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Effect of Process Parameter in Laser Cutting of PMMA Sheet and ANFIS Modelling for Online Control

Anamul Hossain, Y. Nukman and A. M. Sifullah

Department of Mechanical Engineering, Faculty of Engineering, University of Malaya, Kuala Lumpur 50603, Malaysia

Abstract. Laser beam machining (LBM) is a promising and high accuracy machining technology in advanced manufacturing process. In LBM, crucial machining qualities of the end product include heat affected zone, surface roughness, kerf width, thermal stress, taper angle etc. It is essential for industrial applications especially in laser cutting of thermoplastics to acquire output product with minimum kerf width. The kerf width is dependent on laser input parameters such as laser power, cutting speed, standoff distance, assist gas pressure etc. However it is difficult to get a functional relationship due to the high uncertainty among these parameters. Hence, total 81 sets of full factorial experiment were conducted, representing four input parameters with three different levels. The experiments were performed by a continuous wave (CW) CO_2 laser with the mode structure of TEM_{01} named Zech laser machine that can provide maximum laser power up to 500 W. The polymethylmethacrylate (PMMA) sheet with thickness of 3.0 mm was used for this experiment. Laser power, cutting speed, standoff distance and assist gas pressure were used as input parameters for the output named kerf width. Standoff distance, laser power, cutting speed and assist gas pressure have the dominant effect on kerf width, respectively, although assist gas has some significant effect to remove the harmful gas. ANFIS model has been developed for online control purposes. This research is considered important and helpful for manufacturing engineers in adjusting and decision making of the process parameters in laser manufacturing industry of PMMA thermoplastics with desired minimum kerf width as well as intricate shape design purposes.

1 Introduction

Laser beam machining is one kind of thermal process that can provide good quality product by its outstanding advantages such as non-contact, no tool wear, high accuracy, intricate shape etc. [1], [2]. In laser cutting processes, kerf width should be formed that is allowed to design an intricate shape. Research interest topic is successful cut with minimum material removal or kerf width. Li *et al.* [3] studied on laser cutting of polymer/ceramic materials and concluded that laser is a suitable fabricating processes for ceramics, glass and polymers. Caiazzo *et al.* [4] applied CO_2 Laser cutting on different polymeric plastics. He evaluated the values of kerf widths on top and bottom side, melted area, melted volume per unit time and surface roughness values on cut edges. Choudhury *et al.* [5] developed mathematical model of heat affected zone and surface roughness models by response surface methodology (RSM) of three polymeric materials namely polypropylene (PP), polycarbonate (PC) and polymethylmethacrylate (PMMA). Dubey *et al.* [6] also developed models of material removal rate and kerf width, considering the input parameters as cutting speed, gas pressure, pulse width and pulse frequency. The uses of PMMA are myriad and its applications in different fields include not only the substitute of glass but also in some essential medical equipment namely bone cement, intraocular lens, dentures, prostheses, biosensors and biomechanical device [7]. Laser machining is a complex process moreover CO_2 laser interaction with PMMA begins vaporization while it is subjected to melt shearing [2], [8]. ANFIS model has a capability to manage this kind of complex situation. However, as per our review it has not found very much model of kerf width for PMMA sheet materials including laser power, cutting speed, standoff distance, assist gas pressure together. Hence an attempt has been taken to see the influence of the laser cutting process of PMMA sheet and ANFIS model for online control by including these four input parameters.

2 Methodology

The purpose of this research is to cut PMMA sheets into small rectangle shapes with the aim of determining the minimum kerf width and to investigate the effect of the input parameters on output quality of PMMA sheet. Hence, among all the design of experiment (DOE) methods, a full factorial design was chosen to evaluate the whole area of the quality although it consumes significant amount of experimental resources and time. In the present study, four factors with three levels were

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employed, representing a total 81 (3^4) sets of experiments. Digital caliper was used to measure side line lengths H_1 and H_2 as shown in Fig. 1. To calculate the kerf width, H_1 and H_2 are measured three times at different location and was calculated using Eq. 1.

