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# Analysis of the effecting parameters on laser cutting process by using response surface methodology (RSM) method

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## ABSTRACT

**Purpose:** The main aim of this research is to analyse the effects of the laser cutting parameters on the kerf width of stainless steel (2505), and develop a model of laser cutting that can predict the relation between the characteristics of the resultant kerf width and the process input parameters.

**Design/methodology/approach:** To achieve the minimum kerf width; the optimal setting of the effecting parameters like; power supply, cutting speed, and gas pressure for the response surface methodology, and factorial design-based optimal parametric analysis has been carried out for this purpose. A mathematical model for analysis of the kerf width was developed using the (Minitab 16) on the basis of experimental results.

**Findings:** It's found that the interaction between power value, cutting speed, and pressure has a significant effect on the response value. Also, it's found that, when the power and cutting speed are set at optimal values i.e. 1250 watt and 5 mm/min, the minimum kerf width will be 0.389 mm. The mathematical model has been established based on regression analysis by factorial design and response surface model.

**Research limitations/implications:** The cutting quality in this process widely depend on the technical specifications of a laser machine. Consequently, machine operation parameters are considered the main limitations factor in this process.

**Practical implications:** In this current work, the 4 mm thickness stainless steel (2505) has been used in the experimental investigation to measure the Influence of laser cutting machine parameters. In addition, optimal laser cutting parameter values that minimize the width of kerf width were identified. The optimization problem was formulated and solved by the second-order model method. The laser cutting experiment was planned and conducted according to the (RSM) central composite design approach (uncode).

**Originality/value:** The validation with experimental results shows that the factorial analysis gives an average error 5%, and the (R-sq) is equal to 69.02%. It's concluded that the model that has the (R-sq) value greater than 41% is considered as a fit model and can be used for the next machining process.

**Keywords:** Laser cutting process, Non-linear inclined cutting, Kerf width, Laser parameters

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MANUFACTURING AND PROCESSING

## 1. Introduction

Laser is unlike many types of electromagnetic radiations especially in terms of its straight-line propagation, cohesion, and spectral purity. For these advantages laser is very important in many industries and applications such as medical, communication, military, and others. The use of laser cutting is very important due to some specific properties like monochromaticity, pulsed, pulsed power density, low divergence, and high continuous, spatial, and temporal coherence [1].

The ability of laser to serve as a heat source is considered as one of its main applications, and this is defined as laser materials processing. These features can be so benefits in manufacturing, deposition, forming, and surfaces machining. Laser is widely used in multi-industrial purposes, especially for hard metals cutting [2].

Laser cutting is a non-contact process that affords many advantages and prefers due to some important features like low heat input, no vibration, minimal distortion, and the capability to be controlled automatically. Determining the Laser cutting parameters is the important key toward the best quality in this cutting process [3,4].

Good machining quality by laser cutting is possible to achieve by selecting suitable machining parameters. Results revealed that cutting speed decreases exponentially with sheet thickness decrease [5]. The quality of the cutting surface by the laser machine is affected by many parameters, but most important is assist gas pressure, focal length, pulse width, and nozzle distance [6]. Depth of heat affected area will decrease according to the increase in thickness of the cutting sheet, and the quality indicators of the cutting surface will increase with respect to the elevation in radiation power [7].

The most cutting process relevant to different materials is the process of using carbon dioxide ($CO_2$) laser cutting. It's widely used in the industry and in many commercial applications. Thence, the low-power requirements are one of the significant properties of using $CO_2$ laser cutting. The generation of the heat-affected zone (HAZ) is one of the important problems reported with laser cutting. It was observed that HAZ decreased when gas pressure decreased while increasing when laser power increased [8].

$CO_2$ laser source used for cutting different thicknesses of sheet metals. For getting good control on cutting surface quality by using the $CO_2$ laser source cutting process, it's essential to define process parameters properly. Besides the highly-automated process, other benefits of using $CO_2$ laser beam cutting include homogeneous cutting with highly precise as well the kerf width is too narrow [the minimum width 0.370 µm and dross height are 0.166 mm] with a smooth surface [9].

The kerf width, high power consumption, taper cutting, and surface roughness are the most issues associated with the laser cutting process. The investigation of the most influenced factors as power, and speed was found as 600-700 watt, and (4, 8) mm/s respectively.

Minimum (HAZ), precise cutting quality, and smooth surfaces are some of the benefits that Laser cutting can offer. Also, the cutting is not affected by material hardness [10].

