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Original Article

Effect of filler wires on mechanical properties of super-duplex stainless steel UNS S32750 and austenitic stainless steel 304 dissimilar joints welded with PCGTAW technique

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Abstract

This study addresses the effects of fillers (ERNiCrMo-3, ERNiCrMo-4 and ER309L) for joining 5 mm dissimilar metals of super-duplex steel (UNS S32750) and austenitic stainless steel (AISI 304) by using pulsed current gas tungsten arc welding. Welding parameters were fixed across all cases with the three alternative filler wires. Mechanical properties of weldments were evaluated by conducting impact, tensile and microhardness tests. Microstructural changes were studied by optical microscopy. The ratio of proof stress to ultimate tensile strength, and the ultimate tensile strength were found to be higher with ERNiCrMo-4 (0.6, 642 MPa) filler weldment than with ERNiCrMo-3 (0.57, 624 MPa) or ER309L (0.56, 612 MPa) filler weldments. Microhardness of the weldment with ERNiCrMo-4 filler was higher than with the other two fillers. It was observed from the impact test results that the ERNiCrMo-4 filler weldment exhibited superior toughness of 189 J.

Keywords: super-duplex stainless steel, austenitic stainless steel, PCGTAW technique, mechanical properties, microstructural studies

1. Introduction

Super-Duplex Stainless Steel (SDSS) use in critical structural applications, such as submarines and natural gas pipelines, is increasing and replacing other materials that were used owing to their high mechanical strength and corrosion resistance. The combined mechanical and corrosion resistance properties have been attributed to the presence of ferrite (α) and austenite (γ) phases in equal proportions (Lippold & Damian, 2005). UNS S32750 duplex stainless steel is also known to have comparatively high pitting resistance among stainless steels. The austenite stainless steels were mainly used in many industrial applications as a substitute of structural steel when corrosion resistance at elevated temperatures was required. AISI 304 austenitic stainless steels has applications in petroleum, gas and nuclear industries, where high corrosion resistance is required at high temperatures (Lippold, Dupont, & Kiser, 2009). Similarities in utilization of austenitic and super duplex stainless steels are due to their corrosion resistance and mechanical properties, and this has gained major attention in the industries. Joining dissimilar stainless steels is most challenging as regards producing quality weld structures, and the challenges are overcome by selecting suitable filler materials and welding techniques (Yelamasetti *et al*., 2020). Some of the problems encountered are related to the weld quality, especially solidification cracks near the weld zone while joining austenitic dissimilar metals. Formation of phase structures with desired metallurgical properties depends on filler wire, which improves fatigue and corrosion resistances (Balram *et al*., 2019). The composition of filler and its essential alloying elements affects the development of new phases in the fusion zone, the micro-segregation of elements, the changes in microstructure, and hence the quality of the welded structures (Yelamasetti & Rajyalakshmi, 2020).

Devendranath *et al*., (2014) developed dissimilar joint weld of SDSS UNS S32750 and AISI316L by using two different fillers namely, ERNiCrMo-3 and ER2553. The same portions of austenite and ferrite phases with an improvement in hardness at the fusion zone were observed when Pulsed

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Current Gas Tungsten Arc Welding (PCGTAW) method was employed. They also suggested that ER2553 filler is the most suitable for these dissimilar weldments for improving tensile properties. Devendranath *et al*., (2015) reported on the effects of fillers on AISI 430 and AISI 904L stainless steel combinations and concluded that there is an improvement in mechanical properties when Ni-based filler is employed. Arun, Devendranath & Vimala (2019) investigated similar metal weldments of SDSS UNS S32750 joined with ERNiCrMo-4 and ER2553 filler wires. High impact toughness and tensile strength properties were observed when ERNiCrMo-4 filler was employed. Rahmani *et al*., (2014) evaluated the weld quality, mechanical properties and metallurgical aspects of dissimilar joints between UNS S30403 and UNS S32750 with GTAW technique using ER2594 and ER309L as fillers. Impact strength and hardness of duplex filler weldment were better than for austenitic filler weldment. Zhou & Lothman (2017) employed the GTAW technique to develop dissimilar weldments of UNS S32750 and UNS S31254 by using two Ni-based filler wires. Multi-pass welding was used to join these dissimilar 12 mm thick plates. The Ni-based ERNiCrMo-13 filler was recommended for improving corrosion resistance and mechanical properties.

