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Investigation of the Parameters Effects on the Kerf Width in Plasma Jet Cutting Process of Aluminium 5083 using Fuzzy Logic Technique

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Abstract

This paper examined influences of the process parameters such as: gas pressure, cutting speed, arc current and cutting height on the kerf width cut quality response in the plasma jet cutting process of aluminium alloy 5083. Kerf width is important cut quality characteristic that represents the amount of the workpiece material that is wasted during cutting. According to that, aim of each cutting process is to reach as narrow kerf as possible. In this paper, experimentations were conducted on aluminium alloy 5083 thickness 8 mm according to Taguchi L_{27} orthogonal array. In order to check as wider experimental space as possible constraints regarding process parameters values that do not allow sheets cutting were identified. Artificial intelligence (AI) technique fuzzy logic was applied to define functional relations between input parameters and kerf width and to analyse process parameters effects. Created fuzzy logic model was checked by comparison between experimental and predicted response data by using mean absolute percentage error (MAPE) and coefficient of determination (R^2) as validation measures. Defined fuzzy logic system proved good prediction accuracy of kerf width response and represents good basis for further more detailed experimentations and analysis in this area.

Keywords: Plasma jet cutting, kerf width, fuzzy logic, aluminium 5083

1. INTRODUCTION

Plasma jet cutting process is very present in shipbuilding as well as in construction and automotive industry. It can be effectively used for cutting different types of materials, especially steels and non-ferrous metals, at various thicknesses. Result of each cutting process is cut and its quality characteristics such as: surface roughness, kerf width, bevel angle, dross formation on the exit of the plasma jet from the workpiece sheet. Usually, plasma cutting precedes the welding process and due to that the goal is to achieve the best possible cut quality so the cutting postprocessing and welding preparing actions are minimal. In order to achieve good cut quality many plasma equipment manufacturers define process parameters recommendations. These instructions mostly correspond to manufacturers business goals and concentrate on the several cut quality characteristics but not all of them simultaneously. Also, there is lack of understanding different process parameters effects on multiple cut quality characteristics and their optimization.

Aluminium alloy 5083 has very good corrosion resistance and strength and according to that it is very convenient in many shipbuilding applications. Also, aluminium characterizes high thermal conductivity and due to that it is quite sensitive to thermal cutting processes such as plasma jet cutting. There exist many insecurities in aluminium plasma cutting in defining process parameters values that lead to optimal cutting conditions and cut quality characteristics. This requires comprehensive researches in order to explore the influence of different process parameters on various cut quality responses and to determine optimal cutting zones. A few papers were already made in this area.

Peko et al. [1] conducted experimentations on the aluminium alloy 5083 thickness 3 mm by varying three process parameters cutting speed, arc current and cutting height. Artificial intelligence method fuzzy logic was applied for prediction of dross height as cut quality response. Prediction accuracy of developed fuzzy logic model was proved by comparison between experimental and predicted data of dross heights. Developed fuzzy logic model was applied to created surface and contour plots to define optimal cutting areas where dross is minimal. Peko et al. [2] defined artificial neural network (ANN) model for prediction of kerf width in plasma jet cutting process of aluminium alloy 5083 thickness 3 mm. Process parameters that were analysed are cutting speed, arc current and cutting height. Developed mathematical model was checked by using response data sets for validation and testing. Furtherly, contour and surface plots were generated to discuss influence of process parameters values on kerf width response and to determine optimal cutting conditions that lead to kerf width as narrow as possible. Peko et al. [3] conducted comprehensive research in order to develop mathematical models for prediction of kerf width, bevel angle, surface roughness *Ra* and *Rz*, and material removal rate (MRR) in plasma jet cutting process of aluminium alloy 5083 thickness 3 mm. Experimentations were conducted by varying process parameters: cutting speed, arc current and cutting height. Mathematical modelling was performed by using regression analysis. Analysis of variance (ANOVA) was applied to define contribution of each parameter as well as their interactions on each cut quality response. Finally, in order to define optimal cutting area multi-objective optimization of defined cut quality responses functions was conducted by using desirability analysis. Solutions were presented numerically and graphically. Kadirgama et al. [4] conducted experimentations on aluminium alloy sheet 6061 to investigate the influence of arc current, standoff gap and gas pressure on the heat affected zone (HAZ). Mathematical modelling of HAZ was performed by using response surface method. Cutting conditions that lead to minimal HAZ were defined by partial swarm optimization algorithm. Peko et al. [5] applied Taguchi method to find out process parameters values that lead to minimal bevel angle in plasma jet cutting process of aluminium 5083 thickness 3 mm. Experimentations were made according to Taguchi L_{27} orthogonal array by varying parameters such as: cutting speed, arc current and cutting height. Main and interactions effects plots were generated to discuss effects of each process parameter and parameters interactions on the bevel angle response. Hamid et al. [6] investigated influence of arc current, feed rate, gas pressure and cutting distance on surface roughness and conicity in plasma jet cutting process of aluminium alloy 5083 thickness 10 mm. Multi-objective optimization as well as significance of process parameters on analysed responses was discussed by application of grey relational analysis combined with ANOVA. Patel et al. [7] conducted experimentations on the aluminium 6082 thickness 5 mm by varying arc current, standoff distance, gas pressure and cutting speed to determine their influence on MRR, top and bottom kerf width and bevel angle responses. Main effects plots were generated to discuss process parameters influence as well as to define their levels that result with optimal cutting conditions. ANOVA was applied to define contribution of parameters and their interactions on analysed cut quality responses.