Response surface methodology (RSM) is useful for analysis and modelling many applications. It is a combination of statistical and mathematical techniques. It's normally used whenever the aim is to optimize the response, and this response of interest is affected by some variables. The relationship between the independent variables and the response in many (RSM) problems is unknown. However, finding a suitable approximation for the exact relationship between the independent variables and (Y) will be the first step in (RSM).

Normally in some regions, low-order polynomial independent variables are employed. The approximating function will be as a first-order model whenever the response is well modeled by a linear regression model function of the independent variables, as in equation (1) [11-19].

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_k x_k + \in \qquad (1)$$

where (Y) is the dependent variable, ($\beta_0$, and $\beta_1$) are the coefficients, and ($\in$) is the error term or residual. A polynomial of higher degree such as a second-order model must be used whenever a curvature in the system, as in equation (2), and many (RSM) problems use one or both of these approximating polynomials.

$$Y = \beta_0 + \Sigma\, \beta_{i} x_{i} + \Sigma\, \beta_{ii} x^2_i + \Sigma\, \beta_{ij} x_i x_j + \in \qquad (2)$$

The polynomial model is not reasonable for approximating the exact relationship in a wide range of variables for entire spaces, but it normally works and is active for relatives. Determining the ideal operating factors, the factor space region, and the ideal operating conditions for the system are the final objectives of (RSM) [12].

Nevertheless, experiments carried out using this approach are called optimization experiments [13,14].

To ensure that the selected polynomial equation will be the best representation for this model, and to minimize the residual error measured by the sum of square deviations between the estimated responses and the actual; a Least square technique is used for this purpose [14].

To estimate the regression coefficients, some calculations should be made, and for statistical significance, the calculated coefficients need to be tested.

Spark plasma sintering is considered a good method to produce cutting tools in spite of the high cost and lower productivity. The spark plasma cutting process results in a softer matrix and this will lead to high cutting efficiency [15].

This type of test is usually implemented by using the Analysis of Variance Approach (ANOVA), especially when the tests are accomplished for the significance of individual model coefficient, lack of fit is performed, and significance of the regression model. To identify the effecting factors of a particular process on some outputs and to specify the optimal conditions; many authors are using the Design of Experiment (DOE) to create the final mathematical model [5-16].

The optimizing of cutting parameters is one of the main aims and objectives of this research. The goal is to achieve the optimal cutting kerf width in this research through laser cutting energy for a plate of stainless steel material. The process input parameters that were selected to identify their influence on the cutting process include; power output, gas pressure, and speed on cutting responses were analysed. While the output variables are kerf width and surface roughness. To estimate the effects of any of these parameters on the cutting quality its need to change it and fix the values of other parameters sequentially.

## 2. Materials and methods

Both response surface methodology (RSM) and the design of expert software (DOE) are used to determine the kerf width in the cutting process of steel metal by using the laser cutting process. It found that quadratic equations can be used for modelling the relationship between display and input parameters [17]. The use of plasma-treated surfaces is developed and became usual and widespread in many applications due to high performance compared with traditional methods. Unique structural changes will provide by using plasma treatment and can be used or many functional applications [18]. Figure 1 below illustrates the details of the research idea.

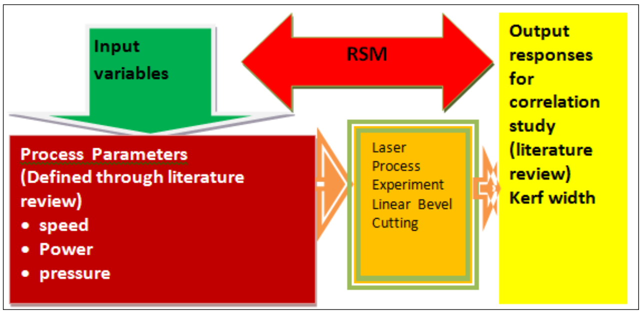

Fig. 1. The overall approach of laser process non-linear inclined cutting study

The major aspect of the research is to study the effects of important parameters like; power supply, gas pressure, and cutting speed on the kerf's width and surface roughness. In addition; the other aspect is to find the responses of this parameter to the statistical representation. For this experiment; the low and high values of input parameters which normally depend on the used material should be identified, and some of the other parameters will be kept in the same values. The values and levels of these parameters are illustrated in Table 1.

Stainless steel with a thickness of 4 mm is the type of material used here. It's heavy, reactive with some limitations in some elevated temperatures [20].

The laser cutting machine used to implement this cutting process is shown in Figure 2.

