LASER CUT SURFACE ROUGHNESS MODELLING USING REGRESSION ANALYSIS

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This Publication has to be referred as: Pasic, M[irza]; Begic-Hajdarevic, D[erzija] & Bijelonja, I[zet] (2018). Laser Cut Surface Roughness Modelling Using Regression Analysis, Proceedings of the 29th DAAAM International Symposium, pp.0838-0845, B. Katalinic (Ed.), Published by DAAAM International, ISBN 978-3-902734-20-4, ISSN 1726-9679, Vienna, Austria
DOI: 10.2507/29th.daaam.proceedings.121

Abstract

In the modern industry the use of lasers has proven to be very useful due to the high precision and quality of cut. Important indicators of the cutting surface quality are roughness of the cutting surface R_a and R_z . In this research experiment is performed to analyse the influence of laser power P , cutting speed v and assist gas pressure p as independent variables on dependent variables R_a and R_z during HSG fiber laser cutting of 1.4307 DIN stainless steel plates, 1 mm thick, using nitrogen as assist gas. During the experiment 75 samples are cut and 225 values of each cutting surface roughness R_a and R_z are measured. Data obtained during the experiment are analysed using regression analysis. Mathematical model is developed for each independent variable R_a and R_z depending on the significant independent variables. Surface roughness values R_z are compared and analysed according to the quality categories defined by ISO 9013: 2002 (E). It can be seen that regression analysis is good tool in modelling cutting surface quality R_a and R_z .

Keywords: fiber laser cutting; surface roughness; regression; stainless steel plates; variables

1. Introduction

The increasing need for production of high precision parts involves higher usage of unconventional cutting methods like laser cutting. During laser cutting there is no physical contact with sample, but thermal energy is used for cutting. Due to high temperatures caused by this laser cutting thermal process, material is melted and then removed by assist gas. Although laser cutting is very precise technique, influence of cutting parameters on surface roughness remains major research problem. For different materials it is important to provide optimal cutting parameters.

Statistical control charts were used to analyse influence of cutting parameters on surface roughness [1]. Lower laser power and higher cutting speed lead to weakening of process control status of tungsten alloy using nitrogen as assist gas. The influence of cutting parameters on cut perpendicularity during HSG fiber laser cutting of stainless steel 1.4307 DIN, 1 mm thick, using linear regression analysis was analysed in [2], since cut perpendicularity is important aspect of cutting surface quality. Mathematical model was developed using linear regression analysis. The model shows that the cutting speed is the only significant independent variable in the model and that the values of cut perpendicularity increase with the increase of cutting speed values.

The correlation between cutting speed and heat affected zone and surface roughness during laser cutting, of 316L stainless steel was discussed in [3]. It is shown that the increase of cutting speed increases quality of surface roughness and very low heat affected zone. In [4] ANOVA was applied to analyse surface roughness and top kerf width based on influence of laser power, cutting speed and gas pressure. Stainless steel (ASTM 304), 3 mm of thickness, was used in this experiment. The lowest surface roughness values were obtained having the lowest laser power and gas pressure and with the highest cutting speed [4]. Investigation of impact of use oxygen, air and nitrogen as assist gas and assist gas pressure on surface roughness, heat affected zone and kerf width was done in [5]. Nitrogen as assist gas was recommended for laser cutting process since it produced best experimental results of three quality cutting process characteristics. However, for each quality characteristics different assist gas pressures were recommended.

Research [6] showed effect of laser cutting parameters during CO₂ laser cutting polymethylmethacrylate 6 mm thick, on surface roughness and optical transmittance ratio using grey relational analysis method. Flow rate of assist gas and beam focus depth are the most influential factors of the surface cut quality. Evaluation of the cut quality based on surface roughness, shape and width of the cut, heat affected zone and burr was done in [7] using metallographic methods during CO₂ laser cutting of INCONEL 625 alloy. It was suggested to increase inert gas pressure, decrease distance of the nozzle and decrease movement speed on the parts where there are changes in the shape. Surface roughness was analysed in [8] during abrasive water jet machining on two different carbon fiber reinforced plastics using regression analysis. ANOVA and F test showed that the most important parameters that affect surface roughness are jet pressure, standoff distance and traverse speed [8].

In this paper surface roughness values R_a and R_z during HSG fiber laser cutting were analysed using regression analysis. Independent variables were laser power P , cutting speed v and assist gas pressure p . Obtained experimental values of R_z were compared to quality groups according to ISO 9013:2002 (E) standard.

2. xperimental setup

This experiment was aimed to establish the effect of laser power P , cutting speed v and assist gas pressure p on the surface roughness R_a and R_z for 1.4307 DIN stainless steel (X2CrNi18-9) 1 mm thick after the laser cutting process on HSG fiber laser. The laser model was the HS - G3015A with the maximum power of 1000 W. The constant cutting parameters during the experiment were: focus position, type of assist gas and the distance between the nozzle and the cutting surface. The focus position was $FP = -1$ mm, the nozzle distance was 1 mm and the diameter of the nozzle $DML = 1,5$ mm. The assist gas used in the experiment was nitrogen (N_2).

