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Microstructural evolution and precipitation behavior in heat affected zone of Inconel 625 and AISI 904L dissimilar welds

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Abstract: In the present investigation an attempt has been made to join the dissimilar combination of Inconel 625 super alloy and super austenitic stainless steel (AISI 904L) using manual multi-pass continuous current gas tungsten arc (CCGTA) welding processes. Two different filler wires such as ERNiCrMo-4 and ERNiCrCoMo-1 have been used to compare the metallurgical properties of these welded joints. Both optical microscopy and scanning electron microscopy techniques were adopted to disseminate the microstructure traits of these weldments. Formation of secondary phases at the HAZ and weld interface of AISI 904L was witnessed while using the ERNiCrCoMo-1 filler, along with Solidification Grain Boundary (SGB) and Migrated Grain Boundary (MGB) were also observed at the weld zone.

1. Introduction

In the present scenario, dissimilar metal welding are extensively used in numerous industrial applications due to their economic potentials. Inconel 625 is a nickel-chromium alloy derived from by adding the strengthening elements of molybdenum (Mo) and niobium (Nb) on its matrix of nickel-chromium. Similarly super austenitic stainless steels (904L) are a Fe-based system containing high amounts of Cr, Ni and Mo. Independently, these materials have broad range of applications in thermal and nuclear power plants, chemical and petro-chemical industries due to excellent corrosion resistance and high temperature strength [1].

Many researchers reported the influence of fusion welding of above said individual metals on metallurgical and mechanical properties. Further, few researchers reported about the issues on dissimilar joints of Inconel 625 with 304 and 316L stainless steel. Dissimilar welding is quite complicated because of their difference in melting temperatures, i.e. one of the metals will melt prior to the other metal. The major issues on the dissimilar weldment of Inconel and Stainless steels are the formation of precipitates of hard brittle phases in the fusion zone and HAZ due to the Nb content in the Inconel 625 [2]. So filler metal selection to enhance the mechanical properties such as ductility, toughness etc., is really a challenging task.

During welding of 904L alloy, it has susceptible of hot cracking due to its high content of Mo. To avoid hot cracking, low impurity level welding consumables have to be used in spite of fully austenitic fillers. On the other hand due to the presence of Mo, Cr and Ni rich in amount can enhance the precipitation of intermetallic phases including carbides and nitrides in these steels during prolonged exposure at elevated temperatures between 550 to 800°C [3].

Caironi et al. [4] reported that during weld metal solidification, a hard brittle compound Nb-rich phase forms in regions of inter-dendritic due to the segregation of Nb, thereby deteriorate the mechanical



properties. Dupont et al. [5] investigated the bimetallic joints of two nickel alloys (Inconel 622 and Inconel 625) with AL-6XN super stainless steel and reported that the filler metal chemistry and the effect of welding processing parameters influences on the weldability and microstructure. The addition of iron to the weld (occur due to the increasing dilution) causes more segregation of Mo and Nb. Therefore this behavior attributes the lower solubility of Mo and Nb in austenite phase due to the increase in iron addition. One of the main issues is the selection of appropriate filler metal for welding between Ni-based super alloy and stainless steels. Patterson et al. [6] studied the dissimilar joints of AISI 304L and Inconel 625 by autogenous GTA and PCGTA welding and found the solidification cracking at the weld zone. Also the authors reported that the susceptibility of cracking in the interdendritic phase was mainly due to the elemental segregation such as S, P and Nb. Dissimilar welding between super alloy and SS has a lot of challenges like hydrogen cracking, Ductility Dip Cracking (DDC), and in the weld interface formation of brittle phases deteriorate mechanical and metallurgical properties. D.J. Lee et al. [7] observed that during the multi-pass welding of Inconel 625 ductility-dip cracking susceptibility is one of the major problem. J. N. Du Pont et al. [8] recommended that during welding process cracking may be avoided in the fusion zone by lowering the heat input. The authors strongly believed that the selection of welding parameters have an influence on susceptibility of cracking.

Devendranath et al. [9] studied the dissimilar joints between AISI 304 and Inconel 625 and reported that in the HAZ of Inconel 625, segregation enrichment was observed due to the use of high Nb rich filler metal (ERNiCrMo-3) and also in the HAZ of SS side, the precipitation of chromium carbides was observed. The authors recommended that while employing PCGTA welding, the secondary phase effects were lowered slightly.

To avoid the hot crack formation during welding specially designed welding consumables with lower impurity level have to be used. So joining the Inconel 625 with AISI 904L by adopting suitable fillers and welding techniques which offers the same metallurgical properties is one of the cumbersome tasks and also from the literature it is evident that, by using CCGTA welding techniques, joining of Inconel 625 with AISI 904L has not been reported hitherto.

The main objective of this research is to investigate the microstructure on the bimetallic joints of Inconel 625 super alloy with AISI 904L super austenitic stainless steel obtained by CCGTA welding techniques employing Nb free and Ni, Mo and Cr rich based fillers of ERNiCrMo-4 and ERNiCrCoMo-1 to improve the metallurgical properties. These bimetallic joints were characterized by macro/micrograph, line mapping, SEM/EDS point analysis to understand the metallurgical behaviour. The results revealed in this paper will be really useful to the Original Equipment Manufacturers (OEM) operating with these bimetallic joints.

