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Multi-response optimization of process parameters for GTAW process in dissimilar welding of Incoloy 800HT and P91 steel by using grey relational analysis

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Abstract- The dissimilar welding of Incoloy 800HT and P91 steel using Gas Tungsten arc welding process (GTAW) This material is being used in the Nuclear Power Plant and Aerospace Industry based application because Incoloy 800HT possess good corrosion and oxidation resistance and P91 possess high temperature strength and creep resistance .This work discusses on multi-objective optimization using gray relational analysis (GRA) using 9CrMoV-N filler materials. The experiment conducted L9 orthogonal array. The input parameter are current, voltage, speed .The output response are Tensile strength, Hardness and Toughness. To optimize the input parameter and multiple output variable by using GRA. The optimal parameter is combination was determined as A2B1C1 so given input parameter welding current at 120 A, voltage at 16 V and welding speed at 0.94 mm/s. The output of the mechanical properties for best and least grey relational grade was validated by the metallurgical characteristics.
Key words: optimization, Grey relational grade, Microstructure, Fractography

1. Introduction

In next generation of power plant and nuclear plant industry, the dissimilar welding was used in many applications. They are used in super heater, reheater and heat exchanger tube etc Earlier the ferritic and austenitic based materials were used for this dissimilar joint but to create many problem such as cyclic thermal stress between two base metal due difference in co efficient of thermal expansion and also due to stress oxidation cracking and accelerated creep which occur in ferritic side interface. To avoid this issue one such material the austentic based Incoloy 800HT and ferritic based P91 materials are used [1].The Incoloy 800HT are nickel based super alloy and oxidation and carburization resistance at high temperature and also they possess good corrosive resistance steel[2]. But in ferritic based P91 materials they have high tensile strength and creep properties compared to other ferritic steels and also it's a excellent mechanical properties [3]. This dissimilar welding is suitable for GTAW process in order to avoid the cyclic thermal stress to using nickel based filler material .Additionally GTAW process is being multi pass welding they have improve tempering of welds and also toughness of weld can be increased[4].In general the quality of the weld depends on the Input process parameter .Traditionally the skill of the operator and engineer is considered while selecting the trail and error method with suitable process parameter , also it is more time consuming and as the required specification of the weld does not meet some times. So to overcome this problem the author has used design of experiment (DOE), evolutionary algorithms and computational network to select the suitable welding parameter and required output and meet the specification.[5]. Gray relational analysis (GRA) is used to convert multiple responses into single response by assigning gray relational grade (GRG) to individual responses [6]. Shanmugarajan .B et al.[7] applied Taguchi based gray relation analysis results to optimum parameters have been derived by considering the responses such as depth of penetration, weld width and heat affected zone (HAZ) width. Hsuan-Liang Lin et al [8]. Analysis of dissimilar welding between JIS SUS 304 stainless steel and SAE1020low carbon steel. This paper presents an integrated approach using the Taguchi method (TM), grey relational analysis (GRA) and a neural network (NN) to optimize the weld bead geometry in a novel gas metal arc (GMA) welding process K.F. Tamrin et al [9]. applied the GRA technique and it was found that the weld speed has dominant effect on joint characteristics in comparison to stand-off distance at a fixed laser power. R. Adalarasan et al[10]. The G-PCA method employed for optimization combines the non-parametric approach of PCA with the uncertainty handling capabilities of GRA to predict the optimal setting of parameters in friction welded dissimilar joints involving AA 6061 and AA 6351 alloys. Deepan Bharathi Kannan et al[11] successfully implemented GRA technique for predicting optimization parameter in laser welding of Nitinol shape memory alloys.

From the above literatures, it is clear that none have been carried out in dissimilar welding of Incoloy 800HT and P91 steel using GTAW process in optimization and characterization. It was also clear that GRA can be used to optimize the GTAW process parameter to obtain the desired quality weldments. In this work, multi-objective optimization using GRA has been carried out to optimize the GTAW process parameter (welding speed, current and voltage). The output response was tensile strength, Impact Toughness and Hardness in room temperature. By analyzing the grey relational grade, the most influential factor was determined. Further, the best and least grey grade obtained experiments mechanical properties were validated by their metallurgical features like microstructure and SEM fractography.