The technical specification of this laser cutting machine is listed in Table 2.

Table 1.
Parameters levels

| Parameter | Low levels | High levels |
|---|---|---|
| Power supply, Watt | 1250 | 2500 |
| Cutting speed, mm/min | 500 | 1000 |
| Gas pressure, bar | 100 | 175 |

Fig. 2. The laser cutting machine LVD model (2513) is used in cutting stainless steel 2505

Table 2
Technical specifications of laser cutting machine

| Material | Metal |
|---|---|
| Thickness | 20 mm |
| Size | 540 x 1080 mm |
| User size | 275 x 350 mm |
| Kerf width | 2 mm |
| Cutting speed | 500-1000 mm/min |
| Positioning speed | 60 m/min |
| Power | 2 kW |
| Pressure | 1.2 MPa |
| CNC control | Yes |
| Max. loading on the table | 500 kg |

Two coordinate optical microscopies with the clear penetrative and enlarged force of (1.2 x) are used for measuring the kerf width as shown in Figure 3.

Fig. 3. Optical microscopy with (mag. 1.2x) used for measuring kerf width

## 3. Optimization of the cut kerf width

The optimization consists of the (RSM) analyses to define and represent the relationships between Laser cutting input parameters (the pressure, power, and speed) and the resultant kerf width. Twenty runs are used to assess the results and validation of the developed model, and for this purpose, the quantitative validations are deployed to meet the following conditions:

A. To specify whether the model is able to predict and validate the outcome results according to the input parameters with a predictive interval of 95%.

B. To determine the percentage between the values of predicted roughness and the validation roughness depending on specific input parameters. These values must not exceed 5% for this model.

Performed qualitative validations for this model is possible by justifying the relationships between the kerf width and individual laser process parameters and comparing them with published studies.

## 4. Modelling of kerf width

Twenty experiments have been carried out as shown in Table 2. Kerf width for each experiment was analysed by using optical microscopy test kerf width measurement.

The kerf data was obtained using an Enlarge force of 1.2 mm with a clear penetrative of less than of cut 6 mm thickness. Three kerf measurements were collected per sample and the output response will be the calculated average of the process. Figure 4 illustrates the principal work on the laser cutting machine at a bevel angle 22°.

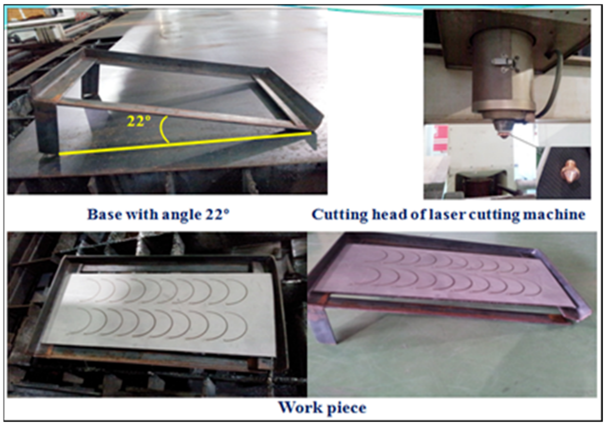

Fig. 4. Principal of practical work

Measurement of kerf width and the resultant of cut kerf by using laser cutting are illustrated in Figures 5 and 6.

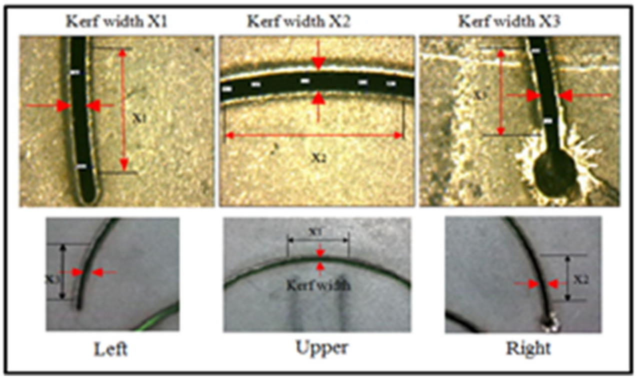

Fig. 5. Measuring for kerf width at three areas (x1, x2, and x3) for one run

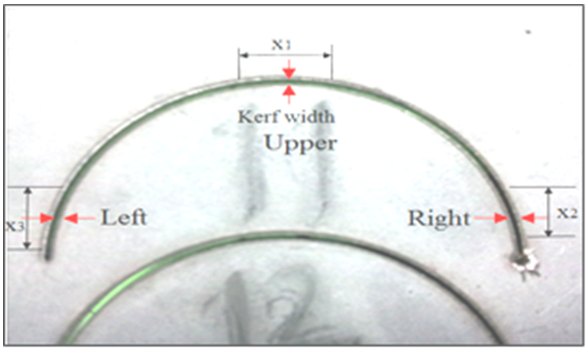

Fig. 6. Result of kerf width implemented through laser cutting process

The measuring reading results of kerf width by inclined laser cutting process for three specific areas (x1), (x2), and (x3) are illustrated in Table 3.

