Development of statistical model to predict R_a and R_z in laser cutting

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Abstract

Laser cutting is one of the advanced machining methods for the material removing process. This paper explores the prediction model of the surface roughness (R_a) and roughness height (R_z) of laser beam cutting on acrylic sheets. The Box-Behnken design based Response Surface Method (RSM) was used to predict the effect of the laser cutting parameters, which are laser power, cutting speed and tip distance on R_a and R_z. The predictive models are in good agreement with the experimental results. The first order equation revealed that the power requirement was the dominant factor, followed by tip distance and cutting speed respectively. This observation indicates the potential of using RSM in predicting cutting parameters, thus eliminating the need for exhaustive cutting experiments to obtain the optimum cutting condition and enhance the surface roughness.

Keywords: laser beam cutting, Box-Behnken design, surface roughness, acrylic sheets, surface height.

1 Introduction

Laser light differs from ordinary light in that it has photons of the same frequency, wavelength and phase. Thus, unlike ordinary light, laser beams are highly directional, have high power density and better focusing characteristics [1, 2]. These unique characteristics of laser beams are useful in the processing of materials. The laser beams are widely used for machining and other manufacturing processes, such as cutting, drilling, micromachining, marking, welding, sintering and heat treatment. Lear beam machining (LBM) is a thermal

WIT Transactions on The Built Environment, Vol 112, © 2010 WIT Press
www.witpress.com, ISSN 1743-3509 (on-line)
doi:10.2495/HPSM100371

energy based advanced machining process in which the material is removed by melting, vaporization and chemical degradation.

According to Powell [3] and Rooks [4], applications of laser cutting in polymeric materials have grown considerably in many industries. Polymeric materials generally fall into main groups. There are thermoplastics, such as polyethylene (PE), polycarbonate (PC), polymethylmethacrylate (PMMA) (acrylic), polyvinylchloride (PVC) and thermoset plastics, which include epoxy and phenolic resins. Rooks [4], Caiazzo *et al.* [5], Zhou and Mahdavian [6], Mathew *et al.* [7] and Lum *et al.* [8], when reporting on the laser cutting of polymeric materials, have shown that the processing parameters have an essential role on the quality of the surface obtained. Lum *et al.* [8] presented a study about the CO2 laser cutting of medium-density fibreboard (MDF). This work reports on the determination of processing parameters setting for the effective cutting of MDF by CO2 laser, using an established experimental methodology developed to study the effects of varying laser set-up parameters. According to these authors, striation patterning is evident but is of little significance to the overall quality of cut as evidenced by the low roughness values obtained. A recent study by Davim *et al.* [9] on the experiences in CO2 laser cutting of polymers/composites notes, it is evident that the HAZ increases with the laser power and decreases with the cutting velocity.

When a high energy density laser beam is focused on a work surface the thermal energy is absorbed, which heats and transforms the work volume into a molten, vaporized and chemically changed state that can easily be removed by flow of high pressure assist gas. LBM can be applied to a wide range of materials, such as metals and non-metals. Laser surface texturing may be an ideal technology for applications in mechanical face seals, as well as in various components in engines, such as piston rings and cylinder and thrust bearings, involving the creation of an array of micro dimples or channels artificially distributed on the mating surface with a pulsed laser beam [11]. With the development of laser technology and flat panel display (FPD) technology, many studies have been carried out to investigate the methods of cutting glass using lasers [1, 2, 12–20]. Li *et al.* [10] put forward a mathematical model to explain the heat transfer of glass heated by lasers and to analyze the differences of the effect on the thermal behaviour of glass between the application of lasers as a volumetric heating source and that of a surface heating source. Wei *et al.* [11] and Tian and Chiu [13] investigated the thermal behaviour of glass heated by a CO2-laser beam numerically, and concluded that the resulting temperature distribution was strongly dependent on the speed of the moving laser beam and the laser parameters, i.e., the size of the laser beam and the power of the laser. Tsai [14] studied the thermal stress of alumina ceramic substrates irradiated by a moving laser beam. R_z is the arithmetic mean value of the single roughness depths of consecutive sampling lengths. Z is the sum of the height of the highest peaks and the lowest valley depth within a sampling length.

In any manufacturing process, it is always desirable to know the effect of variation of input parameters on process performance in order to achieve the goal of a better product quality. LBM, being a non-conventional machining process, requires high intensity and offers poor efficiency. Therefore, high attention is required for better utilization of resources. The values of process parameters are determined in order to yield the desired product quality and also to maximize the process performance. In LBM, there are various variables, including beam power, cutting speed and tip distance, which affect the surface roughness. Surface roughness value reduces on increasing cutting speed and frequency, and decreasing the laser power and gas pressure. In addition, nitrogen gives a better surface finish than oxygen [15]. The laser power and cutting speed has a major effect on surface roughness, as well as striation frequency [16]. From the above review, it can be concluded that, in the past, very few papers reported on the relationship of variables and response when machining acrylic sheets. This paper emphasises the development of surface roughness and surface height models in machining with laser beams and discusses the relationship of the variables with response.

