JCARME
ISSN: 2228-7922
Journal of Computational and Applied Research in Mechanical Engineering
Vol. 7, No. 2, pp. 189-198
jcarme.srttu.edu

Optimization of gas metal arcwelding parameters of SS304 austenitic steel by Taguchi –Grey relational analysis

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Article info:
Received: 18/01/2017
Accepted: 09/10/2017
Online: 10/03/2018

Keywords:
SS304H,
Mechanical properties,
Taguchi technique,
Grey relational analysis,
SEM.

Abstract
This study investigated the optimization of three welding parameters (wire feed speed, arc voltage, and shielding gas flow rate) for SS 304H by using Taguchi based Grey relational analysis. In this research work, pure argon was used as shielding gas. Numbers of trials were performed as per L_{16} ($4^{xx}3$) orthogonal array design and the mechanical quality such ultimate tensile strength, microhardness, Toughness, and microstructure of SS304H optimized by Grey-based Taguchi analysis and result shows that the optimal parameters combination were as A4B4C3 i.e. flow rate at 23L/min, voltage at 25 V and welding speed at 350IPM and it was observed that wire feed speed had the most significant effect followed by voltage and gas flow rate. An optimal combined parameter of the welding operation was obtained via Grey relational analysis. By analyzing Grey relational grade matrix, the degree of influence for each controllable process factor onto individual quality targets can be found.

1. Introduction

Welding is a fabrication process which is used to bond same or different materials that can be either ferrous or nonferrous metal, and most of the welding process utilize heat, pressure or both for fabrication of join. The gas metal arc welding is considered to be a key of arc welding processes [1]. The gas metal arc welding process provides a high quality of mechanical properties and metallurgical welded joints. SS304H is widely used in various industries such as petrochemical, automobile, thermal power plant, aerospace, paper, food process industries, kitchen applications due to its corrosion resistance and superior tensile strength [2-3]. Toughness and ductility of SS304H are excellent. The thermal conductivity of austenitic steel is insignificant, and it is easy to heat and weld. However, it can't be hardened by heat treatment and have no magnetic property [4]. Joo et al. [5] welded two dissimilar materials (steel) AH32/STS304L by hybrid CO_2 laser- gas metal arc welding and optimized welding parameters by using grey-based Taguchi analysis. Srirangan and Paulraj [6] welded Incoloy 800HT by TIG welding and optimized the process parameters by Taguchi into several sentences of Grey relational analysis (GRA) and finally, they reported that output of the mechanical properties for the best and least Grey relational grade was validated by the metallurgical characteristics. Sathish et al.

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[7] optimized the TIG welding process parameters for welding of dissimilar pipe joints via Taguchi method, and they mentioned in their conclusion that higher heat input results in lower tensile strength. Hakan et al. [8] examined the optimization of friction stir welding process parameters for an optimal parametric combination to yield favorable tensile strength and elongation using the Taguchi based GRA. Sharma et al. [9] optimized the turning parameters in turning operation of AISI 8620 steel using Taguchi and Grey-Taguchi analyses to obtain an acceptable surface roughness.
Ghosh et al. [10] optimized the gas metal arc welding process parameters on 316L steel by Grey relational based Taguchi method, and the current was found to be more significant parameter than gas flow rate influencing the strength of the welded joints. Datta et al. [11] applied Taguchi technique followed by GRA to solve multi-response optimization problem during the submerged arc welding. Sathiya et al. [12] optimized the weld bead characteristics of a super austenitic stainless steel (904L) by application of Grey-based Taguchi method, and they reported that Gray relational grade helps quantifying the integrated performance of bead-on-plate welding of the gas metal arc welding process. Rizvi et al. [13] optimized the process parameters that affect the weldability of IS2062, and in their result, they mentioned that welding current and voltage have significant effects whereas gas flow rate has an insignificant effect on tensile strength of the welded joint. Khalilpourazary et al. [14] applied Taguchi-based Grey technique for optimization of the process parameters during the turning of ST7 steel, and they mentioned that the optimum values of parameters can be achieved for a high degree of surface roughness.

