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Prediction Modelling of Surface Roughness for Laser Beam Cutting on Acrylic Sheets

M.M.Noor[1,a], K.Kadirgama[1,b], M.M.Rahman[1,c], N.M.Zuki.N.M.[1,d], M.R.M.Rejab[1,e], K.F.Muhamad[1,f], Julie J Mohamed[2,g]

[1]Faculty of Mechanical Engineering, Universiti Malaysia Pahang, Tun Razak Highway, 26300 Gambang, Kuantan, Pahang, Malaysia. Email: [a] muhamad@ump.edu.my, [b] kumaran@ump.edu.my, [c] mustafizur@ump.edu.my, [d] nikzuki@ump.edu.my, [e] ruzaimi@ump.edu.my, [f] fikri@ump.edu.my,

[2]School of Material Engineering, Engineering Campus, Universiti Sains Malaysia, 14300 Nibong Tebal, Pulau Pinang, Malaysia Email: [g] srjuliewatty@eng.usm.my

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Abstract. This paper develops the predicting model on surface roughness of laser beam cutting (LBC) for acrylic sheets. Box-Behnken design based on Response surface method was used to predict the effect of laser cutting parameters including the power requirement, cutting speed and tip distance on surface roughness during the machining. Response surface method (RSM) was used to minimize the number of experiments. It can be seen that from the experimental results, the effects of the laser cutting parameters with the surface roughness were investigated. It was found that the surface roughness is significantly affected by the tip distance followed by the power requirement and cutting speed. Some defects were found in microstructure such as burning, melting and wavy surface. This simulation gain more understanding of the surface roughness distribution in laser cutting. The developed model is suitable to be used in the range of (power 90 to 95, cutting speed 700 to 1100 and tip distance 3 to 9) to predict surface roughness.

1. Introduction

Laser light differs from ordinary light due to it has the photons of same frequency, wavelength and phase. Thus, unlike ordinary light laser beams are high directional, have high power density and better focusing characteristics [1,2]. These unique characteristics of laser beam are useful in 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 energy based advanced machining process in which the material is removed by melting, vaporization and chemical degradation. When a high energy density laser beam is focused on work surface the thermal energy is absorbed which heats and transforms the work volume into a molten, vaporized and chemically changed state that can be 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 seal, as well as in various components in engine such as piston ring and cylinder and thrust bearings, involving creation of an array of micro dimples or channels artificially distributed on the mating surface with a pulsed laser beam [3 -4]. The most widely used lasers for sheet cutting are continuous wave (CW), CO_2 and pulsed Nd:YAG [5]. Pulsed Nd:YAG laser cutting becomes an excellent cutting process because of high laser beam intensity, low mean beam power, good focusing characteristics, and narrow heat affected zone (HAZ) [6, 7]. Lei et al. [8] have found that the laser-assisted turning (LAT) of silicon nitride ceramics economically reduces the surface roughness and tool wear in comparison to only conventional turning process.

The study reveals that low pulse frequencies and high peak powers were found to be favourable for higher cutting speeds.

In any manufacturing process it is always desired to know that the effect of variation of input parameters on process performance in order to achieve the goal of 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 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. Also nitrogen gives better surface finish than oxygen [9]. The laser power and cutting speed has a major effect on surface roughness as well as striation frequency [10]. The aim of this work is to present and discuss about the experimental investigations using response surface method and acrylic sheets in order to predict the significant factors and their effects on quality characteristics for better cutting performance and showing the effect relationship between process variables and performance characteristics.

2. Response Surface Method

Response surface method (RSM) is a collection of statistical and mathematical methods that are useful for the modelling and optimization of the engineering problems. In this technique, the main objective is to optimize the responses that are influencing by various parameters. RSM also quantifies the relationship between the controllable parameters and the obtained response. In modelling of the manufacturing processes using RSM, the sufficient data is collected through designed experimentation. In general, a second order regression model is developed because of first order models often give lack-off fit [11]. The study uses the Box-Behnken design in the optimization of experiments using RSM to understand the effect of important parameters. Box-Behnken Design is normally used when performing non-sequential experiments. That is, performing the experiment only once. These designs allow efficient estimation of the first and second –order coefficients. Because Box-Behnken design has fewer design points, they are less expensive to run than central composite designs with the same number of factors. Box-Behnken Design do not have axial points, thus we can be sure that all design points fall within the safe operating. Box-Behnken Design also ensures that all factors are never set at their high levels simultaneously [12 - 14].

