MECHANICAL AND MICROSTRUCTURAL STUDIES OF OPTIMIZED TAGUCHI GREY RELATIONAL ANALYSIS OF PCGTAW PROCESS PARAMETERS FOR JOINING MONEL 400 AND AISI 316

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In the present paper an approach for producing sound weld quality characteristics using pulsed current gas tungsten arc welding process to join base metal combination of Monel 400 and AISI 316 with ERNiCrMo-3 as filler while employing Taguchi method to design experiments and analyze the experimental data is presented. For optimizing the size of HAZ and tensile properties of weldments, an L9 array has been used. The grey relational analysis was performed for optimizing process parameters with multi-objective responses. Analysis of variance was performed to find the significance in effect of the welding parameters on dissimilar weldments. The analysis results of 8th trail were obtained as best performance set of values with main current at 180 A, background current at 90 A and frequency at 4 Hz. Further, mechanical and metallurgical properties have been evaluated for optimum process parameter experiment. Improved mechanical properties and fine grain structure in the weld zone were observed from the best performance set of parameters.

Keywords: PCGTAW, Taguchi Methods, Grey Relational Analysis, ANOVA, Mechanical Properties, Microstructural Studies

1. Introduction

One of the chosen base metals, i.e., Monel 400, has applications in petrochemical and marine industries, exhibit its toughness and high strength at high temperatures with good corrosion resistance [1]. Similarly, AISI 316 shows better properties when subjected to cryogenic temperatures, especially in pitting and crevice corrosion. Addition of 2% of Molybdenum to a standard AISI 304 has shown an increase of 40% in tensile strength at 760 $^\circ$C temperature [2]. Balram et al. [3] reported that the bimetallic combination of austenitic steels and Monel 400 has various applications in nuclear industries, petrochemical and food processing equipment. Choosing a proper filler wire is a critical step in joining of heterogeneous metals which significantly affect mechanical and metallurgical properties. Venukumar et al. [4] studied on joints of austenitic steel 416 and Ni-Cr based super alloy Inconel 718 developed with Pulsed Current Gas Tungsten Arc

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Welding (PCGTAW) process and results have revealed that the Ni-Cr based fillers are most suitable for improving toughness of combination joints of AISI 416 and Inconel 718. The addition of other elements, such as Molybdenum, Niobium, will help to pass the formation of carbides after solidification. This is an effective method to increase resistance to ductility dip cracking in Ni-based filler wires [5].

In Constant Current Gas Tungsten Arc Welding (CCGTAW) technique, due to continuous heat input, high amount of heat energy is produced and consequently results in weld zones containing coarse grain structures. Ramkumar et al. [6] discussed results on weldments of Monel 400 and stainless steel 304 weldments developed by CCGTAW and PCGTAW process. The metallurgical results revealed that the segregation of filler elements like Cu and Cr occur at the interface of weld zone when CCGTAW technique was employed. Continuous heat inputs in the CCGTAW technique has caused the development of new phases and micro-segregation and thus causing an overall reduction in quality of weldments [7]. From the literature review on pulsed current welding process, it was stated to have advantages over continuous welding process and hence it is suggested for various applications requiring fusion welding. By using PCGTAW process, some of the microstructural improvements, like grain refinement, lower segregation effect can be achieved and thus an improvement in mechanical properties of welded joints [8]. Devendranath et al. [9] developed the dissimilar weldments between AISI 416 and Inconel 718 by employing PCGTAW process to study the metallurgical properties. From the results it is revealed that the lower segregation effect of alloying elements with reduced coarse grain weldments were obtained in PCGTAW process. Reddy et al. [10] developed the aluminum-lithium alloy weldments by using PCGTAW process at different pulse frequencies. The results indicating that the strength of weldments has improved at low pulse frequency due to the formation of fine grains structures around the fusion zone.

