

MODELLING OF PERPENDICULARITY OF CUT IN HIGH POWER CO₂ LASER CUTTING OF 5 MM THICK ALUMINIUM ALLOY

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ABSTRACT: Beside productivity and costs, the cut quality is the third most important criteria in laser cutting. An important quality indicator of laser cutting is perpendicularity of cut. In this paper, the effects of the laser power, cutting speed and assist gas pressure on perpendicularity of cut in CO₂ laser cutting of 5 mm thick aluminium alloy was studied. In order to develop mathematical relationship between laser cutting parameters and perpendicularity of cut, full factorial design experimentation, by varying each parameter at three levels, was conducted. Based on the obtained experimental data, regression based mathematical model was developed upon which the effects of considered laser cutting parameters on perpendicularity of cut were analysed.

KEYWORDS: CO₂ laser cutting, aluminium alloy, perpendicularity of cut, regression analysis

1. INTRODUCTION

After steel, aluminium and its alloys are second most used materials in industry [1]. Such wide application in automotive, aerospace, transport, marine, food and other industries is due to their favourable ratio of tensile strength and density, corrosion resistance, suitability for surface treatments and other unique properties.

The presence of magnesium as major alloying element in the 5xxx series (from 0.8 to up 6 wt %) leads to good formability and weldability and high corrosion resistance. Aluminium alloy 5083 has fair machinability, very good weldability and cold formability and excellent corrosion resistance especially to seawater and industrial atmosphere. Typical applications of aluminium alloy 5083 include welded structures, pressure vessels, marine applications, architectural use, appliances etc. [2].

In industry, for complex contour cutting of aluminium and its alloys nonconventional machining technologies are predominantly used, particularly laser cutting and abrasive water jet cutting [1, 3]. In the case of laser cutting, Nd:YAG lasers are commonly used because wavelength of 1.06 μm is better absorbed by most of the reflective materials including aluminium and its alloys. On the other hand, although CO₂ lasers can achieve higher powers at a lower cost [1], the use of CO₂ lasers for cutting of aluminium and its alloys is not common [4], however, from the industrial point of view, such a possibility would be very welcome [3].

The use of laser cutting technology for cutting of aluminium and its alloys was investigated by a

number of researchers and from different aspects. The pioneered work on the use of use of CO₂ lasers for cutting pure aluminium was made by Olsen [5]. Stournaras et al. [1] investigated the effect of laser power, cutting speed, pulsing frequency and assist gas pressure on cut quality characteristics such as kerf width, surface roughness and the size of the heat affected zone (HAZ), while cutting 2 mm thick AA5083 aluminium alloy sheet. Madić et al. [3] developed mathematical relationship between process parameters (laser power, cutting speed and assist gas pressure) and kerf width obtained in CO₂ laser cutting of aluminium alloy (AlMg3) sheet with thickness of 3 mm. With the use of discrete Monte Carlo method, the optimal values of laser power, cutting speed and assist gas pressure for kerf width minimization were determined. Riveiro et al. [6] examined the effects of cutting parameters in cutting of an aluminium–copper alloy. Regarding the surface roughness, the most influencing parameters were those related to the assist gas such as pressure, nozzle diameter and stand-off distance. Riveiro et al. [7] investigated the influence of different assist gases (argon, nitrogen, oxygen and air) on the edge quality and its surface chemistry during laser cutting of a typical 2024-T3 commercial aluminium-copper alloy, with a thickness of 3 mm. Araujo et al. [8] performed microstructural examination of the HAZ while cutting 1.6 mm thick aluminium 2024 sheet. Leone et al. [9] investigated laser cutting of 6061 T6 aluminium alloy through the employment of a 150 W multimode pulsed Nd:YAG laser. Dubey and Yadava [10] applied Taguchi quality loss function for simultaneous optimization of kerf deviation and kerf width in pulsed Nd:YAG laser beam cutting of

aluminium alloy sheet. Assist gas pressure, pulse frequency, pulse width and cutting speed were considered as input parameters.