2. Experimental Procedure

As-received base metal plates of Inconel 625 and AISI 904L were 5mm thick. By using spectroscopy method the chemical compositions studies were carried out and also represented in the Table 1 along with the filler metals (ERNiCrMo-4 and ERNiCrCoMo-1) used for this study. By using the wire cut EDM the base metals were machined to have the dimensions of 155 x 55 x 5mm. The process parameters were obtained based on bead on plate welding and resulted in the Table 2. Before welding, standard butt joint configuration (V-groove with an included angel of 70°, with the root gap of 1mm) were used in the present study. Continuous Current GTA welding was carried out in a specially designed fixture (holding the plates with accurate grip to avoid bending and distortion during welding) with a copper back plate. After welding, the gamma ray radiography technique were used to determine, if there are any flaws to in micro level surface defects like lack of penetration, under cut and inclusions. After ensuring that the weldment is defect free from NDT results, the

coupons were sliced from the welded samples as per ASTM standards by using the wire cut Electrical Discharge Machining (EDM) to study the metallurgical properties.

Table 1. Chemical composition (% wt.) of the base metal and filler metal

Chemical Composition (% wt.)									
Base metal/ Filler metal	C	Ni	Cr	Mo	Nb	Fe	Mn	Si	Others
Inconel 625	0.024	Rem.	22.04	9.00	3.47	4.38	0.106	0.203	0.186 (Al); 0.082 (Co); 0.029 (V); <0.001 (Ta); 0.002 (P); <0.001(S)
AISI 904L	0.018	26.1	19.72	3.93	Nil	Rem.	1.65	0.145	0.959 (Cu); 0.036 (Al); 0.034 (Co); 0.007 (Ti) 0.018 (P); <0.001 (S)
ERNiCrMo-4	0.015	57.8	Rem.	16.2	Nil	5.1	0.6	0.002	0.022 (Cu); 2.2 (Co); 4.08 (W); 0.051 (V); 0.001 (P); 0.008 (S)
ERNiCrCoMo-1	0.08	45.8	Rem.	9.4	Nil	2.2	0.05	0.11	0.28 (Ti); 13.2 (Co); 0.08 (Cu); 0.96 (Al); 0.001 (P); 0.002 (S)

*Remainder

Table 2 Process parameters employed in CCGTA welding of Inconel 625 and AISI 904L

Filler Wire	Filler wire dia. (mm)	No. of pass	Voltage (V)	Current (A)	Shielding gas flow rate (l/min)	Heat Input (kJ/mm)
ERNiCrMo-4	2.4	Root	11.0	160	15	3.65
		Filling pass 1	13.0	150		
		Filling pass 2	13.0	150		
		Cap	13.5	150		
ERNiCrCoMo-1	2.4	Root	11.5	160	15	3.76
		Filling pass 1	12.5	150		
		Filling pass 2	13.5	150		
		Cap	13.0	150		

Macrostructure and microstructure studies were carried out on the weld coupons using Optical Microscopy (Om), line mapping analysis and SEM/EDAX point analysis in the composite regions (parent metal, HAZ and weld zone) having the dimensions of 30 x 10 x 5mm. Standard metallography procedure has been adopted i.e. coupons of weldments (composite region) were polished with different grit sizes of emery sheets from 200 to 2000 and followed by disk polishing to obtain mirror finish of 1 μ using alumina solution to determine the microstructure of these bimetallic joints. Revealing the microstructure is the challenging the task in the dissimilar weldments due to their difference in chemical compositions across the weldments. Microstructure was revealed by electrolytic etching process (10g of oxalic acid + 100ml of water– 6 V DC supply; current density of 1A/cm²). The line mapping was carried out on the electrolyte etched samples to determine the elemental variation across the weldments. Also EDS point analysis was carried out on the etched weld coupons to analyse the quantitative elemental profile.

From the microstructure studies the data obtained were used to correlate the precipitation of phases in heat affected zone and the results obtained are outlined in detail in the subsequent headings.

3. Results

3.1 Macro-structure examination

Figure 1(a & b) depict the cross-section macro-photographs of the bimetallic joints of Inconel 625 and AISI 904L employing continuous current GTA welding techniques using ERNiCrCoMo-1 and ERNiCrMo-4 fillers. It is inferred that the complete penetration was observed in both cases. Also it is well clear from the NDT results, the bimetallic joints were free from micro and macro level defects like lack of penetration, inclusions, porosities, voids, undercut etc.

