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Research article

Artificial Intelligence Fuzzy Logic Modeling of Surface Roughness in Plasma Jet Cutting Process of Shipbuilding Aluminium Alloy 5083

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A B S T R A C T

In this paper the influence of different process parameters on surface roughness responses in plasma jet cutting process was investigated. Experimentations were conducted on shipbuilding aluminium 5083 sheet thickness 8 mm. Experimental work was performed according to Taguchi L27 orthogonal array by varying four parameters such as gas pressure, cutting speed, arc current and cutting height. Due to complexity of manufacturing process and aim to cover wide experimental space few constraints regarding cutting area were defined. Surface roughness parameters Ra and Rz were analysed as cut quality responses. In order to define mathematical model that will be able to describe effects of process parameters on surface roughness artificial intelligence (AI) fuzzy logic (FL) technique was applied. After functional relations between input parameters and surface roughness responses were defined prediction accuracy of developed fuzzy logic model was checked by comparison between experimental and predicted data. Mean absolute percentage error (MAPE) as well as coefficient of determination (R2) were used as validation measures. Finally, optimal process conditions that lead to minimal surface roughness were defined by creating response surface plots.

1. INTRODUCTION

Plasma jet cutting process is nonconventional manufacturing process widely used in shipbuilding and metal industry in preparing metal sheets of various thicknesses for welding techniques. Aluminium alloy 5083 is due to its good strength and corrosion resistance very convenient for applications in different constructions. In order to save money and time for plasma cutting postprocessing procedures it is desirable to reach the best possible cut quality. Cut quality is usually described by measurable characteristics such as: kerf width, bevel angle, surface roughness, dross height formation, heat affected zone (HAZ), material removal rate (MRR) etc. In order to achieve acceptable cut quality very often process parameters settings were defined by machine operator previous experience and try-error approach. In these cases, due to process complexity only one or two process responses can be optimized. In order to better understand process parameters effects on multiple responses comprehensive application of various mathematical modeling and optimization techniques should be performed. Many researchers conducted detailed investigations in this area especially in plasma jet cutting of aluminium alloy. Aluminium as material is very sensitive especially in thermal intensive manufacturing processes such as plasma jet cutting. Accordingly, performed investigations and findings regarding optimal cutting conditions are even more interested.

Hamid et al. [1] conducted experimentations in plasma jet cutting process of aluminium alloy 5083 thickness 10 mm. They investigated influence of parameters such as arc current, feed rate, gas pressure and cutting distance on surface roughness and conicity responses. Grey relational analysis combined with analysis of variance (ANOVA) were applied to discuss process parameters effects as well as for defining process cutting conditions that lead to minimal surface roughness and conicity. Patel et al. [2] analysed influence of arc current, standoff distance, gas pressure and cutting speed on material removal rate, top and bottom kerf width and bevel angle quality responses in plasma jet cutting process of aluminium 6082 thickness 5 mm. They defined main effects plots to describe effects of process parameters on analysed responses and ANOVA to check significance of parameters and their interactions. Kadirgama et al. [3] performed experimental investigations on aluminium alloy 6061 to analyse the influence of the arc current, standoff gap and gas pressure on the heat affected zone as cutting process response. Mathematical modeling of analysed process response was conducted by using response surface method. Partial swarm optimization algorithm was applied to define optimal process parameters values that result with minimal heat affected zone. Peko et al. [4] applied regression analysis combined with ANOVA to define mathematical models that describe the influence of process parameters cutting speed, arc current and cutting height on cut quality responses kerf width, bevel angle, surface roughness *Ra, Rz* and material removal rate. They conducted experimental trials on aluminium alloy 5083 thickness 3 mm. Desirability analysis was applied for multi objective optimization and to graphically present optimal cutting area. Peko et al. [5] performed experimental trials on aluminium alloy 5083 thickness 3 mm in order to check the influence of cutting height, cutting speed and arc current on kerf width cut quality response. Artificial neural network (ANN) model was generated to mathematically define relations between process inputs and output. Experimental trials served as basis for training artificial neural network model. In order to check prediction accuracy of developed artificial intelligence model two additional experimental data sets for validation and testing were applied. Finally, from generated AI model 2D and 3D plots were derived to discuss process parameters effects as well as to define process conditions that lead to minimal kerf width values. Peko et al. [6] developed artificial intelligence fuzzy logic model to predict dross height response depending on various process parameters values such as cutting speed, arc current and cutting height in plasma jet cutting process of aluminium alloy 5083 thickness 3 mm. Prediction accuracy of developed fuzzy logic model was checked by comparison between experimental and predicted data. Process parameters effects as well as optimal cutting regions where dross formation is minimal were discussed by created 3D response surface plots. Peko et al. [7] generated artificial neural network model for prediction of surface roughness in plasma jet cutting process of aluminium alloy 5083 thickness 3 mm. Experimental trials were conducted by varying two process parameters cutting speed and arc current. Prediction accuracy of developed ANN model was proved by comparison between experimental and predicted response data. Validation measures were mean squared error (MSE) and coefficient of determination (R^2). Also, results data were divided into three data sets: for training, for validation and for testing ANN model. Finally, response surface plot was created to analyse process parameters effects and to define optimal cutting speed and arc current values where surface roughness is minimal. Peko et al. [8] applied artificial intelligence fuzzy logic technique to establish functional relations between inputs, process parameters: gas pressure, cutting speed, arc current and cutting height and output dross height cut quality response. AI fuzzy logic model was generated according to results obtained in experimentations. Experimental trials were conducted on aluminium alloy 5083 thickness 8 mm. Developed fuzzy logic dross height model served as a good basis for prediction of dross formation depending on various process parameters values as well as basis for further experimental investigations in this area to cover wider experimental space. This will result with better understanding and control of plasma jet cutting process of aluminium alloys. Peko et al. [9] applied AI fuzzy logic technique for prediction of top and bottom kerf width in plasma jet cutting process of aluminium alloy 5083 thickness 8 mm. Developed fuzzy logic model establish mathematical relations between process parameters: gas pressure, cutting speed, arc current and cutting height and kerf widths as process responses. Validation of fuzzy logic model was performed by comparison between experimental and predicted data of top and bottom kerf width. After, prediction accuracy was proved 3D response surface plots were created to define process conditions that results with as narrow cuts as possible. Narrow cuts are desirable due to higher cutting precision and lower workpiece material losses.