3. Experimental Set-Up

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

Figure 1: Laser machine

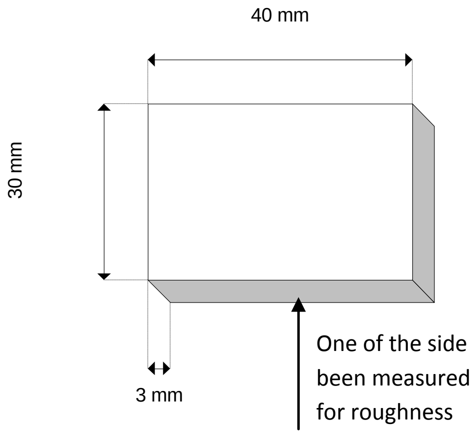


Figure 2: Dimension of the specimen

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 1: Material properties of specimen

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

Table 2: Level of design variables

4. Results and Discussion

After conducting the 15 cutting experiments, the surface roughness readings are used to predict the parameters appear in the postulated first and second-order model, which is expressed as Eq. (1) and Eq. (2) respectively. In order to calculate these parameters, The least square method was used to determine these parameters with the help of statistical software. The first and second-order linear and quadratic equation used to predict the surface roughness, whic is expressed as Eq.(1) and Eq. (2).

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

$$\begin{aligned} Ra^{(2)} &= 152.618 - 3.23\,\mathrm{Pr} - 0.050 C_{speed} + 2.62 GD + 0.017\,\mathrm{Pr}^2 - 0.022 GD^2 \\ &+ 0.00053\,\mathrm{Pr}\,C_{speed} - 0.023\,\mathrm{Pr}\,GD \end{aligned} \tag{2}$$

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

From this linear equation, one can easily notice that the response surface roughness is affected significantly by the power requirement, followed by tip distance and cutting speed. Eq. (1) shows that 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 (*GD*) has the most dominant effect on the surface roughness. The contribution of power requirement (Pr) is the least significant. Also, owing to the P-value of interaction is 0.092 (>0.05), one can easily deduce that the interactions of distinct design variables are not significant. In other words, the most dominant design variables *GD* and Pr have the minimum interaction with others in the current context. As seen from Figure 3 and Table 3, the predicted surface roughness using the second order RSM model is able to produce values close to those with experimental, and, as it should be the case, it exhibits better agreement as compared to those from the first-order RSM model. The ANOVA analysis shown in Tables 4 and 5, those indicate that the model is adequate as the P-value of the lack-of-fit is not significant (> 0.05).

No. Exp.	Power requirement (%)	Cutting speed (pulse/s)	Tip distance (mm)	Surface roughness (μm)	1st order-RSM	2nd order-RSM
1	90.0	900	9	0.826	0.543	0.656
2	95.0	900	9	0.23	0.605	0.333
3	90.0	1100	6	0.241	0.488	0.345
4	92.5	900	6	0.423	0.526	0.539
5	95.0	700	6	0.525	0.564	0.421
6	90.0	900	3	0.277	0.447	0.174
7	92.5	900	6	0.794	0.526	0.539
8	92.5	700	9	0.398	0.581	0.400
9	92.5	700	3	0.496	0.484	0.430
10	92.5	1100	3	0.291	0.471	0.290
11	90.0	700	6	0.852	0.502	1.021
12	95.0	900	3	0.451	0.509	0.621
13	95.0	1100	6	1.238	0.550	1.069
14	92.5	900	6	0.399	0.526	0.539
15	92.5	1100	9	0.448	0.568	0.514

Table 3: RSM models prediction for surface roughness

Source of variation	Degree of freedom	Sum of squares	Mean squares	*F*-ratio	*P*-value
Regression	3	0.02676	0.00892	0.09	0.964
Linear	3	0.02676	0.00892	0.09	0.964
Residual Error	11	1.09008	0.099098		
Lack-of-Fit	9	0.992	0.110222	2.25	0.346
Pure Error	2	0.09808	0.04904		
Total	14	1.11684			

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

Source of variation	Degree of freedom	Sum of squares	Mean squares	*F*-ratio	*P*-value
Regression	9	0.8524	0.094711	1.79	0.27
Linear	3	0.02676	0.00892	0.17	0.913
Square	3	0.22292	0.074306	1.4	0.344
Interaction	3	0.60273	0.200908	3.8	0.092
Residual Error	5	0.26444	0.052888		
Lack-of-Fit	3	0.16636	0.055453	1.13	0.501
Pure Error	2	0.09808	0.04904		
Total	14	1.11684			

