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Comparative assessment on microstructure and mechanical properties of continuous and pulse-current GTA welds of AISI 304 and Monel 400

K. Devendranath Ramkumar*, N. Arivazhagan, S. Narayanan

School of Mechanical & Building Sciences, VIT University, Vellore, India

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Abstract

This study investigates the weldability, microstructure and mechanical properties of dissimilar AISI 304 and Monel 400 welds using continuous and pulse-current GTA welding processes. Dissimilar joints of AISI 304 and Monel 400 are widely used in the marine and offshore environments, oil and gasification plants. These welding processes are carried out using three filler wires, namely E309L, ENiCu-7 and ENiCrFe-3. Microstructure examination is carried out on these dissimilar weldments. In addition, a comparative analysis on the microhardness, tensile test values on these welds using the above-said filler materials is also discussed. The weldments obtained from ENiCu-7 and ENiCrFe-3 filler wires offer high strength and ductility. These studies would be useful for the fabricators implementing these dissimilar weldments in the offshore applications.

Key words: dissimilar metal welding, mechanical properties, Monel 400, AISI 304 stainless steel

1. Introduction

Welding of dissimilar metals is generally a challenging task because of the major problems encountered during welding. Due to the differences in the chemical composition and thermal expansion coefficients, the major problems likely to occur during welding would be dilution of weld metals, solidification cracking and hot cracking. The dissimilar combinations of Monel 400 and AISI 304 can be used in moderately high temperature and corrosive environments as in the case of oil gasification plants, chemical processing equipments, etc. In addition, a combination of moderate oxidation resistance and creep strength extends their application to steam generator tubing and other components operating at temperatures up to 550 °C in conventional fossil-fuel power plants [1, 2]. Pulse current gas tungsten arc welding (PCGTAW) is one of the widely used welding techniques that have been reported to have numerous advantages over the conventional gas tungsten arc welding (GTAW) or continuous current GTA welding (CCGTAW) process. The beneficial effects most often reported in the literature include claims that the total heat input to the weld is reduced, which results in the reduction of weld bead size, residual stresses by the reduction of heat input, thermal distortion, porosity and micro segregation [3, 4].

Current pulsing has been used in the past for obtaining grain refinement in weld fusion zone. Significant refinement of the solidification structure and a transition from columnar to equiaxed growth were reported in aluminium alloys by Madhusudhan Reddy et al. [5, 6], austentitic stainless steels by Ravivishnu [7], and tantalum by Grill [8]. Several investigators like Sundaresan et al., Janakiram et al., and Prasad Rao et al. [9–12] have used current pulsing to obtain grain refinement in weld fusion zones and improvement in weld mechanical properties.

In the pulse GTA welding process, welding current is a pulse between high and low levels of short or long time interval so that it brings the weld zone

*Corresponding author: tel.: +91-99409 98200; e-mail address: deva@vit.ac.in

to the melting point during the pulse current period and allows the molten weld pool to cool and solidify during the background current period. The weld bead shape will be a series of overlapping weld spots and the amount of overlap depends upon the pulse frequency and welding speed [13].

The critical issue to be addressed in case of dissimilar welds between Monel 400 and AISI 304 is the evaluation of proper filler materials. Weld defects such as micro-segregation, secondary phase formation and dilution cracks would be observed on improper selection of the welding process and filler material.

It was reported in the literature that the major and well known problem in dissimilar metal joint is the elemental migration near the fusion zone [1]. Also this elemental migration during welding severely affects the mechanical, metallurgical and corrosion properties of the dissimilar weldments [14].

The carbon migration between the weld and base metals is also one of the major concerns, which would cause the carbon denuded soft zone. This zone normally deteriorates the mechanical properties of the joint at elevated temperatures [15]. The possibility of catastrophic failure of the tubing system in fossil-fuel power plants is increased due to the formation of the carbon denuded soft zone. A carbon denuded soft zone was observed in the lower-chromium base metal adjacent to the weld interface while welding Cr-Mo weldments. The carbon migration is primarily driven by elemental differences, especially in chromium content, between the weld metal and base metal. It is also reported that nickel based filler cannot completely prohibit the formation of the soft zone, but it can greatly decrease the growth rate of the soft zone [16]. It was concluded that Ni based filler wire is widely used for dissimilar welding.

Ul-Hamid et al. [17] have addressed that carbon diffusion in the dissimilar joint between carbon steel pipe and type 304 stainless steel elbows resulted in cracking after a relatively short period of usage. Similarly, many researchers [18, 19] reported about the effect of carbon diffusion against strength and corrosion properties of the dissimilar weldment.

Dilution has been a major problem in the dissimilar weldments that have been applied for sheathing the offshore structures of corrosion-poor steels with corrosion resistant Ni-Cu/Cu-Ni alloys. Rudovskii [20] studied the dilution at the fusion boundary of austenitic stainless steel welded with ENiCu-7 filler wire. The author reported that Ni-Cu alloys comprised a perfectly isomorphous system, i.e., it showed perfect solubility. However, Fe and Cr are not completely soluble in the Ni-Cu alloy. Secondary phases such as precipitates and intermetallic compounds can be formed. Newcombe [21] also reported the formation of Fe-rich phase in the weld of Cu-Ni alloy and steel, which caused reduction in corrosion resistance. The as-solidified microstructure in the weld metal usually contains a segregation problem from the interface through the weld centre. The localized concentration zone in the Ni-Cu alloy existed as a form of coring in the dendrites. Galvanic corrosion and localized corrosion are predominant in welding stainless steel to Monel which is different in composition [22–24].

For such real welds, it is also important to consider the corrosion resistance of the consumables which forms the part of the fusion boundary region, where steep chemical and metallurgical changes would occur [20, 25]. The typical applications of the bimetallic welding of Monel-stainless steel and Monel-low carbon steel have been reported [1, 26]. These combinations were obtained by GTAW and SMAW fusion welding techniques, respectively. A comparative analysis was made on the electrodes such as ENiCu-7 and ENiCrFe-3 for welding Monel 400 and low carbon steel.

In recent past, investigations have been carried out on bimetallic welding of Monel-stainless steel and Monel-carbon steel by GTAW and SMAW fusion welding techniques through selecting appropriate filler metals. Bimetallic joints of Monel 400 and 316 SS, welded by orbital TIG welding with Inconel insert, were examined for application in Umbilical Interface Assembly for Space Station [26].

In another study, the combination of Monel 400 and low carbon steel [1] was welded by SMAW using ENiCu-7 and ENiCrFe-3 filler wires and it was characterized. Such dissimilar weldments are employed in the oil gasification plants. It is to be noted that these plants employ weldments exposed under corrosive medium of H_2S, SO_2 and SO_3. Also it was reported that the sound weld can be obtained using ENiCrFe-3 for welding Monel 400 and low carbon steel and the problem of sensitization could be minimized by using ENiCrFe-3 filler wire [2]. Earlier attempts were made by the authors on the weldability of Monel 400 and AISI 304 by CCGTA welding method utilizing E309L and ENiCu-7 filler metals [27].

From the extensive literature review, the information available on the weldability, structure-property relationships of CCGTA and PCGTA welded AISI 304 and Monel 400 is inadequate. This work reports on the possibility of welding AISI 304 and Monel 400 using CCGTA and PCGTA welding processes employing three different filler wires; also very limited work has been reported in joining of dissimilar metals using PCGTA welding technique, and hence this work assumes lot of importance. Further, the influence of filler wires on the mechanical and metallurgical properties of the weldments is characterized. The correlation between the microstructure and mechanical properties and corresponding fracture behaviour forms the goal of the study, and therefore assumes special focus on these weldments since such detailed studies are not hitherto reported.

