Journal of Manufacturing Engineering, December, 2011, Vol. 6, Issue. 4, pp 226-232

MODELING AND ANALYSIS OF MATERIAL REMOVAL RATE IN LOW POWER LASER ENGRAVING PROCESS BASED ON STATISTICAL ANALYSES

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ABSTRACT

Material removal rate is an important factor which decides productivity of any machining process. This paper focuses on effects of machining parameters on material removal rate in the low power continuous wave (CW) CO_2 laser cutting of thermoplastic materials. The effect of machining parameters, such as laser beam power, cutting speed and focal length offset of focusing lens on material removal rate has been studied using statistical techniques. An L18 (21×37) Taguchi standard orthogonal array was chosen for the design of experiments. The level of importance of the machining parameters on the material removal rate was determined by using analysis of variance (ANOVA). The optimum machining parameters combination was obtained by using the analysis of signal- to-noise (S/N) ratios. The variation of material removal rate with machining parameters was mathematically modelled by using the regression analysis method. Finally, experimentation was carried out to identify the effectiveness of the proposed method. The presented model is also verified by a set of verification tests.

Keywords: *Low Power Laser, Thermoplastics, Material Removal Rate, ANOVA and Signal-to-Noise Ratio.*

1. Introduction

In recent years laser beam machining is gaining popularity for cutting all types of materials including plastics as it is possible to achieve superior quality product with greater reliability. The lasers can be used to cut as well as engrave plastics of varying thickness by simply altering the intensity of the beam energy. The quality of cut mainly depends on the setting of process parameters such as laser power, type and pressure of assist gas, type and sheet material thickness, cutting speed and mode of operation (continuous mode or pulsed mode).

Several researchers [1-4], have investigated the role of processing parameters on the quality of the surface obtained, when reporting on laser cutting of polymeric materials. Most of them have carried out their investigation with high power lasers which are built for heavy industrial application with high operation cost.

Caiazzo *et. al.* [3], investigated the application of continuous wave CO_2 laser for cutting polyethylene (PE), polypropylene (PP) and polycarbonate (PC) sheets in different thickness ranging from 2 mm to 10mm. A 1.5 KW CO2 laser with N_2, Argon, and compressed air used as cooling gas. And they also reported that in many cases the employment of powerful CO_2 laser sources is not necessary, just a few hundred watts may be all that is required.

Davim *et. al.* [4] used 4 KW CO_2 laser to evaluate the effect of the processing parameters (laser power and cutting speed) on the quality of the cut for acrylic, polypropylene, polycarbonate and reinforced thermoset plastics.

Chudhary and Shirley [5] used 500 W continuous CO_2 laser to study surface quality of PP, PC and PMMA. A planned experiments based on the central composite design was conducted to develop predictive models using response surface method. The influence of process variable, namely air pressure, cutting speed and laser power on surface roughness, Heat affected zone (HAZ) and dimensional deviation along the diameter have been investigated.

It has suggested by Zhou and Mahdavian [6], that low-power 60 W CO_2 laser can be used for cutting non-metallic materials and plastic board. Voisey *et. al.* [7] has studied the melt ejection phenomena in metals (aluminium, nickel, titanium, mild steel, tungsten, copper and zinc) by conducting Nd: YAG laser drilling experiments at different power densities. Some investigators have used machining speed and/or

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machining time to represent the material removal rate (MRR). Cutting speed of continuous wave (CW) and pulsed Nd: YAG laser beam was compared in [8] for cutting bare and coated metal plates (0.8–2.0mm thick) of car frame using oxygen assist gas. The experimental study of micromachining of sapphire (381 mm) and silicon (533 mm) wafers show that the MRR increases with beam energy density irrespective of machining speed [9].

Experimental study by Lau et al. [10] shows that compressed air removes more material in comparison to argon inert gas during laser cutting of carbon fibre composites. The effect of pulse intensity (kW) on depth of cut or MRR during pulsed Nd: YAG laser cutting shows increasing effect for all metal matrix composites, carbon fibre composites and ceramic composites [11].

