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ANALYSIS OF THE EFFECTS OF CUTTING SPEED AND FOCUS POSITION ON OXIDATION MARKS IN FIBER REACTIVE LASER CUTTING

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Abstract: *Reactive laser cutting is well established laser cutting method in industry for contour cutting of carbon and low alloyed steels. This study was focused on the analysis of the oxidation marks formed due to existence of thin oxide films in the vicinity of the cut edge. To this aim a 3^2 factorial design was performed to define nine cutting regimes in fiber reactive laser cutting of carbon steel S235JR by varying the focus position and cutting speed at three levels. Microscopic pictures were used to determine the extent of surface oxidation along the straight cut profile on both upper and lower plate surface. The performed analyses considered the effects of these input parameters on the resulting oxidation mark widths both on upper and lower plate surface and ratio of oxidation mark widths on upper and lower plate surface. In addition, a nonlinear mathematical model for the prediction of oxidation mark widths was developed. The oxidation mark widths are consistently narrower at the upper plate surface. Results indicate a negative correlation between the cutting speed and oxidation mark width, while the effect of focus position is more variable, particularly on the upper plate surface.*

Keywords: *fiber laser, reactive cutting, oxidation mark, carbon steel, 3^2 experimental design*

1. INTRODUCTION

Since its introduction in the practice in 1967 [1], reactive laser cutting is one of the most widely used laser cutting techniques in industry for contour cutting of carbon steels and low alloyed steels. The workpiece material in the cut zone is also heated by the energy of the laser beam and by the energy resulting from the exothermic reaction of the material and oxygen which is used as assist gas. Approximately, exothermic reaction typically contributes half of the required energy for cutting [2]. This laser cutting technique generates relatively high cut quality and in comparison to laser fusion cutting it offers better productivity and process economics due to significantly lower assist gas flow rates. It has to be noted that purity level of oxygen is of the utmost importance given its multiple effects on dross formation, achievable cutting speed and overall cut quality [3]. CO_2 and Nd:YAG lasers are traditionally used for reactive laser cutting, and recently fiber laser cutting technologies are widely used for 'striation free' reactive laser cutting [4].

Although offering a number of advantages and capabilities [5], effective application of reactive laser cutting technology requires careful consideration of required process performances and cut quality characteristics and associated main input parameters. Likewise, optimization of laser cutting processes requires synergy of different knowledge, methods and approaches, such as design of experiments, statistical data analysis, artificial intelligence and machine learning methods, process specific knowledge, etc. [6]. A number of studies were carried out with the aim of analyzing the influence of inputs on surface roughness [7], dimensional accuracy of cut features [8], heat affected zone [9], kerf width [10], kerf taper [11], dross formation [12], material removal rate [13], cutting efficiency [14], oxidation marks [15], etc.

In reactive laser cutting darkening of the processed surface in the vicinity of the cut edge on both sides of the plate is evident due to the formation of thin oxide films. Al-Mashikhi et al. [15] observed significant correlation between the oxidation mark widths and size of the heat affected zone (HAZ). Given that knowing oxidation mark widths can serve as an approximate, simple and fast assessment for HAZ extension, the analysis of the oxidation marks in fiber reactive laser cutting of carbon steel is in the focus of the present study. To this aim a 3^2 factorial design was performed to define nine cutting regimes in fiber reactive laser cutting of carbon steel S235JR by varying the focus position and cutting speed at three levels. The performed analyses considered the effects of these input parameters on the resulting oxidation mark widths both on upper and lower plate surface and ratio of oxidation mark widths on upper and lower plate surface. In addition, a nonlinear mathematical model for the prediction of oxidation mark widths was developed and analyzed.

2. EXPERIMENTAL DETAILS

HGTECH fiber laser machine with Raytools cutting head was used for experimentation. The machine has a maximum power of 6000 W and a wavelength of 1070 nm. Fiber laser reactive cutting method was chosen since specimens were cut from the plate with thickness of 4 mm made of carbon steel S235JR. Oxygen 3.5 was used in the experiment. During the experiment, key laser cutting parameters were set at constant values: laser power (3.3 kW), stand-off distance (0.8 mm), oxygen pressure (0.65 bar) and nozzle diameter (1.2 mm). A 3^2 factorial design without replication was used to define 9 experimental trials while varying cutting speed and focus position at three levels. The levels of variation of are given in Table 1.

