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BEAD-ON-PLATE SUBMERGED ARC WELDING OF MILD STEEL: PARAMETRIC STUDIES AND OPTIMIZATION

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ABSTRACT

Selection of process parameters has great influence on the quality of a welded joint. The joint quality can be defined in terms of properties such as weld bead geometry, mechanical properties and distortion. A detailed experimental approach on the quality of weld joint in terms of weld bead geometry, mechanical properties and distortion to understand the parametric influence of single wire submerged arc welding(SAW) on final weld bead. The experiments are designed using Taguchi method L9 orthogonal array and Grey Taguchi Relational Analysis with ANOVA has being carried out to solve multi-objective optimization problem. Further microstructural studies, surface studies and compositional studies have been carried out by SEM-EDAX with micro hardness test.

KEYWORDS: SAW, Grey Taguchi Analysis, SEM-EDAX, Orthogonal Array

INTRODUCTION

Demand of welding technology with high productivity is ever increasing in manufacturing industries especially pressure vessels and ship building industries which led to the development of Submerged arc welding in 1930s and 1940s. The ability to join thick plates (as thick as 1.5 inch) in a single pass, with high metal deposition rate has made this process useful in large structural applications, particular in horizontal flat position by a non-continuously fed consumable solid or tubular (flux cored) electrode in which molten weld and the arc zone are protected from atmospheric contamination by being "submerged" under a blanket of granular fusible flux. Weld bead size and shape are important considerations for design and manufacturing engineers in the fabrication industry. The various parameters like welding current, arc voltage, wire feed speed, travel speed, torch angle and the electrode stick out are affecting on the weld quality.

The research on controlling metal transfer modes in SAW process is essential to high quality welding procedures. The SAW parameters are the most important factors affecting the quality, productivity and cost of welding joint. Dhas and Satheesh [1] presented the effects of welding process parameters on welding current, arc voltage, welding speed and electrode extension on weld bead geometries and percentage of dilution in submerged arc welding of A516 grade 70 carbon steel. Welding current is the parameter that controls weld deposition rate. It also controls the depth of weld penetration and the amount of base metal melted. It is designed to produce high deposition rates. Yang et al. [2] carried out experiments on bead-on-plate submerged arc welding and the results presented to determine the effects of process variables on the weld deposit area at a constant heat input of 3kj/mm. It was found that the deposit area was a function of the welding current, welding voltage, welding speed, electrode polarity, electrode diameter and electrode extension.

Researchers have several attempted to predict the process parameters of submerged arc welding to get smooth quality of weld. Taguchi-method was used to formulate the experimental layout, to analyze the effect of each welding parameter on welding performance, and to predict the optimal setting for each welding parameter. Tarng and Yang (1998) applied Taguchi-method to the optimization of the submerged arc welding process. Bandyopadhyay et al. (2008) analyzed the grey-based Taguchi method for optimization of bead geometry in submerged arc bead on plate welding. Taguchi's orthogonal array design and signal to noise ratio were used to derive objective functions which optimized within experimental domain. The objective functions selected in relation to parameters of bead geometry viz bead width, bead reinforcement, and depth of penetration and depth of HAZ. Taguchi's approach followed by grey relational analysis applied to solve the multiresponse optimization problem. The significance of the factors on overall output features of weldment was evaluated quantitatively by ANOVA.

This paper includes optimization with response prediction and experimental design. Taguchi method of optimization and Grey-Taguchi optimization with ANOVA analysis was used to optimize the bead geometry parameters to get a better weld. After welding, quality of the weld judged through visual inspection, micro-hardness test, scanning electron microscopy and microstructural study, with prediction of the weld bead geometry by developing mathematical models .