The MRR during laser machining of concretes shows increasing trend with both laser power and scan speed [12]. The survey of literature indicates that most of the experimental study is limited to metals, whereas only few researchers have given attention to cutting study of ceramic and composite sheets. Low power lasers are widely used for engraving gift articles made from plastics, cutting thin plastic sheets, marking and cutting decorative cards, making of plastic moulds for casting polymer resins and rubbers.

The aim of the present work was to study the material removal rate during continuous wave (CW) CO_2 laser cutting of thermoplastics namely Poly-Propylene (PP), Polymethylmethacrylate (PMMA). Experiments were employed in this study to consider the effects of cutting power, cutting speed and focal length offset of focal lens on the material removal rate during continuous wave (CW) CO_2 laser cutting process. A proper design of experiments (DOE) plan was conducted to perform more accurate, less costly, and more efficient experiments. Three different analyses were performed on the data obtained from the experiments: firstly, the Analysis of Variance (ANOVA) which helps one to determine significant factors [13], secondly regression analysis established a relationship between factors and responses [14], thirdly Signal-to-Noise (S/N) ratio analysis was conducted to find the influence of factor levels [15].

2. Design of Experiments

Cutting power, Cutting speed and offset of focal length of focusing lens are adopted as factors (independent variables) which vary during the experiments and effects of their variation is studied systematically. The factors and their levels are shown in Table 1.

Table 1: Factors and their Levels

Name of the Factors	**Factor levels**		
	1	**2**	**3**
Cutting Power (P): indicates laser beam power (W)	20	22.5	25
Cutting Speed (V): indicates linear speed of the laser beam head (mm/sec)	25.6	32	38.4
Lens's focal length offset (O): indicates the deviation in focal length of focusing lens (mm)	50.3 (+)	50.8 (0)	51.3 (-)

For each factor, three levels are deliberately chosen and set during the experiments according to the DOE. Besides laser beam power and cutting speed, offset in focal length of the focusing lens is also an important factor during laser cutting. Laser beam is focused with the focusing lens having focal length 50.8 mm. So, three levels of focal length offset of focusing lens are considered in this study. Level one is when focal length is adjusted 1 mm above the cutting material, second level is one when focal length is adjusted exactly on the top surface of the cutting material. Third level is when focal length is adjusted 1 mm below the top surface of the cutting material. The level of cutting power, cutting speed and focal length offset was so chosen which evaporate the plastic materials with sufficient depth. In order to avoid any trend effect (nuisance factor), sequence of the test was randomized and with every new combination of cutting power and speed lens was properly cleaned and machine was lubricated.

Here, only the main effects of factors are of interest and their interactions are excluded from the data analysis. In order to avoid any trend effect (nuisance factor) sequence of the test was randomize and with every new combination of cutting power and speed lens was properly cleaned and machine was lubricated.

3. Experimentation and Measurements

3.1 Laser machine

For all cutting experiments the laser beam was supplied by a 25 W continuous laser (Synrad, Inc., mod-48-2) operating with TEM_{00} mode. The laser beam is directed through an optical assembly to a focusing lens (50.8 mm focal length), generating a focused spot with 10.5 μm diameter. The machine has a honeycomb table work area 790 x 530 mm^2, and the movement of work-table is controlled in X-Y axes by a PC. Compressed air was used as a shield gas. The gas was made to strike the specimen orthogonally to its surface through a nozzle 25 mm in diameter. The purpose of the shield gas in CO_2 laser machining is to blown away the molten material from the cut zone and at the same time protects the lens from smoke emitted due to vaporization of the material.

3.2 Workpiece materials

Two engineering plastics namely Poly-Propylene (PP), Polymethylmethacrylate (PMMA) were chosen in this research based on specific manufacturing requirements in terms of product and process in local industry. The properties of the polymers are given in Table-2. Test specimens for both polymeric materials are moulded from virgin plastic granules with dimensions 10 X 5 X 5 cm^3.

