Fuzzy Logic based Optimization of Weld Properties in Submerged Arc Welding using Agglomerated Fluxes

Siddharth Choudhary*, Rohit Shandley* and Aditya Kumar*,[a]
* Division of Manufacturing Processes & Automation Engg, Netaji Subhas Institute of Technology, New Delhi, India
[a]Corresponding author. Email: aditya_rathihere@yahoo.com

Abstract: Welding fluxes play a pivotal role in imparting requisite characteristics to the weld in submerged arc welding. The present study deals with agglomerated fluxes containing CaO, Al_2O_3, TiO_2 and MgO and their effect on hardness and impact strength of the weld. Fluxes were designed in accordance with the Taguchi L8 orthogonal array, making use of the larger the better condition for two levels of voltages, namely 28 V and 32 V. A fuzzy logic based multi response performance index (MRPI) with thirty six fuzzy rules was developed to optimize the hardness and impact strength of the weld whereby a numerical value was assigned to the multiple responses for each combination of flux.

Keywords: Submerged arc welding (SAW), Agglomerated fluxes, Fuzzy logic, Taguchi method, Optimization.

Introduction

Submerged arc welding is a well accepted process, especially in the fabrication of heavy steel plates. In SAW, the welding arc is shielded by a granular flux consisting of lime, silica, manganese oxide, calcium fluoride and other compounds. The flux is fed into the weld zone by means of a hopper by gravity flow. The thick layer of flux completely envelopes the molten metal, preventing spatter and sparks, along with the suppression of ultraviolet radiations and fumes which are characteristic of shielded metal arc welding (SMAW). The flux acting as a thermal insulator, promotes deep penetration of heat. Unfused flux is recovered and can be reused [15-17]. The SAW process is most commonly applied to weld in a flat or horizontal position with a backup piece. Circular welds can be made on pipes and cylinders-provided that they are rotated during welding. SAW is an automated process [18] capable of welding carbon, alloy and stainless steel sheets and plates at speeds as high as 5 m/min. The quality of the welds in SAW is dependent on the process parameters which include variables such as arc voltage, arc length, travel speed, composition of flux and other parameters [9, 10, 12, 14, 19].

Fluxes are a means of introducing alloying elements in the base metal [3-5]. Mechanical properties such as strength, hardness and impact strength [6-8] can be enhanced with the addition of elements such as Si, Mn, Ni, Ti, V. Nickel and titanium promote the formation of acicular ferrite which is characterized by fine grain structure [1,2,11]. CaO helps control the amount of acicular ferrite in the weld. The presence of manganese fluxes promotes lower residuals of sulphur while calcium silicate based fluxes reduce phosphorus content [23].

Multi objective optimization techniques prove to be convenient when dealing with multiple response variables. GRA, PCA [33], Fuzzy logic and other intelligent computational techniques are some of the widely used techniques. Fuzzy logic takes precedence when dealing with diversity in data. Grey based fuzzy logic optimization of process parameters has been satisfactorily used in the past [24-32].

The aim of this work is to evaluate the influence of flux composition on the hardness and impact strength of mild steel welded using SAW. Design of experiments was utilized to make 8 combinations of fluxes containing CaO, Al_2O_3, TiO_2 and MgO. The fluxes were manufactured using the agglomeration route. Furthermore, Taguchi's robust design methodology [21, 22] was used and a L8 orthogonal array was designed to obtained quality loss values corresponding to the impact energy and hardness obtained. Fuzzy logic was used to calculate a multi response performance index (MRPI) to optimize the results obtained.

Methodology

Design and Fabrication of Fluxes

The following eight fluxes were designed as per L8 orthogonal array shown in Table 1. The composition and the levels of flux constituents are shown in Table 2.