Table 1. Chemical composition of filler materials

Base/filler metal	Composition (wt.%)									
	Ni	Cu	C	Si	Mn	Fe	S	P	Cr	Others
Monel 400	65.38	Bal	0.10	0.40	1.07	2.11	Nil	Nil	Nil	–
AISI 304	8.13	Nil	0.045	0.39	1.64	Bal	0.006	0.022	18.01	–
ENiCu-7	67.6	Bal	0.03	0.9	3.2	0.95	0.006	0.009	–	0.05 (Al) 0.65 (Ti)
E309L	12.6	–	0.035	0.53	1.58	61.76	0.021	0.024	Bal	Nil
ENiCrFe-3	61.2	0.5	0.05	0.8	5.5	10.5	0.015	0.03	Bal	0.8 (Al) 1.5 (Nb) 0.68 (Mo)

Table 2. GTAW process parameters (a), PC-GTAW process parameters (b)

(a)

Filler wire	V (V)	I (A)	Electrode ø (mm)	Argon gas pressure ψ	Filler wire ø (mm)
ENiCu-7	11.4	129	2.5–3	10–13	2.5
E309L	10	128	2.5–3	10–13	2.5
ENiCrFe-3	10	130	2.5–3	10–13	2.5

(b)

Filler wire	Peak current I_p (A)	Base current I_b (A)	Frequency (Hz)	Argon gas pressure ψ	Filler wire ø (mm)
ENiCu-7	215	125	30	10–13	2.5
E309L	215	125	30	10–13	2.5
ENiCrFe-3	215	125	30	10–13	2.5

2. Experimental procedure

2.1. Candidate metals and welding procedure

The candidate metals employed in the study are Monel 400 and AISI 304 having dimensions of $100 \times 50 \times 6$ mm^3. Filler materials used for welding these metals include E309L, ENiCu-7 and ENiCrFe-3, and their chemical composition is listed in Table 1. A special welding jig (rigid fixture) is designed and fabricated with a copper back plate so as to hold the parts in alignment and to ensure for accurate grip without bending during welding. Standard butt joint configuration (single V-groove having a root gap of 2 mm, size land of 1 mm and included angle of 35°) is selected for the current study. CCGTA and PCGTA weld parameters employed for welding these dissimilar metal combinations for all passes are mentioned in Table 2. These weldments were subjected to mechanical tests and are outlined in the following sections.

2.2. Characterization of weldment

The CCGTA and PCGTA weldments obtained from different filler materials were characterized initially for macrostructure studies to analyze the weld symmetry and penetration. Dissimilar weld combinations of AISI 304 and Monel 400 were examined for microstructure at various zones of the weldment using Carl Zeiss optical microscope by adopting standard metallographic procedures. Microstructures of parent metal and HAZ of Monel 400 were characterized using Marble's reagent and for parent metal and HAZ of AISI 304, electrolytic etching (10 % oxalic acid; 6 V DC supply; current density of 1 A cm^{-2}) was used. Weld regions were also examined using Marble's reagent for ENiCu-7, ENiCrFe-3 and electrolytic etching for E309L filler wire.

Further, micro-hardness evaluation was carried out across the width of the dissimilar welded samples covering all the regions of the weldment using Vickers micro-hardness tester. A standard load of 500 gf was applied for a dwell period of 10 s and the measurements were carried out at regular intervals of 0.25 mm. Also the samples were typically dimensioned to carry out the tensile tests as per ASTM E-8 standards using electronic tensometer with an accuracy of +1 %. Tensile trials were conducted on three samples for each weldment employing different filler wires. XRD analysis was carried out for both CCGTA and PCGTA welded dissimilar samples in the as-welded condition to reveal the phases. Further the fractured samples were characterized for SEM analysis to study the mode of fracture on the weldments.

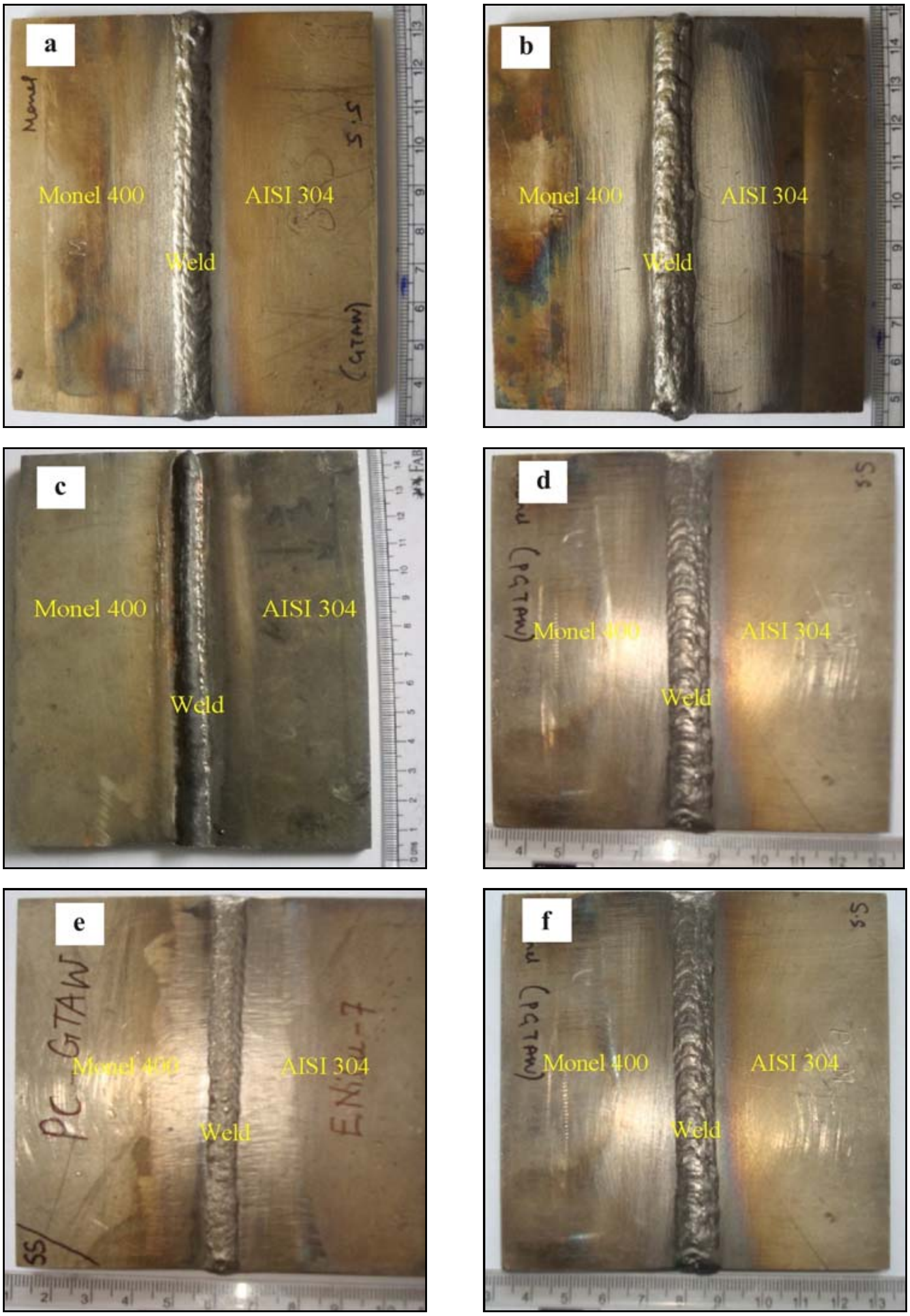

Fig. 1. Dissimilar welds of AISI 304 and Monel 400 using E309L(a), ENiCu-7 [27] (b), ENiCrFe-3 (c) by CCGTAW process and E309L (d), ENiCu-7 (e), ENiCrFe-3 (f) by PC-GTAW process.