Fusion welding technique has been widely used for the fabrication of petrochemical equipment and pressure vessels used offshore and in nuclear industries (Javadi *et al*., 2017). Constant current in GTAW technique, where the heat inputs are continuous, have resulted in coarse grains and also elemental segregation near the fusion boundary (Dev, Ramkumar, Arivazhagan & Rajendran, 2018; Mohammed, Madhusudhan & Srinivasa, 2018). The problems associated with GTAW due to its continuous heat input rate can be minimized by using PCGTAW technique, which alters the arc characteristics from high to low levels. The beneficial effect most often stated was due to a reduction in heat input to the joint, helping to minimize porosity, segregation effects, distortions and induced stresses (Devendranath, Pavan & Chandrasekar, 2018; Verma & Taiwade, 2017). In PCGTAW technique, the base metals are heated and fusion will occur during main current and the weld zone is allowed to cool the molten pool while background current is maintained. The pulse frequency has a major influence on inter-mixing of filler in the fusion zone with the base metals, to create a proper overlap of molten metals in multi-pass welding to achieve desired bead shape and size (Yousefieh, Shamanian, & Saatchi, 2011). High frequency in PCGTAW technique practically do not result in thermal cycles with distinguishable high and low levels in current, rather it produces thermal cycles similar to GTAW, and hence the frequency range 0.5 – 5 Hz was suggested along with 40-60% duty ratio. The welding arc is found to be stable at low frequencies during PCGTAW operation within peak and background time intervals (Chennaiah, Kumar, & Rao, 2015; Dzelnitzki, 2000). Teng, Chang & Tseng (2003) reported on results of maintenance of low pulse spaces that increased the energy density of the heat sources. The results showed reduced distortions in the weldments prepared at low frequencies. Balram & Rajyalakshmi (2019) reported on residual stress distribution in dissimilar weldments of Monel 400 and stainless steel joined by GTAW and PCGTAW techniques. The residual stress distribution was observed to be lower when PCGTAW technique is used. Karunakaran (2012) studied the effects of peak current on size of aluminum weld bead and also reported that grain refinement is observed in weld joints with enhanced mechanical properties on using the PCGTAW technique. The mechanical and metallurgical properties were found to be improved in PCGTAW welds in comparison to GTAW welds of duplex and austenitic steels. An equal distribution of austenite and ferrite phases near the weld zone was observed when employing PCGTAW technique, which resulted in improved mechanical properties (Topolska, 2018).

In this research, mechanical properties and microstructural changes in the weldments of dissimilar stainless steels were studied with alternative filler wires used for joining the base plates. The dissimilar stainless steel metals, super-duplex stainless steel UNS S32750 and austenitic stainless steel AISI 304, were welded by PCGTAW technique with three alternative filler wires viz., ERNiCrMo-4, ERNiCrMo-3 and ER 309L. The welding conditions and input parameters were fixed for the three types of filler weldments. The study involved observation of uniformity of ferrite and austenite phases in microstructures, that affects the weld quality.

2. Materials and Experimental Set-Up

The base metals, UNS S32750 and AISI 304, were sliced into specimens of size 150 mm × 80 mm × 5 mm with Wire Electrical Discharge Machining (WEDM) technique. The chemical composition analysis of base metals, UNS S32750 and AISI 304, and filler wires, ERNiCrMo-4, ERNiCrMo-3 and ER309L, was carried out using spectroscopy. The analyzed elemental compositions by wt.% of base metals and fillers are listed in Table 1. PCGTAW technique was employed to join the base metals UNS S32750 and AISI 304 by using three alternative filler wires. The process parameters of PCGTAW technique were fixed for the three types filler weldments and the values are listed in Table 2. The heat input rates were calculated using equations 1 & 2 (Giridharan & Murugan, 2009; Traidia & Roger, 2011). Before proceeding with welding, tack welding was employed to maintain equal root gap between base metals. To protect the weld regions, argon gas was purged with a flow rate of 10 liters per minute. The dissimilar joints of UNS S32750 and AISI 304 were developed by LINCOLN 375 machine and developed weldments are shown in Figure 1.

$$Q_{\mathrm{PCGTAW}} = \eta \ \frac{V \ \mathrm{x} \ I_m}{s} \tag{1}$$

where η = welding arc efficiency (η_{PCGTAW} = 60%) (Abdollahi, Shamanian & Golozar, 2018), I_m = mean current.

$$I_m = \frac{I_b \ \mathrm{x} \ T_b + I_p \ \mathrm{x} \ T_p}{T_b + T_p} \tag{2}$$

Here, I_b and I_p are the background and pulse current; and T_b and T_p are the time intervals of background and pulse current.

