ISSN: 0974-5823 Vol. 7 No. 6 June, 2022

International Journal of Mechanical Engineering

Design of FLC with Mamdani Approach for the Estimation of weld ductility of MIG welded Al-65032 Alloy

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Abstract: The fuzzy logic controller (FLC) is particularly suited to situations when there is a high level of uncertainty in the process. Welding parameters such as shielding gas pressure, current, torch angle, electrode size, arc length, electrode wire feed, and others affect the material properties of a weldment in Metal Inert Gas Welding (MIG). Joint characteristics such as groove angle, land, root gap, and preheating temperature all have an impact. However, a variety of noise characteristics, such as variations in base material properties, inert gas quality, ambient conditions, worker skill, and so on, add uncertainty into the process. An FLC is designed and validated to deal with such uncertainty. The effect of four input parameters, namely inert gas pressure, current, groove angle of the joint, and preheating temperature of base metal, on the percentage of elongation, which is a measure of ductility, is investigated in the current work. Each parameter is described using three language phrases. An L-9 orthogonal array is chosen for experimentation to reduce the number of experiments in data base architecture. MIG welding is used, and a data base containing nine rules is created. The FLC is designed in MATLAB and analytically validated. The Fuzzy controller is built using the Mamdani technique.

Key words: Crisp value, Fuzzy logic controller, GMAW, Mamdani approach, Membership function, Orthogonal array, Triangular function.

Introduction

A fuzzy logic controller is defined as a set of rules of the kind IF (condition) THEN (action) that are used to convert a human expert's linguistic control strategy into a well-adapted automatic control strategy [1]. Fuzzy logic controllers have a wide range of applications in engineering [2-6]. Al-65032 is a precipitation-hardening aluminium alloy that is one of the most widely used for general-purpose applications. Aluminium alloys are difficult to weld materials. Gas Metal Arc Welding is extensively used for welding aluminium alloys. MIG welding process is influenced by number of parameters individually and combinedly with a high complexity of interactions. The complex interaction of the parameters results into a wide variation in the weldment properties, geometry, and metallurgical features.

Input Parameter selection

The input variable selected is pressure current groove angle and preheating. Three linguistic terms for the FLC design, are selected for each parameter; Low, Medium and High. For 4 parameters with 3 linguistic terms, the size of the rule base is 4^3. i.e 64. So, a minimum of 64 experiments are to be conducted for developing the rule base which involves a huge cost and time. So for reducing the no. of experiments an orthogonal array L-9 is selected for experimentation. Experiments conducted with the Taguchi Orthogonal arrays will give the reasonably accurate results even in partial factorial case. The hypothesis was validated by Ankamma et.al [7]. In the current work the FLC is designed using MATLAB and validated with the analytical results.

Table 1: The input variables

S.No	Input Parameter	Level 1	Level 2	Level 3
1.	Pressure (KPa)	90	104	125
2.	Current (Amps)	220	230	245
3.	Groove angle (Deg)	45	60	70
4.	Pre-heating (^{O}C)	125	150	175

The three levels of the parameters selected after preliminary experiments are given in table 1. With four parameters and three levels Orthogonal array L9 was selected for the experimentation and the levels of the parameters shown in table 1 are assigned to the OA and presented in table 2.

Experimentation

Standard test pieces with dimensions 150mm X 150mm X 6mm are cut from the Al-65032 alloy sheet are prepared with an a saw machine. The plates are grooved to the desired angle on a milling machine. The milled pieces were engraved with a specific number for identification. The pieces were pickled. Hydrochloric Acid is used for the process. A ready to weld sample of weld specimen is presented in Fig 1 and the test pieces are shown in Fig 2.

Table 2: OA after assigning the values

Run	Pressure (KPa)	Current (Amps)	Groove angle (Deg)	Pre-heating (^{O}C)
1.	90	220	45	125
2.	90	230	60	150
3.	90	245	70	175
4.	104	220	60	175
5.	104	230	70	125
6.	104	245	45	150
7.	125	220	70	150
8.	125	230	45	175
9.	125	245	60	125

The tensile test was carried out. The % Elongation values which is an indication of ductility of a material, for various trials are presented in Table 3. For all the parameters output values at the levels 1,2,3 are summed up and averaged. The averaged values are presented in the table 3 against A1, A2 and A3 and the values are plotted in Fig 3 to know the variation.

