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EXPERIMENTAL INVESTIGATION AND PREDICTION OF TENSILE STRESS FOR SS 304–CP COPPER DISSIMILAR METAL COUPLE JOINT BY PULSED WAVE TIG WELDING PROCESS

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ABSTRACT

The current study investigates the mechanical characteristics of SS 304 – CP copper dissimilar metal joint by pulsed wave TIG welding process followed by prediction of response using FUZZY rule-based model. A statistical design of experiment based on Taguchi orthogonal array has been used for design and optimization of process parameters. The developed design model is checked for their adequacy and significance by ANOVA analysis and respective confirmation test are also carried out to check the accuracy of predicted values. The tensile stresses of all welding specimens are determined by universal testing machine (UTM). The FUZZY rule-based prediction method is used to predict the output response and also compared with the experimental results to validate the model. The metallurgical investigation of the fusion zone has been carried out using Scanning Electron Microscopy (SEM) analysis.

KEYWORDS: Anova, Dissimilar Metal Welding, Fuzzy, Taguchi Orthogonal Array

The importance of dissimilar metal couples in the process industries goes on increasing exponentially in opposition to that of similar metals due to an ever increase of contrasting properties requirements. These are widely used in industries like automobile, nuclear application, food processing, steam turbine, heat exchangers etc. The academic engineering fraternities are largely focused on process development and optimization for welding parameters applied to commercially available metal and alloys being used as a dissimilar couple. The stainless steel 304 and copper (ferrous and non-ferrous) dissimilar metal couple is extensively used in various industrial applications due to their complementary properties like high thermal and electrical conductivity of copper & corrosion resistance of SS 304.

A numerous research work related to dissimilar metal welding by conventional fusion welding processes has been described related to mechanical strength, microstructure analysis, parametric optimization, numerical modelling etc. of the weld bead orientation. The mechanical and metallurgical behaviour of weldpool of copper (UNSC11000) and alloy steel (En31) dissimilar metal couple by Shielded Metal Arc Welding (SMAW) explained by Velu and Bhat [2015]. They failed to define any detrimental intermetallic compounds around the weld interface region. They also investigated the fracture toughness and fatigue crack growth behavior of mode-I cracked bi-metallic compact tension specimens. For getting a successful weld, they were used nickel as filler metal. The welding of Mg alloy and copper by TIG welding process explained by Liu et al. [2013]. They used a Fe interlayer in between two base metals. The author reported that the oxide produced in the interface between Mg and Fe caused reduction mechanical properties of the weld. Roy et al. [2014] inspected the effect of different electrodes such as Inconel (ENiCrMo3), Monel (ENiCu7) and stainless steel (E316L) over commercially pure copper and 304 stainless steel weldment by shielded metal arc welding. Defects like copper globules and porosity were observed in SS 304 weld interface. The microstructure analysis for copper weldment with Fe filler by using MIG welding process was explained by Suresh Kumar et al. [2002]. The presence of copper globules embedded in the iron matrix was revealed from their microstructural analysis.

As per here concern, very limited work has been reported using pulsed wave TIG welding process for both similar as well as dissimilar metal joint. Yu et al. [2013] proposed a technique to monitor the wire feed used to detect a defect in Al-Me alloy using pulsed TIG welding. Shiri et al. [2012] performed the dissimilar metal welding in between CP copper and 304 SS using gas tungsten arc welding process. Three different types of filler materials such as Ni−Cu−Fe, SS and Cu were used for the investigation of weld zone. They also concluded that the copper is a new and good candidate for gas tungsten arc welding of copper to 304 SS. Rajkumar and Arivazhagan [2014] explained the role of pulsed current on weld properties of Maraging steel and AISI 4340 aeronautical steel dissimilar couple. The authors recommended that the pulsed TIG welding demonstrate superior weldability performance in every mechanical and metallurgical aspect, and it is highly reliable for joining dissimilar material

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combinations. The joining of marine grade alloys (Monel 400) and AISI 904L using ERNiCu-7 and ERNiCrMo-4 filler metals by pulsed current gas tungsten arc welding process is inspected by Ramkumar et al. [2015]. Madadi et al. [2012] investigated the hardness and dilution ratio for pulsed TIG cladding process of Stellite 6 (Co-based alloy) on carbon steel. They described that the penetration depth, and dilution increases with pulse frequency but a decrease in cladding layer hardness.