Table 1. L8 orthogonal array

Run	CaO	Al_2O_3	TiO_2	MgO
1	1	1	1	1
2	1	1	2	2
3	1	2	1	2
4	1	2	2	1
5	2	1	2	2
6	2	1	1	1
7	2	2	2	1
8	2	2	1	2

Table 2. Different levels of flux constituents

Parameter		Level 1	Level 2
CaO (Wt in gms)	A	600	900
Al_2O_3 (Wt in gms)	B	750	1050
TiO_2 (Wt in gms)	C	300	1200
MgO (Wt in gms)	D	200	400

A mechanical ball mill was used to mix the flux ingredients for 15 minutes. A 20% solution of sodium silicate was added to wet the dry mixed powder and mixed for 15 min, followed by passing through a number 10 mesh screen to form small pallets. These pallets were mixed and dried separately in air for 24 hours and then baked at 500°C for 3 hours in a furnace. This baked mass was crushed and sieved to the required size.

Base Metal and Electrode Wire

Welding was performed on low alloy steel bars. The welding electrode was a copper coated low alloy steel wire with a diameter of 3.15 mm. The copper layered electrodes were chosen due to enhancement in the current carrying capability of the electrode. The electrode composition was same as the base metal. It took three passes to fill the weld groove.

Welding Parameters

Voltage levels were also varied along with the flux composition. The two levels of voltages were: 28V and 32V as shown in Table 3.

Table 3. Voltage Levels

Factor	Low Level	High Level
Voltage	28V	32V

Weld sample preparation

A power hacksaw equipped with a high speed steel (HSS) blade was utilized to cut the mild steel bars into standard sizes of 150mm in length, followed by machining on a vertical milling machine to produce a single V groove. The groove angle was 45° with a root face of 1.5mm. An end-mill, 8 mm in diameter, made of HSS was used to perform the milling operation. Each pair of the plates was numbered with the help of a punching tool. A total of 16 pairs of plates were prepared.

Welding of Plates on SAW Machine

Initially, MIG (Metal Inert Gas) welding was performed to tack the two plates of each pair to be welded, leaving a root gap of 2 mm. The voltage and flux levels were set in accordance with the design matrix. Once the welding was complete, the plates were left to cool. This was followed by the removal of the slag layer and brushing of the weld bead.

Specimen Preparation for Testing

Test specimens for the Charpy impact strength test were prepared by cutting the welded plates along the transverse direction by an abrasive cutter. The welded plates were ground flush with the help of surface grinders. A V shaped notch was cut on the bead surface for each sample to be tested for the Charpy impact test with the help of milling operation.

Impact Testing

A total of 16 specimens were prepared and tested with the help of a pendulum type impact testing machine by Charpy impact test. Test specimens were made in accordance with ASTM E23-16B standard. Fig.1 shows the dimensions of the Charpy impact test specimen.

Hardness Testing

Sections of the welded plates were tested for Rockwell hardness on the B scale to determine the hardness following the ASTM E18-02 standard. A minor load of 10 Kgf was applied in order to compensate the effect of surface roughness on the indentation depth, followed by a major load of 100 Kgf.

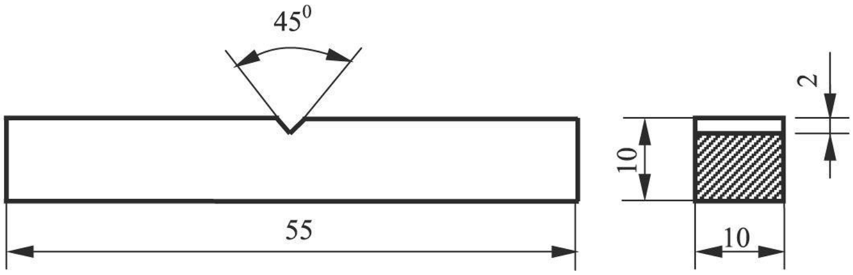


Figure 1. Charpy impact strength test specimen

Taguchi Quality loss Value

The following was followed to obtain optimum parameter settings [20]:

Based on Impact Strength and HRB value, the quality loss value is calculated by the equation (1)

$$\eta = -10\log_{10}\left[\frac{1}{n}\sum_{i=1}^{n} 1/y_i^2\right] \qquad (1)$$

Where i=1, 2 ….n

MRPI is obtained by making use of Fuzzy Logic, which is explained in the next section.