2. Research Method

2.1. Experimental procedures

SS304H plates of dimension 260 mm × 70 mm × 5 mm were welded using Lincoln, USA gas metal arc welding machine, with Polarity Direct Current Electrode Negative [DCEN]. The chemical composition of base metal and filler wire is listed in Table 1. Filler wire of 2.0 mm diameter was used in this experimental work. Welded plates were machined on horizontal milling machine for making V-groove.

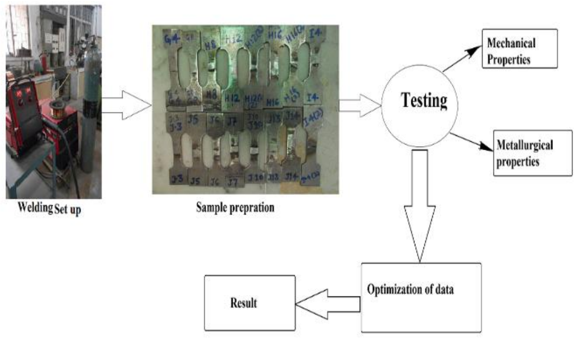


Fig. 1. Graphical abstract.

Figure 1 shows the graphical abstract of the paper, whereas Figs. 2 and 3 show the actual experimental setup and the milling process to fabricate V-groove on the SS plate before the welding to get the proper penetration, respectively.

Table 1. Chemical composition of parent metal and filler wire.

Material	Elements (wt%)						
	C	Cr	Ni	Si	Mn	P	Fe
SS304H	0.08	18.20	8.5	0.45	1.55	0.03	Rem.
Filler wire ER 308	18.5	10	0.4	1.7	0.05	-----	Rem.

In the experiments, pure Argon (Ar) was used as shielding gas for spray transfer mode and was adopted during the gas metal arc welding, which produced consistent bead width and good appearance with a stable arc formation. After welding of 16 samples, tensile test specimens were prepared as per ASTM standard [15] by cutting and machining on a milling machine. The size and shape of each tensile test specimen are shown in Fig. 5.

Fig. 2. Actual experimental setup.

Fig. 3. V-groove making on milling m/c.

2.2. Optimization of welding process via Grey-based Taguchi analysis

Figure 4 shows the proposed flow chat of the process adopting during the welding of this experimental work. Fig. 4 clearly shows which step is the first in the optimization of the process and which one is the last.

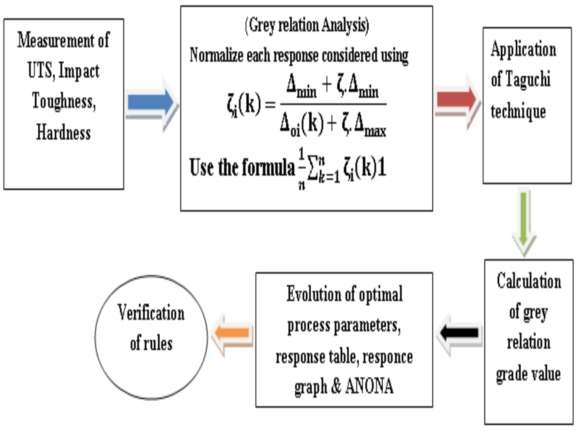


Fig. 4. Proposed Grey-based Taguchi method.

2.2.1. Experimental procedure

In the present research article, three-level gas metal arc welding process parameters i.e. welding current, wire feed speed, and gas flow rate were selected. Values of process parameters are shown in Table 2. Optimum welding process parameters, which considered the multiple performance characteristics, were acquired. The initial values of the welding parameters were wire feed speed of 250 IPM, gas flow rate of 10 l/min, and arc voltage of 20 V. Welding experiments for determining the optimal welding parameters were carried out by setting the wire feed speed at 250, 300, 350, and 400 IPM, arc voltage at 20, 21, 22, and 23 V, and gas flow rate at 10, 15, 20, and 25 l/min.

Table 2. Welding process parameters and their levels.