Table 3.
Illustration of the values and the average values of kerf width

| Run | X1, mm | X2, mm | X3, mm | Average, mm |
|---|---|---|---|---|
| 1 | 0.095 | 0.085 | 0.086 | 0.089 |
| 2 | 0.11 | 0.12 | 0.09 | 0.11 |
| 3 | 0.09 | 0.09 | 0.09 | 0.09 |
| 4 | 0.10 | 0.096 | 0.10 | 0.10 |
| 5 | 0.098 | 0.10 | 0.11 | 0.10 |
| 6 | 0.11 | 0.11 | 0.11 | 0.11 |
| 7 | 0.15 | 0.16 | 0.17 | 0.16 |
| 8 | 0.15 | 0.15 | 0.16 | 0.15 |
| 9 | 0.16 | 0.15 | 0.15 | 0.15 |
| 10 | 0.13 | 0.12 | 0.15 | 0.13 |
| 11 | 0.15 | 0.15 | 0.17 | 0.16 |
| 12 | 0.14 | 0.13 | 0.15 | 0.14 |
| 13 | 0.13 | 0.13 | 0.14 | 0.13 |
| 14 | 0.14 | 0.14 | 0.14 | 0.14 |
| 15 | 0.13 | 0.12 | 0.14 | 0.13 |
| 16 | 0.12 | 0.12 | 0.13 | 0.12 |
| 17 | 0.14 | 0.13 | 0.15 | 0.14 |
| 18 | 0.14 | 0.13 | 0.16 | 0.14 |
| 19 | 0.14 | 1.13 | 0.16 | 0.14 |
| 20 | 0.14 | 0.14 | 0.15 | 0.14 |

## 5. Results and results discussion

For data analysis, and to represent (RSM) model by determination of the appropriate polynomial equation; the (RSM) design expert software has been deployed for this purpose. The approach of this determination is to represent the relation between the output response and the input parameters.

Lack of fit test and the sum of squares sequential model SMSS are carried out for cutting kerf width estimation. Test results are shown in Table 4 and Table 5 respectively.

The relationship between the resultant cutting kerf and input parameters is suggested to be modelled by both analyses through using the quadratic equations.

The analysis of Variance for kerf width summarizes the interactions, the linear terms, and the squared terms. The small interactions values P = 0.024 and speed squared (speed*speed) P = 0.044 reveals that, there is a curvature in response surface. The small p-value for the interaction of power by speed P = 0.014, indicates significant statistical effects because these values are less than the α-value (α-value = 0.05). The speed parameter is the most significant that affects the kerf width followed by power and pressure.

Table 4.
Test results of the estimated values for kerf width

| Source | DF. | Seq. SS | Adj. SS | Adj. MS | F | P |
|---|---|---|---|---|---|---|
| Regression | 9.0 | 0.006305 | 0.006305 | 0.000701 | 2.48 | 0.087 |
| Linear | 3.0 | 0.000212 | 0.000212 | 0.000071 | 0.25 | 0.859 |
| Power | 1.0 | 0.000018 | 0.000018 | 0.000018 | 0.06 | 0.804 |
| Speed | 1.0 | 0.000023 | 0.000023 | 0.000023 | 0.08 | 0.780 |
| Pressure | 1.0 | 0.000171 | 0.000171 | 0.000171 | 0.60 | 0.455 |
| Square | 3.0 | 0.001967 | 0.001967 | 0.000656 | 2.32 | 0.137 |
| Power*Power | 1.0 | 0.000319 | 0.000224 | 0.000224 | 0.79 | 0.395 |
| Speed*Speed | 1 | 0.001580 | 0.001500 | 0.001500 | 5.30 | 0.044 |
| Pressure*Pressure | 1 | 0.000068 | 0.000068 | 0.000068 | 0.24 | 0.635 |
| Interaction | 3 | 0.004125 | 0.004125 | 0.001375 | 4.86 | 0.024 |
| Power*Speed | 1 | 0.002485 | 0.002485 | 0.002485 | 8.79 | 0.014 |
| Power*Pressure | 1 | 0.000820 | 0.000820 | 0.000820 | 2.90 | 0.119 |
| Speed*Pressure | 1 | 0.000820 | 0.000820 | 0.000820 | 2.90 | 0.119 |
| Residual Error | 10 | 0.002828 | 0.002828 | 0.000283 | | |
| Lack-Of-Fit | 5 | 0.001745 | 0.001745 | 0.000349 | 1.61 | 0.307 |
| Pure Error | 5 | 0.001083 | 0.001083 | 0.000217 | | |
| Total | 19 | 0.009133 | | | | |