In this paper experimentations were made on aluminium alloy 5083 thickness 8 mm in order to investigate influence of gas pressure, cutting speed, arc current and cutting height on top and bottom kerf width responses. Due to complexity of the manufacturing process and the goal to investigate as wider experimental space as possible some constraints regarding parameters values that do not allow sheets cutting were identified. In this case, where application of conventional mathematical modelling approaches is not possible, artificial intelligence technique fuzzy logic was proved as a good solution to define functional relations between input process parameters and output kerf widths. Such defined kerf widths fuzzy logic model represents good base for further design of fuzzy expert system that will be upgraded with additional more detailed experimental data and that will enable better understanding of cutting process as well as more precisely determination of optimal cutting conditions.

2. EXPERIMENTAL PROCEDURE

In this paper experimental trials were made on the aluminium alloy 5083 thickness 3 mm. Plasma jet cutting machine was CNC FlameCut 2513 (Arpel Automation). LG 100 IGBT Inverter Air Plasma Cutting Machine was used as arc current source. As plasma gas compressed air prepared in compressor SCK5 200 PLUS (ALUP Kompresoren Gmbh) was applied. This compressor has an integrated system for gas purifying and drying. Experimental trials were conducted according to Taguchi L_{27} orthogonal array by varying gas pressure, cutting speed, arc current and cutting height on three levels. In all trials nozzle has constant outlet diameter 1.2 mm.

Due to complexity of cutting process and aim to investigate as wider experimental space as possible there are several constraints regarding process parameters levels where cutting process is not possible. These constraints are shown in Figure 1. bold with blue lines. Consequently, there are 9 experimental points excepted from Taguchi L_{27} experimental plan.

In all experimental trials parallel straight cuts length 80 mm were made. Top and bottom kerf width measurements were performed by using Universal Toolmaker's Microscope in the middle of the cut and 15 mm left and right on the top and bottom side of the workpiece sheet. Average value of all three measurements was treated as single experimental result. Whole experimental setup is presented in Figure 2 while experimental results as well as process parameters are shown in Table 1.

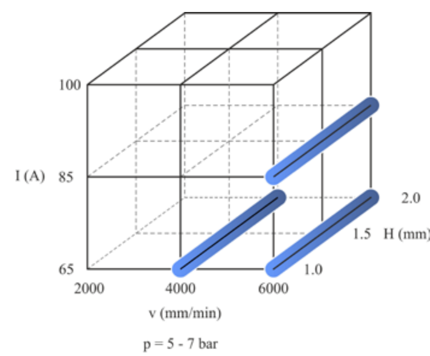


Fig. 1. Cutting process constraints

3. FUZZY LOGIC MODELLING

Fuzzy logic is artificial intelligence method quite convenient for modelling complex manufacturing processes that have imprecise, incomplete and ambiguous measurements data and where application of conventional mathematical modelling techniques is not possible. In this case, due to incomplete data in covered experimental space, aim is to apply fuzzy logic technique to model relations between plasma jet cutting process inputs and outputs. Developed fuzzy logic model will serve as base for fuzzy expert system that will be upgraded with additional experimental results to achieve greater understanding of the cutting process as well as for better prediction and optimization of analysed process responses.

