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MODELING AND OPTIMIZATION OF KERF WIDTH OBTAINED IN CO_2 LASER CUTTING OF ALUMINUM ALLOY USING DISCRETE MONTE CARLO METHOD

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Abstract: *In this paper, mathematical model for the establishing relationship between laser cutting parameters such as laser power, cutting speed and assist gas pressure, and kerf width obtained in CO_2 laser cutting of aluminum alloy ($AlMg_3$) was developed. To this aim, second order polynomial model was developed by using experimental data obtained in laser cutting experimentation planned as per standard full factorial experimental design. Statistically assessed as adequate, developed model was then used to investigate the effect of the laser cutting parameters on the kerf width angle by generating 3D plots. In addition to modeling, by applying discrete Monte Carlo method laser cutting parameter values that produce the minimal kerf width were identified.*
Key words: *CO2 laser cutting, aluminum-magnesium alloy, kerf width, discrete Monte Carlo method*

Modeliranje i optimizacija širine reza kod CO_2 laserskog sečenja legure aluminijuma primenom diskretne Monte Carlo metode. *U ovom radu je kreiran matematički model za uspostavljanje relacija između parametara laserskog sečenja kao što su snaga lasera, brzina sečenja i pritisiak pomoćnog gasa, i širine reza kod CO_2 laserskog sečenja legure aluminijuma ($AlMg_3$). U tom cilju koristeći eksperimentalne podatke, dobijene realizacijom punog faktornog eksperimenta, kreiran je polinomski model drugog reda. Nakon što je statistički ocenjen kao adekvatan, kreirani model je korišćen za istraživanje uticaja parametara laserskog sečenja na širinu reza kreiranjem 3D grafika. Pored modeliranja, primenom diskretne Monte Carlo metode određene su vrednosti parametara laserskog sečenja kojima se postiže minimalna širina reza.*
Ključne reči: *CO_2 lasersko sečenje, legura aluminijum-magnezijum, širina reza, diskretni Monte Carlo metod*

1. INTRODUCTION

Aluminum and its alloys are among the most versatile engineering materials in many industries such as the automotive, construction, and aerospace industry because of their unique properties [1]. Pure aluminum is soft and ductile, and it is often alloyed with small amounts of copper, magnesium, manganese, silicon, zinc or lithium to improve its techno-technological characteristics.

In industry for cutting of aluminum and its alloys nonconventional machining technologies are predominantly used, particularly laser cutting and abrasive waterjet cutting. CO_2 laser cutting of aluminum and its alloys is considered difficult because of high reflectivity and thermal conductivity of aluminum and its alloys. Therefore, it is a common practice to use Nd:YAG lasers for cutting aluminum alloys since higher absorptivity of the Nd:YAG laser enables its processing with relatively less laser power. On the other hand, the use of CO_2 lasers for cutting of aluminum alloys is not usual, however, from the industrial point of view, such a possibility would be very welcome [1].

To this aim, a number of research investigations were carried out each covering a specific aspect of laser cutting of aluminium and its alloys by using laser cutting technology. As already mentioned a number of of previous studies investigated laser cutting of aluminium and its alloys by using Nd:YAG lasers [2-4]. These and many other researches were focused on different aspect of laser cutting such as analysis of the effects of process parameters on kerf width, kerf deviation, kerf taper, dross formation, surface roughness etc. Modeling and single and multi-objective optimization problems were also solved by applying different methods such as Taguchi's robust design methodology, grey relational analysis and regression analysis. Regarding the use of CO_2 lasers for cutting of aluminum and its alloys the same modeling and optimization methods were used while investigating the effect of process parameters on kerf geometry, HAZ, surface roughness, dross formation, surface chemistry and microstructural examination [1, 5-7].

The scope of this paper is development of mathematical relationship between process parameters (laser power, cutting speed, assist gas pressure) and kerf width obtained in CO_2 laser cutting of aluminum alloy ($AlMg_3$). To this aim, full factorial experimental design was adopted for the purpose of experimentation and obtained data were used for the development of kerf width mathematical model by using second order polynomial. In addition to modeling, the kerf width mathematical model was optimized, i.e. an attempt has been made to determine process parameter values such that kerf width is minimized. To this aim, discrete Monte Carlo method was applied. To the authors' knowledge, little work has been reported in the literature on optimization using discrete Monte Carlo method, although it has many benefits such as high probability of success, parameter free optimization approach and fast computation.

2. EXPERIMENTAL DETAILS AND RESULTS

For conducting the experiment trials, CO_2 laser cutting machine (Prima Industry) with a maximal power of 4 kW was employed. Straight cuts performed with a Gaussian distribution beam mode (TEM_{00}) in continuous wave mode on 3 mm thick $AlMg_3$ sheet sheet. The laser beam was focused on the bottom surface of the sheet using a focusing lens with a focal length of 5 in (127 mm). The conical shape nozzle with 2 mm diameter was used. The nozzle–workpiece distance was set at 0.8 mm.