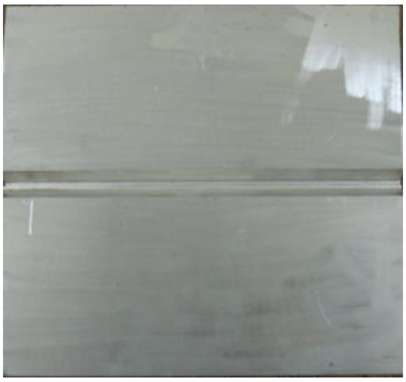

Fig 1 A sample of specimen before welding

Fig 2: Tensile Test pieces

Table 3: % Elongation values for various trials

Run	Pressure	Current	Angle	Pre-heating	% EL
1	1	1	1	1	17.23
2	1	2	2	2	17.57
3	1	3	3	3	19.49
4	2	1	2	3	18.09
5	2	2	3	1	16.17
6	2	3	1	2	15.63
7	3	1	3	2	14.98
8	3	2	1	3	17.89
9	3	3	2	1	17.45
A1	18.10	16.77	16.92	16.95	
A2	16.63	17.21	17.70	16.06	
A3	16.77	17.52	16.88	18.49	

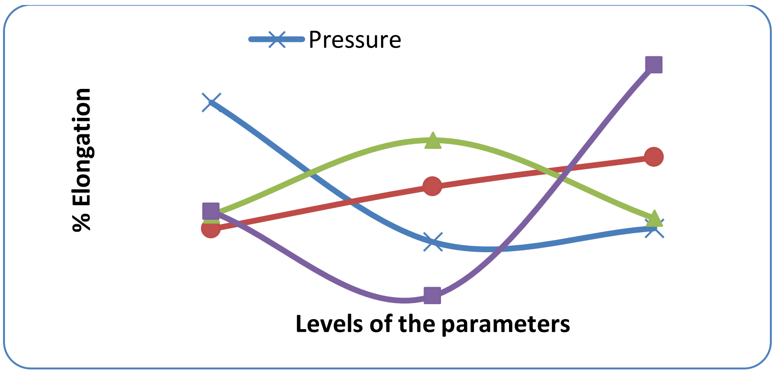

Fig 3 : Variation of % Elongation at various levels

Design of Fuzzy Logic Controller

Mamdani approach is used for the design of FLC (Fuzzy logic controller). Fig 3 reveals that the variation % elongation is almost linear with current and nonlinear with other parameters. As the experiments are conducted at three levels, for each input three linguistic terms are used to denote low, medium and high. Table 4 presents the linguistic terms selected for the input parameters.

4.1 FLC Design with triangular member function

The triangular membership functions of the pressure; Current, Groove angle and preheating are given in Fig 4, Fig 5, Fig 6and Fig 7 respectively. The triangular member ship function of the output, percentage elongation is presented in Fig 8.

Table 4: input & output variables and their linguistic terms

S.No	Input variable	Low	Medium	High
1.	Pressure	LP	MP	HP
2.	Current	LC	MC	HC
3.	Groove angle	LG	MG	HG
4.	Pre-heating	LH	MH	HH
5.	% Elongation	LE	ME	HE