In this paper AI fuzzy logic (FL) technique was applied to define functional relations between plasma jet cutting process parameters: gas pressure, cutting speed, arc current and cutting height and cut quality response surface roughness. Surface roughness response was defined by two main parameters *Ra* and *Rz.* In order to save money and time for postprocessing it is desirable to achieve as smoother cut surface as possible. Generated AI fuzzy logic model served as basis for further development of AI fuzzy logic expert system that will be able to predict surface roughness depending on different process parameters as well as for better control and optimization of aluminium plasma manufacturing process.

2. EXPERIMENTAL PROCEDURE

In this paper workpiece material is aluminium sheet 5083 thickness 8 mm. This aluminium alloy is very present in shipbuilding industry due to its high corrosion resistance. As it was already mentioned aluminium is very sensitive especially in treatment by thermal manufacturing processes. Due to that it is welcome to conduct investigations in the area of aluminium plasma jet cutting process to identify process parameters combinations that lead to optimal cut quality.

Experimentations for this paper were conducted on CNC plasma manufacturing machine FlameCut 2513 (Arpel Automation). As arc current source LG 100 IGBT Inverter Air Plasma Cutting Machine was used. Compressed air served as plasma gas. Compressed air was prepared, dried and purified in compressor SCK5 200 PLUS (ALUP Kompresoren Gmbh).

Taguchi L_{27} orthogonal array was applied for experimental plan design. Four process parameters were varied on three levels: gas pressure *p* [bar], cutting speed *v* [mm/min], arc current *I* [A], and cutting height *H* [mm]. Constant parameter in all trials was nozzle diameter: 1.2 mm. Due to complexity of cutting process of sheet thickness 8 mm and intention to cover as wider experimental space as possible a few constraints regarding parameters values combinations at which cutting process is not possible were identified. These parameter values combinations were subtracted from Taguchi L_{27} experimental plan and marked in Figure 1 with bold blue lines.

In all experimental trials parallel straight cuts length 80 mm were made. Surface roughness *Ra* and *Rz* responses were measured by using

Talysurf Hobson 6 profilometer. Each surface roughness measurement was conducted in the middle of the cut length and in the middle of the cut height. Measurements were repeated three times and mean value was derived as single experimental trial result. Experimental plan and surface roughness results were presented in Table 1. Figure 2 and Figure 3 show surface roughness of specimens obtained at various process parameters values.

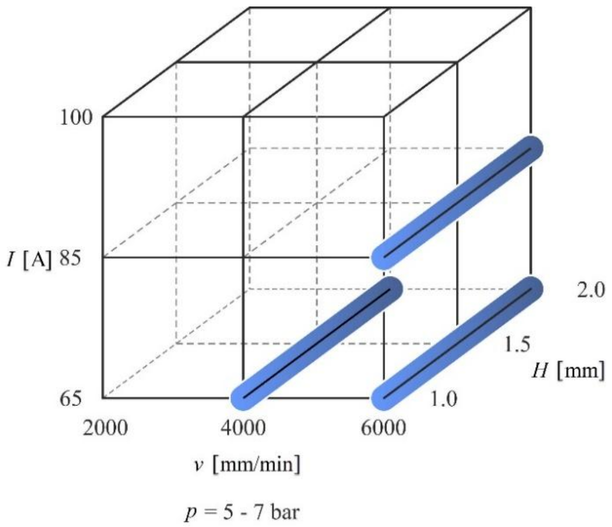


Fig. 1. Cutting process constraints.

