Journal of Engineering Science and Technology Review 8 (3) (2015) 143-150

JOURNAL OF
Engineering Science and Technology Review

www.jestr.org

Research Article

Fuzzy Logic Approach for the Prediction of Dross Formation in CO_2 Laser Cutting of Mild Steel

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Received 9 October 2015; Accepted 2 November 2015

Abstract

Dross free laser cutting is very important in the application of laser cutting technology. This paper focuses on the development of a fuzzy logic model to predict dross formation in CO2 laser oxygen cutting of mild steel. Laser cutting experiment, conducted according to Taguchi's experimental design using L25 orthogonal array, provided a set of data for the development of a fuzzy rule base. The predicting fuzzy logic model is based on using Mamdani-type inference system. Developed fuzzy logic model considered the cutting speed, laser power and assist gas pressure as inputs. Using this model the effects of the selected laser cutting parameters on the dross formation were investigated. Additionally, 3-D surface plots were generated to study the interaction effects of the laser cutting parameters. The analysis revealed that the cutting speed has the most significant effect, followed by laser power and assist gas pressure. The results indicated that the fuzzy logic modeling approach can be effectively used for the dross formation prediction in CO2 laser cutting of mild steel.

Keywords: CO_2 laser cutting, dross, fuzzy logic, mild steel

1 Introduction

Among various advanced machining processes, laser cutting is one of the most widely used thermal-based processes applied for contour cutting of a wide variety of materials. Numerous advantages such as convenience of operation, high precision, small heat-affected zone, minimum deformity, low waste, low level of noise, flexibility, ease of automation etc., along with technological improvements in laser cutting machines, made laser cutting technology more prevalent in today's production systems.

By focusing the laser beam on the workpiece surface, the high power density of the focused laser beam in the spot melts or evaporates material in a fraction of a second, while coaxial jet of an assist gas removes the evaporated and molten material from the cutting zone [1]. An important function of the assist gas is to protect lenses in the cutting head from the fumes formed during the laser cutting process. In laser cutting of metals two types of assist gasses are mainly used, oxygen and nitrogen. For carbon steels, oxygen is commonly used, whereby exothermic reaction provides additional energy which is used in the cutting process. In the case of stainless steel cutting, in order to achieve high cut quality nitrogen is commonly used. This is because some of the oxides such as CrO, which are normally formed when cutting with oxygen, have high viscosity and are difficult to eject from the cutting zone. In both the cases, the assist gas impinges on a section processed and drags away the molten metal in the cutting zone. Depending upon the laser cutting parameters, the molten layer thickness varies. Moreover, a jet of dross, consisting of small metal droplets is formed at the onset of melting leaving the cutting kerf [2]. The size of the droplets depends on the liquid metal Reynolds number, as well as the liquid and gas Weber numbers [3].

Laser cutting is a complex process characterized by a number of input parameters which determine efficiency of the entire process in terms of material removal rate, cut quality and cost. Majority of experimental studies dealt with the analysis of the effects of process parameters on kerf width, surface roughness and size of heat affected zone [4]. The reduced laser cut quality in the cutting of thinner steel sheets is attributed mainly to dross formation at the lower cutting edge [5].

Dross formation is one of the typical imperfections generated at the lower cut edges. If the applied laser energy, cutting speed, focus position and assist gas pressure are not controlled properly, incomplete melting occurs or traces of molten metal re-solidify over the cut sides forming undesired dross [6]. The mechanism behind the dross formation is very complex. The process is a consequence of the agglomeration of molten material which flows along the lower cut edge [7]. The dross formation depends on the liquid properties of the molten material, such as viscosity, density and surface tension, as well as laser and cutting properties, such as assisting gas velocity, kerf size and liquid layer thickness [2].

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ISSN: 1791-2377

From the technological point of view, dross formation can be regarded as one of the most important criteria. Dross free laser cutting reduces/eliminates post-processing operations. Moreover, dross formation is undesirable as it causes the release of energy back to the metal leading to increased width of heat affected zone.