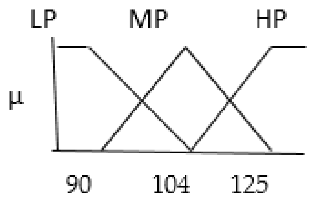

Fig 4: Pressure

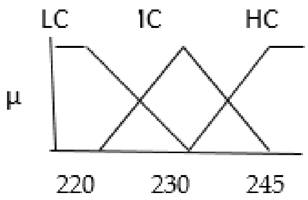

Fig 5: Current

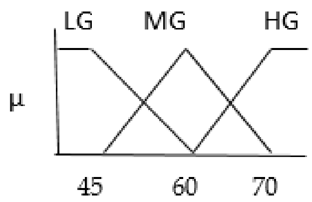

Fig 6: Groove Angle

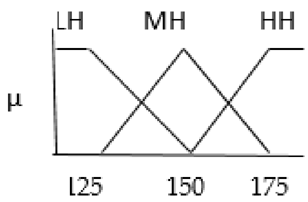

Fig 7: Pre-heating

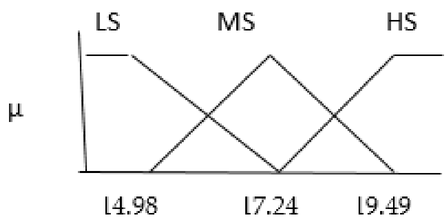

Fig 8 : % Elongation

From the results of the experiments shown in table 3, the rule base is designed and given in table 5. Since for the reduction of no. of experiments, partial factorial experimentation is done a rule base of 9 rules can only be obtained instead of 64 rules.

Table 5: Rule Base

Run	Pressure	Current	Angle	Pre-heating	UTS
1	LP	LC	LG	LH	ME
2	LP	MC	MG	MH	ME
3	LP	HC	HG	HH	HE
4	MP	LC	MG	HH	HE
5	MP	MC	HG	LH	LE
6	MP	HC	LG	MH	LE
7	HP	LC	HG	MH	LE
8	HP	MC	LG	HH	ME
9	HP	HC	MG	LH	ME

Further experiments are conducted for validation of the FLC. The Experimental results are presented in table 6

Table 6: Results of further experiments

Run	Pressure (KPa)	Current (Amp)	Angle (Degree)	Pre-heating (^{0}C)	% Elongation (Experimental)
1	95	220	50	130	15.98
2	100	225	55	170	17.79
3	100	230	60	140	17.00
4	120	240	50	160	15.44
5	100	220	70	140	16.02

Calculation of out using analytical formulae

A sample calculation is provided here under for the first case i.e Pressure 95 KPa, Current 200 A, groove angle 50^0 and preheating 130^0 C

From the Fig 9 it is noted that 95 Kpa pressure can be termed as low pressure or medium pressure with different membership functions. The member ship functions can be calculated by similarity of triangles and found out as μ_{Lp}=0.714286 and μ_{MP}=0.285714.

Similarly membership functions pressure, current, groove angle and preheating can be calculated as μ_{LC}=0.8 and μ_{MC}=0.2; μ_{LG}=0.666667 and μ_{MG}=0.333333; μ_{LH}=0.8 and μ_{MH}=0.2.

So there 16 possible rules those can be fired and are presented in table 7.

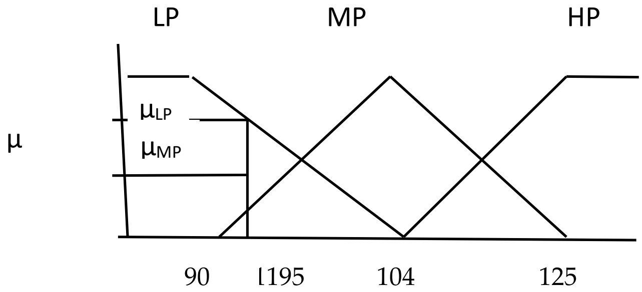

Fig 9: Sample calculation for Pressure

Firing strength of each rule can be found out by taking the minimum value of the member ship of functions of each rule. For example firing strength of rule 1 given in table 7 can be found out as

$$\text{Min}\ (\mu_{LP}, \mu_{LC}, \mu_{LA}, \mu_{LH}) = \min\ (0.714286, 0.8, 0.666667, 0.8) = 0.666667$$

Similarly the firing strength of each rule is found out and are given in the table 7

Table 7: Firing strength of the rules

Rule	Pressure	Current	Angle	Pre-heating	Firing strength
1	LP	LC	LG	LH	0.666667
2	LP	LC	LG	MH	0.2
3	LP	LC	MG	LH	0.333333
4	LP	MC	LG	LH	0.2
5	MP	LC	LG	LH	0.285714
6	LP	LC	MG	MH	0.2
7	LP	MC	MG	LH	0.2
8	MP	MC	LG	LH	0.2
9	MP	LC	MG	LH	0.2
10.	LP	MC	LG	MH	0.2
11.	MP	LC	LG	MH	0.2
12.	LP	MC	MG	MH	0.2
13.	MP	MC	MG	LH	0.2
14.	MP	LC	MG	MH	0.2
15.	MP	MC	LG	MH	0.2
16	MP	MC	MG	MH	0.2