Table 1. Experimental plan and results.

Exp.	Process parameters				Surface roughness	
	p [bar]	v [mm/ min]	I [A]	H [mm]	Ra [µm]	Rz [µm]
1	5	2000	65	1	28.70	107.00
2	5	2000	85	1.5	19.10	79.00
3	5	2000	100	2	23.15	101.60
4	5	4000	85	2	9.91	54.60
5	5	4000	100	1	8.64	43.30
6	5	6000	100	1.5	8.38	38.50
7	6	2000	65	1	20.40	92.00
8	6	2000	85	1.5	16.80	77.00
9	6	2000	100	2	19.10	81.00
10	6	4000	85	2	7.24	38.30
11	6	4000	100	1	6.83	38.60
12	6	6000	100	1.5	8.35	45.00
13	7	2000	65	1	28.09	110.60
14	7	2000	85	1.5	21.24	95.10
15	7	2000	100	2	19.67	96.60
16	7	4000	85	2	14.24	61.70
17	7	4000	100	1	12.25	65.20
18	7	6000	100	1.5	8.19	46.60

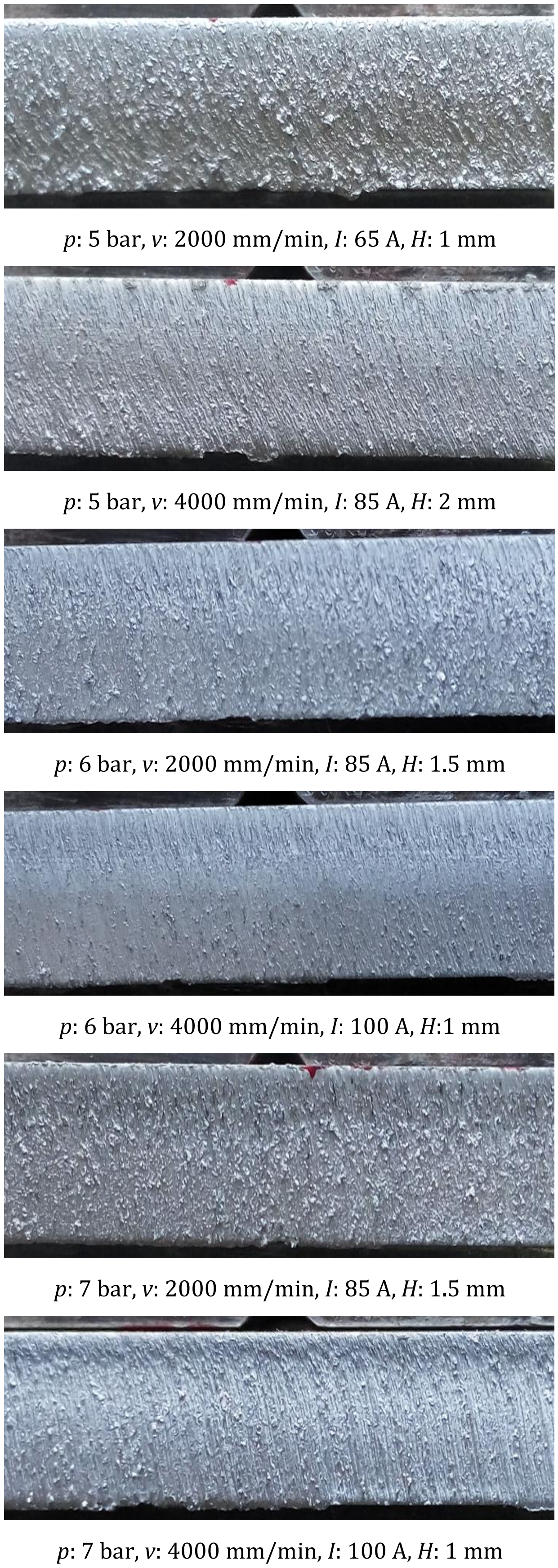


Fig. 2. Surface roughness of specimens at different process parameters values.

a)
p: 5 bar
v: 2000 mm/min
I: 65 A
H: 1 mm

b)
p: 6 bar
v: 2000 mm/min
I: 100 A
H: 2 mm

c)
p: 6 bar
v: 4000 mm/min
I: 100 A
H: 1 mm

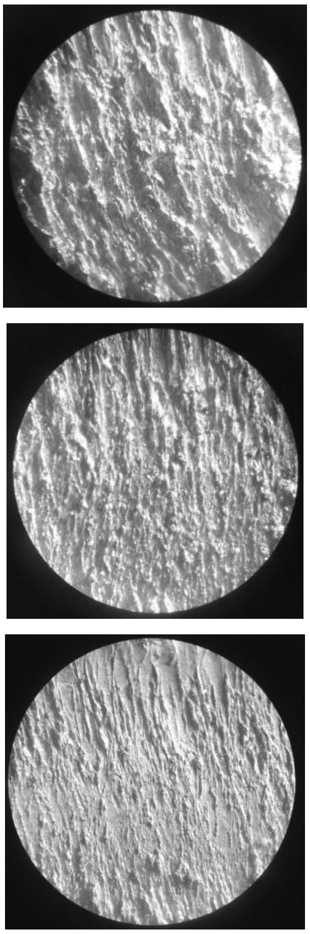


Fig. 3. Microscopic view of surface roughness at different process parameters values.