Table 5.
Results of the kerf width by using (ANOVA)

| Terms | Coef. | Se. Coef. | T | P |
|---|---|---|---|---|
| Constant | 0.131244 | 0.006859 | 19.135 | 0.000 |
| Power | 0.001158 | 0.004551 | 0.255 | 0.804 |
| Speed | 0.001305 | 0.004551 | 0.287 | 0.780 |
| Pressure | 0.003535 | 0.004551 | 0.777 | 0.455 |
| Power*Power | 0.003939 | 0.004430 | 0.889 | 0.395 |
| Speed*Speed | 0.010203 | 0.004430 | 2.303 | 0.044 |
| Pressure*Pressure | 0.002172 | 0.004430 | 0.490 | 0.635 |
| Power*Speed | 0.017625 | 0.005946 | 2.964 | 0.014 |
| Power*Pressure | 0.010125 | 0.005946 | 1.703 | 0.119 |
| Speed*Pressure | 0.010125 | 0.005946 | 1.703 | 0.119 |

For adequate modelling of this non-linear process; a high order model is important to use for accurate response. Hence, the full quadratic model is fitted. However, estimating each effect independently is so important due to using orthogonal design. Consequently, all the linear terms coefficients are fitting as a linear model. However, the error values, S=0.0168175, PRESS = 0.0155191, are small due to reducing the accounted variability by error. The speed squared (speed*speed) P = 0.044 is less than α-value (α-value=0.05). Therefore, this suggests that there are significant quadratic effects (curvature in response surface). That is, the relationship between speed and kerf width follows a curved line, rather than a straight line. The small interactions values P = 0.024 and small p-values for the interaction of speed by power P = 0.014 are less than 0.05, which is considered as a significant effect. The impact of power on kerf width depends on the speed. This model will be useful to predict the values of kerf width for different combinations of laser cutting process parameters. As the significant parameter has been identified and the interactions between the factors were understood, it is important to establish the regression model which provides the relationship between the kerf width and the critical effect. The regression value of R-sq is equal to 69.02%, so this model can be said as a good model. The model that has the R-sq value greater than 41% is considered as a fit model and can be used for the next machining process. The mathematical model can be obtained from the regression analysis according to the following values: Kerf = 0.131244-0.00115 power supply + 0.0013 cutting speed – (0.0035) gas pressure. The contour plot of kerf width against speed and power is shown in Figure 7, and Figure 8.

## 6. Optimization process

This zone is found at the lower-left corner and upper right corner of the plot. It's now very clear that the shape of the response surface is giving a good indication with various settings of speed and power. Finally, it's normal to say that the model should be adequate before interpreting the plots.

