Modeling and Optimization of Kerf Geometry during Nd:YAG Laser Cutting of Aluminum Alloy Sheet

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Abstract- Aluminum alloys are widely used sheet metals in aerospace, food processing and automotive industries for their specific applications. The unique properties of the Al-alloy make it the most used metal after the steel worldwide. To create complex geometries in sheet materials with close tolerances stipulates advanced sheet cutting processes. Due to the requirement of advance engineering materials in modern manufacturing industries, highly precise cutting process is needed to cut them. Laser beam cutting (LBC) is the most common method for precise cutting of sheet metals with stringent design requirements. But, the reflective nature of Al-alloys can pose the problems to laser light. Hence, Nd: YAG laser is the most suitable laser for cutting of sheet metals in general and for reflective sheet metals in particular due to its shorter wavelength. This paper presents the modeling and optimization of multiple quality characteristics of kerf geometry during pulsed Nd: YAG laser cutting of thin Al-alloy thin sheet along the straight cut profile. Top kerf width (TKW) and Top kerf deviation (TKD) are considered as quality characteristics. These laser cut quality characteristics are the function of four input process parameters namely: Lamp current, pulse width, pulse frequency and cutting speed. First, Box-Behnken design (BBD) based experiments have been conducted to obtain experimental results of cut quality characteristics. The experimental results have been used to develop response surface models for TKW and BKW. Finally, these models have been optimized using the response surface optimizer module of MINITAB software.

Keywords: Aluminum alloy; laser cutting; Box-Behnken design; Response surface methodology

I. INTRODUCTION

In recent years aluminum alloys have attracted attention of many researchers engineer and designer as promise structural materials for automotive industry or aerospace application [1]. Al-alloy is widely used in numerous engineering application including transport and construction due to superior mechanical properties. Aluminum can be easily machined through different removal process, but the most common and fast process for cutting complex geometries is laser cutting [2]. Aluminum alloys have become the primary structural material for commercial and military air-craft for almost 80 years due to their unique mechanical behavior, easiness with design and manufacturing process [3]. Al-alloys have the exceptional properties including tensile strength, hardness, and higher corrosion resistance. Due to these properties makes it an appropriate applicant material for marine structural applications [4].

Aluminum alloy 6061T6 is one of the most extensively used to 6000 series of aluminum alloy. Aluminum alloy (Al-6061T6) is a versatile to high strength capabilities. Al-6061 alloy highly interest for advanced industries like aerospace, automobile, electrical, chemical, food processing and sport equipment [5].These alloys have medium to high strength, good toughness and good surface finish. Especially 6XXX aluminum alloys have been studied extensively because of their benefits such as medium strength, formability, weldability, corrosion resistance and low cost, Comparing to other aluminum alloys, Al-6061 alloy, a typical Al-Mg-Si alloy. Since the 6061 alloy is age hardening alloy. It can be strengthened appreciably by heat treatment. The 6061 alloy has been also currently attracted interests of many researchers.
due to its based metal matrix composite shows high strain rate super plasticity [6].

The most common and fast technique of profile cutting in sheet materials is the Laser beam cutting (LBC) process. LBC is the thermal energy based non contact type process. In LBC process, laser light is utilized to melt the workpiece material. The molten material is further removed by assist gas such as (oxygen gas, nitrogen gas, argon gas) at high pressure [7-8]. The schematic diagram of LBC system has been shown in Fig. 1.

![Fig. 1 Schematic diagram of LBC system](image)

Due to converging–diverging nature of laser beam geometry the deviation may be exists in the laser cut along the length in the sheet material during LBC [9]. Many researchers have been studied the laser cut quality characteristics such as Kerf width (TKW, BKW), Kerf taper (KT) and Kerf deviation (KD) to analyze the effect of different input process parameter on these cut qualities.

Ghany and Newishy [10] Found that the variation in kerf width with the increment of cutting speed, laser power, pulse frequency and type of gas pressure during Nd: YAG laser cutting of austenitic stainless steel sheet of 1.2 mm thickness. They used the laser in pulsed as well as continuous wave mode. Continuous wave mode of laser is employed when the maximum speed upto 8mm/min is achieved. They conclude that the kerf width is decreased by increasing the pulse frequency and cutting speed while it is increasing the laser power, focus position and gas pressure. Thawari et al. [11] Studied the effect of spot overlap in pulses Nd: YAG laser cutting of nickel based superalloy thin sheet (Hastello-Y-X) having thickness 1 mm. They observed that the kerf width increase at top and bottom side while surface roughness decrease with the increment of spot overlap. They also found that the longest pulse duration (2 ms) considered in the study provides results in higher kerf taper.