The scope of this paper is to develop mathematical model for the prediction of perpendicularity of cut, which is considered as one of the most important quality characteristics, in CO₂ laser cutting of aluminium alloy (AlMg3) sheet with thickness of 5 mm. To this aim, full factorial experimental design was adopted while varying laser power, cutting speed and assist gas pressure at three levels. The obtained experimental data were used for the development of cut perpendicularity mathematical model by using second order polynomial. In addition to modelling, the developed mathematical model was optimized and laser cutting parameter values for minimization of perpendicularity of cut were determined using exhaustive iterative search algorithm.

2. EXPERIMENTAL DETAILS

Aluminium alloy (AlMg3) in sheet form of 5 mm thickness was used as workpiece material. Laser cutting experimental trials were performed by means of Prima Industry laser cutting machine delivering a maximum output power of 4 kW at a wavelength of 10.6 μm, operating in continuous wave mode. A focusing lens with focal length of 127 mm was used to perform the cut with a Gaussian distribution beam mode (TEM₀₀). Nitrogen as assist gas with purity of 99.95 % was supplied coaxially with the laser beam. The nozzle used has a conical shape with nozzle orifice diameter of 2 mm. The nozzle-workpiece stand-off distance was controlled at 1 mm. Laser beam was focused as the bottom of the workpiece material (-5 mm).

Rectangular specimens with dimensions 20 mm x 40 mm were cut in every experimental trial and the cut quality was evaluated in terms of perpendicularity of the cut (*u*). Perpendicularity is defined as the distance between two parallel straight lines, which limit the upper and lower boundaries of the cut surface profile at the theoretically correct angle of 90°. For achieving high cut quality with close dimensional tolerances, it is important to obtain accurate perpendicularity of cut edge, especially when using sheet thickness over several millimetres [11]. The perpendicularity of the cut edge was measured in accordance to ISO 9013 (2002) standard [12] according to which the quality of the cut is classified into three classes. For 5 mm thick sheet, the perpendicularity tolerances are as follows: class 1 ($u \leq 0.0625$ mm), class 2 ($0.0625 \text{ mm} \leq u \leq 0.175$ mm) and class 3 ($0.175 \text{ mm} \leq u \leq 0.375$ mm).

The laser cutting experiment was planned using full factorial design with three input parameters which were varied at three levels. This design has all possible combinations of all levels and all input parameters, thus 27 experimental trials were performed.

The main laser cutting parameters such as the laser power (*P*), cutting speed (*v*) and assist gas pressure (*p*) were considered as variable input parameters. Levels of variation of these parameters were selected by considering manufacturer's recommendation for parameter settings and pilot one parameter at time experimentation. The experimental matrix with experimentally measured perpendicularity of the cut is given in Table 1.

3. MATHEMATICAL MODEL FOR PERPENDICULARITY OF CUT

Multiple regression analysis is often employed for modeling a process, i.e. for deriving mathematical equations that relate input and the output parameters (process functions) based on some experimental data. To this aim, different regression functions such as linear, curvilinear, logarithmic or other nonlinear are used.

Based on the experimental results from the full factorial design (Table 1) and the use of method of least squares, the second-order regression equation in terms of laser cutting parameters for the prediction of perpendicularity of cut was obtained as follows:

$$u = 1.867 - 0.793 \cdot P - 0.028 \cdot p - 0.062 \cdot v + 0.089 \cdot P^2 + 0.0001 \cdot p^2 + 0.065 \cdot v^2 + 0.012 \cdot P \cdot p - 0.012 \cdot P \cdot v - 0.009 \cdot p \cdot v \quad (1)$$

With the average percentage error of about 5.6 % between experimentally measured perpendicularity of cut values and mathematical model predictions, it can be concluded that developed model is adequate.

4. RESULTS AND DISCUSSION

The developed mathematical model can be used to predict perpendicularity of cut within the covered experimental hyperspace. The main effects of the laser cutting parameters on the perpendicularity of cut are given in Figure 1. These graphs are obtained by changing one parameter at a time, while keeping the other parameters constant at centre level.

From Figure 1, it can be seen that the increase in the laser cutting parameter values results in an increase in perpendicularity of cut values, however, the effect of the laser power is dominant, followed by the cutting speed and assist gas pressure. Higher laser power levels result in the higher heat input during cutting operation so as more material is being melted which

results in larger kerf widths on top and bottom of the workpiece material.