3. AI FUZZY LOGIC MODELING

Fuzzy logic is artificial intelligence technique which is proved very useful for describing processes and systems where application of traditional mathematical modeling and optimization procedures such as regression analysis, Taguchi optimization etc. is not possible due to various complexities such as incomplete, vague informations, uncertainties and noises. In these cases, fuzzy logic technique enables creating artificial intelligence reasoning system that will be able to model analysed process and predict future situations depending on various inputs values. In this paper, fuzzy logic was applied to define functional relations between process parameters: *p*, *v*, *I*, *H* and analysed cut quality responses: *Ra*, *Rz*. Such created AI model represents basis for creating fuzzy logic reasoning system that will be able to predict surface roughness responses values and to derive useful conclusions regarding optimal process conditions.

In order to generate AI fuzzy logic model between inputs and output it is obvious to assemble fuzzy logic system that consist of few modules: fuzzification module, fuzzy inference module and defuzzification module. Fuzzification module converts real inputs data into a linguistic variables by using different membership functions. Membership functions assign to each input value degree of membership between 0 and 1. There are different membership functions such as Gaussian, triangular, trapezoidal etc. Fuzzy inference module applies knowledge base of fuzzy IF-THEN rules and membership functions to form cause-effect functional relations between inputs and outputs. Such created functional relations represent basis for AI fuzzy logic reasoning system that will generate fuzzy linguistic output values. Fuzzy IF-THEN rules and membership functions are connected by using specific system settings. There are several fuzzy inference systems. The two most famous are Mamdani and Sugeno. Finally, defuzzification module converts aggregated fuzzy outputs into a non-fuzzy values [10-16].

In this paper Mamdani fuzzy inference system was applied to define relations between inputs: gas pressure, cutting speed, arc current and cutting height and outputs: *Ra* and *Rz* surface roughness parameters, Figure 4. Mamdani system settings are: and method: min, or method: max, implication: min, aggregation: max, defuzzification method: centroid.

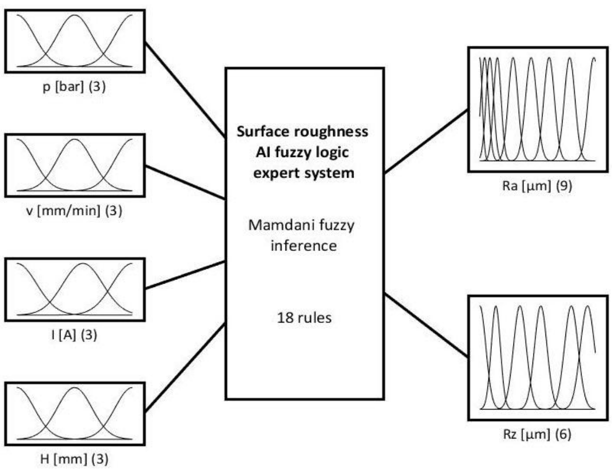


Fig. 4. AI fuzzy logic system for modeling and prediction surface roughness response.

For each input three Gaussian membership functions were defined: L (low), M (medium), H (high), Figure 5. Surface roughness parameter *Ra* was described by nine Gaussian membership functions: EL (extra low), VL (very low), L (low), LM (low medium), M (medium), MH (medium high), H (high), VH (very high), EH (extra high), Figure 6 a). Surface roughness parameter *Rz* was described by six Gaussian membership functions: L (low), LM (low medium), M (medium), MH (medium high), H (high), VH (very high), Figure 6 b).