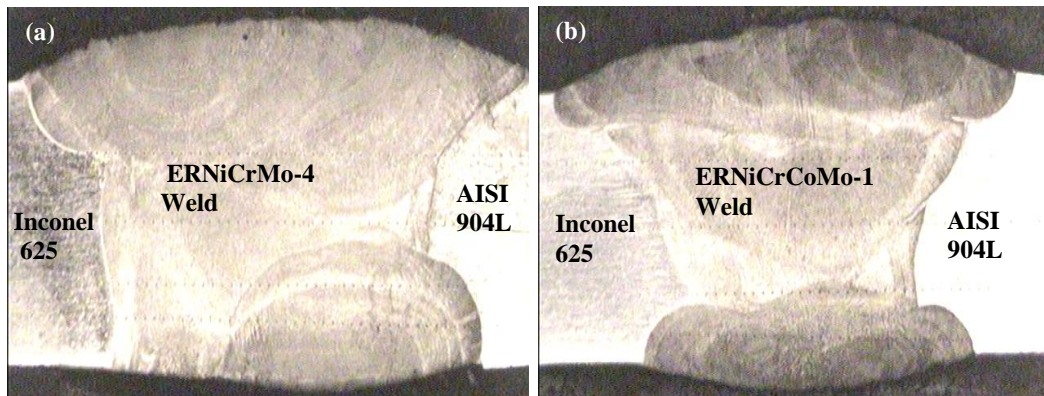


Figure 1. Macro-photographs of the bimetallic joints of Inconel 625 and AISI 904L employing (a) ERNiCrMo-4; (b) ERNiCrCoMo-1 fillers

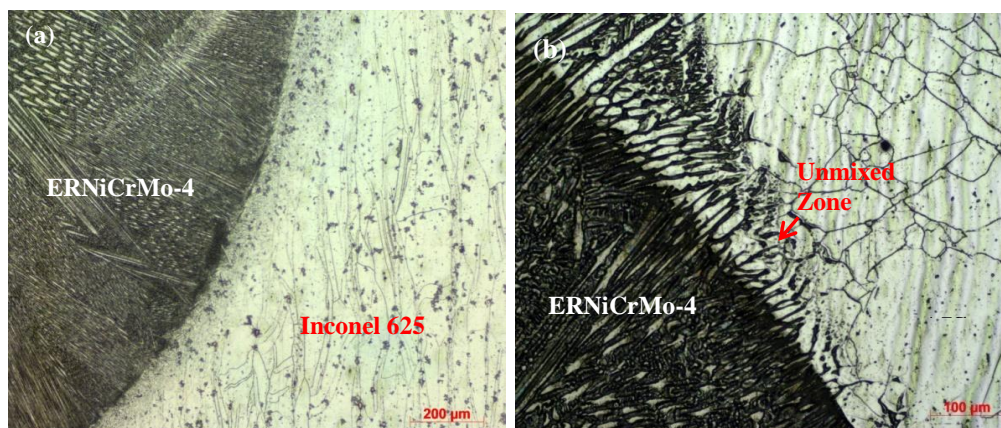
3.2 Micro-structure studies

3.2.1 CCGTA weldment employing ERNiCrMo-4 filler

Interfacial and fusion zone microstructures of the continuous current GTA weldments employing ERNiCrMo-4 filler are represented in Figure 2(a-c). In the HAZ of Inconel 625 side the grain coarsening effect was observed (Figure 2a), whereas in the AISI 904L side the secondary phases formation and the presence of unmixed zone were observed in the HAZ also it was evident from the Figure 2b. The weld microstructures were completely in austenitic phase along with multi-directional competitive growth has been observed in the weld microstructures, consisting of cellular, equi-axed and columnar dendrites (Figure 2c).

3.2.2 CCGTA weldment employing ERNiCrCoMo-1 filler

Interfacial and fusion zone microstructures of the CCGTA weldments employing ERNiCrCoMo-1 fillers are showed in Figure 3(a-c). Grain coarsening was observed in the interface of Inconel 625 (Figure 3a). The presence of unmixed zone has been seen at the HAZ of AISI 904L (Figure 3b). From the Figure 3c multi-directional grain growth (columnar, equi-axed, and cellular dendrites) was observed at the weld zone. The weld microstructures were completely in austenitic phase, also Solidification Grains (SGs) and Migrated Grains (MGs) were clearly observed at the fusion zone.



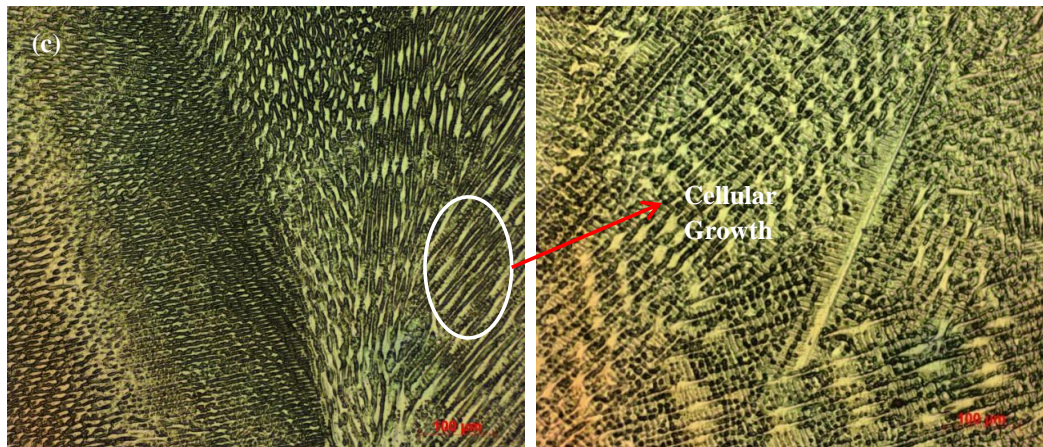


Figure 2. Microstructures of bimetallic joints of Inconel 625 and AISI 904L employing ERNiCrMo-4 filler (a) Interface of Inconel 625; (b) Interface of AISI 904L; (c) fusion zone