Table 1. Three levels of variation of parameters

Input parameter	Unit	Level 1	Level 2	Level 3
Focus position (f)	mm	1.2	1.4	1.6
Cutting speed (*v*)	m/min	3	3.3	3.6

As a process output of interest oxidation marks at the upper and lower plate surface were measured. To this aim Delta Optical Smart PRO digital microscope with 5MP camera, LED illumination and tripod was used. Three measurements of oxidation marks along the straight cut profile on both sides of the plate surface were performed to obtained averaged values in accordance to measurement procedure proposed in literature [15]. Examples of microscope pictures for oxidation mark measurements are given in Figure 1. Due to oxidation, the darkening of the material in the vicinity of the cut edge can be clearly seen. Oxidation marks correspond to the localized presence of thin oxide films on the surface of the cut material [15].

a)

b)

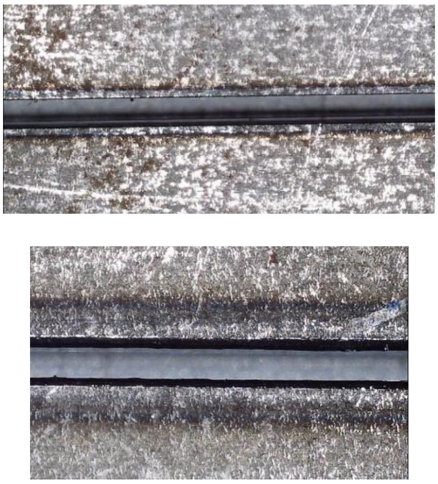

Figure 1. Microscope pictures for oxidation mark measurement: a) upper plate surface, b) lower plate surface

3. RESULTS AND DISCUSSION

The results of experimental measurements of oxidation marks at the upper and lower plate surfaces of the specimens are graphically represented in Figure 2.

a)

b)

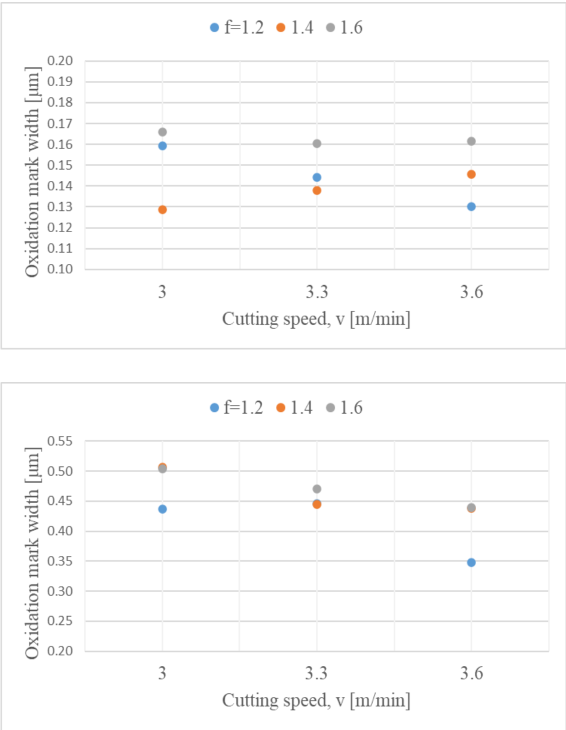

Figure 2. Experimental values of oxidation marks widths: a) upper plate surface, b) lower plate surface

There is tendency for an increase in the oxidation mark width with an increase in the focus position and this is particularly pronounced on the lower plate surface. The variation of the oxidation mark widths is more pronounced on the upper plate surface, with an increase in focus position it can be increased, decreased or rather be approximately constant. Experimental measurements of kerf width on lower and upper plate surface show average kerf width values of 0.589 mm and 0.645 mm on lower and upper plate surface, respectively. However, for focus position of f=1.6 mm and across all cutting speed range the kerf width has the largest increase. This increase of the kerf width may explain the formation of widest oxidation marks. Namely, increased kerf width decreases the pressure loss of the assist gas flow and enables more easier assist gas flow inside the kerf [16], which results in high temperature oxidation reactions [17].