For the purpose of experimentation, the full factorial design was used in which the experiment trials were performed as per standard 3^3 full factorial design. Based on the pre-analysis and pilot experimentation, three laser cutting parameters were selected, i.e. laser power (P), assist gas pressure (p) and cutting speed (v). Since it was assumed that there exist a non-linear relationship between laser cutting parameters and kerf width, P, p and v were were varied at three levels: P = 3, 3.5, 4 kW; p = 6, 8, 10 bar; v = 3, 3.25, 3.5 m/min. Therefore, 27 experimental trials in total were performed (Table 1).

Rectangular specimens with dimensions 20 mm × 40 mm were cut in every experimental trial (Figure 1). Kerf width (w) was measured using optical coordinate measuring device Mitutoyo (type: QSL-200Z) with resolution of the length measuring system of 0.5 µm. The kerf width of each specimen was measured by analyzing pictures of the top (laser beam entry) and bottom surface (laser beam exit) of the specimens using Q-spark image processing software. The kerf width was measured at 3 equally distanced positions along the picture of the kerf.

Fig. 1. Plate with specimens obtained after laser cutting,

Kerf width is an important feature of the laser cutting process that provides the advantage of this technology compared to other methods of contour cutting. By focusing the laser beam and by flow stream of assist gas material is removed from the cutting zone and the kerf occurs with a certain width. Kerf width increases with the increase of material thickness, and depends on the size of the spot, laser power, cutting speed, the characteristics of the material, the wavelength, method of cutting, etc. When cutting with oxygen kerf width is largely affected by assist gas pressure. The dynamic nature of the exothermic reaction produces an irregular, non-uniform kerf width as well as periodic striations on the surface of the cut. When cutting with nitrogen a significantly better and more regular cut is obtained. Cutting width at the bottom "output" side of the sheet is usually smaller, and is somewhat larger than the diameter of a focused laser beam at optimum cutting conditions. In general, when using laser cutting technology the goal is to obtain the smallest possible kerf width because this minimizes the amount of removed material.

Trial	P (kW)	p (bar)	v (m/min)	Kerf width (mm)
1	3	6	3	0.41
2	3	6	3.25	0.40
3	3	6	3.5	0.40
4	3	8	3	0.47
5	3	8	3.25	0.39
6	3	8	3.5	0.42
7	3	10	3	0.43
8	3	10	3.25	0.41
9	3.5	10	3.5	0.47
10	3.5	6	3	0.41
11	3.5	6	3.25	0.44
12	3.5	6	3.5	0.48
13	3.5	8	3	0.52
14	3.5	8	3.25	0.48
15	3.5	8	3.5	0.50
16	3.5	10	3	0.54
17	3.5	10	3.25	0.51
18	4	10	3.5	0.47
19	4	6	3	0.39
20	4	6	3.25	0.43
21	4	6	3.5	0.45
22	4	8	3	0.46
23	4	8	3.25	0.36
24	4	8	3.5	0.51
25	4	10	3	0.54
26	4	10	3.25	0.53
27	4	10	3.5	0.42

Table 1. Experimental trials and results

3. KERF WIDTH MATHEMATICAL MODEL

Raw data are impractical for interpretation and analysis of experimental results. Therefore, for the purpose of the detailed analysis of the conducted experimentation, based on obtained data the mathematical model using regression analysis was developed. To include first, second order main effects and interaction effects of the laser cutting factors, full second order regression model was developed:

$$w = -0.81791 + 1.5983 \cdot P + 0.32929 \cdot p - 1.72637 \cdot v - 0.23837 \cdot P^2 - 0.00612 \cdot p^2 + 0.36 \cdot v^2 + 0.01072 \cdot P \cdot p + 0.00622 \cdot P \cdot v - 0.07778 \cdot p \cdot v \quad (1)$$

With mean average percentage error of about 5 % between experimentally measured kerf width values and predictions it can be concluded that developed mathematical model is quite accurate.

To analyze the effects of laser cutting factors on the kerf width Eq. (1) was plotted. Three 3-D surface plots (Figure 2) were generated by varying two factors of interest, while other the third was held constant at middle level.