Factors	Parameters	**Unit**	Level I	Level II	Level III	Level IV
A	Wire feed rate	IPM	250	300	350	400
B	Arc voltage	V	20	21	22	23
C	Gas flow rate	l/min	10	15	20	25

The summary of experimental conditions is shown in Table 3. The experimental results after metal arc welding were estimated in terms of the following measured performance: (1) ultimate tensile strength (UTS), (2) absorbed energy (AE) of Charpy impact test results of the welded specimen, and (3) % age elongation. In order to attain supreme weldability, Taguchi's experimental design was utilized for conducting experiments. For this, an L_{16} orthogonal array was used for the experiment. Tensile specimens (shown in Fig. 5) were prepared as per ASTME8/E8M – 11.Standard specimens adopted in the tensile experiments are tested by a universal testing machine at room temperatures.

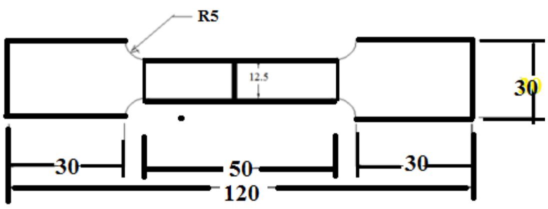


Fig. 5. Tensile test diagram for gas metal arc welding as per ASTM [12].

Charpy V-notched impact specimens were machined with a dimension of 55 mm X 10 mm X 10 mm according to ASTM E23-12c standard. V typed notch/groove (depth of V-groove of 2 mm at 45^0) perpendicular to weld surface was fabricated in the middle of the welded metal (WM) as shown in Fig. 6. Figure 7 shows the actual tensile test specimens prepared as per ASTM before fracture.

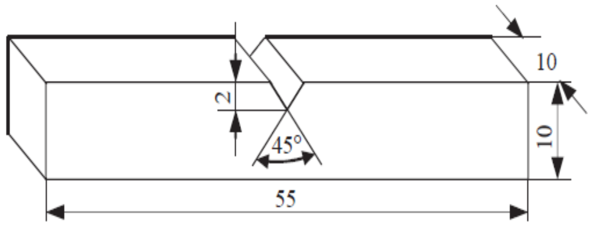


Fig. 6. Impact test sample with V groove.

Fig. 7. Actual tensile test specimens.

3. Grey relational analysis

3.1. Data pre-processing

Let the original reference sequence and sequence for comparison are represented as $x_o(k)$ and $x_i(k)$, i=1, 2, ...,m; k=1,2, . . ., n, respectively, where m is the total number of the experiment to be considered, and n is the total number of observation data. Optimization of multiple responses can be simultaneously performed with Grey relation analysis to find out the optimal levels that consist of many outputs [15-18].With the meager information available, GRA can judge or evaluate the performances of a complex process that involves more than one output. In GRA, the raw data have to be pre-processed into a quantitative index for subsequent analysis [19–20]. Pre-processing raw data involves conversion or raw data into a decimal sequence that lies between 0.00 and 1.00, which is useful for comparison. The sequence can be normalized for the condition Higher-the-better as:

$$\mathbf{x_i^*(k)} = \frac{\mathbf{x_i^o(k)-min x_i^o(k)}}{\mathbf{max\, x_i^o(k)-min x_i^o(k)}} \tag{1}$$

$X_i^*(k)$ represents the data sequence after pre-processing, $x_i^o(k)$ represents the original sequence, largest value of $x_i^o(k)$ is max $x_i^o(k)$, and smallest value of $x_i^o(k)$ is min $x_i^o(k)$.

Normalizing the data for lower-the-better condition is given as:

$$\mathbf{x_i^*(k)} = \frac{\mathbf{max x_i^o(k)-x_i^o(k)}}{\mathbf{max x_i^o(k)-min x_i^o(k)}} \tag{2}$$

However, if there is "a specific target value" then the original sequence is normalized using:

$$\mathbf{x_i^*(k)} = \mathbf{1} - \frac{\mathbf{|x_i^o(k)-OB|}}{\mathbf{max\{max.x_i^o(k)-OB, OB-min.x_i^o(k)\}}} \tag{3}$$

where OB is the target value.Alternatively, the original sequence can be normalized using the simplest methodology that is the value of the original sequence that can be divided by the first value of the sequence,$\mathbf{x_i^o(1)}$.

$$\mathbf{x_i^*(k)} = \frac{\mathbf{x_i^o(k)}}{\mathbf{x_i^o(1)}} \tag{4}$$

where $\mathbf{x_i^o(k)}$ is the original sequence, $\mathbf{x_i^*(k)}$is the sequence after the data pre-processing, $\mathbf{max.\,x_i^o(k)}$ is the largest value of$\mathbf{x_i^o(k)}$,$\mathbf{min\,.\,x_i^o(k)}$ is the smallest value of $\mathbf{x_i^o(k)}$.