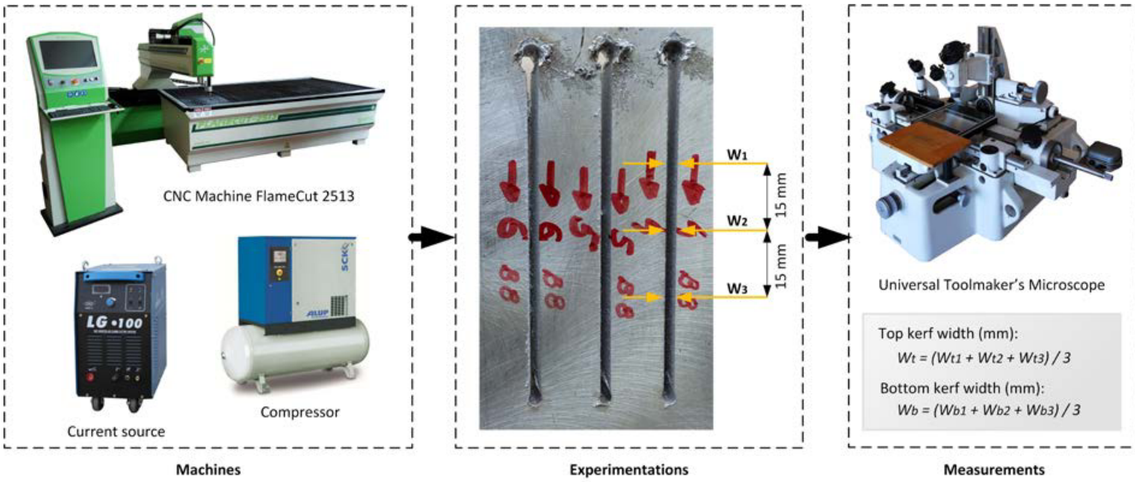


Fig. 2. Experimental setup

Table 1. Experimental results

Exp. Trial	Gas pressure p / bar	Cutting speed v / mm/min	Arc current I / A	Cutting height H / mm	Top kerf width Wt / mm	Bottom kerf width Wb / mm
1	5	2000	65	1	2.306	1.249
2	5	2000	85	1.5	2.697	1.569
3	5	2000	100	2	2.967	1.967
4	5	4000	85	2	2.478	1.267
5	5	4000	100	1	2.465	1.456
6	5	6000	100	1.5	2.679	1.480
7	6	2000	65	1	2.448	1.217
8	6	2000	85	1.5	2.691	1.499
9	6	2000	100	2	3.090	1.857
10	6	4000	85	2	2.779	1.355
11	6	4000	100	1	2.735	1.262
12	6	6000	100	1.5	2.363	0.958
13	7	2000	65	1	2.643	1.514
14	7	2000	85	1.5	2.068	1.567
15	7	2000	100	2	2.653	1.896
16	7	4000	85	2	2.388	1.320
17	7	4000	100	1	2.386	1.314
18	7	6000	100	1.5	2.689	1.254

In order to define relations between process/system inputs and outputs fuzzy logic technique uses few modules: fuzzification module, fuzzy inference module and defuzzification module [8, 9]. Fuzzification module converts numerical values of inputs and outputs, obtained usually in experimentations, into a fuzzy linguistic variables using different membership functions such as: triangular, Gaussian, trapezoidal etc. Membership functions define for each numerical value of inputs and outputs degree of membership between 0 and 1. Fuzzy inference module uses knowledge base composed of fuzzy IF-THEN rules and chosen membership functions to perform fuzzy reasoning and to create functional relations between process inputs and outputs. There are several fuzzy inference systems. Two of them the most popular are Mamdani and Sugeno. Defuzzification module converts outputs fuzzy values into a real values [9-11].

In this paper, Mamdani fuzzy inference system was used to define functional relations between process parameters: gas pressure, cutting speed, arc current and cutting height and cut quality responses: top and bottom kerf width. Process parameters were defined as inputs in fuzzy inference system while top and bottom kerf width as outputs. Settings of applied Mamdani fuzzy inference system are: and method: min, or method: max, implication: min, aggregation: max, defuzzification method: centroid. Scheme of created fuzzy logic system is presented in Figure 3.