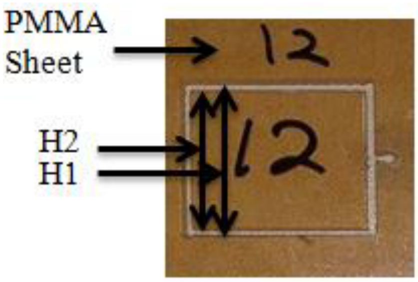


Figure 1. A schematic diagram for Kerf width measurements

$$\textit{Upper kerf width} = \frac{(H_1 - H_2)}{2} \quad (1)$$

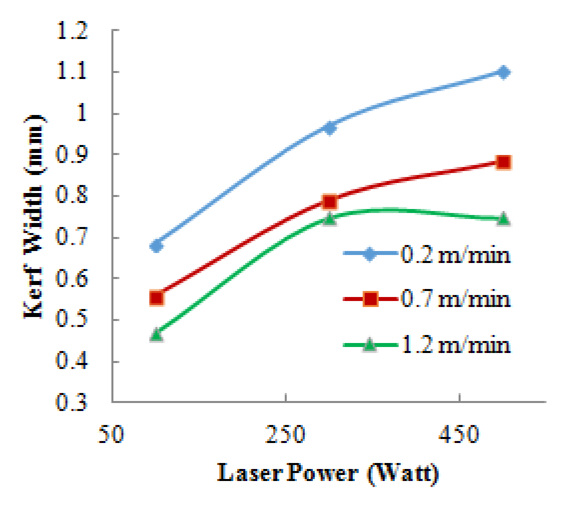
Table 1 shows the lists of levels for assist gas pressure, laser power, cutting speed and standoff distance used in the experiment.

Table 1: Input variables and their levels.

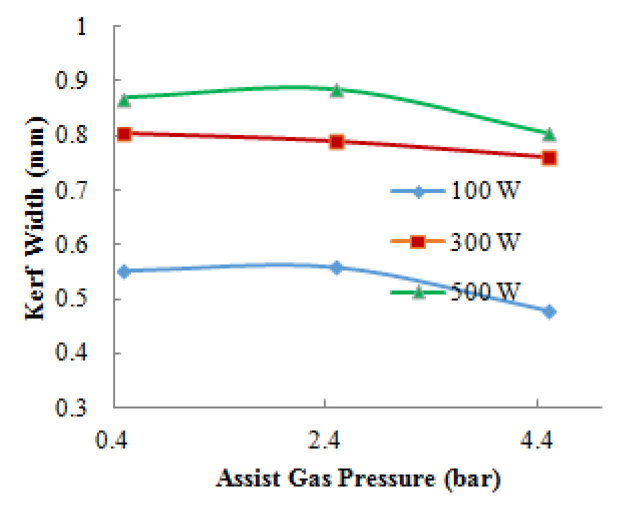
Input Parameters	Level 1	Level 2	Level 3	Units
Laser Power	100	300	500	Watt
Cutting Speed	0.2	0.7	1.2	m/min
Standoff Distance	1	5	10	mm
Assist Gas Pressure	0.5	2.5	4.5	Bars

3 Effects of laser input parameters on kerf width from experimental study

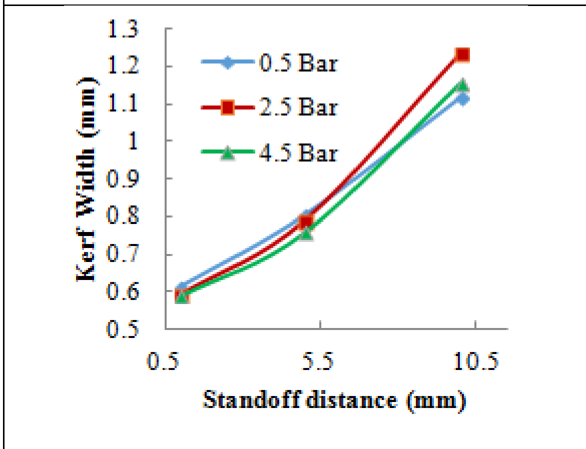
Fig. 1 (a) shows the combined effects of laser power and cutting speed on kerf width at mid-level assist gas pressure and standoff distance. Based on the Fig. 1 (a) the kerf width increases with the increase of laser power. The reported increase also depends on cutting speed. At low-level cutting speed, kerf width is bigger than that of high-level cutting speed.