Tarng et al. [1999] used neural network theory to build a relationship between process parameters and the weld pool geometry in TIG welding process. The optimization of process parameter was carried out by simulated annealing algorithm. They also verified the pool geometry by using fuzzy clustering technique. Prediction of weld bead geometry for TIG welding process by fuzzy logic was also explained by Narang [2011]. The weld bead geometry involves the weldment macrostructure zones and shape profile characteristics. A Neuro-Fuzzy Approach was studied by Moon and Na to Select Welding Conditions for Welding Quality Improvement in Horizontal Fillet Welding, Moon et. al., [1996]. Shanben [1997] suggested the fuzzy inference-artificial neural network control approach may use for avoiding the difficulties of modelling as well as the control of process parameters for pulsed TIG welding process. Chi and Hsu [2001] developed an intelligent decision support system based fuzzy radial basis function (RBF) neural network to established a quality prediction of output response for plasma arc welding process. Jafarian and Vahdat [2012] explained a fuzzy multi-attribute approach for selecting the welding process at high pressure vessel manufacturing.

It is observed from previous literature survey pertaining to pulsed TIG welding process without using any filler material that there is a big research gap regarding process parameter optimization as well as the implementation of numerical prediction approaches in addition to mechanical as well as microstructure study of fusion zone. Very limited works are pursued for CP copper – 304 SS couple weldment. The purpose of this study to give at most useful information about welding possibilities of two dissimilar (SS 304 and copper) thin sheets using pulsed mode TIG system without filler material to the fabrication industries.

RESEARCH METHODOLOGY

Design of Experiment

Based upon the literature survey, it is observed that the Taguchi orthogonal array is one of the best alternatives for the design of experimentation among all others. It is a systematic application of design for the improvement of product quality. The Taguchi design matrix uses a special orthogonal array to study every process parameter with a minimum number of experimental runs. Signal-to-noise (S/N) ratios for each factor are evaluated to assess the influence over output responses. For the current study, three input process parameters such as peak current, scan speed, and standoff distance are taken with four levels of variations as shown in Table 1. The whole experiments are carried out according to Taguchi L16 (4 3) orthogonal array design matrix with three replicates. Therefore, total 48 numbers of samples are welded. All factor levels are equally weighted to ensure a balanced design of experiments.

Experimental Work

For the present research work, two different materials such as AISI 304 SS and CP copper are welded by pulsed wave TIG welding process without using any filler material. The chemical composition of for respective materials obtained by EDS analysis are listed in Table 2. In this case the butt type welding is considered maintaining zero gap in between two materials. As no groove is preferred, so the edge of the welding specimen maintained very flat i.e. making as angle of 90^0 as shown in Fig. 1.

Table 1: Variable process parameters for welding

Parameters	Units	Levels			
		1	2	3	4
Peak current (I_P)	Amp	80	90	100	110
Scan speed (S)	mm/min	90	120	150	180
Stand-off distance (D)	mm	0.85	1.00	1.15	1.30

Table 2: Chemical composition of AISI 304SS and copper (weight fraction, %)

	Fe	Cu	Si	Cr	Mn	Ni	C
SS	74.11	---	0.29	17.71	0.72	7.13	0.04
Cu	---	99.63	0.37	---	---	---	---

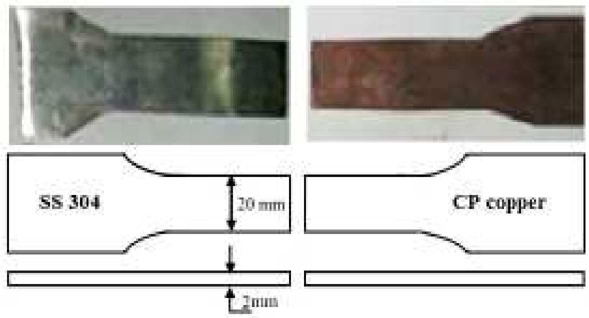

Figure 1: Orientation of butt joint

All welding experiments are carried out on a "Fronius magicwave® 2200" TIG welding unit. The unit is assembled with a CNC workstation for better control in terms of accuracy over standoff distance, scan speed with respect to mounting of welding specimen. The process parameters such as electrode size, flow rate of shielding gas, frequency and ramp down time are kept constant as 1.6 mm, 10 lpm, 500 Hz and 0.75 sec respectively during all experiments.

