ESTIMATION OF THE LASER CUT PERPENDICULARITY USING LINEAR REGRESSION ANALYSIS

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Abstract

The aim of this paper is to develop a mathematical model using a linear regression analysis for the laser cut perpendicularity depending on the cutting parameters and to compare the values of the cut perpendicularity according to ISO 9013:2002 (E) standard. Cutting parameters that are used as independent variables in this research are: laser power P , cutting speed v and assist gas pressure p . During the experiment 75 samples of 1.4307 DIN stainless steel and 1 mm of thickness were cut on HSG fiber laser using nitrogen N_2 as an assist gas. Each sample was cut using different combination of values of independent variables. Cut perpendicularity was measured on these samples with total of 225 measurements. Obtained results show that the cutting speed is only significant variable in the model and that the linear regression analysis is suitable for the analysis of the cut perpendicularity. Every experimental value of the cut perpendicularity is located in the first quality category according to ISO 9013:2002 (E) standard.

Keywords: laser cutting; fiber laser; regression analysis; cut perpendicularity; stainless steel

1. Introduction

Multiple regression analysis is shown to be useful technique for mathematical modeling of many industrial engineering processes including material cutting process. These processes happen as result of interaction of variables. Some of these variables are independent, while some are dependent. To explain these processes, it is important to determine relations between these variables and to create the model that will explain certain process and prediction of dependent variables [1].

During the laser cutting process there are many variables. Some of them are independent variables, known as cutting parameters, defined before laser cutting process, while some are dependent variables which determine cut quality and their values depend on variability of independent variables. Regression analysis is used to obtain mathematical model that explains variability of dependent variables based on variability of independent variables.

Nowadays in many fields like informatics, measurement technique, telecommunications and medicine there is increasing need for the high precision of small parts and for reduction of material and energy used in production processes. The use of laser is more and more present and necessary in industrial practice. Laser cutting is the modern cutting method and its use is in expansion because of many advantages in comparison to conventional cutting processes. Laser cutting is thermal cutting process and has advantages even to other thermal cutting processes [2, 3]. Advantages of the laser cutting are high quality of the cut surface, narrow kerf width, low heat affected zone and sharp and perpendicular edges. However, during the laser cutting process the cut quality can vary depending on many factors such as cutting parameters, type of assist gas and type of material [4].

Many papers examine influence of these factors on certain aspects of the cut quality. In [5] influence of cutting speed, focus position, assist gas pressure and stand-off on surface roughness R_a and heat affected zone using two different types of steel is investigated. It is concluded that R_a is smaller when the cutting speed is higher and with focus position above the surface, while the assist gas pressure does not affect R_a .

In [6] dependency of kerf width is analyzed based on variability of laser power and type of assist gas. The cutting is performed on 3 stainless steel plates of different thickness. It is concluded that with increase of energy per unit of length there is increase of the kerf width. With the same laser power kerf width is higher if nitrogen is used as an assist gas instead of oxygen.

In [7] influence of laser power and cutting speed on surface roughness R_a is examined during CO₂ laser cutting using oxygen as assist gas. Influence of increase of cutting speed on surface roughness and heat affected zone is analyzed in [8]. Research [9] uses regression analysis for development of model that describes influence of laser power on kerf width, surface roughness, heat affected zone and striation frequency.

Regression analysis is shown to be very reliable method for analysis of parameters and quality of laser cutting process. Analysis of research papers shows that general model of dependency of the laser cutting quality on cutting parameters has not been developed yet, but each experiment is special case depending of laser type, type of assist gas, thickness of material etc.

In this paper regression analysis is used to analyze cut perpendicularity with respect to cutting parameters: laser power, cutting speed and assist gas pressure during fiber laser cutting with N₂ as assist gas. Multiple regression analysis is performed to develop mathematical model to predict cut perpendicularity and to determine which cutting parameters are significant for cut perpendicularity.

2. Experimental setup

In this experiment 75 samples of 1.4307 DIN (X2CrNi18-9) stainless steel of 1 mm of thickness were cut on HSG fiber laser using nitrogen N₂ as an assist gas. HSG fiber laser with nominal power of 1000 W was used in this experiment. Cutting parameters that were varied in this experiment were laser power P , cutting speed v and assist gas pressure p . These cutting parameters were used as independent variables in the linear regression analysis. During cutting process five different values of laser power and cutting speed and three different values of assist gas pressure were used. Those values are shown in table 1, table 2 and table 3.