3.2. Grey relational coefficients and Grey relational grades

After completing data pre-processing, in order to express a relationship between actual and ideal normalized values, a Grey relational coefficient [21-23] is determined, as expressed in Eq. (5):

$$\boldsymbol{\zeta_i(k)} = \frac{\mathbf{\Delta_{min}+\zeta.\Delta_{min}}}{\mathbf{\Delta_{oi}(k)+\zeta.\Delta_{max}}} \tag{5}$$

$\Delta_{oi}(k)$ represents the deviation sequence, which is calculated by:

Δ_{oi} (k)=|| X_o^* (k)- X_i^* (k) ||,

$\Delta_{max.}$ (k)=$\frac{max.}{\forall j i \varepsilon}\frac{max}{\forall k}$|| X_o^* (k)- X_i^* (k) ||,

$\Delta_{min.}$ (k)=$\frac{max.}{\forall j i \varepsilon}\frac{max}{\forall k}$|| X_o^* (k)- X_i^* (k) ||,ζ is the distinguishing coefficient and ζ = 0.5 is generally used.

A Grey relational grade is a weighted sum of the Grey relational coefficients, and is defined as follows:

$$_{\gamma}\,(\mathbf{x_0^*, x_i^*}) = \sum_{k=1}^{n} \boldsymbol{\beta_k}\, \boldsymbol{\gamma^n}(\mathbf{x_0^*(k), x_i^*(k)}$$
$$\sum_{k=1}^{n} \boldsymbol{\beta_k} = \mathbf{1} \tag{6}$$

Here the Grey relational grade $\gamma(\mathbf{x}_0^*, \mathbf{x}_i^*)$ represents the level of correlation between the reference and comparability sequences. If the two sequences are identical, then the value of the Grey relational grade equals to one. The Grey relational grade also indicates the degree of influence exerted by the comparability sequence on the reference sequence. The GRA is actually a measurement of the absolute value of data difference between the sequences and can be used to approximate the correlation between the sequences.

4. Results and discussion

4.1. Results

The tensile test specimens, prepared corresponding to L_{16} Taguchi orthogonal array experiments, were tested for tensile strengths and the results obtained are given in Table 3.
The experimental results were processed further with the requirements of GRA. The grey relational coefficient, grey relational grade and the rank of each experiment were found from Table 4, and the results as well.
The GRG values offer a single representation of the three responses, and a higher value of GRG is chosen. From Table 4, it is found that the experiment number 5 has the highest Grey relational grade of 0.7371. Therefore, parameter setting of the experiment number 5 is likely to be optimal. With the help of Response graph from Fig.8 for mean grey relational grade the optimal welding parameters determined and the optimal combination is A4B4C3 i.e. arc voltage at 23V, gas flow rate of 25l/min and wire feed rate at 350 ipm.

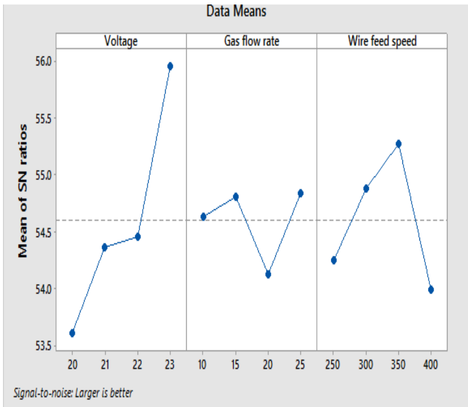


Fig. 8. Main effects plot for SN ratios.

