Abstract — Laser cutting of sheet metal has become an economically viable method of production through advances in technology. The quality of laser cut is of the utmost importance in laser cutting process. CO₂ laser machine has been used in industry for many applications such as laser cutting, laser engraver and laser marking. Laser cutting process is one of the famous applications of laser machine in industry. Laser beam usually used to cut small and precise products for assembly parts. The finished product of laser cutting process does not need any further finishing process. However, poor quality of cut has been rise as critical issues in industry due to the improper setting of cutting parameters. All cutting parameters might have significant influence on the resulting quality of work. In general, cutting parameters are adjusted and tuned to provide the quality of cut desired. But this consumes exhaustive amounts of time and effort. Therefore, it is important to investigate the impact of cutting parameters on quality of cut.

The aim of this study is to relate the CO₂ laser cutting parameters namely Laser Power, Gas Pressure and Cutting Speed to the quality of cut of Stainless Steel Sheet. The quality parameters considered include the measurement of Outlet Diameter, Inlet Diameter and the Operation Cost. The effects of each cutting parameters on quality of cut was establish and the interactions between the cutting parameters were investigated. Design of Experiment was used by implementing Design Expert Software to identify the main effects and interactions of the parameters. Once the best value is found out the other quality parameter like Surface Roughness, Kerf Width and Heat Affected Zone are examined.

Keywords — AISI 304 SS, Laser Cutting, Laser Power, Gas Pressure, Cutting Speed, Inlet Dia, Outlet Dia, Operation Cost.

I. INTRODUCTION

CO₂ Laser machine has been used in industry for many applications such as laser cutting, laser engraver and laser marking. Laser cutting process is one of the famous applications of laser machine in industry. Laser beam usually used to cut small and precise products for assembly parts. The finished product of laser cutting process does not need any further finishing process. However, poor quality of cut has been rise as critical issues in industry due to the improper setting of cutting parameters. In order to solve this problem, a research study on the impact of cutting parameters on quality of cut was carried out. In this research, the main objective will focus on the impact of the cutting parameters of a specify machine on the quality of cut on AISI 304 SS sheet.

II. PROBLEM STATEMENT

Quality of cut has been a critical issue in laser cutting process. For stainless steel cutting such as AISI 304 (L) SS sheet, when the profile cut is a hole the required outer diameter, inner diameter measured is found to be unsatisfactory for the customer. The edges will always be brown or yellow, and it produces hydrochloric acid during the cutting, which will eat up everything inside the laser and in the exhaust system. Currently, there are some problems with the laser cutting process which require immediate attention.

III. PARAMETERS INVOLVED

The main objectives of this project is to find out the optimum

i. Laser power in Watts
ii. Laser cutting speed in mm/min
iii. Laser gas pressure in Mpa

Such that the operation cost involved is minimum. Once the new specimen is prepared it is been examine under Tool Makers Microscope and the following factor are compared with specimen that is prepared on experimental run.

i. Inlet Diameter in mm
ii. Outlet Diameter in mm
iii. Cutting Cost in Rs/hr

IV. CO₂ LASER CUTTING PROCESS

Carbon dioxide lasers are the highest-power continuous wave lasers that are currently available. The laser creates a beam of light that is used to cut through the material, so there is no part of the laser system in contact with the material.

The laser beam must first penetrate the material at a certain point, before a contour can be cut. The piercing can be done quickly with full laser power or slowly using the so- called “ramp”. When creating a start hole in the ramp mode, the laser output is gradually increased, and then it is held constant unit the start hole has been formed and finally the output the again slowly reduced.
Using high laser power, the material is heated, melted and partly vaporized. The material is blown out of the Kerf. The cutting flow of gas, which aids the removal of melting, is emitted together with the laser beam out of the nozzle. The Kerf is created by moving the work piece or the cutting head. Both the piecing and the laser cutting can be aided by adding a gas and thereby influence the cutting results. The choice of piercing gas or cutting gas depends on which material is being machined and level of quality needed for the work piece.

V. QUALITY OF CUT

Quality of the cut is satisfied only when the following three factors are satisfied they are
i. Geometry Factor (Inner, Outer diameter)
ii. Cost Factor (Operation Cost)
iii. Other Quality Factors (HAZ, Surface Roughness, Kerf Width)

Quality of Cut on Geometry Factor:

The geometry factor includes measurement of the outer diameter, the inner diameter, length, breadth, arc and straight cut after the cutting operation is performed. The outer diameter is the diameter of the hole on the upper surface of the work piece where the laser beam hit the surface at first. The inner diameter is the diameter of the hole on the lower surface of the work piece where the laser beam leaves the work piece.