2. Experimental Procedure

The base metal dimension is 200mmX 100mm X 4mm cutting by using wire cutting EDM machine and the chemical compositions of the as-received base metals and filler metals have been studied using wet spectroscopic method and are presented in Table 1.

Table 1. Base material and filler material Chemical compositions (in wt %)

		C	S	N	Cr	Ni	Mn	Si	Ti	Nb	Cu	P	Al	Co	Mo	V	Fe
Base Materials	Incoloy 800HT	0.06	0.002	0.013	20.63	30.56	0.69	0.46	0.34	0.01	0.10	0.008	0.87	0.08	-	-	46.177
	P91	0.11	0.0038	-	9.46	0.09	0.46	0.31	-	-	-	0.015	-	-	0.88	0.20	Bal
Filler Material	9CrMoV-N	0.12	0.003	0.04	9.10	0.42	0.72	0.26	-	0.06	0.08	0.008	0.002	-	0.94	0.19	Bal.

The filler metals such as 9CrMoV-N have been chosen as these filler metals are compatible with the base metals employed, and also thickness of filler materials is 2.4 mm. Standard V-groove butt joints (single V-groove having a root gap of 2 mm, size land of 1 mm, and included angle of 70°) were employed for welding these dissimilar metals The weld experiments were conducted by using manual GTAW with direct-current and negative electrode. The GTAW process parameters and levels are shown in table 2.

Table 2. Welding process parameters and levels

Factor	Unit	Level1	Level2	Level3
Welding current	A	90	120	150
voltage	V	16	18	20

Welding speed	mm/sec	0.94	0.98	1.2

Several trials were carried out to select the upper and lower levels of the process parameter. Taguchi L9 orthogonal array was selected, and the experiments were carried out accordingly. The process parameter and their levels are given in Table 3. Shows the process parameters used during the welding process.

Table 3. Experimental desgin using L9 orthogonal array and performance result

Experiment number	Current (amps)	Voltage (volts)	Speed (mm/s)	Tensile strength (Mpa)	Hardness (Hv)	Toughness (J)
1	90	16	0.94	598.24	181.215	46
2	90	18	0.98	603.12	180.876	47
3	90	20	1.2	583.14	187.651	43
4	120	16	0.98	634.34	165.976	52
5	120	18	1.2	586.23	193.124	43
6	120	20	0.94	644.21	169.243	51
7	150	16	1.2	638.67	175.908	50
8	150	18	0.94	642.26	161.745	51
9	150	20	0.98	588.17	183.654	44

A specially designed fixture with a copper back plate that could clamp the base metals firmly so as to avoid distortion and bending. During welding to maintain Interpass temperature at 200°C.The weldments were characterized for any defects using gamma ray radiography technique. Subsequent to the results, after welding the samples are shown in Figure.1

Figure 1. Welded specimens of 9CrMoV-N filler materials

The welded samples were cut into different coupons for further analysis. For metallographic analysis using Sic paper for different grade like 120 upto1200 and further automatic polishing machine the specimen was polished by mirror to provide mirror like polish , The specimens were etched in two different solutions: electrolyte etching solution (10g of CrO_3 +100ml distilled water) followed by villas reagent solution (1g of $C_6H_3N_3O_7$ + 5ml of HCL + 100ml of C_2H_6O). Was employed to examine the microstructure of Incoloy 800HT and P91. Further to estimate the mechanical properties of dissimilar joints various tests were performed. Nine samples were tested for tensile, Hardness and impact test for determining results

Tensile studies were carried out on the weldments which were fabricated as per ASTM E8/8M standards. These samples were tested at a strain rate of 2 mm/min at room temperature. Charpy V-notch impact test samples were prepared and tested according to ASTM E23-12C standards of sub-sized specimens by simple beam method. Notches were made such that fracture occurred only within the weld fusion zones. Furthermore the fractured samples were characterized for SEM analysis to determine the mode of fracture. Hardness measurement was carried out on the composite region of the weldments across weld zones by using Vickers's micro-hardness tester with a load of 500grams for a dwell time period of 10 s at regular intervals of 0.25 mm.