Table 2: Measured Thermal & Physical Properties for Thermoplastics

Name of the Material	Glass transition Temperature (˚C)	Specific Energy (J/g)	Density (g/cm^3)
PP	163	777.80	0.1223
PMMA	256	2000.00	1.2123

3.3 Test conditions

Material removal during laser cutting is proved to be influenced by the following variables: 1. Nozzle & distance between nozzle and sample, 2. Lens focal length, 3. Beam spot diameter, 4. Type of inert gas, pressure and flow of the inert gas, 5. Laser power and cutting speed.

Nozzle employed for experimentation was having diameter 1 mm, which ensures efficacious jet of gas that rapidly removes molten material from the cut zone and avoid formation of recast polymer layer. As mentioned by F.Caiazzo *et. al* in [3], nozzle-sample distance was fixed at 1 mm, because at this distance it is possible to obtain an optimum gas jet convergence and pressure in the cutting channel. The engraving machine was equipped with ZnSe type with 50.8 mm focal length, which makes it possible to focus the beam in a small sized focal spot with 0.0105 mm which is almost constant with all setting of laser cutting power. Same has been reported by G.caprino *et. al.* [17] that beam spot diameter has almost no variation with laser power.

During all the test focal length of the lens is adjusted by touching auto focus probe on the top surface of the test specimens. It was noticed by F.Caiazzo *et. al*, [3] that compressed air is sufficient and economical for cutting polymeric materials. As, a result compressed air was selected as cooling gas for engraving all test specimens. In past it was reported by various researchers [3, 6, and 7] that compressed air pressure levels have less significance on laser cutting of polymeric material. As a result sufficient air pressure was kept constant for all tests.

3.4 MRR Measurements

Material Removal Rate (MRR) is the volume of material removed per unit time. MRR decides productivity of manufacturing process. For all test 2 cm × 4 cm rectangular piece was cut from the specimen moulded from virgin plastic granules. On each of these pieces total 25 parallel line was engraved (each having 3.5 cm length) with different combination of cutting power, cutting speed and focusing lens focal length offset as shown in the Table-1. The weight measurement of each of these pieces before and after machining is carried out on digital weight balance of accuracy 0.0001 gm. Calculations of MRR (mg/min) was carried out using following expression [16]:

$$MRR = \frac{(\Delta w \times V)}{l} \quad (1)$$

In order to avoid the effect of any uncontrolled parameters all the test are conduct in random order. Figure-1 shows the specimens of PP and PMMA for material removal test.

Fig.1 Photographs of the Specimens of PP and PMMA for Material Removal Test

4. Data Analysis

Effect of variation in cutting power, cutting speed and offset of focal length of focusing lens is analyses first by considering the main effects of the factors. Figure 2 a-f depicts the plot of factor effects on material removal rate.