Considering afore-mentioned, development of mathematical models for the prediction of dross formation is of practical importance. However, very few researchers focused on mathematical modeling of dross formation in laser cutting. Analytical modeling approaches can be found in [2, 8]. Yilbas and Abdul Aleem [2] investigated dross ejection during laser cutting. The melt depth and dross size were formulated using a lump parameter analysis. It was found that the liquid layer thickness increases with increasing laser power and reduces with increasing assist gas velocity. The droplet formed was spherical and the droplet size predicted agreed well with the experimental results. Tani et al. [8] developed analytical model for dross formation prediction in laser cutting of steels. The model was developed as a part of an analytical prediction system dedicated to kerf geometry and heat affected zone, which minimizes the trial and safe phase during setting the process parameters. The authors indicated that the predictions for dross formation were in good agreement with the experimental findings. Kek and Grum [5] proposed a method for prediction of laser cut quality (size of the dross and the waviness of the cut surface) by capturing and evaluating of acoustic emission signals. The experimental measurements confirmed that this method of laser cut quality prediction is applicable to unalloyed and alloy steels with different thicknesses. Syn et al. [9] presented artificial intelligence approach for prediction of surface roughness and dross formation in laser cutting of Incoloy(R) alloy 800 by employing fuzzy logic system. Based on the results of prediction runs of the fuzzy logic model, it was shown that there are high interaction effects between assist gas pressure, cutting speed and laser power on surface roughness and dross formation. Madić and Radovanović [10] applied modeless approach, based on robust design methodology for the identification of the near optimal laser cutting conditions such that dross formation in CO_2 laser cutting of stainless steel is minimized. The laser cutting experiment was planned and conducted in accordance with Taguchi's L_{27} experimental design in which four laser cutting parameters such as laser power, cutting speed, assist gas pressure and focus position were arranged.

The objective of this paper is to develop dross formation prediction model for CO_2 laser oxygen cutting of mild steel. As the present investigation is based on visual inspection of the laser cut edge, i.e. dross formation, application of fuzzy logic approach is thought to be an appropriate method. Three main laser cutting parameters such as the cutting speed, laser power and assist gas pressure were considered. To obtain experimental database for generation of the fuzzy rule base, 25 laser cutting experiment trials were conducted using the L_{25} Taguchi's experimental design.

2 Experimental details

In the present study, the laser cutting experiment was performed to provide a knowledge-base of input/output data pairs to model the CO_2 laser oxygen cutting process using a fuzzy logic approach with the aim to predict the dross formation for any combination of input values within the covered experimental hyper-space.

The energy input by laser oxygen cutting comprises of the absorbed laser power at the cut front and the exothermic heat. Laser oxygen cutting is commonly used for cutting carbon steels where the exothermic reaction between oxygen and iron enhances the cutting process in terms of providing higher cutting speeds (3-6 times), than those achieved when using inert gas. The exothermic reaction is given by the following equation [11]:

$$\mathrm{Fe}+\frac{1}{2}\mathrm{O}_2 = \mathrm{FeO}+\text{energy (258 kJ/mol)} \quad (1)$$

Both the exothermic heat and absorbed laser energy increase with the cutting speed, but the percentage of exothermic heat to the total cutting energy decreases with increase in the cutting speed [12]. The schematic of the CO_2 laser oxygen cutting process is shown in Fig. 1.

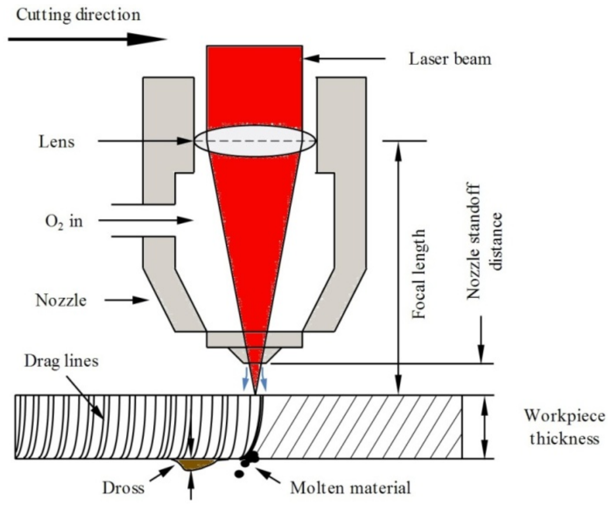


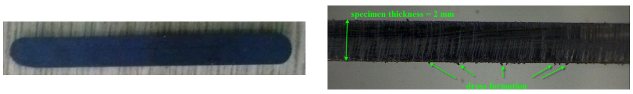
Fig. 1 Illustration of laser cutting process and dross formation

The cutting performance in laser oxygen cutting strongly depends on the percentage of impurity in oxygen gas. It was observed previously [13] that dross free cut cannot be obtained at oxygen level lower than 75 % when cutting mild steel with thickness of 3 mm using laser power of 1.5 kW and gas pressure of 2 bar. Due to the relative wider kerf width during laser oxygen cutting, as the result of sideways burning and low viscosity of melt with FeO, laser beam is recommended to be focused at the top of workpiece surface [14]. Laser oxygen cutting also helps reducing dross formation, since the viscosity of the molten metal decreases when oxidized, making it easier to be removed by the gas jet [11].