2.1 Grey relational analysis (GRA)

The transformation of S–N ratio values from the original response values was the initial step. For that the equation (1) of 'larger the better' was used. Subsequent analysis was carried out on the basis of these S/N ratio values. This is shown in Table 4.

Table 4. S-N ratio for the responses

Experiment Number	Tensile strength (Mpa)	Hardness(Hv)	Toughness(J)	S-N ratio for UTS	S-N ratio for Hardness	S-N ratio for Toughness
1	598.24	181.215	46	55.53751	45.16388	33.25516
2	603.12	180.876	47	55.60807	45.14762	33.44196
3	583.14	187.651	43	55.31546	45.46702	32.66937
4	634.34	165.976	52	56.04644	44.40091	34.32007
5	586.23	193.124	43	55.36136	45.71672	32.66937
6	644.21	169.243	51	56.18055	44.57021	34.1514
7	638.67	175.908	50	56.10553	44.90571	33.9794
8	642.26	161.745	51	56.15422	44.17662	34.1514
9	588.17	183.654	44	55.39006	45.28001	32.86905

$$S/N_L = -10 * \log (1/y^2) \quad (1)$$

In GRA, initially the experimental data are normalized. By using this normalized data, grey relational coefficient were evaluated, the grey relational grade was obtained by averaging the GRC values related to selected experimental results.

2.2 Grey relational generation

GRG can be categorized into three types namely Smaller the Better, Larger the Better or Nominal is a better (NB) criterion. The preferred quality characteristics for ultimate tensile strength, yield strength and impact toughness are Larger the Better criterion; then it is expressed by using equation (2):

$$y_i^*(k) = \frac{y_i(k) - \min y_i(k)}{\max y_i(k) - \min y_i(k)} \quad (2)$$

Where i=1,…..m; k=1,2,3,…n; m= no of experimental data, n= number of factor, $y_i(k)$=original sequvance, $y_i^*(k)$ after gray relation generation; min $y_i(k)$ and max $y_i(k)$ are the minimum and maximum value of $y_i(k)$,respectively. The normalized value are shown in Table 5

Table 5. Sequences of each performance characteristic after data processing

Experiment Number	UTS	Hardness	Toughness
1	0.257	-0.641	0.355
2	0.338	-0.630	0.468
3	0.000	-0.838	0.000
4	0.845	-0.146	**1.000**
5	0.053	**-1.000**	0.000
6	**1.000**	-0.256	0.898
7	0.913	-0.473	0.794
8	0.970	0.000	0.898
9	0.086	-0.716	0.121

2.3 Grey relational coefficient (GRC)

The calculation for grey relation coefficient was done using equation (3):

$$\varepsilon_i(k) = \frac{\Delta \min + \omega \Delta \max}{\Delta_{oi}(k) + \omega \Delta \max} \quad (3)$$

Where

$\varepsilon_i(k)$ is the grey relation coefficient; Δ_{oi} is deviation among $y_o^*(k)$ and $y_i^*(k)$; $y_o^*(k)$ = ideal (reference) sequence; Δmax = highest value of $\Delta_{oi}(k)$, Δmin = least value of $\Delta_{oi}(k)$.

2.4 Grey relation grade

The grey relational grades (GRG) are determined by taking average of the Grey Relational Coefficient related to every observation as presented in equation (4):

$$\Gamma_i = \frac{1}{n} \sum_{=1}^{Q} i(k) \quad (4)$$

Where, Q = total quantity of responses and n denotes the quantity of output responses. The GRG represents level of relationship among the reference or ideal sequence and the comparative sequence. If larger GRG is obtained for the equivalent set of process parameters compared to other sets, it is considered to be the most favorable optimal setting.

3. Results and Discussion

The GTAW dissimilar welding process on Incoloy 800HT and P91 was performed according to L9 orthogonal array to investigate the effect of the welding process parameters, namely, welding current, voltage and welding speed on the output responses, ultimate tensile strength, Hardness and impact toughness. An effort has been taken to determine the best possible set of welding parameters for dissimilar welding the Incoloy 800HT and P91 effectively and efficiently.