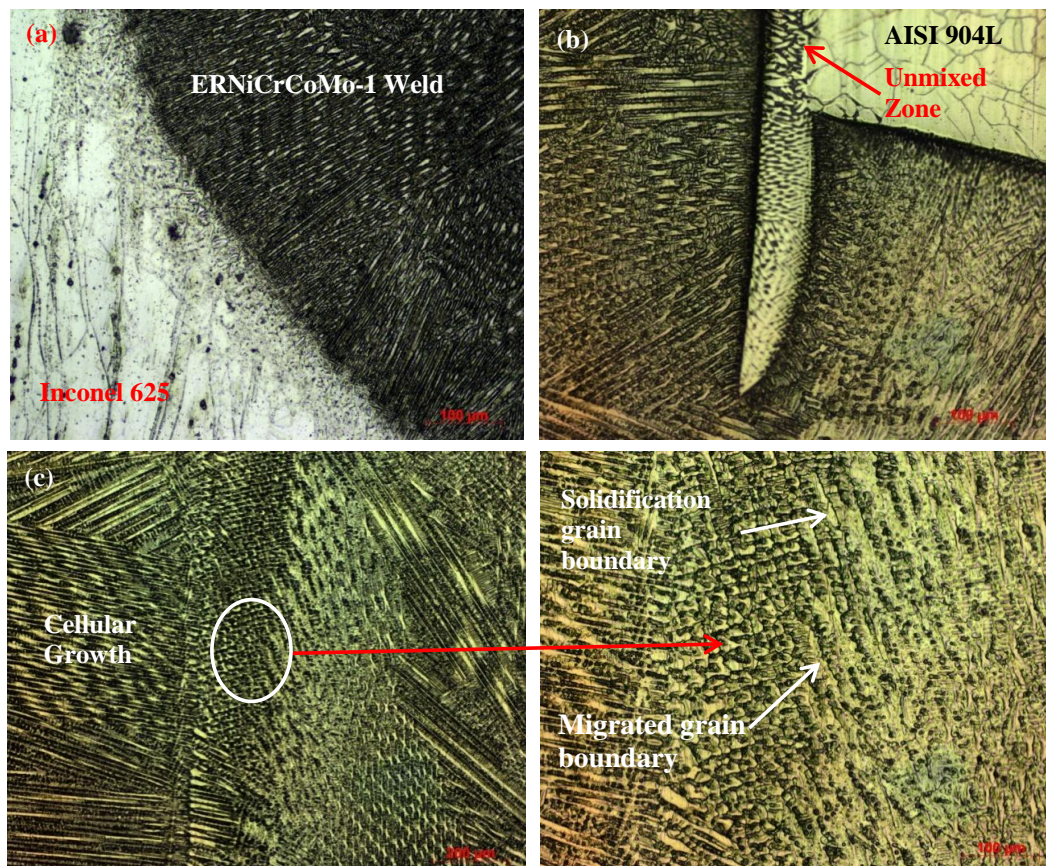


Figure 3. Microstructures of bimetallic joints of Inconel 625 and AISI 904L employing ERNiCrCoMo-1 filler (a) Interface of Inconel 625; (b) Interface of AISI 904L; (c) fusion zone

3.3 Line mapping analysis

Line mapping analysis were used to infer the elemental variation on the dissimilar weldments of continuous current GTA welding techniques of Inconel 625 and AISI 904L employing ERNiCrMo-4 and ERNiCrCoMo-1 fillers is represented in Figs. 4& 5.

3.3.1 CCGTA weldment employing ERNiCrMo-4 filler

From the Figure 4a, it was inferred that the movement of element Ni from Inconel 625 towards weld or vice-versa was almost nil due to the same chemical composition of Nickel percentage (Table-1). The enrichment of Mo along with tiny white phases has been observed in the weld interface of Inconel 625. Also the Cr movement was observed from the Inconel 625 to weld zone. Whereas Fe from the HAZ of AISI 904L has been moved towards the weld zone (Figure 4b) however Ni and Mo has migrated from the weld zone towards the HAZ of AISI 904L.