But the database only consists of 2 rules Fuzzified outputs as evident from table 3; Rule 1 and rule 12 calculations are done on these two rules

From Fig 3 the two rules can be stated as

Rule 1: If Pressure is LP and current is LC and Groove angle is LG and preheating is LH then the Impact Energy is ME

Rule 12: If Pressure is LP and current is MC and Groove angle is MG and preheating is MH then the Impact Energy is ME

The representation the above two rules on the triangular membership function are graphically presented in Fig 10 and Fig 11

Fig 10: Rule 1

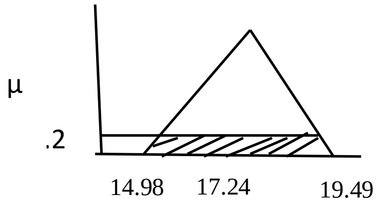

Fig 11: Rule 12

Centre of sums method is applied for defuzzificaiton. The hatched areas of the membership functions and the centres of areas shown in the Fig 10 and 11 are computed and presented in the table 8. Areas can be easily calculated by the geometry i.e Sum of area of a triangle and a rectangle for each case. Length of the rectangle and the base of the triangle can be found out by similarity of triangles. Centre of the rectangle is at half of its length and centre of the triangle is 1/3 of its length.

The centre of whole area is obtained by weighted average Centre of area = (area of rectangle X centre of rectangle+ area of the triangle and centre of the triangle)/ (area of the rectangle + Area of the triangle)

Table 8: Area and centre of areas

Rule	Area	Centre
1	13.342	17.24
12	11.453	17.24

The fuzzified output can be calculated by the equation (1)

$$Defuzzified\ output = \frac{A_1 * C_1 + A_{12} * C_{12}}{A_1 + A_{12}} \ldots\ldots (1)$$

Defuzzified output for this case is computed to be 17.24

Design of FLC using MATLAB

The FLC design is carried out using MATLAB, The input parameters and out parameter of FLC are shown in Fig 12. Triangular membership functions selected for input variables pressure, current, groove angle and preheating are presented in Fig 13, Fig 14, Fig 15 and Fig 16 respectively. The triangular membership function of output, percentage elongation is presented in Fig 17.