Laser Power P	Values
P_1	800 W
P_2	850 W
P_3	900 W
P_4	950 W
P_5	1000 W

Table 1. Laser power values

Cutting speed v	Values
v_1	320 mm/s
v_2	300 mm/s
v_3	280 mm/s
v_4	260 mm/s
v_5	240 mm/s

Table 2. Cutting speed values

Assist gas pressure p	Values
p_1	1 bar
p_2	1,3 bar
p_3	2 bar

Table 3. Assist gas pressure values

Cutting parameters that were constant during the cutting process are presented in table 4.

Constant cutting parameters	Values
Focus position	-1 mm
Distance of the nozzle	1 mm
Diameter of the nozzle	1,5 mm

Table 4. Values of cutting parameters that were constant during the cutting process

Each sample was made with different combination of values of cutting parameters. There are 75 different combinations of values of cutting parameters and thus 75 samples were cut. Kerf width was measured by microscope Mitutoyo TM 505 and camera Motic 10 MP. Camera was placed on the microscope and they both were connected to computer via software Motic Images Plus 3.0.

On each sample nine places were marked on both input and output side of the laser beam side of the sample. By microscope and camera, on each marked spot, kerf was captured and the picture was downloaded to the computer. After that kerf width was measured on each captured picture using software Motic Images Plus 3.0. Nine measurements of the kerf width were made on each side of the sample, leading to 675 measurements for input and 675 measurements for output side of laser beam.

Next step was to calculate average values of the kerf width for input and output side of laser beam for each sample. Difference between average values of the kerf width on the input and the output side of the laser beam was calculated for each sample. This difference is called cut perpendicularity. There were 75 values of cut perpendicularity. After the measurements, linear regression analysis was done using cut perpendicularity as dependent variable and laser power P , cutting speed v and assist gas pressure p as independent variables. These 75 values of cut perpendicularity were categorized according to the ISO 9013:2002 (E) standard.

3. Analysis of results

Based on the experiment, backward multiple regression model was developed using sample size $n = 75$ and number of independent variables $k = 3$. Regression analysis results are given in table 5.

Regression Statistics	
Multiple R	0,732
R Square	0,536
Adjusted R Square	0,517
Standard Error	6,961
Observations	75

ANOVA					
	df	SS	MS	F	Significance F
Regression	3	3980,351	1326,784	27,379	0,000
Residual	71	3440,641	48,460		
Total	74	7420,992			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	25,469	13,274	1,919	0,059	-0,999	51,937
P	-0,078	0,011	-6,889	0,000	-0,101	-0,056
v	0,166	0,028	5,846	0,000	0,109	0,223
p	1,373	1,918	0,716	0,477	-2,452	5,198

Table 5. First results of regression analysis

Calculated F test value ($F_{stat} = 27,379$) is greater than the critical F value ($F_{crit} = 2,734$) for $\alpha = 0,05$ level of significance with 3 and 71 degrees of freedom which means that there is at least one regression coefficient b_i ($i = 1, 2, 3$) different from zero. Comparing statistical t values with critical t value, as well as comparing p values with $\alpha = 0,05$ it can be seen that b_1 and b_2 regression coefficients are statistically different from zero, while b_3 is zero as shown in (1), (2) and (3).

$$b_1: t_{stat}(P) = -6,889 < t_{crit} = -1,99; p - value(P) = 0 < \alpha = 0,05; \Rightarrow b_1 \neq 0 \quad (1)$$

$$b_2: t_{stat}(v) = 5,846 > t_{crit} = 1,99; p - value(v) = 0 < \alpha = 0,05; \Rightarrow b_2 \neq 0 \quad (2)$$

$$b_3: t_{crit} = -1,99 < t_{stat}(p) = 0,716 < t_{crit} = 1,99; p - value(p) = 0,477 > \alpha = 0,05; \Rightarrow b_3 = 0 \quad (3)$$

Since assist gas pressure is not significant variable, regression analysis was done again, this time with cutting speed and laser power as independent variables. Regression analysis results are presented in table 6.