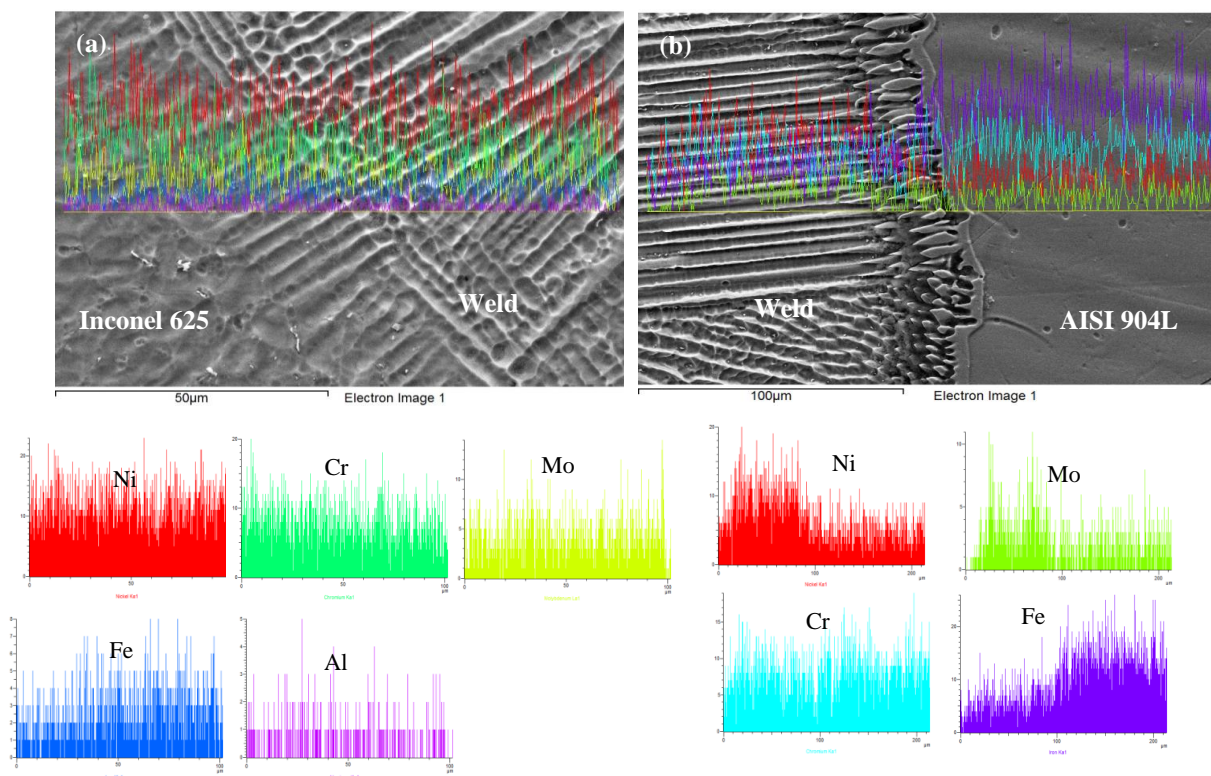


Figure 4. Line mapping ED SEM analysis of bimetallic joints of Inconel 625 and AISI 904L employing ERNiCrMo-4 filler (a) Interface of Inconel 625; (b) Interface of AISI 904L

3.3.2 CCGTA weldment employing ERNiCrCoMo-1 filler

Line mapping analysis of continuous current GTA weldments employing ERNiCrCoMo-1 filler is showed in Figure 5(a & b). The movement of element Ni from the Inconel 625 alloy to the fusion zone were observed; whereas the elements Fe and Co migrated from weld zone towards the HAZ of

Inconel 625 side (Figure 5a). Alongside the elements Ni, Mo and Co has moved from the fusion zone towards the HAZ of AISI 904L. From the HAZ of AISI 904L side element Fe migrated towards the weld zone (Figure 5b). The Cr enrichment has been observed in the weld interface of Inconel 625 and AISI 904L.