Fuzzy Logic

A typical fuzzy logic unit consists of a fuzzifier, membership functions, a fuzzy rule base, an inference engine, and a defuzzifier. The fuzzifier makes use of membership functions to fuzzify the signal to- noise ratios that have been generated by the response. Next, the inference engine performs fuzzy reasoning on fuzzy rules to generate a fuzzy value by this. Finally, the defuzzifier converts the fuzzy value into a multi response performance index (MRPI). Fig. 2 shows a block diagram of the fuzzy logic unit. The structure of the two-input-one-output fuzzy logic unit is shown in Fig. 3. The input is hardness and impact strength and output is (MRPI). The fuzzy rule base consists of a group of if–then control rules with the two inputs, $x1$ and $x2$, and one output y, that is:

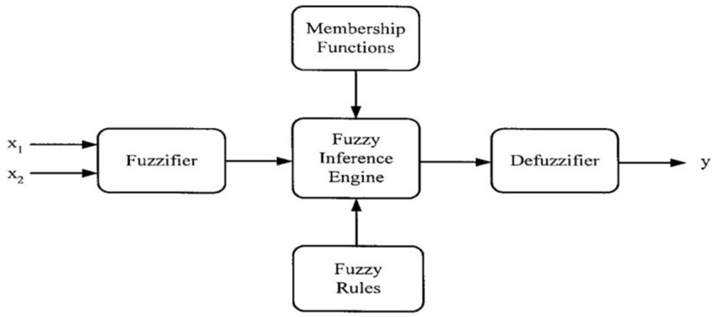
Rule 1: if $x1$ is $A1$ and $x2$ is $B1$ then y is $C1$ else

Rule 2: if $x1$ is $A2$ and $X2$ is $B2$ then y is $C2$ else

:

Rule n: if $x1$ is An and $x2$ is Bn then y is Cn.

Ai, Bi and Ci are fuzzy subsets defined by the corresponding membership functions [26].



X_1 : S/N ratio for Impact Strength; X_2 : S/N ratio for Hardness; Y : Multi-Response Performance Index