Taguchi's method is a systematic method to model and analyze the experimental values for enhancing the desired outcome like quality etc. Srirangan et al. [11] applied Taguchi Grey Relational Analysis (GRA) to design the factors like, welding speed, arc voltage and welding current to optimize the breaking strength and yield properties at the temperature about 27 $^{\circ}$C and at 750 $^{\circ}$C. From the GRA analysis, a combination of welding current (I_A) of 110 A with voltage (V) of 12 V and weld speed (s) of 1.5 mm/s were found as optimum parameters. Magudeeswaran et al. [12] used Taguchi technique in their experiments for optimizing parameters of CCGTAW technique that included weld current, voltage drop, electrode gap and travel speed for the development duplex stainless steels weldments. The optimum parameters to obtain best weld quality were reported as 140 A for welding current, 1 mm electrode gap with a weld speed of 130 mm/min and arc voltage at 12 V. Kumar et al. [13] developed the regression model for

improving the tensile properties of PCGTAW of aluminum alloys. Esme et al. [14] optimized geometry of weld pool of CCGTAW weldments by using GRA and Taguchi method wherein an L-16 array is used for optimizing bead height, width, depth of penetration and penetration area. Reports suggested that GRA is the best statistical multi-objective optimization tool with the combination of Taguchi method. Choudhury et al. [15] used L-16 array for welding parameters that included main current, flow rate and diameter of filler using Taguchi technique. The statistical tools Analysis of Variance (ANOVA) and S/N (Signal to Noise ratio) methods have been employed to study the effect input factors on output response i.e., Ultimate Tensile Strength (UTS). The optimal welds geometry was also reported that would produce sound welds. Agrawal et al. [16] examined the effect of welding speed, pulsed current and frequency on SS 304 thin sheets in the PCGTAW technique. It is reported that the tension and hardness properties were enhanced about 12% at high welding speed and higher mean current.

In this research, multi-objective optimization using Taguchi based GRA was used to optimize the PCGTAW input parameters which includes main and background currents and frequency. The output responses were yield strength, UTS and Heat Affected Zone (HAZ) width of Monel 400 and AISI 316. ANOVA method was adopted to understand the effect of individual parameters on weld characteristics. Further, the low grey grade obtained from the experiments were validated by conducting confirmation test. Also, the present research work studies the effect of PGCTAW parameters on mechanical behavior and metallurgical changes on weldments of Monel 400 and AISI 316 for optimum condition weldment.

2. Experimentation

The chosen base metals were EDM cut to a size of 120 x 80 x 5 mm. The filler wire ERNiCrMo-3 was used to join base plates of Monel 400 to AISI 316 by employing PCGTAW machine. The chemical composition of base materials and filler are given in Table 1. For edge preparation V-grooves configuration is chosen while maintaining prescribed root gap (1.5 mm). Taguchi L9 array was used for conduction experiments and the process parameter of PCGTAW technique and their experimental levels are given in Table 2.

Table 1

Chemical composition (in wt.%) of base materials and filler wire

Base and filler metal	Ni	Cr	Mo	Fe	Cu	C	Mn	C	Si	Others
Monel 400	Rem	-	-	2.5	31.5	0.12	1.6	0.12	0.4	-
AISI 316	10.4	17.9	2.1	Rem	-	0.08	2.0	0.08	0.4	P- 0.002
ERNiCrMo-3	Rem	21.5	9.0	5.0	0.5	0.1	0.5	0.1	0.5	Nb-3, Co-9.0 and Ti-0.4