Laser cutting experiment was performed in real industrial environment by using ByVention 3015 (Bystronic) CO_2 laser cutting machine delivering a maximum output power of 2.2 kW at a wavelength of 10.6 μm. The cuts were performed in a continuous wave operating mode with Gaussian distribution beam mode (TEM_{00}) on 2 mm mild steel plate. A focusing lens with a focal length of 5 in. (127 mm) was used to perform the cut. Oxygen with purity of ≥ 99.95 % was supplied using conical shape nozzle (HK10) with diameter of 1 mm. The nozzle-workpiece stand-off distance was controlled at 0.7 mm. In all experimental trials laser beam was focused on the top surface of the workpiece material.

Twenty-five experimental trials with different combination of laser cutting parameters (cutting speed, laser power and assist gas pressure) were conducted in accordance with the standard L_{25} Taguchi's orthogonal array. The interval range for each parameter was chosen such that wider experimental range is covered and by considering manufacturer's recommendation for laser cutting parameter settings.

From a mild steel plate with thickness of 2 mm, specimens with dimensions of 60 × 10 mm were cut in experiment trial 1, as shown in Fig. 2a. The cut quality was evaluated in terms of dross formation by visual inspection of the lower cut edge. Analysis of the experimental results revealed that in 15 out of 25 experimental trials dross formation was observed. Depending on the selected values of laser cutting parameters, along the lower cut edge droplet-like dross was formed. An advantage is that the dross is no longer a metal but is usually an oxide, which for mild steel flows well and does not adhere to the base metal as strongly as if it were metal [15]. Dross formation was examined at along the cut section (Fig. 2b) by the use of optical microscope (Leitz, Germany).



a) b)

Fig. 2 Mild steel plate specimen obtain after laser cutting: a) top view of laser cutting specimen, b) cut surface pattern of laser cutting specimen

3 Fuzzy logic modeling

In laser cutting practice, the expert or machine tool operator will experimentally determine the appropriate laser cutting conditions for achieving dross free cuts for a particular material and workpiece thickness. Although this approach may produce satisfactory results, the entire procedure may be time consuming and resource demanding. On the other hand, with the limited number of experimental trials, by the use of fuzzy logic modelling approach, the entire procedure for the selection of laser cutting conditions can be quickened and also the efforts can be eliminated.

In that sense this study aims at developing fuzzy logic model for the prediction of dross formation in CO_2 laser oxygen cutting of mild steel. The main goal was set to determine such model that yields best fit of experimental data. The purpose of this fuzzy logic model is to assist in laser cutting process planning. In situations when one need to to increase productivity, product quality or other process characteristics, the laser cutting conditions need to be changed and this fuzzy logic model could be used in order to verify whether dross occurs.

Besides the application of artificial neural networks for process modeling, fuzzy logic modeling represents one of the most important modeling approaches in the field of artificial intelligence. The application of fuzzy logic modeling is well suitable for modeling complex processes, where limited understanding of the physical laws that describe the underlying process does not allow development of accurate mathematical models. For complex processes where there are a few numerical data and where only ambiguous or imprecise information are available, fuzzy logic modeling provides a way to better understand the process behavior by allowing the functional mapping between input and output observations [16]. Although, fuzzy logic modeling is quite complex and requires considerable knowledge and experience it provides the opportunity to encompass some of our available expert knowledge and previous experience on the laser cutting process. Moreover, this approach has proved to be an effective means for dealing with objectives that are linguistically specified [17].

The core of a fuzzy logic model is the fuzzy inference system, which performs the function of (fuzzy) reasoning mechanism [9]. Fuzzy reasoning (approximate reasoning) is an inference procedure used to derive conclusions from a set of fuzzy IF–THEN rules and from one or more given conditions [18].

The two most popular types of inference systems that are used in implementing fuzzy logic models are Mamdani and Sugeno type inferences. In terms of use, the Mamdani fuzzy inference is more widely used, mostly because it provides reasonable results with a relatively simple structure, and also due to the intuitive and interpretable nature of the rule base [17]. For Mamdani-type inference, the IF-THEN rule is a conditional statement and may be expressed as:

$$\text{if "}X_1 \text{ is A" and "}X_2 \text{ is B" then "}Y \text{ is C".} \quad (2)$$

where X_1, X_2 and Y are fuzzy (linguistic) variables, and A, B and C are linguistic values of X_1, X_2 and Y, respectively, defined in terms of fuzzy sets and corresponding membership functions, i.e. μ_A, μ_B and μ_C.