METHOD & MATERIAL

In this study, experiment was conducted on INDARC AUTOWELD MAJOR (Maker: IOL Ltd.India), Type : CPRA 800(S) with AWM (LW) tractor for single wire SAW equipments with a constant voltage, rectifier type power source with a 1000A capacity was used to carry out Bead-on-plate on AISI1018 mild steel of size 160 mm length X 35mm width X 10 mm thickness. Matching low carbon steel electrode: ESAB SA1 (E8) of 2.5 mm diameter had been used in welding. Granular flux of basicity index of 1.4 (OKflux10.71L) was used. The chemical composition of base material and flux is given in Table 1 and 2.

Table 1 Chemical composition of Base metal: AISI 1018 mild steel

Chemical composition (%)	C(Carbon)	Mn (Manganese)	Si (Silicon)	Fe (Iron)	S (Sulphur)	P (Phosphorous)
Base Metal (AISI 1018 mild/low carbon steel)	0.14% - 0.20%	0.60% - 0.90%	Negligible	98.81% - 99.26%	≤0.050%	≤ 0.040%

Table 2 Chemical composition of Flux: OK Flux 10.71

Compositions	SiO_2+TiO_2	CaO+MgO	Al_2O_3+MnO	CaF_2
Percentage	20%	25%	35%	15%

The input parameters were current, voltage and traverse speed. Nine welded samples in Figure1 had been prepared using different levels of current, voltage and traverse speed. The output responses measured are penetration depth, bead width and deposition rate. Taguchi's idea of L9 orthogonal array had been adopted for planning the experiments .After the bead-on-plate welding, the cut out pieces by power hack saw (Figure 2) had been grounded, polished specimens are etched with 2% nital (98% methyl alcohol and 2% nitric acid) and finally obtained samples for microstructural studies were studied using Leica Microscope. Micro-hardness test had also been performed by LECO LM-248AT and measured at several points in different zones: weld metal, HAZ, and base metal. This was followed by visual inspection, SEM to visualize the crack and discontinuities in the weld beads in Figure 2.

Fig 1: Samples of 9welded samples after welding

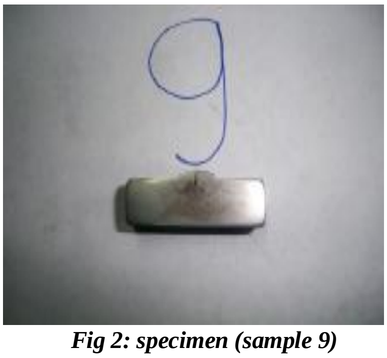

Fig 2: specimen (sample 9)

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Fig 3: Photographic view of the set up of Submerged arc welding

Design of experiments

Taguchi's L9 orthogonal array had been selected, considering 3 factors, and 3 levels of each factor. The input parameters are current, voltage and traverse speed. Nine welded samples had been prepared using different levels of current, voltage and traverse speed. The output responses measured were penetration depth, bead width and deposition rate. In order to evaluate optimal parameter settings, Taguchi method uses a statistical measure of performance called signal-to-noise ratio. The standard S/N ratios generally used are as follows: Nominal is the best (NB), lower the better (LB) and higher the better (HB). The optimal setting is the parameter combination, which has the highest S/N ratio. Table 3 and 4 shows the factors and the levels used in the experiments.

Grey Taguchi method is combining the orthogonal array (OA) design of experiments (DOE) with grey relational analysis (GRA) which enables the determination of the optimal combination of submerged arc welding parameters for multiple process response. Analysis of Variance (ANOVA) which is routinely used to provide a measure of confidence. Depending on F-value, P-value (probability of significance) was then calculated. If the P-value for a term appears less than 0.05 (95% confidence level) then it can be concluded that, the effect of the factor(s)/ interaction of factors is significant on the selected response.

