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PREDICTION MODEL FOR DEPTH OF SEPARATION LINE OBTAINED IN CO_2 LASER CUTTING OF STAINLESS STEEL

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ABSTRACT: *In this paper, an empirical mathematical model for the prediction of separation line obtained in CO_2 laser cutting of stainless steel using nitrogen as assist gas was developed. Laser cutting experimental trials were planned and conducted by varying four laser cutting factors according to design of experiment method using Taguchi's L_{27} design. Multiple regression analysis was used to develop mathematical relationship between laser power, cutting speed, assist gas pressure and focus position, and depth of separation line. ANOVA analysis confirmed the adequacy of the quadratic model at p<0. 05. Based on the obtained results it can be concluded that the effects of cutting speed, focus position and laser power on depth of separation line were most pronounced, while the effect of assist gas pressure was not so significant.*
KEYWORDS: *depth of separation line, prediction, CO_2 laser cutting, stainless steel*

INTRODUCTION

The use of laser cutting has been widely accepted in metal cutting industry. High material removal rate, low operational cost and high cut quality made laser cutting superior to the existing competing methods of contour cutting. Although the edge quality of a laser cut is generally superior to that achieved by other conventional methods, the periodic striations limit the quality of the finished component edges [10].

The continuous-wave CO_2 laser has most commonly been used for metal cutting over the last two decades [7]. A typical laser cutting system consists of laser beam unit, laser beam guidance optics, cutting head and CNC motion system which provides relative motion between laser beam and workpiece along the programmed contour. By focusing the laser beam on the workpiece, high energy intensity is concentrated on a small spot causing melting and evaporation of material in a fraction of second. The molten material is then removed by the jet of assist gas which is supplied coaxially with the laser beam through the nozzle in the cutting head. Depending on the workpiece material, the assisting gas can be inert (helium, argon, etc.) or reactive (oxygen). Inert gas is used when processing plastics, wood, etc., whilst oxygen is employed when cutting metals, those metals where oxidation of the metal can provide extra heat [10].

In laser cutting of materials, examination of cut surface provides valuable information about cut quality such as surface roughness, striation characteristics, grooves, heat affected zone, burr formation and other metallurgical characteristics. The striation formation has received a lot of attention due to its effect on the cut quality in laser cutting [9]. However, the mechanism for striation formation is not fully understood and several explanations for its occurrence in laser cutting have been proposed in literature. The two possible explanations for the striation formation have been offered based on the pulsation in the molten layer and the side burning phenomenon [2]. The first explanation for the periodic striation formation is based on the fluctuations and oscillations of the liquid layer caused by instabilities associated with the dynamic nature of laser cutting [6]. By this theory, fluctuations of the liquid layer induce perturbations on the cutting edges due to movement of the liquid layer, with the cutting front, which subsequently solidifies into characteristic striation pattern. However, the most widely accepted theory for striation formation is proposed by Arata et al. [1]. By this theory, striation formation is based on the side burning effect and is achieved in burning-extinction-reinititation cycle.

The striation formation is influenced by the laser and workpiece parameters, such as power intensity distribution across the irradiated spot, repetition rate of the laser pulse, focus setting of focusing lens, purity of assisting gas and its pressure, cutting speed, workpiece thickness, etc [10]. Numerous investigations have been reported in literature to analyze the effects of the laser cutting factors on the striation characteristics in laser cutting. Rajaram et al. [5] investigated the combined effect of laser power and cutting speed on striation frequency in CO_2 laser cutting of 4130 steel. The *authors observed that striation frequency is almost independent of laser power, but a slight increase in striation frequency occurs with an increase in cutting speed up to a critical cutting speed. Beyond this critical value, the striation frequency remains almost constant with further increase in cutting speed. Furthermore, the critical value of cutting speed is dependent on laser power. Yilbas and Rashid [10] studied CO_2 laser cutting of Incoloy 800HT. A statistical analysis employing a factorial analysis was carried out to determine the significance levels of the cutting speed, laser output intensity, thickness, and the pulse frequency of the laser beam for the waviness, out of flatness, and overall quality of the cut edges. It was found that the dross ejection frequency is directly related to the striation frequency. The authors indicated temporal behavior of the molten metal production rate as a possible explanation for the periodic striations. Sobih et al. [7] demonstrated striation-free laser cuts on 1 mm thick mild steel using fiber laser. Wee at al. [9] presented a detailed parametric study for investigation of the effects of the interaction time, irradiance and assist gas pressure on striation wavelength, striation angle and depth of separation line during laser cutting of ceramics. A statistical model based on multivariate regression was applied to determine the parameters affecting cut quality. Di Pietro et al. [3] presented a technique for determining striation frequency and depth of the periodic structure by using dispersion analysis based on autoregressive moving average model. The findings of the authors strongly support the sideways burning theory for the mechanism governing striation formation.*

In this paper, an experimental study was conducted to investigate the effects of main laser cutting factors such as laser power, cutting speed, assist gas pressure and focus position on depth of separation line in CO_2 laser nitrogen cutting of stainless steel. On the basis of the data obtained from experiment conducted according to the Taguchi's experimental design, the mathematical model for separation line prediction was developed by using regression analysis.