Table 1. Chemical compositions (wt.%) of base plates and filler wires.

Base plates/ filler wires	Ni	Cu	Fe	C	Mn	Si	Mo	P	Cr	Others
UNS S32750	6.55	0.18	Bal	0.025	0.86	0.28	3.6	0.037	25.0	V – 0.077, N – 0.28, Co – 0.05, Nb – 0.05
AISI 304	8.14	Nil	Bal	0.04	1.64	0.39	Nil	0.022	18.01	S-0.005
ERNiCrMo-3	Bal	0.5	5.0	0.09	0.5	0.5	9.0	0.022	21.5	Co-9.1, Nb-3.5, Ti-0.4, Al-0
ERNiCrMo-4	Bal	0.05	5.45	0.02	0.5	0.03	16.9	0.007	15.9	Ti-0.10, V-0.18, Co-0.36, W-3.4
ER309L	12.2	Nil	Bal	0.03	1.5	0.53	Nil	0.024	23.4	Nil

Table 2. Process parameters used in PCGTAW technique in each welding pass.

Welding pass	Arc current (A)		Voltage (V)	Welding torch speed (mm/min)	Pulse frequency (Hz)	Heat input rates (kJ/mm)
	I_m	I_b				
Root pass	180	80	14±2	80	4	0.819
Filling pass	170	80	13±2	92	4	0.685
Capping pass	170	80	13±2	84	4	0.75

Figure 1. Dissimilar weldments of UNS S32750 and AISI 304 joined by using (a) ERNiCrMo-4, (b) ERNiCrMo-3 and (c) ER309L fillers

2.1 Sample preparation and testing

After welding the developed dissimilar weldments were tested using X-ray radiography for determining defects like porosity, voids, inclusions, etc. CEREM 235 machine was employed for radiography with an exposure time of 120 s. After this non-destructive testing, weldments were sliced into different sizes as per test standard on WEDM to carry out mechanical tests and microstructural studies. Uniaxial tension test using ADITYA UTE 40 was performed on the weld samples according to ASTM E8 standard. Tensile properties were determined with the cross-head velocity to 2 mm/min. Hardness measurements using MATSUZAWA MMT X7 were carried out on transverse samples of the weldments. The hardness readings were taken across the entire width of the weldments at regular 0.25 mm intervals using Vickers microhardness tester. A standard test load of 500 gf was applied for a dwell time of 10 s. Charpy-impact tests were carried out on the transverse coupons with notches machined at the center of the fusion zone as per ASTM E23:12C standard.

The weld specimens of size 50 mm × 5 mm × 5 mm were molded so as to show every zone of weldment for microstructural studies using OLYMPUS BX41M. Standard metallographic procedures were applied to the samples, which include mechanical polishing with emery sheets of various grit sizes, followed by disc polishing using alumina-distilled water solution to get scratch-free and mirror-like surfaces. The weldments were electrolytically etched using 10% oxalic acid for 10 s by use of a 6 V DC supply at current density of 1.6 A. The microstructures of weldments that were made using three alternative filler wires were photographed through an optical microscope.

3. Results and Discussion

3.1 Radiography test

The X-Ray Radiography Test (XRT) films of dissimilar welds are shown in Figure 2. The dissimilar weldments developed by using three types of filler wires were free from surface and sub-surface defects, such as inclusions, spatters, micro voids, etc. Also, uniformity in bead geometry was observed in weldments with all of the filler wires. The macrostructures of dissimilar weldments in all cases are shown in Figure 3. From the macro-structural examination and visual inspection, it was clear that narrow and uniform beads with complete fusion were attained in all three types of filler weldments. Also, ERNiCrMo-3 filler weldment showed superior penetration into the base metals over the other two types of filler weldments. The width of the fusion zone in ER309L filler weldment, especially at the cap region, was larger when compared to the other two types of filler weldments.