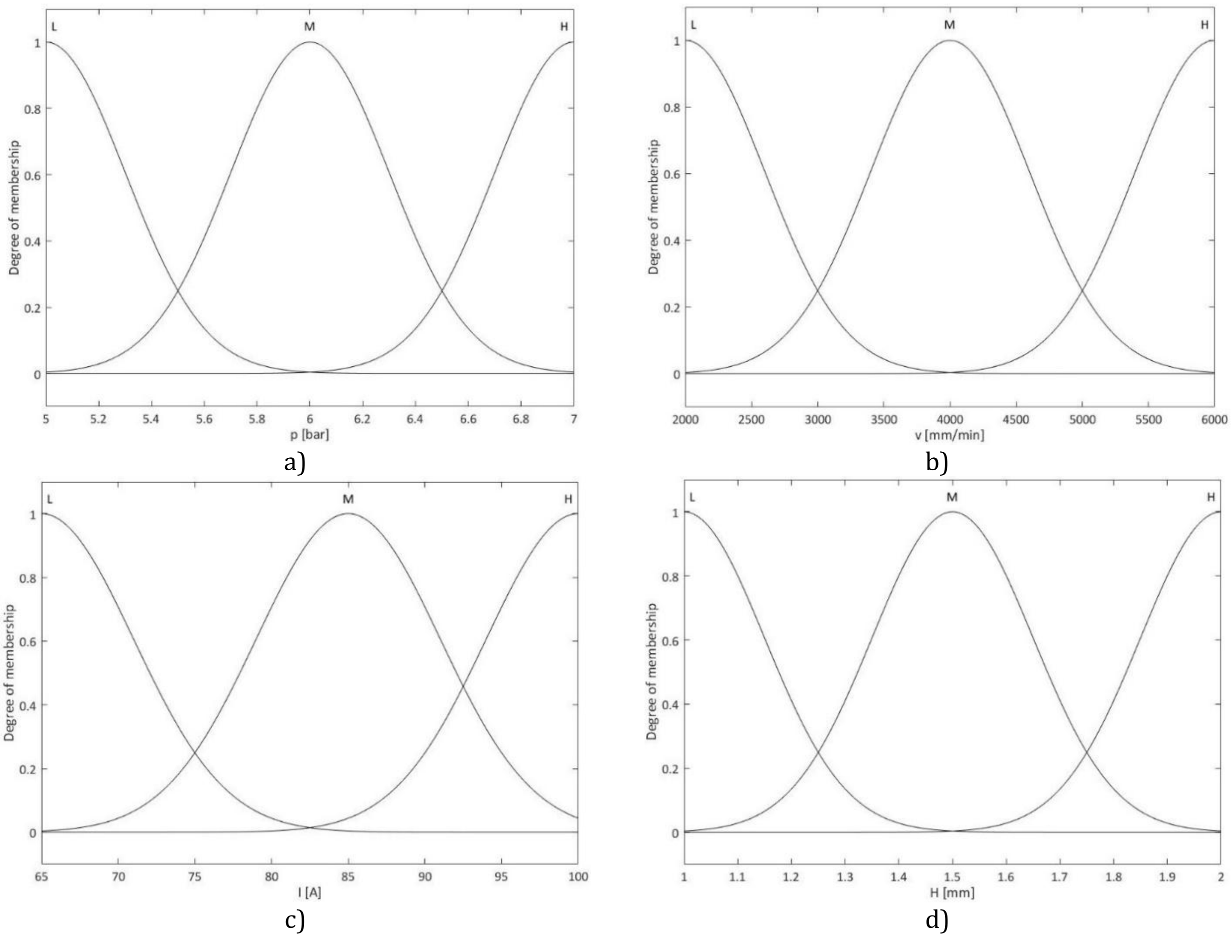


Fig. 5. Memb5ership functions for: a) gas pressure, b) cutting speed, c) arc current, d) cutting height.

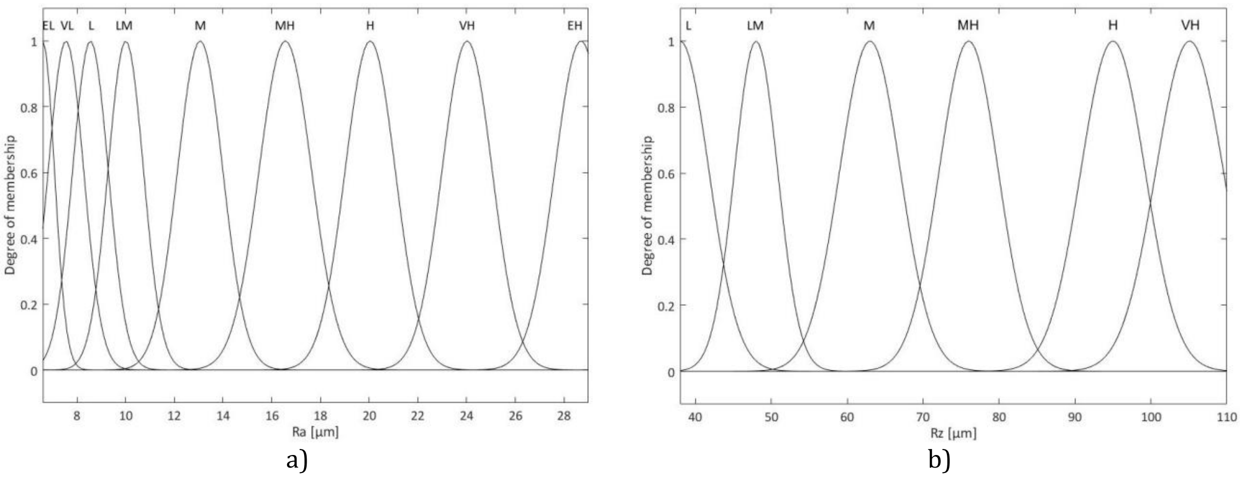


Fig. 6. Membership functions for: a) surface rougness *Ra*, b) surface roughness *Rz.*