In the context of the experiments carried out, the normalized bead width, corresponding to lower-the better (LB) criterion is calculated by using equation 1

$$x_i(k) = \frac{\max\ y_i(k) - y_i(k)}{\max\ y_i(k) - \min\ y_i(k)}$$

Equation 1

Bead penetration, deposition rate and micro hardness should follow larger-the-better criterion, Normalized values for these responses are calculated by using equation 2

$$x_i(k) = \frac{y_i\ (k) - \min\ y_i(k)}{\max\ y_i(k) - \min\ y_i(k)}$$

Equation 2

ISSN: 2277-9655
Impact Factor: 4.116
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Table 3 Experimental Runs Corresponding To The Factors And Levels Shown

Process Parameters	Unit	Symbols	Values	Level 1	Level 2	Level 3
Current	A	C	Numerical	300	360	390
			Coded	1	2	3
Voltage	V	V	Numerical	25	26	28
			Coded	1	2	3
Traverse speed	mm/min	T	Numerical	40	42	50
			Coded	1	2	3

Table 4 Experimental Design As Per L9 Orthogonal Array

	Current		Voltage		Traverse speed	
S.No.	Coded	Uncoded(A)	Coded	Uncoded(V)	Coded	Uncoded(mm/min)
1	1	300	1	25	1	40
2	1	300	2	26	2	42
3	1	300	3	28	3	40
4	2	360	1	25	2	42
5	2	360	2	26	3	50
6	2	360	3	28	1	40
7	3	390	1	25	3	50
8	3	390	2	26	1	40
9	3	390	3	28	2	50

RESULT & DISCUSSION

Results of Visual Inspection and discussion

The visual inspection results indicate that defects like undercut, incomplete fusion, small holes etc. had occurred in some of the samples. The main cause of defect undercut in samples 5 and 8 may be the wire tracking which is too close to the groove face which can be adjusted by the wire tracking location. In sample 4, lack of fusion was observed which may probably be occurred due to narrow joint preparation, incorrect welding parameter settings, poor welder technique and magnetic arc blow.

Measurement of Bead geometry parameters and discussion

It was found that increase of welding speed has a negative effect on weld bead parameters. An increase in penetration was observed with increase in the current but the bead width was decreased. However increase in arc voltage had made the weld bead wider and flatter but penetration had decreased with increase in voltage. It was observed that the sample corresponding to run 7 was the most preferable one because in this sample bead width was minimum (9.46 mm), penetration 59 maximum (5.42 mm) and deposition rate was the largest (67.298 g/min). It was observed from the results shown in Table 5 that at same level of voltage, penetration increases with increase in current. Increase in current puts in higher energy for faster melting, which caused deeper penetration. Further, it was also observed from Table 5 that increases in voltage, generally increases bead width at same level of current. However traverse speed also influences the characteristics of bead geometry. At faster traverse speed heat input per unit length decreases, this influences bead width, penetration and deposition rate. Total volume of the weld bead was one of the important bead parameters controlled by most of the other bead parameters. But for a sound and strong weld, bead penetration should be maximized.

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Table 5: L9 Orthogonal array design and output responses

Run	Current (c)	Voltage (v)	Traverse (t)speed(mm/min)	Beadwidth(mm)	Bead(mm) penetration	Deposition rate (g/min.)
1	300	25	40	11.00	3.38	40.584
2	300	26	42	10.92	3.70	41.655
3	300	28	40	13.04	3.80	46.913
4	360	25	42	13.00	5.25	48.231
5	360	26	50	12.10	3.70	50.616
6	360	28	40	13.12	4.02	50.312
7	390	25	50	9.46	5.42	67.298
8	390	26	40	13.07	5.02	34.808
9	390	28	50	12.72	5.04	65.892