In any welding experiments, the tensile stress is one of the most effective parameter to evaluate the quality of weld. So, tensile stress is taken as the output response for evaluation of process parameter effectiveness. The tensile tests are performed at room temperature using an automated universal testing machine Instron® 600KN. The whole experimental design matrix with respective tensile stress results are listed in Table 3.

As S/N ratio is used to evaluate the influence of process parameter over the output response, so there are three kinds of quality characteristics in S/N ratio analysis i.e. smaller-the-better, larger-the-better and nominal-the-better based on the output responses. In the present analysis, larger-the-better criterion is chosen for quality characterization of tensile stress in order to maximize the response. The respective formulation is given in "(1)".

$$S/N = -10\log_{10}\left(\sum \frac{1/y^2}{n}\right) \tag{1}$$

Where, y = Average tensile stress measured

n = Number of experimental runs.

The optimization of the process parameters are carried out with the help of the statistical design software Minitab 16®. The main effect plot and residual plot are given in Fig. 2 and 3 respectively. The main effect plot expresses the optimum design level for the selected design matrix. As the output response is based on larger-the-better analysis, the peak values from plot are taken as the optimum settings to maximize the response. The peak setting obtained from main effect plot is found to be "P = 100 Amp, S = 90 mm/min and D = 1.15 mm". The confirmatory test also carried out for the peak setting. The residual plot expresses the normal probability plot, residual versus fitted value as well as the histogram for normal distribution of residuals. The normal probability plot indicates a very good response as all the values are in between -2 to 2 and also the very much fitted to the normal line. Histogram shows a well fitted value with respect to the distribution line tends to a good agreement with the response. The linear regression equation for tensile stress based on the quadratic model is expressed in "(2)" as follows:

$$\text{Tensile stress} = 375.492 - 0.6425\,(I_P) - 0.9092\,(S) - 8.1667\,(D) \tag{2}$$