In order to perform fuzzy logic reasoning beside membership functions knowledge base of fuzzy IF-THEN rules should be generated. In this case base of 18 fuzzy IF-THEN rules was created. These rules are graphically presented in Figure 7.

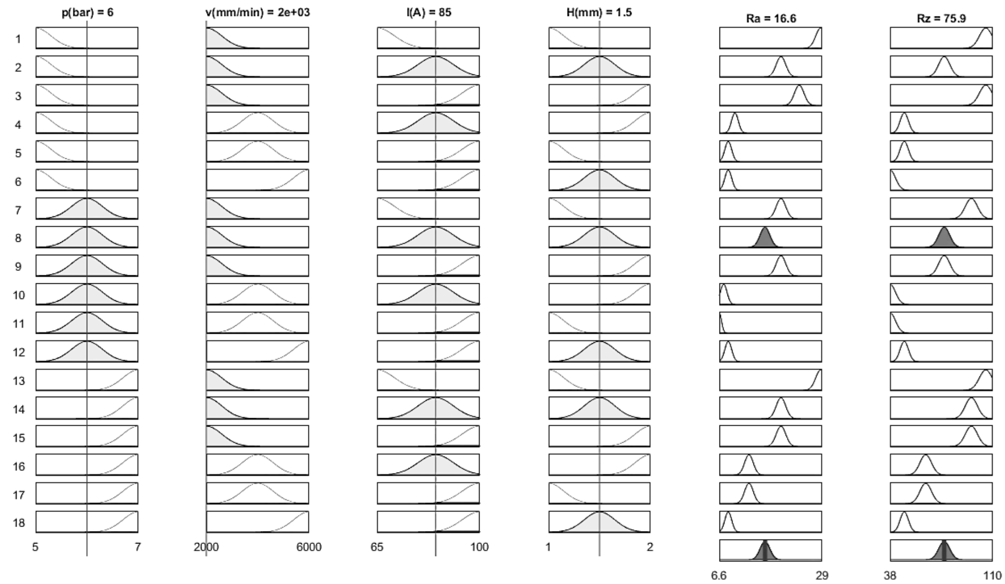
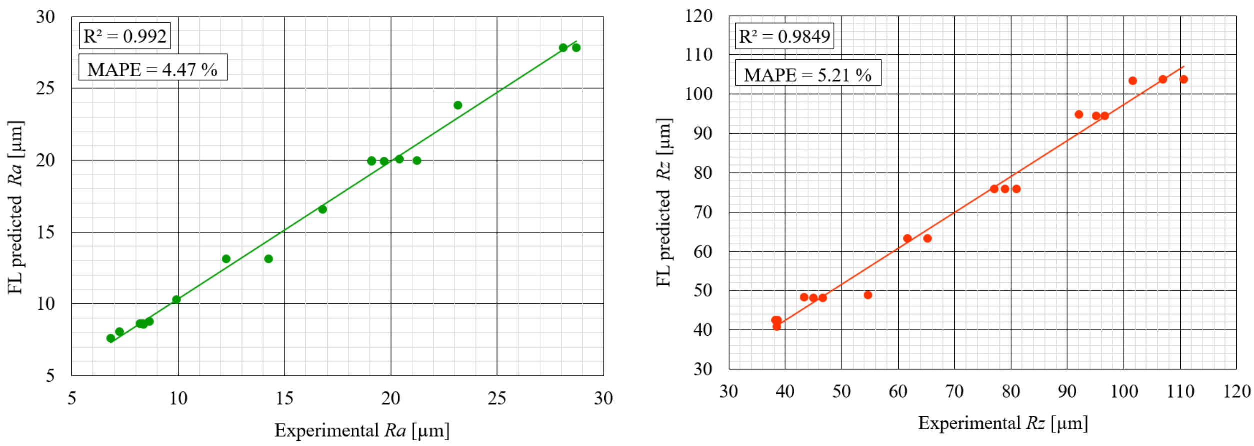


Fig. 7. Base of fuzzy IF-THEN rules between inputs: *p*, *v*, *I*, *H* and outputs: *Ra*, *Rz.*