Table 1. Laser cutting experimental design and results

| Experimental trial | Laser power, P (kW) | Assist gas pressure, p (bar) | Cutting speed, v (m/min) | Perpendicularity of cut, u (mm) |
|--------------------|---------------------|------------------------------|--------------------------|---------------------------------|
| 1 | 3.2 | 10 | 1.6 | 0.232 |
| 2 | 3.2 | 10 | 1.8 | 0.215 |
| 3 | 3.2 | 10 | 2 | 0.241 |
| 4 | 3.2 | 12.5 | 1.6 | 0.206 |
| 5 | 3.2 | 12.5 | 1.8 | 0.209 |
| 6 | 3.2 | 12.5 | 2 | 0.203 |
| 7 | 3.2 | 15 | 1.6 | 0.195 |
| 8 | 3.2 | 15 | 1.8 | 0.184 |
| 9 | 3.2 | 15 | 2 | 0.216 |
| 10 | 3.6 | 10 | 1.6 | 0.186 |
| 11 | 3.6 | 10 | 1.8 | 0.180 |
| 12 | 3.6 | 10 | 2 | 0.204 |
| 13 | 3.6 | 12.5 | 1.6 | 0.189 |
| 14 | 3.6 | 12.5 | 1.8 | 0.184 |
| 15 | 3.6 | 12.5 | 2 | 0.199 |
| 16 | 3.6 | 15 | 1.6 | 0.197 |
| 17 | 3.6 | 15 | 1.8 | 0.204 |
| 18 | 3.6 | 15 | 2 | 0.200 |
| 19 | 4 | 10 | 1.6 | 0.180 |
| 20 | 4 | 10 | 1.8 | 0.188 |
| 21 | 4 | 10 | 2 | 0.195 |
| 22 | 4 | 12.5 | 1.6 | 0.192 |
| 23 | 4 | 12.5 | 1.8 | 0.184 |
| 24 | 4 | 12.5 | 2 | 0.188 |
| 25 | 4 | 15 | 1.6 | 0.205 |
| 26 | 4 | 15 | 1.8 | 0.195 |
| 27 | 4 | 15 | 2 | 0.193 |