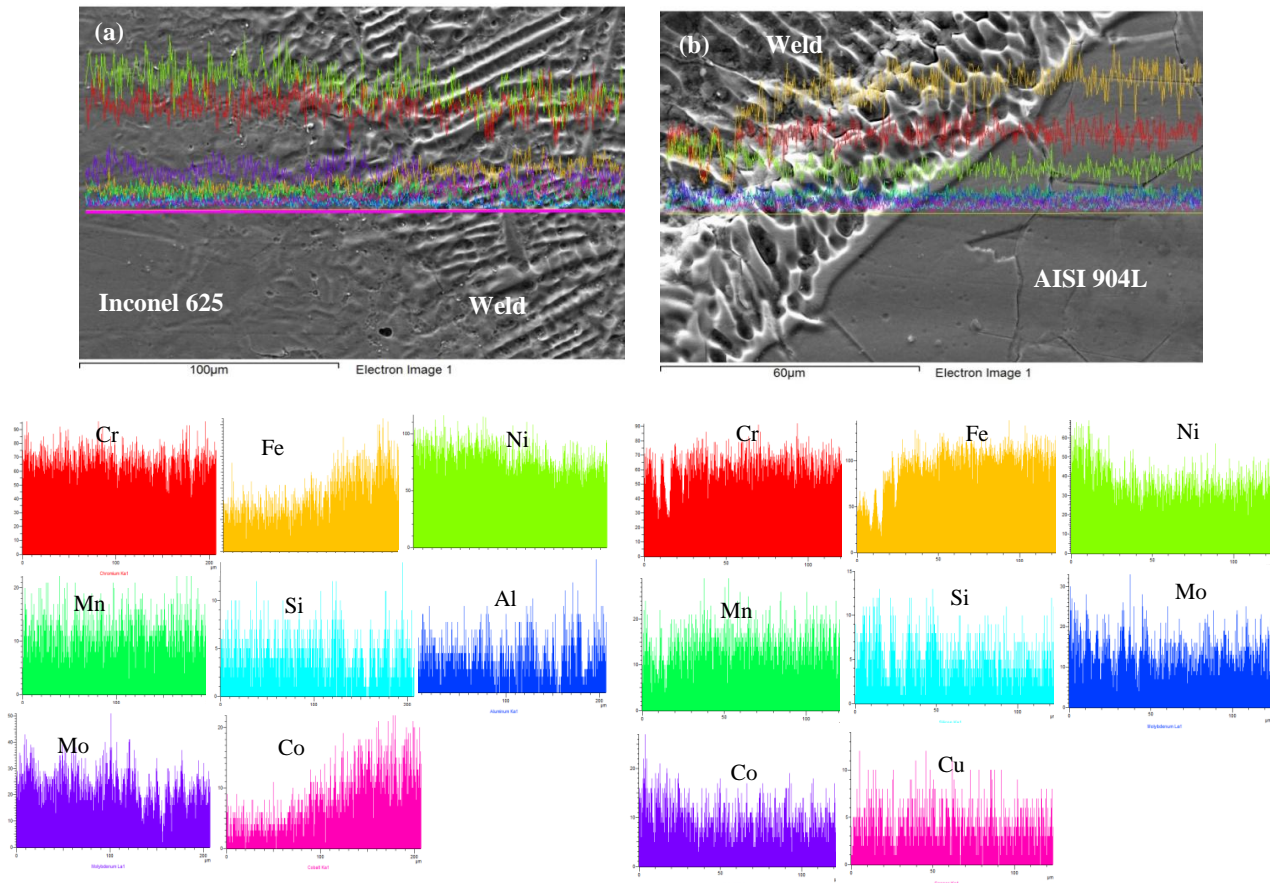


Figure 5. Line mapping ED SEM analysis of bimetallic joints of Inconel 625 and AISI 904L employing ERNiCrCoMo-1 filler (a) Interface of Inconel 625; (b) Interface of AISI 904L

3.4 SEM/EDAX analysis

SEM/EDAX point analysis was carried out on composite zones of the dissimilar weldments of Inconel 625 and AISI 904L employed by CCGTA welding technique using ERNiCrMo-4 and ERNiCrCoMo-1 fillers is represented in Figs. 6(a &b) and 7(a &b).

3.4.1 CCGTA weldment employing ERNiCrMo-4 filler

From the SEM/EDAX, it was observed that a tiny white secondary phases appearing at the interface of Inconel 625 due to the presence of rich Nb and Mo (Figure 6a). Also it was inferred that the strengthening elements such as Ni, W and Mo in the weld interface of the Inconel side contains more amount compared to the weld interface of AISI 904L (Figure 6b). Tiny white phases clustered in the matrix of the weld zone contains enriched amount of Mo.

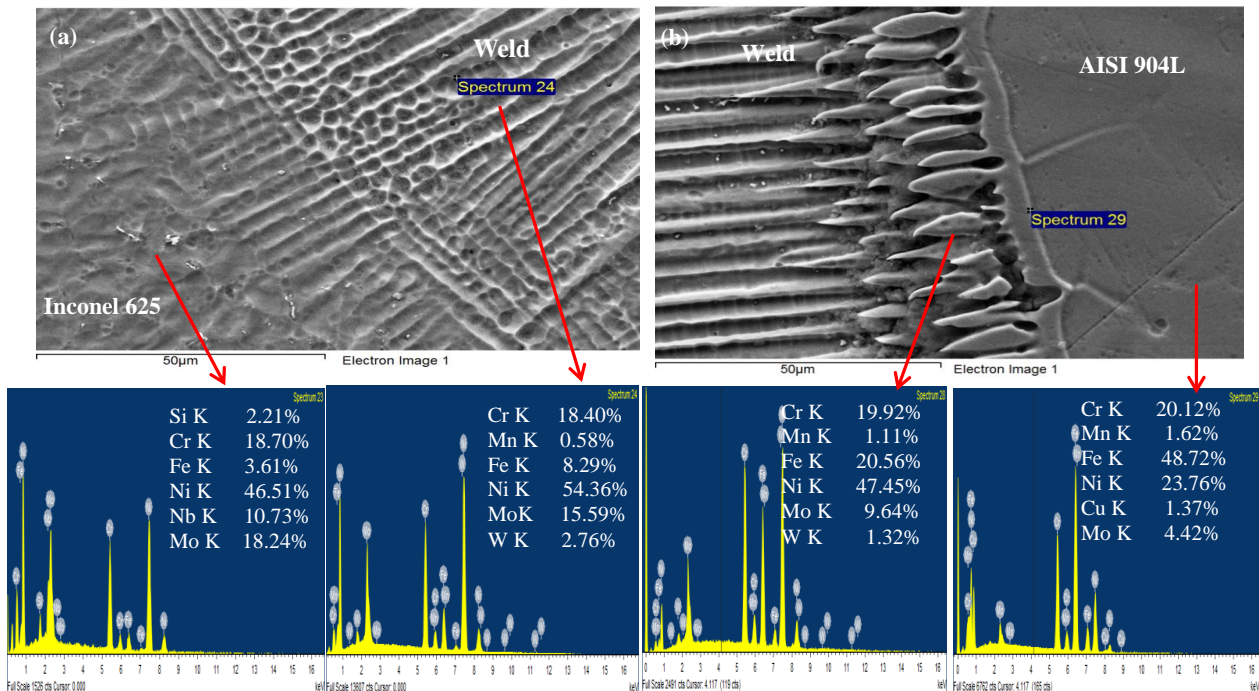


Figure 6. SEM-EDAX point analysis of bimetallic joints of Inconel 625 and AISI 904L employing ERNiCrMo-4 filler (a) Interface of Inconel 625; (b) Interface of AISI 904L