3.2 Behavior of joints under mechanical tests

3.2.1 Hardness test

The microhardness studies were performed across the welded joint covering fusion zone, HAZ and base metals. The hardness measurement was done at a distance of 2.5 mm from the weld root of the welded joint. The hardness profiles of all dissimilar weldments were plotted and are shown in

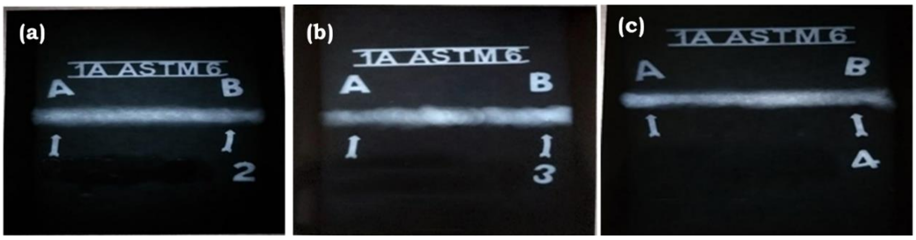

Figure 2. X-ray radiographs of dissimilar welds joined by using (a) ERNiCrMo-4, (b) ERNiCrMo-3 and (c) ER309L fillers.

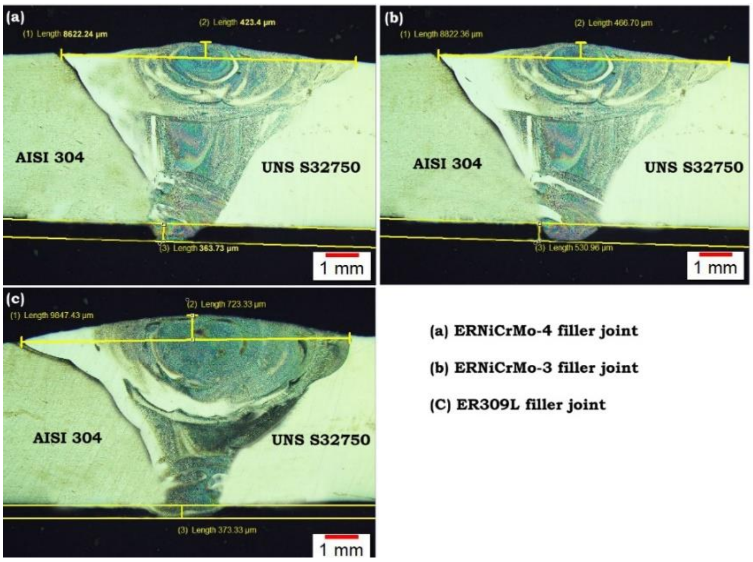

Figure 3. Macrostructures of dissimilar UNS S32750 and AISI 304 weldments prepared with three alternative filler wires.

Figure 7. In Figure 7, the microhardnesses of ERNiCrMo-4, ERNiCrMo-3 and ER309L filler weld zones were 318±2 $HV_{0.5}$, 306±2 $HV_{0.5}$ and 286±2 $HV_{0.5}$, respectively. The average microhardness and heat affected region width of dissimilar weldments were computed and are shown in Table 4. The average hardness in ERNiCrMo-4 and ERNICrMo-3 filler weldments was observed to be higher than of the base Metals UNS S32750 (284 HV) and AISI 304 (202 HV). As reported by Ramkumar *et al*. (2017), the presence of alloying elements such as Mo, W and Co in ERNiCrMo-4 and ERNiCrMo-3 fillers, increases the distortion of the matrix lattice and thus increases the microhardness at the fusion zone. The drop in hardness about HAZ of dissimilar UNS S32750 and AISI 304 has been observed in both ERNiCrMo-4 and ERNiCrMo-3 weldments when compared to fusion zones of the same. Abdollahi, Shamanian & Golozar (2018) reported that the presence of more ferrite phase in PCGTAW weldment caused improved microhardness. From Table 4, it is observed that the HAZ width of the ERNiCrMo-4 weldment is reduced on either sides of the parent materials compared to those of ERNiCrMo-3 and ER309L weldments.