3. Results

3.1. Macro and microstructure of the weldments

The GTA and PCGTA welded samples using the filler wires aforementioned are shown in Fig. 1. Also the macro-photographs shown in Fig. 2a,b of the GTAW and PCGTAW weldments exemplified that all the filler wires confirmed superior penetration to the base metals. For GTA welded dissimilar metals, it was observed that the weld zone was more uniform and spread equally along both sides of the candidate metals [27]. In particular, in case of E309L, the filler material was more diffused and spread maximum at AISI 304 side. On analyzing the root of ENiCu-7 welds, the diffusion of the filler wire was found to be uniform and spread equally along the candidate

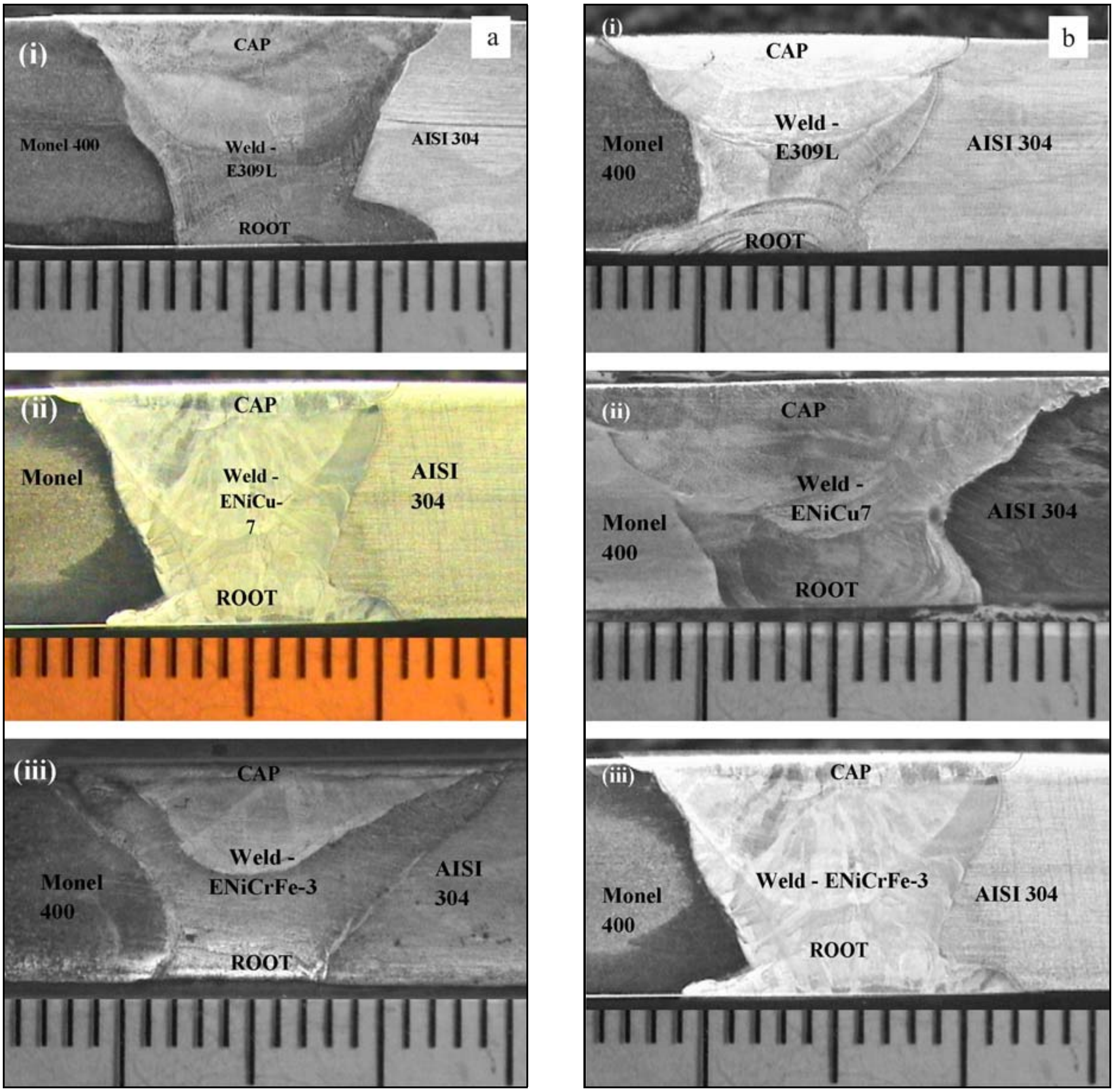

Fig. 2. Macro-photographs of the CCGTA welds of dissimilar AISI 304 and Monel 400 using (i) E309L (ii) ENiCu-7 and (iii) ENiCrFe-3 (a) and macro-photographs of the PCGTA welds of dissimilar AISI 304 and Monel 400 using (i) E309L (ii) ENiCu-7 and (iii) ENiCrFe-3 (b).

metals. In case of ENiCrFe-3 filler wire, the width of the root was narrower.

Furthermore, the PCGTA weldment with E309L filler showed better penetration towards Monel 400 side. Moreover, the width of the weld zone using ENiCu-7 filler, especially the cap region, was more as compared to other filler materials.

Microstructure studies (Figs. 3, 4) confirmed that the weld zone of dissimilar joints obtained by different filler wires was highly dendritic in nature for both CCGTAW and PCGTAW processes. The HAZ of the Monel 400 side was found to have coarse grains due to high temperature prevailing during GTAW. The partial liquation zone was also observed adjacent to the HAZ of Monel 400 for E309L and ENiCu-7 which might tend to lower the mechanical properties and also the corrosion resistance of this zone [28], whereas it was found in the meagre amounts for ENiCrFe-3. Moreover, the formation of secondary phases was witnessed in the HAZ of AISI 304 in all the GTA weldments. The precipitates of chromium carbides were also being revealed for GTA welds of E309L and ENiCu-7 and almost nil for ENiCrFe-3 filler material.

Similarly, the welds produced from PC-GTAW process also revealed that the partial liquation zone on the HAZ side of Monel 400 was very much minimized for all these filler wires. Segregation effects were not being found for E309L and ENiCrFe-3; however, there existed the secondary phases in the HAZ of AISI 304 for ENiCu-7 filler wire.

