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Characterization of weld strength and toughness in the multi-pass welding of Inconel 625 and Super-duplex stainless steel UNS S32750

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Abstract

The present study investigated the weldability of dissimilar metals involving Inconel 625 and Super-duplex stainless steel obtained from continuous current (CC) and pulsed current (PC) gas tungsten arc welding (GTAW) processes employing ER2553 and ERNiCrMo-4 fillers. A comparative analysis on these dissimilar weldments was carried out to establish the structure-property relationships. Microstructure examination was carried out using optical microscopy (OM) and scanning electron microscopy (SEM) techniques. Grain coarsening was observed at the HAZ of UNS S32750 for all the cases. Mechanical tests ascertained that the PCGTA weldments employing ERNiCrMo-4 offered better weld strength and impact toughness. Elaborative studies on the structure – property relationships of these dissimilar weldments were discussed.

Keywords: Inconel 625; super-duplex stainless steel; CCGTAW; PCGTAW; tensile strength; impact toughness.

1. Introduction

Dissimilar metal combinations have become more acquainted and are widely used in oil refineries, chemical and petrochemical industries, power plants including nuclear, aerospace and other engineering applications due to economic considerations and offered flexibility to design. Both Inconel 625 and Super-duplex stainless steels are used in geothermal and offshore industries due to their excellent combination of strength and corrosion resistance. It was reported by Michael van Wijngaarden and James Chater [1] that CalEnergy, an independent power producer in California produces 340 megawatts of electricity through geothermal operations. Further the authors addressed that in different applications throughout the plant, the combinations of Inconel 625 (in high- temperature) and duplex stainless steels (in low- temperature) had performed well.

Several researchers [2-5] reported about the weldability of bimetallic combinations on Inconel and stainless steel grades. As claimed by these researchers, the major concern associated with dissimilar metal welding of Ni based super alloys with stainless steel grades is the selection of appropriate filler wire. Solidification cracking, heat affected zone (HAZ) liquation cracking, formation of secondary phases / unmixed zone at the HAZ were some of the major drawbacks associated with the improper selection of filler metal [6].

Sridhar et al. [7] investigated the micro-structural features of dissimilar joints of Inconel 625 and SAF 2205 obtained by GTAW process employing ER2209 and ERNiCrMo-3 filler wires The authors observed the formation of laves phase while welding these bimetals using ERNiCrMo-3 filler. Similarly the ER2209 weldments offered lower toughness. Shah Hosseini et al. [5] studied the microstructure and mechanical properties of Inconel 657 and AISI 310 stainless steel dissimilar joints using different filler wires such as Inconel 82, Inconel 617 and 310SS. The authors reported that amongst the filler metals employed for joining these dissimilar metals, Inconel 617 offered better impact toughness. Devendranath et al. [2] investigated the bimetallic combinations of Inconel 718 and AISI 316L employing ER2553 and ERNiCu-7 fillers with an objective to control the

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deleterious phases containing enriched constituents of Nb, Mo, Ti and Si. Even though Nb additions in the filler wire helps in reducing the hot cracking tendency, the higher constituents of Nb and Mo leads to the formation of hard, intermetallic phases which tend to deteriorate the strength and ductility of the welds [3,8,9]. Mismatching of composition and strengths of the base and filler metal tends to lower the yield strength due to the agglomeration of large amount of residual stresses during joining process [10, 11]. Hence a filler metal plays a major role in the joining of dissimilar metals. Devendranath et al. [12] investigated the metallurgical and mechanical properties of the GTA welds of UNS S32750 employing ER2553 and ERNiCrMo-4 fillers. The authors inferred that the weldments employing ER2553 offered better tensile and impact properties compared to the weldments employed over-alloyed filler such as ERNiCrMo-4. Fabrizia Caiazzo et al. [13] investigated the disk-laser welding of dissimilar aerospace materials such as Haynes 188 and Inconel 718 super alloys by autogeneous mode. The authors reported the absence of laves phase on employing the welding technique and further they inferred that the tensile fractures occurred at the weld interface of Inconel 718 side.

The use of current pulsing in GTA welding process has received attention in the recent past due to several advantageous effects in terms of metallurgical and mechanical properties. Researchers reported the typical benefits accrued from PCGTA welding process that include (i) lower distortion (ii) lower residual stresses (iii) reduced porosity and segregation (iv) minimized width of HAZ. Several researchers addressed the use of PCGTA welding for joining similar metals such as aluminium alloys [14], austenitic stainless steels [15], Tantalum [16], Inconel 617 [17]. Patterson and Milewski [18] investigated the PCGTA weldments of Inconel 625 and AISI 304L by autogeneous mode and inferred that the PCGTA welds were prone and more sensitive to weld solidification cracks. In another study, Devendranath et al. [3] compared the CCGTA and PCGTA welding for joining Inconel 625 and AISI 304 employing ERNiCrMo-3. It was inferred from the study that although both the weldments offered almost same tensile strength, however the segregation effects were almost nil for the PCGTA weldments.

Hitherto, there is a limited work reported on these bimetallic combinations involving Inconel 625 and super-duplex stainless steel. Hence this work assumes lot of significance in the chemical, petro-chemical industries and geothermal plants employing these joints. The present study addressed the weldability of these dissimilar metals using CCGTA and PCGTA welding employing two fillers namely ER2553 and ERNiCrMo-4. As claimed by the other researchers, the Nb rich filler wire such as ERNiCrMo-3 is expected to produce deleterious laves phase which in turn affects the strength and ductility of the weldments and hence not being used in the current study. Hence over-alloyed Ni based ERNiCrMo-4 filler wire which is enriched with the alloying elements such as Mo, Co etc. and the super-duplex stainless steel filler such as ER2553 has been employed in the current study. Detailed structure – property relationships of the weldments were carried out using combined techniques of optical microscopy (OM) and scanning electron microscopy (SEM).

2. Experimental procedure

2.1 Base metals and welding procedure

The as-received base metals were cut to the dimensions of 20 x 20 x 5 mm to carry out chemical composition analysis using wet spectroscopic methods. The nominal chemical composition of the base and filler metals employed in the present investigation is represented in Table 1. The microstructure of the base metals Inconel 625 and UNS S32750 is shown in Fig. 1(a), 1(b). Further the base metals of dimensions 170 mm × 50 mm × 5 mm were sliced using the Wire-cut Electrical Discharge Machining (WEDM) process to carry out welding. Standard V-Butt configurations (single V-groove having a root gap of 2 mm, size land of 1 mm and included angle of 60 degrees) were employed on these base metals before welding. A specially designed welding fixture with grooved copper back plate was used to facilitate the heat dissipation during welding and the fixture was clamped firmly in order to keep these base metals in alignment and for providing accurate gripping to avoid bending during the process.