2 Response surface method (RSM)

The RSM is a collection of statistical and mathematical methods that are useful for the modelling and optimization of engineering problems. In this technique, the main objective is to optimize the responses that are influenced by various parameters. The RSM also quantifies the relationship between the controllable parameters and the obtained response. In modelling of the manufacturing processes using the RSM, sufficient data is collected through designed experimentation. In general, a second order regression model is developed because first order models often give lack of fit [17]. The study uses the Box-Behnken design in the optimization of experiments using the RSM to understand the effect of important parameters. The Box-Behnken design is normally used when performing a non-sequential experiment, which is performing the experiment only once. These designs allow the efficient estimation of the first- and second- order coefficients. The Box-Behnken design has fewer design points; it is less expensive to run than central composite designs with the same number of factors. The Box-Behnken Design does not have axial points, thus it is certain that all the design points fall within the safe operating parameters. The Box-Behnken DESIGN also ensures that not all factors are being set at their high levels simultaneously [18-20].

3 Experimental set-up

The experiment was performed on a 30W pulsed CO_2 laser beam system with a CNC work table. Oxygen was used as an assist gas. The variable process parameters taken are: beam power, cutting speed and tip distance. The focal length of the lens used is 50 mm, 1.0 mm nozzle diameter and 1.0 mm nozzle tip distance, which were kept constant throughout the experiments. The 15 experiments are carried out using the laser machine, as shown in Fig. 1. An acrylic sheet of 3.0 mm thickness, 30.0 mm width and 40.0 mm long was taken as the specimen and was cut into a rectangular shape in order to measure the surface roughness. The dimension of the acrylic sheet specimen is shown in Fig 2. Four sides were measured to get the average roughness. Surface roughness tester Perthometer S2 was used for the roughness measurement. The material properties of the work piece are shown in Table 1. The suitable levels of the factors were used in the statistical Minitab software to deduce the design parameters for acrylic sheets, which are given in Table 2. The lower and higher speed values were selected of 700 pulses/s and 1100 pulse/s, respectively. The higher and lower values of power requirement of 95% and 90% are considered. The range of the tip distance is 3 mm to 9 mm.

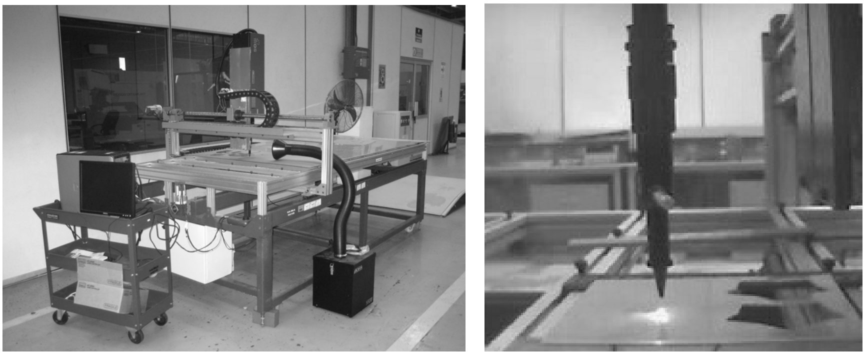

Figure 1: Laser machine.

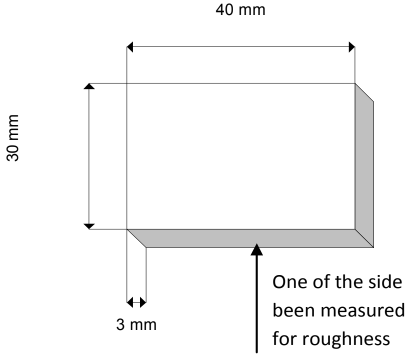

Figure 2: Dimensions of the specimen.

Table 1: Material properties of the specimen.

Properties	Value	Unit
Density	1170	kg/m^3
Yield Tensile Strength	52.1	MPa
Processing temperature	156	°C
Modulus of elasticity	2.31	GPa

Table 2: Level of design variables.

Design Variables	**Coding of levels**		
	1(lowest)	**0(middle)**	**1(highest)**
Power requirement (%)	90	92.5	95
Cutting speed (pulse/s)	700	900	1100
Tip distance (mm)	3	6	9

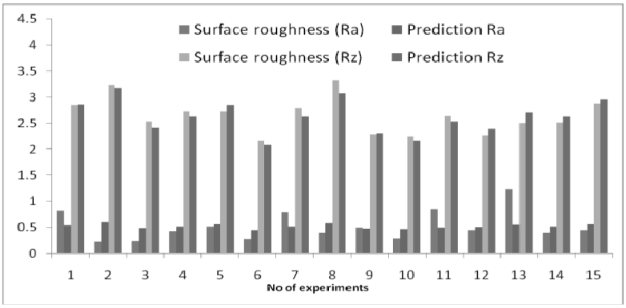

Figure 3: Prediction value of the predicted value by RSM for R_a and R_z.