Quality of Cut on Cost Factor:

Laser cutting operating costs can be estimated as cutting per hour or per unit length. The laser system used in this work utilized CO2 using a static volume of laser gases of approximately 7.5 liters every 72 h. For this laser system with 3 KW maximum output power the operating costs is calculated as follows.

Cost Calculation:

\[ \text{Laser Electrical Power} = \frac{22 \text{ KVA} \times 0.8 \times \text{Rs. 10}}{0.5} = \frac{22 \times 0.8 \times 10}{0.5} = \text{Rs. 177.30} \]

\[ \text{Chiller Electrical Power} = \frac{12 \text{ KVA} \times 0.8 \times \text{Rs. 10}}{10} = \frac{12 \times 0.8 \times 10}{10} = \text{Rs. 96} \]

\[ \text{Motion Controller Power} = \frac{0.3 \text{ KVA} \times 0.8 \times \text{Rs. 10}}{10} = \frac{0.3 \times 0.8 \times 10}{10} = \text{Rs. 9} \]

\[ \text{Exhaust Power System} = \frac{0.9 \text{ KVA} \times \text{Rs. 10}}{10} = \frac{0.9 \times 10}{10} = \text{Rs. 9} \]

\[ \text{Laser Gas } = \frac{\text{Rs. 8500}/ \text{bottle}}{1500/ \text{bottle}} \times 75 h = 5.66 \times 0.104 \]

\[ \text{Gas Bottle Rental } = \text{Rs. 0.389/} \text{h} \]

\[ \text{Compressed Nitrogen } = 0.8 \]

\[ \text{Nozzle Tip } = \frac{\text{Rs. 600}}{100 \text{ hrs}} = \text{Rs. 6} \]

\[ \text{Exhaust System } = \frac{\text{Rs. 120}}{100 \text{ hrs}} = \text{Rs. 1.2} \]

\[ \text{Maintenance & Labor } = \frac{12}{3000 \text{ hrs}} \times \text{Rs. 4750/} \text{hr} = 0.006 \times 4750 = \text{Rs. 24.9} \]

\[ \text{Total Cost } = \text{Rs. 117.30} + \text{Rs. 96} + \text{Rs. 40} + \text{Rs. 9} + \text{Rs. 0.589} + \text{Rs. 20.80} + 0.8f + \text{Rs. 3} + \text{Rs. 4.20} + \text{Rs. 15} + \text{Rs. 24.9} \]

\[ \text{Total Cost } = \frac{213.489 + 0.8f + 117.3f}{0.051 \times 2000} \]

\[ \text{Flow Rate (f) } = \frac{492 \times d^2 \times (P_f + 1)}{d} \]

\[ \text{d } = \text{ Diameter of Nozzle } = 2 \text{ mm} \]

\[ P_f = \text{ Gas Pressure in } \text{bar} \]

\[ P = \text{ Power in Watts} \]

\[ f = \text{ Flow Rate (Gas) in Liter/Sec} \]

\[ \text{Power Factor } = 0.8 \]

VI. MEASURING TECHNIQUES

In order to attain good cutting results, measurement of work piece parameters after the laser cutting process is done and checked for quality of cut. The work piece parameters include measurement of Inner diameter, Outer diameter and the Taper angle. Along with the work piece parameter the effect of process parameter which includes Kerf width, Surface roughness and HAZ over the quality of cut is measured. The work piece parameter and effect of process parameter over the work piece after laser cutting is measured using two types of instrument and they are,

a. Tool Markers Microscope WM2.

b. Marvision MMS20 SEM Microscope.
VII. METHODOLOGY

In order to evaluate this project, the methodology based on System Development Life Cycle (SDLC), generally three major step, which is planning, implementing and analysis.

Methodology Flow Chart:

- Planning
  - Data Collection
  - Hardware and software measurement
  - Testing point
- Implementing
  - Implement the project
  - Analyze the performance
- Analysis
  - Identify the conclusion

VIII. LEVEL SELECTION

Gas Pressure = 0.7 Mpa to 0.9 Mpa.
Cutting Speed = 3500 mm/min to 5000 mm/min.
Laser power = 2000 W to 3000 W.