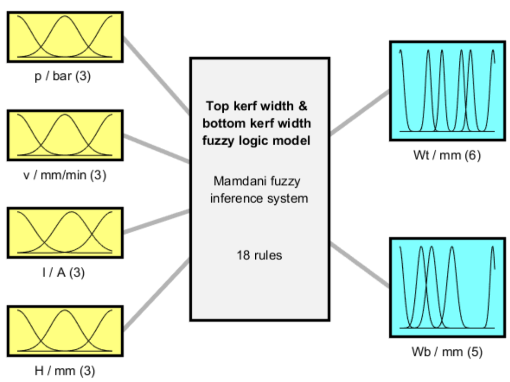
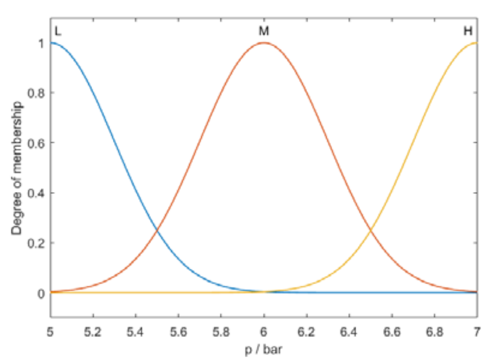
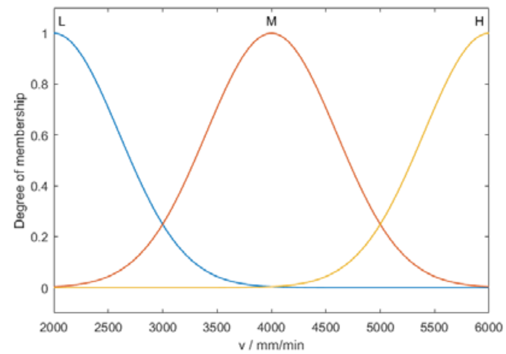


Fig. 3. Fuzzy logic system for modelling of top and bottom kerf width

For each of input parameters three Gaussian membership functions were defined: low (L), medium (M), high (H), Fig. 4. a), b) c), d)). Top kerf width was described with six Gaussian membership functions: low (L), medium low (ML), medium (M), medium high (MH), high (H), very high (VH) (Fig. 5.). Bottom kerf width was defined with five Gaussian membership functions: low (L), medium low (ML), medium (M), medium high (MH), high (H) (Fig. 6.).



a)



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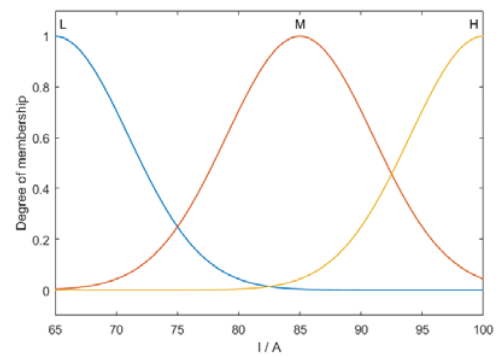

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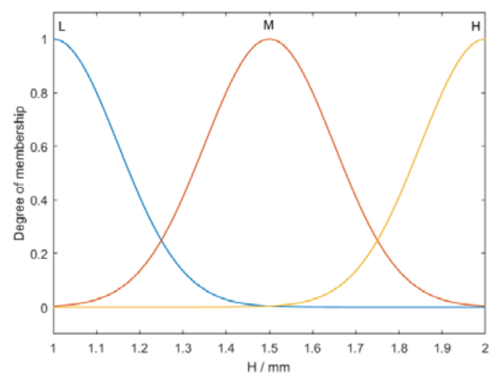

d)

Fig. 4. Membership functions for: a) gas pressure, b) cutting speed, c) arc current, d) cutting height