Table 5: Analysis of variance (ANOVA) for second-order equation

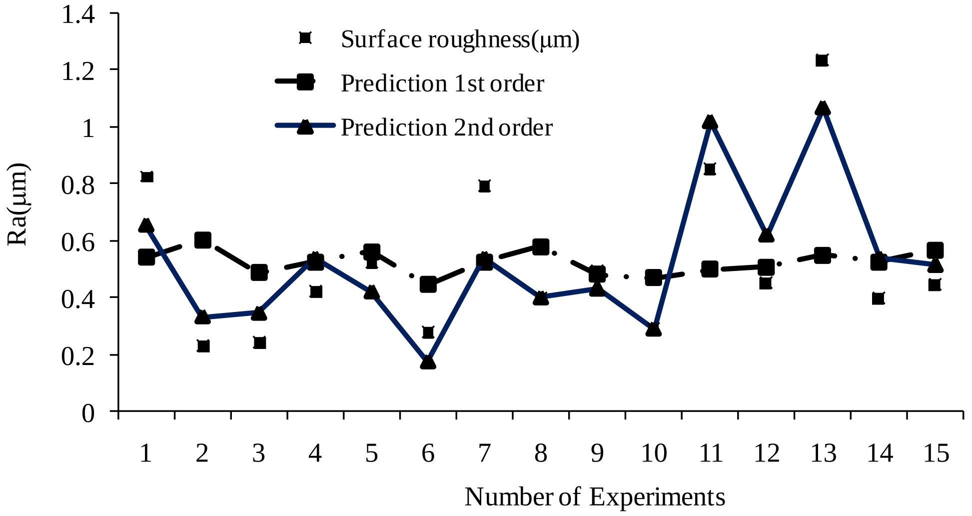


Figure 3: Comparison of RSM models against experimental values

Figure 4 shows the surface roughness condition for the experimental with high power and cutting speed. It is clearly seen that the melting and burning are occur. Even though, the surface roughness is around 0.451 µm, however, the surface structure is very poor. This is due to high temperature causing by power and cutting speed.

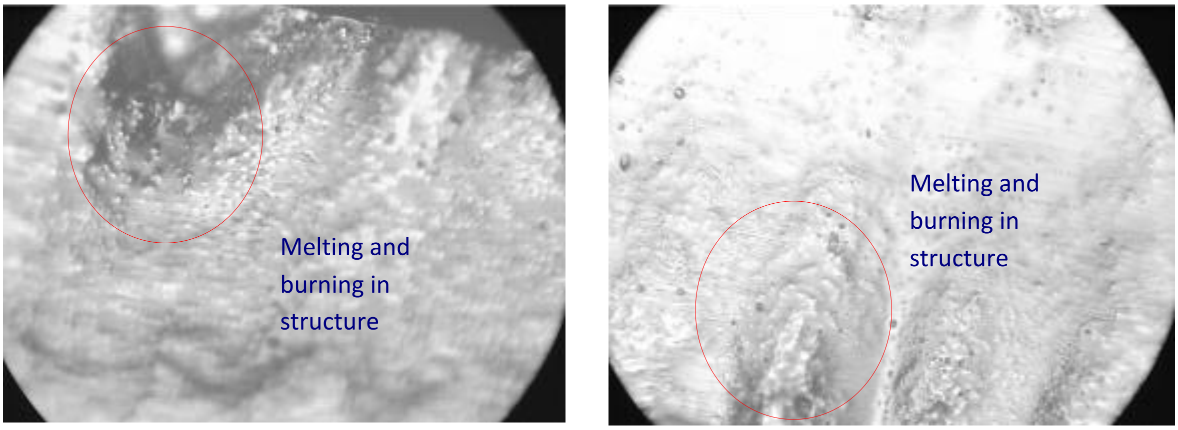


Figure 4: Microscope picture for roughness 0.451 µm

Figure 5 shows the surface texture for the surface roughness of 0.277 µm for two different specimens. The surface texture is without melting surface compare with Figure 4, however, it is quite wavy at the surface. It's very important to verify the surface texture since the defect at the microstructure cause the materials pathetic and less strength. Surface plot for first-order and second-order are shown in Figure 6. It is clearly seen the relationship between surface roughness with power requirement and tip distance.