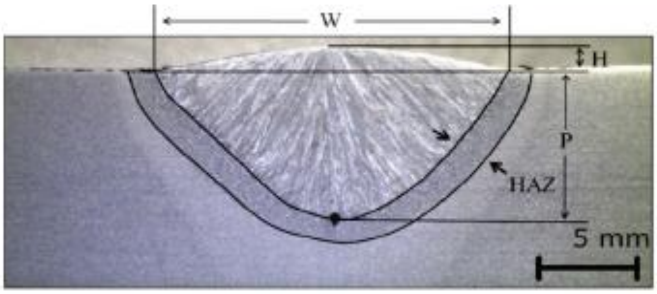

Fig 4: Weld bead geometry: bead penetration (P), bead height (H), beadwidth (W) and HAZ

Results of Microhardness test and discussion:

For each sample, hardness has been measured at four different positions around 1, 2, 3 and 4 as shown in Figure 5. The average hardness values at four locations are listed in Table 6. Result of hardness test of sample 9 is shown graphically in Figure 6, is quite different in nature with respect to the other plots. Hardness values in different regions of the welded samples also indicate the effect of heating cycles during welding and subsequent cooling cycle of the nine samples, made under varied conditions of welding. Now, weld consists of both parent material and electrode material. Further, heat input rate, cooling rate and many other factors influence the final microstructure of the weld metal. Hardness of weld metal is thus dependent on the development of the type of microstructure developed in the weld region.

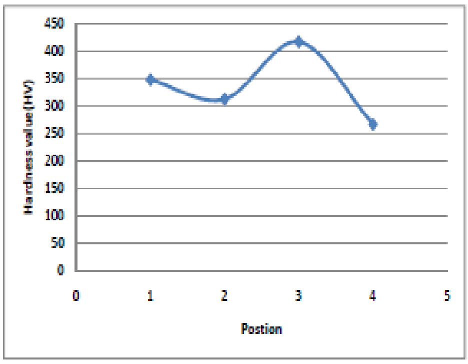

Fig 5: Hardness graph of sample 9

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Impact Factor: 4.116
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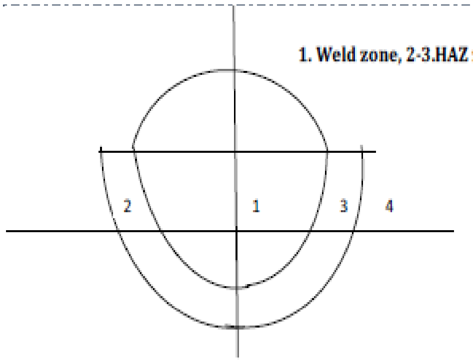

Fig 6: Different positions of hardness measurements

Table 6: Microhardness in HV values of welded samples

Sample no	Weld zone(1)	HAZ zone(2)	HAZ zone(3)	Base metal(4)
1	308	396	362	233
2	358	363	341	245
3	360	345	355	257
4	378	379	378	265
5	365	362	382	233
6	418	417	420	243
7	305	316	364	256
8	313	355	404	275
9	348	313	417	267

Results of Scanning Electron Microscopy and discussion

From the SEM photographic view, sample 7 is found to be almost defect free, due to favorable parametric combination of input parameters. Magnified SEM image of sample 9 reveal some defects like hot cracks and slag inclusions/impurities