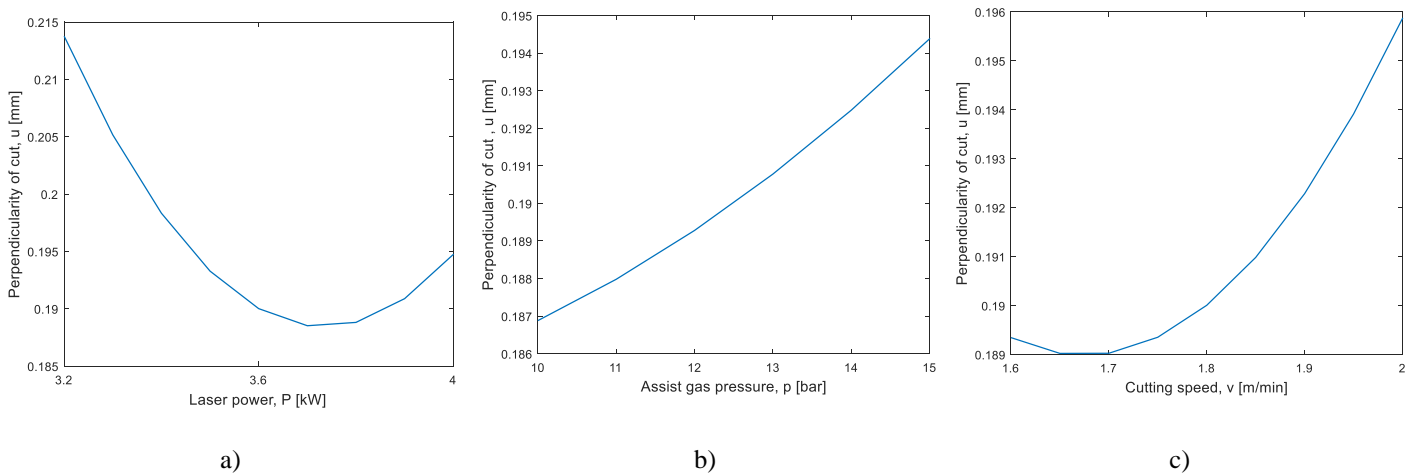
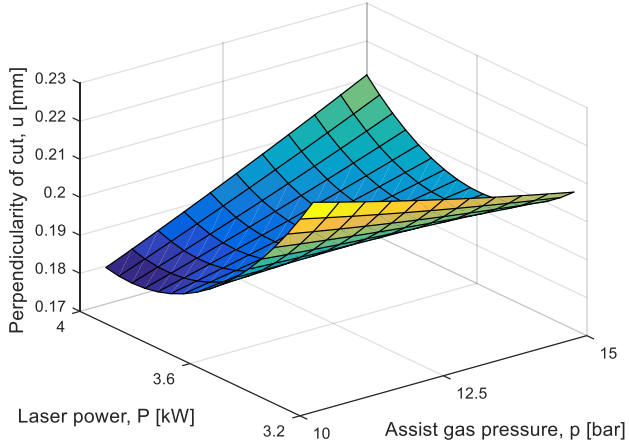
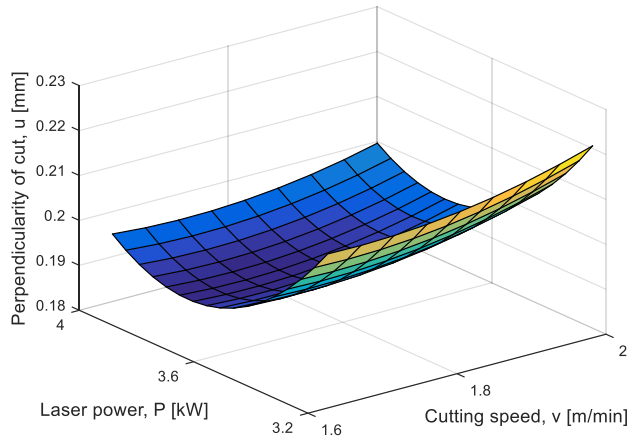


Figure 1. Effects of laser cutting parameters on perpendicularity of cut

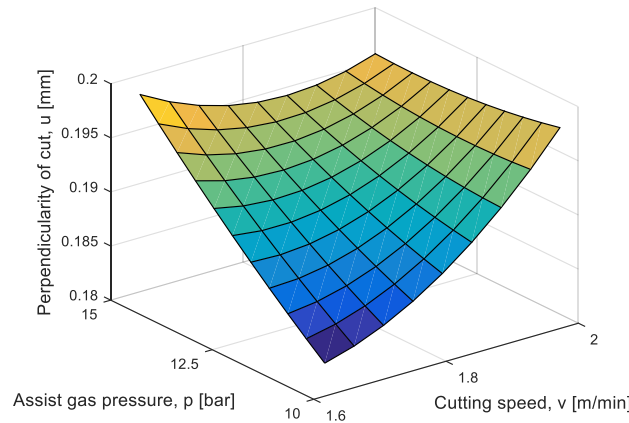
For the purpose of investigation of interaction effects of laser cutting parameters on perpendicularity of cut, three 3-D surface plots were generated so as to cover all possible interaction effects. To draw interaction plots, two parameters of interest were varied from its low level to its high level, while other third parameter was held constant at their central level (Figure 2).



a)



b)



c)

Figure 2. Effects of laser cutting parameter interactions on perpendicularity of cut

As could be observed from Figure 2, a and b, for the given assist gas pressure or cutting speed, there exists an optimum value of laser power where

perpendicularity of cut is minimal. Generally, an increase in the assist gas pressure increases perpendicularity of cut, whereas the influence of the cutting speed is less pronounced. However, at low power level, high assist gas pressure decreases perpendicularity of cut (Figure 2, a). In the cutting speed and the assist gas pressure interaction plot (Figure 2, c), it can be seen that increase in cutting speed and assist gas pressure increases perpendicularity of cut, whereas these effects are less pronounced at higher levels of cutting speed and assist gas pressure.