3.2.2 Tensile properties

Tensile stress-strain graphs of base plates, UNS S32750 and AISI 304, as well as dissimilar weldments of UNS S32750 and AISI 304 obtained with three fillers, are shown in Figure 5. The average tensile properties were computed from testing three tensile coupons for each dissimilar welding joint type, and the values are listed in Table 3. Necking and fractures in specimens under tension were observed at the base metal AISI 304 indicating an improvement in the resistance of the weldments under tension. The failure location of weldments is shown in Figure 6. The average UTS of ERNiCrMo-4, ERNiCrMo-3 and ER309L filler weldments was observed as 642 MPa, 624 MPa and 612 MPa, respectively. The ratio of yield strength to ultimate tensile strength of ERNiCrMo-4 filler weldment was observed as 0.60, which is higher than for ERNiCrMo-3 (0.57) and ER309L (0.56) filler weldments. The results match the hardness data and the fracture occurred at base metal AISI 304. Results from stress-strain plots show that the proof stress of ERNiCrMo-4 weldment (389 MPa) was superior to the ERNiCrMo-3 weldment (354 MPa) and the ER309L weldment (343 MPa). The percentage of elongation of ERNiCrMo-4 weldment was larger than with the other two fillers or of the base metal UNS S32750.

3.2.3 Impact test

Impact test results of dissimilar weldments of UNS S32750 and AISI 304 are listed in Table 3. A photograph of fracture surfaces under toughness test of dissimilar welded samples is shown in Figure 4. It was observed from the impact studies that the ERNiCrMo-4 (189 J) filler weldment exhibited better toughness than the ERNiCrMo-3 (164 J) and

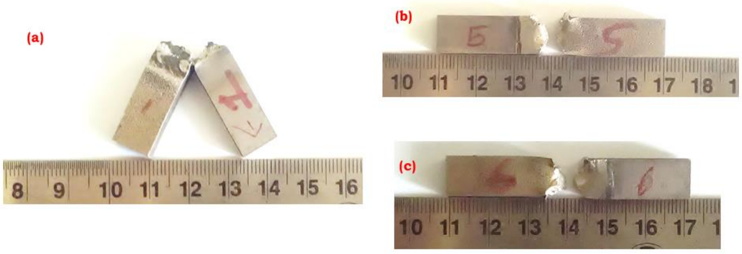

Figure 4. Impact test specimens of dissimilar joints joined by using (a) ERNiCrMo-4, (b) ERNiCrMo-3 and (c) ER309L fillers.

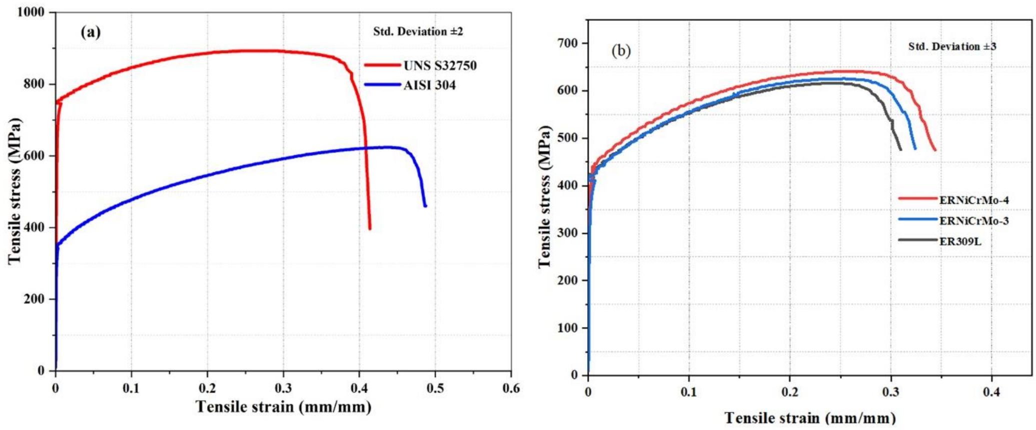

Figure 5. Stress-strain plots of (a) base metals, and (b) dissimilar weldments of UNS S32750 and AISI 304

Table 3. Impact and tensile test results of base metals and dissimilar weldments prepared with three alternative fillers.