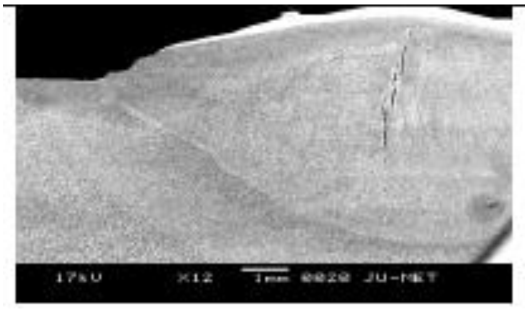

Fig 7: Weld bead region of sample 9

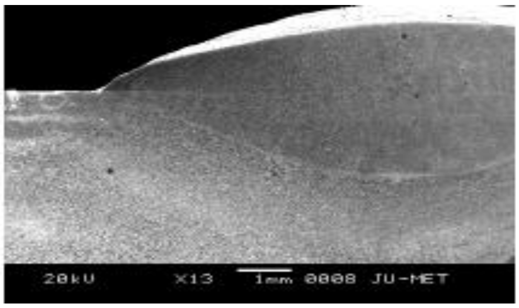

Fig 8: Weld bead region of sample 7

Results of Microstructural study & discussion

In so far as microstructure of base metal is concerned mainly ferritic structure is present and traces of pearlite are also seen in the given photographs of microstructures. HAZ is a combination of ferrite-pearlite structure with small traces of inoculants and primary cementite formed due to rapid cooling. HAZ region of sample 9 (Figure 10), grain sizes of ferrites are larger in which pearlites are also mixed and grains are more or less equiaxed. In case of HAZ-base transition region, in some samples most of the structure has ferrite and pearlite, in most cases more or less dominant phase is ferrite.

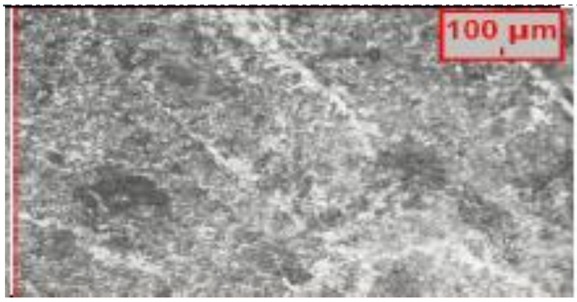

Fig 9: Weld region of sample 9

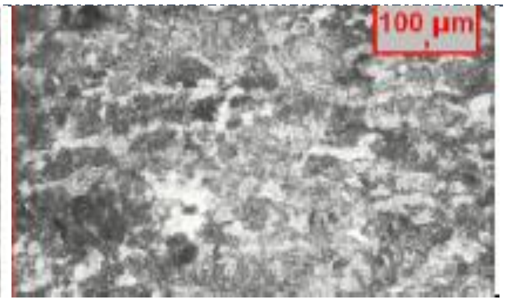

Fig 10: HAZ region of sample 9

Analysis of data

Single–objective optimization of bead penetration and deposition rate by Taguchi method
As requirement is maximization of bead penetration and deposition rate, ''higher is the better'', Equation 2. is used for calculation of S/N ratio values. Figure 11(a) and 11(b) shows the main effects plot for S/N ratios. This is obtained by using the observed results given in Table 5 and using the MINITAB 16 software for solving single objective optimization problem using Taguchi. From the Figure 11(a) and 11(b), in case of bead penetration the optimized parametric combination is welding current(C) = 390A, voltage (V) =25V and traverse speed (T) = 50mm/min, (C3-V1-T3) and in case of deposition rate welding current(C) = 390A, voltage (V) = 28V and traverse speed (T) = 50mm/min, (i.e., C3-V3-T3). Table 7(a) and 7(b) is the table results analysis of variance for bead penetration and deposition rate. It is observed that current is the most significant factor in case of bead penetration and traverse speed in case of deposition rate, because corresponding P value is the lowest and it is below 0.05

Table 7(a): Analysis of variance for bead penetration

Source	DF	Seq SS	Adj SS	Adj Ms	F	P
Current	2	14.139	14.477	7.2384	12.93	0.042
Voltage	2	1.470	1.639	0.8916	1.46	0.406
Traverse Speed	2	3.304	3.304	1.6519	2.95	0.253
Residual error	2	1.120	1.120	0.05599		
Total	8	20.033	S = 0.7482 R-Sq = 94.4% R-Sq(adj) = 77.6%			

Where DF = Degree of freedom, SS = Sum of squared deviation, MS = Mean squared deviation F = Fisher's ratio, P = Probability of significance