Process parameters of PCGTAW technique and their levels

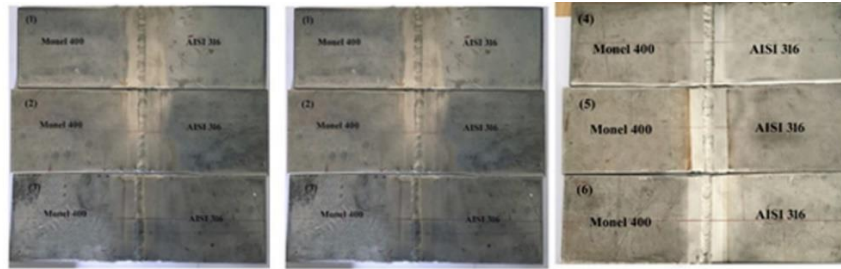| Parameters	Unit	Level-1	Level-2	Level-3
Main current (I_m)	A	160	170	180
Background current (I_b)	A	80	90	100
Pulse frequency (f)	Hz	4	6	8

Fig. 1. Dissimilar joints developed by PCGTAW process

The output responses were considered to be YS, UTS and HAZ width of Monel 400 and AISI 316. The fabricated weldments of base plates are shown in Fig. 1.

3. Taguchi GRA

The Taguchi's GRA is a quantitative analysis used to optimize the multiple responses simultaneously. It combines all the responses considered (multi-objectives) into a single response which can be used to solve the single response (objective) optimization problem. To apply this method, input characteristics (objective function) need to be normalized. This way of optimizing the responses is called grey relational analysis. The experimental results of tension test and HAZ width of base metals considered for output responses are given in Table 3.

3.1 Signal to noise ratio

The conversion of S/N ratio value was computed for the investigational response values by using Eqs. 1 and 2. For "the larger the better" criteria equation (1) is used whereas for "the larger the better" criteria equation (2) is used. In the present study, the quality characteristics "the larger the better" is selected for optimizing the tensile properties and "the smaller the better" for HAZ width of AISI 316 and Monel 400. The S/N ratio of each level of response were calculated using Eqs.1 and 2 and are tabulated in Table 4. In GRA, the normalized data are used for evaluating the grey relation coefficient.

$$\frac{S}{N} = -10 * log_{10}(\frac{1}{n} \sum_{i=1}^{n} \frac{1}{Y^2}) \tag{1}$$

$$\frac{S}{N} = -10 * log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} Y^2\right) \qquad (2)$$

Where, n= number of runs and Y=performance results.

3.2 Grey relation generation

The preferred characteristics for YS and UTS is "the larger the better" criterion. The "larger the better" characteristics can be normalized by using the following Eq. 3.

$$Y^*(k) = \frac{Y_i(k) - Min(Y_i(k))}{Max(Y_i(k)) - Min(Y_i(k))} \qquad (3)$$

Where, i= number of runs 1, 2, 3……9, $Y_i(k)$ = response factor, $Y^*(k)$= Grey relation generation.

The preferred characteristics for HAZ width is "the smaller the better" criterion and this characteristic can be normalized by using following Eq. 4.

$$Y^*(k) = \frac{Min(Y_i(k)) - Y_i(k)}{Max(Y_i(k)) - Min(Y_i(k))} \qquad (4)$$

Similarly, for remaining experiments the calculated is repeated for all the sequences after preprocessing data using Eqs. 3 and 4. The Grey Relational Generation (GRG) values are listed in Table 5.

Table 3

Experimental results of tensile properties and HAZ width

Exp. No	UTS, MPa	YS, MPa	HAZ Width of SS 316, mm	HAZ width of Monel 400, mm
1	518	281	2.82	2.53
2	543	303	3.05	2.62
3	514	301	3.14	2.68
4	504	319	2.92	2.59
5	502	309	3.18	2.75
6	526	324	3.14	2.65
7	544	310	3.25	2.80
8	546	363	3.04	2.59
9	539	320	3.34	2.91

3.3. Grey relation coefficient and grade

After normalization of sub-sequence data, a Grey Relation Coefficient (GRC) can be evaluated with deviation sequence and GRG. The GRC relation is defined in Eq. 5.

$$\xi_i(k) = \frac{\Delta min + (\zeta * \Delta max)}{\Delta_{oi}(k) + (\zeta * \Delta max)} \qquad (5)$$

where, $\Delta_{oi}(k)$= deviation sequence among $Y_i^*(k)$ and $Y_o^*(k)$; $\xi_i(k)$ =Grey relation coefficient, ζ= identification coefficient, (ζ= 0.5, since equal consideration is given to all the weldment responses).