The weld process parameters were established based on the iterative trials and the parameters chosen for the current study are shown in Table 2(a) and 2(b). Bimetallic joints of Inconel 625and UNS S32750 obtained from CCGTA and PCGTA welding techniques using ER2553 and ERNiCrMo-4filler wires. The filler wires were chosen based on their compatibility with any one or both of the parent metals in terms of chemical composition. The welded specimens were subjected to different metallurgical and mechanical characterization and are outlined in the subsequent chapters.

Table 1. Chemical composition of the base and filler metals

Base/ Filler metal	Chemical composition (% by Weight)									
	C	Si	Mn	Cr	Mo	Fe	Ni	Nb	N	Others
Inconel 625	0.022	0.104	0.169	Rem.	9.33	4.24	59.65	2.98	---	Cu - 0.157; P - 0.004; S - 0.010; Al - 0.101; Co - <0.005; Ti - 0.235; Ta - <0.02
UNS S32750	0.029	0.395	0.789	24.86	3.63	Rem.	6.42	---	0.262	P - 0.029; S - 0.005
ER2553	0.025	0.28	0.82	25.2	3.3	Rem.	5.5	---	0.25	P - 0.02; S - 0.003
ERNiCrMo-4	0.02	0.05	0.85	15.5	15.2	6.5	Rem.	---	Nil	Cu - 0.35; Co - 0.12; W - 3.1 V - 0.13

Table 2(a). Process parameters employed in CCGTA welding

Welding	Filler wire	No. of Pass	Current (A)	Voltage (V)	Filler wire dia. (mm)	Shielding gas flow rate (lpm)
CCGTAW	ER2553	Root	160	11.0-11.5	2.4	15
		Filler Pass 1	165	11.6-12.4		
		Filler Pass 2	170	13.1-14.5		
		Cap	170	13.1-14.5		
	ERNiCrMo-4	Root	160	11.0-12.0	2.4	15
		Filler Pass 1	165	11.8-13.4		
		Filler Pass 2	170	12.5-13.6		
		Cap	170	12.5-13.6		

Table 2(b). Process parameters employed in PCGTA welding

Welding	Filler wire	No. of Pass	Current (A)		Voltage (V)	Pulse Time		Frequency	Duty Cycle	Filler wire dia.	Shielding gas flow rate
			Peak Current	Back ground current		T_{on}	T_{off}	(Hz)		(mm)	(lpm)
PCGTAW	ER2553	Root	220	165	10.6-11.8	0.4	4	10	25	2.4	15
		Filler Pass 1	220	165	11.7-12.8	0.4	4				
		Filler Pass 2	220	165	12.3-13.6	0.4	4				
		Cap	220	165	12.9-14.1	0.4	4				
	ERNiCrMo-4	Root	220	165	10.8-11.6	0.4	4	10	25	2.4	15
		Filler Pass 1	220	165	12.4-13.6	0.4	4				
		Filler Pass 2	220	165	13.0-14.4	0.4	4				
		Cap	220	165	12.5-13.4	0.4	4				

2.2 Metallurgical and mechanical characterization of dissimilar weldments

Gamma ray Non-Destructive Testing (NDT) technique was carried on these dissimilar weldments to determine for any flaws. Followed by NDT analysis, the as-welded plates were cut to coupons of various dimensions according to the standards using WEDM process for assessing the metallurgical and mechanical properties. The microstructure studies and hardness measurements were carried out on the coupons termed as “composite zone” having dimensions of 30 mm × 10 mm × 5 mm obtained by keeping the weld as centre. Standard metallographic procedures including polishing with emery sheets of SiC with grit size varying from 220 to 1000 followed by disc polishing using alumina and distilled water were employed on these coupons to obtain a mirror finish of 1μ on the weldments. It is normally difficult to reveal the microstructure of the dissimilar metal joints as there exists the differences in composition and phases. Hence it is normally difficult to use a single etchant for revealing the structure for the dissimilar joints. However in the present study, electrolytic etching (10% oxalic acid; 6 V DC supply; Current density 1.6 A/cm^2) was employed to reveal the grain structure of the different zones of the weldments.

Micro-hardness studies were carried out on the transverse coupons of these dissimilar weldments. Hardness measurements were carried out across the entire width of the weldments by keeping weld as center using Vicker's Micro-hardness tester. A standard load of 500 gf was employed for a dwell period of 10 s and the measurements were carried out at regular intervals of 0.25 mm. Transverse tensile studies were carried out on the coupons prepared as per the ASTM E8/8M standards using Instron universal testing machine. The cross-head velocity was set to 2 mm/min to produce a strain rate of 3.3 × 10^{-4} s^{-1}. This strain rate is well in the range as prescribed by ASM International handbook of Mechanical Testing and Evaluation [6]. To study the response of the weldments to sudden loads, Charpy V-notch impact studies was also carried out on the sub-sized samples (55mm × 10mm × 5 mm) fabricated as per ASTM E23-12C standards. Notches were made in such a way that the fracture occurred only within the weld fusion zones.

3. Results

3.1Base metals

The microstructure of the base metals Inconel 625 and UNS S32750 are shown in Fig. 1.

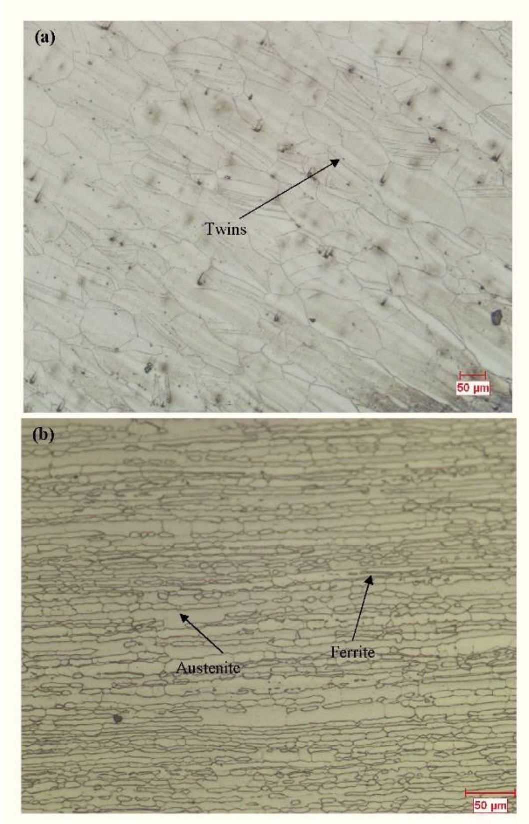

Fig. 1. Microstructure showing the base metal of (a) Inconel 625 (b) Super-duplex stainless steel.