Regression Statistics	
Multiple R	0,656
R Square	0,431
Adjusted R Square	0,415
Standard Error	4,163
Observations	75

ANOVA					
	df	SS	MS	F	Significance F
Regression	2	943,428	471,714	27,219	0,000
Residual	72	1247,785	17,330		
Total	74	2191,213			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	-28,259	7,766	-3,639	0,001	-43,740	-12,778
P	0,002	0,007	0,365	0,716	-0,011	0,016
v	0,125	0,017	7,369	0,000	0,091	0,159

Table 6. Second results of regression analysis

For $\alpha = 0,05$ level of significance with 2 and 72 degrees of freedom $F_{crit} = 3,124$. From table 4 it can be seen that $F_{stat} = 27,219$. F test shows that at least one out of two regression coefficients is different from zero. Comparing t_{stat} values for each regression coefficient with critical t value ($t_{crit} = \pm 1,99$) it can be concluded that laser power is not significant variable in the model. Finally, regression analysis with cutting speed as only independent variable was performed. Results of regression analysis are presented in table 7.

Regression Statistics	
Multiple R	0,655
R Square	0,429
Adjusted R Square	0,422
Standard Error	4,138
Observations	75

ANOVA					
	df	SS	MS	F	Significance F
Regression	1	941,113	941,113	54,957	0,000
Residual	73	1250,099	17,125		
Total	74	2191,213			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	-26,023	4,754	-5,474	0,000	-35,499	-16,548
v	0,125	0,017	7,413	0,000	0,092	0,159

Table 7. Third results of regression analysis

From table 5 it can be seen that cutting speed is significant variable since $t_{stat} = 7,413 > t_{crit} = 1,99$. Regression equation for the cut perpendicularity U is given by (4).

$$U = -26,023 + 0,125 \cdot v \quad (4)$$

Figures 1 and 2 depict diagrams of residuals and standardized residuals respectively.

Fig. 1. Residuals vs. predicted cut perpendicularity

Fig. 2. Standardized residuals vs. predicted cut perpendicularity

From figures 1 and 2 it can be seen that the values of residuals are located around zero value without visible pattern, while standardized residuals are within three standard deviations. There are no extreme values of residuals and it can be concluded that regression equation is suitable to predict cut perpendicularity with respect to cutting speed. Histogram of residuals is depicted on figure 3.

Fig. 3. Histogram of residuals

From figure 3 it can be seen that the residuals are approximately normally distributed and that the condition of normality of residuals is satisfied.

Coefficient value for the cutting speed is 0,125 which means that with the unit change of cutting speed the cut perpendicularity change is 0,125. Standardized coefficient value for cutting speed is 0,356 which means that with unit change of standard deviation of cutting speed, the change of the cut perpendicularity is 0,356 standard deviation. Since coefficient of determination is $R^2 = 0,429$, it can be concluded that 42,9% of variability of the cut perpendicularity is explained with variability of the cutting speed.

4. Verification of results according to ISO standard

During the experiment for the each sample average cut perpendicularity was computed, so 75 values of the variable cut perpendicularity was obtained. Since cut perpendicularity depends on the cutting speed, diagram of the cut perpendicularity vs. cutting speed was made as presented in figure 4. Diagram shows average values of cut perpendicularity, as well as horizontal line which presents the border of the first quality category of the cut perpendicularity according to ISO 9013:2002 (E) standard.

Fig. 4. Cut perpendicularity values

From figure 4 it can be seen that all average values of the cut perpendicularity are located well beyond the border of the first quality category of the cut perpendicularity according to ISO 9013:2002 (E) standard. It means that there are no large deviations of the kerf width at input and output side of the laser beam.

5. Conclusion

In this research the stainless steel 1.4307 DIN, 1 mm of thickness was cut by HSG fiber laser. The effect of laser power, cutting speed and assist gas pressure on the cut perpendicularity was examined. Backward elimination linear regression analysis was used to create mathematical model for the estimation of the laser cut perpendicularity. From the regression model, it can be concluded that cutting speed is the only significant independent variable and that 42,9% variability of the cut perpendicularity is explained by the cutting speed. According to the model, cut perpendicularity increases with the increase of the cutting speed.

Analysis of residuals shows that there is no visible pattern. Also, analysis of standardized residuals shows that all standardized residuals are within three standard deviations. Histogram of residuals shows that residuals are approximately normally distributed. It can be concluded that there are no extreme measured values and that the obtained regression model is suitable to predict values of the laser cut perpendicularity depending on the cutting speed.

Every experimental value of the cut perpendicularity is located in the first quality category according to ISO 9013:2002 (E) standard. The recommendation could be to use the highest experimental speed of 320 mm/s so to increase efficiency of the cutting process.

In the future research experiment with the same combination of the laser power and assist gas pressure values could be performed, but to use higher cutting speeds. In that way, it can be determined at which cutting speed the value of the cut perpendicularity moves into the second category of the quality according to ISO 9013:2002 (E) standard.

6. References

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