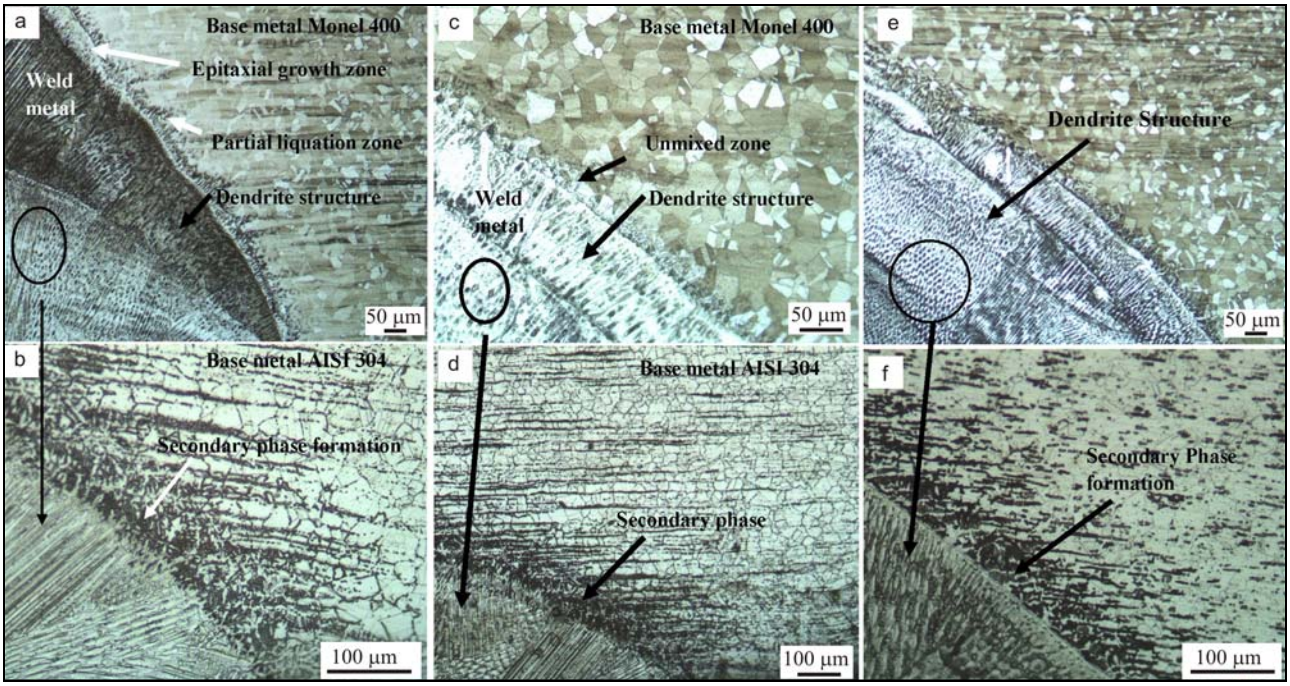

Fig. 3. Microstructures showing the CCGTA welds of dissimilar Monel 400 and AISI 304 using E309 L filler wire (a, b); ENiCu-7 filler wire (c, d) [27]; ENiCrFe-3 (e, f).

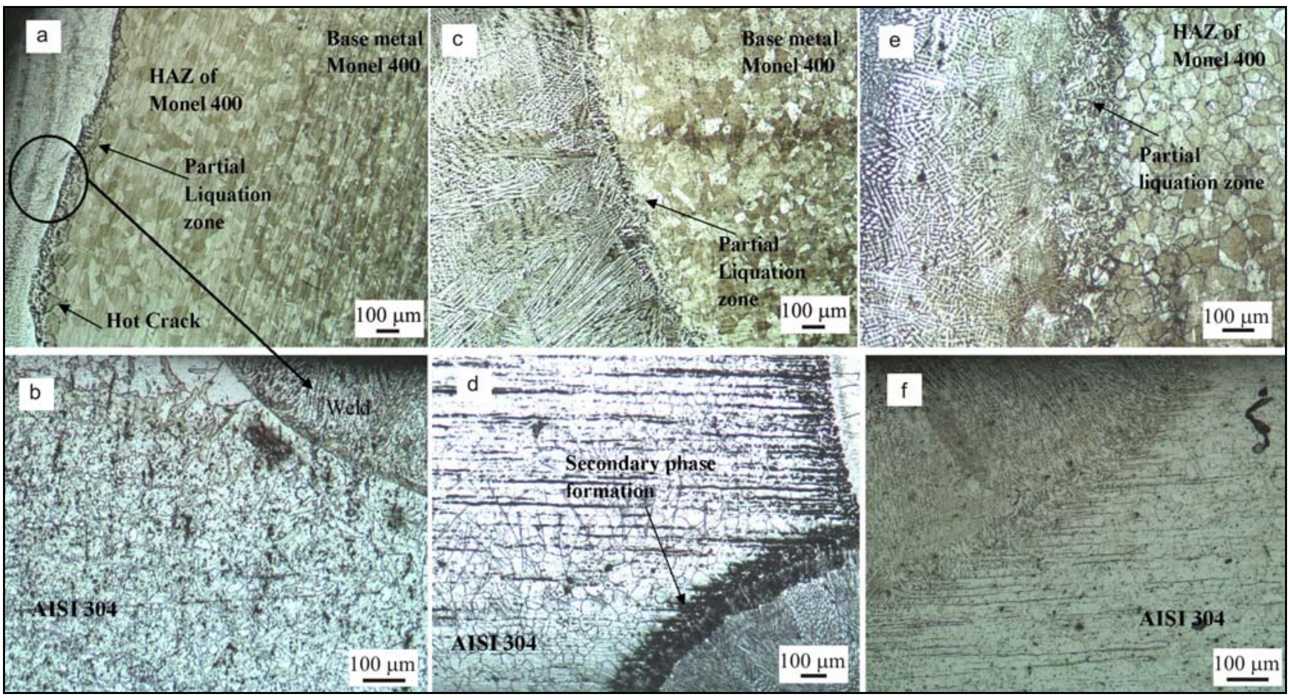

Fig. 4. Microstructures showing the PCGTA welds of dissimilar Monel 400 and AISI 304 using E309 L filler wire (a, b); ENiCu-7 filler wire (c, d); ENiCrFe-3 (e, f).

3.2. Hardness measurements

Micro-hardness measurements were carried out on the dissimilar weldments by keeping the weld centered as depicted in Fig. 5. From the hardness profile, it was evident that the average hardness was greater for ENiCrFe-3 as compared to ENiCu-7 and E309L filler materials. The weld region of E309L was found to have the peak hardness value as compared to HAZ sides. The hardness value of HAZ, weld region and