EXPERIMENTAL

The presence of periodic striations along the cut surface is undesirable since they may act as stress raisers in addition to the unpredictable geometric changes and necessitation of the further finishing operations to achieve smooth surface [2]. In the case of thin materials, these striations are generally clear and regular from the top of the cut edge to the bottom, whereas in the case of thick materials, these striations may be well defined at the top of the cut edge and become more random towards the bottom [4]. Typical striation patterns formed during CO_2 laser nitrogen cutting at different combination of laser cutting factor values are shown in Figure 1.

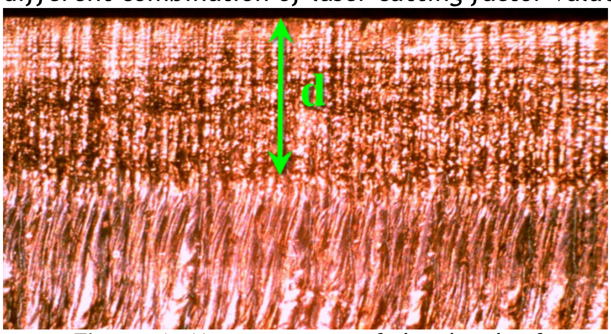

Figure 1. Measurement of the depth of separation line (laser cutting conditions: laser power = 1.6 kW, cutting speed = 3 m/min, assist gas pressure = 9 bar, focus position –0.5 mm)

At this separation line the shear stress exerting on the melt is significantly reduced due to wake formation, which results in inefficient melt ejection and thicker molten layer. To achieve more or less uniform cut quality the gas flow in the kerf should be laminar in nature [8].

The depth of separation line (d) evaluation was carried out on a photo of cut sample with the aid of stereo microscope (KONUS, Diamond #5420, magnification 40 X). The measurements were made at five equally distanced positions along the photo of cut sample and the average values were calculated and recorded.

For conducting the experiment trials, CO_2 laser cutting machine (Bystronic, ByVention 3015) with a maximal power of 2.2 kW was employed. Straight cuts performed with a Gaussian distribution beam mode (TEM_{00}) in continuous wave mode on 3 mm thick AISI 304 stainless steel sheet. Through the experimentation, the following constant factors were used: lens focal length of 127 mm, nozzle diameter of 2 mm, distance between nozzle and workpiece of 1 mm and assist gas with purity of ≥ 99.95 %. The main laser cutting factors such as laser power (P), cutting speed (v), assist gas pressure (p) and focus position (f) were varied at three levels: P=1.6, 1.8, 2 kW; v=2, 2.5, 3 m/min; p=9, 10.5, 12 bar; and f=-2.5, -1.5, -0.5 mm. To carry out experimental work laser cutting experiment was planned and conducted in accordance with the standard L_{27} (3^{13}) Taguchi's orthogonal array. Laser cutting factors P, v, p and f were assigned to columns 1, 2, 5 and 12, respectively.

PREDICTION MODEL AND ANALYSIS

In order to analyze the effects of laser cutting factors on depth of separation line a mathematical model is needed. Assuming that between laser cutting factors and depth of separation line nonlinear relationship exists, second order nonlinear mathematical model was develop.

To include first, second order main effects and interaction effects of the laser cutting factors, initially full second order regression model was developed. However, as it is well known in mathematical modeling, the goal is to find as simple model as possible which describes adequately the *underlying process. Best subsets regression is an efficient way to identify models that achieve specified goal with as few predictors as possible. Considering four criteria for assessing the mathematical models such as coefficient of determination (R^2), adjusted coefficient of determination, Mallow's C_p statistic and square root of mean square error and using the experimental data, the following mathematical model for prediction of depth of separation line (d) was developed:*

$$d = 16.6 - 2.57P - 2.48v - 1.66p - 1.02f + 0.0195P^2 - 0.151f^2 + 0.406Pp + 0.509Pf + 0.191vp \quad (1)$$

The R^2 statistical value of 0.734 indicates that the proposed mathematical model explains 73 % of the variability in depth of separation line values. P value of 0.002 from ANOVA analysis confirms the validity of the model.

To analyze the effects of laser cutting factors on the depth of separation line Eq. (1) was plotted. Six 3-D surface plots (Figure 2) were generated by varying two factors of interest, while other two factors were held constant at their middle levels.

From Figure 2 (a, b, c) it could be seen that, irrespective of other laser cutting factors, an increase in laser power increases depth of separation line. This can be explained considering that the high laser power generates a high temperature causing increasing melt formation down the kerf.

From Figure 2 (a, d, e) it could be seen that, apart from other laser cutting factors, an increase in cutting speed decreases depth of line separation line. As the cutting speed is decreased there is an increase in kerf width which results in an increase in the melt flow velocity and a reduction in the melt film thickness [8], simultaneously increasing the depth of separation line.