Similarly, the GRC of each experiment is calculated by the Eq. 6. After computing GRC, the grades of each experiment are determined by considering the average of GRC for every inspection as represented in Eq. 6.

$$\gamma_i = \frac{1}{n}\sum_{i=1}^{Q}\xi_i(k) \qquad (6)$$

Table 4

S/N ratio of response parameters

Exp. No	S/N ratio of UTS	S/N ratio of YS	S/N ratio of HAZ of SS 316	S/N ration of HAZ of Monel 400
1	54.2911	48.9979	-9.0050	-8.0624
2	54.7115	49.6309	-9.6860	-8.3660
3	54.2201	49.5924	-9.9386	-8.5627
4	54.0608	50.0951	-9.3077	-8.2660
5	54.0215	49.8000	-10.0485	-8.7867
6	54.4332	50.2088	-9.9386	-8.4649
7	54.7169	49.8124	-10.2377	-8.9432
8	54.7542	51.2165	-9.6575	-8.2660
9	54.6466	50.1011	-10.4749	-9.2779

Table 5

Taguchi grey relational generation

Exp. No	UTS	YS	HAZ of SS 316	HAZ of Monel 400
1	0.3680	0.0000	1.0000	1.0000
2	0.9417	0.2853	0.5367	0.7502
3	0.2711	0.2679	0.3649	0.5884
4	0.0537	0.4945	0.7941	0.8325
5	0.0000	0.3615	0.2901	0.4041
6	0.5620	0.5458	0.3649	0.6688
7	0.9491	0.3671	0.1614	0.2754
8	1.0000	1.0000	0.5561	0.8325
9	0.8531	0.4972	0.0000	0.0000

4. Results and discussions

From the Taguchi GRA, the maximum grey relational grade (81.97%) has been observed in the 8th experiment of orthogonal array which has better multi-response characteristics. A rank is assigned to each experiment based on GRG value. The optimized parameters of PCGTAW from Taguchi GRA with main current as 180 A, base current of 90 A with pulse frequency of 4 Hz were taken for welding chosen base materials. Since L9 array was used, it would be easy to estimate the effect of individual process parameter on GRG by separating values at all the levels. As an example for instance, the mean of GRG for the pulse frequency at levels 1, 2 and 3 can be computed by taking the average of GRG of (Exp. No.1, 6 and 8), (Exp. No. 2, 4 and 9) and (Exp. No. 3, 5 and 7) as listed in Table. 6. Similarly, the mean values of peak current and background current are computed. The maximum values of average GRG are highlighted in Table 7. From the experimentation, the order of effecting parameters are 1) pulse frequency, 2) base current and 3) peak current. The means of mean effect on GRG are shown in Fig. 2.
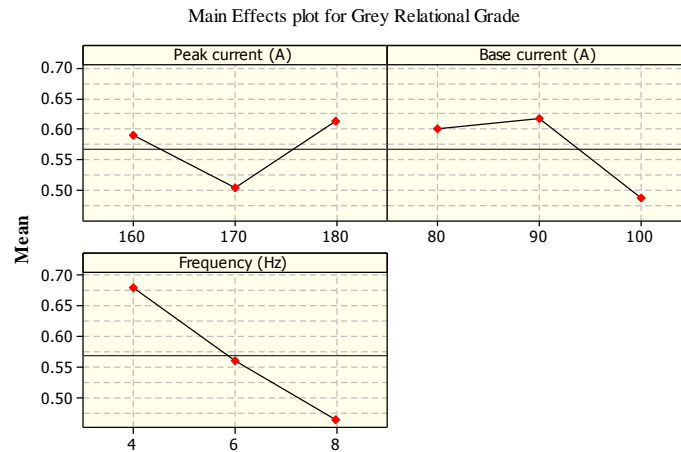

Fig. 2. Main effect plot of GRG

Basically, the higher GRG gives the product quality closer to the best and hence it is desirable for best performance. Therefore, the optimal process parameters setting for better pulse frequency and lesser peak current and background current.