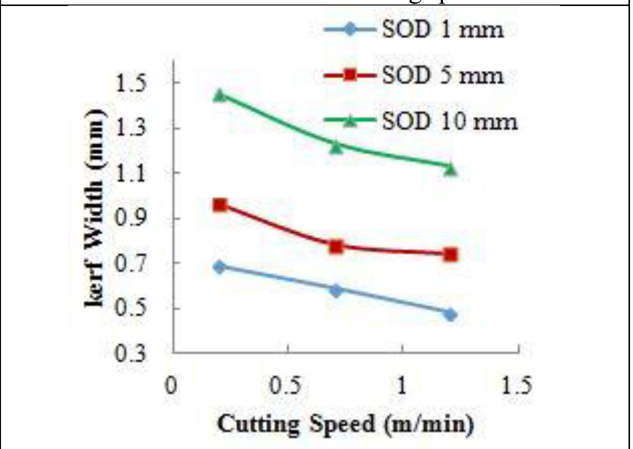
(a)Effect of laser power and cutting speed at constant Mid SOD & GP.



(b) Effect of laser power and assist gas pressure at mid standoff distance & cutting speed.



(c) Effect of standoff distance and assist gas pressure at mid laser power and cutting speed.



(d) Effect of cutting speed and standoff distance at mid laser power and assist gas pressure.

Figure 2: Effect of process parameters on kerf width in laser cutting.

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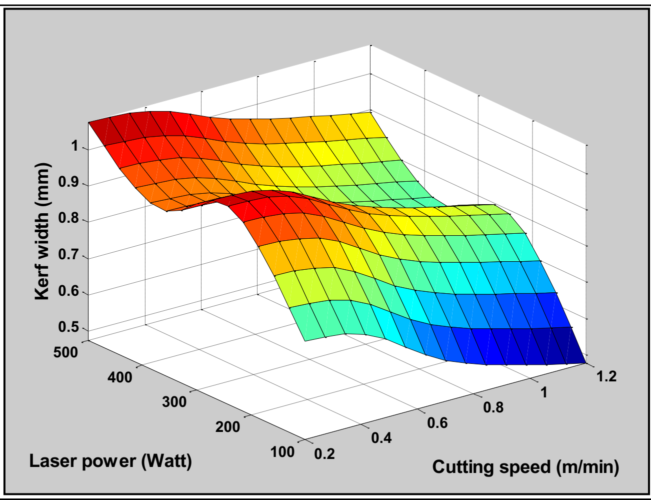
This is because at low-level cutting speed the workpiece had longer exposure to laser radiation which is reliable for vaporization. Moreover, it can be observed that the increase of kerf width is more noticeable as the power increases from 150 W to 300 W. The increase in kerf width is less significant as the power increases from 300 W to 450 W. As shown in Fig. 2(b), the effect of assist gas pressure on kerf width is not so much significant as laser power. However, it is important to blow away any harmful gases and also vaporize material from the workpiece. In addition, the measured kerf width decreases with the increase of assist gas pressure due to the cooling effect of the assist gas. As shown in Fig. 2(c), the kerf width also increases with the increase of standoff distance and assist gas pressure. This is due to the fact that with the increase in standoff distance the laser beam diameter also increases. Hence the kerf width increases. As shown in Fig. 2(d), the kerf width also increases with the increase of standoff distance.

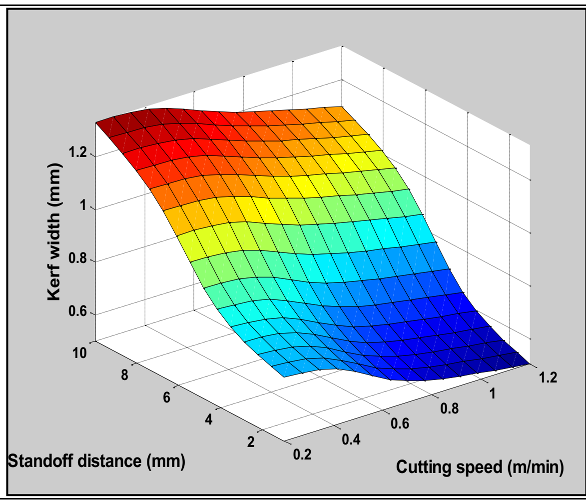
This is due to the fact beam diameter increases as well. Meanwhile, an increase of cutting speed leads to a smaller kerf width because the localized spot on the workpiece had less exposure to laser radiation. From the analysis of the Fig. 2 it can be seen that standoff distance, laser power, cutting speed and assist gas pressure have the dominant effect on kerf width, respectively.