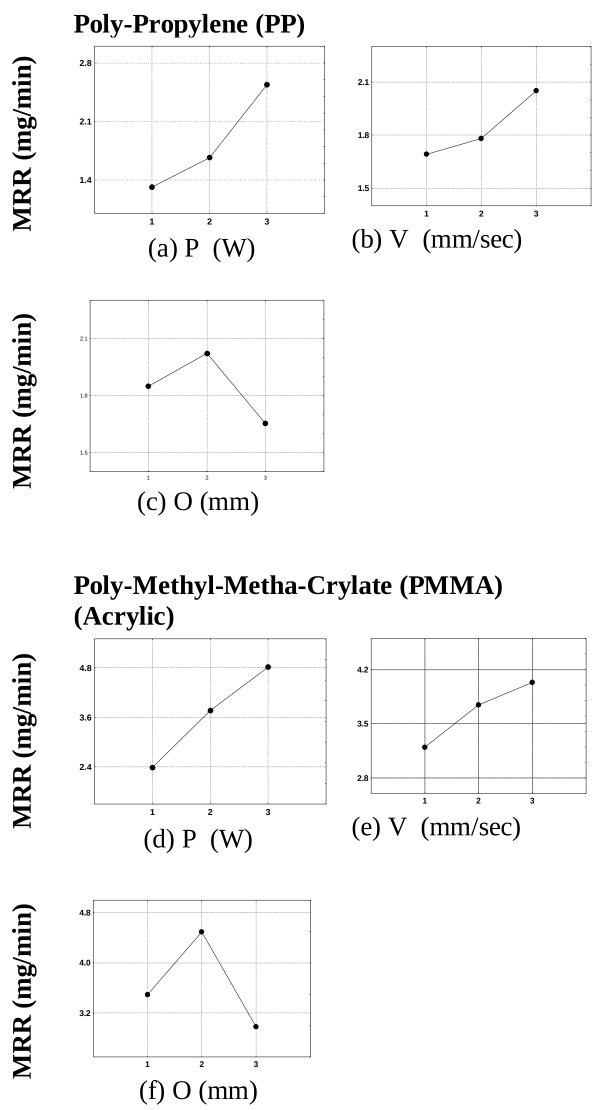

Fig. 2 (a-f) Effects of Factors on Material Removal Rate (mg/min)

Note that the data mean is used to determine each factor's effect. This figure serves the purpose of graphical assessment.

Figure 2a shows the effect of cutting power on material removal rate. It indicates that cutting power has the most significant effect on material removal rate. In addition power has direct proportion to the material removal rate; that is, by increasing power, the material removal rate increases significantly. Figure 2 b, c, and e, f present the effect of cutting speed, and focal length offset on material removal rate. As shown, both the factors have significant effect on material removal rate.

The main effects are calculated and shown in Table 2. The factor effect is defined as the difference between the two extreme values of the response obtained for the corresponding factor [17]. The same conclusion as the graphical assessment can be drawn.

Table 2: Main Effects of Factors on MRR (mg/min)

Factors	Factor effects
PP	
P (W)	1.22553
V (mm/sec)	0.3584
O (mm)	0.36836
PMMA	
P (W)	2.43047
V (mm/sec)	0.83554
O (mm)	0.51298

Analysis of Variance (ANOVA) has been often employed by experimenters, since it covers the shortcomings of graphical assessment. Two of these shortcomings are inaccuracy in the inferences made and that the inferences are only comparatively valid. Before conducting ANOVA, the assumptions used during this analysis are verified as follows.

The normal probability plot of residuals for material removal rate, Anderson-Darling (AD) statistic, and *p*-value are displayed in Figure 3 and 4.

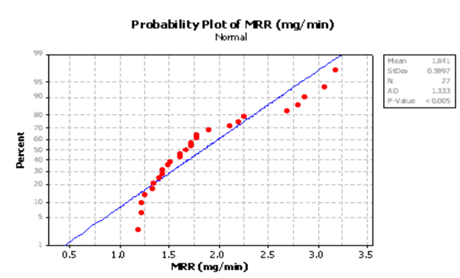

Fig. 3 Normal Probability Plots of Residuals of Material Removal Rate for PP

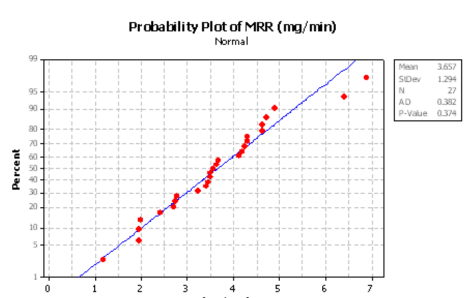

Fig.4 Normal Probability Plots of Residuals of Material Removal Rate for PMMA

A normal probability plot is just a normal probability paper, that is, graph paper with the ordinate scaled so that the cumulative normal distribution is plotted as a straight line. In this figure:

$$P_k = \frac{K - \frac{1}{2}}{N} \qquad (2)$$

in which P_k is calculated for the k^{th} point, while there are N data points in total [18]. The p-value is higher that α- level of confidence (0.05), so it is concluded that the error (residual) is normally distributed. Figure 5 and 6 shows the plot of residuals versus fitted values of material removal rate for both materials PP and PMMA. It is revealed that data points are structurelessly distributed. This indicates that variance constancy and error independency are valid.