During the experiment, 75 samples were cut. Dimensions of the samples were 100x60x1 (mm). For each combination of 5 laser power values, 5 cutting speed values and 3 gas pressure values, one sample was cut. After the laser cutting process, roughness of the surface on each piece was measured. The roughness is measured on the Surftest SJ - 210 Mitutoyo roughness measuring device on all 75 samples. Three places along the cut were selected on each sample and R_a and R_z were measured. On each of 75 samples, three measurements were performed, so that a total of 225 values of R_a and 225 values of R_z were measured. After the values of R_a and R_z were measured, the dependences of the values of R_a and R_z on the laser power P , the cutting speed v and the assist gas pressure p were analysed. In the end, the measured values of R_z were compared with the quality categories according to ISO 9013: 2002 (E).

3. Result analysis

Three scatter plots of relationship between R_a and three independent variables (P, v, p) are depicted at figure 1, figure 2 and figure 3 respectively.

Fig. 1. Relationship between R_a and independent variable P

Fig. 2. Relationship between R_a and independent variable v

Fig. 3. Relationship between R_a and independent variable p

From above figures it can be seen that variability of velocity and pressure do not contribute much to the variability of R_a , while nonlinear quadratic pattern of relationship between R_a and laser power P can be observed. Relationship between R_z and three independent variables (P , v , p) are depicted at scatter plots at figure 4, figure 5 and figure 6 respectively.

Fig. 4. Relationship between R_z and independent variable P

Fig. 5. Relationship between R_z and independent variable v

Fig. 6. Relationship between R_z and independent variable p

Above scatter plots show that variability of velocity and pressure do not contribute much to the variability of R_z as well. It can be seen that there is nonlinear quadratic pattern of relationship between R_z and laser power P .

Existence of nonlinear quadratic relationships was the main reason for the use of quadratic regression analysis in this research. The basic form of quadratic regression equation with three independent variables including quadratic, linear and interaction terms is shown in (1).

$$y = b_0 + b_1 \cdot x_1 + b_2 \cdot x_2 + b_3 \cdot x_3 + b_4 \cdot x_1 \cdot x_2 + b_5 \cdot x_1 \cdot x_3 + b_6 \cdot x_2 \cdot x_3 + b_7 \cdot x_1^2 + b_8 \cdot x_2^2 + b_9 \cdot x_3^2 + b_{10} \cdot x_1 \cdot x_2 \cdot x_3 \quad (1)$$

Backward regression analysis is used in this analysis. Because of large number of steps during the backward regression analysis only the first and the final regression models are shown in this paper.

Regression analysis results for R_a are depicted in table 1.

SUMMARY OUTPUT

Regression Statistics						
Multiple R	0,721					
R Square	0,520					
Adjusted R Square	0,498					
Standard Error	0,435					
Observations	225					

ANOVA					
	df	SS	MS	F	Significance F
Regression	10	43,887	4,389	23,222	0,000
Residual	214	40,444	0,189		
Total	224	84,331			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	-96,369	14,662	-6,573	0,000	-125,270	-67,468
P	0,191	0,019	9,990	0,000	0,154	0,229
v	0,106	0,053	2,017	0,045	0,002	0,210
p	14,799	8,835	1,675	0,095	-2,614	32,213
P sq	0,000	0,000	-13,777	0,000	0,000	0,000
v sq	0,000	0,000	-1,630	0,104	0,000	0,000
p sq	-0,114	0,300	-0,379	0,705	-0,706	0,478
P*v	0,000	0,000	-1,520	0,130	0,000	0,000
P*p	-0,016	0,010	-1,687	0,093	-0,036	0,003
v*p	-0,052	0,031	-1,661	0,098	-0,113	0,010
P*v*p	0,000	0,000	1,710	0,089	0,000	0,000

Table 1. First results of regression analysis for R_a

For significance level $\alpha=0,05$ with 10 and 214 degree of freedom $F_{crit} = 1,87$. Since $F_{stat} = 23,22 > F_{crit}$ it can be concluded that at least one regression coefficient is different from zero. Using t-test all coefficients that are not significantly different from zero are observed and variable with the lowest absolute value of t_{stat} is excluded from the model. These steps are repeated until all non-significant variables are excluded from the model. The final regression model is shown in table 2.

SUMMARY OUTPUT

Regression Statistics						
Multiple R	0,711					
R Square	0,506					
Adjusted R Square	0,499					
Standard Error	0,434					
Observations	225					

ANOVA					
	df	SS	MS	F	Significance F
Regression	3	42,633	14,211	75,319	0,000
Residual	221	41,698	0,189		
Total	224	84,331			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	-71,803	5,587	-12,853	0,000	-82,813	-60,793
P	0,170	0,012	13,599	0,000	0,145	0,194
P^2	0,000	0,000	-13,788	0,000	0,000	0,000
v^2	0,000	0,000	-2,278	0,024	0,000	0,000

Table 2. Final results of regression analysis for R_a

Final regression model shows that laser power P and cutting speed v are significant variables. The final quadratic regression equation is shown by (2).

$$R_a = -71,803 - 0,0000954 \cdot P^2 + 0,1695386 \cdot P - 0,0000042 \cdot v^2 \quad (2)$$

The same steps were applied during R_z analysis. In table 3 are shown the results of regression analysis for R_z .