The IF parts of the rule "X_1 is A" and "X_2 is B" are called antecedents or premises, while the THEN part "Y is C" is called consequent or conclusion. The overall (aggregated) conclusion for a set on n rules is obtained in the process called aggregation by using "AND" and "OR" connectives. Thus, the input of the aggregation process is the list of clipped consequent membership functions, and output is one fuzzy set [19]. Finally, a defuzzification method is used to transform the fuzzy output into a real value.

3.1 Development of fuzzy logic model

Development of a fuzzy logic model for the dross formation prediction in CO_2 laser cutting of mild steel was divided into several phases:

Phase 1: Identification of the type of fuzzy system,

Phase 2: Identification of inputs and outputs and corresponding minimum and maximum values,

Phase 3: Assignment of membership functions for inputs and outputs,

Phase 4: Generation of fuzzy rule base upon experimental data,

Phase 5: Determination of the appropriate fuzzy inference functions and defuzzification method,

Phase 6: Statistical evaluation of the developed fuzzy logic model.

Phase 1. For the purpose of CO_2 laser oxygen cutting modelling, Mamdani type fuzzy max-min approach was used as an inference system.

Phase 2. In this study, three inputs were considered: cutting speed, laser power and assist gas pressure. The output is laser cut quality characteristic i.e. dross formation. Fig. 3 illustrates selected inputs and output.

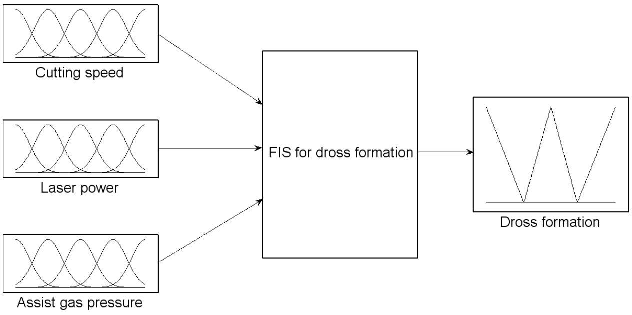


Fig. 3 Input and output variables of the fuzzy logic model

In this study, five fuzzy sets are chosen for inputs ("Low", "Low-Medium", "Medium", "Medium-High", and "High") and three fuzzy sets are used for output "NO", "LOW" and "HIGH". The minimum and maximum values of inputs and outputs, corresponding to experimental hyper-space covered, and fuzzy linguistic variables for inputs and output are given in Table 1.

Table 1 The minimum and maximum values of laser cutting parameters and fuzzy linguistic variables

Table 1 Nominal chemical composition of AISI 304 stainless steel

INPUTS			
Parameters	Min.	Max	Linguistic variables
Cutting speed, [m/min]	3	7	Low, Low-Medium, Medium, Medium-High, High
Laser power, [kW]	0.7	1.5	
Assist gas pressure, [bar]	3	7	
OUTPUTS			
Dross formation	visual inspection		No, Medium, High

Phase 3. The membership function is a graphical representation of the magnitude of participation of each parameter. It associates a weighting with each of the inputs that are processed, defines functional overlap between inputs, and ultimately determines an output response [17]. The membership function defines how each point in the input and output space is mapped to a membership value between 0 and 1 [9]. There are many membership functions available like triangular, trapezoidal, Gaussian, etc. The selection of membership functions is subjective and problem dependent. In this study, Gaussian membership functions were applied for all inputs because these functions have the advantage of being smooth. A Gaussian membership function can be expressed as [19]:

$$\mu(x) = e^{\frac{-(x-c)^2}{2\cdot\sigma^2}} \qquad (3)$$

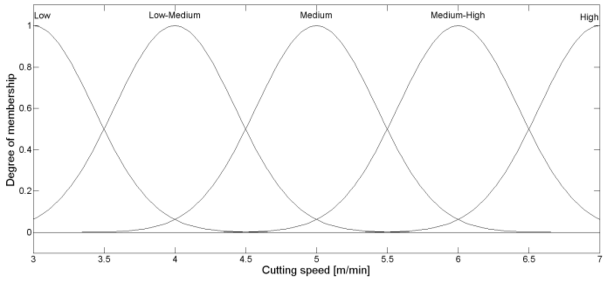
where c represents the mean values and σ is the standard deviation.

On the other hand, triangular membership function was used for output. A triangular membership function can be mathematically expressed as [19]:

$$\mu(x) = \begin{cases} 0, \; x < l \\ \dfrac{x-l}{m-l}, \; l \le x \le m \\ \dfrac{h-x}{h-m}, \; m \le x \le h \\ 0, \; x > h \end{cases} \qquad (4)$$

where l, m and h stands for the triangular fuzzy triplet and it determines the x coordinates of the three corners underlying triangular membership function.