Basically, the larger the S/N ratio, the better the corresponding performance characteristics, as shown in Fig. 8.
Grey relation grade values provided in Table 4 and a curve between grey relation grades and number of experiment is shown in Fig. 9, for all 16 experiments run as per L16 orthogonal arrays, and it is observed from Fig 9 that a change in the response happens when factors go from one level to another. It is also very clear from the figure that experiment no 16 has the highest grey relation grade value. Therefore, it is proved that all 16 run has optimal parameters setting for the best multi response characteristics.

Table 3. Experimental data.

Experiment no	Voltage	Gas flow rate	Wire feed speed	UTS (MPa)	Impact strength (J)	Micro hardness
1	20	10	250	470	182	178
2	20	15	300	490	180	200
3	20	20	350	510	222	240
4	20	25	400	449	184	198
5	21	10	300	524	160	161
6	21	15	250	540	170	184
7	21	20	400	446	162	185
8	21	25	350	591	120	206
9	22	10	350	574	240	188
10	22	15	400	526	260	175
11	22	20	250	454	222	202
12	22	25	300	569	232	187
13	23	10	400	596	216	215
14	23	15	350	657	210	216
15	23	20	300	647	142	218
16	23	25	250	615	216	198

Table 4. Proposed data, GRC and GRG for SS304H.

Experiment No	Normalized Values			Grey relation coefficient				
	UTS	Impact strength	Micro hardness	UTS	Impact strength	Micro hardness	Grey relation grade	Rank
1	0.1137	0.4428	0.2151	0.8147	0.5303	0.6992	0.6814	2
2	0.4454	0.4285	0.4936	0.5288	0.5385	0.5032	0.5235	11
3	0.0379	0.7285	1.0000	0.9295	0.4070	0.3333	0.5566	8
4	0.8009	0.4571	0.4683	0.3843	0.5224	0.5163	0.4743	13
5	0.3696	0.2857	0.0000	0.5749	0.6363	1.000	0.7371	1
6	0.3696	0.3571	0.2911	0.5749	0.5928	0.6639	0.6073	4
7	0.5829	0.3000	0.3037	0.4617	0.6250	0.6221	0.5696	7
8	0.9526	0.0000	0.5696	0.3442	1.0000	0.4674	0.6038	6
9	0.3033	0.8571	0.3417	0.6224	0.3684	0.5940	0.5282	10
10	0.6872	1.0000	0.1772	0.4211	0.3333	0.7383	0.4975	12
11	0.4786	0.7285	0.5189	0.5109	0.4070	0.4907	0.4695	14
12	1.0000	0.8000	0.3291	0.3333	0.3846	0.6030	0.4403	16
13	0.0142	0.6857	0.6835	0.9723	0.4216	0.4224	0.6056	5
14	0.0000	0.6428	0.6962	1.0000	0.4375	0.4179	0.6184	3
15	0.5924	0.1571	0.7215	0.4577	0.7609	0.4093	0.5526	9
16	0.7109	0.6857	0.4683	0.4129	0.4216	0.5163	0.4502	15

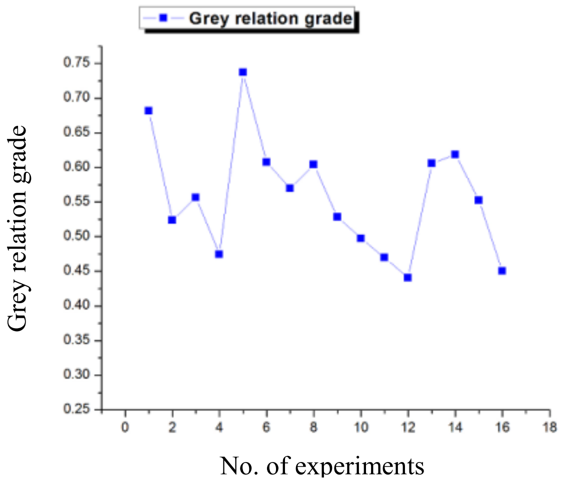


Fig. 9. Grey relation grade for multi response

4. 2. Signals to noise ratios

Signal to noise ratio (S/N) is used to determine that which parameter of design of experiments significantly affect the quality characteristic.

Table 5. Response table for signal to noise ratios.