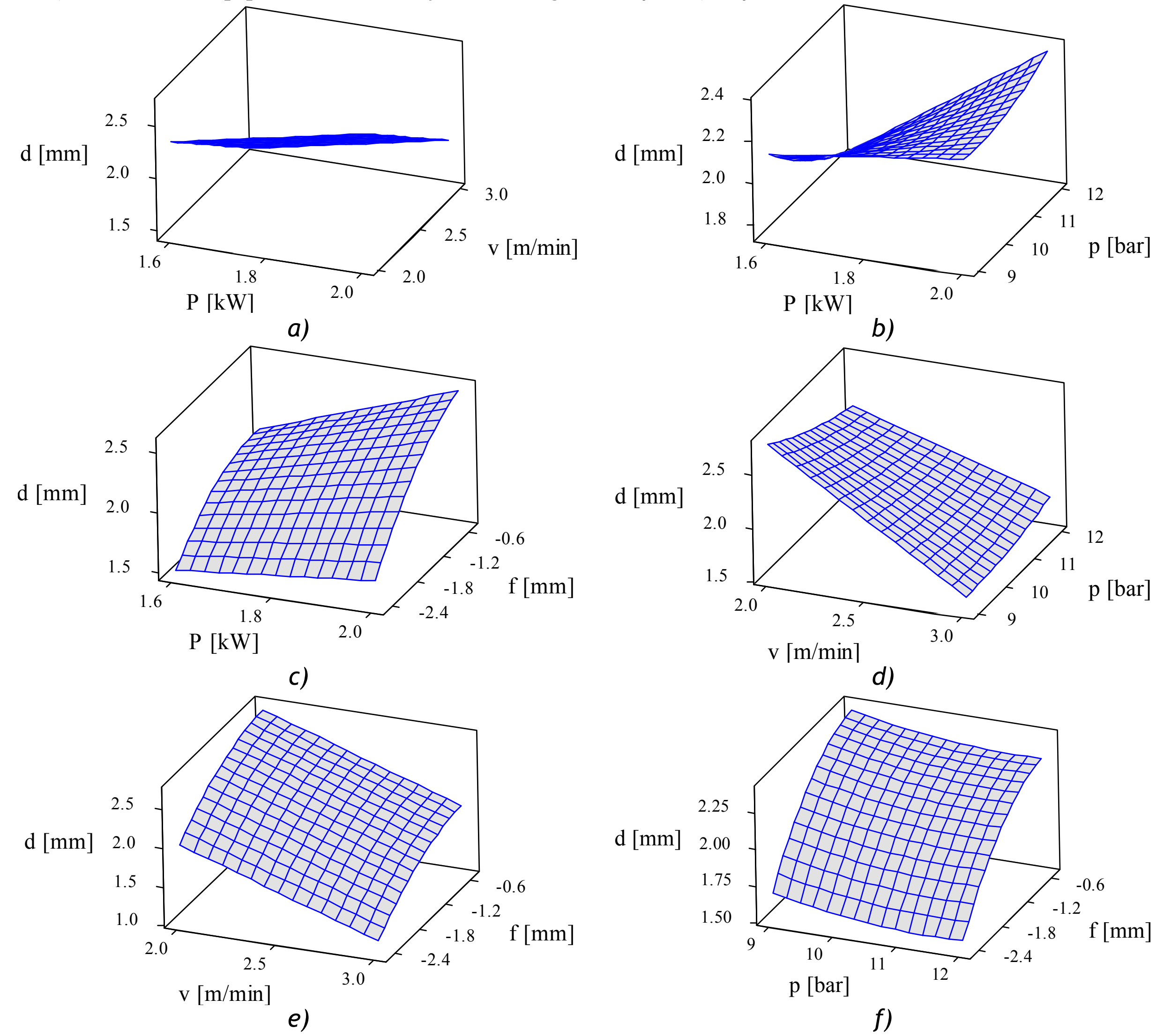

Figure 2. Effects of the laser cutting factors on depth of separation line

From Figure 2 (b, d, f) it could be seen that, depending on other laser cutting factors, an increase in assist gas pressure decreases or increases the depth of line separation line. The higher laser power and the greater assist gas pressure is used, that melt flow velocity increases and the melt film thickness decreases so that the depth of the separation line is increased.

From Figure 2 (c, e, f) it could be seen that, irrespective of other laser cutting factors, an increase in focus position (focusing the laser beam nearer to the bottom surface) increases depth of *line separation line. Increased focus positions produce wider cut kerfs which enhance the melt flow velocity in the cut kerf allowing laminar flow up to larger depths.*

CONCLUSIONS

An empirical mathematical model for the prediction of separation line in CO_2 laser cutting of stainless steel using nitrogen as assist gas has been developed. Good correlation was found between the predicted and experimental values of depth of separation line. Based on the analysis of the model, the following points can be made:

- *Increase in laser power and focusing the laser beam nearer to the bottom surface increases the depth of separation line.*
- *Increase in cutting speed decreases the depth of separation line.*
- *The effect of the assist gas pressure on depth of separation line is variable and should be considered through the interaction with other laser cutting factors.*
- *Quantitatively, the effects of cutting speed, focus position and laser power on depth of separation line were most pronounced. The effect of assist gas pressure was not so significant.*

The developed prediction model for the depth of separation line can be used in conjunction with other process models so as to determine laser cutting factor values which produce high cut quality.

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