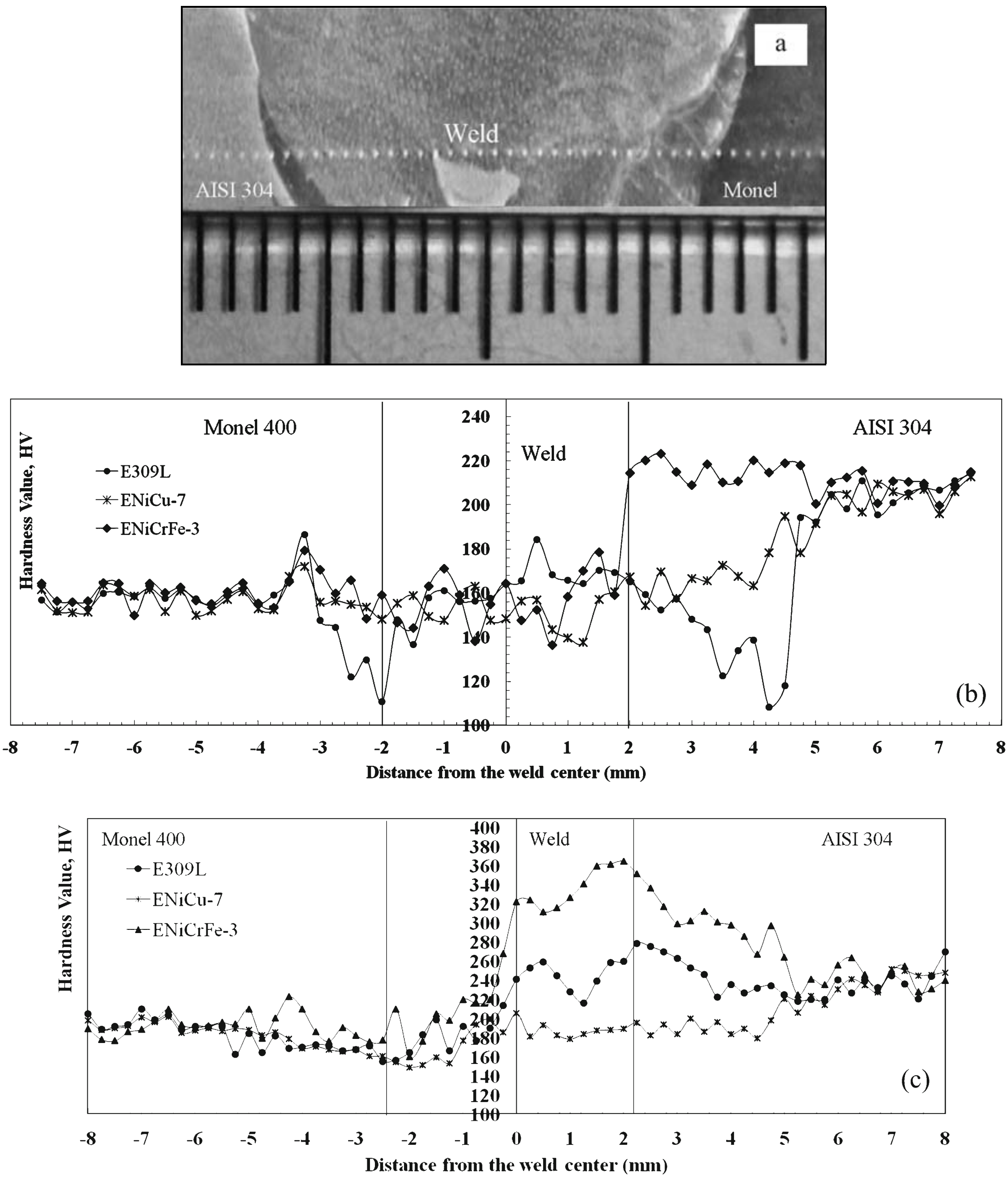

Fig. 5. Macrograph showing the hardness measurement across the entire length of the weldment (a); hardness profile of the CCGTAW dissimilar weld combinations of AISI 304 and Monel 400 (b) and hardness profile of the PCGTAW dissimilar weld combinations of AISI 304 and Monel 400 (c).

the base metal of Monel 400 witnessed for almost the same hardness value as in case of ENiCu-7; however, the HAZ, base metal side of AISI, possessed maximum hardness value [27]. On the other hand, the HAZ side of AISI 304 was found to possess higher hardness value as compared to HAZ of Monel 400 for ENiCrFe-3.

Further, the investigations on PCGTA welded samples showed that the hardness of the weld regions of E309L and ENiCrFe-3 was found to be higher as compared to ENiCu-7. This might be attributed due to the chromium carbide precipitation at the weld interface of AISI 304 side. However, the hardness trend of ENiCu-7 showed the steady values which were found to be almost the same in the parent, HAZ, and in the weld regions of Monel 400.

3.3. Tensile test

Tensile test trails were conducted on three samples of each weldment. Fractured samples showed that the CCGTA dissimilar welds produced by ENiCrFe-3 and ENiCu-7 filler wire exhibited the maximum tensile

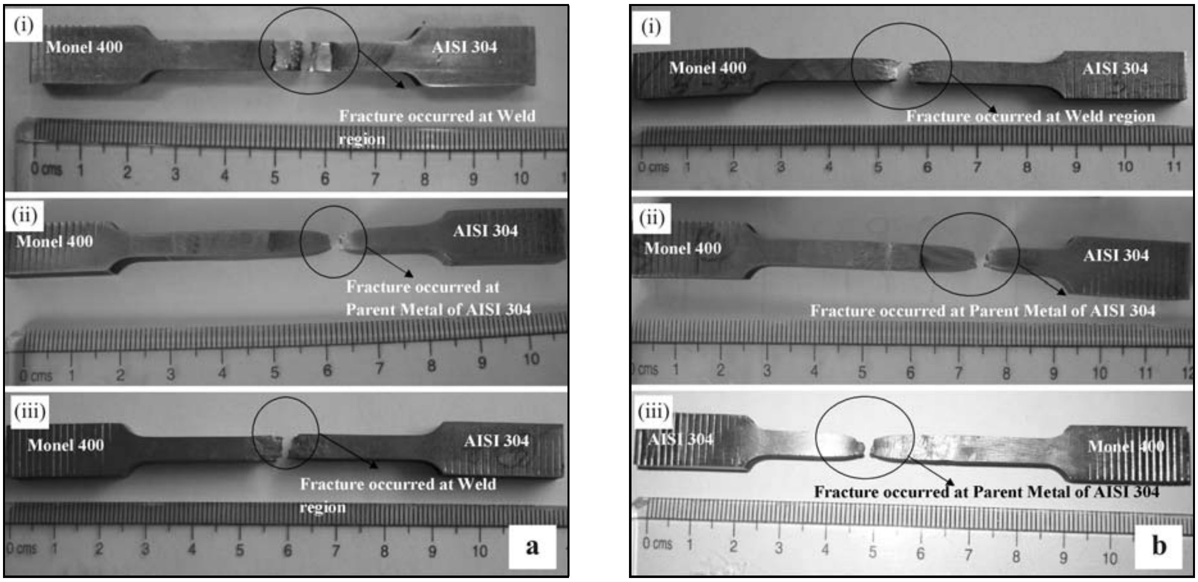

Fig. 6. (a) Fractured tensile samples of the CCGTA welds of AISI 304 and Monel 400 using E309L(i), ENiCu-7 [27] (ii), and ENiCrFe-3(iii) filler wires (a); fractured tensile samples of the PC-GTA welds of AISI 304 and Monel 400 using E309L (i), ENiCu-7 (ii), and ENiCrFe-3(iii) filler wires (b).