4 Results and discussion

After 15 cutting experiments were conducted, the surface roughness readings are used to predict the parameters that appear in the postulated first order model, which were expressed as Eqs. (1) and (2) respectively. In order to calculate these parameters, the least square method was used to determine these parameters with the help of statistical software. A linear equation used to predict the surface roughness and surface height, which are expressed as Eqs. (1) and (2).

$$R_a^{(1)} = -0.7059 + 0.0124\,\mathrm{Pr} - 0.0000265\,C_{speed} + 0.016GD \quad (1)$$

$$R_z^{(1)} = -0.4899 + 0.02695\,\mathrm{Pr} - 0.000485C_{speed} + 0.1372GD \quad (2)$$

where R_a is surface roughness, R_z is surface height, Pr is the power requirement, C_{speed} is cutting speed and TD is the tip distance.

From this linear equation, the response surface roughness and surface height are affected significantly by the power requirement, followed by tip distance and cutting speed. Eqs. (1) and (2) show that the combination of high power and tip distance produce a rough surface. On other hand, high cutting speed produces a very smooth surface. Similar to the first-order model, by examining the coefficients of the first-order terms, the tip distance (*TD*) has the most dominant effect on the surface roughness. The contribution of power requirement (*Pr)* is the least significant. The ANOVA shown in Tables 3 and 4 indicates that the model is adequate as the P-value of the lack-of-fit is not significant (> 0.05). Figs. 4 and 5 show the contour plot for R_a and R_z. One easily can observe the relationship between variables and response.

Table 3: Analysis of variance (ANOVA) for first-order equation R_a.

Source of variation	Degree of freedom	Sum of squares	F-ratio	P-value
Regression	3	0.02676	0.09	0.964
Linear	3	0.02676	0.09	0.964
Residual Error	11	1.09008		
Lack-of-Fit	9	0.992	2.25	0.346
Pure Error	2	0.09808		
Total	14	1.11684		

Table 4: Analysis of variance (ANOVA) for first-order equation R_z.

Source of variation	Degree of freedom	Sum of squares	F-ratio	P-value
Regression	3	1.47441	36.82	0
Linear	3	1.47441	36.82	0
Residual Error	11	0.14682		
Lack-of-Fit	9	0.10291	0.52	0.798
Pure Error	2	0.04391		
Total	14	1.62123		

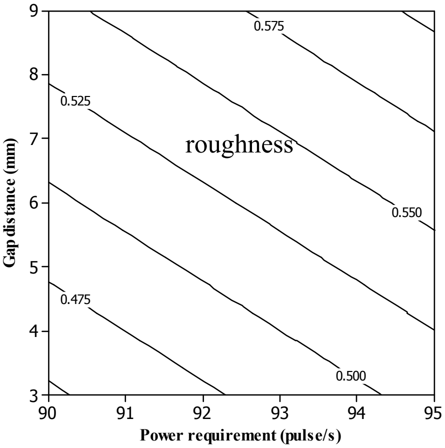

Figure 4: Surface roughness contours in the power requirement-gap distance plane for cutting speed 900 pulses/sv.

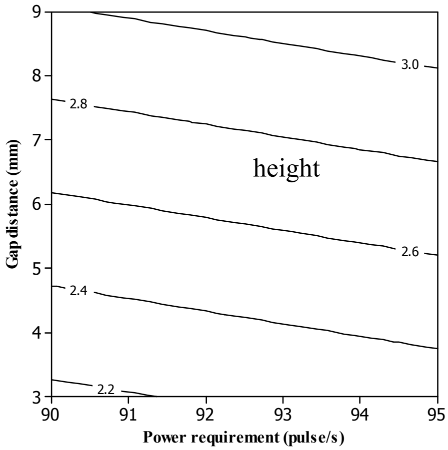

Figure 5: Surface height contours in the power requirement-gap distance plane for cutting speed 900 pulses/s.

5 Conclusions

In the current work, the response surface methodology has been proven to be a successful technique to perform the trend analysis of surface roughness and surface height with respect to various combinations of three design variables. By using the least square method, the first-order models have been developed based on the test conditions in accordance with the Box–Behnken design method. The models have been found to accurately represent the surface roughness and surface height values with respect to those experiment values. The equations have been checked for their adequacy with a confidence interval of 95%. Both models reveal that the power requirement and tip distance are the most significant design variables in determining the surface roughness response as compared to the others. In general, within the working range of the power requirement and tip distance considered, the surface roughness and surface height increase as the both variables increase. The models have been found to be accurately representing surface roughness values with respect to experimental results. The RSM model reveals that power requirement is the most significant design variable in determining surface roughness and surface height response as compared to cutting speed and tip distance. With the model equations obtained, a designer can subsequently select the best combination of design variables for achieving optimum surface roughness. This eventually reduces the machining time and saves cutting tools.

Acknowledgement

The authors would like to express their deep gratitude to Universiti Malaysia Pahang (UMP) for providing the laboratory facilities and financial support.

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