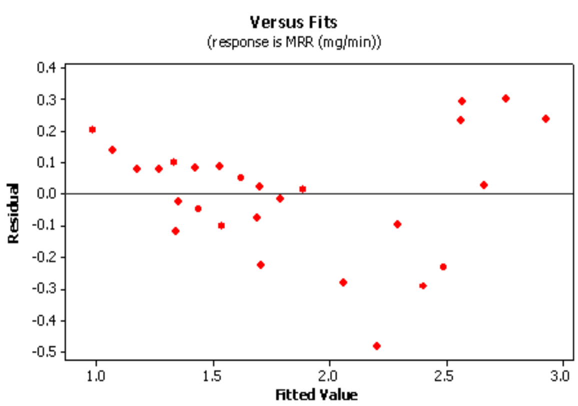

Fig. 5 Plot of Residuals versus Fitted Values of Material Removal Rate for PP

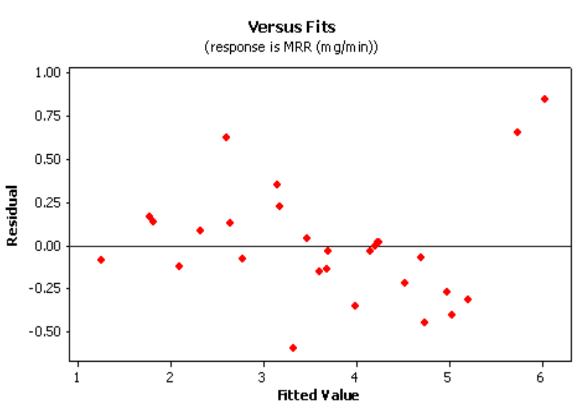

Fig. 6 Plot of Residuals versus Fitted Values of Material Removal Rate for PMMA

So, ANOVA assumptions (error normality, error independency, variance constancy) are proved to be valid, so ANOVA can be performed and the inference made based on its table will be valid. In Table 3, the ANOVA table for material removal rate is presented. All the three factors presents a *p*-value lower than the α-level of confidence. So it is concluded that all the three factors have a significant impact on material removal rate.

Table 3: ANOVA for Material Removal Rate (mg/min) for both Thermoplastics

PP					
Source	SS	D.F.	MS	F	P
P	27.9475	2	13.9738	23.0699	0.00006
V	4.6746	2	2.3373	3.8588	0.000261
O	23.6569	2	11.8284	19.5281	0.0020
Error	12.1143	20	0.6057		
PMMA					
Source	SS	D.F.	MS	F	P
P	26.7386	2	13.3693	91.560	0.00007
V	3.2412	2	1.6206	11.099	0.000572
O	10.6551	2	5.3275	36.486	0.00012
Error	2.9203	20	0.1460		

5. Tables and Figures

5.1 Regression Analysis

To establish the prediction model, regression analysis is conducted using the experimental data. Regression analysis is considered to be one of the most important and most popularly used data mining techniques [18]. Equation 3 and 4 presents the relationship between machining parameters and material removal rate, which is the result of multiple linear regression analysis:

The regression equation for PP is, MRR (mg/min) = 0.453 + 0.613 Cutting Power (W) + 0.179 Cutting Speed (mm/sec) - 0.0981 Focal Length offset (mm) (3)

And regression equation for PMMA is, MRR (mg/min) = 0.905 + 1.22 Cutting Power (W) + 0.418 Cutting Speed (mm/sec) - 0.257 Focal Length offset (mm) (4)

ANOVA is performed for regression analysis and is presented in Table 4. The *p*-value in Table 4 indicates that the estimated model by regression analysis is significant at the α-level of 0.05. This implies that at least one coefficient is different from zero [19].

