Experimental Studies on Hastealloy C276 while Machining with CO$_2$ Laser Cutting Machine

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Abstract. Laser cutting process is well suitable process for the cutting applications of high strength temperature resistant alloys, that are very difficult to cut with conventional process. Moreover, the lasers are widely using now-a-days for variety of cutting operations in many varieties of industries. Because of its complex nature of its operation, it is not easy to control so as to get the desired quality of cut in case of laser beam cutting process. This necessitates the importance of research to be carried out on the various processes i.e cutting, drilling, and welding etc by using the laser apparatus. The research mainly concentrated on the conduction of experiments i.e the cutting operation on Haste alloy C276 with CO$_2$ laser beam. Total 31 trails are done using the CO$_2$ laser beam apparatus. Laser power, speed, gas pressure and focal distance were the parameters chosen to vary. The outputs measured are surface roughness and the burr height which are direct measure to the quality of the cut surfaces. Two dimensional plots are plotted and analyzed the reasons for the increase or decrease of output with either the increase or decrease of input process parameters. Also, 3D plots are plotted to know the interactions.

Key words. Laser Machining, Cutting process, Hastealloy C276, Process variables, Output responses

1. Introduction to Laser Cutting

Advances in Manufacturing technology is key to the development of a country’s industrial sector. The increase in demand for better quality and faster production is one of the factors for the rapid advancement of manufacturing technology in the recent years. Laser Machining (LBM) is a growing importance in recent years due to the following advantages with the lasers i.e High speed, accuracy, less tendency to cracking, less heat affected zone etc. Moreover the availability and usage of advanced high strength temperature resistant alloys for various applications in industries, necessitates the usage of advanced machining processes. During cutting process of HSTR alloys, the major problem that the manufacturers are facing is the quality of cut achieving using the conventional cutting processes. Alternatively, the application of lasers improving the quality of cut, provided the entire process is controlled in a desired manner.

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Also, Laser cutting does not need fixtures and jigs for holding and guiding the work piece because it is a non-contact operation. Moreover, it does not need costly or disposable tools and also it does not produce mechanical forces that can damage thin work piece. 

LASER stands for light amplification by stimulated emission of radiation [1]. Laser beam cutting (LBC) is a method uses the laser beam to cut the metals based on the thermal separation process. The LBC setup generates and directs the high-power laser on to the workpiece surface to be cut. The material then either melts, burns, vaporizes away, or is blown away by a jet of gas, leaving an edge with a high-quality surface finish [2]. Laser cutting is the most widely used LBM process. Advantages of laser cutting over mechanical cutting include easier work holding and reduced contamination of work piece (since there is no cutting edge which can become contaminated by the material or contaminate the material). Precision may be better, since the laser beam doesn't wear during the process. There is also a reduced chance of warping the material that is being cut, as laser systems have a small heat-affected zone. The capability of the laser cutting mainly depends on the way how it operates i.e if the process parameters are controlled in a proper manner, the quality of cut is going to be at the acceptable level, otherwise it produces inferior cut quality which may not be suitable for industrial applications. Hence it is very crucial to operate the LBC apparatus with full knowledge. But due to the arrival of new materials, it becomes very difficult for the manufacturing engineers to set the right combination of parameters at the right levels. Hence there is a need to develop some method to find the optimal process parameters to be set inorder to achieve high speed accurate cuts. So the research is mainly concentrated on carrying out the research which enables the future engineers to have clear picture and understanding of the cutting process using the Laser beam.