For example, the functions considered for dross formation are "NO", "MEDIUM", and "HIGH" as shown in Fig. 4d. Fig. 4 shows the membership functions for all inputs and output. To the contrary to membership functions of the primary fuzzy sets of inputs variables, triangular membership functions of the fuzzy sets for output variable do not overlap. Since input membership functions overlap multiple rules are fired for various input combinations and neither normal operation nor defuzzification of fuzzy model are jeopardized, but non overlapping output membership functions allowed us to interpret each crisp model output as single output fuzzy set or single linguistic value of output variable in Table 1. Thus, outputs of our fuzzy model are easily readable and provide simple feedback on model predictions.



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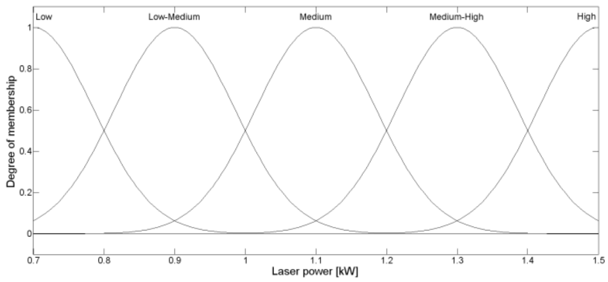

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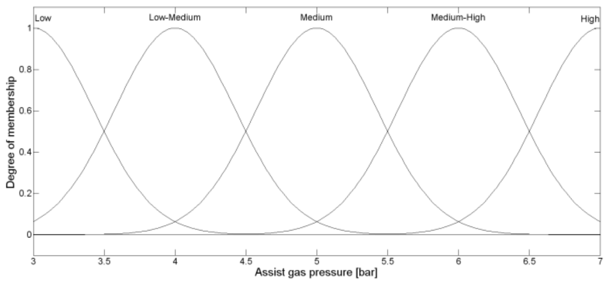

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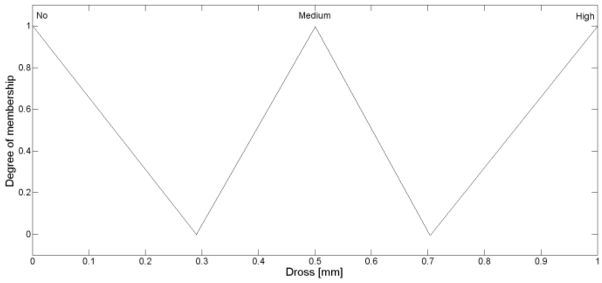


d)

Fig. 4 Membership functions for inputs and output

Phase 4: After selection of membership functions, fuzzy rules were described to obtain fuzzy values. Based on conducted experimental trials, a set of 25 fuzzy IF-THEN rules with three inputs, X_1 (cutting speed), X_2 (laser power) and X_3 (assist gas pressure) and one output Y (dross formation) was constructed.

Phase 5: Fuzzy inference process was defined by the following: (*i*) and method = min; (*ii*) or method = max; (*iii*) implication = min; (*iv*) aggregation = max and (*v*) defuzzification method = centroid.

The most commonly used method in defuzzification is the center of area method (centroid) [9]. This method is the most prominent and physically appealing of all defuzzification methods. In this method, the crisp (real) value is obtained by [19]:

$$x^* = \frac{\int x\mu(x)zdx}{\mu(x)dx} \tag{5}$$

where $\mu(x)$ is the aggregated membership function and x is the output (the centre value of the regions).

Phase 6: In order to assess the prediction accuracy of the developed fuzzy logic model, the prediction and experimental data were compared. Because the dross formation evaluation was performed by visual inspection, the comparison is based on linguistic variables. The comparison of output values and predicted by fuzzy logic model are given in Table 2. As can be seen from Table 2 there is perfect fit agreement for dross formation.