Level	Voltage	Gas flow rate	Wire feed speed
1	53.61	54.63	54.25
2	54.36	54.81	54.88
3	54.46	54.12	55.28
4	55.96	54.84	53.99
Delta	2.35	0.71	1.29
Rank	1	3	2

In this case, for S/N ratio larger is better considered. Table 5 shows the signal to noise ratio.

4.3. ANOVA

ANOVA is developed by R.A. Fisher. It is defined as a collection of statistical models used to analyze the difference between group means and their associated procedures. The purpose of ANOVA experimentation is to reduce and control the variation of a process. It is also used to investigate which design parameters significantly affect the quality characteristic. Table 6 shows the ANOVA value. It is very clear from ANOVA that wire feed speed (65.82%) has the most significant effect followed by the voltage (24.16%) and gas flow rate (22.83). ANOVA table shows that the results are nearby related with Grey relation method.

4.4. Microstructural characterization

For microstructure examination of the welded joints, the specimens were cut from the joints and molded in PVC blocks. The cross-section surface of the specimens was ground and polished on double disk polishing machine with the different grades of emery papers from 200 to 1500 micron for 10 min each and then chemically etched with Glyceregia.- 15 mL HCl+10 mL glycerol + 5 mL nitric acid solution through swabbing for up to 2 min for optical observation. Microhardness was measured using a hardness tester with a constant load of 10kg for 10 s. Optical (Dewinter make, Italy) and scanning electron (SEM) microscopes were also used. Some typical microstructures of the weldments are shown in Fig. 10(a-d). The microstructures of the welded joints consist predominantly of delta ferrite and austenite matrix. It was found from the results that changing the flow rate of shielding gas, causes some variations in the microstructure of the welded joints. Fig. 10(a-d) also shows the different grain patterns of the welded joints which is only due to the different welding parameters. Fig 10(a) shows coarse grain while Fig. 10(d) displays fine grains of the welded joint.

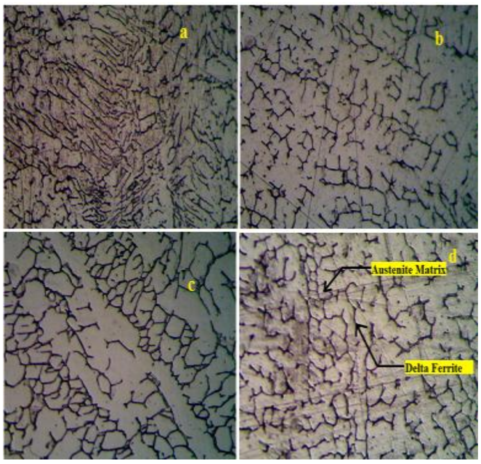
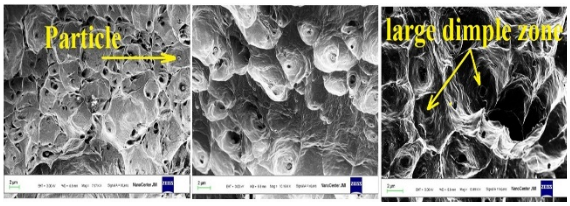


Fig. 10. Microstructure of weld metal (skeletal delta ferrite in austenite matrix) in samples (a) No. 1, (b) No. 2, (c) No. 3, and (d) No. 4.



(a) (b) (c)

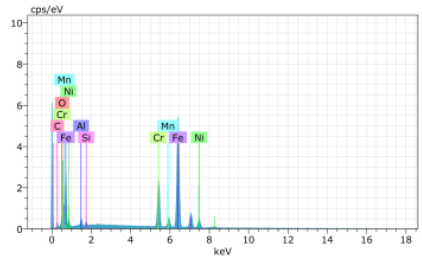
Fig . 11. (a), (b) & (c) Fractography of a MIG welded joint after the tensile test at room temperature.

4.5. Fractography

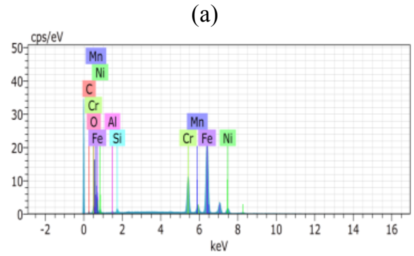
Figure 11(a, b & c) shows SEM fractographic images of the tensile test specimen. The images clearly reveal numerous dimples indicating ductile fracture has occurred. It is also observed that there are some spherical particles with small and large dimensions near the bottom of the dimples.