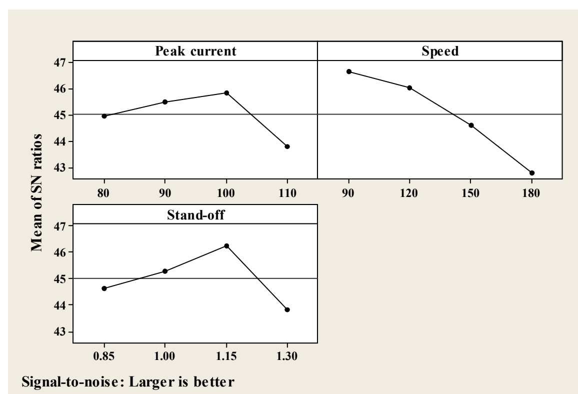

Figure 2: Main effect plot for output response tensile stress

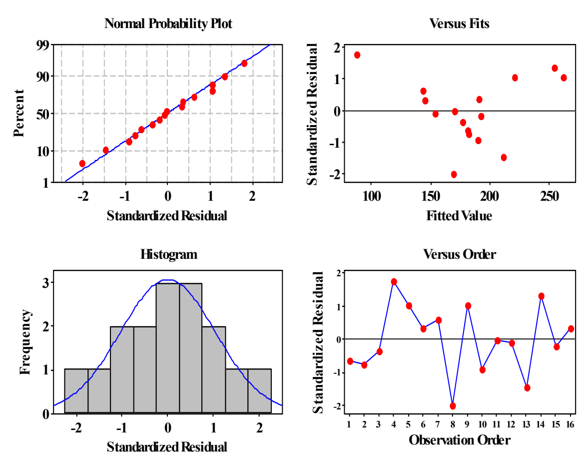

Figure 3: Residual plot for output response tensile stress

Table 3: Experimental design matrix with results

Run No.	I_P	S	D	Tensile stress (MPa)	S/N ratio	Normalized value for tensile stress	Predicted Fuzzy value	Error
1	110	90	0.85	171	44.6599	0.340	0.546	0.378
2	110	120	1.00	170	44.6090	0.333	0.402	0.171
3	110	150	1.15	171	44.6599	0.340	0.391	0.132
4	110	180	1.30	116	41.2892	0.000	0.071	1.000
5	80	90	1.00	237	47.4950	0.747	0.913	0.182
6	80	120	0.85	196	45.8451	0.494	0.631	0.217
7	80	150	1.30	153	43.6938	0.228	0.386	0.408
8	80	180	1.15	137	42.7344	0.130	0.198	0.345
9	90	90	1.15	278	48.8809	1.000	0.927	-0.079
10	90	120	1.30	175	44.8608	0.364	0.397	0.083
11	90	150	0.85	169	44.5577	0.327	0.394	0.170
12	90	180	1.00	152	43.6369	0.222	0.391	0.432
13	100	90	1.30	188	45.4832	0.444	0.487	0.087
14	100	120	1.15	275	48.7867	0.981	0.971	-0.011
15	100	150	1.00	189	45.5292	0.451	0.569	0.208
16	100	180	0.85	150	43.5218	0.210	0.347	0.395

Analysis of Variance (ANOVA)

The ANOVA table investigates the effectiveness of the each process parameter for the enhancement of the weld strength. In addition to that the table also represents the suitability of the developed numerical model. Here the confidence level for this design model is taken as 95 %, which reflects the significant parameter from 'P' values (as the 'P' value should be below 0.05). The 'F' value indicates the greatest effect of the process parameter over the output response. A detailed ANOVA table including R^2, adj. R^2 and the standard error values are represented in Table 4.

Table 4: Analysis of variance for output response

Source	DF	SS	Adj. MS	F	P
I_P	3	9.421	3.1403	3.74	0.080
S	3	34.872	11.624	13.8	0.004
D	3	12.766	4.2552	5.06	0.044
Error	6	5.042	0.8404		
Total	15	62.101			
S = 0.9167 R^2 = 91.9 % R^2 (adj.) = 79.7 %					

It is concluded from the ANOVA table that the scan speed and the stand-off distance give significant value whereas the peak current shows insignificant with a very minimum margin. This will be clearer from 'F' value, i.e. the scan speed obtained highest value of 13.83 followed by stand-off distance and peak current as 5.06 and 3.74 respectively. So scan speed having utmost effect on the output response compared to others two process parameters. The model adequacy represents from R^2 and adj. R^2 values. Here the R^2 and adj. R^2 value obtained from the ANOVA i.e. 91.9 % and 79.7 % respectively. This concludes the greatest fitness of the designed model with respect to output response.

Fuzzy Logic System

A fuzzy logic system is an unique system in which the numerical data and the linguistic knowledge is simultaneously handle in an effective way. It is a nonlinear mapping of an input data (feature) vector into a scalar output, i.e., it maps numbers into numbers. Linguistic variables are the input or output variables of the system whose values are words or sentences from a natural language, instead of numerical values. The system consists of a fuzzifier, membership functions, a fuzzy rule base, interface engine and difuzzifier as shown in Fig. 4. Membership functions are used in the fuzzication as well as de-fuzzication to map the non-fuzzy input values to fuzzy linguistic terms and vice versa. A membership function is used to quantify a linguistic term [10].

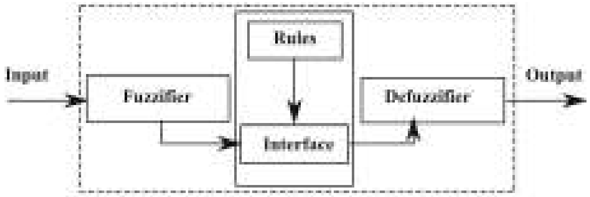

Figure 4: Fuzzy logic system

In the present study, the tensile stress is predicted through the fuzzy logic by using MATLAB 7.6 in terms of normalized value. The inference engine i.e. Mamdani type performs fuzzy reasoning with fuzzy rules to generate a fuzzy value. These fuzzy rules are written in the form of if-then control rule. There are sixteen fuzzy rules are directly derived based on fact that larger is better characteristics. For each rule, four fuzzy subsets of Small, Medium, Large and Very large are assigned in three input membership functions and five fuzzy subset such as Very Small, Small, Medium, large and Very Large are assigned to one output membership function. The graphical presentations for both input and output membership function are shown in Fig. 5. By tracking maximum-minimum compositional operation, the fuzzy reasoning of these rules yields a fuzzy output. Lastly, the resulting fuzzy output is mapped to an output using the membership functions in the defuzzication step. These predicting fuzzy values are shown in Table 3.