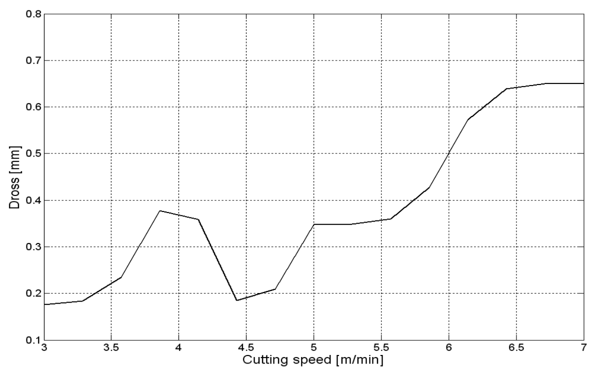
Table 2 Comparison of dross formation experimental data with results obtained from fuzzy logic model

Table 2 Comparison of dross formation experimental data with results obtained from fuzzy logic model

Cutting speed [m/min]	Laser power [kW]	Assist gas pressure [bar]	Dross formation experimental	Dross formation fuzzy logic predicted
3	0.7	3	NO	NO (0.09)
3	0.9	4	NO	NO (0.09)
3	1.1	5	NO	NO (0.171)
3	1.3	6	HIGH	HIGH (0.823)
3	1.5	7	HIGH	HIGH (0.823)
4	0.7	4	NO	NO (0.151)
4	0.9	5	NO	NO (0.151)
4	1.1	6	NO	NO (0.174)
4	1.3	7	NO	NO (0.174)
4	1.5	3	NO	NO (0.151)
5	0.7	5	medium	medium (0.502)
5	0.9	6	NO	NO (0.215)
5	1.1	7	NO	NO (0.151)
5	1.3	3	medium	medium (0.473)
5	1.5	4	medium	medium (0.473)
6	0.7	6	HIGH	HIGH (0.782)
6	0.9	7	medium	medium (0.502)
6	1.1	3	medium	medium (0.532)
6	1.3	4	medium	medium (0.532)
6	1.5	5	medium	medium (0.503)
7	0.7	7	HIGH	HIGH (0.85)
7	0.9	3	HIGH	HIGH (0.85)
7	1.1	4	HIGH	HIGH (0.849)
7	1.3	5	medium	medium (0.532)
7	1.5	6	medium	medium (0.503)

4 Data analysis, results and discussion

At this stage, the developed fuzzy logic model can be used to analyze the effect of the selected laser cutting parameters on the dross formation. Initially the effect of the laser cutting parameters on the dross formation was analyzed by changing one parameter at a time, while keeping the other two laser cutting parameters constant at centre level. The effects of the laser cutting parameters on the dross formation are given in Fig. 5.



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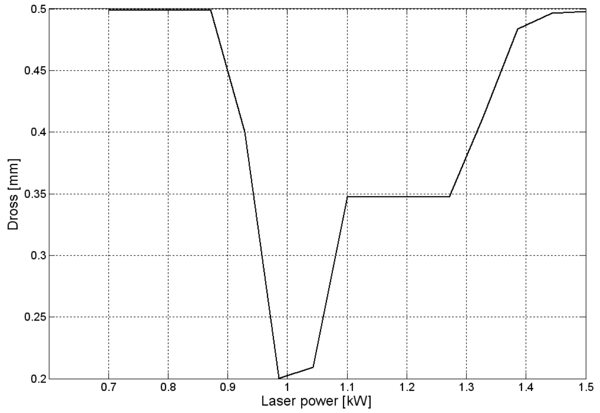

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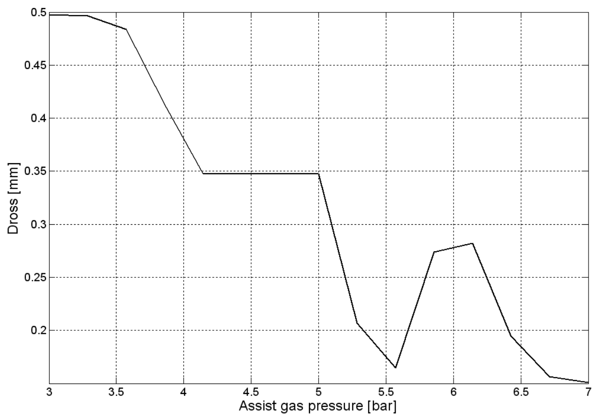


c)

Fig. 5 Main effects of the laser cutting parameters on the dross formation: a) laser power = 1.1 kW, assist gas pressure = 5 bar, b) cutting speed = 5 m/min, assist gas pressure = 5 bar, c) cutting speed = 5 m/min, laser power = 1.1 kW

As can be seen from Fig. 5a, an increase in the cutting speed increases the tendency for dross formation. The dross formation at higher cutting speeds is due to the strong disturbance of the melt flow [20].