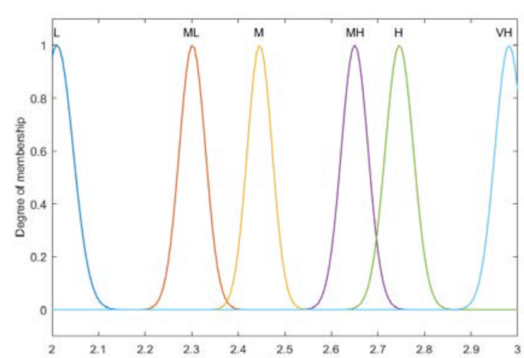

Fig. 5. Membership functions for top kerf width

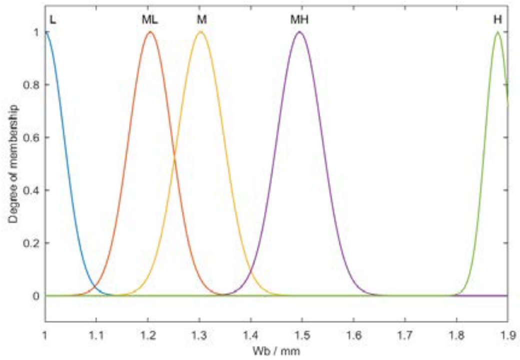

Fig. 6. Membership functions for bottom kerf width

Functional relations between process parameters and analysed responses were established by defining set of 18 fuzzy IF-THEN rules. Graphically these rules are shown in Figure 7.

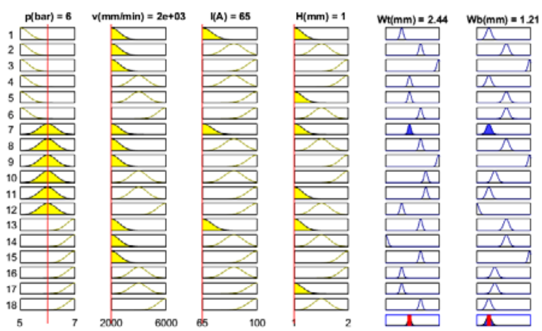

Fig. 7. Graphical representation of fuzzy IF-THEN rules

Finally, defuzzification module converted fuzzy values of top and bottom kerf width into a real numerical values. In order to check accuracy of developed fuzzy logic model for top and bottom kerf width comparison between experimental and predicted data was performed. As prediction accuracy measures mean absolute percentage error (MAPE) and coefficient of determination were applied (R^2). Comparison results as well as MAPE and R^2 are shown in Figure 8. and Figure 9. From these figures it is visible that developed fuzzy logic model for top kerf width (MAPE: 1.36%, R^2: 0.9775) as well as for bottom kerf width (MAPE: 2.98%, R^2: 0.9733) has high prediction accuracy and can be furtherly used for process parameters effects analysis as well as for additional experimentations and creation of fuzzy expert system.

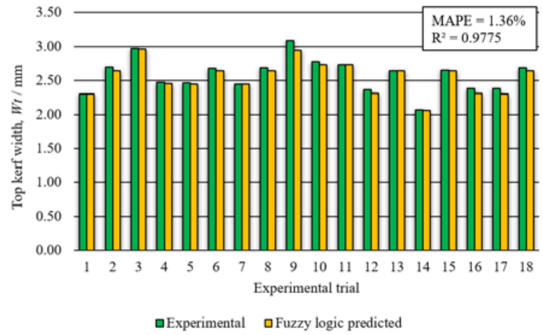

Fig. 8. Comparison of experimental and fuzzy logic predicted data for top kerf width

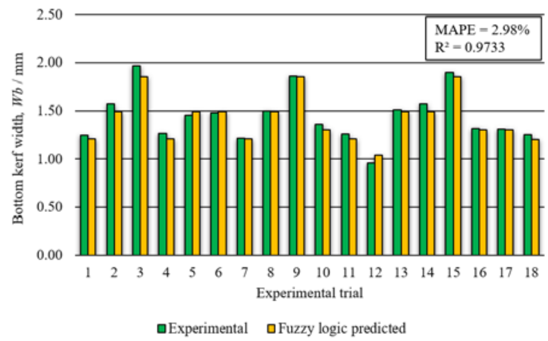

Fig. 9. Comparison of experimental and fuzzy logic predicted data for bottom kerf width

4. RESULTS

In order to discuss process parameters effects on analysed cut quality responses developed fuzzy logic model was used to generate surface plots. These plots represent interactions process parameters effects while two of parameters are kept constant (Fig. 10., Fig. 11.).

From Figure 10. and Figure 11. it is visible that lower cutting speed and higher arc current result with the larger top and bottom kerf width. Cutting heat input is proportional to the arc current and arc voltage and inversely proportional to the cutting speed. That means that higher arc current and lower cutting speed lead to the higher heat input in the workpiece sheet and consequently to the increase of the top and bottom kerf width [3, 12]. From Figure 10. a) and b) it can be derived that higher gas pressure results with the lower kerf width at cutting speed: 2000 mm/min, arc current: 100 A and cutting height: 2 mm. Higher gas pressure makes plasma jet more focused and regular that finally brings to the narrower cut.