Finally, defuzzification module converts fuzzy outputs data into a non-fuzzy values. Whole development process of AI fuzzy logic expert system for surface roughness *Ra*, *Rz* modeling and prediction was conducted in Matlab R2022a software. In order to prove prediction accuracy of developed *Ra* and *Rz* fuzzy logic model comparison between experimental and FL predicted surface roughness data was performed. Coefficient of determination (R^2) and mean absolute percentage error (MAPE) were used as validation measures. Comparison results for both responses are shown in Figure 8. From Figure 8 it is visible that developed fuzzy logic model has acceptable prediction capability and consequently it can be used for further analysis as well as basis for building more complete AI-FL expert system that will be upgraded with additional experimental data.



a) b)

Fig. 8. Comparison between FL predicted and experimental data of: a) *Ra*, b) *Rz.*

4. RESULTS AND DISCUSSION

After prediction accuracy of developed fuzzy logic model for surface roughness *Ra* and *Rz* responses was proved it can be furtherly used to create response surface plots to discuss process parameters effects on surface roughness as well as to approximately determine optimal process conditions that result with as smoother cut surface as possible. Accordingly, Figure 9 presents 3D surface plots with two variable process parameters while other two parameters were kept constant. On the left side *Ra* response surface plots are shown while on the right side these that refer to *Rz* response.

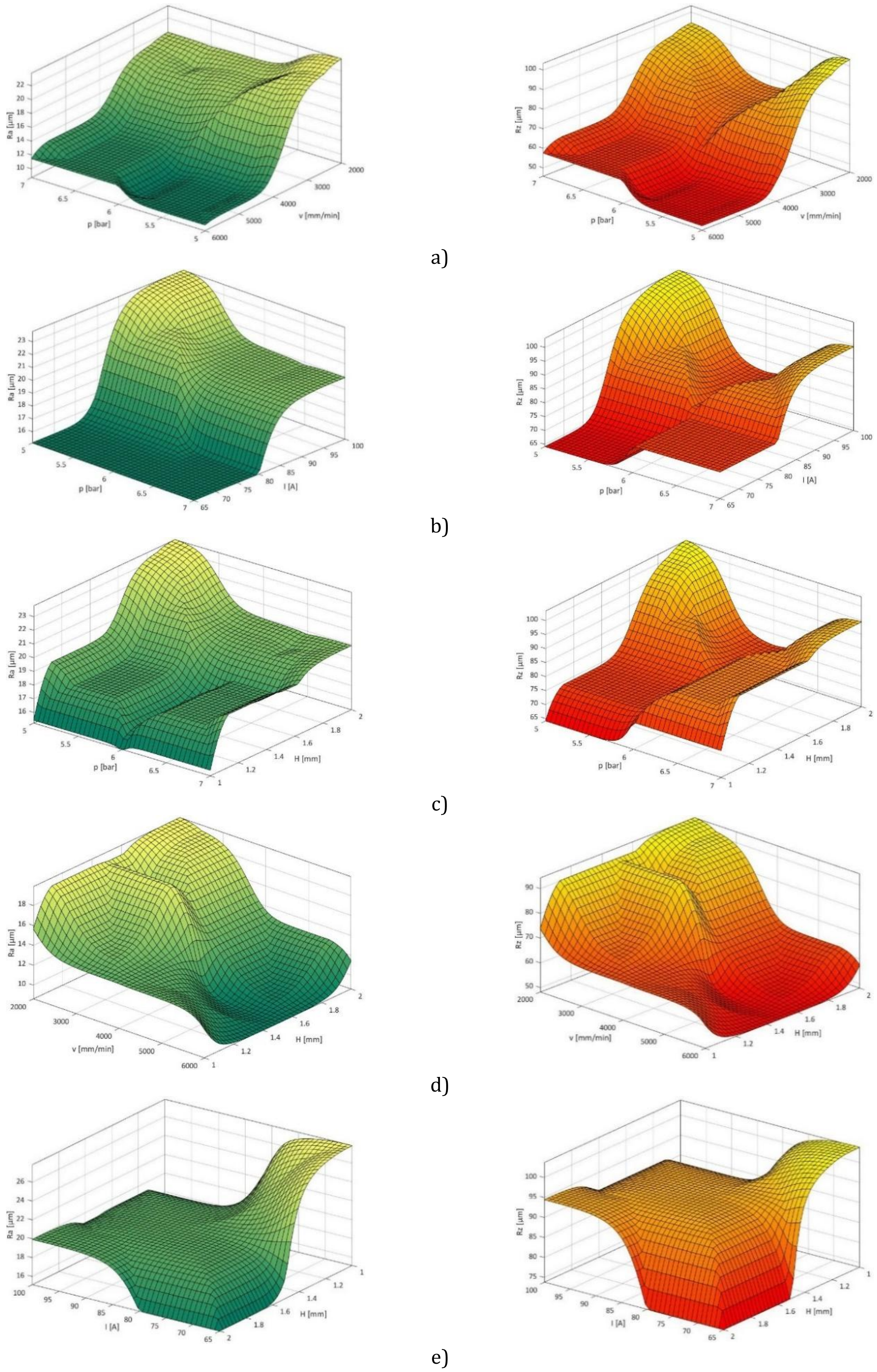


Fig. 9. Process parameters effects on surface roughness *Ra* and *Rz* when constant parameters are: a) I = 100 A, H = 2 mm, b) v = 2000 mm/min, H = 2 mm, c) v = 2000 mm/min, I = 100 A, d) p = 7 bar, I = 100 A, e) p = 7 bar, v = 2000 mm/min