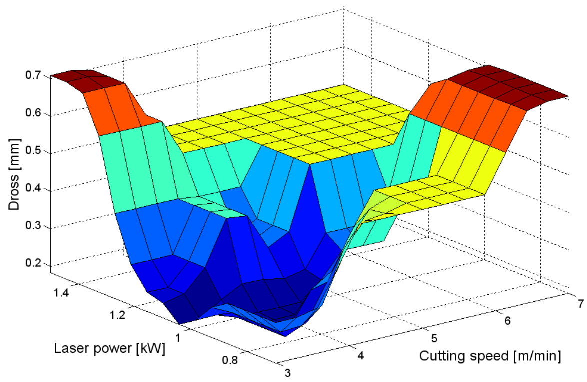
Fig. 5b indicates that there is optimal laser power which prohibits dross formation. Laser cutting is less stable at low power levels, and on the other hand, increasing the laser power above optimal level, increases the energy input i.e. the absorbed laser power at the cut front which results in wide irregular kerf and dross formation.

By increasing the oxygen pressure, the exothermic-induced burning of the cut surface is increased but also drag force on the cutting front is enhanced which results in reduced dross formation (Fig. 5c).

In laser oxygen cutting, if the pressure of assist gas is not enough to quickly blow away the viscous molten material, the high temperature molten material (adhering on cut surface) continues its oxidation reaction (or burning). This makes the cut surface more irregular, the undercut angle not very sharp and the striation on the cut surface more curved [13]. Although higher assist gas pressure can increase to some degree maximal cutting speed, the cut surface quality is more irregular than when using lower assist gas pressure. Regarding surface roughness of the cut surface, in previous investigation [21], it was observed that there is a nonlinear increase of surface roughness from 1.4 to 2.8 µm, when the assist gas pressure is increased from 3 to 7 bar. It has to be noted that this functional dependence follows the same trend apart from the values of the laser power.

However, considering dross formation it was observed that the effect of one parameter should be considered through the interaction with other parameters. For example, when using laser power of 1.1 kW and cutting speed of 3 m/min, the increase of assist gas pressure results in dross formation. From the above reasons, it is necessary to investigate the interaction effects of the laser cutting parameters on the dross formation. In order to determine the interaction effects of the cutting parameters on the dross formation, 3-D surface plots were generated considering two parameters at a time, while the third parameter was kept constant at centre level.

Since there are three possible two-way interactions between the laser cutting parameters (cutting speed × laser power, cutting speed × assist gas pressure, and laser power × assist gas pressure), three 3-D surface plots were generated using the developed fuzzy logic model (Fig. 6).



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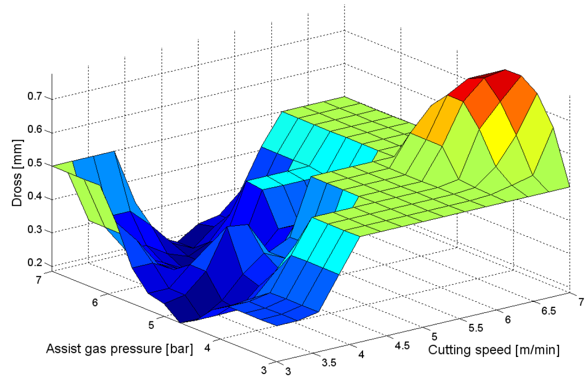

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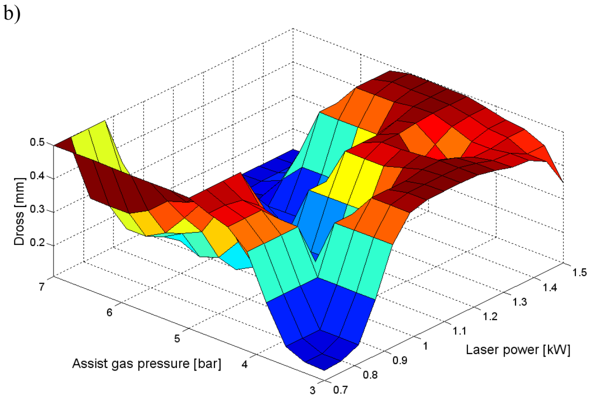


c)

Fig. 6 Interaction effects of the laser cutting parameters on the dross formation: a) assist gas pressure = 5 bar, b) laser power = 1.1 kW, c) cutting speed = 5 m/min

Fig. 6a shows the dross formation as a function of the laser power and cutting speed. The interaction is expressed by the difference between the relatively smaller influence of the laser power when using higher cutting speeds, and the big influence of the laser power when using smaller cutting speeds. It could be observed that both combinations of low laser power and high cutting speed and high laser power and low cutting speed result in dross formation. Clearly, there exists a region of optimal laser power to cutting speed ratio by which the dross formation is avoided.

From Fig. 6b, it could be observed that when the cutting speed is at low level, lower assist gas pressure is preferable to obtain dross free cut. However, as the cutting speed is increased the effect of the assist gas pressure on dross formation becomes significant. It could be observed that increase of the cutting speed demands a higher assist gas pressure, however dross formation is not avoided.