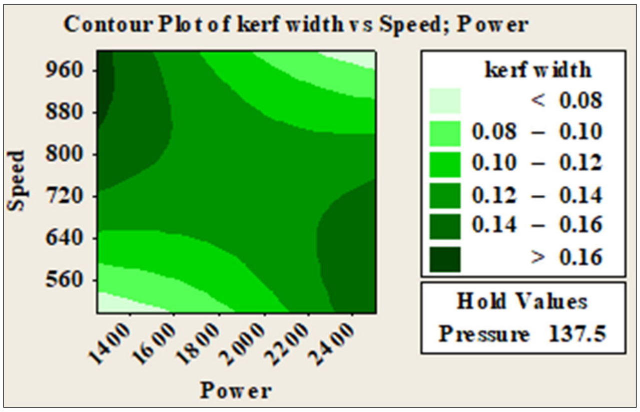

Fig. 7. Contour plot for the (power, speed) vs kerf width values

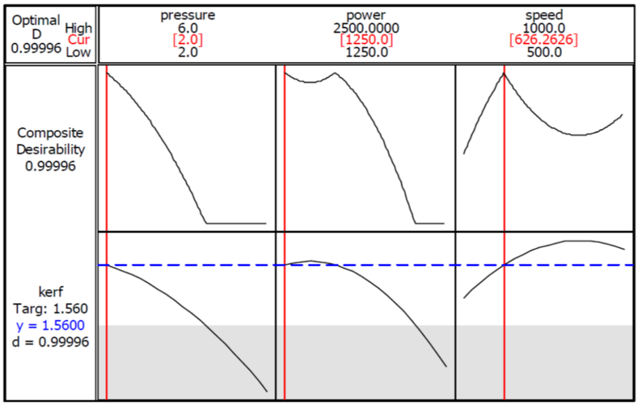

Fig. 8. The contour of the kerf width surface plot

The two-dimensional view was provided in a contour plot. All points that have the same response will be connected to produce contour lines of the surface plot providing a three-dimensional view and constant responses. That will provide a clearer picture of the response surface. The contour of the surface plots indicated that the highest yield (a small kerf width) is found when speeds values are high with high and opposite power values too. The predicted Responses of kerf width and desirability were 0.124504, 0.999888 respectively. Figure 9 illustrates the optimization of kerf width.

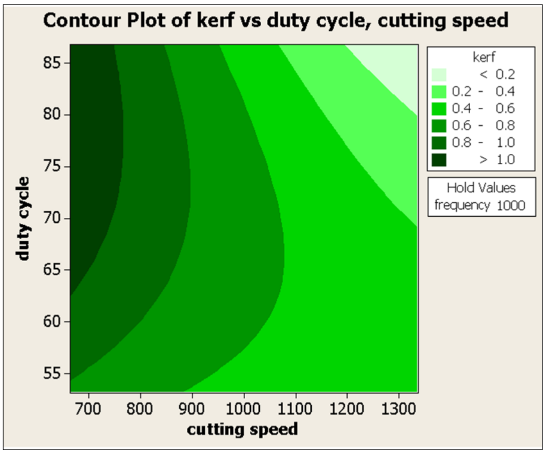

Fig. 9. Optimization plot of kerf width

## 7. Discussion of optimization results

The settings that optimize a single response can evaluate by the individual desirability (d), and the settings that optimize a set of the overall responses can evaluate by the composite desirability (D).

The range of desirability is from zero to one, where zero indicates that one or more responses are outside their acceptable limits, and one represents the ideal case. When the composite desirability is close to 1 (0.999888); this will be a good indication that favourable results, responses, and the whole setting is close to achieving. As a comparison of these results, it was found that these values are compatible with the findings of the literature [10]. Regression analysis was used in correlation with analysis of variance (ANOVA) to develop a linear model-based quadratic regression for parameters optimization purposes and verify the quality of final kerf.

It's also observed that the combination of optimal parameters of the value of cutting speed is 4, 8, 12 mm/s, laser power 950 and 1350 W, and 5 bars of gas pressure. The quality improvement was ranged from 5% to about 35%. It found that these findings as a comparison between this study and some other researchers' findings with respect to cut quality and functional properties reveal good repeatability and good surface finish [9,10].

## 8. Conclusions

The current study is focusing on the machining cutting parameters like gas pressure, cutting speed, and power supply for 4 mm thickness of stainless steel by laser cutting machine. The procedure was implemented by using a factorial design and response surface model. Parameters were tested at their high and low levels. Two variables are used to analyse the influence of design parameters on the machining characteristics, namely surface roughness, and kerf width. Significant parameters like roughness and cutting kerf width were identified in this study by using ANOVA (analysis of variance).

Cutting kerf width was influenced by the speed squared (speed*speed) with the interaction between power supply and cutting speed (power*speed). It's found that the speed parameter is the main remarkable effect on width kerf followed by power and pressure. The predicted response of kerf width was 0.125, the composite desirability was 0.9998, and the global solution of the parameters was as follows power 1250, speed 500, and pressure 104.154. Therefore, to obtain this desirability, it's recommended to put the values of factor levels below the global solution. Hence the power value is 1250, speed value 500, and pressure value 104.154. The quality improvement was ranged from 35% to about 35%. As a recommendation, and to make these types of cutting more predictable, the suggestion for further research should be to focus on other missing parameters. These parameters such as auxiliary gas flow rate and composition. It's concluded that there's a possibility to hold the pressure value at any level to get a small kerf width when increasing or decreasing the power and speed levels together. In optimization, the kerf width was about 95% of the developed models and the residual errors were less than 5% compared to the predicted values.

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