Fig.1. Schematic diagram of a laser cutting system

2. Literature Survey
H. A. Eltawahni et al. [7] investigated the CO₂ laser cutting process parameters by considering the composite material. M. Zaied et al. [8] carried out the analysis between the laser power, cutting speed, gas pressure on the quality of cut. Low carbon steel is taken as the workpiece. Milos Madici et al. [9] applied Taguchi method and the surface roughness is measured at different levels of input variables. K.F.Tamrin et al. [10] performed multiple-objective optimization in precision laser cutting of different thermoplastics. Shaikh, B et al. [11] conducted experiments using the Taguchi Design of Experiments. Omer Ozgur et al. [12] carried out analysis on the rectangular profiles using the aluminum alloys. Kiran Kumar and P. Venkataramaiah [13] carried out the experimental investigation on the surface integrity of Inconel 718. The experiments are conducted for the Design matrix developed using Taguchi DOE. Dong-Gyu AHN et al. [14] carried out the experiments on the Inconel 718 sheet applying the DOE. Also studied the surface roughness variations. Ahmet Cekic et al. [15] has done experimentation on the CO₂ laser cutting. Alloys were considered as the workpieces. K. Venkatesa et al. [16] conducted experiments on LBC apparatus for difficult to cut materials. Xavierarockiaraj.S et al. [17] Investigated the effect of cutting forces, surface roughness and tool wear during Laser assisted machining on the tool steel. Yoshihiro Morimoto et al. [18] analyzed the effects of vertical and high frequency oscillations and mainly focused on the quality of cut in thick plates. Vipul K Shah et al. [19] carried out the analysis on the input process parameters for the optimization of surface roughness. As per the literature survey, in most of the experimental investigations of the LBC process researchers have considered only two or three input variables while carrying out the experiments. But this research considered four parameters and the levels are found for each of the process parameters by conducting the trial experiments. And also interaction effects among various input process parameters are not considered. To overcome these problems, this work is proposed to use Design of Experiments to reduce the number of experiments with the same accuracy. In the present work, a total of 27 experiments were carried out based on the Taguchi. with the aim of analyzing the effect of process parameters on cut geometry and cut surface quality. In this paper, after conducting the experiments, the graphs were drawn (both 2D and the 3D) using the design expert software. 2D graphs are drawn to know the exact trends between the input variables and the output responses. 3D graphs are also drawn to know the interaction effects.

3. EXPERIMENTAL WORK

The experiments were conducted on a 3 axes CNC controlled CO₂ laser cutting machine which is available in Meera Laser Solutions, Ambattur, Chennai. The maximum average power produced at laser is 100W. The most widely used lasers for sheet cutting are continuous wave (CW), CO₂ and pulsed Nd.YAG laser [20]. High quality cutting surface is obtained by proper selection of parameters and application of appropriate assisted gases. As the laser cutting of steel, using N₂ gives brighter and smoother surface finish. For research purpose, the Laser light was developed by gaseous state CO₂ laser (Fig.1) with larger power up to 3200W, frequency10000 Hz, maximum gas pressure 8.0 bar, maximum cutting speed 5000 mm/sec and prepared with stand-off distance regulating by servo motor and sensory devices. The workpiece setup is shown in Fig.2 and the process is shown in Fig.3.
The material chosen for research is Hastelloy C-276 with a thickness of 2 mm. The chemical composition of the material is given in Table 1.

Table 1. Hastelloy C276 composition in weight percentage

<table>
<thead>
<tr>
<th>Element</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni</td>
<td>57</td>
</tr>
<tr>
<td>Mo</td>
<td>15.0 - 17.0</td>
</tr>
<tr>
<td>Cr</td>
<td>14.5 – 16.5</td>
</tr>
<tr>
<td>Fe</td>
<td>4.0 – 7.0</td>
</tr>
<tr>
<td>Tn</td>
<td>3.0 – 4.5</td>
</tr>
<tr>
<td>Co</td>
<td>2.5</td>
</tr>
<tr>
<td>Mn</td>
<td>1</td>
</tr>
<tr>
<td>C</td>
<td>0.01</td>
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<tr>
<td>Vn</td>
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<td>Ph</td>
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<td>Su</td>
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<tr>
<td>Si</td>
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</table>

After going through the literature survey, it was found that Hastelloy C-276 exhibits high resistance to uniform attack, outstanding localized corrosion resistance, excellent stress corrosion cracking resistance, and ease of machining, welding and fabrication. Also, Hastelloy C-276 finds widespread applications in Chemical process, Petrochemical, Oil & Gas, Mining, Nuclear Power, Solar Power etc. Keeping in view of the importance and applications of Hastelloy, the material is chosen as the workpiece material to carry out the research on Laser beam machining.