Regarding the effect of the cutting speed one can observe an overall trend of decreasing oxidation mark width with an increase in the cutting speed. This can be explained given that with an increase in the cutting speed interaction time between the laser beam, reactive assist gas (oxygen) and workpiece material is decreased [18]. As discussed by Al-Mashikhi et al. [15] increased cutting speeds more rapidly ejects the melt from the kerf and therefore there is less time to conduct heat into the surrounding material.

The observed increase in oxidation mark width at the upper plate surface for focus position of f=1.4 mm with an increase in the cutting speed may be attributable to changes in cut front angle and melt flow. In an experimental study of fiber laser cutting of mild steel of different thicknesses Al-Mashikhi et al. [15] similar observations made, particularly in the case of lower plate surface.

As could be observed from Figure 2, oxidation marks at the upper plate surface are consistently smaller than the oxidation marks at the lower plate surface. For the entire experiment, regardless of the selected cutting speed and focus position, upper oxidation marks are three times smaller. This indicates significant heat accumulation in fiber laser reactive cutting which should be taken into account when cutting sharp corners, small details, thin walls or zones near piercings [19].

In order to determine values of oxidation mark width for arbitrarily chosen cutting speed and focus position, the mathematical model is needed. The mathematical relations between process parameters and oxidation mark widths on lower and upper plate surface were developed in terms of non-linear models:

$$y_1=0.138+0.01\cdot x_1-0.003\cdot x_2 +0.005\cdot x_1\cdot x_2+0.013\cdot x_1^2+0.003\cdot x_2^2 \quad (1a)$$

$$y_2=0.468+0.028\cdot x_1-0.037\cdot x_2 +0.008\cdot x_1\cdot x_2-0.022\cdot x_1^2-0.007\cdot x_2^2 \quad (1B)$$

where x_1 is the coded value of focus position, x_2 is the coded value of cutting speed, y_1 is the oxidation mark width on the upper plate surface and y_2 is the oxidation mark width on the lower plate surface.

With correlation coefficient values of 0.86 and 0.93 for both empirical models one can argue that discrepancies between predicted and actual values of oxidation mark widths are quite acceptable. The mean absolute percentage error between model predictions and actual values were found to be 3.75% and 3.18%, which further indicates the validity of the developed models. 3D surface plots of second order models are given in Figure 3.

a)

b
)

