4. Plots of the main effects for Surface Roughness

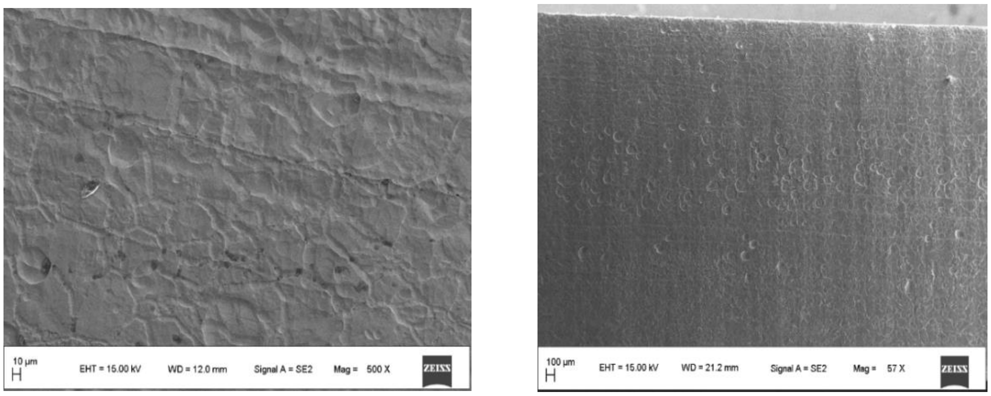

Fig. 5. Effect of laser process parameter on surface roughness

After the principal effects plots have been drawn, the HAZ should also be assessed (Fig 6). Control parameters are organized using an orthogonal matrix. Table 7 displays the HAZ measurements as represented by the signal-to-noise ratio (S/N).

Table 7. Response chart for HAZ Signal-to-Noise ratios

Level	LP (Watt)	CS (mm/min)	GP (bar)
1	17.14	14.50	14.74
2	15.42	15.13	15.02
3	13.03	15.96	15.83
Delta	4.10	1.47	1.08
Rank	1	2	3