Table 7(b): Analysis of variance for deposition rate

Source	DF	Seq SS	Adj SS	Adj Ms	F	P
Current	2	5.759	0.0500	0.02499	0.04	0.958
Voltage	2	7.828	9.3955	4.69774	8.20	0.109
Traverse Speed	2	13.216	13.2158	6.60790	11.54	0.020
Residual error	2	1.145	1.1453	0.57265		
Total	8	27.948	S = 0.7567 R-Sq = 95.9% R-Sq(adj) = 94.4%			

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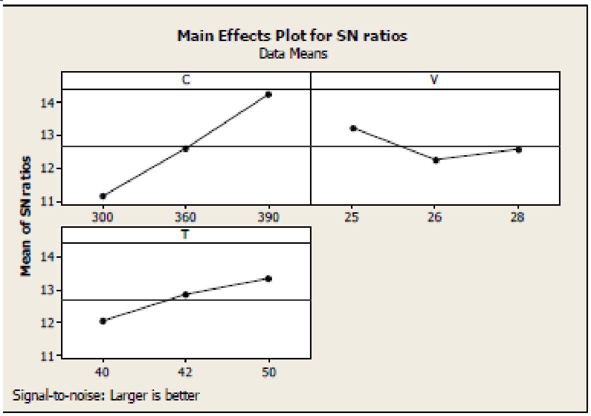

Fig 11(a): Main effects plot for S/N ratio of bead deposition

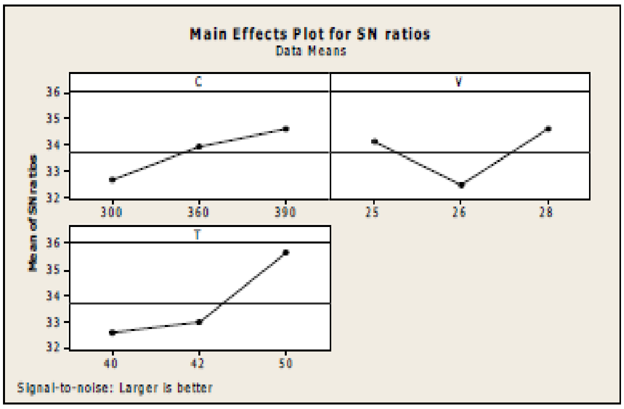

Fig 11(b): Main effects plot for S/N ratio of deposition rate

Single–objective optimization of bead width by Taguchi method

As requirement is minimization of bead width, ''lower is the better'', Equation 2 is used for calculation of S/N ratio values..Figure 12 shows the main effects plot for S/N ratios. The optimized parametric combination is welding current(C) =390A, voltage (V) =25V and traverse speed (T) =50 mm/min, i.e., (C3-V1-T3). Table 8 is the results analysis of variance for width. On examining the 'P' values, observed that voltage is the most significant factor.

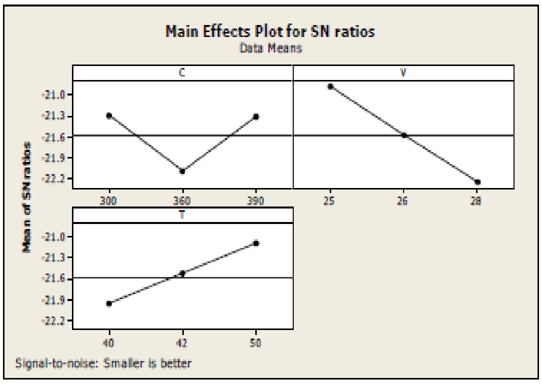

Fig 12: Main effects plot for S/N ratio of bead width

ISSN: 2277-9655
Impact Factor: 4.116
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Table 8: Analysis of variance for bead width

Source	DF	Seq SS	Adj SS	Adj Ms	F	P
Current	2	1.257	1.795	0.8977	0.80	0.554
Voltage	2	2.843	2.432	1.2159	1.09	0.039
Traverse Speed	2	1.592	1.592	0.7962	0.71	0.584
Residual error	2	2.233	2.233	1.1166		
Total	8	7.925	S = 0.1002 R-Sq = 99.3% R-Sq(adj) = 98.4%			