The elongated, coarser austenitic grains with the presence of twin boundaries and some inter-metallic dark phases were observed in the parent metal of Inconel 625; whereas the base metal UNS S32750 showed the dual phase microstructure containing almost equal amounts of ferrite (54%) and austenite (46%) as inferred from the ferrite measurement study through Fischer Ferritoscope. The average tensile strengths of the base metals were observed to be 798 MPa (Inconel 625) and 820 MPa (UNS S32750).

3.2 Macrostructure examination

Macrographs of dissimilar weldments of Inconel 625 and UNS S32750 obtained by different welding techniques and filler wires are shown in Fig. 2.

Fig. 2. Photographs showing the dissimilar weldments of Inconel 625 and UNS 32750 by CCGTA and PCGTA welding techniques employing ER2553 and ERNiCrMo-4 filler.

It is evident that proper fusion had occurred with the base metals for all the cases. NDT analysis corroborated that the weldments were free from any surface and sub-surface flaws such as porosities, under-cut, inclusions etc.

3.3 Microstructure studies

3.3.1 CCGTA weldments

Interface microstructures of the CCGTA weldments are shown in Fig. 3. The austenitic matrix with the presence of twins was observed at the parent metal of Inconel 625. A slight grain coarsening was noticed at the HAZ of UNS S32750 for both the fillers [Fig. 3(a), 3(c)]. Also the presence of unmixed zone or grain boundary thickening was inferred at the HAZ of Inconel 625 employing ER2553 weldments [Fig. 3(b)]. Well defined fusion boundary was observed at the Inconel 625 side for ERNiCrMo-4 filler [Fig. 3(d)].

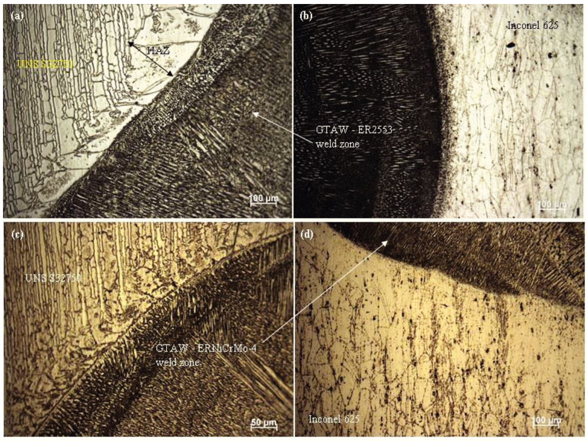

Fig. 3. Interfacial microstructures of CCGTA weldments of Inconel 625 and UNS 32750 employing (a), (b) ER2553 filler and (c), (d) ERNiCrMo-4 filler respectively.

3.3.2 PCGTA weldments

In case of PCGTA weldments, as stated above, the grain coarsening at the HAZ and the presence of skeletal ferrite was observed at the fusion zone adjacent to UNS S32750 for ER2553 filler [Fig. 4(a)]. Both cellular and dendritic growth was observed at the weld zone for all the weldments. Fine equi-axed dendritic growth was also noticed at the fusion zone adjacent to the UNS S32750 side for all the weldments [Fig. 5(a) to 5(d)].

3.4 SEM/EDAX analysis

3.4.1 CCGTA weldments

SEM/EDAX point analysis carried out on the various zones of the CCGTA weldments employing ER2553 filler is shown in Fig. 6. It was observed that the weld matrix contained higher amounts of Fe, Cr and Ni whereas the spectrum analysis at the dendritic arms showing white, tiny precipitates reflected the presence of enriched amounts of Nb, Cr, Mo, Ni and Fe [Fig. 6(a)]. Similarly the formation of secondary phases (appeared to be white precipitates) was also observed at the weld interface of Inconel 625. Also the formation of laves phase was noticed at the weld interface and HAZ of the CCGTA weldments. EDAX point analysis showed that these phases were enriched with the elements such as Nb, Cr, Mo, Ni and Fe [Fig. 6(b)]. SEM analysis at the fusion zone of ERNiCrMo-4 weldments revealed cellular and dendritic growth at UNS S32750 side. It is inferred from the point spectra analysis [Fig. 7(a)] that the grain coarsened HAZ and the fusion zone adjacent to UNS S32750 showed enriched amounts of Fe, Cr, Ni and Mo. On the other hand, the HAZ of Inconel 625 depicted the presence of higher amounts of Ni, Cr and limited amount of Fe, Mo. The fusion zone adjacent to the Inconel 625 showed the presence of enriched amounts of Ni, Mo, Cr, Fe and W [Fig. 7(b)].

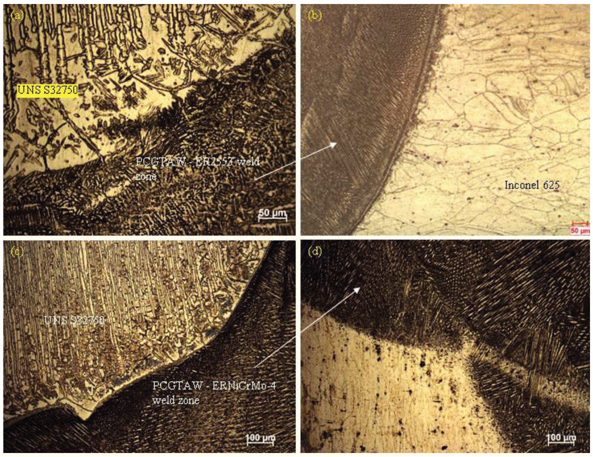

Fig. 4. Interfacial microstructures of PCGTA weldments of Inconel 625 and UNS 32750 employing (a), (b) ER2553 filler and (c), (d) ERNiCrMo-4 filler respectively.