3.1. Experimentation on HASTE ALLOY C-276
3.2. Design of Experiment

The need of process development is to increase the performance of the process related to customer expectations. The purpose of DOE is to understand how to deduce and control the variations of a process; however, things must be made concerning which variables are affecting the performance of a process.

The selected design matrix is a five-level, four-factor, central composite rotatable factorial design consisting of 31 sets of coded conditions. It comprises a full replication of 24 (=16) factorial design plus seven center points and eight star points. All cutting variables at their intermediate level (0) constitute the center points, and the combinations of each of the cutting variables at either its lowest (-2) or highest (+2) with the other three variables at their intermediate level constitute the star points. Subsequently, the 31 exploratory runs permitted the estimation of the quadratic and two-way intuitive impacts of the cutting variables on the cut edge quality.

The process parameters according to the experimental conditions are mentioned in Table 2, and the experimental design matrix is shown in Table 4.

Table 2. Experimental Conditions

<table>
<thead>
<tr>
<th>Process parameters</th>
<th>Units</th>
<th>Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser Power</td>
<td>KW</td>
<td>1.7, 1.75, 1.8, 1.85, 1.9</td>
</tr>
<tr>
<td>Cutting Speed</td>
<td>mm/sec</td>
<td>3, 3.75, 4.5, 5.25, 6</td>
</tr>
<tr>
<td>Focal Distance</td>
<td>mm</td>
<td>0.4, 0.5, 0.6, 0.7, 0.8</td>
</tr>
<tr>
<td>Gas Pressure</td>
<td>bar</td>
<td>2, 2.25, 2.5, 2.75, 3</td>
</tr>
</tbody>
</table>
where \( x_i \) is the required value of a variable \( X \). \( X \) is any value of the variable from \( X_{\text{min}} \) to \( X_{\text{max}} \). \( X_{\text{min}} \) is the lower level of the variable and \( X_{\text{max}} \) is the upper level of the variable.

After the experiments, the output responses i.e. Surface roughness was measured using Talysurf (Mitutoyo) [fig.5] and Burr height was measured using Micrometer (Mitutoyo). The controlled parameters have been the burr height and surface roughness. Surface roughness of the square grooves was measured in terms of the aggregate roughness \( R_a \), using a Talysurf instrument. Roughness was measured along the length of cut at approximate medium of thickness. The size of burr height was measured using a 2 to 25 mm micrometer.

![Talysurf equipment](image-url)
Table 4. Influence of the Process Parameters on Output Responses

<table>
<thead>
<tr>
<th>Exp No</th>
<th>Laser Power) [(KW)]</th>
<th>Cutting Speed</th>
<th>Focal Distance</th>
<th>Gas Pressure</th>
<th>Surface Roughness</th>
<th>Burr Height</th>
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<td>0.6</td>
<td>2.5</td>
<td>3.21</td>
<td>0.489</td>
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</table>

4. Influence of the Process Parameters on Output Responses

4.1. Laser power influencing on the surface roughness:

The influence of laser power on the surface roughness is as shown in fig. 6. The effect of laser power on the surface roughness of cut reduces where the thicker sheet is considered to be cut. The surface roughness values are investigated on the different laser power conditions. A very fast increment in surface roughness occurs at low, medium and high values of laser power.
4.2. Cutting speed influencing on the surface roughness:

The influence of cutting speed on the surface roughness as shown in fig. 7. The most favorable cutting parameters for a group of related steel is possible on the basis of presented indicators. The higher cutting speeds give maximum surface roughness. The good surface finish is to be obtained at optimal cutting speeds in this investigation.

Fig. 7.

4.3. Gas pressure influencing on the surface roughness:

The influence of gas pressure on the surface roughness as shown in fig. 8. The gas pressure is most significant parameter affecting the surface roughness variation. For obtaining the minimal roughness the gas pressure should be kept at low level.
4.4. Focal Distance influencing on the surface roughness:

The influence of focal distance on surface roughness as shown in Fig. 9. The surface roughness value increases if both laser power and focal distance increases. The focal distance has the most significant effect on the surface roughness.