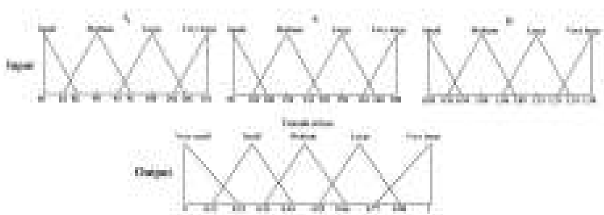

Figure 5: Input and output membership functions

For comparing the fuzzy predicted values with the experimental results, all experimental values are first normalized using “(2)” and all respected values are listed in Table 3.

$$\text{Normalized value} = 1 - \frac{\text{Max.} - X_i}{\text{Max.} - \text{Min.}} \quad (2)$$

Where, X_i is for Value obtained for each run (i = 1, 2, 3…..16), Max is for Maximum value obtained from whole experiments and Min is for Minimum value obtained from whole experiments.

Comparison between Experimental and Predicted Results

After successful welding of SS-Cu metal couple, the tensile stress (normalized) result obtained from experimental and fuzzy prediction model are listed in Table 3. The error between them also tabulated there. The comparisons between experimental and predicted results are shown in Fig. 6. The graph shows a very good comparison between two results. The proposed fuzzy logic has the modeling competence with average accordance ratio of almost 95.881 % i.e. the average error is ±4.119.

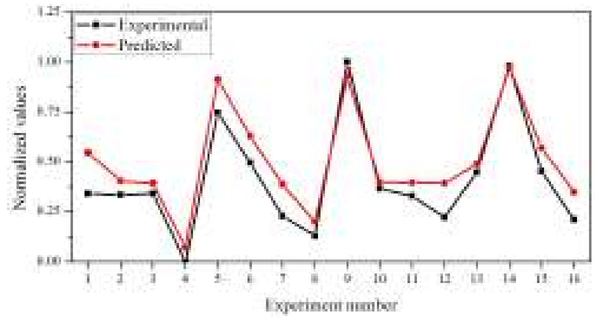

Figure 6: Comparison between experimental and fuzzy prediction

Microstructure Study

Full penetration always a problem in TIG welding but here in every specimen good penetration is observed. In some cases full penetration is not obtained but achieved an acceptable penetration depth (> 85 % of the material thickness) as a whole. The welded specimens are observed under scanning electron microscope (SEM) for the proper investigation about fusion zone details. The macrostructure analyses across the fusion zone shown in Fig. 7 confirm the welds are having good sidewall fusion and good penetration depths.

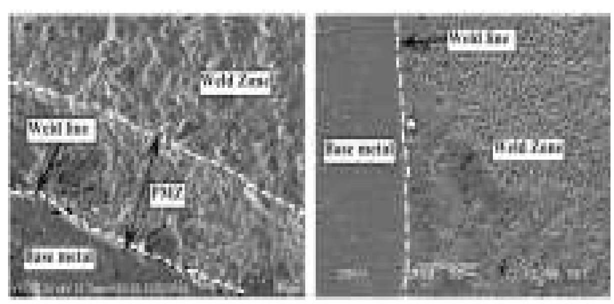

Figure 7: Microstructure of the weld zone

Partially melting zone (PMZ) as well as the weld line is clearly visible in the image. The weld line preferably divides the weld zone and the base material. The PMZ is present in the weld zone next to the base metal clearer from the different grain size. The SEM image also represents the well distribution of two base metals inside the weld zone. The epitaxial growth of the grains happens from weld line to the weld pool, which tends to strengthen the weld.

CONCLUSION

A successful weld between two dissimilar metals i.e. AISI 304 SS and copper has been carried out and the following conclusions can be drawn from the investigations:

- A greater fitness of the Taguchi orthogonal design model for pulsed wave TIG welding for SS-Cu dissimilar couple, confirms from the ANOVA table and average error calculation.
- Acceptable tensile stress (as varies from 190-278 MPa) is observed.
- A desired high quality dissimilar metal weld can be achieved by using optimal parameters obtained by Taguchi design.
- The fuzzy logic prediction was successfully implemented for predicting the welding output response. The average error between experimental result and fuzzy predicted is ±4.119.
- The comparison concluded that a fuzzy logic system is one of the best alternate to predict the response. Hence it can propose for real time work environment.
- The microstructure shows the well distribution of materials in the fusion zone to strengthen the joint. In addition to that the weld line and PMZ are also clearly detected.

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