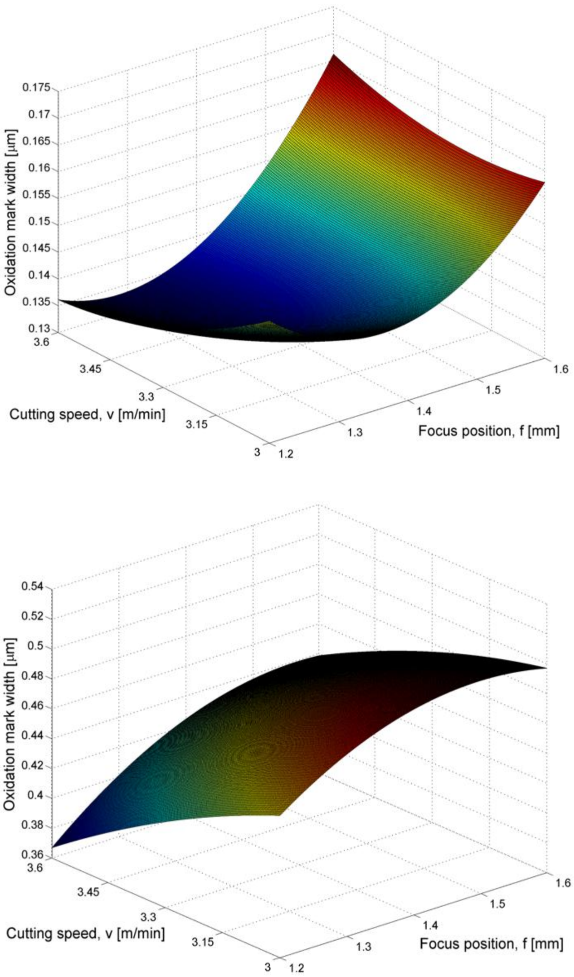

Figure 3. Change in the width of oxidation marks: a) upper plate surface, b) lower plate surface

Based on models' coefficient values and analysis of Figure 3 one can observe more pronounced effect of the focus position on the oxidation mark width at the upper plate surface. However, changes in oxidation mark widths at the lower plate surface were more affected with the change in the cutting speed. Since there are no significant interaction effects of the cutting speed and focus position on the resulting oxidation mark widths, one can conclude that for minimization of oxidation marks one should focus the laser beam closer the upper plate surface and use higher cutting speed levels.

4. CONCLUSION

The present study analyses oxidation mark width in fiber reactive laser reactive cutting of carbon steel S235JR. The performed analyses considered the effects of focus position and cutting speed on the resulting oxidation mark widths both on upper and lower plate surface, ratio of oxidation mark widths on upper and lower plate surface and development of nonlinear oxidation mark prediction model. Some of the main conclusions are the following:

- On average, for the entire experiment, oxidation mark widths stand in a ratio of 1 to 3, with average oxidation mark width of 0.15 mm at the lower plate surface.
- Focus position has variable effect on the oxidation mark widths. It tends to increase oxidation mark width on the lower plate surface, while an increase in the focus position may adversely affect size of oxidation marks on the upper plate surface.
- With an increase in the cutting speed there is an overall trend of decreasing oxidation mark widths on both sides of plate surface.
- Based on the analysis of developed prediction models one can observe more pronounced effect of the focus position on the oxidation mark width at the upper plate surface and more pronounced effect of the cutting speed on the oxidation mark width at the lower plate surface. Analyses of the developed models revealed that there are no significant interaction effects of the cutting speed and focus position.

Analysis of the effects of other important parameters, such as laser power, assist gas pressure and plate thickness, on oxidation marks and analysis of correlations between oxidation mark widths and size of HAZ is in the scope of future research.

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REFERENCES

[1] A. B. J. Sullivan and P. T. Houldcroft, “Gas-jet laser cutting,” *British Welding Journal*, vol. 14, no. 8, pp. 443–445, 1967.

[2] A. Ivarson, J. Powell and C. Magnusson, “Laser cutting of steels: analysis of the particles ejected during cutting,” *Welding in the World*, vol. 30, no. 5-6, pp.116–125, 1992.

[3] S. L. Chen, “The effects of gas composition on the CO_2 laser cutting of mild steel,” *Journal of Materials Processing Technology*, vol. 73, no. 1–3, pp. 147-159, 1998, doi: 10.1016/S0924-0136(97)00224-0.

[4] S. O. Al-Mashikhi, J. Powell, A. Kaplan, and K. T. Voisey, “An explanation of ‘striation free' cutting of mild steel by fibre laser,” in 5th International WLT-Conference on Lasers in Manufacturing, Munich, Germany, June 15-18, 2009, pp. 1–6.

[5] C. Corba, C. A. Tripe-Vidican, C. Chioreanu, and M. B. Fazecaș, “Laser cutting technology: applications, techniques–a review,” *Annals of the University of Oradea: Facscile of Management & Technological Engineering*, vol. 32, no. 1, pp. 1–8, 2024, doi: 10.15660/AUOFMTE.2024-1.3694.

[6] S. Ürgün, H. Yiğit, S. Fidan, and T. Sınmazçelik, “Optimization of laser cutting parameters for PMMA using metaheuristic algorithms,” *Arabian Journal for Science and Engineering*, vol. 49, no. 9, pp. 12333–12355, 2024, doi: 10.1007/s13369-023-08627-6.