Where DF = Degree of freedom, SS = Sum of squared deviation, MS = Mean squared deviation F = Fisher's ratio, P = Probability of significance

Multi-objective Optimization by Grey-based Taguchi method

To solve multi-objective problem of minimization of bead width, maximization of deposition rate and bead penetration combinedly, grey relation analysis combined with Taguchi method was used . The grey-Taguchi method is an effective optimization tool to optimize two or more responses simultaneously

Step 1: Grey relational generating

In this step, a linear normalization of the experimental results for responses, viz., maximum deposition rate, bead width and bead penetration are performed in the range of 0 to 1, which is called the grey relational generation.

For Lower-the-better quality characteristics data preprocessing is calculated by

$$x_i^0(k) = \frac{max\ x_i^0(k) - x_i^0(k)}{max\ x_i^0(k) - \min x_i^0(k)}$$

Where $x_i^0(k)$ is the original sequence ,max $x_i^0(k)$ is the largest value of $x_i^0(k)$ and min $x_i^0(k)$ implies the smallest value of $x_i^0(k)$ and for "the larger the better" characteristics, original sequences can be normalized as

$$x_i^0(k) = \frac{x_i^0(k) - \min x_i^0(k)}{max\ x_i^0(k) - \min x_i^0(k)}$$

Table 9: Grey relational generations

Sample no. (SL.NO.)	Beadwidth(smaller the better)	Bead penetration(larger the better)	Deposition rate(larger the better)
1	0.5792	0	0.1777
2	0.6011	0.1568	0.2107
3	0.0218	0.2058	0.3725
4	0.0327	0.9166	0.4131
5	0.2786	0.1568	0.4865
6	0	0.3137	0.4771
7	0.0136	1	1
8	1	0.8039	0
9	0.1092	0.8137	0.9567

Step 2: Generation of Grey Relation Co-efficient

After normalization, grey relational co-efficient (GRC) is calculated as

$$\xi_i(k) = \frac{\Delta_{min} + \xi_i \Delta_{max}}{\Delta_{oi}(k) + \xi_i \Delta_{max}}$$

Δ_{oi} is the deviation sequence of the reference sequence (x_0) and the comparability sequence (x_i), ξ is the distinguishing coefficient set between zero and unity; in this study, it will be set to $\xi = 0.5$

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Table 10: Grey relational coefficients

Sample no (sl.no.)	Beadwidth(smaller the better)	Bead penetration(larger the better)	Deposition rate(larger the better)
1	0.5428	0.3333	0.3782
2	0.556	0.3722	0.3878
3	0.3382	0.3863	0.4436
4	0.3407	0.8571	0.4599
5	0.4093	0.3723	0.4935
6	0.3333	0.4214	0.4887
7	0.3364	1	1
8	1	0.7183	0.3333
9	0.3594	0.7286	0.9208

Step 3: a weighting method is used to integrate the grey relational coefficients of each experiment into the grey relational grade.

$$\xi(x_o, x_i) = \frac{1}{n}\sum_{1}^{n} \xi_i(k)$$

n is the number of quality performance. In calculating the grey relational grade, the weighting ratio for all the responses is set as 1:1, i.e. each characteristic has equal importance or relative weighting.