Figure 2. Block diagram of fuzzy logic unit

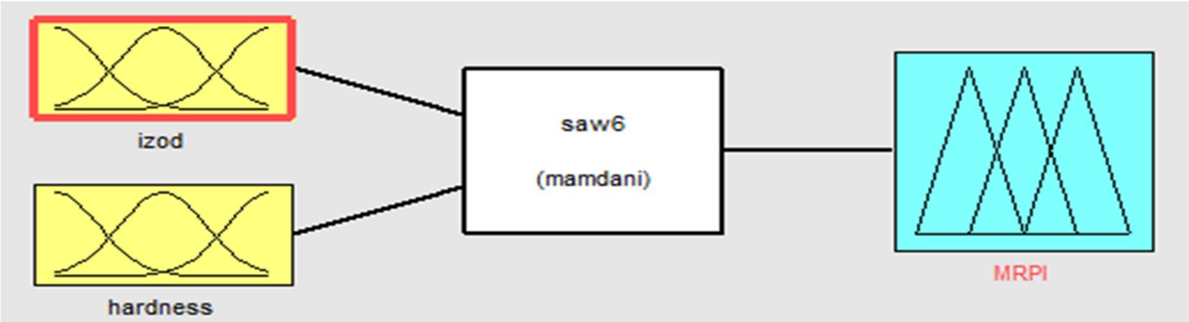


Figure 3. Fuzzy logic with Mandani interface for current study

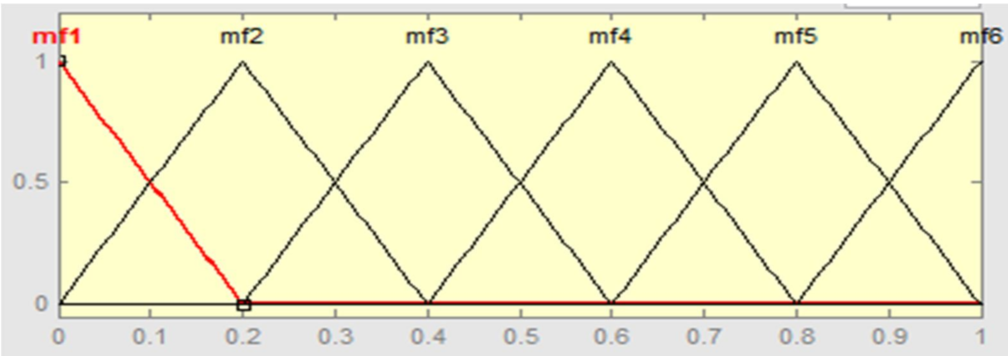


Figure 4. Membership functions for Hardness, Impact strength and MRPI

In the present study, six fuzzy subsets were assigned to each of the two inputs as well as one output (Fig 4). Thirty six fuzzy rules were directly derived based on the larger the better the signal-to noise ratio as shown in Fig. 5. Table 4 shows the details of the proposed fuzzy model.

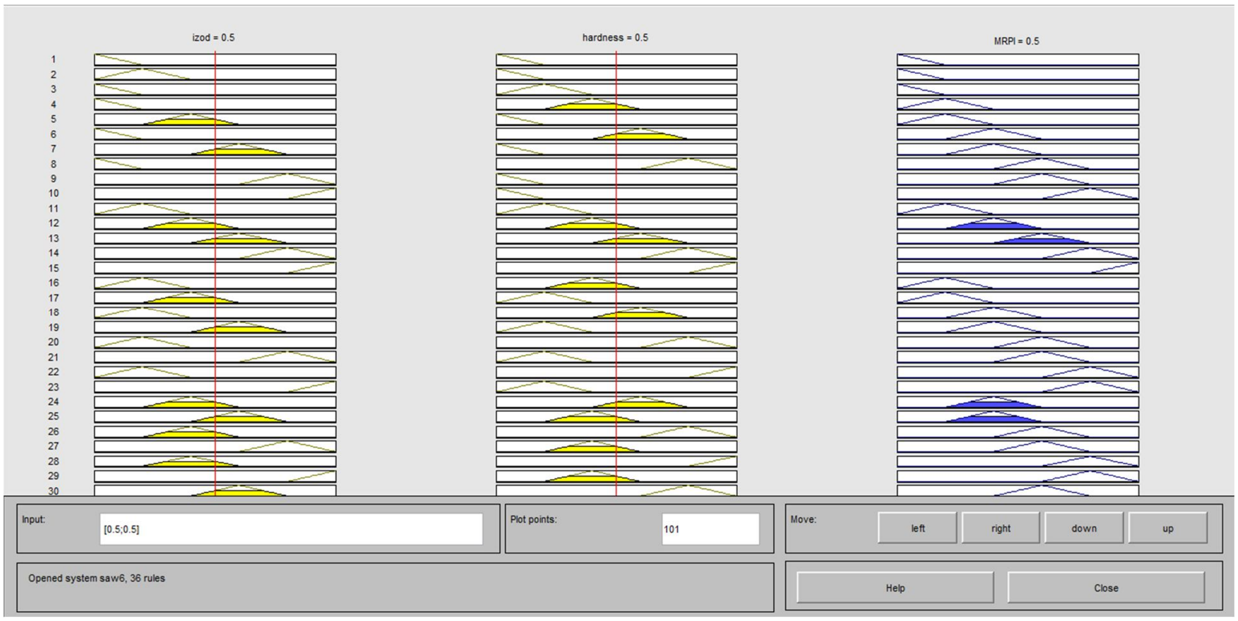


Figure 5. Rules for MRPI

Table 4. Details of the proposed fuzzy model

Type of fuzzy inference system (FIS)	Mamdani
Inputs/Output	2/1
Input membership function types	Triangular
Output membership function types	Triangular
Number of input membership functions	6/6
Number of output membership function	6
Rules weight	1
Number of fuzzy rules	36
And method	Min
Implication method	Min
Aggregation method	Max
Defuzzification method	Centroid

Results

The proposed fuzzy model, comprising of two input parameters (Hardness and Impact energy) and one output parameter (MRPI) fuzzifies the data as shown in Table 5 and 7 for 28 V and Table 6 and 8 for 32 V respectively.