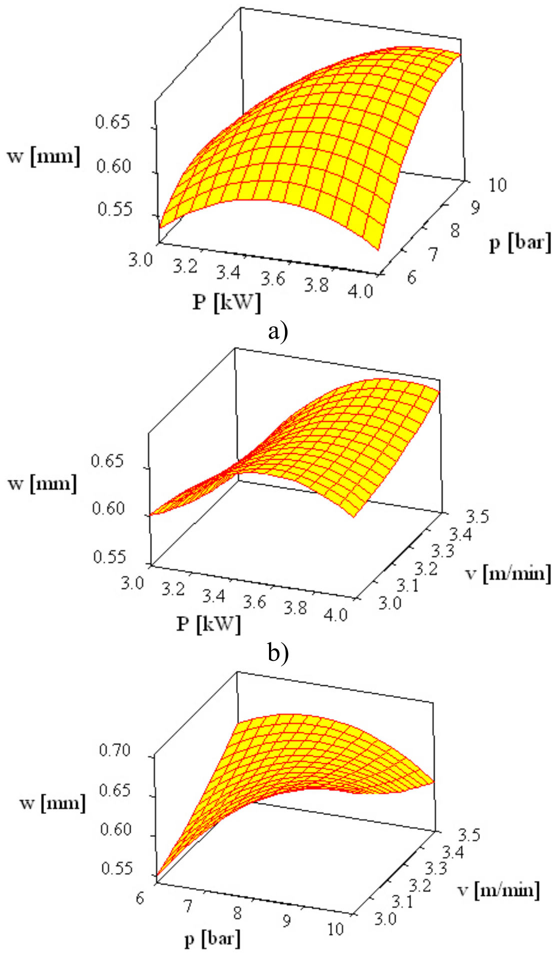

Fig. 2. Effect of laser cutting parameter interactions on kerf width [8]

As seen from Figure 2 the effect of the laser cutting parameters on the kerf width is nonlinear and variable.

As could be expected, low laser power and the higher cutting speed results in the low heat input during cutting operation so as lower kerf width is obtained (Figure 2). For higher laser power levels more material is being melted which results in larger kerf width. Similarly, when using higher levels of cutting speeds, there is lesser interaction time between laser beam and workpiece material, i.e. the material is heated within a relatively narrower zone around the laser beam thus forming a narrower kerf. These results are in agreement with those reported in literature.

Besides these, some unusual observations from Figure 2 are evident. Namely, it can be observed that for some specific combinations of laser cutting parameter values, kerf width decreases with the increase in laser power. Also, for certain laser cutting conditions, the increase in cutting speed results in an increase in kerf width. A more detailed analysis of the Figure 2 can reveal that these may be result of higher laser power levels or lower assist gas pressure levels used. Namely, in situations when greater proportion of material are evaporated and there is no sufficient gas pressure, one can expect the formation of surface plasma that reduces the amount of irradiated energy absorbed in the cutting region.

4. OPTIMIZATION OF KERF WIDTH

From Figure 2 it is obvious that achieving desired kerf width can be obtained by a set of different combinations of laser cutting parameter values. However, finding a set of the laser cutting parameter values to meet the desired kerf width, calls for the parameter optimization in three-dimensional laser cutting parameter hyperspace.

The goal of the optimization is to determine the optimal laser cutting parameter values at which the minimum kerf width is obtained. Mathematically, the optimization problem is as follows:

$$\begin{aligned} &\text{Find: } P_{opt}, v_{opt}, p_{opt} \\ &\text{to minimize: } w = \mathrm{f}(P, v, p) \\ &\text{subject to: } 3 \le P \le 4 \text{ [kW]} \\ &\qquad 6 \le p \le 10 \text{ [bar]} \\ &\qquad 3 \le v \le 3.5 \text{ [m/min]} \end{aligned} \quad (2)$$

The optimization problem in Eq. 2 was solved with discrete Monte Carlo method. The details about Monte Carlo method can be found in [9, 10]. This method 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, discrete Monte Carlo method takes into account techno-technological possibilities of machine tools and the determined solutions can be easily set on a given machine tool [9].

Before the actual application of discrete Monte Carlo method one needs to define the search step for each laser cutting parameter. This step defines the number of possible values that can take a given parameter within the given range. In order to create relatively dense search grid and by considering laser cutting machine technological characteristics, search steps for laser power, cutting speed and assist gas pressure were set to 0.01. This resulted in 2065551 parameter values combinations. The probability of finding a desire objective value (minimum) is only 1/2065551, but running it 10000000 times results in probability of finding optimal value over 99.99%. The optimization problem formulated in Eq. 2 was solved using the developed software solution “Analysis VirtuoLab” which supports the application of exhaustive iterative search, continual and discrete Monte Carlo method for solving optimization problems with and without constraints [11]. Here it should be noted that optimization was performed within few seconds on desktop Intel Core i7-2600 CPU@3.4GHz with 12 GB RAM computer.

As a result of the application of discrete Monte Carlo method, the minimal value of kerf width of w = 0.497 mm was obtained. This solution corresponds to the following combination of the laser cutting parameter values: P = 3 kW, p = 6 bar, v = 3.02 m/min.

These values can be easily set for performing a given laser cutting operation.

5. CONCLUSION

In this paper, regression based mathematical model is developed in order to relate the laser cutting parameters i.e. laser power, cutting speed and assist gas pressure, and kerf width in CO_2 laser cutting of aluminum alloy. Experiment trials were performed according to full factorial design. By applying the discrete Monte Carlo method, the optimal laser cutting parameter settings, which minimize kerf width were determined. It was found that focusing the laser beam on the bottom surface of the sheet using assist gas pressure of 6 bar at combination of laser power of 3 kW and cutting speed of 3.11 m/min, produced an minimal kerf width.

The conclusions drawn can be summarized by the following points:

- the kerf width is highly sensitive to the selected laser cutting parameters and their interactions,
- the effect of a given laser cutting parameter on the kerf width must be considered through the interaction with other parameters,
- the discrete Monte Carlo approach is found to be very simple, easy to implement and efficient for the optimization.

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