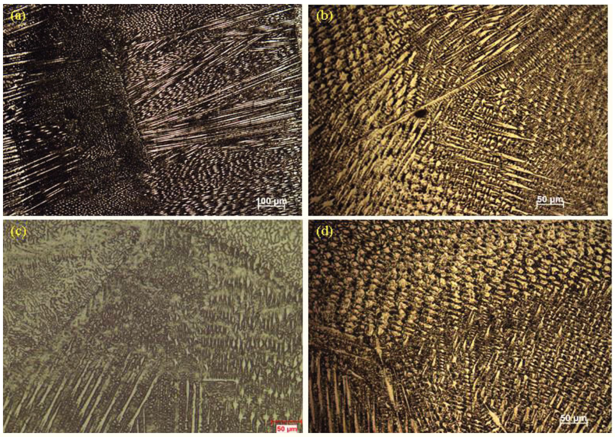

Fig. 5 Weld microstructure showing the multi-directional grain growth in CCGTA weldments employing (a)ER2553 (b)ERNiCrMo-4 and PCGTA weldments employing (c)ER2553 (d) ERNiCrMo-4 fillers respectively.

3.4.2 PCGTA weldments

The EDAX point analysis carried out at the HAZ of UNS 32750 employing ER2553 filler depicted the presence of elements such as Fe, Cr, Ni and Mo whereas the weld zone is enriched with elements such as Fe, Cr, Ni, Mo and lesser amounts of Nb and Al [Fig. 8(a)]. The tiny white precipitates appeared at the weld interface of Inconel 625 contained Ni, Nb, Mo, Cr and Fe which would be probably the Laves phase. These tiny phases were found to be scarce as compared to CCGTA weldments employing the same filler wire [Fig. 8 (b)].

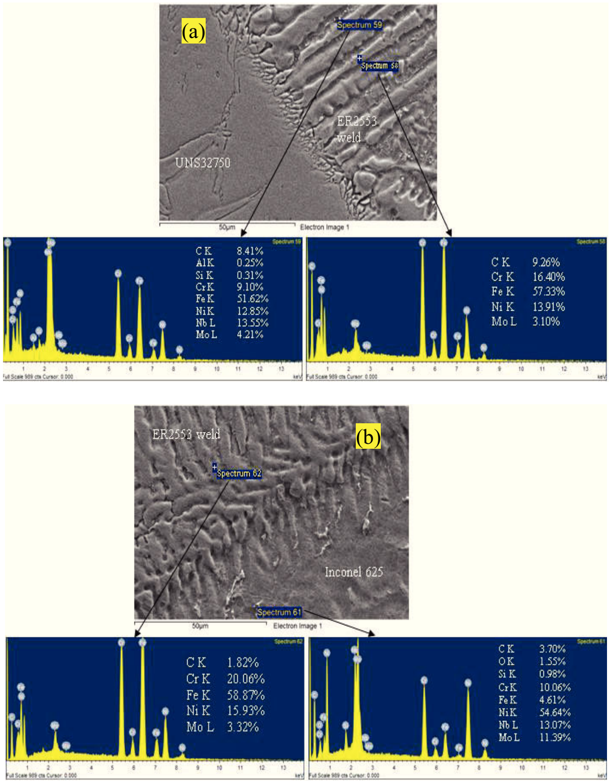

Fig. 6. SEM photographs showing the CCGTA weldments employing ER2553 (a) weld interface of UNS 32750 and (b) weld interface of Inconel 625.

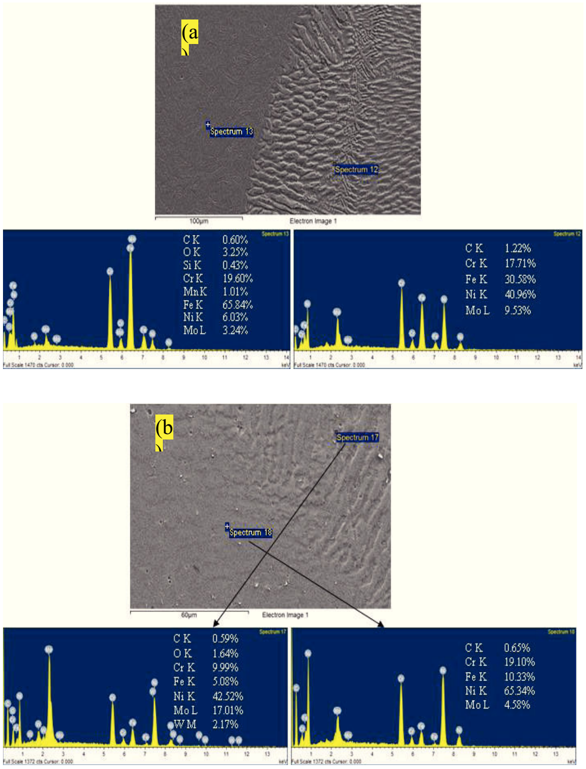

Fig. 7. SEM photographs showing the CCGTA weldments employing ERNiCrMo-4 (a) weld interface of UNS 32750 and (b) weld interface of Inconel 625.

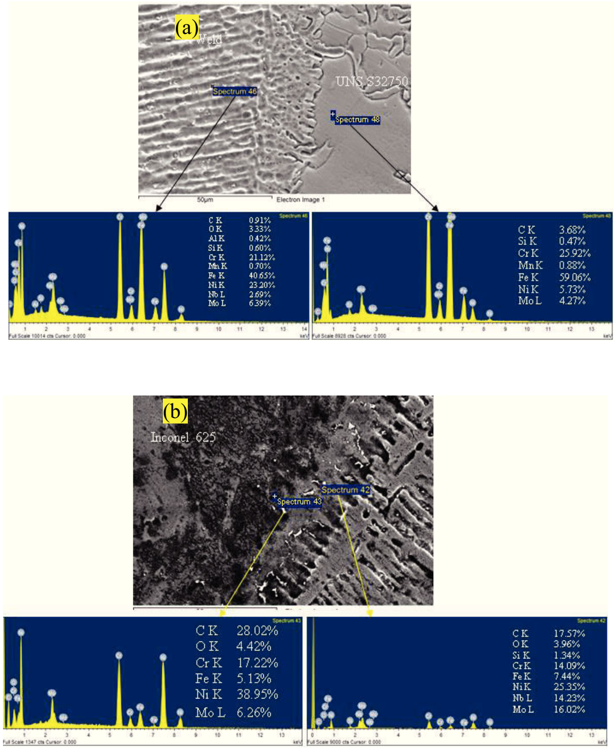

Fig. 8. SEM photographs showing the PCGTA weldments employing ER2553 (a) weld interface of UNS32750 and (b) weld interface of Inconel 625.