Table 5. Response measured at 28V

Run	CaO	Al_2O_3	TiO_2	MgO	Impact energy	HRB
1	1	1	1	1	136	96
2	1	1	2	2	133	94.5
3	1	2	1	2	148	95
4	1	2	2	1	144	94
5	2	1	2	2	158	93
6	2	1	1	1	150	92
7	2	2	2	1	176	92.5
8	2	2	1	2	170	90

Table 6. Response measured at 32V

Run	CaO	Al_2O_3	TiO_2	MgO	Impact energy	HRB
1	1	1	1	1	128	91
2	1	1	2	2	135	95
3	1	2	1	2	140	89
4	1	2	2	1	146	95
5	2	1	2	2	148	88.5
6	2	1	1	1	156	92.5
7	2	2	2	1	168	87
8	2	2	1	2	174	91

Table 7. L8 OA for Rockwell hardness and Impact strength with S/N ratio and Fuzzy Multi-response Performance Index at 28 V.

					Quality loss values (dB)		
Run	CaO	Al_2O_3	TiO_2	MgO	Impact Energy	HRB	MRPI
1	1	1	1	1	42.67078	39.64542	0.8
2	1	1	2	2	42.47703	39.50864	0.542
3	1	2	1	2	43.40523	39.55447	0.643
4	1	2	2	1	43.16725	39.46256	0.476
5	2	1	2	2	43.97314	39.36966	0.5
6	2	1	1	1	43.52183	39.27576	0.324
7	2	2	2	1	44.91025	39.32283	0.8
8	2	2	1	2	44.60898	39.08485	0.67

Table 8. L8 OA for Rockwell hardness and Impact strength with S/N ratio and Fuzzy Multi-response Performance Index at 32 V

					Quality loss values (dB)		
Run	CaO	Al_2O_3	TiO_2	MgO	Impact Energy	HRB	MRPI
1	1	1	1	1	42.1442	39.18083	0.3
2	1	1	2	2	42.60668	39.55447	0.8
3	1	2	1	2	42.92256	38.9878	0.259
4	1	2	2	1	43.28706	39.55447	0.8
5	2	1	2	2	43.40523	38.93887	0.243
6	2	1	1	1	43.86249	39.32283	0.615
7	2	2	2	1	44.50619	38.79039	0.676
8	2	2	1	2	44.81098	39.18083	0.8

The thirty six rules developed in the Mamdani Interface, give a numerical value of the Multi-Response Performance Index (MRPI) for each experiment using the centroid method of defuzzification. The average MRPI for each level of CaO, Al_2O_3, TiO_2 and MgO is shown in Table 9 and 10 for a voltage of 28 V and 32 V respectively.

Table 9. Average MRPI for each level of CaO, Al_2O_3, TiO_2 and MgO at 28 V

Level	CaO	Al_2O_3	TiO_2	MgO
1	0.6153	0.5415	0.6093	0.6
2	0.5735	0.6472	0.5795	0.588

Table 10. Average MRPI for each level of CaO, Al_2O_3, TiO_2 and MgO at 32 V

Level	CaO	Al_2O_3	TiO_2	MgO
1	0.5397	0.4895	0.4935	0.5978
2	0.5835	0.6338	0.6298	0.5255

The combinations of A1B2C1D1 and A2B2C2D1 seem to give the optimum combination of hardness and impact energy absorption to the weld at 28 V and 32 V respectively, owing to the higher value of average MRPI as seen from Fig.6 and Fig.7 respectively.