As it could be seen from Figure 2, variation of laser cutting parameter values produces different perpendicularity of cut values, however, in most cases, only quality class 3 is obtained. In order to investigate whether there exist a set of the laser cutting parameters values which produces lower values of perpendicularity of cut, one needs to formulate optimization problem in the covered three-dimensional laser cutting parameter hyperspace. Mathematically, the optimization problem was stated as follows:

$$\begin{aligned}
 & \text{Determine : } P, v, p \\
 & \text{to minimize : } u = 1.867 - 0.793 \cdot P - 0.028 \cdot p \\
 & \quad - 0.062 \cdot v + 0.089 \cdot P^2 + 0.0001 \cdot p^2 \\
 & \quad + 0.065 \cdot v^2 + 0.012 \cdot P \cdot p \\
 & \quad - 0.012 \cdot P \cdot v - 0.009 \cdot p \cdot v \\
 & \text{Subject to : } 3.2 \leq P \leq 4 \text{ [kW]} \\
 & \quad 10 \leq p \leq 15 \text{ [bar]} \\
 & \quad 1.6 \leq v \leq 2 \text{ [m/min]}
 \end{aligned} \tag{2}$$

The optimization problem in equation (2) was solved with exhaustive iterative search algorithm using the developed software solution “BRUTOMIZER” which supports the application of exhaustive iterative search algorithm, continual and discrete Monte Carlo method for solving optimization problems with and without constraints [13]. The iterative search algorithm was selected as it represents a parameter free approach that only requires performing a large number of simulations that are, however, executed very fast. Moreover, one can take into account techno-technological possibilities of laser cutting machine in terms of setting particular values for laser power, cutting speed and assist gas pressure.

As a result of the application of exhaustive iterative search algorithm, the minimal value of perpendicularity of cut of $u = 0.174$ mm was obtained (class 2). This solution corresponds to the following combination of the laser cutting parameter values: P

= 3.9 kW, $p = 10$ bar, $v = 1.6$ m/min (Figure 3). These values can be easily set for performing a given laser cutting operation.

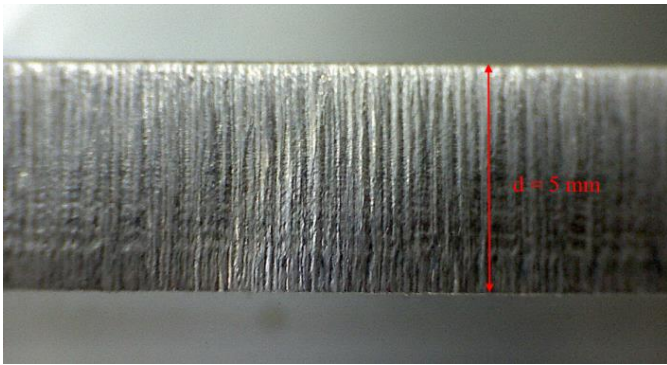


Figure 3. Laser cut surface at $P = 3.9$ kW, $p = 10$ bar, $v = 1.6$ m/min

As could be seen from Figure 3, under these laser cutting conditions, clean, fine cut surface in the cut surface with regularly spaced striations and dross-free edge was obtained.

5. CONCLUSIONS

The CO₂ laser cutting of aluminium alloy sheet with thickness of 5 mm was performed in order to investigate the effect of laser power, assist gas pressure and cutting speed on perpendicularity of cut. Laser cutting experimentation was based on the use of full factorial design. The obtained experimental results were used for the development of perpendicularity of cut prediction model, in terms of second order polynomial. Within the covered experimental hyperspace and obtained results, one can conclude that laser power is the most significant parameter affecting the perpendicularity of cut, followed by assist gas pressure and cutting speed. It has been observed that perpendicularity of cut is inversely proportional to considered laser cutting parameters, however, in some cases, the effect of a given laser cutting parameter on perpendicularity of cut is variable and must be considered through the interaction with other parameters. As a result of optimization, it was found that focusing the laser beam on the bottom surface of the sheet, using assist gas pressure of 10 bar at combination of laser power of 3.9 kW and cutting speed of 3.6 m/min, produced a minimal perpendicularity of cut and fine cut surface.

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