Karatas et al. [12] investigated the kerf width during CO2 laser cutting of hot rolled ad pickled steel sheet of 1.5 mm thickness. They found the kerf width reduces to its minimum level when the focus setting is maintained at the Workpiece sheet surface. However the laser beam is focused inside the sheet of 3.5 mm thickness during the process to obtain the lower kerf width.

Leone at al. [5] investigated the kerf geometry during 150 MW multimode pulsed Nd: YAG laser cutting of aluminum alloy (Al-6061T6) sheets of 1mm thickness. They found the kerf width reduces to its minimum level when the focus setting is maintained at the Workpiece sheet surface. However the laser beam is focused inside the sheet of 3.5 mm thickness during the process to obtain the lower kerf width.

Elsen and Ramesh [13] applied Box-Behnken (BBD) with response surface methodology (RSM) to optimize the quality characteristics. They coupled RSM and GRA to optimize the quality characteristics i.e. pressure and temperature.

Sharma and Yadava [14] applied Taguchi methodology (TM) with response surface methodology (RSM) to optimize the average kerf taper and average surface roughness during pulsed Nd: YAG laser cutting of thin Al-alloy sheet for straight profile. They coupled TMGRA with entropy measurement to optimize the quality characteristics simultaneously.

In this paper two quality characteristics such as TKW and TKD have been optimized simultaneously during pulsed Nd: YAG Laser beam cutting (LBC) of aluminum alloy sheet using RSM with multi optimizer. Input process parameters taken are Lamp current (LC), Pulse width (PW), Pulse frequency (PF), Cutting speed (CS). The sheet material is aluminum based alloy (Al-6061T6) having thickness 1.3 mm. First Box-Beihken technique in Response surface methodology (RSM) based 27 experimental runs have been performed for straight cut geometry. RSM multi-optimizer results have been found using the MINITAB software.
II. EXPERIMENTAL SETUP

The experiments of Laser beam cutting were conducted using a 250W pulsed Nd: YAG laser beam system (CNCPTC-300 model) supplied by RRCAT (Raja Rammna Center for Advance Technology), Indore (India). Compressed gas was used as the assist gas. The assist gas passes through a conical nozzle of diameter 1.5 mm co-axially with the laser beam. The laser beam was focused using a lens of focal length 35mm. The stand-off distance (SOD) was set at 2 mm. The Workpiece was an aluminum based alloy (Al-6061T6) thin sheet having thickness 1.3 mm supplied by Krishnan engineering works ghatkopar Mumbai. The chemical composition of Al-6061T6 is tabulated in Table I. Nozzle diameter, focal length of lens; nozzle stand-off distance, Workpiece material thickness and gas pressure (10 kg/cm²) were kept constant throughout the experiment.

Table I Chemical composition of Al-6061T6

<table>
<thead>
<tr>
<th>Element</th>
<th>Mg</th>
<th>Si</th>
<th>Cr</th>
<th>Mn</th>
<th>Fe</th>
<th>Cu</th>
<th>Zn</th>
<th>Ti</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>%</td>
<td>1.2</td>
<td>0.8</td>
<td>0.3</td>
<td>0.1</td>
<td>0.2</td>
<td>0.2</td>
<td>0.1</td>
<td>9</td>
<td>6</td>
</tr>
</tbody>
</table>

Four input process parameters were selected and their effect on the quality characteristics was studied for straight profile cutting using laser beam cutting process. The chosen input process parameters for the experimental procedure are; Lamp current (LC), Pulse width (PW), Pulse Frequency (PF), Cutting speed (CS). The considered input process parameters and their levels are tabulated in Table II. The selection of the parameters range was based on exhaustive pilot experimentation for through cutting of Al-6061T6 sheet along a straight cut.

Table II Input parameters and their levels

<table>
<thead>
<tr>
<th>Input parameter</th>
<th>Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>PW(ms)</td>
<td>4, 5, 6</td>
</tr>
<tr>
<td>PF(Hz)</td>
<td>4, 7, 10</td>
</tr>
<tr>
<td>CS(mm/min)</td>
<td>20, 40, 60</td>
</tr>
</tbody>
</table>

III. MODELLING AND OPTIMIZATION OF PROCESS PARAMETERS USING RSM

Response Surface Methodology (RSM)

RSM is a collection of mathematical and statistical technique which is useful for the modeling and analysis of problems [19]. RSM requires the following procedure like selection of parameters with significant effects, selection of proper experimental design, fitting of adequate mathematical model, checking the accuracy of the fitted model and evaluation of its prediction behavior with respect to the experimental data [20]. Fitting of poly-nominal equation with experimental data, RSM is applied to predict the parametric relationship from the responses obtained in a series of experiment. A polynomial model of the second order type has been proposed to represent the functional relationship between the independent variables (cutting parameters) and the response surface to optimize the output variables (responses) in RSM. In the present work, the independent variables are LC, PW, PF and CS; responses are BKD and KT. A response surface model generally expressed as

\[ Y = b_0 + \sum b_i x_i + \sum b_{ij} x_i^2 + \sum b_{ij} x_i x_j \]  

Where \( b_0, b_i, b_{ij} \) are the coefficient and \( x_i, x_{ij}, x_i x_j \) are the input variables that influence the responses these are determined using regression analysis. The response surface analysis is then done in terms of the fitted surface. The lack of
fit and degree of freedom of the model have been tested by analysis of variance (ANOVA) using the software MINITAB by using coded units.