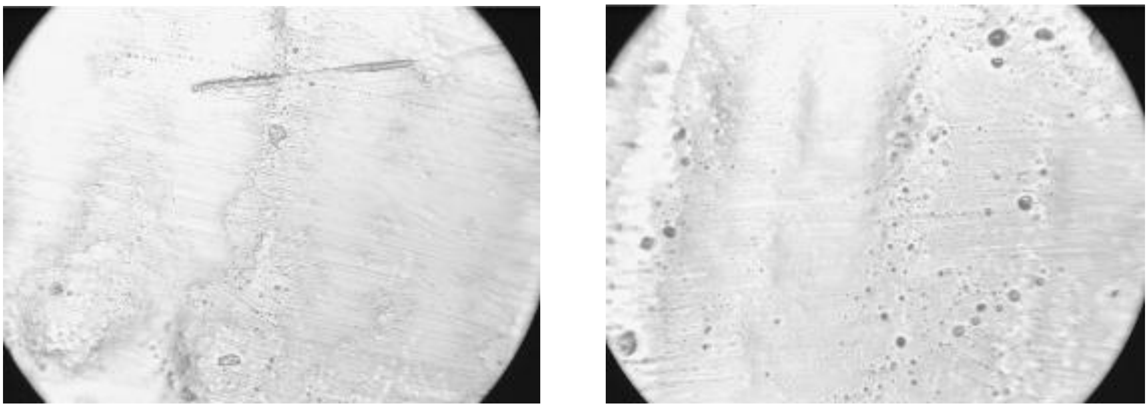
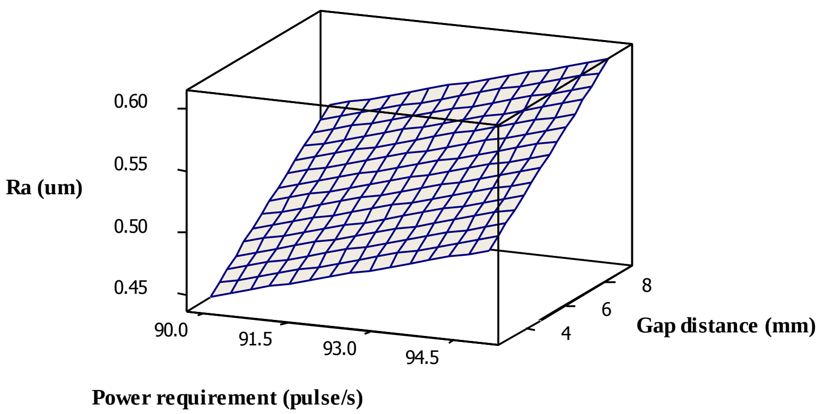
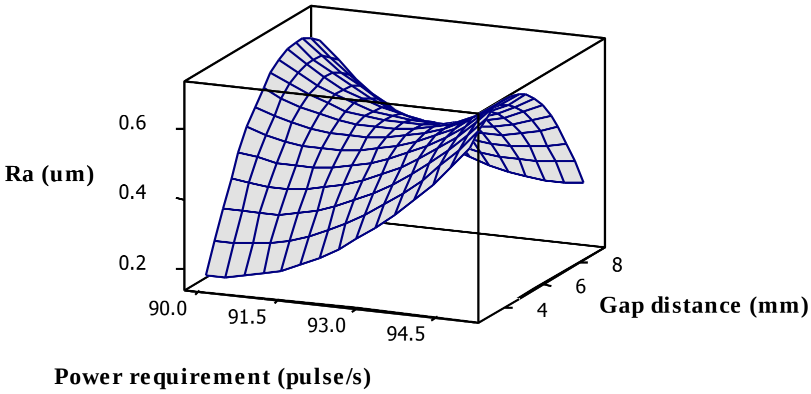


Figure 5: Microscope picture for roughness 0.277 µm



(a)



(b)

Figure 6: Surface plot for (a) first-order; (b) second-order

5. Conclusion

In the current work, the response surface methodology has been proven to be a successful technique to perform the trend analysis of surface roughness with respect to various combinations of three design variables. By using the least square method, the first- and second-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 representing the surface roughness values with respect to those experiment values. The equations have been checked for their adequacy with a confidence interval of 95%. Both RSM models reveal that the power requirement and tip distances are the most significant design variable 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 increases as the both variables increases. Based on the second-order RSM model, the power requirement and tip distance does not interact much with the remaining design variables. With the model equations obtained, a designer can subsequently select the best combination of design variables for achieving optimum roughness. Microscopy reveals that some of good surface roughness got defect in microstructure such as burning, melting and wavy surface. This will cause the materials to suffer in terms of less strength.

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