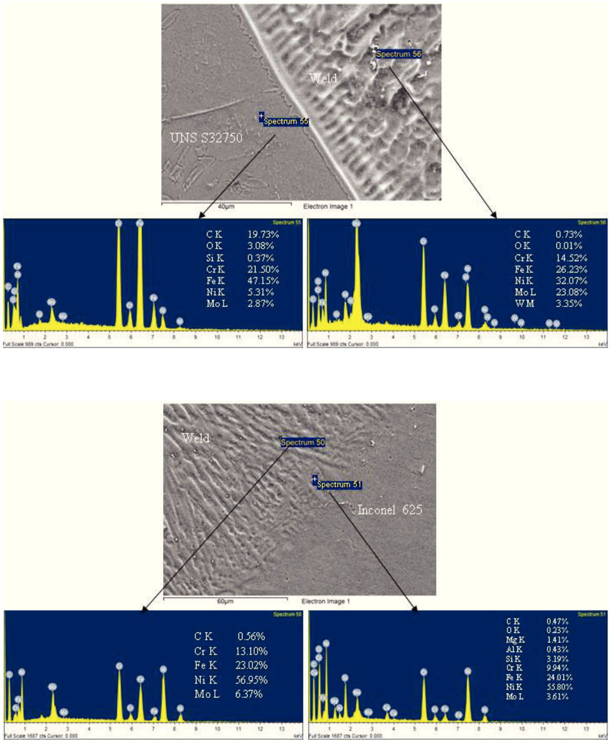

Fig. 9. SEM photographs showing the PCGTA weldments employing ERNiCrMo-4 (a) weld interface of UNS 32750 and (b) weld interface of Inconel 625.

3.5 Micro-hardness measurements

3.5.1CCGTA weldments

Hardness measurements were carried out in three different passes vis-à-vis cap, middle (filler) and root of the CCGTA weldments. Hardness plots of the CCGTA weldments are shown in Fig. 10. The average hardness of the base metals is found to be 296 HV for UNS S32750 and 255 HV for Inconel 625 respectively. It was inferred from the hardness studies that the average hardness was found to be greater for the weldments employing ER2553 filler (288 HV) as compared to ERNiCrMo-4 (268 HV). Similarly the average hardness at the weld zone in various passes was found to be 277 HV (ER2553 weld) and 243 HV (ERNiCrMo-4 weld) respectively. A closer observation divulged that across the various passes, maximum hardness (300 HV) was observed in the cap region for ER2553 weldment and middle pass for ERNiCrMo-4 weldment (250 HV).

3.5.2 PCGTA weldments

The cumulative hardness plot at the various passes of PCGTA weldments are shown in Fig. 11. The average hardness of the ERNiCrMo-4 weldment (278 HV) was found to be greater compared to ER2553 weldments (265 HV). Similarly the average hardness observed at the weld zone was found to be 261 HV for ERNiCrMo-4 and 252 HV for ER2553 filler. It is well understood that the root region of both the weldments reported to have maximum hardness. The cumulative hardness data of CCGTA and PCGTA weldments across the various passes are represented in Fig. 12 and Table 3.

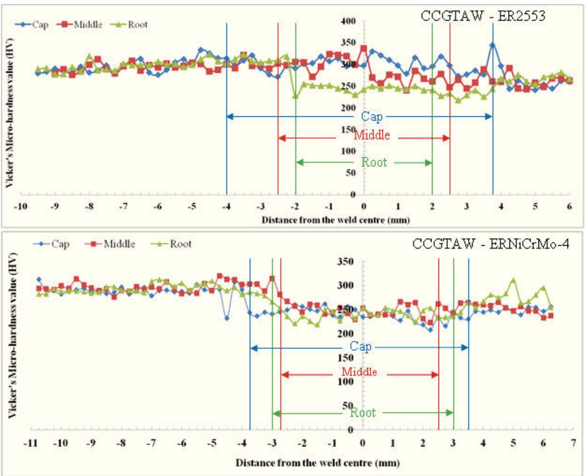

Fig. 10. Hardness profile of the CCGTA weldments of Inconel 625 and UNS S32750 employing (a) ER2553 and (b) ERNiCrMo-4 filler.

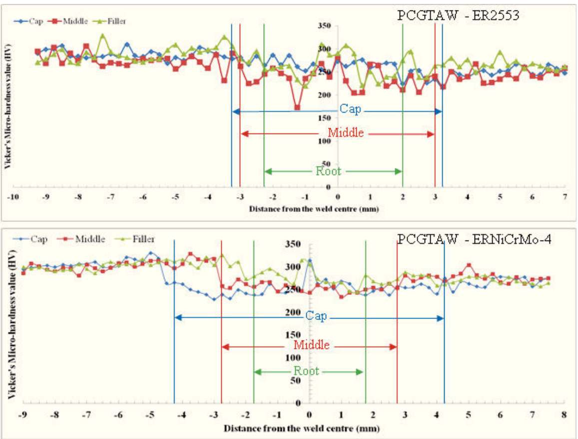

Fig. 11. Hardness profile of the PCGTA weldments of Inconel 625 and UNS S32750 employing (a) ER2553 and (b) ERNiCrMo-4 filler.

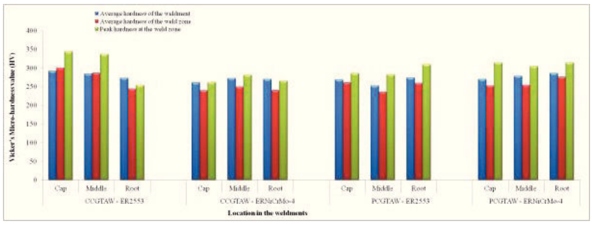

Fig. 12. Cumulative hardness comparison plot of Inconel 625 and UNS S32750 dissimilar welds.

3.6 Tensile test

3.6.1 CCGTA weldments

Tensile studies showed that the weldments employing ERNiCrMo-4 offered better ductility and strength compared to ER2553 weldments. The average tensile strength and proof stress of the ERNiCrMo-4 weldments were found to be 762 and 285 MPa respectively whereas for ER2553 weldments, the corresponding values were 653.5 and 313.4 MPa respectively. The average ductility was reported to be 22.4% and 6.1% for ERNiCrMo-4 and ER2553 weldments respectively. It was noticed that tensile failures occurred at the weld zone for both the weldments in all the trials [Fig. 13].

Further SEM analysis was carried out on the fractured samples to depict the mode of fracture. The results showed that the CCGTA weldments employing ER2553 filler was observed to have shiny ductile tearing ridges with the cleavage facets [Fig. 15(a)] whereas presence of micro-voids with cracked boundaries and shiny tearing, fibrous networks were the features observed at ERNiCrMo-4 weldments [Fig. 15 (b)].