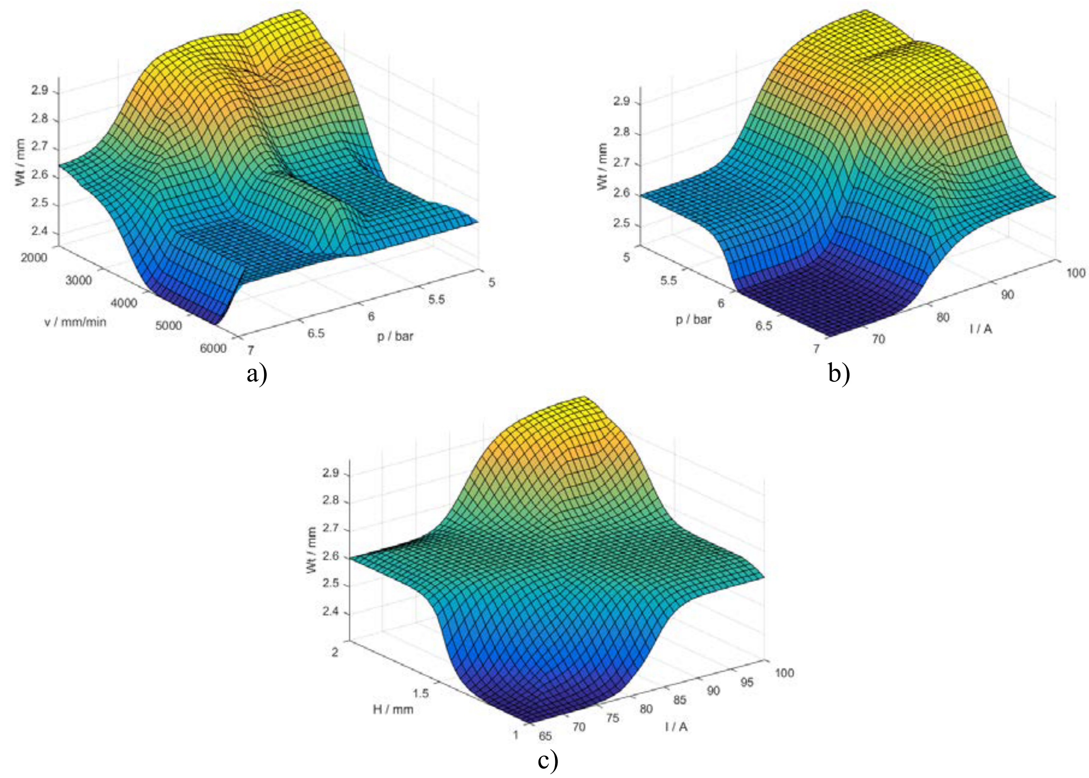

Fig. 10. Process parameters effects on top kerf width when: a) I = 100 A, H = 2 mm, b) v = 2000 mm/min, H = 2 mm, c) p = 5 bar, v = 2000 mm/min