3.1 Multiple response models using GRA

By using GRA complicated optimization, problem can be solved effectively. The higher grey relational grade will have better multiresponse characteristics. Table 6 shows the grey relational grade for all experiments. Hence, it is clear that experiment 6 has the optimal parameters setting for best multi-response characteristics, such as ultimate tensile strength, yield strength and toughness.

Table 6. Grey relational coefficient, grey relational grade and their Rank

Experiment Number	Gray Relation coefficient			Gray relation Grade	Rank
	UTS	Hardness	Toughness		
1	0.402	0.234	0.437	0.357	6
2	0.430	0.235	0.485	0.383	5
3	0.333	0.214	0.333	0.294	8
4	0.763	0.304	1.000	0.689	3
5	0.346	0.200	0.333	0.293	9
6	**1.000**	**0.285**	**0.830**	**0.705**	**1**
7	0.852	0.253	0.708	0.604	4
8	0.943	0.333	0.830	0.702	2
9	0.354	0.226	0.363	0.314	7

3.2 Mean Response table for GRG using S/N ratio

Mean response for the Gray relation grade value for every level of the input parameters is shown in Table 7. Its been calculated by taking the average for each level group in all the levels of process parameters. Since it denotes the level of correlation between references

Figure 2. Tensile specimen before testing

Figure 3. Tensile specimen after testing

Table 7. Mean response for the Gray relation grade

Parameters	Symbol	Level1	Level2	Level3	Main Effect (Max-Min)	Rank
Welding current	A	0.345	**0.562**	0.540113	0.218	1
Voltage	B	**0.550266**	0.459371	0.437455	0.11281	3
Welding speed	C	**0.588132**	0.462019	0.396942	0.19119	2

Sequence and obtained sequence, the higher value of average grey grade indicates stronger correlation between them. It indicates optimal level of process parameters. It depicts that the optimal set of process parameter is A2B1C1, which means the current of 120 A, voltage of 16 V and welding speed of 0.94 mm/s. Current was the main influencing factor, followed by the welding speed and voltage.

The influence of GTAW welding process parameters on the output response is shown in table.3. Tensile testing is one of the most basic types of mechanical test used to qualify a welding procedure. By performing this test, it is easy to determine how the material will react against forces when applied in tension. As the material is being pulled, the strength of the weld joint along with the elongation can be calculated. The point of failure is of much importance, and it is typically called as ultimate tensile strength. The base material ultimate tensile strength of Incoloy 800HT in and as received condition was 530 MPa and P91 is 580Mpa. Before testing of tensile specimen as shown in Figure .2. The entire welded specimen exhibited higher strength than the base material. This section discusses the reason for the need for variation in output response for experiment 6 and 8 in relation to some of the metallurgical characteristics. Figure. 3 shows the fractured location for the tensile tested specimens.

From the Figure.3 it is seen that the fracture location is 10mm away from the weld center for experiment number 4, whereas the fracture occurred in the weld region for experiment number1. From the output result obtained during tensile testing, The tensile value 1.95 Mpa and GRC value 0.003 and more for experiment 6 as compared to experiment 8.

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3.3 Fractography analysis

The impact tested specimen was analyzed on the fractured surface by scanning electron microscope to investigate the type of fracture that has occurred. There were two types of fracture, brittle and ductile, depending on the ability of the material to undergo plastic deformation before the fracture. The ductile mode of fracture undergoes extensive plastic deformation ahead of the crack, and the crack was stable which could resist further extension unless the applied stress was increased. In brittle mode, the crack was unstable and propagated rapidly without increase in applied stress. The ductile mode of fracture is preferred in most of the applications. Figure. 4a corresponds to the fractography images taken for experiment 6 showed deep and wide dimples which revealed ductile fracture mode, whereas Figure. 4b which corresponds to experiment 8 showed mostly cleavages micro voids which revealed brittle mode of failure.