IX. EXPERIMENT DESIGN

The experiment was designed based on a three level Box-Behnken design with full replication. Laser power, cutting speed and gas pressure are input parameters of the CO$_2$ laser beam cutting process. The inlet diameter $D$, Outlet diameter $d$ and Cutting Cost are the response measured. The step involved in generating the table of run using Design-Expert software is given below.

From the previous equation of the cost factor is calculated for the different table of run. The table below gives us the cost incurred in running the experiment to prepare sample with laser cutting operation at different levels of input parameters that is obtained in Design expert software.

VII. PROFILE SPECIFICATION

The diagram below specifies the geometry value of the profile that is to be cut using the CO2 laser. In the diagram the $D$ specifies the outer diameter, $d$ specifies the inner diameter and "$\alpha$" specifies the tapper angle which occurs when there is change in value of the outer diameter and inner diameter. The change in inner and outer diameter occurs when the quality of cut is poor. The required value of cut is $D = 10$ mm, $d = 10$ mm, $B= 9$mm.

![Geometric specification Top View](image)

![Geometric specification Bottom View](image)
X. MEASUREMENT OF GEOMETRIC PARAMETERS (D & d)

The tool maker's microscope WM2 is a robust and easy to operate device for the universal use in the workshop. This microscope is used to measure the inner diameter d, outer diameter D and taper angle α. The out-of-the-reading which include the measurement of inner and outer diameter that is measured are obtained digitally in Tool Markers Microscope WM2. The measured value D & d of different specimen that is obtained is shown in the table below.

<table>
<thead>
<tr>
<th>Experiment No</th>
<th>Power in Watts</th>
<th>Cutting Speed in m/min</th>
<th>Gas Pressure in Mpa</th>
<th>Flow Rate in Lit/h</th>
<th>Cutting Cost in Rs/hr</th>
</tr>
</thead>
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<tr>
<td>1</td>
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<td>3500</td>
<td>0.7</td>
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<td>143.21</td>
</tr>
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<tr>
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<td>143.21</td>
</tr>
<tr>
<td>4</td>
<td>2500</td>
<td>5000</td>
<td>0.8</td>
<td>18683</td>
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<td>0.8</td>
<td>18683</td>
<td>158.75</td>
</tr>
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<td>0.8</td>
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</tr>
<tr>
<td>8</td>
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<td>0.8</td>
<td>18683</td>
<td>158.75</td>
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<tr>
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<td>2500</td>
<td>4250</td>
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<tr>
<td>15</td>
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<td>0.6</td>
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<td>17712</td>
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<td>4250</td>
<td>0.6</td>
<td>17712</td>
<td>143.21</td>
</tr>
</tbody>
</table>

D, d & Cutting Cost for different Specimen.

X. RESPONSE ANALYSIS

The response which includes measurement of inlet diameter D, outlet diameter d, and cutting cost is analyzed using the design expert software. The Design expert software is used carried out the following analysis (i). ANOVA analysis, (ii). Analysis of response with that of input parameter, (iii). Obtaining final equation in terms of actual factors and (iv). Analysis of Experimental value with that of Theoretical value.

a. Analysis of Inlet Diameter, D

The Model F-value of 3.95 implies the model is significant. There is only a 4.18% chance that a “Model F-Value” this large could occur due to noise.

Values of “Prob > F” less than 0.0500 indicate model terms are significant. In this case A, B2 are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model.

The "Lack of Fit F-value" of 7.92 implies the Lack of Fit is significant. There is only a 3.70% chance that a "Lack of Fit F-value" this large could occur due to noise. Significant lack of fit is bad -- we want the model to fit.

Analysis Inlet Diameter, D vs input parameter

The Analysis of Inlet diameter D, with that of cutting speed, Power and Gas pressure is carried out using the Design Expert software. The Graph so obtain is shown below in the figure. From the graph it is noted that when the Power is increased, the diameter values are increased. So, the factors are mainly depends upon the Power value.
From the graph it is clearly understood that the theoretical value is nearer to the required value than the experimental value and hence the final equation for $D$ in terms of actual factor satisfy the requirement.