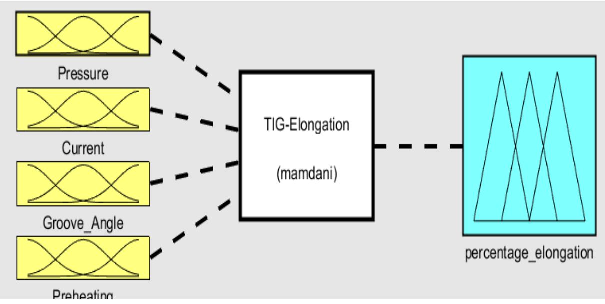

Fig 12: Inputs and Output of FLC

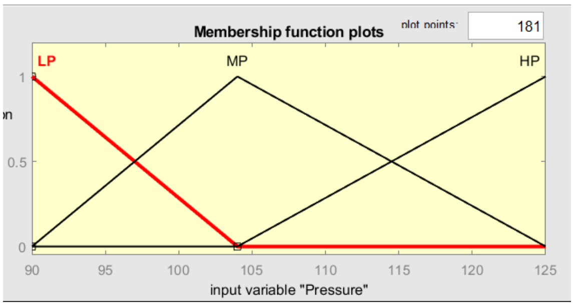

Fig 13: Triangular Membership function of pressure

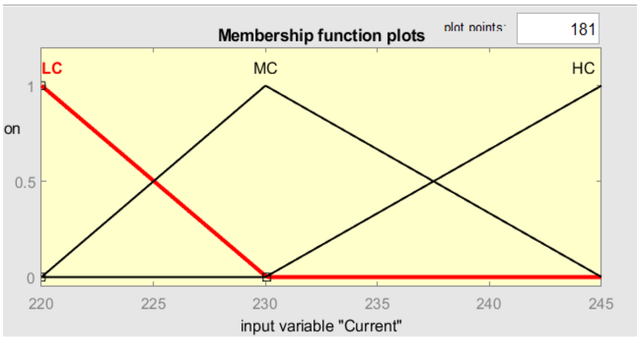

Fig 14: Triangular Membership function of current

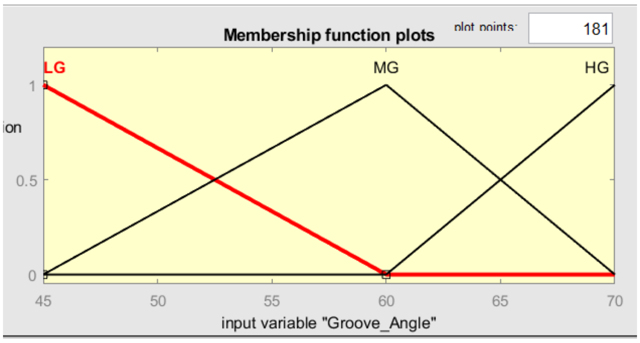

Fig 15: Triangular Membership function of Groove angle

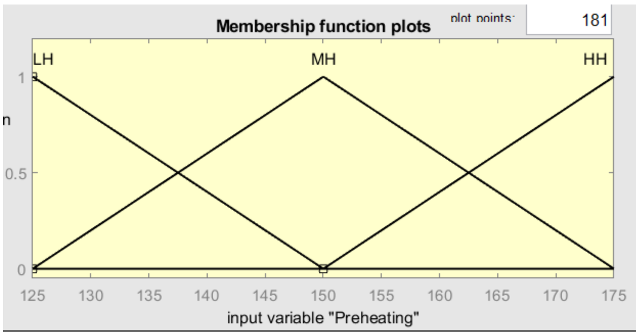

Fig 16: Triangular Membership function of Preheating

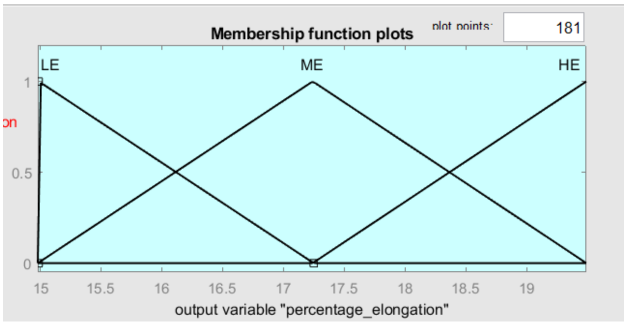

Fig 17: Triangular Membership function of % Elongation

The rules stated in table 5 are input into the MATLAB and are graphically presented in Fig 18.

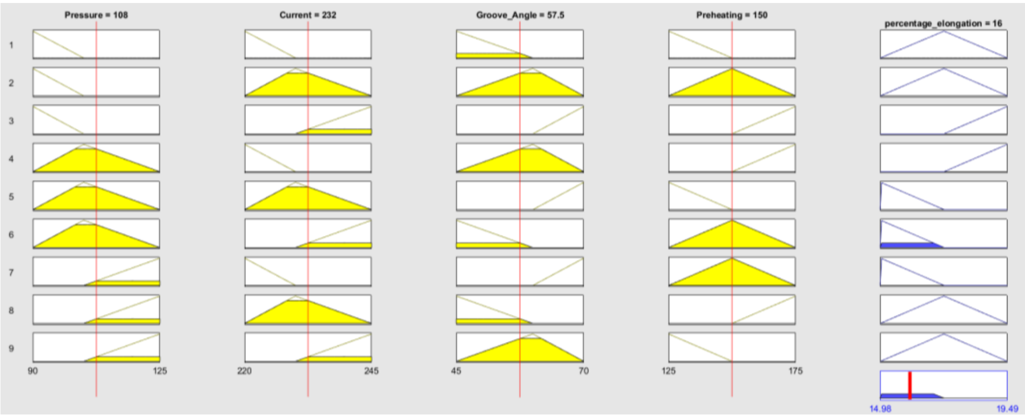

Fig 18: Graphical representation of rules

Validation of FLC

The FLC designed using MATLAB is validated with analytical result obtained in section 4.2. For the same case i.e for the run 1 in table 5 the result obtained MATLAB is presented in Fig 19.