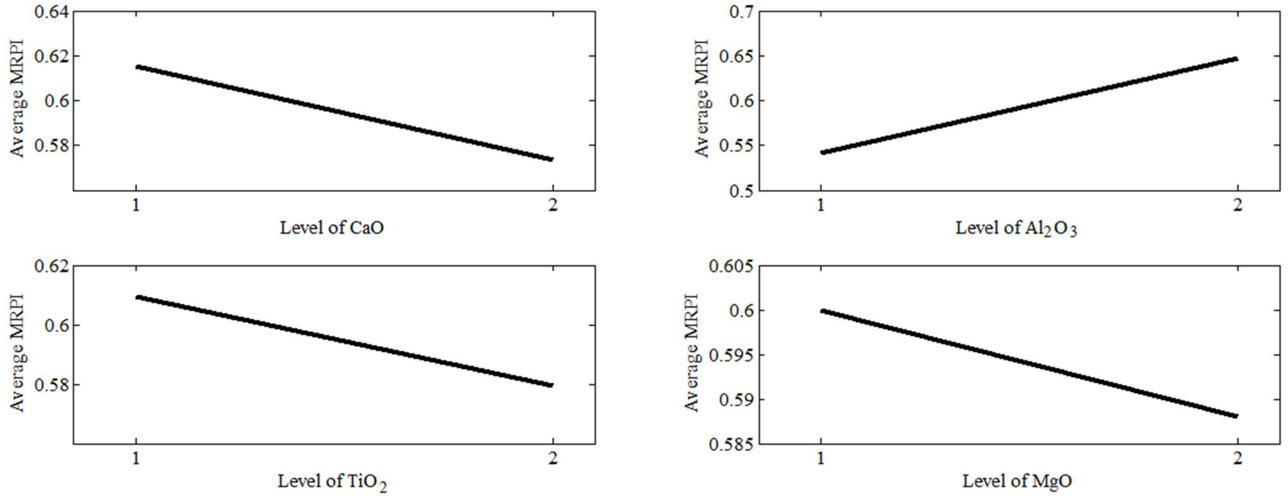


Figure 6. MRPI v/s Level of each flux component at 28V

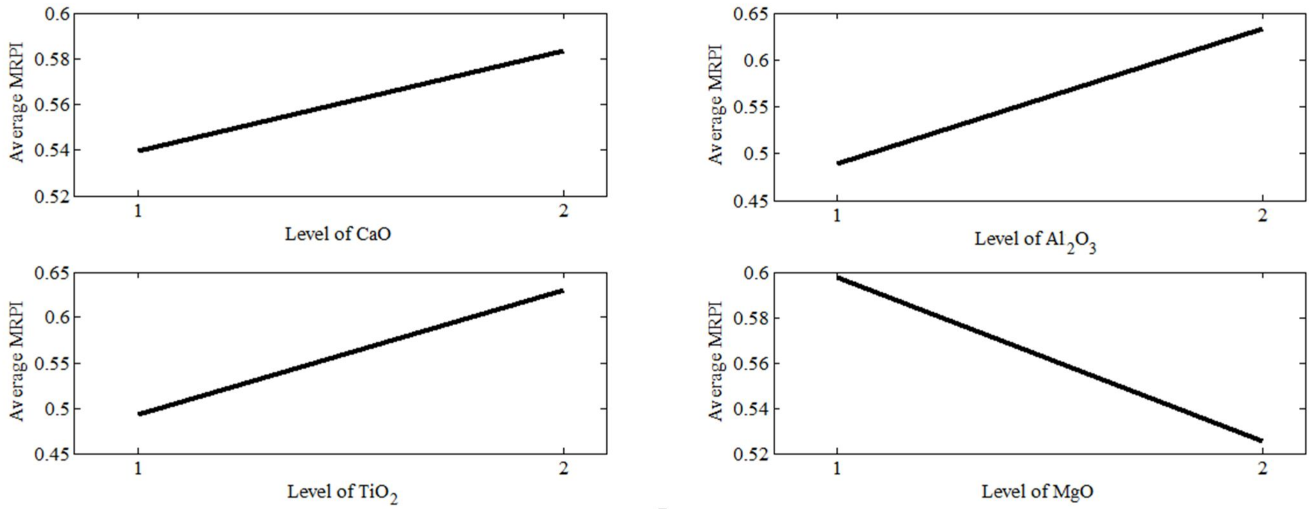


Figure 7. MRPI v/s Level of each flux component at 32V

CaO, MgO are basic oxides, while TiO_2 and Al_2O_3 are acidic in nature. The basicity index of a flux is defined as the ratio of all basic oxides to the all acidic oxides. A low basicity index flux has better current carrying capacity, slag detachability and weld bead appearance with poor crack resistance and mechanical properties of weldment. A high basicity index flux possess better mechanical properties and resistance to cracking in weldment, but the bead appearance and current carrying capacity is low. CaO plays critical and influential role in arc stability and controlling the acicular ferrite content in the weldment. The presence of acidic and basic of fluxes in our composition minimizes the ill effects of both these components.