3.4.2 CCGTA weldment employing ERNiCrCoMo-1 filler

Figure 7a depicts the EDS point analysis on the ERNiCrCoMo-1 weldments, showed tiny white phases enriched with elements Nb and Mo in the HAZ of Inconel 625 alloy. The precipitates observed in the matrix of fusion zone consist of enriched amount of Ni, Cr, Mo, Ti and Nb. Nb- and Mo rich phases were predominantly found in the interface of Inconel side. At the interface of AISI 904L, strengthening elements such as Ni, Nb, Co and Mo has been enriched with substantial amount (Figure 7b).

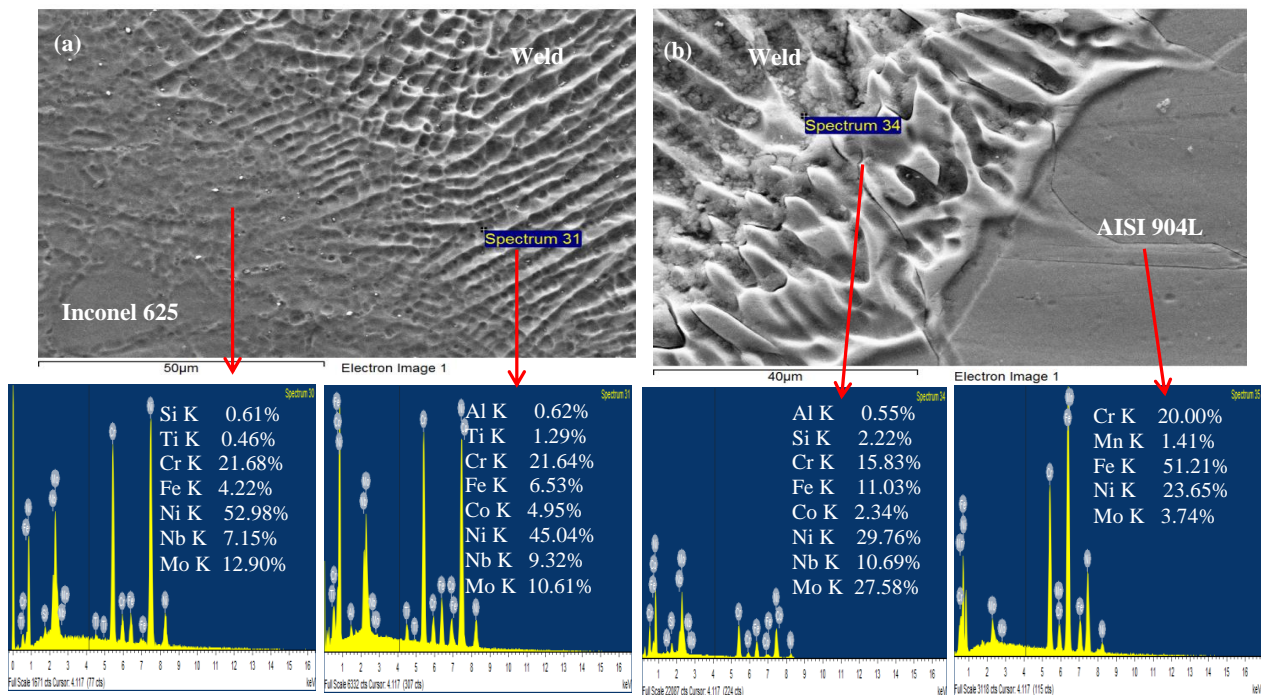


Figure 7. SEM-EDAX point analysis of bimetallic joints of Inconel 625 and AISI 904L employing ERNiCrCoMo-1 filler (a) Interface of Inconel 625; (b) Interface of AISI 904L

4. Discussion

The present study investigates the metallurgical properties on the bimetallic joints of Inconel 625 and AISI 904L using multi-pass continuous current GTA welding process employing ERNiCrMo-4 and ERNiCrCoMo-1 fillers. From the macro-photographs (Figure 1a & b) and the gamma ray NDT analysis, the results clearly corroborated that there is no any macro/micro level defects (porosity, undercuts, inclusions etc.) in welded joints. The filler metals were well compatible by showing proper fusion with both parent metals.

Interfacial microstructures of the Inconel 625 employed by both the fillers clearly exhibited the secondary phase formation at the HAZ (Figure 2a & 3a). Along with grain coarsening and segregation also been observed. The width of the segregated zone in the weld interface of Inconel 625 is meagre for ERNiCrMo-4 compared with ERNiCrCoMo-1 welds, might be due to the filler metal diluted properly with the base metals. These are predominantly more visible in the ERNiCrCoMo-1 weld (Figure-3a) due to the migration of carbon from the weld metal towards the side of Inconel base metal, due to the higher carbon percentage in the filler ERNiCrCoMo-1 than base metal as it is

evident from chemical composition analysis (Table 1). According to Mortezaie et al. [10] the migration of elements is inevitable during the welding process especially the migration of carbon. Due to high penetration rate of carbon in Ni, carbon easily diffuse from the weld metal into the Inconel 625 base metal during welding.