IV. RESULT AND DISCUSSION
The experimental run has been done using BBD considering four cutting parameters. This experimental runs have been performed to get the values of TKW and TKD and further used for mathematical relationship between the responses and input process parameters of pulsed ND: YAG laser cutting. The developed model for TKW and TKD for straight cut based on RSM approach is given below.

Developed response surface model for TKW and TKD for straight cut

\[
\begin{align*}
\gamma_{TKW} &= 0.587467 \times 0.026842 \times LC + 0.020892 \times PW + 0.006483 \times PF - 0.009676 \times CS
- 0.000012 \times LC^2 - 0.018813 \times PW^2 - 0.004000 \times PF^2 + 0.012575 \times CS^2
+ 0.011300 \times LC \times PW - 0.025325 \times LC \times PF - 0.006600 \times LC \times CS
- 0.018875 \times PW \times PF - 0.019600 \times PW \times CS + 0.007800 \times PF \times CS \\
\gamma_{TKD} &= 0.100000 - 0.004500 \times LC - 0.002667 \times PW + 0.004917 \times PF + 0.000250 \times CS
+ 0.001667 \times LC^2 - 0.000083 \times PW^2 + 0.009292 \times PF^2 + 0.006792 \times CS^2
+ 0.009000 \times LC \times PW + 0.003500 \times LC \times PF + 0.015000 \times LC \times CS
- 0.018750 \times PW \times PF + 0.014750 \times PW \times CS - 0.022000 \times PF \times CS
\end{align*}
\]

Analysis of variance (ANOVA) Consequent F- value and P-value tests have been carried out to test the adequacy of developed models for TKW and TKD for straight cut is tabulated in Table III. To test whether the data are fitted in model or not, in the Table III calculated S value of the regression analysis for TKW and TKD are obtained as 0.02224 and 0.01042 respectively, which are smaller and R-Sq value for these responses, are 81.6% and 83.9% respectively. These values are reasonably high therefore models fit the data. Further P-value of the source of regression and linear have been found to be lower than the 0.05 for TKW. Similarly P-value of the interaction is lower than 0.05 for TKD. Computed F-value of the lack-of-fit for TKW and TKD are 1.07 and 0.68 respectively. Developed regression model for responses are significant for straight cut. Therefore, the developed second order regression models for the TKW and TKD are satisfactory at 95% confidence level.

Multi-objective optimization analysis for Nd-YAG laser cutting of thin aluminum alloy sheet has been carried using MINITAB-14 software and optimization results for TKW and TKD are shown in Fig.2. This figure represents the Top kerf width and Top kerf deviation have been optimized simultaneously in one setting. Each column of the graph corresponds to an input process parameter. Each row of the graph corresponds to a response variable. Every one cell of the graph represent how one of the response variables changes as a function of one of the input process parameters, while all others parameters remain fixed. At the left of the every row, target for the responses (minimum).predicted response y, composite desirability D and individual desirability dare also shown in graph. The predicted optimum values of TKW and TKD during multi-objective optimization are 0.5923mm and 0.1099mm,respectively at lamp current (LC)=240.0 amp, pulse width (PW)=4.0ms, Pulse frequency (PF) and cutting speed (CS)= 20mm/min. The value of composite desirability ,D is 0.74321 and individual desirability ,d for TKW and TKD are 0.58735 and 0.83603. Iside the graph vertical lines represents the input parameter settings and Horizontal dotted lines represent the current response values.

Fig. 2 Optimization results for minimum TKW and TKD
V. CONCLUSIONS

The modeling and multi-objective optimization has been applied for the pulse Nd: YAG laser cutting of aluminum alloy(Al-6061 T6) thin sheet along the straight cut by using the RSM. The following conclusions are found out the present study.

(1) The developed second order response surface model for TKW and TKD for straight cut has been found satisfactory. It is also find from the results of regression effects of input process parameters are significant for developed RSM model for both quality characteristics.

(2) The preferred operating values for TKW and TKD obtained from multi-objective optimization using RSM optimizer are 0.5923 and 0.1099.

(3) From the RSM multi-optimizer optimal values of the input process parameters have been found such as: lamp current is 240amp, pulse width is 4ms, pulse frequency is 4.22 Hz and cutting speed is 20mm/min.

References