Table 4: ANOVA for Material Removal rate (mg/min) using SS for Tests

Source	DF	SS	MS	F	P
PP					
Source	DF	SS	MS	F	P
Regression	3	7.5098	2.5033	31.27	0.000
Residual Error	23	1.8412	0.0801		
Total	26	9.3509			
PMMA					
Source	DF	SS	MS	F	P
Regression	3	30.911	10.304	18.74	0.000
Residual Error	23	12.645	0.550		
Total	26	43.555			

DF : degree of freedom SS: sum squares MS: mean squares F: *F*-value P: *p*-value

Table 5 shows verification of the test results. The predicted machining parameters' performance is compared with the actual machining performance and a good agreement is observed between these performances.

The above mathematical model for material removal rate in CO_2 laser cutting is of great importance for the proper selection of machining parameters during the machining of thermoplastics.

Table 5: Results of Confirmation Test MRR (mg/min)

Level	P	V	O	MRR model	MRR Experimental	Error (%)
PP						
1	20	25.6	50.3	1.23	1.25	0.24
2	22.5	32	50.8	1.49	1.77	0.32
3	25	38.4	51.3	2.76	2.79	1.7
PMMA						
1	20	25.6	50.3	2.30	1.93	1.4
2	22.5	32	50.8	2.86	4.62	1.2
3	25	38.4	51.3	3.42	4.30	2.1

5.2 S/N ratio analysis

To find the optimal factor levels, the S/N ratio analysis is used. The kind of problem which matches surface roughness and roundness is "the-larger-the-better" [20]. For such type of problems, η (S/N ratio) is defined as in Eq. 5:

$$\eta = -10 \times \log\left[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^{2}}\right] \quad (5)$$

Here, η is the S/N ratio, y_i is the response, and *n* is the number of replications. The rationale behind S/N ratio analysis is to find a setting of parameters in which signals are predominant. This rationale eventually leads to a situation in which the system is least sensitive to noises [15]. The η values for material removal rate are presented in Tables 6 and 7 for PP and PMMA, respectively.

Table 6: η Values (dB) for Material Removal Rate with PP

Level	P	V	O
1	2.355	4.244	5.011
2	4.407	4.726	5.682
3	7.945	5.736	4.015
Delta	5.590	1.492	1.667

Table 7: η Values (dB) for Material Removal Rate with PMMA

Level	P	V	O
1	7.169	9.425	10.584
2	11.411	10.956	12.634
3	13.477	11.676	8.838
Delta	6.308	2.251	3.796

Table 8: Optimal Setting for Material Removal Rate (mg/min)

PP			
Level	P	V	O
Level Number	3	3	2
Factor magnitude	25	38.4	50.8
PMMA			
Level	P	V	O
Level Number	3	3	2
Factor magnitude	25	38.4	50.8

6. Conclusions

The effects of laser power, cutting speed, and offset of focal length of focusing lens on material removal rate are experimentally investigated with two different groups of thermoplastics namely PP and PMMA using 25 W continuous wave CO_2 laser.

As the experimental results show, both laser power and cutting speed has a significant effect on the material removal rate, whereas effect of offset in focal length of focusing lens is less significant.

A multiple linear regression equation is found for material removal rate in terms of cutting power, cutting speed and offset in focal length of focusing lens. The developed mathematical model for the different machining performance characteristics of the CO_2 laser cutting process is successfully proposed for the proper selection of machining parameters for the evaluation of material removal rate under various machining combinations during the machining of PP and PMMA by the CO_2 laser cutting process. The analysis of variance (ANOVA) for regression analysis indicates that the estimated model for surface roughness is significant.

An optimum parameter combination for the maximum material removal rate is obtained by using the analysis of S/N ratios. From the experimental results as well as analysis of S/N ratios it was confirmed that material removal rate can be maximized when the lens is focused at second level, that is when the focusing lens is focused exactly at its focal length 50.8 mm and is adjusted exactly on the top surface of the cutting material.

The confirmation tests indicate that it is possible to increase the material removal rate significantly by using the proposed statistical technique.

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Nomenclature

Symbol	Meaning	Unit
P	Cutting Power	W
V	Cutting Speed	mm/sec
O	Lens's focal length offset	mm
Δw	Weights difference	gram
l	Length of cut	mm