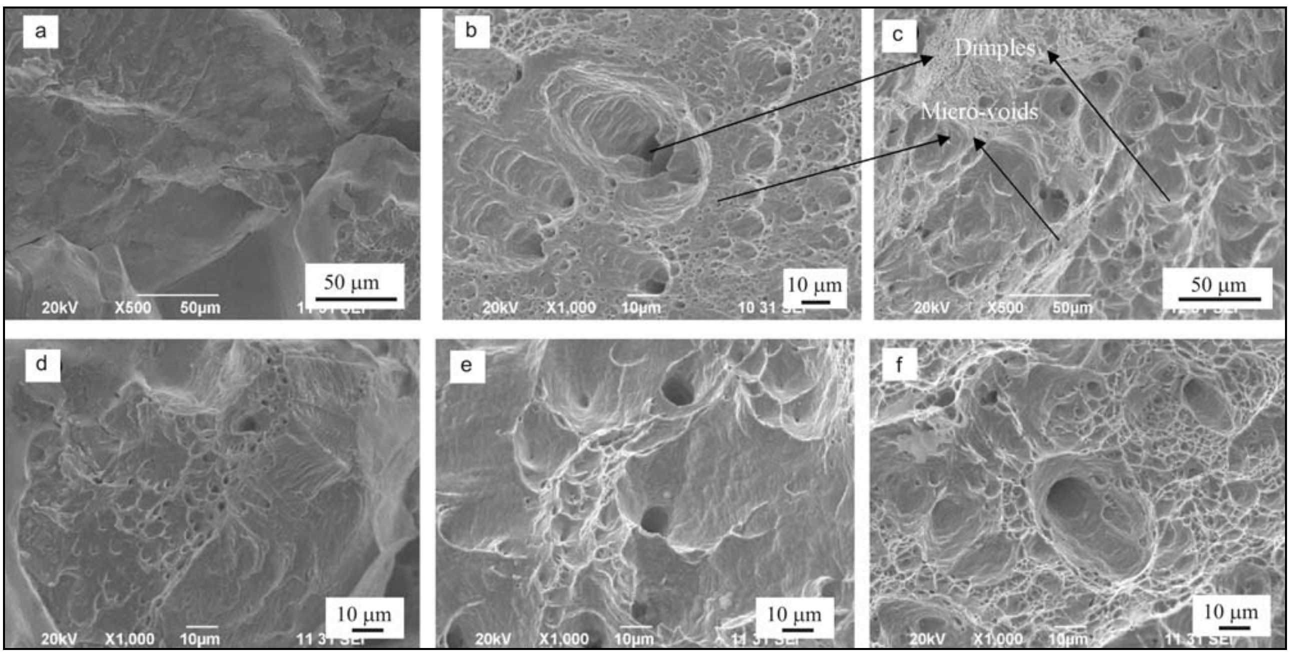

Fig. 7. SEM fractographs of the CCGTA welds of dissimilar Monel 400 & AISI 304 using E309L (a) ENiCu-7 [27] (b), ENiCrFe-3 (c) filler materials; SEM fractographs of the PCGTA welds using E309L(d), ENiCu-7 (e), and ENiCrFe-3 (f).

strength of 645 and 659 MPa, respectively, in contrast to E309L (245 MPa) [27]. The fracture was noticed at the parent metal side of AISI 304 for ENiCu-7 and at the weld region in case of E309L and ENiCrFe-3 (Fig. 6a).

On the other hand, tensile test trails on PC-GTAW samples showed that the tensile strength was found to be maximum for ENiCu-7 (551 MPa) and ENiCrFe-3 (537 MPa) as compared to E309L (225 MPa) filler material. The fracture occurred at the parent metal side of AISI 304 for both ENiCu-7 and ENiCrFe-3 whereas the weld region was fractured for E309L filler wire (Fig. 6b). In addition, the SEM fractographs confirmed the contribution of microvoids and dimples in a fibrous network and in turn coalesced to undergo ductile fracture for GTA as well as PCGTA welded samples using ENiCu-7 and ENiCrFe-3 filler materials (Fig. 7). E309L contributed for the brittle fracture

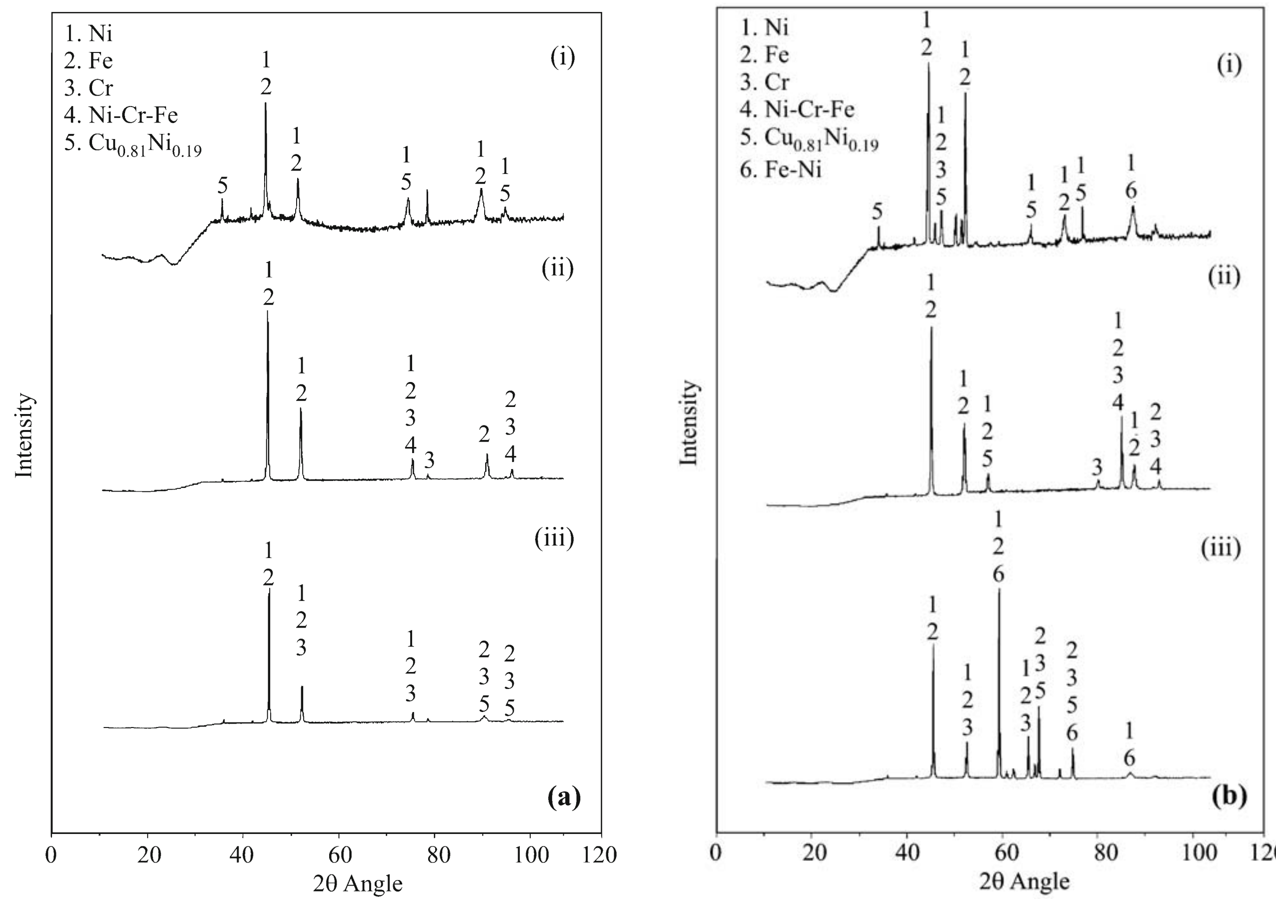

Fig. 8. XRD analysis of CCGTA weldments employing E309L (i) ENiCu-7 (ii) and ENiCrFe-3 (iii) filler wires in the as-welded condition (a) and XRD analysis of PCGTA weldments employing E309L (i) ENiCu-7 (ii) and ENiCrFe-3 (iii) filler wires in the as-welded condition (b).

on both the weldments which could be confirmed by the presence of radiating tearing edges and with very small amount of micro-voids.