Conclusions

This study shows that Fuzzy logic can be effectively applied to the experimental design based on Taguchi analysis. The numerical values of MRPI can be quantitatively used to estimate the performance, especially in the case of optimization of multiple responses.

From this study, the following conclusions are drawn-

1. Applying Taguchi orthogonal array, 8 agglomerated fluxes were prepared and tested for mechanical properties of weld metal.
2. A multi-objective optimization is done using a Fuzzy Logic model for mechanical properties of weld metal.
3. The combination of A1B2C1D1 and A2B2C2D1 of agglomerated fluxes at 28 V and 32 V would give the optimal level of hardness and impact strength of weld metal.

References

[1] V.B. da Trindade Filho, A.S. Guimaraes, J. da C. Payao Filho and, R. P. da R. Paranhos “Normalizing heat treatment effect on low alloy steel weld metals.” Journal of the Brazilian Society of Mechanical Sciences and Engineering, vol. 26, no. 1, pp. 62−66, 2004.
[2] B. Beidokhti, A.H. Koukabi, A. Dolati “Influence of titanium and manganese on high strength low alloy SAW weld metal properties.” Material Characterization, 60, pp. 225-233, 2009.
[3] P. Kanjilal, T.K. Pal and S.K. Majumdar “Combined effect of flux and welding parameters on chemical composition and mechanical properties of submerged arc weld metal.” Journal of Materials Processing Technology, 171(2), pp. 223−231, 2006.
[4] P. Kanjilal, T.K. Pal and S.K. Majumdar “Prediction of Elements transfer in submerged arc welding.” Welding Journal, 86(5), pp. 135−146, 2007.
[5] Kumar, H. Singh and S. Maheshwari “Modeling and analysis by RSM of hardness for welded joints using developed agglomerated fluxes.” Indian Journal of Engineering and Material Sciences, 19, pp. 379−385, 2012.
[6] Kerr, H. W. "A review of factors affecting toughness in welded steels."International Journal of PressureVessels and Piping 4, no. 2 (1976): 119-141.
[7] Stallybrass, Charles, et al. "Influence of alloying elements on the toughness in the HAZ of DSAW-welded large-diameter linepipes." 2012 9th International Pipeline Conference. American Society of Mechanical Engineers, 2012.
[8] Singh, Brijpal, et al. "Effect of CaF 2, FeMn and NiO additions on impact strength and hardness in submerged arc welding using developed agglomerated fluxes." Journal of Alloys and Compounds 667 (2016): 158-169.
[9] Tewari, S. P., Ankur Gupta, and Jyoti Prakash. "Effect of welding parameters on the weldability of material." International Journal of Engineering Science and Technology 2.4 (2010): 512-516.
[10] USHIO, Masao, et al. "Effect of Submerged Arc Welding Flux Chemical Composition on Weldment Performance (Materials, Metallurgy & Weldability)." Transactions of JWRI 24.1 (1995): 45-53.