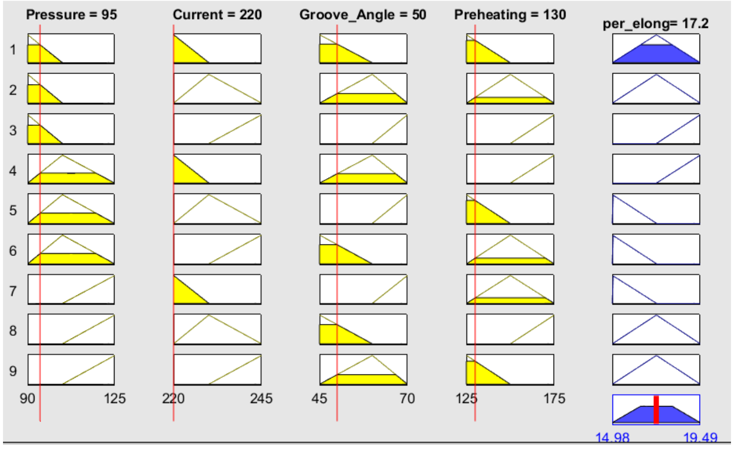

Fig 19: Result obtained with MATLAB for run-1

The result obtained from the analytical calculation is 17.24 and the result obtained from the MATLAB for the same case is 17.2. Hence it is treated that the FLC design with MATLAB is validated and further readings can be from the MATLAB FLC to compare with the experimental results presented in table 6. The results obtained from the FLC for the runs 2,3,4 and 5 presented in table 6 are shown in Fig 20, Fig 21, Fig 22 and Fig 23 respectively and the values are tabulate in table 9 against the experimental values. From the table 9 it is noted that the percentage error between FLC and experimental results vary from 0.06% to 9.47%. The error may be accepted. This error may also be due to the assumption of linearity. But from the Fig 3 linearity was strictly observed for current only.