3.4. X-ray diffraction analysis

X-ray diffraction analysis was carried out on the CCGTA and PCGTA weldments in the as-welded conditions, and the results are shown in Fig. 8. The intensity of the peaks Ni, Cu, Fe, Cr and $Cu_{0.81}Ni_{0.19}$ was observed for E309L and ENiCrFe-3 filler wires, and of the peaks Ni, Fe, Cr and $Cu_{0.81}Ni_{0.19}$ for ENiCu-7 filler wire.

4. Discussion

Satisfactory joints of dissimilar AISI 304 and Monel 400 can be obtained from CCGTA as well as PCGTA welding processes using E309L, ENiCu-7 and ENiCrFe-3 filler materials (Figs. 1, 2). The weldability and room temperature mechanical properties are good for the joints made from these welding processes. The welding aspects of AISI 304 and Monel 400 using E309L and ENiCu-7 were already discussed by the authors in their earlier research work [27].

In general, it is always difficult to examine the microstructure of the dissimilar joints as the preparation is cumbersome. Specific metallographic procedures and greater attention has been adopted for the current study that includes polishing with emery sheets and disc polishing and followed with ultrasonic cleaning. The microstructure of the weld interface significantly differs from the weld region. There is a prominent white layer termed as the unmixed zone that exists at the Monel 400 side in case of E309L and ENiCu-7 weldments, whereas the unmixed zone is found to be available only in fewer regions for ENiCrFe-3. This is attributed to the improper dilution of the filler metal (Fig. 3). Secondary phases such as $M_{23}C_6$ carbides, Fe-Cr and Ni-Cu-Fe could probably be available in these dissimilar weldments, which is evident from the microstructure and XRD analysis (Fig. 8a,b).The secondary phase formation was also observed at the weld interface for all the filler wires as in case of CCGTA welded samples. However, this secondary phase formation is slightly higher for E309L weldments as compared to ENiCu-7 and ENiCrFe-3.

Table 3. Cumulative mechanical properties of GTA welded dissimilar AISI 304 and Monel 400

Welding	Filler wire	Maximum hardness at weld, HV	Ultimate tensile strength (MPa)	Elongation (%)	Fracture zone (remarks)
GTAW	E309L	184	245	5	Weld region
	ENiCu-7	170	659	26	Base metal of AISI 304
	ENiCrFe-3	215	642.5	17.5	Weld region
PCGTAW	E309L	260	225	10	Weld region
	ENiCu-7	206	551	27	Base metal of AISI 304
	ENiCrFe-3	365	537	27	Base metal of AISI 304

The formation of the secondary phases may degrade the mechanical properties and also the corrosion resistance of the weldments [20, 21]. The welding filler wires of ENiCu-7 and ENiCrFe-3 could readily take into the solution of nickel, copper, chromium and iron to the level likely to be encountered in practice by dilution from parent metals. The weld region, therefore, will have the normal dendritic structure of single phase material, for both filler materials [1]. Also the chromium carbide precipitation is generally observed for E309L and ENiCrFe-3 filler materials, which could contribute for slight improvement in the mechanical properties with the corresponding drop in the ductility and strength [1].

On the other hand, the unmixed zone (white layer formation) is found to be in meagre amounts for all the filler wires employed for PCGTA weldments. However, the hot cracking tendency is more for E309L, which can be witnessed from Fig. 4. The hot cracking tendency is observed for both GTA and PCGTA weldments of these dissimilar weldments on employing E309L filler wire, because the dilution of Ni based alloy by a dissimilar metal can be tolerated to certain extent. When the filler wire of E309L is used to weld Monel 400 and AISI 304, any significant amount of Cu pick up from Monel 400 causes the weld metal to induce hot cracking tendency [28].

The presence of niobium content in ENiCrFe-3 and Al, Ti additions in ENiCu-7 may contribute for the better hot cracking resistance as compared to E309L filler wires. The cumulative mechanical property evaluations are highlighted in Table 3. The hardness profiles of the weldments shown in Fig. 5a,b are so compatible and matching well with the earlier findings by other researchers [1]. The average hardness of ENiCrFe-3 weldment is greater than that of ENiCu-7 and E309L filler wires. The weld region of E309L possesses maximum hardness as compared to HAZ region which can be due to the enrichment of this zone with C and Cr. It is also reported that the carbon denuded soft zone which is observed in the lower chromium base metal adjacent to weld interface tends to deteriorate the mechanical properties at elevated temperatures [15]. Since the activity of diffusion of carbon in high nickel alloy is normally slow, the micro-hardness of the soft zone is greatly decreased while using ENiCu-7 and ENiCrFe-3. Also the inclusions of Al, Ti, Mn, Nb, and Mo in the filler metals impart additional strength and also exhibit reasonable elevated temperature strength up to 650 °C. The solidification temperature range has a direct correlation to the solidification cracking susceptibility of a given alloy. Increased levels of Fe, Cr, Cu, and Si in nickel-based weld metal results in increased solidification temperature ranges and ensures for minimal dilution [29]. This is witnessed on using ENiCu-7 and ENiCrFe-3 while welding the dissimilar AISI 304 and Monel 400.

Tensile results show both CCGTAW and PCGTAW offer good tensile strength. It is evident that PCGTA welding normally yields refined grains at the weld region and the HAZ. This is well identified and proved from the hardness profile shown in Fig. 5b. Also, for PCGTA weldments, the failure occurred at the parent metal of AISI 304. It is confirmed that the weld strength of the PCGTA weldments is higher or equal to the candidate materials employed.

The degree of ductility and strength is found to be more for the weldments utilizing ENiCu-7 and ENiCrFe-3, which is also evident from the formation of large dimples and micro-voids present in the weldments. Furthermore, the fractographs of tensile test specimens of E309L weld joints show that relatively minor sized dimples and high quantity of tearing ridge show brittle nature. In addition, the failure in the fusion boundary of the E309 L weld joint is primarily due to the compositional dilution in the weld metal as reported by Rudovskii et al. [20]. It is further confirmed that the segregation/secondary phase formation in the weld interface reduces the tensile strength which is evident from the microstructure.

Also it is known that Ni and Cu in the ENiCu-7 filler wire are completely soluble in each other thereby forming the iso-morphous system. The presence of copper strengthens the nickel to certain limited extent. Because of the high nickel content, a complete fcc structure would be formed in the weld region. The presence of Al and Ti in the ENiCu-7 filler wire also contributes to the strength by precipitation hardening.

The strengthening precipitates would be the Ni_3Al and Ni_3Ti. These precipitates tend to occupy the grain boundaries and exhibit strength. Hence, during plastic deformation, minor dimples were formed in the weldments employing ENiCu-7 filler wire. In case of E309L, the presence of Ni is relatively low as compared to other filler wires. This might be one of the probable causes for the occurrence of failure in E309L weldments [27]. In case of ENiCrFe-3 weldments, the chromium readily reacts with carbon to form chromium carbides in addition to the nickel content which imparts additional strength with a compensation of ductility during CCGTA welding process. The major contributions of this research work clearly report that the dissimilar combinations of AISI 304 and Monel 400 could be achieved by CCGTA and PCGTA welding techniques. Pulse-current GTA welding could be employed for joining these dissimilar metals of 6 mm thickness. Since the finer grains are observed in the HAZ regions of the weldment for PCGTA welding technique, it would be offering better mechanical properties as compared to CCGTA weldments. The filler metal's choice and the influence on the mechanical properties assume lot of significance and are helpful to the fabricators employing these weldments.