[7] E. Librera, G. Riva, H. Safarzadeh and B. Previtali, “On the use of areal roughness parameters to assess surface quality in laser cutting of stainless steel with CO_2 and fiber sources,” *Procedia CIRP*, vol. 33, pp. 532–537, 2015, doi: 10.1016/j.procir.2015.06.069.

[8] L. Cepauskaite and R. Bendikiene, “Effect of fiber-laser parameters on cutting accuracy of thin and thick S355JR structural steel plates,” *Metals*, vol. 14, no. 6, 723, 2024, doi: 10.3390/met14060723.

[9] C. Leone, E. Mingione and S. Genna, “Laser cutting of CFRP by quasi-continuous wave (QCW) fibre laser: effect of process parameters and analysis of the HAZ index,” *Composites Part B: Engineering*, vol. 224, 109146, 2021, doi: 10.1016/j.compositesb.2021.109146.

[10] M. Madić, D. Jovanović and P. Janković, “Fiber laser cutting technology: pilot case study in mild steel cutting,” *Spectrum of Mechanical Engineering and Operational Research*, vol. 1, no. 1, pp. 1–9, 2024, doi: 10.31181/smeor1120241.

[11] S. Oh, I. Lee, Y. B. Par and H. Ki, “Investigation of cut quality in fiber laser cutting of CFRP,” *Optics and Laser Technology*, vol. 113, pp. 129-140, 2019, doi: 10.1016/j.optlastec.2018.12.018.

[12] Ł. Bohdal and D. Schmidtke, “Effect of fiber and CO_2 lasers parameters on the cut surface quality of RVS 1.4301 stainless steel,” *Journal of Mechanical Engineering and Sciences*, vol. 16, no. 2, pp. 8862–8872, 2022, doi: 10.15282/jmes.16.2.2022.05.0701.

[13] J. Vora, R. Chaudhari, C. Patel, D. Y. Pimenov, V. K. Patel, K. Giasin and S. Sharma, “Experimental investigations and Pareto optimization of fiber laser cutting process of Ti6Al4V,” *Metals*, vol. 11, 1461, 2021, doi: 10.3390/met11091461.

[14] J. Pocorni, D. Petring, J. Powell, E. Deichsel and A. F. Kaplan, “The effect of laser type and power on the efficiency of industrial cutting of mild and stainless steels,” *Journal of Manufacturing Science and Engineering*, vol. 138, no. 3, 031012, 2016, doi: 10.1115/1.4031190.

[15] S. O. Al-Mashikhi, J. Powell, A. Kaplan and K. T. Voisey, “Heat affected zones and oxidation marks in fiber laser–oxygen cutting of mild steel,” *Journal of Laser Applications*, vol. 23, 042003, 2011, doi: 10.2351/1.3614404.

[16] H. Toshihide, M. Toshiharu, Y. Masanori and S. Jun, “Influence of kerf widths to an assist gas

flow in laser cutting" in 4th International Conference on Jets, Wakes and Separated Flows, Nagoya, Japan, September 17-21, 2013, pp. 1-5. doi: 10.1299/jsmeicjwsf.2013.4._1135-1_.

[17] O. Keles and U. Oner, "A study of the laser cutting process: influence of laser power and cutting speed on cut quality," *Lasers in Engineering*, vol. 20, no. 5-6, pp. 319–327, 2010.

[18] M. Madić, S. Mladenović, M. Gostimirović, M. Radovanović and P. Janković, "Laser cutting optimization model with constraints: Maximization of material removal rate in CO_2 laser cutting of mild steel," *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, vol. 234, no. 10, pp. 1323–1332, 2020, doi: 10.1177/0954405420911529.

[19] N. Levichev, A. Tomás García and J. R. Duflou, "Monitoring opportunities in fiber laser flame cutting," *Lasers in Manufacturing and Materials Processing*, vol. 8, no. 4, pp.491–510, 2021, doi: 10.1007/s40516-021-00158-y.