Table 3. Average Hardness data of the dissimilar weldments

Hardness (HV)	CCGTAW						PCGTAW					
	ER2553			ERNiCrMo-4			ER2553			ERNiCrMo-4		
	Cap	Middle	Root	Cap	Middle	Root	Cap	Middle	Root	Cap	Middle	Root
Average hardness of the weldment	293	284	273	261	272	270	269	252	274	270	279	286
Average hardness of the weld zone	300	287	245	240	250	240	271	236	260	253	254	277
Peak hardness at the weld zone	344	337	254	262	281	266	286	282	310	315	304	315

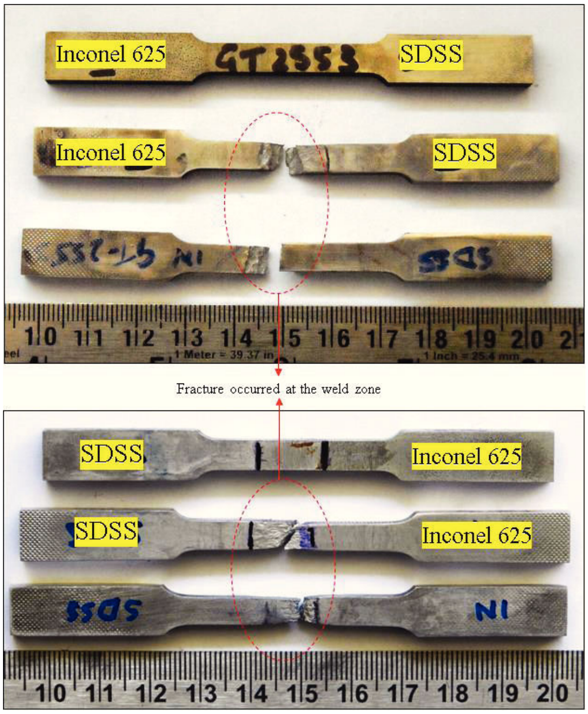

Fig. 13. Photographs showing the tensile tested samples of CCGTA welded Inconel 625 and UNS S32750 employing (a) ER2553 and (b) ERNiCrMo-4 filler

3.6.2 PCGTA weldments

Similar to CCGTA weldments, the PCGTA weldments also showed the similar trend in tensile studies such that the ductility and strength of ERNiCrMo-4 weldments were found to be better compared to ER2553 weldments. The average tensile strength of ERNiCrMo-4 weldments was found to be 791.5 MPa and 669 MPa for ER2553 weldments. Also the proof stress and ductility was reported to be 304 MPa and 5.9% for the weldments employing ER2553 filler and 300 MPa and 27.2 % for the weldments employing ERNiCrMo-4 filler. As observed in CCGTA weldments, the tensile failures occurred at the weld zone in all the trials for both the cases [Fig. 14].

It was well inferred from the SEM fractography analysis that the PCGTA weldments employing ER2553 filler exhibited the cleavage facets with interface de-bonding whereas the ERNiCrMo-4 weldments were observed to have micro-voids and dimples surrounded in the shiny tearing ridges and the formation of fibrous networks [Fig. 15(c) and 15 (d)].The cumulative tensile properties of these dissimilar weldments are shown in Table 4.

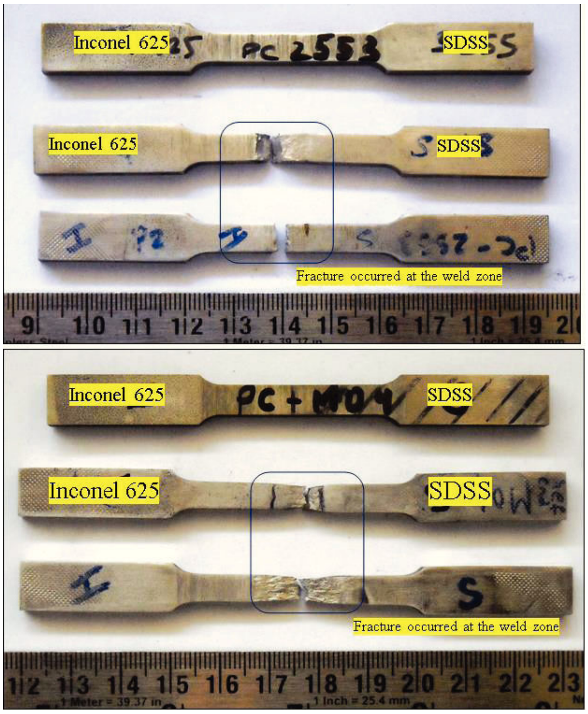

Fig. 14. Photographs showing the tensile tested samples of PCGTA welded Inconel 625 and UNS S32750 employing (a) ER2553 and (b) ERNiCrMo-4 filler.

3.7 Impact Test

It is important to study the response of these weldments to sudden loads and hence the Charpy V-notch studies [Fig. 16] were conducted on the sub-sized ASTM E23-12C standard coupons. It was observed from the test results that both CCGTA and PCGTA weldments employing ER2553 exhibited inferior impact toughness whereas the CCGTA and PCGTA weldments using ERNiCrMo-4 filler offered impact toughness values of 31.4 and 34.3 J respectively.

Table 4. Average tensile properties of the dissimilar weldments

Property	Unit	CCGTA welds		PCGTA welds	
		ER2553	ERNiCrMo-4	ER2553	ERNiCrMo-4
Maximum Load	kN	21.1	24.6	21.9	25.4
Tensile strength	MPa	653.5	762.0	669.0	791.5
0.2% yield strength	MPa	313.4	285.0	304.0	300.0
Ductility	%	6.1	22.4	5.9	27.2
Fracture Zone	---	Weld	Weld	Weld	Weld

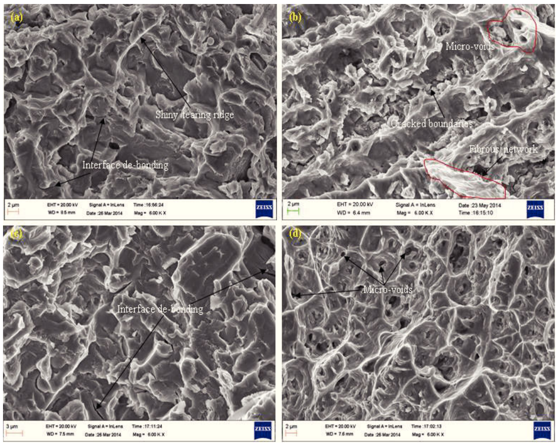

Fig. 15. SEM fractograph of tensile tested samples showing CCGTA weldment employing (a) ER2553 (b) ERNiCrMo-4; PCGTA weldment employing (c) ER2553 (d) ERNiCrMo-4 filler respectively.