5. Conclusions

This paper reports the successful welding of AISI 304 with Monel 400 using E309L, ENiCu-7 and ENiCrFe-3 filler wires by continuous and pulse-current GTA welding processes. The major conclusions arrived in the present study are listed below:

Weldments obtained by the filler materials such as ENiCu-7 and ENiCrFe-3 by both welding processes exhibit satisfactory mechanical properties.

(a) Micro-segregation and secondary phase formation are greatly minimized on employing PCGTA welding for these dissimilar combinations.

(b) Carbon denuded soft zone can be minimized by using high content of Ni based consumables such as ENiCu-7 and ENiCrFe-3.

(c) Hot cracking tendency would be observed while welding AISI 304 and Monel 400 using E309L filler wire for both the welding procedures.

(d) Hardness is found maximum at the weld interface of the PCGTA weldments which contributed to higher tensile strength.

(e) The strength and ductility of GTA and pulse current CCGTA welds using ENiCu-7 and ENiCrFe-3 are comparable to those of AISI 304/Monel 400 base metals. The tensile strength properties of dissimilar metal welds using ENiCu-7 and ENiCrFe-3 filler wires are better than E309L weldment.

(f) Fracture is observed at the parent metal of AISI 304 for the PCGTA weldments employing ENiCu-7 and ENiCrFe-3 which gives a clear indication that the strength of the weld is much higher as compared to the base metals employed.

(g) Both ENiCu-7 and ENiCrFe-3 welds are found to be less reactive as the enrichment of Ni in the weld zone has reduced the soft zones. This in turn has improved the mechanical properties.

(h) It can be concluded that the hardness trend is such that $W_{\text{ENiCrFe-3}} > W_{\text{ENiCu-7}} > W_{\text{E309L}}$.

(i) Higher Ni, Cr, Fe and C content leads to detrimental role in the mechanical properties.

(j) It is highly recommended to use GTA as well as PCGTA welding techniques employing the filler wires ENiCu-7 and ENiCrFe-3 owing to their better mechanical properties.

(k) E309L is not suitable for welding AISI 304 and Monel 400 by both welding techniques.

(l) Since PCGTA weldments produce refined grains, it may not be suitable for hot corrosion environments, and in those zones GTA weldments are usually recommended.

References

[1] Alber Sadek, A., Mahmoud, A., Zaghloul, B., Elrefaey, A., Ushio, M.: Trans. JWRI, *29*, 2000, p. 21.

[2] Lee, H. T., Jeng, S. L., Yen, C. H., Kuo, T. Y.: Journal of Nuclear Materials, *335*, 2004, p. 59. doi:10.1016/j.jnucmat.2004.06.004

[3] Kim, Y. H., Frankel, G. S., Lippold, J. C., Guaytima, G.: Corrosion, *62*, 2006, p. 44. doi:10.5006/1.3278251

[4] Traidia, A., Roge, F., Chidley, A., Schroeder, J., Marlaud, T.: World Academy of Science, Engineering and Technology, issue 51, 2011, p. 73.

[5] Madhusudhan Reddy, G., Gokhale, A. A., Prasad Rao, K.: Journal of Material Science, *32*, 1997, p. 4117. doi:10.1023/A:1018662126268

[6] Madhusudhan Reddy, G., Gokhale, A. A., Prasad Rao, K.: Journal of Material Science and Technology, *14*, 1998, p. 61. doi:10.1179/mst.1998.14.1.61

[7] Ravi Vishnu, P.: Welding in the World, *35*, 1995, p. 214.

[8] Grill, A.: Metallurgical and Materials Transactions B, *12*, 1981, p. 667. doi:10.1007/BF02654135

[9] Janaki Ram, G. D., Venugopal, R., Prasad Rao, K., Madhusudhan Reddy, G., Sambasiva Rao, A.: Trans. Indian Inst. Met, *59*, 2006, p. 85.

[10] Sundaresan, S., Janaki Ram, G. D., Madhusudhan Reddy, G.: Material Science and Engineering A, *262*, 1999, p. 88. doi:10.1016/S0921-5093(98)01010-7

[11] Sundaresan, S., Janaki Ram, G. D.: Science and Technology of Welding and Joining, *4*, 1999, p. 151. doi:10.1179/136217199101537699

[12] Prasad Rao, K.: In: Proceedings of Recent Advances in Materials Processing Technology (RAMP 2001). Chidambaram, Annamalai University 2001, p. 176.

[13] Giridharan, P. K., Murugan, N.: Int J Adv Manuf Technol, *40*, 2009, p. 478. doi:10.1007/s00170-008-1373-0

[14] Arivazhagan, N., Surendra, S., Satya, P., Reddy, G. M.: Materials and Design, *32*, 2011, p. 3036. doi:10.1016/j.matdes.2011.01.037
[15] Lundin, C. D., Khan, K. K., Yang, D.: WRC Bulletin, *407*, 1996, p. 1.
[16] Yuh-Ying, Y., Ren-Kae, S., Chun, C.: Journal of Materials Science Letters, *20*, 2001, p. 1429. doi:10.1023/A:1011616232396
[17] Ul-Hamid, A., Tawancy, H. M., Abbas, N. M.: Eng Fail Anal, *12*, 2005, p. 181. doi:10.1016/j.engfailanal.2004.07.003
[18] Lee, H. Y., Lee, S. H., Kim, J. B., Lee, J. H.: Int. J Fatigue, *29*, 2007, p. 1868. doi:10.1016/j.ijfatigue.2007.02.009
[19] Arivazhagan, N., Narayanan, S., Surendra, S., Satya, P., Reddy, G. M.: Materials and Design, *34*, 2012, p. 459. doi:10.1016/j.matdes.2011.08.034
[20] Rudovskii, Y. A., Leleko, L. N., Timofeeva, E. Y.: Welding Production, *31*, 1984, p. 44.
[21] Newcombe, G.: Welding and Metal Fabrication, *42*, 1974, p. 379.
[22] Zumelzu, E., Cabezas, C.: Journal of Materials Processing Technology, *57*, 1996, p. 249. doi:10.1016/0924-0136(95)02073-X
[23] Campbell, S. A., Radford, G. J. W., Tuck, C. D. S., Barker, B. D.: Corrosion, *58*, 2002, p. 57. doi:10.5006/1.3277305
[24] Scully, J. R., Hack, H. P.: Galvanic Corrosion. ASTM STP 978. Philadelphia, ASTM 1988.
[25] Nelson, T. W., Lippold, J. C., Mills, M. J.: Science and Technology of Welding and Joining, *13*, 1998, p. 249. doi:10.1179/stw.1998.3.5.249
[26] Figert, J., Rybicki, D.: NASA M&P Update Newsletter, *2*, 1998, p. 8.
[27] Devendranath Ramkumar, K., Arivazhagan, N., Narayanan, S.: Materials & Design, *40*, 2012, p. 70. doi:10.1016/j.matdes.2012.03.024
[28] Joseph R. Davis (ed.): Nickel, Cobalt and their Alloys. Materials Park, OH, ASM International 2000. http://doi.wiley.com/10.1002/9780470277270.ch24
[29] Cortial, F., Corrieu, J., Vernot-Loier, C.: Metallurgical and Materials Transactions A, *26*, 1995, p. 1273.