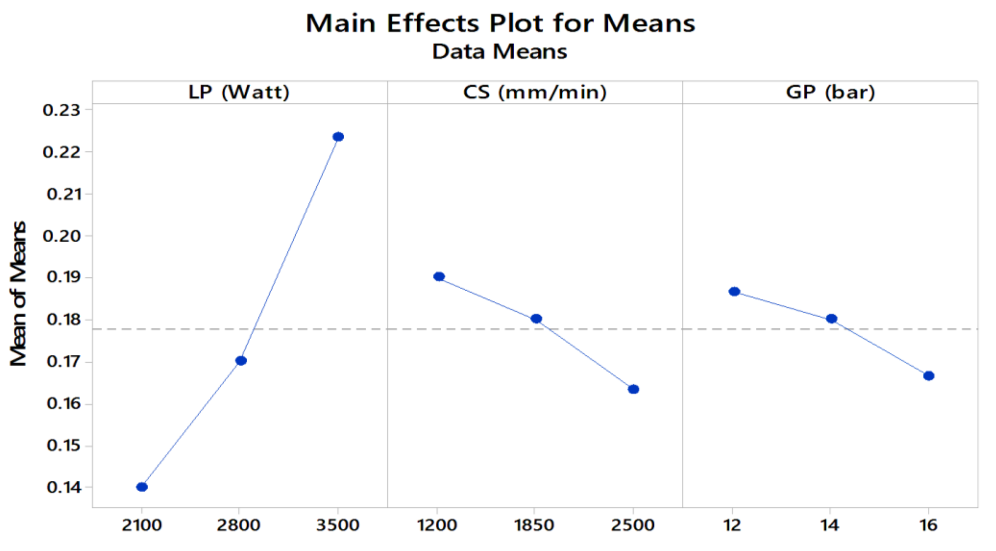

Fig. 6. Plots of the main effects for HAZ

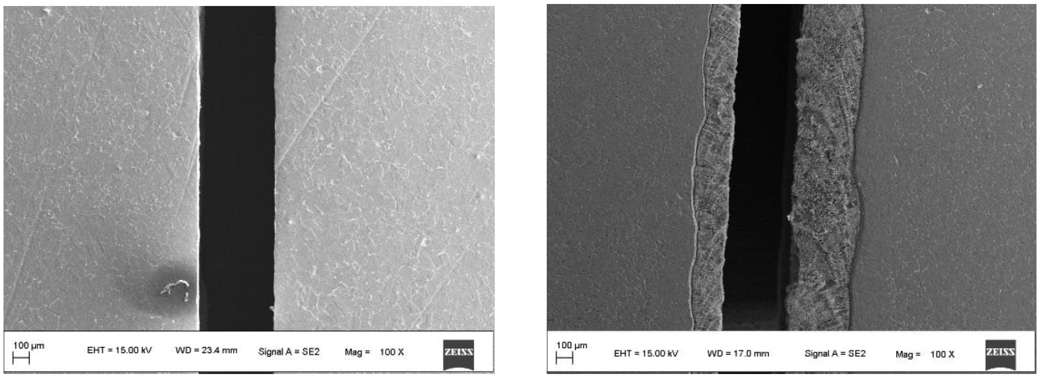

Fig. 7. Effect of laser process parameter on HAZ

During laser processing, the parameters that control the laser can have a substantial impact on the kerf width, surface roughness, and heat-affected zone (HAZ) of the material being processed. The kerf width, surface roughness, and HAZ are all crucial factors that can influence the quality and performance of materials that have been processed with a laser. The kerf width, surface roughness, and height at zone (HAZ) are all affected by the laser process parameters listed below.

Laser power: It was discovered that increasing the power intensity increase the kerf width. Greater melting and evaporation of material with higher laser power typically leads in deeper melting and greater HAZ. Because larger melt pools form and solidification rates increase, this can also lead to increased surface roughness. However, less intense lasers may cause uneven melting and lower surfaces roughness.

Cutting speed: It was discovered that reducing the cutting speed increase the kerf width. Rapid movement of the laser energy across the material at higher cutting speeds results in less heat generation and faster solidification, both of which contribute to a lower surface roughness. When cutting at extremely high speeds, there is a risk of partial melting and lower material removal rates, both of which may lead to an increased surface roughness.

Gas pressure: During laser cutting, the kerf width, surface roughness and HAZ can be changed by the type and flow rate of the gas. Having the right amount of gas flow can help to remove dirt and reducing the formation of oxides which can improve the quality of the surface. But too much gas flow can also cause turbulence and result in higher kerf width, surface roughness. So moderate value of gas pressure is suggested.

In order to achieve the desired kerf width, surface roughness, and HAZ characteristics, it is essential to optimize laser process parameters for a particular material and application, as the effects of these parameters can be complex and may vary depending on the specific material, laser system, and processing conditions.

5. VALIDATION OF EXPERIMENT

Predictions were made for the ratio of kerf width, Surface Roughness, and HAZ by utilizing the information obtained from the Taguchi method and applying it to the ideal circumstances. The Taguchi Method predicted that the kerf width would be 1.30, when the laser power was 2800 watts, the cutting speed was 2500 mm/min, and the gas pressure was 16 bar, while conducting the actual experiment, it was found that the ratio of kerf width is 1.12.

The Taguchi Method predicted a surface roughness of 1.08, where the laser power was 3500 watts, the cutting speed was 1850 mm/min, and the gas pressure was 12 bar. The surface roughness was measured 1.07 when the experiment was being performed. Similarly, the HAZ was predicted to be 0.083 using the Taguchi method, at 2100 watts of laser power, 2500 mm/min of cutting speed, and 16 bars of gas pressure, In the real experiment, under perfect conditions, measured a HAZ of 0.08.

Table 8. Confirmation Test for Ratio of kerf width, HAZ and Surface roughness

Output	LP	CS	GP	Predicted	Actual	%
Ratio of kerf	2800	2500	16	1.30	1.12	1.60
Surface roughness	3500	1850	12	1.08	1.07	1
HAZ	2100	2500	16	0.083	0.08	3.75

6. CONCLUSIONS

In this study, the parameter design of the Taguchi method was used to study and explain the relationship between kerf width, surface roughness, and HAZ in CO2 laser cutting operations. The main goal is to find the best combination of “laser power”, “cutting speed”, and “gas pressure” to get the best output qualities, such as “kerf width”, “Ra”, and “HAZ”. The followingconclusions can be drawn from the experiments conducted for this study:

1. By varying the laser power, cutting speed, and gas pressure, the ideal processing conditions for reducing the ratio of kerf width were determined to be 2800 watts, 2500 mm/min, and 16 bars, respectively.

2. According to the research and findings, the laser power is the most crucial component in determining the appropriate ratio of kerf width.

3. Effective HAZ and Surface roughness characteristics were identified based on the analysis. The best HAZ and surface roughness can be achieved primarily by optimizing the laser's power.

4. The optimum conditions for reducing Surface roughness are 3500 watts of laser power, 1850 mm/min of cutting speed, and 12 bars of gas pressure. The optimal values for reducing HAZ are 2100 watts of laser power, 2500 mm/min of cutting speed, and 16 bar of gas pressure.

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