As shown in Fig. 6c, an increment in the assist gas pressure efficiently reduces the dross formation while using laser power higher than 1 kW, while reduction in dross formation is observed if combination of low levels of laser power and assist gas pressure is used.

Finally, from Fig. 6 one can summarize the order of magnitude of the interaction effects of the laser cutting parameters in descending order as follows: cutting speed × assist gas pressure, cutting speed × laser power and laser power × assist gas pressure. Additionally, from the analysis of the Figs. 5 and 6 it could be concluded that the cutting speed has maximum influence on the dross formation followed by the laser power and assist gas pressure.

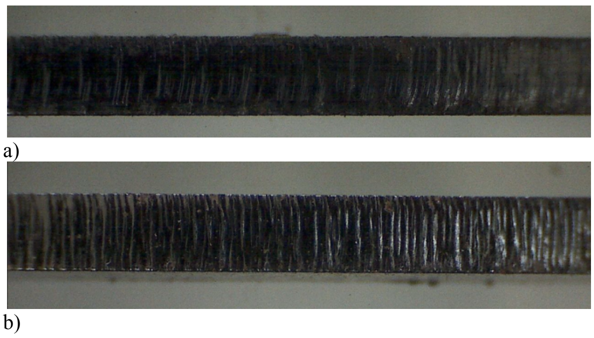
Apart from comparison with obtained experimental results the validation of the developed fuzzy logic model was performed by conducting additional experimental trials with combination of laser cutting parameter values that were not considered in initial experimentation. However, the goal was to use developed fuzzy logic model so as to test experimental trials in order to obtain dross free cuts i.e. cuts with acceptable values of dross. Among others, the following combinations of laser cutting parameter values were tested:

Cut 1: Cutting speed= 5 m/min, laser power= 1.3 kW and assist gas pressure=7 bar,

Cut 2: Cutting speed= 3 m/min, laser power= 1.3 kW and assist gas pressure=7 bar, and

Cut 3: Cutting speed= 3 m/min, laser power= 1.1 kW and assist gas pressure=3 bar.

The cut surface patterns obtained under these conditions are given in Fig. 7.



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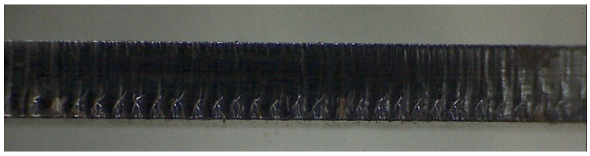

c)

Fig. 7 Cut surface patterns of validation experimental trials: a) cut 1, b) cut 2, c) cut 3

As could be clearly observed from Fig. 7, although represent dross free cuts, the surface patterns of these laser cuts drastically differ. While cut 1 has relatively smooth and regular cut surface, relatively shallow, serrations are obvious in the cut surface of cut 2. On the other hand, very coarse cut surface at the laser beam exit in approximately in the lower third of the cut is obtained in the case of cut 3.

5 Conclusions

In this paper the Mamdani-type fuzzy logic model was developed to predict the dross formation as output function for a set of laser cutting parameters such as the cutting speed, laser power and assist gas pressure in a CO_2 laser oxygen cutting of mild steel. From the analysis of the development and application of the fuzzy logic model within the covered experimental hyper-space the following can be concluded:

- Dross formation is highly sensitive to the selected laser cutting parameters and their interactions.
- There exist nonlinear relationships between the dross formation and the laser cutting parameters as well as their interactions.
- The effect of a given laser cutting parameter on the dross formation should be considered through the interaction with other parameters.
- For a given constant assist gas pressure, an increase in cutting speed enhances dross formation. In order to achieve dross free cut at higher cutting speeds, for a constant laser power, higher assist gas pressure is needed.
- When the cutting speed is at lower level (up to 4 m/min), lower laser power (up to 1 kW) is preferable to obtain dross free cuts. Using higher cutting speeds, dross free cutting requires combination of low levels of laser power (up to 0.8 kW) and assist gas pressure (up to 4 bar) or combination of high levels of laser power (1 – 1.5 kW) and assist gas pressure (over 5 bar).
- Cutting speed has maximum influence on the dross formation followed by the laser power and assist gas pressure.
- Combination of Gaussian and triangular membership functions for inputs and output, respectively, Mamdani max-min inference system and centroid defuzzification method are well suited for dross formation modeling.

Acknowledgments
This work was carried out within the project TR 35034, financially supported by the Ministry of Science and Technological Development of the Republic of Serbia.

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