Due to the variances in chemical compositions and melting temperatures between the filler material and base metal of AISI 904L, the unmixed zone was found in the interface of AISI 904L (Figure-2b&3b). The unmixed zone width was observed to be more in ERNiCrMo-4 weld compared to ERNiCrCoMo-1 filler. During dissimilar welding, the base metal melts as small fraction if the filler metals melting range are greater than the base metal, results in the unmixed zone as stated by Sireesha et al. [11].

The weld zone employed with ERNiCrMo-4 filler shows the combination of equi-axed and cellular dendrite (Figure 3c). For ERNiCrCoMo-1 filler, Solidification Grains (SGs) and Migrated Grains (MGs) were clearly observed at the fusion zone (Figure 4c) with no solidification or liquation cracking. Due to the MGBs formation at the fusion zone, it was inferred that the complete austenitic phases were exists in the fusion zone. DuPont et al. [8] reported that welds employed by Ni rich filler leads to fully austenitic phase in weld zone, were the MGBs will usually occur and also in the multi-pass welding, during reheating also migration of the boundary is possible.

The movement of element Ni from Inconel 625 alloy towards fusion zone or vice-versa was minimal while employing ERNiCrMo-4 due to the same chemical composition of Nickel percentage in base metal and filler (Table 1) also it evident from (Figure 4a). Fe migration has been observed from the HAZ of AISI 904L side towards the fusion zone; alongside the elements Mo and Ni moved from the fusion zone towards the HAZ of AISI 904L (Figure 4b). From the Figure 5a, the movement of Nickel from the Inconel 625 alloy to the weld zone was observed while employing ERNiCrCoMo-1 due to the difference in chemical composition of Nickel percentage in base metal and filler. Whereas the elements Fe and Co migrated from weld zone towards the HAZ of Inconel 625 side. The movement of elements Ni, Mo and Co from the weld zone towards the HAZ of AISI 904L were observed. Alongside from the HAZ of AISI 904L side the element Fe migrated towards the fusion zone (Figure 5b).

A tiny white precipitates enriched with Nb and Mo was observed in the HAZ of Inconel 625 alloy while employing ERNiCrMo-4 filler, might be the formation of NbC and MoC (secondary phases) which was also evident from the SEM/EDAX. Also the strengthening elements such as Mo and W enrichment were also been observed in the interface of Inconel 625 (Figure 6b). In the ERNiCrCoMo-1 weld, enrichment of Mo, Ti and Nb as tiny white phases were observed in the HAZ of Inconel 625 side as well as in weld interface. These phases could be the precipitates of MoC, TiC and other Nb-rich eutectics (Figure 7a). Also enriched amount of Ni, Cr, Mo, Ti and Nb precipitates was observed in the matrix of fusion zone (Figure 7b). The constituents Mo and Cr were found to be more in the weld interface of AISI 904L irrespective of the fillers used (Figure 6b and 7b), might be the formation of Cr rich carbide ($M_{23}C_6$). These precipitates such as intermetallic phases and MC system carbides formed at 550–750°C deteriorates the mechanical properties [12].

From the present studies, it was evident that the process parameters selection and use of suitable filler wire ERNiCrMo-4 resulted in better metallurgical properties. Also from the microstructure studies it was witnessed that the deleterious phases were minimal on the HAZ of Inconel 625 side. The fusion zone of ERNiCrMo-4 was strengthened by a molybdenum, tungsten and niobium in its matrix. Solidification Grains (SGs) and Migrated Grains (MGs) were clearly observed at the fusion zone of ERNiCrCoMo-1. From the outcomes of the investigation, it is recommended to use ERNiCrMo-4 filler for joining the Inconel 625 and AISI 904L bimetallic joints as this technique showed better metallurgical properties.

The results revealed in this work will be really useful to the Original Equipment Manufacturers (OEM) operating with these bimetallic joints.

5. Conclusion

The present study investigates the microstructure and weldability of dissimilar welds between Inconel 625 and AISI 904L obtained by continuous current GTA welding techniques employing ERNiCrMo-4 and ERNiCrCoMo-1 fillers and there by following conclusions are summarized:

- (1) Successful and defect free dissimilar weldments of Inconel 625 and AISI 904L could be obtained by continuous current GTA welding employing these fillers.
- (2) Microstructure observation reveals the grain coarsening effect at the HAZ of Inconel 625 as well as Nb-rich secondary phases for the weldments employing ERNiCrCoMo-1: however while employing ERNiCrMo-4 filler these phases were found to be meagre.
- (3) Weld microstructures exhibited the MGB while employing ERNiCrCoMo-1 filler. Alongside the combination of equi-axed and cellular dendrite were observed in the weld metal microstructures employed by ERNiCrMo-4 filler wire.
- (4) Segregation was observed to be lower at the HAZ of AISI 904L while using ERNiCrMo-4 due to lower constituents of carbon whereas Mo- and Cr- rich carbide ($M_{23}C_6$) enriched in the HAZ of AISI 904L employing ERNiCrCoMo-1 filler.
- (5) Based on the present investigation on metallurgical property, for joining these bimetallic combinations employing ERNiCrMo-4 filler could be better compared to ERNiCrCoMo-1 filler.

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