SUMMARY OUTPUT

Regression Statistics						
Multiple R	0,726					
R Square	0,527					
Adjusted R Square	0,505					
Standard Error	2,640					
Observations	225					

ANOVA					
	df	SS	MS	F	Significance F
Regression	10	1664,691	166,469	23,883	0,000
Residual	214	1491,648	6,970		
Total	224	3156,340			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	-550,931	89,045	-6,187	0,000	-726,449	-375,413
P	1,125	0,116	9,675	0,000	0,896	1,355
v	0,518	0,319	1,622	0,106	-0,112	1,147
p	59,540	53,653	1,110	0,268	-46,215	165,296
P^2	-0,001	0,000	-13,714	0,000	-0,001	0,000
v^2	0,000	0,000	-1,295	0,197	-0,001	0,000
p^2	-0,938	1,825	-0,514	0,608	-4,535	2,658
P*v	0,000	0,000	-1,203	0,230	-0,001	0,000
P*p	-0,065	0,059	-1,108	0,269	-0,182	0,051
v*p	-0,208	0,190	-1,095	0,275	-0,581	0,166
P*v*p	0,000	0,000	1,137	0,257	0,000	0,001

Table 3. First results of regression analysis for R_z

After F test ($F_{stat} = 23,833 > F_{crit} = 119,359$) and t-test, it was concluded that there were coefficients that were not significantly different from zero and the one with the lowest absolute value of t_{stat} was excluded from the model. The procedure was continued until all non-significant variables were excluded from the model. The final results of the regression analysis for R_z are shown in table 4.

SUMMARY OUTPUT

Regression Statistics						
Multiple R	0,720					
R Square	0,518					
Adjusted R Square	0,514					
Standard Error	2,617					
Observations	225					

ANOVA					
	df	SS	MS	F	Significance F
Regression	2	1635,435	817,717	119,359	0,000
Residual	222	1520,905	6,851		
Total	224	3156,340			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	-433,096	33,652	-12,870	0,000	-499,415	-366,778
P	1,022	0,075	13,600	0,000	0,874	1,170
P^2	-0,001	0,000	-13,833	0,000	-0,001	0,000

Table 4. Final results of regression analysis for R_z

After the backward quadratic regression analysis it can be concluded that the only significant variable for R_z is laser power P . The final model for R_z is shown in (3).

$$R_z = -433,096 + 1,0216315 \cdot P^2 - 0,0005770 \cdot P \quad (3)$$

Figures 7, 8 and 9 show diagrams of residuals, stadardised residuals and histogram of residuals for R_a and R_z respectively.

Fig. 7. Residuals vs predicted R_a and standardized residuals vs predicted R_a

Fig. 8. Residuals vs predicted R_z and standardized residuals vs predicted R_z

Fig. 9. Histogram R_a and histogram R_z

Figures 7 and 8 show that residual values are located around zero and that there is no visible pattern and that standardized residuals values are within three standard deviations. It can be concluded that quadratic regression analysis is appropriate to create model for R_a and R_z . Figure 9 shows that the residuals are approximately normally distributed. The condition of normality of residuals is satisfied.

4. Comparison of R_z values with ISO standard

There are 225 values of R_z that were measured during the experiment. Those values were compared to the quality category groups defined by ISO 9013: 2002 (E) standard. Figure 10 shows that the most of the values of R_z are in the second quality group according to ISO standard. But some of the values are in the first quality group.

Those values were obtained for laser power $P = 800$ W and $P = 1000$ W.

Fig. 10. R_z values

5. Conclusion

Since the surface roughness parameters R_a and R_z in laser cutting are very important, the influence of cutting parameters such as laser power, cutting speed and assist gas pressure on R_a and R_z during laser cutting on HSG fiber laser of stainless steel 1.4307 DIN was investigated. In order to examine the dependence of R_a and R_z on the mentioned cutting parameters, a quadratic regression analysis was used. Analysis shows that significant independent variables for R_a are laser power P and cutting speed v and for R_z it is laser power P . From the quadratic equations obtained through regression analysis, it can be concluded that the values of R_a and R_z are lower if the values of laser power P are at minimum value (800 W) and at maximum value (1000 W). Also, at lower values of cutting speed, value of R_a will be lower. The influence of the cutting speed v is much lower than the influence of the laser power P on the values of R_a . Also, assist gas pressure is not significant variable for both R_a and R_z . The comparison of values of R_z with the the quality category groups defined by ISO 9013: 2002 (E) standard was done. Comparison shows that the most values of R_z are in the second quality group according to ISO standard. It can be concluded that the highest chance to have the value R_z in the first quality group is by setting the laser power to 800 W or 1000 W. The highest quality of the cutting surface can be achieved with the laser power of 800 W and 1000 W and with the lower values of cutting speed v . In the future research experiment the same combination of the cutting parameters will be used to predict the values of heat affected zone using regression analysis.

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