Base plate/ filler weldment	Impact strength, J	Proof stress, MPa	UTS, MPa	% Reduction in area	%age of elongation	Fracture location
UNS S32750	203	579	925	50.18	38.68	-
AISI 304	62	354	632	56.72	59.10	-
ERNiCrMo-4	189	389	642	50.18	32	AISI 304
ERNiCrMo-3	164	354	624	56.72	25	AISI 304
ER309L	65	343	612	56.03	23	AISI 304

Table 4. HAZ width and hardness of various zones in the dissimilar weldments ±

Filler weldment	UNS S32750		Weld zone		AISI 304	
	HAZ (mm)	$HV_{0.5}$	Width (mm)	$HV_{0.5}$	HAZ (mm)	$HV_{0.5}$
ERNiCrMo-4	2.6	304 ± 2	4.6	318 ± 2	2.9	183 ± 2
ERNiCrMo-3	2.9	289 ± 2	4.6	306 ± 2	3.0	202 ± 2
ER309L	2.9	302 ± 2	4.7	286 ± 2	3.0	182 ± 2

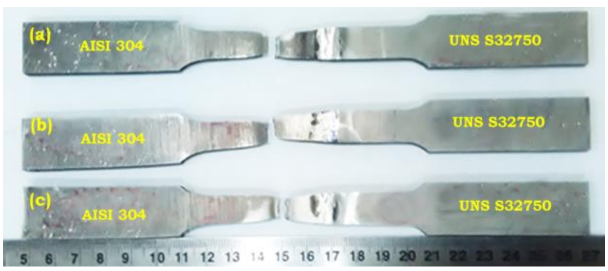

Figure 6. Tensile failure specimens of dissimilar weldments joined by using (a) ERNiCrMo-4, (b) ERNiCrMo-3 and (c) ER309L fillers.

ER309L (65 J) filler weldments. The impact energy of ERNiCrMo-4 filler weldment was improved by 65% when compared to that of ER309L filler weldment. It is inferred that this improvement in toughness was due to a greater amount of ferrite as observed from microstructures and also from hardness studies at the fusion zone of ER2553. Verma & Taiwade (2017) reported that welds exhibiting increased toughness had developed complete ferrite after solidification. Other researchers have made conclusions of improved toughness caused by the presence of appropriate amounts of ferrite and austenite in the fusion zones of duplex or super-duplex grade stainless steel. The mode of failure was identified to be ductile based on visual inspection, and from

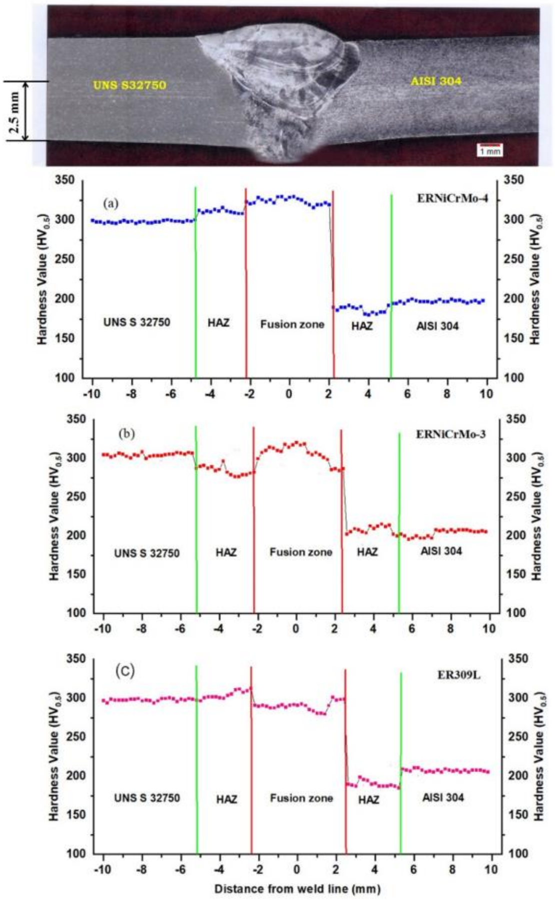

Figure 7. Hardness profiles of dissimilar weldments prepared with (a) ERNiCrMo-4, (b) ERNiCrMo-3 and (c) ER309L fillers.

photographs of impact toughness tests in ERNiCrMo-4 and ERNiCrMo-3 filler weldments, whereas brittle fracture was observed in ER309L filler weldment.