SEM fractography results showed the presence of striation markings with shiny tearing ridges for the CCGTA and PCGTA weldments employing ER2553 filler [Fig. 17(a), (c)].Whereas presence of scarce voids and the secondary phases were the fractography features observed on the weldments employing ERNiCrMo-4 filler [Fig. 17 (b), (d)]. Table 5 shows the average impact toughness of the dissimilar weldments of Inconel 625 and UNS S32750.

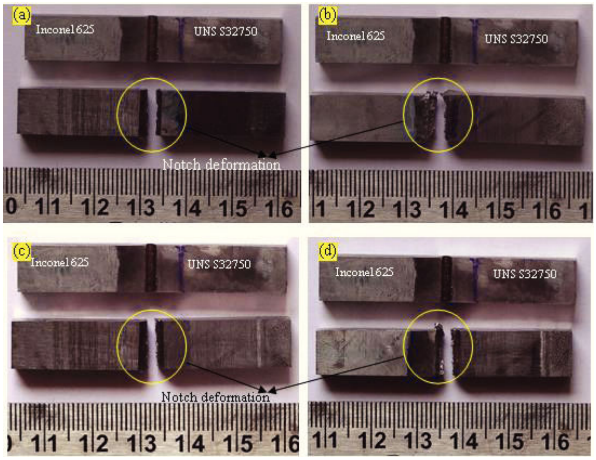

Fig. 16. Impact tested samples of CCGTA weldments employing (a) ER2553 and (b) ERNiCrMo-4 filler and PCGTA weldments employing (c) ER2553 and (d) ERNiCrMo-4 filler respectively.

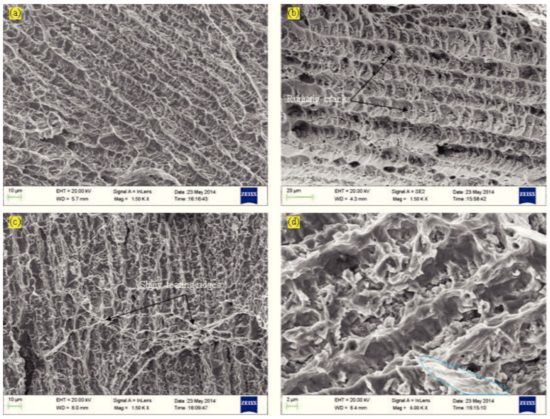

Fig. 17. SEM fractograph of impact tested samples showing CCGTA weldment employing (a) ER2553 (b) ERNiCrMo-4; PCGTA weldment employing (c) ER2553 (d) ERNiCrMo-4 filler respectively

Table 5. Average impact toughness of dissimilar weldments

Weldment	Impact toughness (J)
CCGTA weldment - ER2553	5.0
CCGTA weldment - ERNiCrMo-4	31.4
PCGTA weldment - ER2553	5.9
PCGTA weldment - ERNiCrMo-4	34.3

4. Discussion

This study elucidated the use of both continuous current and pulsed current GTA welding process employing ER2553 and ERNiCrMo-4 for obtaining the bimetallic combinations of Inconel 625 and UNS S32750. Macrostructure studies showed that complete fusion occurred with the base metals on using these filler metals. Further the gamma ray NDT analysis corroborated that the weldments were free from any surface or sub-surface defects which indicated that the process parameters employed in the study were quite appropriate.

Microstructure studies inferred the formation of unmixed zone at the HAZ of Inconel 625 for both CCGTA and PCGTA weldments employing ER2553, which shall be attributed to the differences in the chemical composition and coefficient of thermal expansion values of the base and filler metals. Also there was no solidification cracking observed in any of the weldments. This could arise due to the presence of Mo and Nb in the filler and parent metal. As reported by various researchers [7, 19] the presence of Nb in the filler wire reduces the solidification or hot cracking tendency. As reported by Shah Hossenini et al. [5], higher heat inputs result in lower cooling rates and thereby lower segregation ratio of Mo which also improves the hot cracking resistance. The weld microstructures of both CCGTA and PCGTA weldments employing ER2553 filler showed the presence of skeletal delta ferrite at the cap of the weld zone. It is known that ferrite grows from austenite and requires very slow cooling rate for this transformation to happen. As the filler wire ER2553 has both ferrite and austenite phases and moreover a slow cooling rate exhibited by these welding processes resulted in the skeletal delta ferrite morphology at the weld zone. It is evident from the weld microstructures that the primary solidification mode of ER2553 weldments would be Ferritic – Austenitic (FA) whereas the complete Austenitic (A) mode / Austenitic- Ferritic (AF) was observed for ERNiCrMo-4 weldments.

Multi-directional grain growth containing columnar and cellular dendrites was observed in the middle and filler pass of the weldments which were due to the consequence of multi-pass welding. Also the weld zone was observed to have tiny dark phases precipitated in the dendritic network. Similarly the grain coarsening effect was observed at the HAZ of UNS S32750 for all the cases of weldments. However the width of grain coarsened zone was typically large for CCGTA weldments compared to PCGTA weldments which could be well understood due to the higher heat inputs and slower cooling rate in the CCGTA welding process. Interface microstructure at the HAZ of Inconel 625 side of the CCGTA and PCGTA weldments employing ERNiCrMo-4 revealed the absence of unmixed zone which was nurtured due to the matching composition of the base and filler metals. Similar observations were reported by Shah Hossenini et al. [5]. However the grain coarsening was observed at the HAZ of UNS S32750 for the CCGTA weldments and the effect was minimized in the PCGTA weldments. As witnessed from the EDAX point analysis, tiny white phases appearing in the weld zone and at the HAZ of Inconel 625 were found to have the predominant elements such as Nb, Mo, Ni, Cr and Fe and identified to be Laves phase. However the amount of laves phase was found to be meager in the PCGTA weldments employing ER2553 and ERNiCrMo-4 compared to CCGTA weldments. The formation of laves phase has been controlled in the weld zone while employing these fillers compared to the earlier works of the author [7].

As indicated by several researchers [8, 9], the formation of laves phase could be minimized on employing current pulsing technique. As reported by Naffakh et al. [4], Niobium not only lowers the melting point constitutionally, but also forms low-melting carbide-austenite eutectics during solidification.