Table 11: Grey relational grade

SAMPLE NO (SL.NO.)	Grey Relational grade
1	0.4180
2	0.4386
3	0.3893
4	0.5525
5	0.4256
6	0.4144
7	0.7788
8	0.6838
9	0.6696

S/N ratios of grey relational grades have been calculated by MINITAB 16 software and shown in Table 5.11 where the value of delta is higher in case of current; hence current is the most influencing factor on the grey relational grade. While calculating S/N ratios, larger-the-better idea has been applied, because large value of grey relational grade is the objective

Table 12: Response table for S/N ratio of grey relational grade

Level 1	Current(A)	Voltage(V)	Transverse Speed(T)
1	-7.643	**-4.967**	-6.681
2	-6.742	-5.960	-6.156
3	**-2.986**	-6.443	**-4.358**
Delta	4.658	1.476	2.323
Rank	1	3	2

Analysis of variance for grey relational grade is shown in Table 5.12. To identify the influence of input parameters on output response, analysis of variance (ANOVA) is applied.

value for current is less than 0.05 which means that this parameter has a significant effect on the grey relational grade. Thus, it is observed that contribution of current is highest on the overall objective. The optimized parametric condition by Grey-Taguchi method is determined from Figure 5.17.This is obtained by using the observed results given in the Table 5.8 and using the MINITAB 16 software for solving multi- objective optimization problem using Grey-Taguchi method. The optimized parametric combination is: welding current(C) =390A, voltage (V) =25V and traverse speed (T) =50mm/min, (i.e., C3-V1- T3).This is obtained by studying the plots given in Figure 5.17.

Table 13: Analysis of variance for grey relational grade

Source	DF	Seq SS	Adj SS	Adj Ms	F	P
Current	2	36.6144	29.2054	14.6027	196.05	0.005
Voltage	2	3.3982	1.9737	0.9868	13.25	0.070
Traverse Speed	2	1.8173	1.8173	0.9086	12.20	0.076
Residual error	2	0.1490	0.1490	0.0745		
Total	8	7.925				

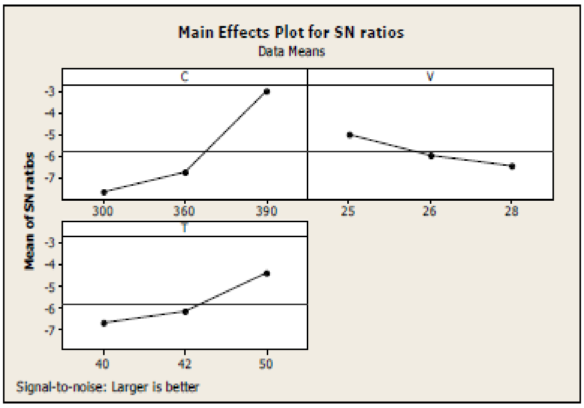

Fig 13: Main effects plot for S/N ratios for grey relational grade

CONCLUSION

In the present work, welding of mild steel AISI 1018 has been done by submerged arc welding, at various levels of current (A), voltage (V) and traverse speed (T). Plate thickness has been 10 mm. Based on the results of the experiments; microstructural studies and analysis of the data, following conclusions are drawn.

(i) In single objective optimization by Taguchi, the objective is to maximize bead penetration and deposition rate and minimize the bead width individually i.e. separately. The optimum parametric condition found in respect of bead width is: current(C) = 390A, voltage (V) =25V and traverse speed (T) =50mm/min. In case of bead penetration the optimum condition is: current(C) =390A, voltage (V) =25V and traverse speed (T) =50mm/min. For deposition rate the optimal combination is found to be: current(C) =390A, voltage (V) =25V and traverse speed (T) =50mm/min.

(ii) Multi-objective optimization has also been carried out by using Grey taguchi method. Each response characteristic has been given equal importance or relative weightage. The optimum parametric condition is found to be: current(C) =390A, voltage=25V and traverse speed=50mm/min.

(iii) Significance of the input parameters in respect of their effects on the output responses has been identified. Current is the most significant factor for bead penetration. Voltage influences most in respect of bead width. Traverse speed is found to be the most significant factor influencing deposition rate. In so far as multi-response characteristic is concerned, current is found to be most significant.

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(iv) Mathematical models have been developed to correlate input parameters with a) bead width, (b) penetration depth and (c) traverse speed. Adequacy of the models has been tested using ANOVA.

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