4.5. Laser power influencing on the Burr height:

The influence of laser power on the burr height as shown in Fig. 10. During cutting, the laser power develops a very high temperature in the form of light wave. The laser power is directly proportional to the burr height because more power causes more metal removal. This large amount of metal removal gives an irregular solidification of the bottom surface. These burr heights also vary with respect to power fluctuations.
4.6. Cutting speed influencing on the Burr height:

![Graph showing the relationship between Power and burr height.]

4.7. Gas pressure influencing on the Burr height:

![Graph showing the relationship between Cutting speed and burr height.]

![Graph showing the relationship between Gas pressure and burr height.]

Design-Expert® Software
Factor Coding: Actual
Burr Height
X1 = A: Power
Actual Factors
B: Cutting Speed = 4.5
C: Focal Distance = 0.6
D: Gas Pressure = 2.5
even with some unnoticeable burrs is attached to lower surface. Increasing the gas pressure gives an increasing the burr height.

Fig. 12. The relationship between Gas Pressure and Burr Height

4.8. Focal Distance influencing on the Burr height:

Fig. 13. The relationship between Focal distance and Burr Height

Design-Expert® Software
Factor Coding: Actual
Burr Height
$X_1 = D$: Gas Pressure
Actual Factors
$A$: Power = 1.8
$B$: Cutting Speed = 4.5
$C$: Focal Distance = 0.6

Design-Expert® Software
Factor Coding: Actual
Burr Height
$X_1 = C$: Focal Distance
Actual Factors
$A$: Power = 1.8
$B$: Cutting Speed = 4.5
$D$: Gas Pressure = 2.5
5. Interaction Effects

The Fig. 14 shows the interaction effects of laser power and cutting speed on surface roughness. The laser power and cutting speed are to be taken as a constant. It can be observed that as the laser power increases from minimum to maximum, the surface roughness is found to increase and as the cutting speed increases.

Fig. 14. Interaction effect of laser power and cutting speed on surface roughness.

Design-Expert® Software
Factor Coding: Actual
Surface Roughness
4.63967
3.05
X1 = A: Power
X2 = B: Cutting Speed

Actual Factors
C: Focal Distance = 0.6
D: Gas Pressure = 2.5

Fig. 15. Interaction effects of focal distance and gas pressure on surface roughness.
The Fig. 15 shows the interaction effects of laser power and gas pressure on surface roughness. Roughness increases with increase of laser power and when gas pressure decreases from maximum to minimum.

The Fig. 16 shows the interaction effects of laser power and cutting speed on burr height. Burr height increases with increase of laser power and when cutting speed decreases from maximum to minimum.

The Fig. 17 shows the interaction effects of laser power and gas pressure on burr height. The burr height gradually decreases with the decrease laser power and increases with increasing the cutting speed.

Design-Expert® Software
Factor Coding: Actual
Burr Height
1.87967
0.2879
X1 = A: Power
X2 = B: Cutting Speed
Actual Factors
C: Focal Distance = 0.6
D: Gas Pressure = 2.5

A: Power (KW)
B: Cutting Speed (mm/sec)

C: Focal Distance (mm)
D: Gas Pressure (bar)
6. Conclusions

In the present study, Design based experiments are carried out on the Hastelloy C276 using the laser beam cutting apparatus. Further 2D plots are drawn using the Design Expert software to know the effects of the individual process parameters on the chosen responses - Surface roughness and the Burr height. Also the interaction effects were studied. Based on the above research, the following conclusions were drawn:

1. The material chosen for research is well suited for the cutting operation using the laser beam cutting equipment. Overall the quality of cut obtained is satisfactory.
2. Design of Experiments concept proved to be the useful one to reduce the number of experiments without losing the accuracy.
3. The power and surface roughness are directly proportional to each other.
4. Increasing the gas pressure gives an increasing the burr height.
5. It can be observed that as the Laser power increases from minimum to maximum, the surface roughness is found to increase and as the cutting speed increases, the burr height gradually decreases with the decrease laser power and increases with increasing the cutting speed.

Acknowledgements

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