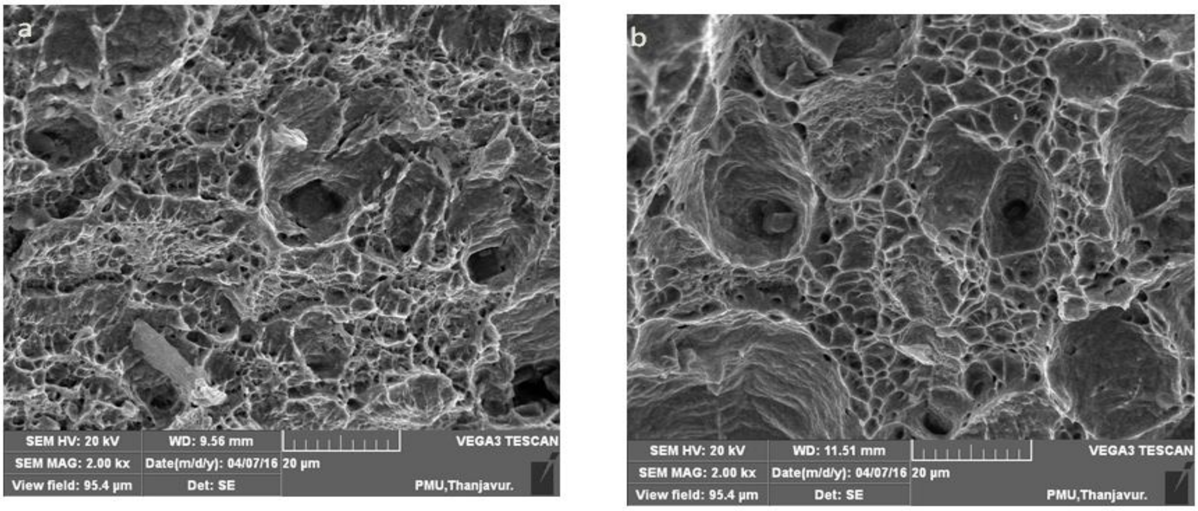

Figure 4 a &b Fractography Images of Tensile samples

3.4 Microstructure analysis

The microstructure of the weld region for experiments 6 and 8 is shown in Figure. 5a & b. The microstructure for experiment 6 shows in Figure 5a.The full austenitic structure carrying fine cellular and equiaxed grains over the welded regions, there is no hard dendritic structure during solidification period because experiment 6 low heat input process compare to experiment 8 .whereas the experiment 8 weld zone microstructure showed in Figure 5b.The weld zone Microstructure cellular and harder dendritic structures, which are prone to cracking. The harder dendritic structure may be due to the higher heat input during the welding. The structure of the weld zone clearly explains the need for the variation in mechanical strength for experiment 6 and 8.from the weld metal Incoloy 800HT side is twinning available so tensile strength is automatically increased.

Figure.5 (a) weld zone microstructure experiment 6

Figure.5 (b) weld zone microstructure experiment 8

3.5 Results of confirmatory test

The results of confirmatory test are shown in Table 8. It is found that prediction of optimal parameter setting is valid.

Table 8. Results of the confirmation test

		Optimal control parameters	
	Initial condition	Prediction	Experimental
Levels	**A2B3C1**	**A2B1C1**	A2B1C1
Pitting potential	0.705	0.736	0.762

Improvement of Grey relational grade: 0.057

3.6 Confirmation run

The purpose of confirmation run is to verify the results obtained. These tests are conducted at an optimum level of input and process variables with three replications. The welding was done at an optimum setting of variables for producing better tensile strength, Hardness and Toughness .Result of confirmation runs presented in Table 8 , all the deviations are less and therefore the optimum values obtained are acceptable.

4. Conclusions

- In this study, Taguchi L9 array with grey relational analysis has been used to optimize the multiple performance characteristics such as ultimate tensile strength and Hardness and impact toughness.
- An optimum combination of three set of test parameters of grey relational grade for quality weld joints was found to be welding current of 120 A, voltage of 16 V and welding speed of 0.94 mm/s.
- Based on the results of GRG, it was observed that the welding current exerted a significant influence on multiple responses followed by welding speed and voltage.
- The mechanical properties were correlated with the metallurgical characteristics. The impact fractography analysis showed ductile mode of fracture for experiment 6 and mixed mode of brittle and ductile fracture for experiment 8.
- The microstructure of the weld region revealed finer cellular structure for experiment 6, whereas harder dendrites were formed for experiment 8 due to higher heat input.

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