Hardness studies showed that the average hardness of the weld zone for CCGTA weldments was found to be greater than the PCGTA weldments for ER2553 filler. From the cumulative hardness plot, it is clearly inferred that the cap zone of CCGTA weldments (300 HV) elucidated for higher hardness compared to PCGTA weldments (261 HV) which is due to the presence of skeletal δ ferrite. It is evident that the austenite to ferrite transformation requires very slow cooling rate. As CCGTA welding employs slow cooling rates compared to PCGTA welding, it resulted in higher amounts of ferrite and austenite which in turn contributed for greater hardness. The hardness plots of CCGTA and PCGTA weldments employing ERNiCrMo-4 filler [Fig. 10 (b) and 11(b)] clearly portrayed that the average hardness of the CCGTA weld zone at different passes exhibited lower hardness compared to the PCGTA weld zone. As reported by Eslam Ranjbarnodeh et al. [23], the residual stresses in welds increase with increasing yield stress of the materials employed. Further the authors reported that higher yield stress would result in the material to resist more against the contraction and will have the higher residual stresses. This is well in agreement with the current studies that the yield stress of Inconel 625 and UNS S32750 was 300, 500 MPa respectively. Due to the presence of residual stresses, the hardness values slightly plummeted at the weld zone of all the weldments compared to the base metals.

The epitome of the tensile studies showed that the failures occurred in the weld zone for all the cases. However the PCGTA weldments employing ERNiCrMo-4 demonstrated better tensile strength (791.5 MPa) compared to other weldments. A closer observation on the tensile studies exemplified that the CCGTA and PCGTA weldments employing ERNiCrMo-4 exhibited better strength and ductility compared to ER2553 weldments. As claimed by DuPont et al. [20], the presence of excess amount of delta ferrite contributed for lower ductility. This statement is well in agreement with the present study that the microstructure of ER2553 was observed to have more delta ferrite which would be the cause for lowering the ductility.

In case of the ERNiCrMo-4 weldments, the presence of W, Mo in the filler wire and Nb in the parent metal contributed for higher strength; however the failures occurred at the weld zone for both the cases. The weld microstructure shown in Fig. 5(b), 5(d) clearly depicted the segregation effect in the dendritic and cellular network. Due to the presence of segregated elements such as Mo, W in the filler and Nb in the parent metal there requires a higher degree of under-cooling to change the solidification mode from dendritic to cellular. The dendrite arm spacings in the weld zone were found to have the segregation of Mo rich phases. It was reported that Mo segregation would affect the ductility of the welds. However the present study showed higher tensile strength and ductility on using ERNiCrMo-4 filler. Moreover the PCGTA welds employing ERNiCrMo-4 showed the strength which was almost equal to the strengths of one of the base metal, Inconel 625 (798 MPa). Further to support the discussion, it was inferred from the SEM fractography results shown in Fig. 14 that the presence of interface de-bonding observed in the ER2553 weldments and the absence of voids clearly indicated that the mode of failure was found to be brittle. Whereas the cracked boundaries with the presence of scarce voids in the fibrous network [Fig. 15(b)] depicted the CCGTA weldments employing ERNiCrMo-4 filler would have undergone mixed mode of fracture i.e. ductile – brittle. Fig. 15(d) clearly demonstrated the presence of micro/macro-voids with shiny tearing ridges which were coalesced in the fibrous network contributing for ductile fracture for PCGTA weldments employing ERNiCrMo-4.

Charpy V-notch results clearly portrayed that the PCGTA weldments employing ERNiCrMo-4 filler showed better response to impact loading compared to the other weldments. However the toughness values offered by these weldments were found to be lower compared to the base metals. The weld toughness of both CCGTA and PCGTA weldments employing ER2553 got lowered as indicated in Table 5. The reason for the deterioration of impact strength of these weldments could be reasoned due to solidification nature of these welds which would have been either ferritic (F) or ferritic-austenitic (FA) mode. As reported by Ogawa et al. [21], if the primary solidification is fully F or FA mode, there shall be degradation in the impact toughness values. Moreover the nitrogen content available in the filler metal apart from its advantageous effect of promoting the austenite formation, introduces the adverse effect of degradation of impact toughness [22]. Devendranath et al. [12] reported the balanced proportion of austenite and ferrite in the weld zone could normally induce better toughness on employing ER2553 filler compared to over-alloyed filler wire. In the present study, the ferrite in the form of skeletal form was observed only in the cap of the weld zone of ER2553 weldments. The microstructure results of ER2553 weldments were also in compassionate to the discussion such that the mixture of austenite and delta ferrite was observed in the weld zone. The hardness plots indicated that the weld hardness of ER2553 CCGTA weldments was quite higher which also supported the same. Even though the ERNiCrMo-4 filler had produced fully austenitic (A) or austenitic – ferritic (AF) solidification mode, the weld impact toughness was lower than the base metals. This could be reasoned due to the presence of dark intermetallic phases as inclusions in the weld zone which were well seen from the weld microstructures [Fig. 5]. As reported by RamazanYılmaz et al. [22], even a small amount of hard particles present in the matrix could cause a decrease in impact toughness values. As evident from the SEM fractography results, both the CCGTA and PCGTA weldments employing ER2553were observed to have brittle mode of fracture when subjected to impact loading, by virtue of the presence of typical striation markings on the fractured zones. The scare voids with the shiny tearing ridges and striations indicated the mixed mode (ductile-brittle) of fracture for CCGTA and PCGTA weldments employing ERNiCrMo-4 filler. Also the cracks were running across the grain boundaries which were surrounded by the inter-metallics containing Mo rich phases as inferred from the EDAX analysis.

In a nutshell, this study investigated the weldability of Inconel 625 and Super-duplex stainless steel (UNS S32750) obtained from CCGTA and PCGTA welding employing ER2553 and ERNiCrMo-4 fillers. In the present study, the two filler wires have been chosen based on their compatibility of the base metals in terms of chemical composition. The intuition of the study is to develop the welding technology for joining these dissimilar metals using the filler wires which should not induce the deleterious phases. The outcomes of the study narrated that these filler wires have not indulged in the formation of harmful laves phase in the weld zone. Also it is evident from the study that the PCGTA weldments employing

ERNiCrMo-4 offered better strength, ductility and impact strength compared to other weldments. The outcomes of the study will be highly beneficial to the industries employing these bimetallic combinations especially in chemical, marine and geothermal applications.

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