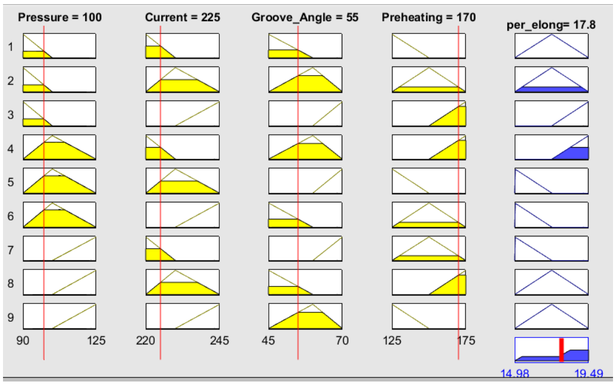

Fig 20: FLC result for run 2

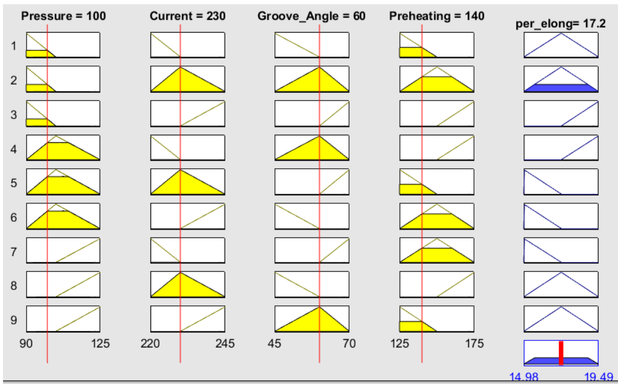

Fig 21: FLC result for run 3

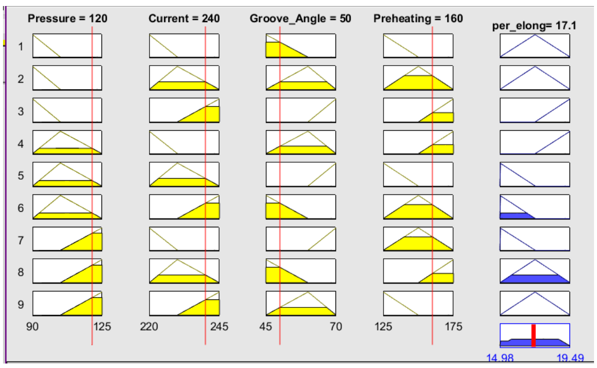

Fig 22: FLC result for run 4

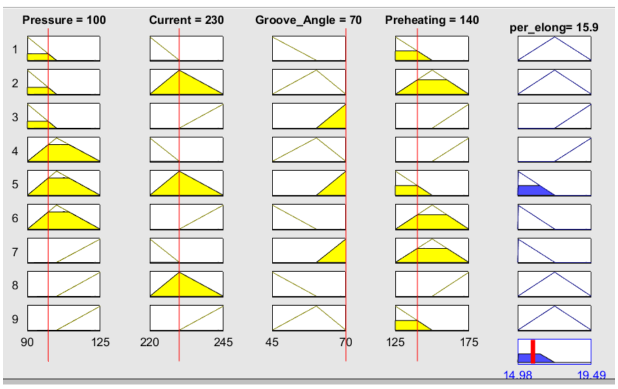

Fig 23: FLC result for run 5

Table 9: Validation of FLC with experimental results

Run	Pressure	Current	Angle	Pre-heating	% Elongation (Experimental)	% Elongation From the FLC	% error
1	95	220	50	130	15.98	17.2	7.6
2	100	225	55	170	17.79	17.8	0.06
3	100	230	60	140	17.00	17.2	1.18
4	120	240	50	160	15.45	17.1	9.47
5	100	220	70	140	16.03	15.9	-0.93

The area plots of percentage elongation with current and pressure, with groove angle and current, with preheating and current are presented in Fig 24, Fig 25 and Fig 26 respectively.

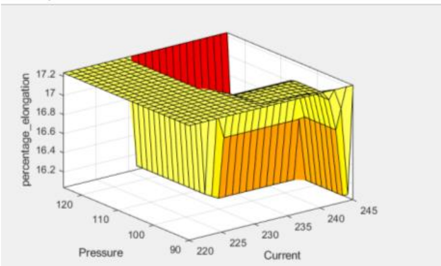

Fig 24. Area plot of % El with pressure and current

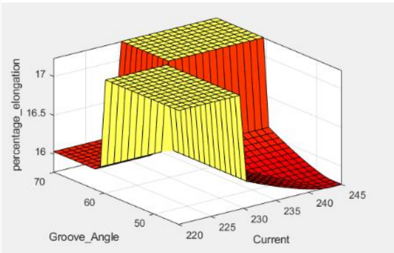

Fig 25. Area plot of % El with Groove angle and current

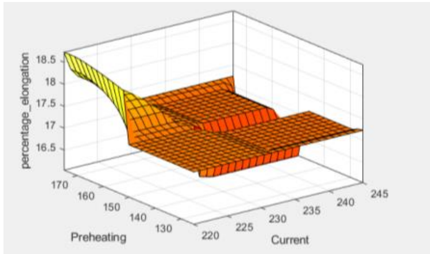

Fig 26. Area plot of % El with preheating and current

Conclusions

In the current work a Fuzzy logic controller is developed with the help MATLAB for predicting the percentage elongation of the aluminium alloy AL 65032 weldment, using Mamdani approach. The FLC developed using the tool MATLAB is validated analytically and experimentally and the validation result is found satisfactory. As design FLC becomes complex with the increase of number of input parameters, the concept of orthogonal array used for experimentation in the development of data base and rule base. Even though a partial data base is developed with the reduced experimentation to save the time, cost and effort, the maximum error in the prediction is found out to be 7.86%. So development of knowledge base using Taguchi technique proved to be accurate enough to design a low cost FLC. Further investigations may be carried out to tune this controller using neural networks or genetic algorithms as the data is getting generated in due course. This off line FLC can be integrated in intelligent manufacturing systems for controlling the process in auto mode and at the same time tuning the FLC continuously to produce the synergic effect.

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