4.1 Analysis of means for GRG

Analysis of mean indicates the optimal combination of parameters. ANOVA was calculated by taking the average of responses of that particular level. The GRG values of welding parameters are given in Table 7. From the analysis of means, the optimal parameters obtained are main current (I_m) at Level-

3 (180 A), background current (I_b) at Level-2 (90 A) and frequency at Level-1 (4 Hz).

Table 6

Grey relational co-efficient and grade

Exp. No	UTS	YS	HAZ of SS 316	HAZ of Monel 400	GRG	Rank
1	0.4417	0.3333	1.0000	1.0000	0.6938	2
2	0.8956	0.4116	0.5191	0.6668	0.6233	3
3	0.4069	0.4058	0.4405	0.5485	0.4504	8
4	0.3457	0.4973	0.7083	0.7491	0.5751	4
5	0.3333	0.4392	0.4132	0.4563	0.4105	9
6	0.5330	0.5240	0.4405	0.6016	0.5248	6
7	0.9077	0.4413	0.3735	0.4083	0.5327	5
8	**1.0000**	**1.0000**	**0.5297**	**0.7491**	**0.8197**	**1**
9	0.7730	0.4986	0.3333	0.3333	0.4846	7

Table 7

Mean values of GRG

Parameters	Level-1	Level-2	Level-3	Main effect (max-min)	Rank
I_m	0.5892	0.5035	**0.6123**	0.0232	2
I_b	0.6005	**0.6178**	0.4866	0.0173	3
f	**0.6794**	0.561	0.4645	0.1184	1

4.2 Analysis of variance for S/N ratios

ANOVA is an approach that extensively considers the involvement of each factor variation made by the overall variance of output response variation. It indicates the % of contribution of each factor towards the output responses. The influence of process parameters background current, main current and pulse frequency on output response to grey relational grade has been determined with statistical tool Minitab 16.0. This could be calculated by separating the total variability of the GRG value as mean square deviation of GRG and its error.

Table 8 shows the analysis of variance of GRG. From the ANOVA results, it is clear that the pulse frequency (53%) influence on the quality of welded joint and subsequently with lower percentage from background current and main current with 23% and 15% respectively.

4.3 Confirmation experiment

For verifying the optimal process parameters obtained from the GRA, a confirmation test has been performed by choosing optimal parameters. The weldments of the chosen combination were developed with optimum parameters and the output responses were measured. The GRA and confirmation test outcomes are listed in Table 9. From this test, it was confirmed that the optimum values of test results are very close to the results obtained from GRA.

Table 8

ANOVA results for GRG

Source	DF	Seq. SS	Adj. SS	Adj. MS	P	F	% of contribution
I_p	2	0.020	0.020	0.010	0.363	1.750	15.06%
I_b	2	0.031	0.031	0.015	0.269	2.710	23.30%
Hz	2	0.070	0.070	0.035	0.139	6.180	53.08%
Error	2	0.011	0.011	0.006			8.56%
Total	8	0.131					

Table 9

Confirmation test and optimal GRA values

Optimal parameters	Ultimate tensile strength, (MPa)	Yield strength, (MPa)	HAZ of AISI 316 (mm)	HAZ width of Monel 400 (mm)
8th trial of array	546	363	3.04	2.59
Confirmation experiment	548	359	3.02	2.62