3.4 Microstructure studies

The microstructures of dissimilar weldments between UNS S32750 and AISI 304 made using ERNiCrMo-4, ERNiCRMo-3 and ER309L fillers are shown in Figure 8. It is observed from Figure 8 (a & b) that the weld zone has ferrite with austenite phases in the fusion zone when ERNiCrMo-4 and ERNiCrMo-3 fillers are employed. Dark ferrite zones with clear boundaries were identified in the ERNiCrMo-4 filler weldment. The fusion zones of ERNiCrMo-3 and ERNiCrMo-4 welds have shown complete austenite phases with ferrite boundaries. Two phases, i.e., ferrite and austenite can be seen in both specimen's microstructures. Different shapes and proportions of these phases can be observed where the difference in ferrite percentages can be related to cooling rate. No grain coarsening was found in ERNiCrMo-4 or ERNiCrMo-3 weldments. Grain coarsening was found at the interface of AISI 304 when ER309L filler was employed.

4. Conclusions

In this experimental study, dissimilar welded joints of SDSS UNS S32750 and AISI 304 were developed successfully by using three alternative fillers, ERNiCrMo-4, ERNiCrMo-3 and ER309L. The following conclusions summarize the results.

- The tensile properties of ERNiCrMo-4 weldment were superior to the other two filler weldment cases (ERNiCrMo-3 and ER309L). This can be attributed to the presence of uniform ferrite and austenite phases. The proof stress of ERNiCrMo-4 weldment was larger by

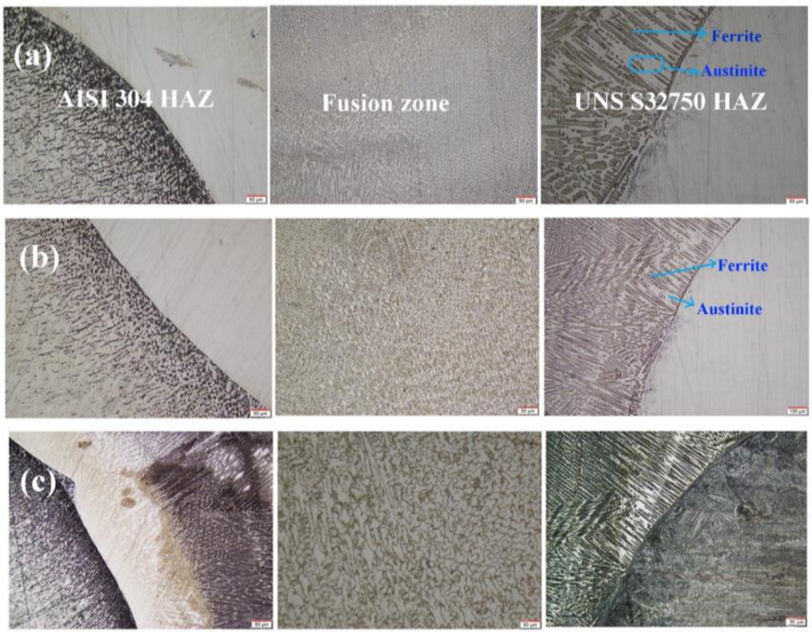

Figure 8. Microstructures of dissimilar weldments prepared with (a) ERNiCrMo-4, (b) ERNiCrMo-3 and (c) ER309L fillers

9.8% and 13.5% when compared to proof stresses of ERNiCrMo-3 and ER309L weldments, respectively. Tensile failures were observed at the parent metal AISI 304 for all three filler weldments.

- The average microhardness of ERNiCrMo-4 weldment was higher than of the other two filler weldments and this could be attributed to the distortions caused in the matrix by Ni and Mo alloying elements from filler. The microhardness of ERNiCrMo-4 filler weldment was larger by 4% and 10% when compared to ERNiCrMo-3 and ER309L filler weldments, respectively.
- In impact studies the ERNiCrMo-4 and ERNiCrMo-3 filler weldments exhibited higher toughness than the ER309L filler weldment.
- For producing mechanically sound weld structures, ERNiCrMo-4 filler was found to be suitable for welds between the dissimilar metals UNS S32750 and AISI 304.

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