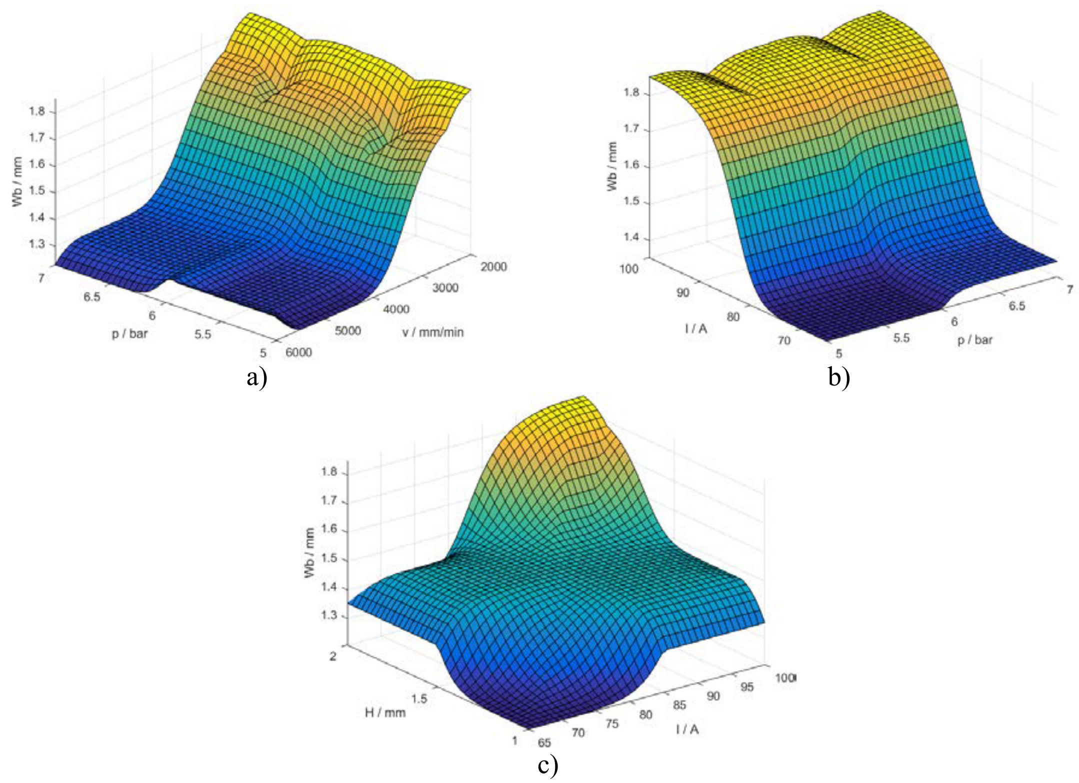

Fig. 11. Process parameters effects on bottom kerf width when: a) I = 100 A, H = 2 mm, b) v = 2000 mm/min, H = 2 mm, c) p = 5 bar, v = 2000 mm/min

From Figure 11. a) and b) it is visible that gas pressure doesn't have so significant effect on the bottom kerf width as on the top. That confirms that higher gas pressure at cutting speed: 2000 mm/min, arc current: 100 A and cutting height: 2 mm contributes more to the focus and regularity of the plasma jet on its top at the nozzle outlet than on its bottom where plasma jet is by itself wider and more erratic. Figure 10. c) and Figure 11 c) confirms that higher cutting height creates a lack of plasma arc coherence resulting with deflection of the arc and larger top and bottom kerf width [3, 13].

Above mentioned statements are derived according to conducted experimental research on aluminium sheet 5083 thickness 8 mm and defined fuzzy logic model. In order to determine more precisely conclusions about process parameters effects on the kerf width it would be desirable to conduct additional experimentations to cover all experimental space and upgrade created fuzzy logic model.

5. CONCLUSIONS

This paper investigated the influence of variable process parameters on the top and bottom kerf width values in plasma jet cutting process of aluminium alloy 5083 thickness 8 mm. Fuzzy logic artificial intelligence technique was applied to define functional relations between process parameters and analysed cut quality responses.

According to conducted experimental research and defined fuzzy logic model next conclusions can be given:

- Application of fuzzy logic technique was shown as a good approach to model manufacturing processes such as plasma jet cutting especially when there is lack of all experimental data and when due to unknown and incomplete informations application of traditional mathematical modelling methods is not possible.
- Mamdani fuzzy inference system combined with appropriately defined Gaussian membership functions, set of fuzzy IF-THEN rules and defuzzification centroid method proved as a good settings to predict top and bottom kerf width depending on variable input parameters values.
- All analysed process parameters have visible and significant effect on the top and bottom kerf width.
- Larger kerf width appears in situations when arc current is lower and cutting speed is higher due to higher energy input in the workpiece material. Also, larger kerf width can be expected in situation when cutting height is higher because of plasma jet deflection.
- Higher gas pressure at cutting speed: 2000 mm/min, arc current: 100 A and cutting height: 2 mm results with narrower cut (lower top kerf width) due to more focused and regular plasma jet.
- Gas pressure doesn't have visible effect on the bottom kerf width.
- Based on conducted experimental research and created fuzzy logic model preferable cutting conditions that lead to optimal top and bottom kerf width are: gas pressure: 7 bar, cutting speed: 6000 mm/min, arc current: 100 A, cutting height: 1 mm.
- This work serves as a base for further experimentations with the aim to upgrade developed fuzzy logic model with additional data and to generate fuzzy expert system capable for prediction of kerf width responses in all analysed experimental space.

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