From Figure 9 it can be observed that cutting speed and arc current are the most significant parameters that affect surface roughness responses while gas pressure and cutting height have lower influence. Surface roughness formation in plasma jet cutting process is mainly determined by molten metal fluctuation, plasma jet flow perturbation, cutting torch vibration and motion of anode spots within the groove of cut [4, 17]. Figure 9 shows that increase of the cutting speed results with lower surface roughness values. Higher cutting speeds lead to more intensive fluctuation of molten aluminium from the cutting groove and consequently to the smoother cut surface. At lower cutting speeds motion of anode spots appears and that leads to the higher roughness values [17]. Regarding arc current, from Figure 9 b) it is visible that increase of the arc current at low cutting speeds (2000 mm/min) results with the higher surface roughness. In these conditions, cutting energy input is higher and fluctuation of the molten aluminium in the cutting groove is less intensive. Finally, all these issues bring together to the rougher cut surface. In principle, at high cutting speeds (6000 mm/min) increase of the arc current results with the slightly lower surface roughness. In this situation higher energy input and more intensive fluctuation of the molten aluminium result with the lower surface roughness [4, 17]. From Figure 9 it can be observed that gas pressure has lower influence on the surface roughness formation but however it should be properly defined to achieve cut surface as smoother as possible. Plasma gas has double role in plasma jet cutting process: to assist in the plasma jet formation and to blow molten metal away from the cutting groove. Very low gas pressure (5 bar) blows molten aluminium less intensively from the cutting area and consequently that results with the higher surface roughness. On the other side, very high gas pressure (7 bar) more intensively blows molten aluminium from the cutting groove. Generally, this results with the lower surface roughness. It is also possible that very high gas pressure (7 bar) causes higher instability and deviation of the plasma jet that can results in some cases with minor increases of the surface roughness. In this situation middle value of gas pressure (6 bar) is good choice to minimize surface roughness. Although cutting height minimally affects surface roughness it is noticeable that higher cutting height at low cutting speed (2000 mm/min) results with less power of plasma jet that penetrates into workpiece material and eliminates it. Hereby a larger forms of molten metal are left behind and rougher cut surface was produced.

Finally, process parameters values that result with optimal surface roughness are: gas pressure: 6 bar, cutting speed: 4000–6000 mm/min, arc current: 85-100 A, cutting height: 1 mm.

5. CONCLUSION

In this paper experimental investigations were conducted on aluminium alloy 5083 thickness 8 mm. Aim of the paper was to explore effects of variable cutting process parameters: gas pressure, cutting speed, arc current and cutting height on the surface roughness cut quality response. Surface roughness was determined by the two most important parameters *Ra* and *Rz*. Also, the goal was to develop AI fuzzy logic expert system for modeling and prediction of surface roughness response in different cutting process conditions. According to conducted experimentations and generated AI fuzzy logic model next findings can be derived:

- Fuzzy logic technique proved as a good tool to describe plasma jet cutting process of aluminium alloy where due to the lot of complexities and noises as well as incomplete and vague informations application of traditional mathematical modeling and optimization procedures is not possible.
- Mamdani fuzzy inference system, Gaussian membership functions and defuzzification method: centroid represent good settings to establish functional relations between gas pressure, cutting speed, arc current, cutting height as inputs and surface roughness parameters as outputs of the process.
- Prediction accuracy of developed AI fuzzy logic model was confirmed by comparison between experimental and predicted data with calculated validation measures MAPE and R^2, for *Ra*: 4.47 %, 0.992, for *Rz*: 5.21 %, 0.984.
- Developed fuzzy logic model served for creation 3D response surface plots. From these plots it was concluded that cutting speed and arc current have the most significant effect on the surface roughness while gas pressure and cutting height are less significant.

- From analysis of response surface plots optimal process conditions can be derived: gas pressure: 6 bar, cutting speed: 4000–6000 mm/min, arc current: 85-100 A, cutting height: 1 mm. These process parameters values result with as lower roughness as possible.
- Generated AI fuzzy logic expert system represents useful basis for further investigations in this area. Also, it can be updated with additional experimental data that will cover wider experimental space. Accordingly, more precise surface roughness response prediction will be performed. Such upgraded AI fuzzy logic expert system will enable better cutting process parameters manipulation. Consequently this will bring better cut quality and postprocessing time and money savings.

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