The final equation for "$D" in terms of actual factor $D$, with that of cutting speed, Power and Gas pressure is carried out using the Design Expert software. The equation so obtained is given below.

\[
\text{Inlet Diameter} = -9.83653 + 7.03000E-005 \times \text{Power} + 3.04556E-004 \times \text{Cutting Speed} - 1.22750 \times \text{Gas Pressure} + 0.00000 \times \text{Power} \times \text{Cutting Speed} - 0.00000 \times \text{Power} \times \text{Gas Pressure} - 1.03000E-004 \times \text{Cutting Speed} \times \text{Gas Pressure} - 9.02000E-009 \times \text{Power}^2 - 2.62222E-008 \times \text{Cutting Speed}^2 + 1.02500 \times \text{Gas Pressure}^2
\]

### b. Analysis of Outlet Diameter, $d$

From the analysis of outlet diameter, $d$, it is noted that when the Power is increased, the diameter values are increased. So, the factors are mainly dependent on the Power value.

The experimental value and the theoretical value is been tabulated and graph is drawn as shown below.

From the following graph it is clearly understood that the theoretical value is nearer to the required value.
than the experimental value and hence the final equation for d in terms of actual factor satisfy the requirement.

The experimental value that is measured and is compared with that of theoretical value which is been calculated. The theoretical value of Inlet diameter is calculated using the following formula,

\[
\text{Outlet Diameter} = 8.75328 + 1.92500 \times \text{Power} + 4.56556 \times \text{Cutting Speed} - 0.15167 \times \text{Gas Pressure} - 8.00000 \times \text{Power} \times \text{Cutting Speed} - 5.00000 \times \text{Power} \times \text{Gas Pressure} - 1.66667 \times \text{Cutting Speed} \times \text{Gas Pressure} - 2.60000 \times \text{Power}^2 - 3.82222 \times \text{Cutting Speed}^2 - 0.60000 \times \text{Gas Pressure}^2
\]

c. Analysis of Cutting Cost

Design Expert software. The Graph so obtain is shown below in the figure.

From the graph it is clearly understand that the theoretical value and the experimental values are nearer and there is no much variation between them.

ANOVA Analysis for Cutting Cost

The Analysis of Inlet diameter d, with that of cutting speed, Power and Gas pressure is carried out using the
XI. OPTIMIZATION

The optimized solution so obtain using the Design Expert software is shown below.

<table>
<thead>
<tr>
<th>Number</th>
<th>Power (W)</th>
<th>Cutting Speed (mm/min)</th>
<th>Gas Pressure (Mpa)</th>
<th>Inlet Diameter (mm)</th>
<th>Outlet Diameter (mm)</th>
<th>Cutting Cost</th>
<th>Desirability</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>10.981</td>
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<td>2000</td>
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<td>0.812</td>
<td>0.821</td>
</tr>
</tbody>
</table>

The optimized value is

- Power = 2000 Watts
- Cutting Speed = 5000 mm/min
- Gas Pressure = 0.72 Mpa.

Desirability Value:

XII. SEM ANALYSIS

The new specimen is prepared based on the optimized value. The cutting speed is set as 5000 mm/min, the Power is taken as 2000 Watts, and the Gas pressure is taken as 0.72 Mpa. Once the new specimen is prepared it is examine under SEM microscope and the following factor are compared with specimen that is prepared on experimental run.

i. Heat affected zone

Effect of Power and Cutting Speed on the width of HAZ:

The heat-affected zone (HAZ) is the area of base material, either a metal or a thermoplastic, which has had its microstructure and properties altered by heat intensive cutting operations. The heat from the laser cutting process and subsequent re-cooling causes this change from the interface to the termination of the sensitizing temperature in the base metal. It is found that increase in Cutting Speed and a decrease in power results in a decrease in the width of HAZ.

XIII. CONCLUSION

The optimized value is Power = 5000 Watts, the Cutting Speed = 2000 mm/min, and Gas Pressure = 0.72 Mpa is founded using the design expert software. The cost involved during the operation when the optimized condition is Rs.131.87/hr. This optimized value improves the required quality parameter like Inlet diameter, Outlet diameter and Cutting Cost. The Specimen is examine under SEM microscope and the Effect of Power and Cutting Speed on kerf width, Effect of Power and Cutting Speed on the width of HAZ and, Effect of power and Cutting Speed on surface roughness is observed and the following factor is concluded.

- Power had a major effect on the kerf width, while feed rate played a minor role. Decreasing power and increasing feed rate generally led to a decrease in HAZ. At low power levels, increasing feed rate led to a slight decrease in HAZ. At high power levels, increasing feed rate led to a slight increase in HAZ.

- Feed rate has a major effect on surface roughness and striation frequency. Increasing feed rate generally led to increasing surface roughness and striation frequency. An optimum feed rate, for which surface roughness is minimum, could be identified. Power has a small effect on surface roughness, and no effect at all on striation frequency.

References