4 Effect of laser input parameters on kerf width from ANFIS model

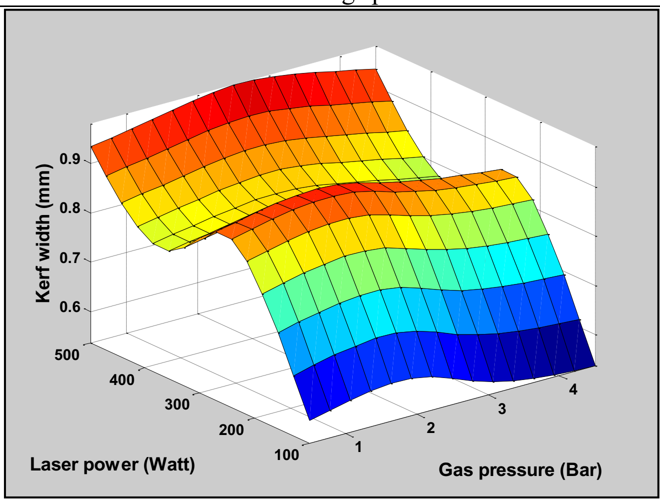
Fig. 3(a) shows the surface plot of kerf width values at different laser powers and cutting speeds. It is evident that the kerf width value decreases with the increase in cutting speed. Kerf width increases with the increase of laser power as well. From Fig. 3(b) it is evident that the kerf width value tends to decrease with the increase in cutting speed and it increases with the increase in standoff distance as well.



(a) 3D Surface plot of kerf width as a function of laser power and cutting speed.



(b) 3D Surface plot of kerf width as a function of standoff distance and cutting speed.



(c) 3D Surface plot of kerf width as a function of laser power and gas pressure.

(d) Graphical operation of the ANFIS prediction model

Figure 3. Effect on kerf width from ANFIS model.

It is evident from Fig. 3(c) that the kerf width increases with the increase of laser power of up to 300 W and exhibits smaller kerf width at 400 W and it gradually decreases when it reaches 400 W and again increases up to 500 W this is due to the turbulent effect of the assist gas. Fig. 3(d) shows the graphical rule viewer for the prediction model. For prediction capability evaluation relative error and goodness of fit were used. The statistical analysis of the ANFIS result for kerf width were relative error (4.23%) and goodness of fit 0.9876 (R2= 0.9754) in training, whereas relative error (3.54%) and goodness of fit 0.9853 (R2= 0.9708) were obtained in testing.

5 Conclusions

The purpose of this research is to cut polymethylmethacrylate (PMMA) sheets into small rectangle shapes with the aim of determining the minimum kerf width. In the manufacturing process, it is important to cut the workpiece with minimum or moderate kerf width because it is related to material loss from the parent material. All the experiments were performed by varying the input parameters with different levels. Experimental data was used to analyse the results. In the study, adaptive neuro fuzzy inference system in laser machining approach of PMMA material has been proposed also to get the minimum KW with low computational cost. According to statistical evaluation criterions of predicted performance of the developed ANFIS model has been found to be a good agreement. From the study, the following conclusions can be drawn:

1. When PMMA sheets of 3 mm thick was cut using a CW CO_2 laser, the resulting kerf width becomes wider with the increase of standoff distance and power, but the kerf width decreases as the cutting speed increases.
2. The minimum kerf width was found to be 0.3167 mm at gas pressure 0.5 bar, laser power 100 W, standoff distance 1 mm and cutting speed 1.2 m/min
3. The statistical analysis of the ANFIS result for kerf width were relative error (4.23%) and goodness of fit 0.9876 (R^2= 0.9754) in training, whereas relative error (3.54%) and goodness of fit 0.9853 (R^2= 0.9708) were obtained in testing.
4. Standoff distance, laser power, cutting speed and assist gas pressure have the dominant effect on kerf width, respectively, although assist gas has some significant effect to remove harmful gas.

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