4.6. Energy dispersive spectrometer (EDS)

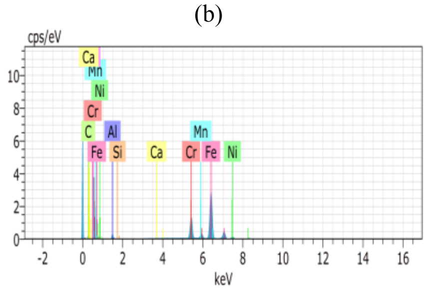
In order to determine microinclusions generated in the welded joints during the welding process, EDS analysis was conducted on the fractured specimen. Fig. 12 shows the results of the analysis indicating that inclusion generated in the weld metal contained Fe, C, Ti, Cr and Mn elements in amounts of 6% or more whereas C, Al, Fe, Si are less than 2%. The EDS results of the specimen imply that the inclusions are the oxides including MnO_2, NiO_2, CrO_2, SiO_2 and Al_2O_3. The size and amount of the oxides in the microstructures usually depend on the amount of CO_2 present in shielding gas.On the contrary, the amount of Al, S, and Si elements are comparatively low. For commercial steels, the typical non-metallic inclusions are oxides, nitrides, and sulphides. Mn and S inclusions are effective in inducing accicluar Ferrite formation.



(a)



(b)



(c)

Fig. 12. EDS analysis results of inclusions.

Table 6. ANOVA table for response and GRD.

Response	Parameter	Degree of freedom	Sum of square	Adj MS	F	P	% contribution
UTS	Wire feed speed	3	47219	15739.6	19.64	0.002	65.82
	Voltage	3	4362	1454.1	1.81	0.245	6.1
	gas flow rate	3	15353	5117.8	6.39	0.027	21.4
	Error	6	4807	801.2			6.7
	total	15	71742				
Impact Strength	Wire feed speed	3	14664.7	4888.2	6.01	0.031	66.44
	Voltage	3	932.8	310.9	0.38	0.770	4.22
	gas flow rate	3	1590.8	530.3	0.65	0.610	7.21
	Error	6	4883.5	813.9			22.12
	total	15	22071.7				
Micro hardness	Wire feed speed	1	2066.2	688.7	4.26	0.062	36.1
	Voltage	1	1383.7	461.2	2.85	0.127	24.16
	gas flow rate	1	1307.2	435.7	2.7	0.139	22.83
	Error	12	969.9	161.6			17
	total	15	5726.9				

5. Conclusions

The Grey relational analysis based on an orthogonal array of Taguchi technique is a way of optimizing the welding of SS304H. The analytical results are summarized as follows:

- The best result was obtained for the sample welded using the arc voltage of 25V, the flow rate of 25 l/min, and the wire feed speed of 350IPM. The worst result in tensile testing was obtained for the sample welded using the arc voltage of 20V, the gas flow rate of 20 l/min, and the wire feed speed of 400IPM.
- Optimization of the process parameters was determined by using Grey based Taguchi methodology; the optimum parametric combination was examined. The optimal factor setting became **V4G4W3** (i.e. arc voltage = 23V, gas flow rate = 25l/min, and wire feed speed = 350IPM).
- Mechanical properties of SS304H were correlated with the metallurgical characteristics.
- Tensile test fractography analysis of SS304 showed a ductile fracture.
- From ANOVA table for the response, it was clear that wire feed speed had the most significant effect followed by voltage and gas flow rate.

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How to cite this paper:

Saadat Ali Rizvi and S. P. Tewari ,“ Optimization of Gas Metal ArcWelding Parameters of SS304 Austenitic Steel by Taguchi –Grey Relational Analysis”, *Journal of Computational and Applied Research in Mechanical Engineering*, Vol. 7. No. 2, pp. 189-198

DOI: 10.22061/jcarme.2017.2215.1207

URL: http://jcarme.srttu.edu/?_action=showPDF&article=765