4.4 Hardness studies

The microhardness of dissimilar welded joint was obtained from Vickers hardness tester and its distribution is shown in Fig. 3.
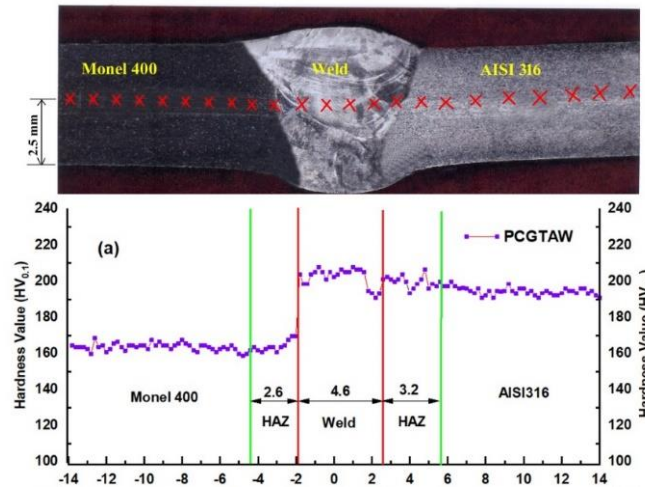

Fig. 3. The Vickers microhardness distribution along fusion zone of Monel 400 and AISI 316

The maximum hardness number was seen at the weld zone than the base materials. It can be seen from the hardness plot, the surface hardness value decreased at the HAZ of AISI 316 as compared to its base materials, whereas the surface hardness number increased at the interface of Monel 400 than that of its base materials. It is also evident from the microstructures, that the grain refinement has been observed at the Monel 400 interface which is the cause of improvement in the hardness value. The width of HAZ is more at the AISI 316 side as compared to Monel 400 side because of its thermal properties.

4.5 Microstructural investigation

For the optimal test experiment, the microstructure of various zones has been evaluated. The OM and SEM structures of the weld interfaces are shown in the Fig. 4.
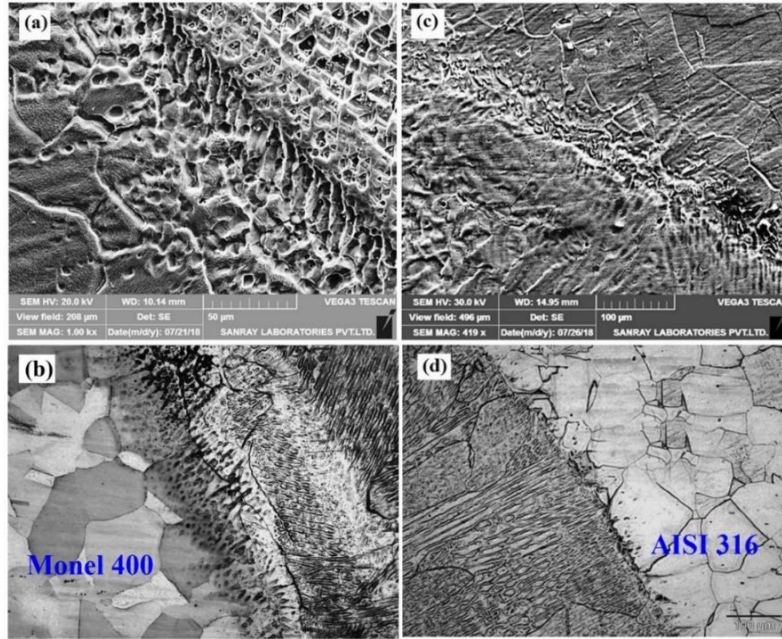

Fig. 4. OM images and SEM micrographs of (a, b) Monel 400 and (c, d) AISI 316 weld joint

No grain coarsening was identified near the HAZ of Monel 400 from Fig. 4a & b, which could be attributed to the controlled total heat input and low frequency. The long dendritic and columnar like structures were seen on the HAZ of Monel 400 weld and fine grain structures near the interface of AISI 316 from Fig. 4c & d. Also, complete austenitic phases were seen on weld region from Fig. 5. Due to Ni-Cu enrich phases at the weld zone the maximum hardness values have been observed. Secondary phase formation and isolation of alloying elements are greatly minimized in this welding technique. SEM micrographs of weld interfaces are presented in Fig. 6. Enrich of Ni, Mo and Cr and also peaks of Cu and Fe were observed. Results of EDS point analysis i.e., the chemical compositions of HAZ and weld zone of dissimilar weldments are listed in Table 10.