[11] Kanjilal, Prasanta, Sujit Kumar Majumdar, and Tapan Kumar Pal. "Prediction of acicular ferrite from flux ingredients in submerged arc weld metal of C-Mn steel." ISIJ international 45.6 (2005): 876-885.
[12] Karaoğlu, Serdar, and Abdullah Secgin. "Sensitivity analysis of submerged arc welding process parameters." journal of materials processing technology202.1 (2008): 500-507.
[13] Murugan, N., and Voldemorte Gunaraj. "Prediction and control of weld bead geometry and shape relationships in submerged arc welding of pipes."Journal of Materials Processing Technology 168.3 (2005):478-487.
[14] Kumar, P., et al. "Effect of process parameters on microhardness and microstructure of heat affected zone in submerged arc welding." Proceedings of the Institution of mechanical Engineers, part B: Journal of Engineering Manufacture 225.5 (2011): 711-721.
[15] Datta, Saurav, Asish Bandyopadhyay, and Pradip Kumar Pal. "Slag recycling in submerged arc welding and its influence on weld quality leading to parametric optimization." The International Journal of Advanced Manufacturing Technology 39.3-4 (2008): 229-238.
[16] Singh, Kulwant, and Sunil Pandey. "Recycling of slag to act as a flux in submerged arc welding." Resources,Conservation and Recycling 53.10 (2009): 552-558.
[17] Paniagua-Mercado, Ana Ma, et al. "Effect of active and nonactive fluxes on the mechanical properties and microstructure in submerged-arc welds of A-36 steel plates." Materials and manufacturing processes 22.3 (2007): 295-297.
[18] Wikle, H. C., et al. "Infrared sensing techniques for penetration depth control of the submerged arc welding process." Journal of Materials Processing Technology 113.1 (2001): 228-233.
[19] Murugan, N., R. S. Parmar, and S. K. Sud. "Effect of submerged arc process variables on dilution and bead geometry in single wire surfacing." Journal of Materials Processing Technology 37.1-4 (1993): 767-780.
[20] Saha, Abhijit, and Subhas Chandra Mondal. "Optimization of Process Parameters in Submerged Arc Welding Using Multi-objectives Taguchi Method." Advances in Material Forming and Joining. Springer India, 2015. 221-232.
[21] Tarng, Y. S., and W. H. Yang. "Application of the Taguchi method to the optimization of the submerged arc welding process." MATERIAL AND MANUFACTURING PROCESS 13.3 (1998): 455-467.
[22] Patnaik, Amar, Sandhyarani Biswas, and S. S. Mahapatra. "An evolutionary approach to parameter optimisation of submerged arc welding in the hardfacing process." International Journal of Manufacturing Research 2.4 (2007): 462-483.
[23] Mitra, U., and T. W. Eagar. "Slag metal reactions during submerged arc welding of alloy steels." Metallurgical Transactions A 15.1 (1984): 217-227.
[24] Tarng, Y. S., W. H. Yang, and S. C. Juang. "The use of fuzzy logic in the Taguchi method for the optimisation of the submerged arc welding process."The International Journal of Advanced Manufacturing Technology 16.9 (2000): 688-694.
[25] Singh, Ankita, et al. "Optimization of bead geometry of submerged arc weld using fuzzy based desirability function approach." Journalof Intelligent Manufacturing 24.1 (2013): 35-44.
[26] Kumar, Aditya, Sachin Maheshwari, and Satish Kumar Sharma. "Fuzzy Logic Optimization Of Weld Properties For Saw Using Silica Based Agglomerated Flux." Procedia Computer Science 57 (2015): 1140-1148.
[27] Lin, C. L. "Use of the Taguchi method and grey relational analysis to optimize turning operations with multiple performance characteristics." Materials and manufacturing processes 19.2 (2004): 209-220.
[28] Lin, J. L., and C. L. Lin. "The use of grey-fuzzy logic for the optimization of the manufacturing process." Journal of Materials Processing Technology160.1 (2005): 9-14.
[29] Antony, Jiju, et al. "Multiple response optimization using Taguchi methodology and neuro-fuzzy based model." Journal of Manufacturing Technology Management 17.7 (2006): 908-925.
[30] Sarkar, Abhijit, et al. "Optimization of process parameters of submerged arc welding by using grey–fuzzy-based Taguchi method for AISI 1518 grade steel." Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 228.11 (2014): 1491-1500.
[31] Greyjevo, O. G. T. V. Z., and A. I. T. Metodo. "Optimization of weld bead geometry in TIG welding process using grey relation analysis and Taguchi method." Materiali in tehnologije 43.3 (2009): 143-149.
[32] Pandey, Rupesh Kumar, and Sudhansu Sekhar Panda. "Optimization of bone drilling using Taguchi methodology coupled with fuzzy based desirability function approach." Journal of Intelligent Manufacturing 26.6 (2015): 1121-1129.
[33] Datta, Saurav, et al. "Application of PCA-based hybrid Taguchi method for correlated multicriteria optimization of submerged arc weld: a case study."The International Journal of Advanced Manufacturing Technology 45.3-4 (2009): 276.