Table 10

Point analysis (% weight) on dissimilar weldments

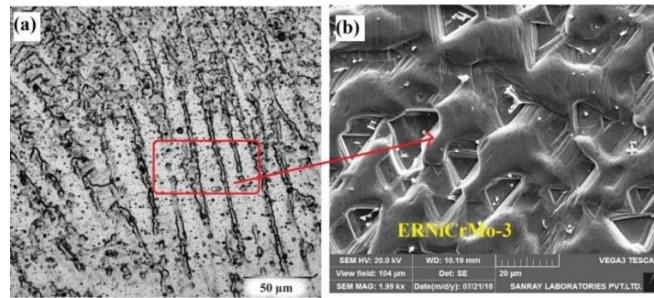| Zone	Ni	Cr	Fe	Cu	Mo	Mn	Si	Others
Monel 400 HAZ	61.93	--	4.17	32.17	--	1.37	0.34	---
Fusion zone	46.07	19.71	18.4	9.4	3.2	1.98	0.4	Nb-0.79
AISI 316 HAZ	9.31	18.74	68.69	--	1.24	1.96	-	-

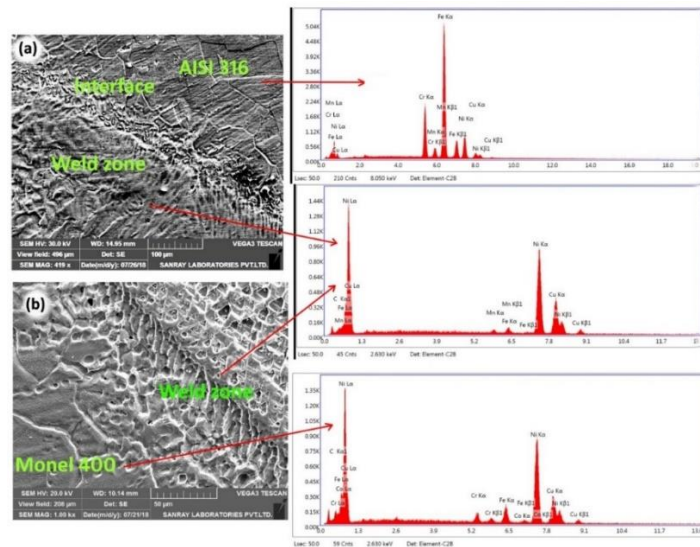Fig. 5. Weld zone of dissimilar PCGTAW weldments: (a) OM and (b) SEM micrographs

Fig. 6. EDS X-ray point analysis of dissimilar weldments: (a) AISI 316 and (b) Monel 400

5. Conclusions

The dissimilar combination of Monel 400 and AISI 316 are joined by PCGTAW technique successfully with ERNiCrMo-3 filler wire. The conclusions drawn from Taguchi analysis are given below;

- The best performance set of parameters from Taguchi's GRA are obtained as main current at 180 A, low current at 90 A and pulse frequency at 4 Hz.
- From the ANOVA grey relational analysis, it is seen that the order of effecting parameters are pulse frequency (53%) followed by background (23%) and main currents (15%) on output factors.
- The HAZ of both sides of base metals has been minimized and a small grain coarsening was identified at the boundary of stainless-steel side because of its thermal properties.
- The microstructure of weld zone has shown complete austenitic structures and grain refinement at the interface of Monel 400 and AISI 316 by maintaining low pulse frequency (4 Hz).

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